# DEVELOPING METHODOLOGY TO PREDICT AND INCREASE GRAIN PROTEIN CONTENT IN SPRING WHEAT

A Thesis
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agricultural and Applied Science

By

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In Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE

Major Department:
Plant Sciences

November 2017

Fargo, North Dakota

# North Dakota State University
## Graduate School

**Title**

Developing Methodology to Predict and Increase Grain Protein Content in Spring Wheat

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

**MASTER OF SCIENCE**

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# ABSTRACT

A challenge for hard red spring wheat (HRSW) (*Triticum aestivum* L. emend Thell.) producers is to obtain both high yields and market-required grain protein content (GPC). The ability to accurately predict HRSW yield with the Decision Support System for Agrotechnology Transfer (DSSAT) crop model early in the growing season may help producers determine probable GPC and lead to management decisions on whether to apply supplemental nitrogen (N) to enhance protein. A management decision HRSW producers may consider in high yielding environments is a late-season foliar N application to increase GPC. A second objective of this research was to test methods to improve the efficiency of a foliar N application. Improving the efficiency of a late-season foliar N application coupled with the ability to predict high yielding environments using DSSAT, can provide producers with effective management tools to determine the optimum situation in which supplementing GPC will have the most economic success.

# ACKNOWLEDGMENTS

I would like to express my gratitude to my advisor, Dr. Joel Ransom, whose leadership and dedication, motivated me to reach my personal and professional goals. I also want to thank him for his time and patience with me.

I gratefully acknowledge Dr. Hans Kandel, Dr. Dave Franzen, and Dr. Rich Zollinger, for their valuable help throughout the graduate process. Their expertise in the plant and soil sciences, as well as their time reading and critiquing this thesis helped immensely towards its completion.

I especially want to thank everyone that helped in maintaining my research plots, recording data, and giving advice: Chad Deplazes, Darin Eslinger, Grand Mehring, Calli Feland, Lizzie Lovering, Tracie Hillenbrand, Ben Cigelske, Melissa Geiszler, Matthew Rellaford, J Stanley, Kory Johnson, and Peder Schmitz.

Furthermore, I would like to thank my family and friends for providing the support while completing my degree. To conclude, I want to extend a special thank you to the state of North Dakota for providing funding of this research, as well as North Dakota State Univsersity and the NDSU experiment stations for supporting this research.

# PREFACE

This thesis was written as two manuscripts that will be submitted for publication in the appropriate scientific journals. The ‘Introduction’ provides a general review of this study and how both chapters are related to the main issue, developing methodology to predict and increase grain protein content in spring wheat. Following the Introduction, the thesis is divided into two manuscripts which contain Introduction, Materials and Methods, Results and Discussion, Conclusion, and References Cited sections that are specific to the chapter. The references for the ‘General Introduction’ can be found in the ‘General References Cited’ section.

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# INTRODUCTION

Hard red spring wheat (HRSW) (*Triticum aestivum* L. emend Thell.) producers not only depend on quantity of grain in terms of yield, but also need to achieve market-standard grain protein content (GPC) in order to achieve maximum economic returns. Previous research has indicated a negative relationship between yield and GPC within a given cultivar and at a given level of fertility, which poses a challenge for HRSW producers as quality discounts at point of sale result when protein levels do not reach the market-standard (Alkier, 1972). However, a premium can usually be obtained when GPC levels exceed the market-standard (Jones and Olson-Rutz, 2012). Environmental and agronomic challenges influence maximum yield, which may encourage some HRSW producers to make in-season management decisions in order to regain the desired yield if the factors are negative, or may prompt some to conduct an in-season nitrogen (N) application if yield is likely to be high and the probability of a price premium for high GPC seems likely.

The ability to accurately predict yield may assist producers in determining probable GPC; however, environmental factors that influence crop growth and yield are highly unpredictable between years. A crop simulation model (CSM), such as the Decision Support System for Agrotechnology Transfer (DSSAT) is a prediction tool that uses environmental and agronomic interactions to determine soil impacts, crop growth, and yield components (Boote et al., 2015). The DSSAT-CSM has been used extensively to predict yield with preseason weather and agronomic inputs such as planting, fertilizer, and irrigation options (Bannayan et. al, 2003). Implementing DSSAT-CSM with in-season weather information has not been as widely studied for HRSW production, but its use may prove be an effective predictive tool to help producers make improved management decisions.

A management decision HRSW producers may consider in high yielding environments is an application of foliar N, such as urea (46-0-0) solution (US) or urea ammonium nitrate (UAN, 28-0-0), to increase GPC. Increasing GPC has been successfully practiced through this additional N application between ZGS 45 and ZGS 73 with the most effective at ZGS 69 (Zadoks et al., 1974); however, the efficiency of N absorption into the plant has been limited (Finney et al., 1957; Jones and Olson-Rutz, 2012). Therefore, developing methods to improve the efficiency of this foliar N application may prove to be economically feasible.

Developing techniques to improve N use efficiency from a late-season foliar N application coupled with improved yield prediction through the use of DSSAT-CSM may result in improved protein management for producers. These tools can assist producers in determining when supplemental N would have the greatest economic benefit.

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# ARTICLE 1: RELIABILITY OF PREDICTING SPRING WHEAT YIELD WITH DSSAT USING EARLY SEASON WEATHER DATA

## Abstract

A crop simulation model (CSM) can be a predictive tool to help hard red spring wheat (HRSW) (*Triticum aestivum* L. emend Thell.) producers make in-season crop management decisions, such as a late-season foliar N application to increase grain protein content (GPC) in high yielding environments. The objective of this research was to evaluate the Decision Support System for Agrotechnology Transfer (DSSAT) CSM in predicting HRSW yield at various points in the growing season to determine how early the model could be implemented to accurately predict final grain yield. Historic weather data was used in three approaches (distribution, historical average, analogue) to forecast weather for the remainder of the season from Zadoks growth stage (ZGS) 14, 45, and 61 for five locations throughout North Dakota. Across environments the strength of relationship between observed and simulated anthesis date and yield was significant at $p \leq 0.01$. The optimum approach to simulate grain yield with forecasted weather was through a distribution style from ZGS 45 or 61.

## Introduction

Weather events are often unpredictable and vary considerably between and within years. These events have a tremendous impact on the success of agricultural producers due to the environmental impact on yield potential. In order to obtain the desired grain quality, HRSW producers often make in-season management decisions based on the weather. However, generalized weather patterns are frequently used, which can make these decisions risky due to lack of specific accuracy (Hansen et al., 2000).

Crop models, such as DSSAT, are software applications that use environmental and agronomic interactions to predict soil processes, vegetative growth, and yield outcomes (Batchelor et al., 2015). The DSSAT has the potential to predict these outcomes with defined weather and agronomic inputs, which allows users to make improved crop management recommendations (Hansen et al., 2000). In this paper the abbreviation ‘DSSAT’ will refer to the software application of the CSM used in this study.

In HRSW production, GPC determined at the point of sale must meet the market-standard level to avoid discounts for low GPC or receive a premium if GPC is greater. For a given cultivar, a negative relationship exists between yield and GPC at a given level of soil fertility. A management technique to increase GPC is through a foliar application of N fertilizer between the ZGS 45 and 73 growth stages (Finney et al., 1957). However, this application is not economical unless crop yields coupled with the premium increase or discount results in revenue that is greater than the cost of the additional N application.

A decision to make the additional application of N carries risk due to the unknown yield of the current crop, since future weather events throughout the season are unpredictable. Yield and protein prediction can be done through multiple strategies, but do not take into consideration the impact of future weather. The DSSAT has predictive capabilities by using updated weather information during the growing season supplemented with estimated future weather. Therefore, the use of DSSAT may be beneficial to agricultural producers by more accurately simulating crop growth, allowing for proactive in-season management practices to achieve maximum economic return.

## Crop Simulation Models and DSSAT Overview

Crop simulation models estimate crop growth and yield throughout the growing season by simulating the multiple ecological and agronomic interactions that impact growth. These include daily weather data, soil characteristics, and crop management practices (Batchelor et al., 2003). The DSSAT is a computer program developed in 1985 and first released in 1986 for maize (*Zea mays* L.), wheat, soybean (*Glycine max* L.), and peanut (*Arachis hypogea* L.) crops (Batchelor et al., 2003). Further upgraded versions included an expansion of 42 crops and improved model calibration. The DSSAT simulates crop development, ontogeny, and phenology through heat unit accumulation and using carbon, N, and water balance principles within a defined area (Clarke et al., 2010).

The DSSAT incorporates models for broadleaf and cereal crops within a single program. The CROPGRO model computes the growth of various broadleaf crops and is further described by Boote et al. (1998). The CERES-maize, wheat, and barley (*Hordeum vulgare* L.) models compute the growth of cereal crops. Crop developments in the CERES models are regulated by growing degree days (GDD), which are computed internally from daily maximum and minimum temperatures uploaded into the program. Clarke et al. (2010) details the function of CERES-wheat model with a base temperature for GDD calculations of 0°C.

The soil program within DSSAT integrates water, temperature, carbon, and N within the soil profile. A soil series is represented by a one-dimensional profile that is vertically layered and horizontally homogenous (Batchelor et al., 2003). Decomposition of organic matter and plant availability of N is determined by two primary soil organic modules, CENTURY (Parton et al., 1988; Parton et al., 1994) and PAPRAN (Seligman and Van Keulen, 1981). Soil water content is determined by soil layer characteristics and changes as water is supplied by precipitation or irrigation. The lower limit and saturated water content within each layer is computed and subsequent water exceeding the drained upper limit percolates to the soil layer below and continues downward for each layer, depending on the initial amount of water added. Surface water runoff is computed using a modified runoff curve number from the USDA-Soil and Conservation Service (Williams, 1990). Soil evaporation is computed by an approach used by Priestly and Taylor (1972). Nutrient availability and movement use similar functions as soil water.

The DSSAT accounts for genotypic and phenotypic variations within a specific crop to environmental conditions. This allows for more accurate representations of cultivar-environment interactions (Batchelor et al., 2003). To represent the genetic makeup of a crop and cultivar, data files within the program have set parameters called genetic coefficients. The genetic coefficients are determined for each cultivar using crop, weather, and soil data (Batchelor, et al., 2003). Crop species may require different coefficients. Wheat genetic coefficients include vernalization, photoperiod response, grain filling duration, interval between leaf tip appearances, kernel number per unit canopy weight at anthesis, kernel size, and non-stressed mature tiller weight.

A strength of DSSAT is that expensive and time-consuming agronomic experiments can be simulated in a relatively short amount of time; however, limitations exist within models. Model performance is limited by the accuracy of the input variables, which can be affected by spatial and temporal variability, costs of measuring data, and technical knowledge. Model performance is only as good as the data quality input (Antle et al., 2016). Misuse as well as misrepresentation or misunderstanding of the tool can affect the usefulness of the model; therefore, limitations of the model output must be understood.

## Crop Modeling Techniques

Crop model development began from a need for improving decisions for multiple environments from a single system that combined soil, climate, crops, and management information (Batchelor et al., 2003). The crop modeling software has been used extensively by researchers as a supplement to experiments and more recently has been used to support management decisions for producers (Boote et al., 1996). The DSSAT has specifically been used for research on the impact of fertilization, irrigation, pest management, climate variability, and site-specific farming on crop production. A new concept in the use of DSSAT by consultants is to forecast yield to help agricultural producers make management decisions (Bannayan et al., 2003).

Spring wheat producers might directly benefit from the use of a CSM if yield can be more accurately predicted for their region. As the growing season progresses, yield prediction is increasingly more accurate, whereas early season weather provides limited guidance for later season conditions and yield prediction. Bannayan et al. (2003) used the CERES-wheat model to predict wheat yield during the growing season with updated weather conditions as the growing season progressed. Results indicated forecasting grain yield improved significantly from early vegetative growth stages through the appearance of the flag leaf, with no significant improvement after that point.

Crop models have been used to forecast yield on both a small and large-scale through different approaches (Bannayan et al., 2003). In these approaches, the weather throughout the entire growing season is unknown, so past weather data are often used as an indication of probable future weather patterns. One technique in forecasting is to use past weather represented by daily averages calculated over multiple years. This approach uses a generalized climate since it does not take into account the variability that can exist between years and will give a single predicted outcome of crop production (Barnett, 2004). A range of crop production expectations for a given year can be achieved when multiple past weather years are used for the same forecast. This range will give a distribution of outcomes with a maximum, median, and minimum expectation. The ability to accurately predict yield early in the growing season would be beneficial to producers and researchers as this would allow them the opportunity to make in-season management decisions more successfully (Batchelor et al., 2001).

## Predicting Yield and Grain Protein

Spring wheat producers can effectively estimate grain yield prior to harvest through multiple techniques including kernel counts (Wiersma and Ransom, 2005), empirical based models (Balaghi et al., 2008), or proximal canopy sensing (Arnall et al., 2006). However, these techniques have limitations. For example, kernel counts are not taken until late in the growing season when it is too late to improve yield with additional inputs. Empirical based models and canopy sensing indicate the current condition of the crop, but cannot take into consideration the impact of future weather. Crop simulation models may be a tool that can assess the current condition of the crop and use estimated future weather to give an accurate assessment of yield. In turn, producers can use this information to make late season management decisions.

A foliar application of N fertilizer during the fruiting period in HRSW may be a management option to increase GPC (Baltensperger et al., 2008). However, this application may not be economical if the yield is not high enough to realize an economic benefit from the additional application. The premium received for protein levels above the market threshold of 140 g kg$^{-1}$ for HRSW and 120 g kg$^{-1}$ for hard red winter wheat is not fully realized until after harvest due to the uncertainty of GPC of the current crop. The level of GPC is only determined after harvest, as there are currently no techniques to predict protein levels in-season.

Grain yield and GPC have an inverse relationship for a given cultivar and at a certain level of soil fertility. Therefore, understanding the impact of weather events on grain yield may indicate whether GPC levels are likely to be high or low. Weather variables such as temperature, solar radiation, soil moisture, and nutrient availability directly impact grain yield. Wheat response to N applications can depend on water and nutrient availability with low response to N in environments with low soil moisture from lack of rainfall or high temperatures. The DSSAT has the ability to depict the effect of weather events on the soil and crop to provide an estimation of end season yield. If high yields are estimated by the crop model, with insufficient N, then the simulations may provide support for a late season foliar N application to increase GPC.

## Objective

The objective of this research was to determine if DSSAT could be used to predict HRSW yield in order to support a decision on the use of a late season foliar N application. If so, a further objective was to determine the best strategy to predict yield with estimated future weather through multiple modeling approaches at various HRSW growth stages.

## Materials and Methods

### Crop Model Experiment Setup

In order for simulations to be conducted within the DSSAT, hypothetical experiments had to be created with the experiment builder called the ‘Crop Management’ program. The program combines management inputs to enable of the simulation of soil and crop behavior. Required inputs for the experiment builder include cultivar, soil series, weather data, planting characteristics, fertility and water conditions, simulation execution and harvest dates, and model functions (water and nutrients on/off). In this study, the DSSAT version 4.6 was used to simulate separate HRSW experiments using inputs for the years 2005-2016 at Carrington, Hettinger, Langdon, Minot, and Williston, ND.

All input variables were the same for each experiment except planting date, soil type, and weather data. Planting dates for each location and all years are presented in Table 1.1. The required planting information included seeding rate, seeding depth, and row width, which were set at 290 seeds $m^{-2}$, 4 cm, and 18 cm, respectively. Other required information includes initial field conditions such as previous crop with N credit. The previous crop was not known; therefore, wheat was set as the previous crop since it provided no N credit. Simulation start date and nutrient and water options were also set the same across all locations. The simulation start date was set to the day of planting and water set to run using recorded precipitation. Fertilization information was not available for all years so the assumption was made that experiments were fertilized to the recommended level and not limited throughout the year so nutrient options were turned off.

Simulations were executed for each year and location for a total of 60 simulations (5 locations, 12 years). Anthesis date (days after planting, DAP) and grain yield were extracted to be used for statistical analysis. Additional simulations were executed within the ‘Sensitivity Analysis’ program with the various formatted weather files. The sensitivity analysis enables the user to change a single variable such as planting population, planting date, weather year, soil type, or cultivar in a previously created experiment. Then, the experiment can be simulated again rather quickly with the new variable.

Table 1.1. Planting dates needed to run model simulations for five locations in North Dakota in 2005-2016.

| Year | Langdon | Carrington | Hettinger | Minot | Williston |
|---|---|---|---|---|---|
| 2005 | 16 May | 21 April | 1 May† | 1 May† | 28 April |
| 2006 | 09 May | 20 April | 1 May† | 1 May† | 05 May |
| 2007 | 24 April | 27 April | 1 May† | 1 May† | 27 April |
| 2008 | 29 April | 15 April | 1 May† | 1 May† | 23 April |
| 2009 | 19 May | 06 May | 1 May† | 07 May | 23 April |
| 2010 | 20 April | 23 April | 12 April | 11 May | 23 April |
| 2011 | 17 May | 06 May | 2 May | 11 May | 13 May |
| 2012 | 24 April | 17 April | 28 March | 25 April | 25 April |
| 2013 | 16 May | 13 May | 23April | 15 April | 10 May |
| 2014 | 14 May | 02 May | 22 April | 15 May | 09 May |
| 2015 | 28 April | 10 April | 10 April | 23 April | 24 April |
| 2016 | 02 May | 12 April | 01 April | 02 May | 03 May |

† Planting date not available. An assumed planting date of 1 May was used to run model simulations.

## Weather Data and Forecasting Approach

Daily minimum and maximum air temperature, rainfall, and solar radiation were collected from the North Dakota Agricultural Weather Network (NDAWN) for the period 1991-2016 for Carrington, Hettinger, Langdon, Minot, and Williston, ND (NDAWN, 2017a). The weather data were uploaded into the WeatherMan program within DSSAT. WeatherMan compiles the weather data with weather station details to be used within the experiment builder (Batchelor et al., 2015). The NDAWN weather station information is presented in Table 1.2.

Table 1.2. Location, coordinates, and elevation of weather station locations obtained from the North Dakota Agricultural Weather Network.

| Location | Latitude | Longitude | Elevation |
|---|---|---|---|
| | °N | °W | m |
| Carrington | 47.51 | -99.13 | 475 |
| Hettinger | 46.01 | -102.64 | 840 |
| Langdon | 48.76 | -98.35 | 492 |
| Minot | 48.18 | -101.29 | 542 |
| Williston | 48.13 | -103.74 | 649 |

The accuracy of crop growth can be predicted by updating DSSAT with measured weather data throughout the growing season. This concept was applied by Bannayan et al., 2003 for forecasting winter wheat yield. A similar approach was used in this study. Weather data had to be in the proper format before being uploaded into WeatherMan. Weather files were formatted with historic daily measured data from January 1 through ZGS 14, 45, and 61, then from that date supplemented with historical measured data throughout the remainder of the year. This procedure was done in three different ways (analogue, distribution, historic average), referred to as modeling approaches. The dates of these growth stages were estimated using the NDAWN wheat GDD calculator (NDAWN, 2017b), which predicts wheat growth stages through a method developed by Bauer et al. (1984).

The historic weather data was formatted in three different ways to forecast weather for the remainder of the season in order to determine the best technique to simulate yield with DSSAT. These were referred to as 'modeling approaches' and are described as analogue, distribution, and historical average. An analogue represents a previous weather year with a similar weather pattern as the current weather year up to the point in the season where future weather data is needed. The weather analogue program (WAP) within DSSAT uses historic weather conditions at a given location and estimates a previous year (analogue year) that is best representative of the current year. The WAP estimated an analogue year from measured weather data up to each growth stage. The weather data from the selected analogue year was then used after each growth stage through the remainder of the year to give a single outcome. The distribution modeling approach used daily historic weather data from 1991-2016 after each growth stage through the remainder of the year. This provided a distribution of outcomes with higher yields in favorable weather years, and poor yield in years when weather was suboptimal for HRSW growth. The historical average modeling approach used daily averages (1991-2016) after each growth stage through the remainder of the year. Figure 1.1 further illustrates how weather data were formatted.

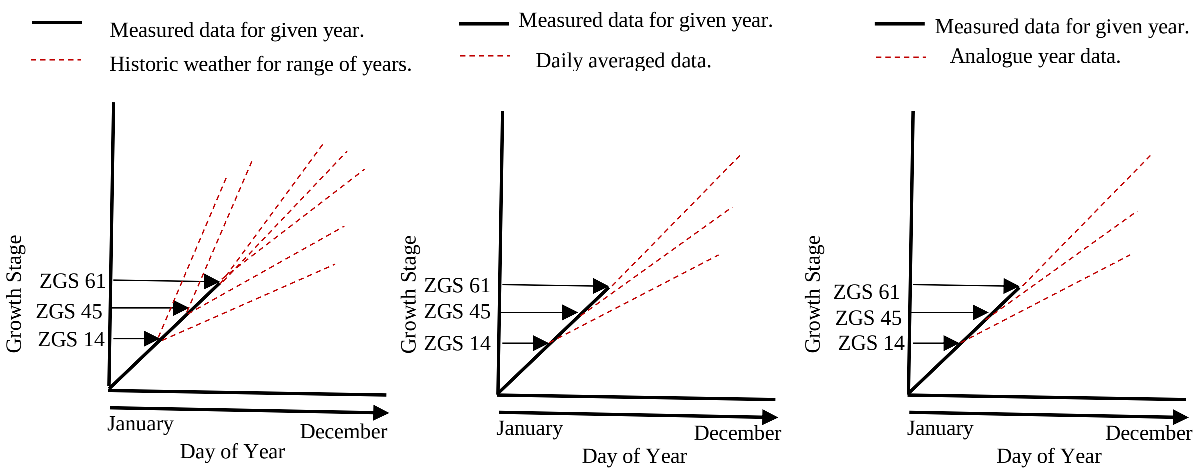

Figure 1.1. Depiction of the different modeling approaches (distribution, historical average, analogue) using historic weather data to forecast the weather for the rest of the season and model wheat growth.

### Genetic Coefficients Development

There were no genetic coefficients for any of the currently grown HRSW cultivars in North Dakota. Therefore, genetic coefficients for the cultivar, Glenn, were estimated using the generalized likelihood uncertainty estimation (GLUE) program within DSSAT. The GLUE program estimates the seven genetic coefficients using an established HRSW cultivar within the model as a template. The program then alters the coefficients of the template cultivar to match the crop measurements of the desired cultivar and give a new output with the estimated genetic coefficients. Crop measurements required to run GLUE include key phenological dates and yield or yield components (Hunt, 1993).

Glenn is a HRSW cultivar developed by North Dakota State University HRSW breeding program and released in 2005 (North Dakota Crop Improvement and Seed Association, 2005). Glenn was selected because many crop measurements needed for the GLUE program to estimate genetic coefficients were available. Information on planting date, harvest date, and grain yield were obtained from North Dakota Research Extension Center (REC) cultivar trials that included Glenn. Emergence date and anthesis date were estimated with the NDAWN wheat GDD calculator (NDAWN, 2017b). These data were collected for 2005-2016 at Carrington, Hettinger, Langdon, Minot, and Williston, ND. Yield trial data has previously indicated to be useful for calibrating crop models (Piper et al., 1998). Additional phenological measurements were collected from plots established in 2016. These plots were seeded at a rate of 2.9 million viable seeds per ha$^{-1}$ with a no-till 3P605NT drill (Great Plains Mfg. Inc., Salina, KS) at Prosper (47.00°N, -97.11°W) and Casselton (46.88°N, -97.23°W), ND. Twenty-five individual tillers were collected in order to obtain kernel and tiller weight. The genetic coefficients estimated for Glenn by the GLUE program are summarized in Table 1.3.

Table 1.3. Genetic coefficients for Glenn estimated by the generalized likelihood uncertainty estimator using data from North Dakota Research Extension Center cultivar trials.

| P1V† | P2D‡ | P5§ | G1¶ | G2# | G3†† | PHINT‡‡ |
|---|---|---|---|---|---|---|
| % day$^{-1}$ | % reduction hr$^{-1}$ | °C day$^{-1}$ | # g$^{-1}$ | mg kernel$^{-1}$ | g | °C day$^{-1}$ |
| 30 | 40 | 475 | 18 | 35 | 2.0 | 76 |

† PIV- Vernalization coefficient.
‡ P2D- Photoperiod coefficient.
§ P5- Thermal time from linear fill through maturity.
¶ G1- Kernel number per unit stem + spike weight at anthesis.
# G2- Kernel growth rate.
†† G3- Tiller death coefficient.
‡‡PHINT- Thermal time between leaf tip appearances .

## Soil Data

The DSSAT requires details of the soil where the simulations are performed. Site-specific soil information for each location where yield data were obtained for cultivar calibration was not available. Cultivar trials were conducted on or near REC’s in Carrington, Hettinger, Langdon, Minot, and Williston, ND so a predominant soil series was determined for each using the Web Soil Survey (USDA-NRCS, 2017). The predominant soil series was chosen to give a good representation of the soil type in the area. A soil profile cannot be created within DSSAT without specific soil profile characteristics, but the soil program within DSSAT has established default soil profiles with soil layer characteristics. An established soil series was chosen from DSSAT that best represented the predominant soil series for each location. The DSSAT soil profile selected may have varied slightly from the site-specific soil, but these profiles were fairly representative of the soil at the location. Soil series information for each location is reported in Table 1.4.

Table 1.4. North Dakota REC† locations with the predominant soil series, soil taxonomy, and slope with the corresponding DSSAT soil series.

| Location | Soil Series‡ | Soil Taxonomy§ | Slope | DSSAT Soil Series |
|---|---|---|---|---|
| | | | % | |
| Carrington | Heimdal- | Coarse-loamy, mixed, superactive, frigid Calcic Hapludolls | 0-5 | Silty Loam |
| Hettinger | Shambo | Fine-loamy, mixed, superactive, frigid Typic Haplustolls | 0-5 | Loam |
| Langdon | Svea | Fine-loamy, mixed, superactive, frigid Pachic Hapludolls | 0-5 | Silty Loam |
| Minot | Forman | Fine-loamy, mixed, superactive, frigid Calcic Argiudolls | 0-5 | Clay Loam |
| Williston | Williams | Fine-loamy, mixed, superactive, frigid Typic Argiustolls | 0-5 | Loam |

† Research extension center.

‡ Soil data obtained from (USDA-NRCS, 2017).

§ Soil taxonomy listed on individual lines based on hyphenated soil series name.

### Statistical Analysis

Model evaluation and verification was done using PROC REG in SAS 9.3 (SAS Institute, Cary, NC) to determine the strength of relationship between observed and simulated anthesis date and yield using full season weather data. Regression analysis was also used to determine the strength of relationship between simulated anthesis date and grain yield using full season weather data to simulated anthesis date and grain yield using forecasted weather with each modeling approach from each growth stage. Root mean square error (RMSE) and coefficient of variation (CV) were determined to explain model performance and the strength of the relationship was determined at the 90%, 95%, and 99% ($p \leq 0.10$, $p \leq 0.05$, $p \leq 0.01$) levels of significance.

Model accuracy was determined by computing the difference of anthesis date and grain yield between simulations using full season weather data and simulations forecasting weather using each modeling approach and from each growth stage. A smaller difference indicated better model predictions. The means of the differences were determined with PROC ANOVA in SAS. Means were separated using Fisher's protected least significant difference at the 95% ($p \leq 0.05$) level of confidence.

## Results and Discussion

### Model Evaluation

The DSSAT-CSM had to be properly validated before conducting experiments. Validation was performed by determining the accuracy between simulated crop growth and observed crop growth. In this study, the 'observed' data included anthesis date, which was determined using the NDAWN wheat GDD calculator (NDAWN, 2017b), and Glenn yield data from North Dakota REC cultivar trials. The NDAWN wheat GDD calculator determines anthesis date through a method developed by Bauer et al. (1984), which showed that wheat development could be accurately estimated using GDD with a base temperature of 0°C. Observed data was used to describe these variables in these comparisons. Anthesis date and yield were used to evaluate model accuracy in order to determine the ability of DSSAT to simulate the vegetative and reproductive development of Glenn. The validation procedure is performed in order to understand the expected error between simulations from the crop model and observed data (Batchelor et al., 2008).

Simulated anthesis date was consistently later than the observed data across all locations. The RMSE between simulated and observed anthesis date ranged between 6 days to 1 day across locations. A lower RMSE indicates better model performance. Overestimation of anthesis date has occurred in other DSSAT applications and may be due to misrepresentation of some of the genetic coefficients that govern the rate of vegetative growth (Boote et al., 2001). Another explanation may be the use of NDAWN to determine anthesis date. Glenn is an earlier maturing cultivar and may mature slightly earlier than what was determined by the NDAWN wheat GDD calculator. Combined across all locations, the relationship between simulated and observed anthesis date was significant at $p \leq 0.01$ ($r^2=0.70$) (Table 1.5). This was similar across all locations except Williston, which resulted in a significant relationship between simulated and observed anthesis date at $p \leq 0.05$.

Table 1.5. Comparison between simulated and observed anthesis date for five locations in North Dakota and combined across all locations and years in 2005-2016.

| | Carrington | | Hettinger | | Langdon | | Minot | | Williston | | Combined | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sim.† | Obs.‡ | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. |
| | --------------------------------------------days after planting---------------------------------------- | | | | | | | | | | | |
| Average§ | 71 | 68 | 74 | 71 | 70 | 63 | 69 | 63 | 69 | 65 | 71 | 66 |
| RMSE¶ | 2 | | 1 | | 6 | | 3 | | 6 | | 2 | |
| CV# | 3 | | 2 | | 9 | | 4 | | 9 | | 3 | |
| $r^2$†† | 0.92*** | | 0.96*** | | 0.73*** | | 0.66*** | | 0.39** | | 0.70*** | |

† Simulated data from model simulations.
‡ Observed data determined using the NDAWN wheat GDD calculator (NDAWN, 2017b).
§ Averaged anthesis date for simulated and observed data in 2005-2016.
¶ Root mean square error.
# Coefficient of variation.
†† Coefficient of determination between simulated and observed.
*, **, *** Significant at ($P \leq 0.10$), ($P \leq 0.05$), and ($P \leq 0.01$) respectively.

In this study, configuring DSSAT to simulate grain yield is critical, but also difficult due to various environmental and agronomic variables that can affect yield throughout the growing season. Simulated yield significantly related to observed yield combined across all locations with a RMSE of 814 kg ha$^{-1}$and $r^2$=0.46 (Table 1.6). Previous research has shown the inability to consistently simulate grain yield. Boote et al. (2002) realized the relationship between simulated and observed yield ranged from $r^2$= 0.33 to 0.74 with simulations using different cultivars in North Carolina. Similar results occurred in this research because the relationship between simulated and observed yield ranged between $r^2$= 0.16 to 0.61 across locations (Table 1.6). The relationship between simulated and observed yield at Carrington and Williston were significant at $p \leq 0.01$, while Hettinger and Minot were significant at $p \leq 0.05$. Simulated yield at Langdon was not well related to observed yield with $r^2$=0.16. For these locations, the RMSE between simulated and observed grain yield was 705, 548, 806, 733, and 617 kg ha$^{-1}$, respectively (Table 1.6). The variability between locations may be due to differences in the management practices between locations that can impact environment x cultivar interactions and cannot be accurately accounted for in the model (Adiku et al., 2017).

Table 1.6. Comparison between simulated and observed yield for five locations in North Dakota and combined across all locations and years in 2005-2016.

| | Carrington | | Hettinger | | Langdon | | Minot | | Williston | | Combined | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sim.† | Obs.‡ | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. |
| | ---kg ha$^{-1}$--- | | | | | | | | | | | |
| Average§ | 4023 | 4028 | 4068 | 3626 | 4594 | 5082 | 4520 | 4225 | 3426 | 3165 | 4126 | 4025 |
| RMSE¶ | 705 | | 806 | | 617 | | 733 | | 548 | | 814 | |
| CV# | 17 | | 22 | | 12 | | 17 | | 17 | | 20 | |
| $r^2$†† | 0.52*** | | 0.52** | | 0.16 | | 0.50** | | 0.61*** | | 0.46*** | |

† Simulated data from model simulations.
‡ Observed data obtained from North Dakota Research Extension Center cultivar trials.
§ Averaged yield for simulated and observed data in 2005-2016.
¶ Root mean square error.
# Coefficient of variation.
†† Coefficient of determination between simulated and observed.
*, **, *** Significant at ($P \leq 0.10$), ($P \leq 0.05$), and ($P \leq 0.01$) respectively.

Overall, the ability to simulate anthesis date and grain yield with DSSAT was deemed adequate across all locations. Therefore, it appeared reasonable to apply the model to predict yield from various growth stages using historic weather data, while understanding the expected error from model simulations. The growth and development processes of crop models and how they respond to environmental conditions can explain the error between the observed data and model simulations. These plant processes are determined by algorithms that respond to the environmental variables (temperature, N status, and moisture) input within the model, which may not adequately account for a plant response when environmental thresholds are exceeded (Bannayan et al., 2003). Model simulations can be improved by better adjusting soil and genetic components. The soil profiles used in this study represented a generalized profile and may account for some error from model simulations. Also, the genetic coefficients for Glenn were an estimation by the GLUE program. Improved cultivar response can be achieved when coefficients are developed using more intensive physical measurements during plant development.

### Assessment of Model Simulations using Different Forecasting Methods

Historic weather data was used in the respective year in order to conduct simulations. Measured weather data was logged from the observed planting date through each growth stage, then supplemented with historic weather data to forecast the weather for the remainder of the season. In order to forecast weather, the weather data were formatted in three modeling approaches to determine the best method for predicting crop growth. The three modeling approaches were referred to as distribution, historical average, and analogue, which are previously described. In this study, simulated anthesis date and grain yield using full season weather data (FSWD) were compared to simulated anthesis date and grain yield with forecasted weather using the three modeling approaches (regardless of growth stage at which forecasting began) for all locations and years of model simulation. The smallest difference between simulated anthesis date and grain yield using FSWD and forecasted weather indicated better model performance. Therefore, the optimum approach for using historic weather data to forecast weather for the remainder of the season was determined. The distribution approach used multiple weather years, which provided a range of outcomes. Therefore, the mean of these simulated values were used for comparisons.

There were significant differences for simulated anthesis date and grain yield when comparing the simulations using each modeling approach. Combined across all locations, the average difference between simulated anthesis date using FSWD and simulated anthesis date using the distribution, historical average, and analogue modeling approaches were 1.0, 0.9, and 1.5 days, respectively (Table 1.7). Data indicated the strength of relationship between anthesis date using FSWD and simulated anthesis date using each modeling approach varied across all locations. However, simulations using distribution and historical average approaches consistently agreed the best with simulations using FSWD with $r^2 = 0.87$ and 0.90 for distribution and historical average modeling approaches, respectively ($p \leq 0.01$) (Table 1.8).

The ability to adequately simulate grain yield using the three modeling approaches varied greatly. The average difference of simulated grain yield using FSWD and simulated grain yield using forecasted weather with each modeling approach was 486, 695, and 648 kg $ha^{-1}$, for distribution, historical average, and analogue approaches, respectively (Table 1.7). The strength of relationship between simulated grain yield using FSWD and each modeling approach was $r^2=0.64$, 0.61, and 0.49 for distribution, historical average, and analogue approaches, respectively (Table 1.9). Data indicated simulating grain yield using the distribution and historical average approaches were the most effective since the relationship between simulated grain yield with FSWD and these two approaches were significant at $p \leq 0.01$. However, simulations using the analogue modeling approach were not as effective since the same relationship was only significant at $p \leq 0.05$. The analogue approach may be less effective due to the inability for short-range weather to match a weather year accurately. This can most likely be attributed to the lack of measured data available since it has only been available over roughly the last 30 yrs., as well as the inability to account for any variability between years (Van den Dool, 1988).

In this study, the optimum technique to simulate crop growth using historic weather data to forecast the weather for the remainder of the season was through a distribution approach. Overall, all three modeling approaches simulated anthesis date satisfactorily when compared to simulated anthesis date using FSWD. The greatest RMSE between simulated anthesis date using FSWD was found using the analogue modeling approach; however, variations between the modeling approaches were minor. Simulating grain yield with the distribution approach resulted in the lowest RMSE from simulated grain yield using FSWD with 348 kg ha$^{-1}$ combined across all locations (Table 1.9). In general, crop development was better represented using the distribution approach because the variability of weather conditions that affect plant growth are taken into account. A historical average or analogue approach used a single data set and may not have effectively taken into account the possible variability of weather for the remainder of the season. This was similar to observations in previous research (Thorton et al., 1997; Bannayan et al., 2003).

Table 1.7. Average difference† for anthesis date and grain yield between simulations using full season weather data and forecasted weather using each modeling approach combined across all locations and years in 2005-2016

| | Anthesis Date | Yield |
|---|---|---|
| | Days | kg ha$^{-1}$ |
| Distribution | 1 | 486 |
| Historical Avg. | 0.9 | 695 |
| Analogue | 1.5 | 648 |
| LSD$_{0.05}$ | 0.2 | 105 |

† Averages calculated by determining the difference between simulations using FSWD and simulations using each modeling approach, combined across all locations and years.

Table 1.8. Comparison between simulated anthesis date using full season weather data and simulated anthesis date using three modeling approaches (distribution, historical average, analogue) in 2005-2016 for five locations.

| | Carrington | | Hettinger | | Langdon | | Minot | | Williston | | Combined | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ |
| | Days | | Days | | Days | | Days | | Days | | Days | |
| Distribution | 1.0 | 0.95*** | 1.3 | 0.92*** | 1.3 | 0.88*** | 1.2 | 0.80*** | 0.7 | 0.97*** | 1.0 | 0.87*** |
| Historical Ave. | 0.9 | 0.96*** | 1.3 | 0.93*** | 1.6 | 0.81*** | 1.4 | 0.74*** | 0.5 | 0.98*** | 0.9 | 0.90*** |
| Analogue | 1.3 | 0.92*** | 1.9 | 0.84*** | 2.3 | 0.61*** | 1.1 | 0.83*** | 0.8 | 0.95*** | 1.0 | 0.87*** |

† Zadoks Growth Stage

*,**,*** Significant at (P≤0.10), (P≤0.05), and (P≤0.01) respectively

Table1.9. Comparison between simulated grain yield using full season weather data and simulated grain yield using three modeling approaches (distribution, historical average, analogue) in 2005-2016 for five locations.

| | Carrington | | Hettinger | | Langdon | | Minot | | Williston | | Combined | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ |
| | kg $ha^{-1}$ | | kg $ha^{-1}$ | | kg $ha^{-1}$ | | kg $ha^{-1}$ | | kg $ha^{-1}$ | | kg $ha^{-1}$ | |
| Distribution | 463 | 0.70*** | 858 | 0.42** | 539 | 0.81*** | 433 | 0.70*** | 470 | 0.76*** | 348 | 0.64*** |
| Historical Ave. | 527 | 0.60*** | 905 | 0.35** | 718 | 0.66*** | 526 | 0.56*** | 510 | 0.72*** | 360 | 0.61*** |
| Analogue | 570 | 0.54*** | 1006 | 0.20 | 1059 | 0.26*** | 772 | 0.06 | 422 | 0.81*** | 411 | 0.49** |

†Zadoks Growth Stage

*,**,*** Significant at (P≤0.10), (P≤0.05), and (P≤0.01) respectively

## Assessment of Model Simulations from Multiple Growth Stages

Measured weather data were logged up to three growth stages (ZGS 14, 45, 61) for the respective year and forecasted weather data was supplemented from that date through the remainder of the growing season (regardless of modeling approach). Simulated anthesis date and grain yield using FSWD were compared to simulated anthesis date and grain yield with forecasts made from ZGS 14, 45, and 61 for all locations and years of model simulation. The ability to effectively predict grain yield early in the season can assist producers in making a range of more informed management decisions (Bannayan et al., 2003).

In theory, simulations that forecasted anthesis date from ZGS 61 should have had zero deviation from the simulated anthesis date using FSWD. Simulated anthesis date resulted in an RMSE of 0.3 days with forecasted weather from ZGS 61 compared to simulated anthesis date using FSWD indicating some error in the model (Table 1.10). However, the relationship between simulated anthesis date using FSWD to forecast anthesis date from ZGS 61 was very high ($r^2$=0.99), indicating satisfactory performance. The maximum difference between simulated anthesis date using FSWD and forecasted anthesis date from ZGS 14 was 2.0 days (Table 1.11). This was significantly greater compared to the difference in anthesis date when forecasting from ZGS 45 and 61 with 1.0 and 0.5 days, respectively (Table 1.11). Overall, the deviation from simulated anthesis date using FSWD was minor. Combined across all locations, anthesis date was significant between simulated anthesis date using FSWD and forecasted anthesis date from ZGS 14 and 45 at $p \leq 0.01$ with $r^2$=0.65 and 0.94, respectively (Table 1.10).

Table 1.10. Comparison between simulated anthesis date using full season weather data and simulated anthesis date with forecasted weather from three growth stages in 2005-2016 for five locations.

| | Carrington | | Hettinger | | Langdon | | Minot | | Williston | | Combined | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ |
| | Days | | Days | | Days | | Days | | Days | | Days | |
| ZGS14 | 2.0 | 0.81*** | 2.5 | 0.73*** | 2.5 | 0.53*** | 2.0 | 0.47*** | 1.0 | 0.92*** | 1.7 | 0.65*** |
| ZGS 45 | 1.1 | 0.94*** | 1.1 | 0.95*** | 1.7 | 0.79*** | 1.3 | 0.77*** | 0.4 | 0.98*** | 0.7 | 0.94*** |
| ZGS 61 | 0.5 | 0.99*** | 0.7 | 0.98*** | 1.0 | 0.92*** | 0.8 | 0.91*** | 0.6 | 0.97*** | 0.3 | 0.99*** |

† Zadoks Growth Stage

*,**,*** Significant at ($P \leq 0.10$), ($P \leq 0.05$), and ($P \leq 0.01$) respectively

Table 1.11. Average difference† for anthesis date and grain yield between simulations using full season weather data and forecasted weather from ZGS 14, 45, and 61.

| | Anthesis Date | Yield |
|---|---|---|
| | Days | kg ha$^{-1}$ |
| ZGS 14‡ | 2.0 | 890 |
| ZGS 45 | 1.0 | 610 |
| ZGS 61 | 0.5 | 331 |
| $LSD_{0.05}$ | 0.2 | 115 |

† Averages calculated by determining the difference between simulations using FSWD and simulations using each modeling approach. Then combined across all locations and averaged.

‡ Zadoks growth stage.

In contrast to the prediction of anthesis date, DSSAT was weaker in predicting grain yield. Generally, predicting yield from any growth stage resulted in an overestimation compared to simulations using FSWD. The maximum deviation of yield resulted when forecasts were made from ZGS 14 and the deviation in yields were reduced at later growth stages. The average difference between grain yield using FSWD and forecasted grain yield from ZGS 14, 45 and 61 was 890, 610, and 331 kg ha$^{-1}$, respectively (Table 1.11). A significant relationship was found for simulations with forecasts from ZGS 45 ($p \leq 0.05$) and 61 ($p \leq 0.01$); however, not from ZGS 14 (Table 1.12). The strength of the relationship between simulated grain yield using FSWD and forecasted grain yield from ZGS 14, 45, and 61 was $r^2=0.24$, 0.41, and 0.86, respectively (Table 1.12). Previous research reported yield predication within 15% when grain yield was forecasted from simulations conducted halfway through the growing season (Thorton et al., 1997). Similar results were obtained with this study with forecasted grain yield from ZGS 45 within 7% of full season grain yield and within 5% when forecasted from ZGS 61 (Data not shown).

Across all locations, model performance improved as measured data was input as the growing season progressed. Anthesis date was significant ($p \leq 0.01$) with the relationship between simulated using FSWD and forecasted from ZGS 14. Improved performance with forecasted anthesis date at ZGS 45 suggested forecasts would have the greatest accuracy when conducted at this growth stage. However, forecasted anthesis date resulted in an average difference from simulated anthesis date using FSWD of only 2 days, indicating only minor differences when simulations are conducted with forecasted weather earlier in the growing season. The relationship between simulated yield using FSWD and simulated yield using forecasted weather also improved as measured weather data was input later into the growing season. In this study, data indicated grain yield should not be simulated with forecasted weather from ZGS 14 since the relationship was not significant with simulations using FSWD. The impact weather will have on grain yield is unknown early in the growing season, since yield is not yet determined in the plant. Predicting yield from ZGS 14 may be unlikely for this reason. However, as crop development progresses, grain yield is further determined; therefore, weather will have less impact and yield prediction will be more accurate (Wiersma and Ransom, 2005).

### Assessment of Forecasted Crop Growth

In this study, data indicated there was no significant interaction when supplementing each of the modeling approaches (distribution, historical average, analogue) to forecast anthesis date or grain yield from each growth stage (ZGS 14, 45, 61). The strength of relationship between simulated anthesis date using FSWD and simulated anthesis date using each modeling approach to forecast from all growth stages varied across locations. However, simulations using distribution and historical average modeling approaches supplemented at ZGS 45 consistently provided the greatest relationship with simulations using FSWD for anthesis date (Table 1.13). Similar results were observed when predicting grain yield. The best relationship consistently occurred with simulations using the distribution and historical average approach when supplemented from ZGS 61 (Table 1.14). Simulated using these approaches from ZGS 61 was significant at $p \leq 0.01$ and when supplemented from ZGS 45 the relationship was still significant ($p \leq 0.05$). Simulating crop growth using the analogue modeling approach to forecast weather was the least effective and should not be used.

Table 1.12. Comparison between simulated grain yield using full season weather data and simulated grain yield with forecasted weather from three growth stages in 2005-2016 for five locations.

| | Carrington | | Hettinger | | Langdon | | Minot | | Williston | | Combined | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ |
| | kg $ha^{-1}$ | | kg $ha^{-1}$ | | kg $ha^{-1}$ | | kg $ha^{-1}$ | | kg $ha^{-1}$ | | kg $ha^{-1}$ | |
| ZGS14 | 789 | 0.11 | 1083 | 0.07 | 1226 | 0.00 | 790 | 0.01 | 773 | 0.35** | 503 | 0.24 |
| ZGS 45 | 418 | 0.75*** | 1041 | 0.14 | 850 | 0.52*** | 686 | 0.26* | 550 | 0.67*** | 444 | 0.41** |
| ZGS 61 | 189 | 0.95*** | 710 | 0.60*** | 464 | 0.86*** | 360 | 0.80*** | 357 | 0.86*** | 215 | 0.86*** |

†Zadoks Growth Stage

*,**,*** Significant at ($P \leq 0.10$), ($P \leq 0.05$), and ($P \leq 0.01$) respectively

Table 1.13. Comparison between simulated anthesis date using full season weather data and simulated anthesis date using three approaches to forecast weather from three growth stages in 2005-2016 for five locations.

| | Carrington | | Hettinger | | Langdon | | Minot | | Williston | | Combined | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ |
| Variable | Days | | Days | | Days | | Days | | Days | | Days | |
| Distribution ZGS† 14 | 1.9 | 0.80*** | 2.3 | 0.77*** | 1.9 | 0.72*** | 1.9 | 0.53*** | 1.3 | 0.86*** | 1.7 | 0.65*** |
| Distribution ZGS 45 | 0.8 | 0.96*** | 1.1 | 0.95*** | 1.6 | 0.80*** | 1.2 | 0.79*** | 0.8 | 0.95*** | 0.8 | 0.92*** |
| Distribution ZGS 61 | 0.6 | 0.98*** | 0.7 | 0.98*** | 0.7 | 0.96** | 0.8 | 0.92*** | 0.7 | 0.96*** | 0.6 | 0.96*** |
| Historical Ave. ZGS 14 | 2.1 | 0.79*** | 2.1 | 0.81*** | 2.7 | 0.47** | 2.0 | 0.47** | 1.2 | 0.89*** | 1.8 | 0.61*** |
| Historical Ave. ZGS 45 | 0.8 | 0.97*** | 1.1 | 0.95*** | 1.8 | 0.76*** | 1.3 | 0.77*** | 0.5 | 0.97*** | 0.8 | 0.92*** |
| Historical Ave. ZGS 61 | 0.4 | 0.99*** | 0.6 | 0.99*** | 0.7 | 0.96*** | 0.6 | 0.95*** | 0.5 | 0.98*** | 0.4 | 0.98*** |
| Analogue ZGS 14 | 2.2 | 0.76*** | 3.3 | 0.55*** | 3.3 | 0.2 | 1.9 | 0.50** | 1.2 | 0.8832*** | 1.8 | 0.58*** |
| Analogue ZGS 45 | 2.2 | 0.75*** | 1.7 | 0.87*** | 2.2 | 0.65*** | 1.3 | 0.77*** | 0.7 | 0.96*** | 0.9 | 0.91*** |
| Analogue ZGS 61 | 0.4 | 0.99*** | 1.1 | 0.95*** | 1.6 | 0.80*** | 1.1 | 0.84*** | 1.0 | 0.92*** | 0.7 | 0.94*** |

† Zadoks Growth Stage

*,**,*** Significant at ($P \leq 0.10$), ($P \leq 0.05$), and ($P \leq 0.01$) respectively

Table 1.14. Comparison between simulated grain yield using full season weather data and simulated grain yield using three approaches to forecast weather from three growth stages in 2005-2016 for five locations.

| | Carrington | | Hettinger | | Langdon | | Minot | | Williston | | Combined | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ | RMSE | $r^2$ |
| Variable | kg ha$^{-1}$ | | kg ha$^{-1}$ | | kg ha$^{-1}$ | | kg ha$^{-1}$ | | kg ha$^{-1}$ | | kg ha$^{-1}$ | |
| Distribution ZGS† 14 | 816 | 0.05 | 1081 | 0.07 | 1218 | 0.01 | 741 | 0.13 | 794 | 0.32 | 513 | 0.21 |
| Distribution ZGS 45 | 451 | 0.71*** | 1004 | 0.20 | 658 | 0.71*** | 608 | 0.42** | 629 | 0.57*** | 440 | 0.42** |
| Distribution ZGS 61 | 217 | 0.93*** | 723 | 0.59*** | 390 | 0.90*** | 251 | 0.90** | 358 | 0.86*** | 223 | 0.85*** |
| Historical Ave. ZGS 14 | 797 | 0.10 | 1098 | 0.04 | 1219 | 0.01 | 744 | 0.13 | 742 | 0.40** | 531 | 0.15 |
| Historical Ave. ZGS 45 | 441 | 0.72*** | 990 | 0.22 | 765 | 0.61*** | 666 | 0.30 | 697 | 0.47** | 437 | 0.43** |
| Historical Ave. ZGS 61 | 296 | 0.88*** | 767 | 0.53*** | 484 | 0.84*** | 345 | 0.81*** | 474 | 0.76*** | 206 | 0.87*** |
| Analogue ZGS 14 | 798 | 0.09 | 1099 | 0.04 | 1226 | 0.00 | 792 | 0.01 | 894 | 0.13 | 517 | 0.20 |
| Analogue ZGS 45 | 497 | 0.65*** | 1099 | 0.04 | 1097 | 0.20 | 794 | 0.00 | 578 | 0.64*** | 494 | 0.27 |
| Analogue ZGS 61 | 251 | 0.91*** | 716 | 0.59*** | 703 | 0.67*** | 617 | 0.40** | 405 | 0.82*** | 305 | 0.72*** |

† Zadoks Growth Stage

*,**,*** Significant at ($P \leq 0.10$), ($P \leq 0.05$), and ($P \leq 0.01$) respectively

In this study, supplementing the distribution and historical average approach to forecast grain yield provided similar results across all locations, therefore, either would be a suitable method to forecast weather and predict crop growth. However, the distribution approach may improve yield forecasting because a generalized average is not being used, but rather a frequency of the distribution can be determined from the range of outcomes. The information obtained from these outcomes can be used as a decision support system to make improved management decisions (Bannayan et al., 2003).

As plant development progresses throughout the growing season, the precision of the simulations will increase as the distribution of the simulated values narrows around the likely outcome. In this study, the precision of simulations using the distribution approach improved when anthesis date and grain yield were forecasted from ZGS 45 and 61. As plant development progressed the range between the projected outcomes decreased for anthesis date with an average range of 10, 6, and 2 days for ZGS 14, 45, and 61, respectively (Table 1.15). Similar results were obtained for grain yield with the range between the projected outcome decreased by 3305, 1910, and 988 kg ha$^{-1}$ for ZGS 14, 45, and 61, respectively (Table 1.16).

Overall, the DSSAT-CSM can effectively predict anthesis date within 1-2 days from ZGS 14 and 45. Therefore, the crop model may be a beneficial decision support system to effectively determine when anthesis date will occur. This would be beneficial for a producer to make management decisions that occur around this time, such as a foliar fertilizer or pesticide application. Also, DSSAT is most accurate in predicting grain yield from ZGS 45 and 61. Therefore, the model may be a useful management tool for producers to make an informed decision for an additional N application to increase GPC if predicted yield is high. However, since grain yield cannot be accurately predicted until ZGS 45, a small time frame is available to make the decision whether or not this additional application should be conducted.

Table 1.15. Mean and range of simulated anthesis date using the distribution approach to forecast weather from ZGS† 14, 45, and 61 for five locations in North Dakota combined across all years in 2005-2016.

| | ZGS 14 | | ZGS4 45 | | ZGS 61 | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean‡ | Range§ | Mean | Range | Mean | Range | Obs.¶ | Sim.# |
| | ----------------------------days after planting---------------------------- | | | | | | | |
| Carrington | 72 | 68 - 77 | 71 | 69 - 74 | 71 | 70 - 73 | 68 | 71 |
| Hettinger | 75 | 70 - 80 | 75 | 72 - 78 | 74 | 74 - 75 | 63 | 70 |
| Langdon | 71 | 67 - 77 | 70 | 68 - 75 | 70 | 69 - 72 | 72 | 74 |
| Minot | 70 | 66 - 77 | 69 | 67 - 74 | 69 | 68 - 71 | 63 | 69 |
| Williston | 70 | 67 - 77 | 70 | 68 - 74 | 70 | 69 - 71 | 65 | 69 |
| Combined | 71 | 68 - 78 | 71 | 69 - 75 | 71 | 70 - 72 | 65 | 71 |
| Avg. Range | | 10 | | 6 | | 2 | | |

† Zadoks growth stage.
‡ Mean anthesis date in 2005-2016 from simulations using the distribution approach to forecast weather from the respective growth stage.
§ Average range of anthesis date in 2005-2016 from simulations using the distribution approach to forecast weather from the respective growth stage.
¶ Mean of anthesis date in 2005-2016 determined from NDAWN wheat GDD calculator.
# Mean of anthesis date in 2005-2016 from simulations using full season weather data.

Table 1.16. Mean and range of simulated grain yield using the distribution approach to forecast weather from ZGS† 14, 45, and 61 for five locations in North Dakota combined across all years in 2005-2016.

| | ZGS 14 | | ZGS4 45 | | ZGS 61 | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean‡ | Range§ | Mean | Range | Mean | Range | Obs.¶ | Sim.# |
| | ------------------------------------------------kg ha$^{-1}$-------------------------------------------- | | | | | | | |
| Carrington | 3951 | 2161 - 5559 | 4099 | 3359 - 4874 | 4034 | 3607 - 4456 | 4028 | 4023 |
| Hettinger | 3885 | 2000 - 5411 | 4012 | 3119 - 5059 | 4020 | 3596 - 4441 | 5082 | 4594 |
| Langdon | 4563 | 2668 - 5959 | 4679 | 3642 - 5683 | 4711 | 4131 - 5319 | 3717 | 4034 |
| Minot | 4409 | 2758 - 5691 | 4559 | 3646 - 5498 | 4562 | 4074 - 5084 | 4225 | 4520 |
| Williston | 3820 | 2285 - 5774 | 3672 | 2782 - 4985 | 3541 | 3120 - 4169 | 3165 | 3426 |
| Combined | 4125 | 2374 - 5679 | 4204 | 3310 - 5220 | 4174 | 3706 - 4694 | 4083 | 4068 |
| Avg. Range | | 3305 | | 1910 | | 988 | | |

† Zadoks growth stage.
‡ Mean yield in 2005-2016 from simulations using the distribution approach to forecast weather from the respective growth stage.
§ Average range of yield in 2005-2016 from simulations using the distribution approach to forecast weather from the respective growth stage.
¶ Mean of observed yield in 2005-2016 from North Dakota Research Extension Centers.
# Mean of simulated yield in 2005-2016 from simulations using full season weather data.

# Conclusion

The ability of DSSAT-CSM to simulate plant development varied across locations, but overall the crop model simulated anthesis date and grain yield with adequate accuracy for HRSW in North Dakota. Simulation error can most likely be attributed to the use of generalized soil types and estimated genetic coefficients, which can be improved with increased physical soil and plant measurements.

The three approaches used to forecast weather for the remainder of the season were all able to forecast anthesis date similarly. However, the greatest precision was obtained when simulating grain yield with the distribution and historical average modeling approaches. The analogue approach was the least effective, which may be explained by the inability to account for the variability of weather between years with this approach. Yield simulations using the distribution and historical average modeling approaches were similar and could predict yield with the greatest accuracy compared to yield simulations using FSWD. However, simulations using the distribution approach may be more beneficial because a frequency of the distribution from the range of outcomes can be determined in addition to a generalized average.

Across all locations, model performance improved as measured weather data was input as the growing season progressed. The associated error with simulated anthesis date using forecasted weather from ZGS 14 and ZGS 45 was minimal. In this study, grain yield was not accurately simulated with forecasted weather from ZGS 14 and should not be attempted. This may be due to yield still undetermined within the plant and the weather for the remainder of the season being unknown, which can have a major impact on plant development. Simulated grain yield with forecasted weather from ZGS 45 and 61 had an average RMSE of 444 and 215 kg ha$^{-1}$

from simulated yield using FSWD. Grain yield was predicted with the greatest accuracy with forecasted weather from ZGS 61.

The method implemented to update measured weather data during the growing season was time consuming and would be very difficult on a large scale. However, an updating system that is incorporated into the model that updates weather data on a daily or weekly basis might provide more accurate forecasting with DSSAT (Bannayan et al., 2003). The information obtained in these yield predictions can provide an effective decision support system that allows producers to make improved management decisions, especially during the later part of the growing season. The results from this study indicate that an informed decision can be better made with simulations conducted from ZGS 45 or later since yield is not accurately predicted until this time. Therefore, a management decision to apply a late-season foliar N application could be determined during the growing season. However, since predictions cannot be made until at least ZGS 45, this decision would have to be made relatively quickly in order to achieve the most success from the additional N application.

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# ARTICLE 2: TECHNIQUES TO IMPROVE GRAIN PROTEIN CONTENT OF HARD RED SPRING WHEAT WITH A LATE SEASON NITROGEN APPLICATION

## Abstract

A late-season foliar nitrogen (N) application may increase grain protein content (GPC) for hard red spring wheat (HRSW) (*Triticum aestivum* L. emend Thell.) in environments or cultivars with low protein potential. Two experiments were conducted to evaluate the effectiveness of a foliar N application through the combination of N solutions with a fungicide, urease inhibitor (N-(n-butyl) thiophosphoric triamide - NBPT), and various adjuvants using multiple droplet sizes. Urea ammonium nitrate (UAN) and urea solution (US) were applied at Zadoks growth stage (ZGS) 65 and 69. Applications resulted in greater leaf burn when combined with a fungicide, NBPT, or adjuvant. The best technique to increase GPC was through a foliar application of UAN or US at ZGS 69. The addition of a fungicide, NBPT, or adjuvants with the N solutions did not increase GPC. Therefore, the associated additional costs do not make these additions economically feasible. Spring wheat growers are advised to only consider a late-season foliar N application when environments are favorable for high yields and a profitable protein premium seems likely

## Introduction

Spring wheat producers depend on grain yield and GPC in order to be economically successful. High grain yield and high GPC can be achieved if N availability and environmental conditions are favorable. However, attaining both high grain yield and GPC can be challenging due to environmental impacts, N availability, and cultivar selection. Protein in the grain has to reach a market threshold at point of sale, otherwise discounts are imposed leading to reduced producer profit. However, if GPC is above the market threshold a premium may be realized by the grower (Jones and Olson-Rutz, 2012). Spring wheat producers may be prompted to make in-season management decisions to increase GPC if environmental factors are positive for greater yield and N supply is perceived to be deficient. A management practice utilized to increase GPC when conditions point to reduced GPC is through a late season foliar application of N fertilizer.

Urea ammonium nitrate (28-0-0) or urea solution (ranging from 14 to 20 percent N by weight) are two possible N fertilizers that HRSW producers use to increase GPC. Increasing GPC has been successfully achieved with this additional N application between ZGS 45 and 73 with the most effective response occurring at ZGS 69 (Zadoks et al., 1974; Finney et al., 1957; Endres and Schatz, 1993). Even at the optimum timing, the efficiency of N absorption into the plant with this method application is limited (Finney et al., 1957; Alkier et al., 1972). Therefore, it may be possible to develop methods to improve the efficiency of this foliar application and could reduce costs and amount of residual N in the environment.

## Wheat Nitrogen Use

Nitrogen is an essential nutrient in the production of chlorophyll and rubisco, which are essential for photosynthesis. Photosynthesis promotes the formation of compounds and carbohydrates needed by the plant for growth, storage, and energy (Lawlor et al., 1989). Nitrogen is also an essential component of amino acids, which are the building blocks of protein. Plant roots absorb inorganic N in the form of $NO_3^-$ and $NH_4^+$ from residual soil N, mineralization of organic matter, or fertilizer applications (Flaten and Grant, 1998). Environmental conditions, concentration of N in the soil solution, and the growth stage and growth rate of the plant can influence the amount of N uptake (Brown et al., 2005).

Grain yield and GPC are produced simultaneously during wheat development, but N is first be allocated towards grain yield before it is allocated to protein development in the kernel

(Goos et al., 1982). Most of the N taken up during early vegetative growth is used in the formation of tillers, leaves, and spikes, which impact grain yield potential (Brown et al., 2005). Nitrogen is supplied to the developing kernel by remobilization from the vegetative biomass or uptake during or after heading. Nitrogen that is taken up around heading will usually influence GPC, but can only marginally influence yield because the number and size of kernels are mostly fixed at this time (Brown et al., 2005)

Environmental and agronomic factors, especially cultivar selection and nutrient and water availability, affect the rate and timing of N uptake (Fowler et al., 1990; Campbell, 1977). Therefore, an inverse relationship between grain yield and GPC result from a certain level of fertility. This can be explained by differences in N uptake and the plants' ability to utilize energy and nutrient reserves from the vegetative stage during kernel development (Brown et al., 2005). Inverse relationships between yield and grain protein has been reported in a number of crops including barley (*Hordeum vulgare* L.), oat (*Avena sativa* L.), corn (*Zea mays* L.), rice (*Oryza sativa* L.), sorghum (*Sorghum bicolor* L. Moench), and wheat (Baltensperger et al., 2008).

The proportion of N supplied to the grain is influenced by concentration of N in the vegetative tissues, cultivar grown, and environmental conditions, particularly soil moisture availability (Flaten and Grant, 1998). Yield potential is higher in favorable environments with adequate soil moisture that promotes N uptake during early plant development, but less N may be available during the grain filling period resulting in kernels with high starch content and low protein. Protein content can be high in environments with sufficient N, but inadequate moisture or environmental stress during early plant development can limit N assimilation during grain filling if the environmental conditions improve (Neidig and Snyder, 1924). High grain yield and

GPC can be obtained when N availability within an environment is greater than what is sufficient to support maximum yield potential for the seasonal environment (Bailey et al., 1992).

### Foliar Nitrogen Application

A late season foliar N application has been found to increase GPC in low protein potential cultivars or environments. A potential increase of 5 to 10 g $kg^{-1}$ in protein has been realized with a 34 kg $ha^{-1}$ application of N between ZGS 45 and 73, when kernel development demands requires high levels of N (Finney et al., 1957; Schatz and Endres, 1993; Ransom et al., 2012). Studies have reported the most effective timing was directly post-anthesis (ZGS 69), with decreased effectiveness before and after this stage (Finney et al., 1957; Gooding and Davis, 1992; Schatz and Endres, 1993; Bly and Woodard, 2003). The optimum N rate for a post-anthesis N application is 34 kg N $ha^{-1}$, with larger rates only slightly increasing protein levels while decreasing yield (Freeman et al., 2002). Schatz (2012) observed a 10 g $kg^{-1}$ increase in protein across three HRSW cultivars when 34 kg $ha^{-1}$ of N was applied to the foliage post-anthesis.

Urea ammonium nitrate or US are commonly used as N sources for foliar applications. A solution of UAN allows for N to be readily absorbed by the foliage in the form of $NO_3^-$ and $NH_4^+$, as well as water-soluble organic N from urea (Christiaens et al., 2015). A US is made by dissolving dry fertilizer urea (46-0-0) in water, which can then be directly applied to the foliage using a sprayer. A US has been found to produce less burn to the foliage than UAN, but is more susceptible to ammonia volatilization from the activity of the urease enzyme present in the soil (Gooding and Davies, 1992).

Liquid forms of fertilizer N can cause leaf burning due to the salt content of the solution and a potential to form high concentrations of ammonia on the leaf tissue (Bremner, 1995). Since

US generally cause less burn than UAN and US are lower in salt and higher in potential ammonia, the greatest cause of leaf burn with these fertilizers is probably salt content. The degree of phytotoxicity depends on the growth stage, N concentration, and the cultivar (Gooding, 1988). The flag leaf in particular can be significantly affected by ammonia accumulation from a foliar application. Maintenance of the flag leaf before and during anthesis is needed for achieving high grain yield and GPC because it is the major source of photosynthates to create carbohydrates and amino acids during the grain filling period (Simpson et al., 1983). A management tactic to reduce phytotoxicity is to make the application in the cool of the day when humidity is high (Garcia and Hanway, 1976; Franzen, 2017). After anthesis, protection of the flag leaf does not appear to be as important as before or during anthesis (Schatz and Endres, 1993).

## Techniques to Improve Efficiency of Foliar Nitrogen Applications

A late season foliar N application can be rapidly absorbed by the foliage, but efficiency is often low (Gooding and Davies, 1992). The foliar fertilizer is often absorbed through the leaf cuticle; however, irregularities of the leaf surface and waxes can prevent wetting of the cuticle, reducing absorption (Akin and Gray, 1984). A greenhouse study reported less than 1% of the N in the foliar application was supplied to the grain (Alkier et al., 1972). The remaining N is subject to environmental losses or washed off by precipitation and absorbed through the roots. However, N absorption through the foliage may be improved with the addition of an adjuvant or urease inhibitor, NBPT. Altman et al. (1983) reported N recovery in the grain was 44% for winter wheat when an adjuvant was added with a US applied directly to the foliage.

Adjuvant is the general term that includes surfactants, oils, and fertilizers, which vary in their chemical makeup, overall effect, and intended use (Zollinger, 2010). The purpose of an adjuvant is to increase uptake of the active ingredient of the pesticide applied by decreasing surface tension and increasing droplet retention (Hanzen, 2000). The addition of an adjuvant to the N solution has been reported to improve uptake; however little exploration has been performed to test multiple types of adjuvants.

Surfactants help spray solutions absorb through the leaf cuticle by emulsifying, dispersing, sticking, and spreading on the leaf surface (Zollinger, 2010). The addition of a surfactant with N solutions can increase retention of the spray solution, more effectively transferring N to the grain (Altman et al., 1983; Brinck et al., 2000). Oil agents, or penetrants, are also common spray adjuvants. These include methylated seed oil (MSO) and various crop oil concentrates (COC). The oil in methylated seed oils are derived from plants, while the oil in COCs are derived from petroleum oil (Zollinger et al., 2017). A penetrant allows the spray solution to infiltrate leaf cuticles by breaking down waxy extracellular and lipid cellular barriers of the plant (Hanzen, 2000).

Droplet size can also impact pesticide absorption, retention, and deposition, which may improve the action of an N solution. Spray pressure, spray mixture, or nozzle type affects droplet size, which ranges from very fine (<145 microns) to ultra-coarse (> 650 microns) (Hofman and Solseng, 2004; Askew et al., 2013). The optimum size varies depending on intended use, volume, or liquid form being applied. Creech et al., (2016) reported that dicamba control of common lambsquarter (*Chenopodium album*) was improved using a medium droplet compared to a fine droplet. However, common sunflower (*Helianthus annuus* L.) was best controlled by dicamba with a very coarse droplet.

Another technique to improve the effectiveness of a foliar N application is through the use of a urease inhibitor in conjunction with a urea containing liquid fertilizer. A urease inhibitor reduces the breakdown of the urea molecule by binding the active site of the urease enzyme (Deiana et al., 1999). The urease enzyme breaks the urea molecule into its component parts of $NH_3$ and $CO_2$. The ammonia can then be lost to the environment if it is located near or at the soil surface, and especially if soil pH is greater than 7. The addition of a urease inhibitor to US has resulted in reduced N loss from ammonia volatilization (Bemner and Douglas, 1971, 1973). Brinck et al. (2000) reported improved N recovery by the crop when a urease inhibitor was added to a soil-applied US, but the urease inhibitor was not significantly beneficial when applied to foliage.

If the environment is favorable for disease development, wheat quality can also be negatively affected. A fungicide application at ZGS 65 in HRSW can prevent the grain-damaging effects of fusarium head blight (*Fusarium graminearum*). Recommendations for fungicide and foliar N applications almost always urge growers to apply them separately in HRSW, even though the recommended application timing overlap. This is due to the phytotoxic effects of the liquid fertilizer on the leaf tissue, which the fungicide is intended to protect (Franzen, 2015). However, information on the effect of applying a fungicide with N solutions simultaneously is lacking. Spring wheat producers might be able to reduce costs if the fungicide and N solution could be applied together.

### Economic Return

Wheat grain yield and GPC are the two most important constituents in generating an economic return in HRSW production. The standard market threshold for GPC are 140 g $kg^{-1}$ for HRSW and 120 g $kg^{-1}$ for hard red winter wheat in the upper Midwest. Price deductions are imposed if GPC falls below this market standard, while premiums may be realized if protein content is greater than the market standard. The price discounts and premiums vary depending on the year (Bly and Woodard, 2003). For example, discounts ranged from \$22.05 $Mg^{-1}$ in September 2010 and \$9.18 $Mg^{-1}$ in September 2015 (Olson, 2015). When high protein HRSW is limited in supply, the premium for high protein may represent as much as 50% or more of the total market price of HRSW in some years (Brown et al., 2005).

A foliar N application carries an additional input cost to growers, but if the environment if favorable for high yields with insufficient N throughout the grain filling period, then an additional N application to increase GPC may be justified. The additional N application may be highly profitable if an increase in GPC reduces low-protein discounts or results in a protein premium payment greater than the cost of the application.

## Objective

The objective of this research was to test techniques that might improve the effectiveness of increasing GPC with a foliar N application of N alone or in combination with a fungicide, a urease inhibitor, adjuvants, and using different droplet sizes.

## Materials and Methods

### General Information

Field experiments were conducted near Casselton (46.88°N, -97.23°W), Fargo (46.93°N, -96.86°W), and Prosper (47.00°N, -97.11°W), ND in 2016 and repeated in 2017 at Ada, MN (47.35°N, -96.41°W), Casselton (46.88°N, -97.23°W) and Prosper (47.00°N, -97.11°W), ND. Soil series, taxonomy, and slope for each location are presented in Table 2.1. Soil samples were collected in the fall to determine the levels of plant-available phosphorous (P), potassium (K), and residual nitrate-N. Five random 2.5 cm core samples at a 0-30.5 and 30.5-60 cm depths were collected from the trial and combined prior to this analysis.  A uniform application of dry urea (46-0-0) was applied at 75% of the recommended rate for each location and incorporated prior to planting using a field cultivator. The North Dakota wheat nitrogen calculator was used to determine the recommended N rate (North Dakota Wheat Nitrogen Calculator, 2017). A full N rate was not applied in order to improve the probability of a protein response from a foliar N application. Table 2.2 indicates N level, previous crop, and N rate applied at each location in 2016 and 2017.

Table 2.1. Soil series, taxonomy and slope at Casselton, Fargo, and Prosper, ND, and Ada, MN in 2016-2017.

| Location | Soil Series† | Soil Taxonomy‡ | Slope |
|---|---|---|---|
| | | | % |
| Casselton | Bearden | Fine-silty, mixed, superactive, frigid Aeric Calciaquolls | 0-2 |
| Fargo | Fargo | Fine, smectitic, frigid Typic Epiquerts | 0-2 |
| Prosper | Bearden | Fine-silty, mixed, superactive, frigid Aeric Calciaquolls | 0-2 |
| Ada | Glyndon | Coarse-silty, mixed, superactive, frigid Aeric Calciaquolls | 0-3 |

† Soil data obtained from (USDA-NRCS, 2016).
‡ Soil taxonomy listed on individual lines based on hyphenated soil series name.

Table 2.2. Previous crop with nitrogen (N) credit, soil N, P, and K test, and N rate applied for locations in 2016-2017.

| Year | Location | Previous crop | Residual soil nitrate-N† | N credit | N rate | P | K |
|---|---|---|---|---|---|---|---|
| | | | ----------------kg ha$^{-1}$---------------- | | | ppm | ppm |
| 2016 | Casselton, ND | Wheat | 37 | 0 | 119 | 25 | 455 |
| | Fargo, ND | Soybean‡ | 20 | 44 | 98 | 25 | --§ |
| | Prosper, ND | Wheat | 103 | 0 | 70 | 18 | 250 |
| 2017 | Ada, MN | Soybean | 16 | 50 | 135 | 11 | 107 |
| | Casselton, ND | Wheat | 83 | 0 | 95 | 11 | 368 |
| | Prosper, ND | Wheat | 108 | 0 | 78 | 17 | 370 |

† 2.5 cm core samples taken at 0-60 cm depth.
‡ Glycine max L.
§ Data not available.

Two experiments were designed as randomized complete blocks with four replications to develop best practices for stimulating a protein response following a foliar N application. The first experiment (Experiment One) consisted of twelve treatments in 2016 and fourteen treatments in 2017 and was constructed to evaluate the effects of separate and combined applications of two N solutions with a fungicide at ZGS 65 and 69 (Table 2.3). Experiment Two consisted of fifteen treatments in 2016 and eighteen treatments in 2017 and was designed to identify the effects a foliar application of N fertilizer combined with four adjuvants using two droplets sizes at ZGS 69 (Table 2.4). Additional treatments in Experiment One included a urease inhibitor. Two dilution ratios and the use of streamer bars to deliver the foliar N fertilizer in a concentrated band instead of broadcast were included in Experiment Two.

Two N solutions, UAN and a US, were used to supply N at a rate of 34 kg N ha$^{-1}$. In treatments receiving foliar fertilizer, N solutions were applied at a rate of 187 l ha$^{-1}$. In both experiments, UAN was applied at a dilution ratio (volume:volume) of 50:50, unless stated otherwise. The US was prepared by mixing dry urea with lukewarm water to provide a solution that was 50% urea by weight (23-0-0). For treatments requiring a urease inhibitor, (NBPT) (Agrotain Advanced, Koch Agronomic Services, LCC, Wichita, KS), was added to the US at a label recommended rate of 2.10 ml kg$^{-1}$ and UAN at 1.05 ml kg$^{-1}$. In treatments receiving fungicide, prothioconazole and tebuconazole at 126 g and 126 g ai ha$^{-1}$, respectively, were applied with a non-ionic surfactant (NIS) (Activator 90, Loveland Products, Loveland, CO) at 0.25% v/v. In Experiment Two, adjuvants included an NIS (Activator 90, Loveland Products, Loveland, CO), MSO (Super Spread MSO, San Francisco, CA), methylated seed oil organosilicone surfactant (MSOOS) (Dyne-Amic, Helena Chemical Company, Collierville, TN), and petroleum oil concentrate (POC) (Herbimax, Loveland Products, Loveland, CO) at 0.5% v/v, 1.8 l ha$^{-1}$, 438 ml ha$^{-1,}$ and 2.3 l ha$^{-1}$, respectively. Foliar applications were made in Experiment One using XR TeeJet 11002 nozzles (TeeJet Technologies, Wheaton, IL), while Experiment

Two utilized streamer bars, and XR TeeJet 11002 and TT11002 nozzles which delivered droplet sizes of 226-325 and 326-400 microns, respectively. Treatments were applied using a $CO_2$ pressurized hand-held backpack sprayer at 207 kPa and constant speed of 3.8 km $h^{-1}$ with the boom height 46 cm above the crop canopy.

## Planting and Plot Maintenance

Experiments One and Two were seeded side by side at a seeding rate of 2.9 million viable seeds $ha^{-1}$ using a no-till 3P605NT drill (Great Plains Mfg. Inc., Salina, KS) with seven rows spaced 18 cm apart. Experimental units were 1.5 m wide by 5.2 m long with 0.3 m gaps between units. Alleys between replications were cut mid-season at a width of 1.5 m, leaving the total harvested area of each experimental unit to be 1.5 m by 3.7 m. Trials at Casselton and Fargo were planted on 13 April and Prosper on 14 April in 2016. In 2017, Ada, Casselton, and Prosper were planted on 17 April, 2 May, and 15 April, respectively. A uniform seed bed was prepared before planting using a field cultivator. The HRSW cultivar, Croplan 3419, was planted across all locations. Cropland 3419 is a 2014 cultivar release of Winfield United (Arden Hills, Minnesota) with high yield potential and intermediate protein potential.

Table 2.3. Treatment structure of Experiment One including tank mix combinations of fungicide, nitrogen solution, and tank mix additions at the specified timing for all locations in 2016-2017.

| Treatment | Nitrogen Solution | Tank Mix Addition | Stage† |
|---|---|---|---|
| 1)‡ Unfertilized Control | | | |
| 2) Fertilized Control | | | |
| 3)‡ Fungicide | | | ZGS 65 |
| 4) Fungicide | | NIS§ | ZGS 65 |
| 5) Fungicide | UAN¶ | NIS | ZGS 65 |
| 6) Fungicide | UAN | NIS, NBPT | ZGS 65 |
| 7) | UAN | | ZGS 65 |
| 8) Fungicide | US# | NIS | ZGS 65 |
| 9) Fungicide | US | NIS, NBPT | ZGS 65 |
| 10) | US | | ZGS 65 |
| 11) Fungicide | | NIS | ZGS 65 |
| | UAN | | ZGS 69 |
| 12) | UAN | | ZGS 69 |
| 13) Fungicide | | NIS | ZGS 65 |
| | US | | ZGS 69 |
| 14) | US | | ZGS 69 |

† Stage = Zadoks growth stage (ZGS) 65 is Anthesis, ZGS 69 is Post-Anthesis.
‡ Treatments included in 2017 only.
§ Nonionic surfactant.
¶ Urea ammonium nitrate (28-0-0).
# Urea (46-0-0) solution.

All locations were scouted throughout the season for pathogens and weed presence. Pathogen pressure was minimal in 2016 and 2017 at all locations; however, a fungicide application of prothioconazole and tebuconazole at 126 g and 126 g ai ha$^{-1}$, respectively, were applied at ZGS 65 in Experiment Two to reduce the influence of disease at anthesis, due to prediction of possible fusarium head blight by the NDSU small grains disease forecasting model (NDSU small grain disease forecasting model, 2017). Broadleaf and grass weeds were controlled with an application at ZGS 14 of fenoxaprop, pyrasulfotole, bromoxynil octanoate, and bromoxynil heptanoate at 56, 18, 74, and 73 g ai ha$^{-1}$, respectively.

Table 2.4. Treatment structure of Experiment Two, including dilution ratio of nitrogen (N) solution and rate of tank mix additions for the specified droplet size for all locations in 2016-2017.

| Treatment, N Solution | Tank Mix Addition | Droplet Size | Dilution Ratio† | Adjuvant Rate | |
|---|---|---|---|---|---|
| 1)‡Unfertilized Control | | | | | |
| 2) Fertilized Control | | | | | |
| 3) UAN§ | | 1¶ | 50:50 | | |
| 4) UAN | | 2# | 50:50 | | |
| 5) UAN | MSO†† | 1 | 50:50 | 1.8 | l $ha^{-1}$ |
| 6) UAN | MSO | 2 | 50:50 | 1.8 | l $ha^{-1}$ |
| 7) UAN | POC‡‡ | 1 | 50:50 | 2.3 | l $ha^{-1}$ |
| 8) UAN | POC | 2 | 50:50 | 2.3 | l $ha^{-1}$ |
| 9) UAN | NIS§§ | 1 | 50:50 | 0.5 | % v/v |
| 10) UAN | NIS | 2 | 50:50 | 0.5 | % v/v |
| 11) UAN | MSOOS¶¶ | 1 | 50:50 | 438 | ml $ha^{-1}$ |
| 12) UAN | MSOOS | 2 | 50:50 | 438 | ml $ha^{-1}$ |
| 13)## UAN | Urease Inhibitor | 1 | 50:50 | 1.05 | ml $kg^{-1}$ |
| 14)## Urea solution | Urease Inhibitor | 1 | | 2.10 | ml $kg^{-1}$ |
| 15) UAN | | 1 | 60:40 | | |
| 16) UAN | | 1 | 75:25 | | |
| 17)‡ UAN | | 3††† | 50:50 | | |
| 18)‡ UAN | | 3 | 50:50 | | |

† Dilution ratio of spray solution %fertilizer:%water.
‡ Treatments included in 2017 locations only.
§ Urea ammonium nitrate (28-0-0).
¶ 226-325 micron droplet size produced by a XR11002 nozzle.
# 236-400 micron droplet size produced by a TT1102 nozzle.
†† Methylated seed oil.
‡‡ Petroleum oil doncentrate.
§§ Non-Ionic Surfactant.
¶¶Methylated seed oil organosilicone surfactant.
## Treatments not included at Fargo location in 2016.
††† Streamer bars.

## Data Collection and Harvest Methods

Plots were harvested using a Wintersteiger Classic plot combine (Wintersteiger Ag, Reid, Austria). In 2016, Fargo was harvested on 26 July, and Casselton and Prosper were harvested on 29 July. In 2017, Ada, Casselton, and Prosper were harvested on 11, 22, and 7 Aug., respectively. After harvest, grain samples were cleaned using a Clipper Office Tester and Cleaner (Seedburo Equipment Co., Chicago, IL) and dried (if necessary). Grain yield, moisture, and test weight (TW) were recorded using a GAC 2100 moisture tester (DICKEY-John Corp., Minneapolis, MN) and GPC was analyzed using Perten Instruments DA 7250 (Perten Instruments, Springfield, IL). Yield was adjusted and expressed at 13.5% moisture.

Field measurements in 2016 included stand counts and the percent of flag leaf phytotoxicity (leaf burn), which was visually estimated seven days after foliar applications. Leaf burn was based on symptoms across the entire plot using a percent scale of 0% (no injury) to 100% (complete leaf necrosis). In 2017, field measurements also included normalized difference vegetative index (NDVI) and normalized difference red edge (NDRE) readings using a handheld CropCircle ACS 470 (Holland Scientific, Lincoln, NE) before each foliar application and seven days post application. Times of application, average temperature, wind speed, and wind direction were recorded for each application using the nearest NDAWN weather station.

### Statistical Analysis

Data were statistically analyzed using the PROC GLM procedure in SAS 9.3 (SAS Institute, Cary, NC). Random variables included year, location, and replicate, while treatments were considered fixed. Experiment One and Experiment Two were analyzed separately by location and year. Bartlett’s test for homogeneity error of variance was conducted to determine if environments could be combined. Application timing and N source were additional factors analyzed in experiment one. Adjuvant and droplet size were separately analyzed as a factorial arrangement in experiment two. Both NDVI and NDRE readings were measured, and the strength of relationship between the two measurements were strong ($r^2$=0.70), therefore, only NDVI readings will be discussed. Main effects and interactions were tested using the appropriate error terms. A square root transformation was applied to percent leaf burn data prior to analysis to obtain a normal distribution of the data. The control was not included in leaf burn analysis because 0 values would provide an inaccurate assessment of means separation for treatments receiving a foliar application. Means were separated using Fisher's protected least significant difference (LSD) at the 95% level of confidence (α=0.05).

## Results and Discussion

### Combined Analysis

Barltett's test for homogeneity error of variance was not significant when comparing environments for both experiments, thus allowing for combining of environments in the ANOVA. In the combined analysis, the environment by treatment interactions (E x T) for GPC, leaf burn, and NDVI measurements were significant between environments in 2016 and 2017. Therefore, GPC, leaf burn, and NDVI measurements and will be discussed separately by environment, then combined across all environments within each year. Test weight and yield did not have significant E x T interactions and were combined across all environments in 2016 and 2017.

### Experiment One: Combined and Separate Applications of Fungicide with UAN and US

#### *Leaf Burn*

Experiment One investigated the effects of combining the applications of a fungicide with two N solutions (UAN or US) applied at ZGS 65 and 69. Across all environments, leaf burning was observed with all treatments receiving a spray solution (fungicide or N solution), but was greatest with treatments receiving an N solution. Phytotoxicity of the leaf tissue following a foliar N application can be described as scorching, burning, or tipping (Gooding and Davies, 1992). Burning was the greatest when fungicide was combined with NIS and UAN and applied at ZGS 65. Less damage was observed when either UAN or US were applied alone at the same timing (Table 2.5). The addition of NBPT to the N solution had no effect on leaf burn. Treatments containing UAN consistently caused significantly greater leaf burn than US, regardless of timing (Table 2.6). Others have also found that the severity of leaf burn varied depending on the type of N solution used (Alkier et al., 1972; Gooding et al., 1992; Bremner, 1995). Some forms of N fertilizer, such as urea has a lower salt concentration compared to UAN. Thus, desiccation of leaf cells with urea through osmosis is reduced and caused less injury than UAN (Gary, 1977).

There was a significant E x T interaction for leaf burning. The severity of burning across environments can be explained by differences in weather conditions at the time of application. In 2016, locations were planted within one day of each other and the plants matured at the same time causing some applications to take place when weather conditions were not ideal. However, in 2017 maturity varied between locations so applications could be made when weather conditions were favorable. The recommended weather conditions to reduce the chance of burning are to apply the solution in the cool of the day and when humidity is high (Garcia and Hanway, 1976). High temperatures and low humidity can lead to less moisture in the leaf tissue, resulting in lower dilution of N compounds in the concentrated solution, causing the burn (Akin and Gary, 1984; Gooding and Davies, 1992).

In 2016, leaf burn was assessed by visually determining the percentage of the flag leaf damaged, seven days after application. Burning was assessed in 2017 from NDVI values measured with a handheld CropCircle ACS-470. The CropCircle is an active optical sensor that is capable of quantifying the leaf biomass through red NDVI values (Sharma, L.K. et al., 2015). Foliage damaged by the N solution was necrotic and less green, resulting in a lower red NDVI value measured by the sensor.

Table 2.5. Effects of treatment applications on leaf burn measured by visual percent leaf burn (2016) and red NDVI† (2017) for all environments and combined within years.

| | | 2016 | | | | 2017 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Leaf Burn‡ | | | | NDVI | | | |
| Treatment | Application Timing | Cass. | Fargo | Pros. | Comb. | Ada | Cass. | Pros. | Comb. |
| | | --------------------%-------------------- | | | | | | | |
| 1) Control, no treatment§ | | | | | | 0.79 | 0.72 | 0.73 | 0.75 |
| 2) Fungicide + NIS¶ | ZGS 65 | 18 a# | 23 a | 15 a | 18 a | 0.74 | 0.74 | 0.74 | 0.74 |
| 3) Fungicide + NIS + UAN†† | ZGS 65 | 53 c | 55 c | 38 bcd | 48 f | 0.60 | 0.59 | 0.62 | 0.60 |
| 4) Fungicide + UAN + NBPT‡‡ | ZGS 65 | 40 bc | 43 bc | 38 bcd | 40 ef | 0.64 | 0.56 | 0.66 | 0.62 |
| 5) UAN | ZGS 65 | 30 ab | 30 ab | 28 abcd | 29 bcde | 0.74 | 0.74 | 0.70 | 0.72 |
| 6) Fungicide + NIS + US§§ | ZGS 65 | 25 ab | 30 ab | 20 ab | 25 abcd | 0.75 | 0.64 | 0.70 | 0.70 |
| 7) Fungicide + US + NBPT | ZGS 65 | 30 ab | 40 bc | 25 abc | 32 bcde | 0.73 | 0.65 | 0.70 | 0.69 |
| 8) US | ZGS 65 | 23 a | 20 a | 23 ab | 22 ab | 0.76 | 0.69 | 0.71 | 0.72 |
| 9) Fungicide + NIS | ZGS 65 | 20 a | 43 bc | 43 cd | 35 cdef | 0.73 | 0.65 | 0.69 | 0.69 |
| UAN | ZGS 69 | | | | | | | | |
| 10) UAN | ZGS 69 | 18 a | 53 c | 45 d | 38 def | 0.73 | 0.55 | 0.69 | 0.66 |
| 11) Fungicide + NIS | ZGS 65 | 18 a | 35 ab | 20 ab | 24 abc | 0.76 | 0.69 | 0.71 | 0.72 |
| US | ZGS 69 | | | | | | | | |
| 12) US | ZGS 69 | 18 a | 28 ab | 23 ab | 23 abc | 0.75 | 0.65 | 0.70 | 0.70 |
| | Mean | 26 | 36 | 29 | 30 | 0.72 | 0.66 | 0.70 | 0.69 |
| | LSD$_{0.05}$ | 15 | 17 | 16 | 12 | 0.06 | 0.08 | 0.02 | 0.06 |

† Normalized difference vegetative index.
‡ Means separation based on transformed values of % leaf burn, which are used to calculate the LSD values.
§ Control excluded % leaf burn analysis because no leaf burn occurred.
¶ Nonionic surfactant.
# LSD values valid for comparisons within locations.
†† Urea ammonium nitrate (28-0-0).
‡‡ N-n-butyl thiophosphoric triamide, urease inhibitor.
§§ Urea (46-0-0) solution.

The average percent leaf burn (PLB) in 2016 was 26, 36, and 29% at Casselton, Fargo, and Prosper, respectively (Table 2.5). Across all environments, the greatest amount of burning was observed for treatments containing fungicide + UAN and fungicide + UAN + NBPT with 48 and 40%, respectively (Table 2.5). Similar results were observed in 2017, with these treatments giving the lowest NDVI values with 0.60 and 0.62, respectively (Table 2.5). This is compared to an average NDVI value of 0.78 for fertilized plots shortly before application (Data not shown). Significantly less burning was observed in treatments with US when combined with a fungicide, as well as US alone. In 2016, treatments containing fungicide alone, fungicide + US, and US alone resulted in average PLB of 18, 25, and 22%, respectively (Table 2.5). The NDVI values for these treatments in 2017 had similar results with 0.74, 0.70, and 0.72, respectively (Table 2.5).

Table 2.6. Effects of treatment applications on leaf burn influenced by nitrogen source and measured by visual percent leaf burn (2016) and red NDVI† (2017) for all environments and combined within years.

|  | 2016 |  |  |  | 2017 |  |  |  |
|---|---|---|---|---|---|---|---|---|
|  | Leaf Burn‡ |  |  |  | NDVI |  |  |  |
|  | Cass. | Fargo | Pros. | Comb. | Ada | Cass. | Pros. | Comb. |
|  | --------------------%------------------- |  |  |  |  |  |  |  |
| Control, no treatment§ |  |  |  |  | 0.79 a | 0.72 a | 0.73 a | 0.75 a |
| Fungicide + NIS# | 17 a¶ | 22 a | 15 a | 18 a | 0.78 a | 0.74 a | 0.74 a | 0.75 a |
| UAN†† | 32 b | 44 b | 38 b | 38 c | 0.69 c | 0.62 c | 0.67 c | 0.66 b |
| Urea Solution‡‡ | 22 a | 30 a | 22 a | 25 b | 0.75 b | 0.66 b | 0.70 b | 0.71 a |

† Normalized difference vegetative index.

‡ Means separation based on transformed values of % leaf burn, which are used to calculate the LSD values.

§ Control excluded % leaf burn analysis because no leaf burn occurred.

¶ Nonionic Surfactant.

# LSD values valid for comparisons within locations.

†† Means derived from all treatments receiving urea ammonium nitrate (28-0-0), regardless of timing.

‡‡ Means derived from all treatments receiving urea (46-0-0) solution, regardless of timing.

### *Test Weight and Yield*

Treatments did not differ significantly for TW and yield whether fungicide or N solutions were combined or applied separately, and with or without NBPT. The combined average TW and yield were 761 kg m$^{-3}$ and 5180 kg ha$^{-1}$, respectively (Data not shown). Previous studies have reported decreased yields when foliar N applications caused severe burning (Mullins and Phillips, 2004). However, these results have not been consistent (Mullins and Phillips, 2004). In this study, burning may not have been sufficient to negatively influence TW and yield.

The N source supplied from UAN or US, as well as the timing of application at ZGS 65 or 69, did not differ significantly for TW or yield. The average TW and yield for treatment applications of UAN or US were 760 and 761 kg $m^{-3}$, and 5158 and 5185 kg $ha^{-1}$, respectively (Data not shown). Treatments with N solutions applied at ZGS 65 or 69 (regardless of N source) had a TW of 760 and 761 kg $m^{-3}$ and yielded 5172 and 5170 kg $ha^{-1}$, respectively.

An additional treatment in 2017 included an unfertilized control with zero N pre-plant and no foliar N application. Test weight and yield of the unfertilized control were significantly lower from all other treatments at Ada and Casselton (data not shown). However, the unfertilized control was not significant from all other treatments in Prosper. This may be due to well below normal rainfall at the beginning of the growing season (Table 2.7). The N in the fertilized plots was not effective because of lack of soil moisture and the plant roots could not effectively uptake N. Colman and Lazenby (1975) reported perennial ryegrass to have a low response to N fertilizer under low soil moisture conditions. The residual N at Prosper was high and therefore the applied N may not have affected the unfertilized plot greatly.

Table 2.7. Monthly rainfall totals from planting to harvest in Casselton, Prosper, and Fargo, ND, and Ada, MN in 2016 and 2017, along with normal (1981-2010)†.

| | Casselton‡ | | | Prosper | | | Fargo | | Ada | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2016 | 2017 | Normal | 2016 | 2017 | Normal | 2016 | Normal | 2017 | Normal |
| Month | ---------- | ---------- | ---------- | ---------- | ---------- | mm | ---------- | ---------- | ---------- | ---------- |
| April | 71 | 32 | 37 | 43 | 17 | 37 | 59 | 35 | 27 | 36 |
| May | 90 | 25 | 77 | 82 | 17 | 77 | 33 | 71 | 34 | 82 |
| June | 77 | 121 | 100 | 38 | 88 | 100 | 69 | 99 | 74 | 114 |
| July | 106 | 53 | 88 | 88 | 50 | 88 | 132 | 71 | 68 | 93 |
| August | 37 | 58 | 67 | 26 | 53 | 67 | 48 | 65 | 32 | 70 |
| Total | 381 | 289 | 369 | 277 | 224 | 369 | 340 | 341 | 235 | 395 |

† Information collected from NDAWN, 2017.

‡ Weather information collected from Casselton Agronomy Farm, Casselton, ND.

### ***Grain Protein Content***

The E x T interaction was significant for GPC. The average GPC in 2016 at Casselton, Prosper, and Fargo was 139, 129, and 134 g kg$^{-1}$, respectively. In 2017, the average GPC was 140, 135, and 135 g kg$^{-1}$ at Casselton, Prosper, and Ada, respectively (Table 2.8). The major differences in GPC across environments can be explained by environmental conditions that impacted grain quality, such as temperature and rainfall. These weather conditions can impact N uptake from the soil, N absorption by the foliage, and redistribution of N within the plant, especially during grain filling (Altenbach et al., 2003; Jenner et al., 1991).

Table 2.8. Grain protein content influenced by all treatments in experiment one for individual and combined environments.

| | | Casselton | | Prosper | | Fargo | Ada | Comb. |
|---|---|---|---|---|---|---|---|---|
| Treatment | Application Timing | 2016 | 2017 | 2016 | 2017 | 2016 | 2017 | 2016-2017 |
| | | -----------------------------g kg$^{-1}$----------------------------- | | | | | | |
| 1) Control, No treatment | | 137 | 129 | 126 | 132 | 132 | 127 | 131 |
| 2) Fungicide + NIS† | ZGS 65 | 138 | 136 | 130 | 132 | 131 | 128 | 132 |
| 3) Fungicide + NIS + UAN ‡ | ZGS 65 | 139 | 141 | 129 | 137 | 133 | 134 | 135 |
| 4) Fungicide + UAN + NBPT§ | ZGS 65 | 137 | 132 | 128 | 135 | 134 | 135 | 134 |
| 5) UAN | ZGS 65 | 138 | 142 | 129 | 135 | 137 | 139 | 137 |
| 6) Fungicide + NIS + US¶ | ZGS 65 | 140 | 133 | 128 | 133 | 132 | 137 | 134 |
| 7) Fungicide + US + NBPT | ZGS 65 | 139 | 141 | 127 | 135 | 132 | 137 | 135 |
| 8) US | ZGS 65 | 139 | 139 | 128 | 135 | 133 | 137 | 135 |
| 9) Fungicide + NIS<br>UAN | ZGS 65<br>ZGS 69 | 142 | 146 | 133 | 138 | 137 | 138 | 139 |
| 10) UAN | ZGS 69 | 144 | 148 | 131 | 139 | 137 | 138 | 139 |
| 11) Fungicide + NIS<br>US§ | ZGS 65<br>ZGS 69 | 140 | 145 | 131 | 138 | 133 | 138 | 138 |
| 12) US | ZGS 69 | 141 | 150 | 132 | 135 | 132 | 136 | 138 |
| | Range# | 7 | 21 | 7 | 7 | 6 | 12 | 8 |
| | Mean | 139 | 140 | 129 | 135 | 134 | 135 | 136 |
| | $LSD_{0.05}$ | 4 | 8 | 3 | 3 | 5 | 3 | 3 |

† Non Ionic Surfactant.

‡ Urea Ammonium Nitrate (28-0-0).

§ N-n-butyl thiophosphoric triamide, urease inhibitor.

¶ Urea (46-0-0) solution.

# Range = Difference between maximum and minimum values across all treatments for that location.

Significant differences in GPC were also found between treatments. The greatest increase between the control and foliar N applications occurred at Casselton in 2017 with 21 g kg$^{-1}$ (Table 2.8). In this study, combining a fungicide with either UAN or US did not significantly influence GPC compared the N solution alone at the same timing. The average GPC for treatments with applications at ZGS 65 were 135, 134, 137, 134, 135, and 135 g kg$^{-1}$ for fungicide + NIS + UAN, fungicide + NIS + UAN + NBPT, UAN alone, fungicide + NIS + US, fungicide + NIS + US + NBPT, and US alone, respectively (Table 2.8). Gooding et al. (2009) reported similar results with no impact in grain N from applications of US combined with propiconazole (250 a.i ha$^{-1}$). However, GPC consistently increased with foliar N applications at ZGS 69, indicating application timing may have a greater influence on GPC.

Data indicated that applications of either UAN or US at ZGS 69 had the highest GPC across all environments. Protein levels were significantly lower in four out of the six environments when foliar N applications (regardless of N solution) occurred at ZGS 65 compared to ZGS 69. Across all environments, average GPC was 135 and 138 g kg$^{-1}$ when foliar N applications occurred at ZGS 65 and 69, respectively (Table 2.9). Findings in this study are contrasting to previous research that has indicated foliar N applications at ZGS 61 had the greatest influence in GPC and responses from a foliar N application decreased as the kernel developed (Finney et al., 1957; Bly and Woodard, 2003; Endres and Schatz, 1993). The N source (UAN or US), regardless of timing, did not significantly influence GPC.

Overall, a combined fungicide and N solution application will not influence GPC compared to a foliar application of N solution alone at the same timing. However, these data indicated that the timing of application may have a greater influence on the effectiveness of this application. Therefore, foliar applications of fungicide and N solutions should be done separately to achieve the greatest increase in GPC.

Table 2.9. Grain protein content influenced by timing of application, regardless of N solution, for individual and combined environments in experiment one.

| | Casselton | | Prosper | | Fargo | Ada | Combined |
|---|---|---|---|---|---|---|---|
| | 2016 | 2017 | 2016 | 2017 | 2016 | 2017 | 2016-2017 |
| | ---------------------------------g $kg^{-1}$------------------------------ | | | | | | |
| Control, No Treatment | 137 a† | 129 a | 127 ab | 132 a | 132 a | 127 a | 131 a |
| Fungicide + NIS‡ | 138 a | 130 a | 130 a | 132 a | 131 a | 130 a | 133 ab |
| ZGS 65§ | 139 b | 138 b | 128 b | 135 b | 134 a | 137 b | 135 b |
| ZGS 69 | 142 c | 147 c | 132 c | 138 c | 134 a | 137 b | 138 c |

† Non Ionic Surfactant.
‡ LSD values valid for comparisons within locations.
§ Zadoks growth stage at which N solution applications occurred, regardless of N source.

### Experiment Two: Adjuvant and Droplet Size Combinations with UAN

#### *Leaf Burn*

Experiment Two investigated the effects of foliar applications of UAN combined with different adjuvants and droplet size combinations at ZGS 69. Across all environments, foliar N applications caused leaf burning. However, the severity of burning was greater than in experiment one, with the flag leaf completely desiccated in some environments. The E x T interactions were significant for PLB and NDVI. The interactions can be explained by weather conditions at the time of application similar to experiment one, since applications occurred at the same time for both experiments.

The adjuvant x droplet interaction was not significant for leaf burning in 2016 and 2017. The droplet size can affect the proportion of spray solution in contact with the leaf surface. Chan et al. (2009) reported the coverage of the spray solution on the leaf surface increased exponentially as droplet diameter increased. Therefore, a larger droplet may increase the potential for burning if it retained. However, in this study, foliar N applications with either medium or coarse droplets did not significantly increase burning across all environments.

The average PLB in 2016 was 47, 49, and 45% at Casselton, Fargo, and Prosper, respectively (Data not shown). Different UAN and adjuvant combinations resulted in different amounts of burning across environments in 2016 and 2017. The greatest burning resulted from foliar treatments of UAN and NIS with average an PLB of 60% in 2016 and NDVI value of 0.62 in 2017 (Table 2.10). This is compared to an average NDVI value of 0.75 for fertilized plots shortly before application. Foliar applications of UAN and all adjuvants resulted in greater burning compared to UAN alone. The average PLB in 2016 was 33, 55, 57, 60, and 55% for UAN, UAN + MSO, UAN + POC, UAN + NIS, and UAN + MSOOS, respectively (Table 2.10). The NDVI values for these treatments had similar results in 2017 with 0.70, 0.65, 0.65, 0.62, and 0.63, respectively (Table 2.10). Burning has occurred in previous research with foliar applications of N solutions combined with an adjuvant. Kaiser (2017) found leaf burning to increase in corn from foliar UAN applications with the addition of an MSO adjuvant.

Overall, the addition of an adjuvant, regardless of formulation, increased burning over UAN applications alone. The addition of an adjuvant to a UAN solution most likely increases burning due to the action of the adjuvant that allows the solution to increase coverage, “stick” to the leaf surface, or dissolve the leaf cuticle. Due to these actions, the accumulation of N on the leaf surface increases resulting in leaf desiccation, especially under favorable weather conditions (Poulton et al., 1990).

Table 2.10. Effects of adjuvant, droplet, and adjuvant x droplet interaction on leaf burn measured by visual percent leaf burn (2016) and red NDVI† (2017) for all environments and combined within years in experiment two.

| | 2016 | | | | 2017 | | | |
|---|---|---|---|---|---|---|---|---|
| | Visual Leaf Burn‡ | | | | NDVI | | | |
| | Cass. | Fargo | Pros. | Comb. | Ada | Cass. | Pros. | Comb. |
| | ------------------%------------------- | | | | | | | |
| UAN§ Medium Droplet | 38 | 25 | 33 | 32 | 0.72 | 0.68 | 0.70 | 0.70 |
| UAN Coarse Droplet | 35 | 38 | 28 | 33 | 0.75 | 0.69 | 0.68 | 0.71 |
| UAN + MSO¶ Medium Droplet | 33 | 65 | 78 | 58 | 0.73 | 0.56 | 0.68 | 0.65 |
| UAN + MSO Coarse Droplet | 33 | 55 | 70 | 53 | 0.69 | 0.58 | 0.67 | 0.65 |
| UAN + POC# Medium Droplet | 75 | 66 | 33 | 58 | 0.69 | 0.56 | 0.70 | 0.65 |
| UAN + POC Coarse Droplet | 75 | 63 | 30 | 56 | 0.70 | 0.55 | 0.68 | 0.65 |
| UAN + NIS†† Medium Droplet | 68 | 60 | 65 | 64 | 0.68 | 0.55 | 0.67 | 0.63 |
| UAN + NIS Coarse Droplet | 60 | 50 | 58 | 56 | 0.69 | 0.53 | 0.60 | 0.61 |
| UAN + MSOOS‡‡ Medium Droplet | 63 | 48 | 65 | 58 | 0.67 | 0.55 | 0.65 | 0.62 |
| UAN+ MSOOS Coarse Droplet | 48 | 48 | 60 | 52 | 0.71 | 0.56 | 0.68 | 0.65 |
| UAN Alone | 36 a | 31 a | 30 a | 33 a | 0.73 | 0.69 | 0.69 | 0.70 |
| UAN MSO | 33 a | 60 b | 74 b | 55 ab | 0.71 | 0.57 | 0.67 | 0.65 |
| UAN POC | 75 c | 64 b | 31 a | 57 ab | 0.70 | 0.56 | 0.69 | 0.65 |
| UAN NIS | 64 bc | 55 ab | 61 b | 60 b | 0.68 | 0.54 | 0.63 | 0.62 |
| UAN MSOOS | 55 ab | 48 ab | 63 b | 55 ab | 0.69 | 0.55 | 0.66 | 0.63 |
| Medium Droplet | 55 | 53 | 55 | 54 | 0.70 | 0.58 | 0.68 | 0.65 |
| Coarse Droplet | 50 | 51 | 49 | 50 | 0.71 | 0.58 | 0.66 | 0.65 |
| Adjuvant x Droplet LSD$_{0.05}$ | NS | NS | NS | NS | NS | NS | NS | NS |
| Adjuvant LSD$_{0.05}$ | NA§§ | NA | NA | NA | 0.02 | 0.05 | NS | 0.05 |
| Droplet LSD$_{0.05}$ | NS | NS | NS | NS | NS | NS | NS | NS |

† Normalized difference vegetative index.

‡ Means separation based on transformed values of % leaf burn, which were used to calculate the LSD values. LSD values valid for comparisons within locations

§ Urea ammonium nitrate (28-0-0).

¶ Methylated seed oil.

# Petroleum oil concentrate.

†† Nonionic surfactant.

‡‡ Methylated seed oil organisilicone surfactant.

§§ Means separation represented by letters in table, LSD values valid for comparisons within locations.

### ***Test Weight and Yield***

A relationship between TW and yield has been reported in previous research, and when yield is reduced, often a decrease in TW is also realized (Lopez-Bellido et al., 2003). The adjuvant x droplet interaction and droplet size (regardless of adjuvant) was not significant for

TW or yield. In this study, data indicated TW and yield were not significantly different between foliar applications of UAN and the control. However, foliar applications of UAN combined with an adjuvant significantly reduced TW and yield.

The combined average TW and yield for all treatments across all environments was 762 g $kg^{-1}$ and 5334 kg $ha^{-1}$ (Data not shown). The average TW for UAN, UAN + MSO, UAN + POC, UAN + NIS, and UAN + MSSOS was 765, 760, 758, 760, and 763 g $kg^{-1}$, respectively (Table 2.11). The differences in TW between UAN and adjuvant combinations can be explained by the severity of burning that occurred from these foliar applications. The burning causes plant stress, especially during the grain-filling period when these applications occur. This stress, along with the reduced photosynthesis of the flag leaf can reduce starch accumulation, thus lowering TW (Altenbach et al., 2003).

Yield decreased only marginally with foliar applications of UAN and adjuvants. A foliar application of UAN and NIS reduced yield the greatest and was significantly lower yielding than UAN alone. The yield for these treatments was 5133 and 5476 kg $ha^{-1}$, respectively (Table 2.11). Foliar applications of UAN and the other three adjuvants were not significantly lower yielding than UAN alone. Yield is also negatively affected if the plant is stressed during the grain filling period. These stresses can include high temperatures, lack of water or N, and phytotoxicity. These stresses reduce the duration of grain filling, limiting starch deposition (Tewolde et al., 2006). The severe phytotoxicity stress may explain the reduction in grain yield (Figure 2.1).

Table 2.11. Average test weight and yield for adjuvant, droplet, and adjuvant x droplet interactions combined across environments in 2016 and 2017 in experiment two.

| | Test Weight | Yield |
|---|---|---|
| | kg $m^{-3}$ | kg $ha^{-1}$ |
| UAN† Medium Droplet | 766 | 5526 |
| UAN Coarse Droplet | 765 | 5426 |
| UAN + MSO‡ Medium Droplet | 760 | 5360 |
| UAN + MSO Coarse Droplet | 761 | 5247 |
| UAN + POC§ Medium Droplet | 758 | 5326 |
| UAN + POC Coarse Droplet | 759 | 5182 |
| UAN + NIS¶ Medium Droplet | 761 | 5093 |
| UAN + NIS Coarse Droplet | 758 | 5173 |
| UAN + MSOOS# Medium Droplet | 764 | 5256 |
| UAN+ MSOOS Coarse Droplet | 761 | 5310 |
| UAN | 765 | 5476 |
| UAN MSO | 760 | 5304 |
| UAN POC | 758 | 5254 |
| UAN NIS | 760 | 5133 |
| UAN MSOOS | 763 | 5283 |
| Medium Droplet | 762 | 5312 |
| Coarse Droplet | 761 | 5268 |
| Adjuvant x Droplet $LSD_{0.05}$ | NS | NS |
| Adjuvant $LSD_{0.05}$ | 4 | 165 |
| Droplet $LSD_{0.05}$ | NS | NS |

† Urea Ammonium Nitrate (28-0-0).
‡ Methylated seed oil.
§ Petroleum oil concentrate.
¶ Nonionic surfactant.
# Methylated seed oil organisilicone surfactant.

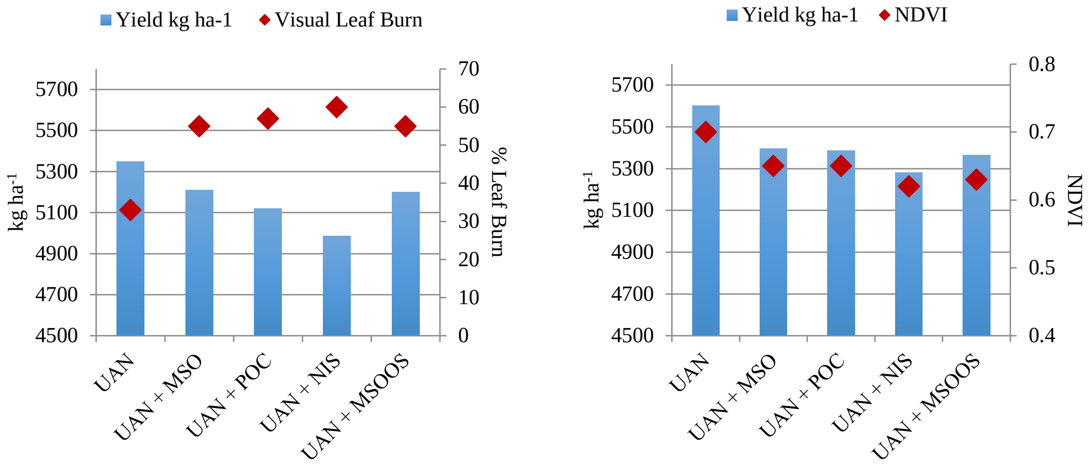

Figure 2.1. Effect of leaf burn on yield in 2016 (left) and 2017 (right) caused by foliar N applications. Leaf burn measured by visual % leaf burn in 2016 and normalized difference vegetative index in 2017.

### *Grain Protein Content*

There were significant E x T interactions for GPC. In 2016, the average GPC for Casselton, Prosper, and Fargo was 139, 132, and 133 g kg$^{-1}$, respectively, and in 2017 was 136, 138, and 135 g kg$^{-1}$ for Casselton, Prosper, and Ada (data not shown). Differences in GPC across environments may be due to weather conditions at the time of application and immediately following the foliar N application. High temperatures and low moisture can affect the efficiency of this application (Terman, 1979). The average temperature during the grain filling period was normal, with minimal variation between locations (data not shown). However, in 2016, average precipitation during the same time was normal, but was below normal in 2017 (Table 2.7). Environments with no response to the late season foliar N application may be due to sufficient N in the soil profile above what is needed to produce yield and GPC under the conditions in that particular year.

Significant differences in GPC were found between treatments in four out of the six environments in 2016 and 2017. An average increase of 8 g kg$^{-1}$ over the control occurred across all environments (Table 2.12). The adjuvant x droplet interaction was not significant for GPC.

Mercer (2007) suggested that decreasing droplet size would lead to an increase in the uptake of the active ingredient and therefore increase grain N. Findings in this study indicated GPC was only marginally different between droplet sizes and was not significant across all environments.

Different UAN and adjuvant combinations (regardless of droplet size) resulted in different GPC, but was not significantly different compared to UAN alone in five out of the six environments. The greatest increase in GPC occurred with a foliar application of UAN and POC at Prosper in 2016 with 136 g $kg^{-1}$ compared to UAN alone with 133 g $kg^{-1}$ (Table 2.12). However, this was not consistent across environments. Grain protein content may not have been increased with the addition of an adjuvant due to phytotoxicity caused by the N solution. After foliar N applications, the solution is either absorbed through the leaf stomata or run off leaf surfaces and absorbed by the roots and redistributed to the grain. The function of the adjuvants are to increase retention of the droplets, improve the interface between the leaf surface and N compounds, or increase penetration of the N compounds. However, the rate or amount of uptake of the N compounds may have been so great that it resulted in localized cell death. The consequence of this resulted in the inability of the N to translocate out of the leaf, reducing the effectiveness of the applications (Brian, 1972; Merritt, 1982; Knoche et al., 1992; Forster et al., 1997).

Overall, combined data confirmed that a late season foliar UAN application at ZGS 69 can reliably increase GPC. Findings in this study suggest the addition of adjuvants used in this experiment (regardless of formulation) will not increase GPC greater than an application of UAN alone. Also, droplet size will not have an impact on the efficiency of this late season application. This is contrasting to previous research that has reported an increase in GPC while using smaller droplet sizes with an adjuvant and UAN (Wyatt, 2013). Different responses in GPC to various adjuvants added to late season foliar N applications across environments suggests that additional research needs to be conducted to help determine favorable environmental conditions to use an adjuvant with UAN.

Table 2.12. Grain protein content influenced by adjuvant, droplet, and adjuvant x droplet interactions for individual and combined environments in experiment two.

| | Casselton | | Prosper | | Fargo | Ada | Comb. |
|---|---|---|---|---|---|---|---|
| | 2016 | 2017 | 2016 | 2017 | 2016 | 2017 | 2016-2017 |
| | ---------------------------g $kg^{-1}$---------------------------- | | | | | | |
| UAN† Medium Droplet | 140 | 139 | 133 | 139 | 136 | 136 | 137 |
| UAN Coarse Droplet | 138 | 138 | 133 | 141 | 130 | 134 | 136 |
| UAN + MSO‡ Medium Droplet | 140 | 138 | 130 | 138 | 132 | 134 | 136 |
| UAN + MSO Coarse Droplet | 140 | 136 | 132 | 138 | 134 | 133 | 136 |
| UAN + POC§ Medium Droplet | 140 | 136 | 135 | 138 | 130 | 135 | 135 |
| UAN + POC Coarse Droplet | 138 | 142 | 136 | 138 | 132 | 134 | 137 |
| UAN + NIS¶ Medium Droplet | 138 | 135 | 130 | 140 | 134 | 134 | 135 |
| UAN + NIS Coarse Droplet | 139 | 137 | 132 | 138 | 134 | 135 | 136 |
| UAN + MSOOS# Medium Droplet | 138 | 132 | 132 | 139 | 132 | 136 | 135 |
| UAN+ MSOOS Coarse Droplet | 138 | 138 | 133 | 138 | 133 | 136 | 136 |
| UAN Alone | 139 | 138 | 133 | 140 | 133 | 135 | 136 |
| UAN MSO | 140 | 137 | 131 | 138 | 133 | 134 | 136 |
| UAN POC | 139 | 139 | 136 | 138 | 131 | 134 | 136 |
| UAN NIS | 139 | 136 | 131 | 139 | 134 | 135 | 135 |
| UAN MSOOS | 138 | 135 | 133 | 138 | 133 | 136 | 135 |
| Medium Droplet | 139 | 136 | 132 | 139 | 133 | 135 | 136 |
| Coarse Droplet | 139 | 138 | 133 | 139 | 132 | 134 | 136 |
| Adjuvant x Droplet LSD$_{0.05}$ | NS | NS | NS | NS | NS | NS | NS |
| Adjuvant LSD$_{0.05}$ | NS | NS | 4 | NS | NS | NS | NS |
| Droplet LSD$_{0.05}$ | NS | NS | NS | NS | NS | NS | NS |

† Urea Ammonium Nitrate (28-0-0).
‡ Methylated seed oil.
§ Petroleum oil concentrate.
¶ Nonionic surfactant.
# Methylated seed oil organisilicone surfactant.

### *Additional Treatments*

In 2016 and 2017, additional foliar N applications included dilution ratios (UAN:Water) of 60:40 and 75:25, as well as NBPT combined with UAN and US. These treatments showed no effect on leaf burn, TW, yield, or GPC, with the exception of UAN and NBPT. Foliar applications of UAN and NBPT significantly reduced TW compared to UAN alone and the control (data not shown). Similar GPC was achieved with UAN:Water dilution ratio of 50:50, 60:40, and 75:25. This suggests that a single volume of the N solution can cover a larger area, and the same N rate can be applied using less total volume, ultimately saving costs for a producer. Foliar applications of UAN and US with NBPT were not significantly different from all treatments receiving a foliar N application.

Experiment Two included an unfertilized control in 2017, similar to experiment one. Parallel results were obtained in experiment two and TW and yield were significantly lower compared to fertilized treatments at Ada and Casselton, but no significant difference was found at Prosper. This can be explained for similar reasons described in experiment one with greater levels of residual N and low soil moisture at the beginning of the growing season in Prosper.

Additional treatments in 2017 included foliar applications of UAN at ZGS 65 and 69 using streamer bars rather than broadcast nozzles. A streamer bar is adapted to a spray nozzle and delivers a uniform stream of the N solution. This is contrasting to broadcast nozzles that deliver the N solution in a pattern to the foliage. A benefit of streamer bars is that foliar applications can be made in windy conditions and less contact of the N solution with the foliage, unlike broadcast nozzles (Arnall et al., 2009). In this study, the severity of leaf burning was significantly decreased when UAN was applied with streamer bars compared to UAN applications with broadcast nozzles. A single stream applies the spray solution allowing less contact to be made with the foliage, thus causing less burning. Test weight and yield were not significantly different between foliar applications of UAN with streamer bars and UAN applications using broadcast nozzles (data not shown). Streamer bars may be an effective method to apply UAN in environments with sufficient soil moisture and adequate rainfall following application. However, without sufficient moisture or rainfall to move N into the soil solution, the plant roots cannot absorb and redistribute N to the grain.

## Conclusion

The severity of leaf burn from a late-season foliar N application can vary depending on the weather conditions at the time of application, as well as the N solution. An application of UAN will often increase leaf burning over US. This has been reported in previous research due to the increased toxicity of ammonia in UAN. Also, combining a fungicide with either UAN or US will increase leaf burning compared to applications done separately. The addition of an adjuvant (regardless of formulation) will most likely cause severe leaf burning when combined with UAN due to increased coverage and absorption of the N compounds. In this study, droplet size did not impact leaf burning, TW, yield, or GPC.

Test weight and grain yield are often significantly related. Previous research has indicated foliar N applications to have variable effects on grain yield. In this study, a foliar application at ZGS 65 of N solution combined with a fungicide to have no substantial effect on TW or yield. However, the addition of an adjuvant, regardless of formulation, reduced TW and yield compared to UAN alone. This is likely due to an increase in leaf burn realized with the additional adjuvant. Damage to the foliage can decrease TW and yield due to reduced starch accumulation during grain filling.

A late-season foliar N application significantly increased GPC. In this study, an increase between 6 to 21 g $kg^{-1}$ was observed between treatments receiving supplemental N and the check for both experiments. The combination of a fungicide with N solution will not have a negative impact on GPC, but rather the timing of this application will more effectively influence GPC.

The greatest increase was realized with an application at ZGS 69, with N source from either UAN or US. The addition of an adjuvant or NBPT will not significantly increase GPC beyond that of UAN alone, therefore, the additional cost of these inputs would not be recommended for producers.

Overall, a benefit from a late season foliar N application can be realized due to an increase in GPC, especially in years that weather conditions favor N uptake and redistribution of N to the grain. However, no benefit in increasing GPC is realized with the use of an adjuvant or NBPT and the additional cost would not be worth the expense for the producer. The additional treatments such as increased dilution ratios and the use of streamer bars to apply the N solution may have some benefits to producers and future research should investigate the effectiveness of these further.

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# CONCLUSION

Grain quality for HRSW producers can be difficult to consistently predict within and across years. The DSSAT can be a valuable tool to accurately predict HRSW growth by updating the CSM with measured weather data during the growing season, while supplementing historic weather data to forecast weather for the remainder of the growing season. In this study, the best approach to forecast weather was through a style that uses daily weather over multiple years to give a range of possible outcomes (distribution). However, plant growth should not be predicted with forecasted weather before ZGS 45. The accuracy of simulations improves as plant development progresses to ZGS 61. Variability in simulation accuracy existed between locations, therefore improved physical soil and cultivar measurements would be needed to improve the accuracy of predictions. However, overall DSSAT was determined to be an effective tool to predict HRSW yield during the growing season. Since yield was predicted with adequate accuracy, DSSAT could be used as a decision support system to allow producers to make informed management decisions after ZGS 45. A decision producers may determine based on grain yield is whether or not a late season foliar N application would be needed to increase GPC.

A late season foliar N application might be considered to optimize GPC, if anticipated grain yields are likely to exceed the yield considered when pre-plant recommendations were determined (Wuest and Cassman, 1992). In this study, a foliar N application at either ZGS 65 or 69 significantly increased GPC, with the greatest increase occurring with applications at ZGS 69 using either UAN or US. An N solution combined with a fungicide and applied at ZGS 65 will not decrease GPC. However, the timing of this application indicated that a more effective increase in GPC can be realized if the applications are done separately. The addition of different adjuvants or NBPT did not improve the effectiveness of a UAN application to increase GPC.

However, phytotoxicity from the N solution was severely increased with these additions. The severity of leaf burn caused by foliar N applications also depended on the weather conditions at the time of application. Depending on the severity of burning, TW and yield were significantly decreased.

The cost of a late season foliar N application must be equal to or less than the economic return from a premium or reduced discount in GPC from the market threshold of 140 g $kg^{-1}$. Implementing DSSAT can be a management tool for producers to accurately predict grain yield from the ZGS 45 if predicted yields are sufficient for an economic return to be realized. This would allow little time for a management decision to be made, since the optimum timing to increase GPC from this application occurs at ZGS 69. The techniques used in this study suggest the additional cost of an adjuvant or NBPT would not increase GPC high enough to realize an economic return.

# APPENDIX

Table A.1. Simulated anthesis date using full season weather data and anthesis date determined by the NDAWN wheat GDD calculator† in 2005-2016.

| | Carrington | | Hettinger | | Langdon | | Minot | | Williston | | Combined | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sim.‡ | Obs.§ | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. |
| Year | ----------DAP¶---------- | | | | | | | | | | | |
| 2005 | 73 | 71 | 71 | 65 | 67 | 52 | 70 | 64 | 73 | 67 | 71 | 64 |
| 2006 | 69 | 66 | 68 | 61 | 67 | 55 | 67 | 61 | 67 | 58 | 68 | 60 |
| 2007 | 69 | 62 | 67 | 62 | 71 | 72 | 67 | 61 | 69 | 63 | 69 | 64 |
| 2008 | 79 | 80 | 73 | 69 | 75 | 76 | 72 | 68 | 75 | 70 | 75 | 73 |
| 2009 | 69 | 67 | 72 | 68 | 69 | 56 | 71 | 66 | 74 | 71 | 71 | 66 |
| 2010 | 69 | 68 | 78 | 78 | 74 | 79 | 69 | 59 | 71 | 70 | 72 | 71 |
| 2011 | 69 | 63 | 72 | 68 | 65 | 52 | 68 | 61 | 66 | 59 | 68 | 61 |
| 2012 | 73 | 69 | 82 | 81 | 72 | 72 | 72 | 68 | 69 | 82 | 74 | 74 |
| 2013 | 63 | 56 | 74 | 70 | 64 | 50 | 63 | 57 | 66 | 58 | 66 | 58 |
| 2014 | 69 | 63 | 74 | 74 | 72 | 54 | 69 | 57 | 66 | 60 | 70 | 62 |
| 2015 | 77 | 76 | 79 | 79 | 72 | 70 | 71 | 68 | 69 | 66 | 74 | 72 |
| 2016 | 73 | 72 | 79 | 78 | 70 | 62 | 68 | 61 | 65 | 59 | 71 | 66 |

† North Dakota Agricultural Weather Network wheat Growing Degree Day calculator (NDAWN, 2017b).

‡ Simulated anthesis date from model output.

§ Observed anthesis date determined by the NDAWN wheat GDD calculator.

¶ Days after planting.

Table A.2. Simulated grain yield using full season weather data and observed grain yield obtained from North Dakota REC† cultivar trials in 2005-2016.

| | Carrington | | Hettinger | | Langdon | | Minot | | Williston | | Combined | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sim.‡ | Obs.§ | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. | Sim. | Obs. |
| Year | ---------------------------------------------kg ha$^{-1}$--------------------------------------------------- | | | | | | | | | | | |
| 2005 | 4128 | 3945 | 4438 | 2623 | 5551 | 4052 | 5066 | 5044 | 4813 | 4830 | 4799 | 4099 |
| 2006 | 4281 | 4104 | 2536 | 2408 | 1744 | 3904 | 2426 | 2170 | 2109 | 2358 | 2594 | 3014 |
| 2007 | 4396 | 3922 | 3425 | 2650 | 5250 | 5631 | 5237 | 5367 | 4275 | *3687* | 4362 | 4406 |
| 2008 | 4968 | 4708 | 3563 | 2585 | 4860 | 5631 | 4531 | 4484 | 2841 | 2548 | 3957 | 4187 |
| 2009 | 3432 | 4032 | 3967 | 2246 | 6041 | 5955 | 4064 | 5203 | 2698 | 3582 | 3696 | 4548 |
| 2010 | 4456 | 5341 | 4807 | 4350 | 5087 | 5373 | 4462 | 4754 | 3660 | 2892 | 4403 | 4633 |
| 2011 | 4250 | 2746 | 4545 | 4486 | 3949 | 5160 | 4418 | 3014 | 2855 | 2715 | 3992 | 3636 |
| 2012 | 4318 | 3778 | 4078 | 4713 | 4854 | 4792 | 4301 | 3330 | 3581 | 2235 | 4353 | 3643 |
| 2013 | 2032 | 2014 | 4779 | 4258 | 3647 | 5105 | 4685 | 3635 | 4682 | 3765 | 3861 | 3860 |
| 2014 | 4926 | 5564 | 4797 | 5392 | 3859 | 5437 | 5124 | 4225 | 2408 | 2340 | 4342 | 4473 |
| 2015 | 3580 | 4207 | 5373 | 4491 | 4565 | 5408 | 5162 | 4757 | 2922 | 2783 | 4144 | 4506 |
| 2016 | 3506 | 3975 | 2507 | 3308 | 5716 | 4540 | 4761 | 4720 | 4267 | 4240 | 4312 | 3996 |

† Research extension center.

‡ Simulated grain yield from model output.

§ Observed yield from North Dakota Research Extension Center cultivar trials.

Table A.3. Weather conditions at the time of treatment applications for all environments in experiment one and two in 2016 and 2017.

| Location, Year | | Experiment One | | Experiment Two | |
|---|---|---|---|---|---|
| | | ZGS† 65 | ZGS 69 | ZGS 65 | ZGS 69 |
| Fargo, 2016 | Date‡ | 18 June 2016 | 21 June 2016 | NA†† | 18 June 2016 |
| | Time§ | 9:00 am | 2:15 PM | | 10:00 am |
| | Temp.¶ | 18 | 28 | | 18 |
| | Wind# | 6 NW | 14-16 N | | 6 NW |
| Prosper, 2016 | Date | 28 June 2016 | 18 June 2016 | NA | 28 June 2016 |
| | Time | 11:00 am | 11:45 am | | 12:00 PM |
| | Temp. | 21 | 27 | | 21 |
| | Wind | 14 N-NW | 3 NW | | 17 N-NW |
| Casselton, 2016 | Date | 28 June 2016 | 18 June 2016 | NA | 28 June 2016 |
| | Time | 12:30 PM | 1:00 PM | | 1:30 PM |
| | Temp. | 22 | 28 | | 22 |
| | Wind | 6-8 N-NW | 16-18 NW | | 6-8 N-NW |
| Ada, 2017 | Date | 3 July 2017 | 26 June 2017 | 26 June 2017 | 3 July 2017 |
| | Time | 7:00 am | 7:30 am | 7:30 am | 8:30 am |
| | Temp. | 20 | 13 | 13 | 20 |
| | Wind | 6-10 S | 5-8 NW | 5-8 NW | 6-10 S |
| Prosper, 2017 | Date | 30 June 2017 | 26 June 2017 | 26 June 2017 | 30 June 2017 |
| | Time | 7:00 am | 2:00 PM | 1:00 PM | 8:00 am |
| | Temp. | 18 | 23 | 23 | 18 |
| | Wind | 3-13 NW | 6-14 NW | 6-14 NW | 3-13 NW |
| Casselton, 2017 | Date | 5 July 2017 | 5 July 2017 | 28 June 2017 | 10 July 2017 |
| | Time | 8:45 am | 7:00 am | 8:30 am | 7:40 am |
| | Temp. | 24 | 23 | 18 | 18 |
| | Wind | 6-11 E-SE | 5-10 E-SE | 8-10 S | 2-5 E |

† Zadoks growth stage.

‡ Date of treatment application.

§ Time of application.

¶ Air temperature (°C).

# Wind speed and direction. Wind speed measured in km $h^{-1}$.

†† Not applicable, no treatment applications at ZGS 65 in 2016

Table A.4. Effects of treatment applications on leaf burn measured by normalized difference red edge (NDRE) in 2017 for individual and combined environments in Experiment One.

| Treatment | Application Timing | Ada | Cass | Pros | Combined |
|---|---|---|---|---|---|
| 1) Control, no treatment | | 0.20 | 0.25 | 0.31 | 0.25 |
| 2) Fungicide + NIS† | ZGS 65 | 0.33 | 0.29 | 0.33 | 0.32 |
| 3) Fungicide + NIS + UAN‡ | ZGS 65 | 0.33 | 0.30 | 0.32 | 0.32 |
| 4) Fungicide + UAN + NBPT§ | ZGS 65 | 0.32 | 0.31 | 0.33 | 0.32 |
| 5) UAN | ZGS 65 | 0.30 | 0.28 | 0.29 | 0.29 |
| 6) Fungicide + NIS + US¶ | ZGS 65 | 0.31 | 0.29 | 0.29 | 0.30 |
| 7) Fungicide + US + NBPT | ZGS 65 | 0.24 | 0.26 | 0.28 | 0.26 |
| 8) US | ZGS 65 | 0.31 | 0.27 | 0.31 | 0.30 |
| 9) Fungicide + NIS | ZGS 65 | 0.30 | 0.33 | 0.31 | 0.31 |
| UAN | ZGS 69 | 0.31 | 0.30 | 0.32 | 0.31 |
| 10) UAN | ZGS 69 | 0.29 | 0.36 | 0.29 | 0.31 |
| 11) Fungicide + NIS | ZGS 65 | 0.30 | 0.28 | 0.29 | 0.29 |
| US | ZGS 69 | 0.25 | 0.23 | 0.29 | 0.26 |
| 12) US | ZGS 69 | 0.30 | 0.28 | 0.30 | 0.29 |
| | Mean | 0.29 | 0.29 | 0.3 | 0.29 |
| | $LSD_{0.05}$ | 0.02 | NS | 0.01 | 0.04 |

† Nonionic surfactant.

‡ Urea ammonium nitrate (28-0-0).

§ N-n-butyl thiophosphoric triamide, urease inhibitor.

¶ Urea (46-0-0) solution.

Table A.5. Test weight and yield for all treatments in experiment one combined across six environments in 2016 and 2017.

| Timing† | Treatment | TW | Yield |
|---|---|---|---|
| | | kg $m^{-3}$ | kg $ha^{-1}$ |
| | 1) Control, No treatment | 763 | 5153 |
| ZGS 65 | 2) Fungicide + NIS‡ | 764 | 5295 |
| ZGS 65 | 3) Fungicide + NIS + UAN | 762 | 5184 |
| ZGS 65 | 4) Fungicide + UAN + NBPT# | 760 | 5140 |
| ZGS 65 | 5) UAN | 760 | 5148 |
| ZGS 65 | 6) Fungicide + NIS + US | 762 | 5221 |
| ZGS 65 | 7) Fungicide + US + NBPT | 761 | 5233 |
| ZGS 65 | 8) US | 760 | 5095 |
| ZGS 65<br>ZGS 69 | 9) Fungicide + NIS<br>UAN§ | 759 | 5179 |
| ZGS 69 | 10) UAN | 755 | 5139 |
| ZGS 65<br>ZGS 69 | 11) Fungicide + NIS<br>US¶ | 765 | 5294 |
| ZGS 69 | 12) US | 760 | 5077 |
| | Mean | 761 | 5180 |
| | $LSD_{0.05}$ | NS | NS |

† Timing of application.

‡ Non Ionic Surfactant.

§ Urea Ammonium Nitrate (28-0-0).

¶ Urea (46-0-0) Solution.

# N-n-butyl thiophosphoric triamide, urease inhibitor.

Table A.6. Test weight, yield, and grain protein content influenced by all treatments in experiment one for individual and combined environments in 2017.

| Application Timing† | Treatment | Test Weight | | | | Yield | | | | Protein | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Ada | Cass | Pros | Comb. | Ada | Cass | Pros | Comb. | Ada | Cass | Pros | Comb. |
| | | --------------kg $m^{-3}$-------------- | | | | -------------kg $ha^{-1}$------------ | | | | ------------g $kg^{-1}$------------ | | | |
| | 1) Control, no Fertilizer | 779 | 758 | 768 | 769 | 3854 | 4185 | 4543 | 4194 | 125 | 128 | 129 | 127 |
| | 2) Control, with Fertilizer | 792 | 769 | 765 | 775 | 6080 | 5818 | 4604 | 5500 | 127 | 129 | 132 | 129 |
| ZGS 65 | 3) Fungicide, no NIS‡ | 794 | 772 | 768 | 778 | 6165 | 5519 | 4524 | 5403 | 132 | 124 | 134 | 130 |
| ZGS 65 | 4) Fungicide + NIS | 801 | 774 | 765 | 780 | 6264 | 5805 | 4871 | 5647 | 128 | 136 | 132 | 132 |
| ZGS 65 | 5) Fungicide + NIS + UAN§ | 791 | 768 | 763 | 774 | 5803 | 5726 | 4426 | 5318 | 134 | 141 | 136 | 137 |
| ZGS 65 | 6) Fungicide + UAN + NBPT¶ | 789 | 766 | 762 | 772 | 5873 | 5502 | 4700 | 5359 | 135 | 132 | 135 | 134 |
| ZGS 65 | 7) UAN | 790 | 772 | 766 | 776 | 6260 | 5993 | 4519 | 5591 | 139 | 142 | 135 | 139 |
| ZGS 65 | 8) Fungicide + NIS + US# | 799 | 775 | 766 | 780 | 6293 | 5645 | 4819 | 5585 | 137 | 133 | 133 | 134 |
| ZGS 65 | 9) Fungicide + US + NBPT | 793 | 771 | 763 | 776 | 6191 | 6046 | 4737 | 5658 | 137 | 141 | 135 | 138 |
| ZGS 65 | 10) US | 790 | 767 | 765 | 774 | 6321 | 5591 | 4378 | 5430 | 137 | 139 | 135 | 137 |
| ZGS 65<br>ZGS 69 | 11) Fungicide + NIS<br>UAN | 793 | 773 | 761 | 776 | 6186 | 5869 | 4523 | 5526 | 137 | 146 | 138 | 141 |
| ZGS 69 | 12) UAN | 793 | 767 | 760 | 774 | 6053 | 5766 | 4517 | 5445 | 138 | 148 | 139 | 142 |
| ZGS 65<br>ZGS 69 | 13) Fungicide + NIS<br>US | 795 | 774 | 764 | 778 | 6257 | 5781 | 4703 | 5580 | 138 | 145 | 138 | 140 |
| ZGS 69 | 14) US | 791 | 764 | 761 | 772 | 5831 | 5295 | 4628 | 5251 | 136 | 150 | 135 | 141 |
| | $LSD_{0.05}$ | 9 | 6 | NS | 56 | 337 | 767 | NS | 561 | 3 | 8 | 3 | 6 |

† Timing of application.

‡ Non Ionic Surfactant.

§ Urea Ammonium Nitrate (28-0-0).

¶ N-n-butyl thiophosphoric triamide, urease inhibitor.

# Urea (46-0-0) Solution.

Table A.7. Effects of treatment applications on leaf burn measured by normalized difference red edge (NDRE) in 2017 for individual and combined environments in Experiment Two.

| | Ada | Cass | Pros | Combined |
|---|---|---|---|---|
| 1) Control, no Fertilizer | 0.22 | 0.23 | 0.29 | 0.25 |
| 2) Control, with Fertilizer | 0.31 | 0.29 | 0.30 | 0.30 |
| 3) UAN† Medium Droplet | 0.28 | 0.29 | 0.29 | 0.29 |
| 4) UAN Coarse Droplet | 0.30 | 0.28 | 0.29 | 0.29 |
| 5) UAN + MSO‡ Medium Droplet | 0.30 | 0.22 | 0.28 | 0.27 |
| 6) UAN + MSO Coarse Droplet | 0.28 | 0.24 | 0.28 | 0.26 |
| 7) UAN + POC§ Medium Droplet | 0.29 | 0.24 | 0.27 | 0.27 |
| 8) UAN + POC Coarse Droplet | 0.29 | 0.23 | 0.29 | 0.27 |
| 9) UAN + NIS¶ Medium Droplet | 0.28 | 0.23 | 0.26 | 0.26 |
| 10) UAN + NIS Coarse Droplet | 0.28 | 0.22 | 0.27 | 0.26 |
| 11) UAN + MSOOS# Medium Droplet | 0.28 | 0.22 | 0.28 | 0.26 |
| 12) UAN+ MSOOS Coarse Droplet | 0.27 | 0.23 | 0.28 | 0.26 |
| 13) UAN 60:40 Dilution Ratio†† | 0.29 | 0.26 | 0.28 | 0.28 |
| 14) UAN 75:25 Dilution Ratio | 0.29 | 0.29 | 0.28 | 0.28 |
| 15) UAN + NBPT‡‡ | 0.28 | 0.26 | 0.26 | 0.27 |
| 16) Urea Solution + NBPT | 0.31 | 0.28 | 0.27 | 0.29 |
| 17) UAN Streamer Bars at ZGS 65 | 0.31 | 0.30 | 0.31 | 0.31 |
| 18) UAN Streamer Bars at ZGS 65 | 0.29 | 0.27 | 0.28 | 0.28 |
| Mean | 0.28 | 0.25 | 0.28 | 0.27 |
| $LSD_{0.05}$ | 0.03 | 0.04 | 0.02 | 0.03 |

† Urea ammonium nitrate (28-0-0).
‡ Methylated seed oil.
§Petroleum oil concentrate.
¶ Nonionic surfactant.
# Methylated seed oil organisilicone surfactant.
†† Dilution ratio of nitrogen solution (UAN:Water)
‡‡ N-n-butyl thiophosphoric triamide, urease inhibitor

Table A.8. Effects of treatment applications on leaf burn measured by visual percent leaf burn (2016) and red normalized difference vegetative index (NDVI) (2017) for individual environments and combined within years in experiment two.

| | 2016<br>Visual Leaf Burn† | | | | 2017<br>NDVI | | | |
|---|---|---|---|---|---|---|---|---|
| | Cass. | Fargo | Pros. | Comb | Ada | Cass. | Pros. | Comb. |
| | -------------------%---------------- | | | | | | | |
| 1) Control, No Treatment | | | | | 0.77 | 0.72 | 0.74 | 0.74 |
| 2) UAN‡ Medium Droplet | 37 ab | 25 a | 33 a | 32 ab | 0.72 | 0.68 | 0.70 | 0.70 |
| 3) UAN Coarse Droplet | 35 ab | 38 bc | 28 a | 33 ab | 0.75 | 0.69 | 0.68 | 0.71 |
| 4) UAN + MSO§ Medium Droplet | 33 ab | 65 d | 78 c | 58 c | 0.73 | 0.56 | 0.68 | 0.65 |
| 5) UAN + MSO Coarse Droplet | 33 ab | 55 cd | 70 bc | 53 bc | 0.69 | 0.58 | 0.67 | 0.65 |
| 6) UAN + POC¶ Medium Droplet | 75 d | 66 d | 33 a | 58 c | 0.69 | 0.56 | 0.70 | 0.65 |
| 7) UAN + POC Coarse Droplet | 75 d | 63 d | 30 a | 56 bc | 0.70 | 0.55 | 0.68 | 0.65 |
| 8) UAN + NIS# Medium Droplet | 68 cd | 60 d | 65 bc | 64 c | 0.68 | 0.55 | 0.67 | 0.63 |
| 9) UAN + NIS Coarse Droplet | 60 cd | 50 cd | 78 bc | 56 c | 0.69 | 0.53 | 0.60 | 0.61 |
| 10) UAN + MSOOS†† Medium Droplet | 63 cd | 48 cd | 65 bc | 58 c | 0.67 | 0.55 | 0.65 | 0.62 |
| 11) UAN+ MSOOS Coarse Droplet | 38 bc | 48 cd | 60 bc | 52 bc | 0.71 | 0.56 | 0.68 | 0.65 |
| 12) UAN 60:40 Dilution Ratio‡‡ | 40 ab | 36 bc | 28 a | 34 ab | 0.73 | 0.64 | 0.69 | 0.68 |
| 13) UAN 75:25 Dilution Ratio | 40 ab | 33 bc | 35 a | 36 ab | 0.72 | 0.68 | 0.67 | 0.69 |
| 14) UAN + NBPT§§ | 25 a | ¶¶ | 35 a | 27 ab | 0.71 | 0.64 | 0.65 | 0.66 |
| 15) Urea Solution + NBPT | 25 a | ¶¶ | 20 a | 23 a | 0.75 | 0.67 | 0.66 | 0.69 |
| Means | 47 | 49 | 45 | 47 | 0.71 | 0.62 | 0.68 | 0.67 |
| ##LSD$_{0.05}$ | | | | | 0.03 | 0.08 | 0.06 | 0.06 |

† Means separation based on transformed values of % leaf burn, which were used to calculate the LSD values.

‡ Urea ammonium nitrate (28-0-0).

§ Methylated seed oil.

¶ Petroleum oil concentrate.

# Nonionic surfactant.

†† Methylated seed oil organisilicone surfactant.

‡‡ Dilution ratio of nitrogen solution (UAN:Water).

§§ N-n-butyl thiophosphoric triamide, urease inhibitor.

¶¶ Treatments not included at Fargo in 2016.

## Least significant difference not indicated due to means separation available in table.

Table A.9. Means for test weight and yield for adjuvant† and droplet‡ treatments combined across all environments in 2016 and 2017 in experiment two.

| | TW | Yield |
|---|---|---|
| | kg $m^{-3}$ | kg $ha^{-1}$ |
| Control, no treatment | 766 | 5397 |
| UAN§ | 765 | 5476 |
| UAN + MSO¶ | 760 | 5304 |
| UAN + POC# | 758 | 5260 |
| UAN + NIS†† | 760 | 5133 |
| UAN + MSOOS‡‡ | 763 | 5283 |
| Medium Droplet | 762 | 5314 |
| Coarse Droplet | 761 | 5268 |
| §§$LSD_{0.05}$ | 4 | 198 |
| ¶¶ $LSD_{0.05}$ | 4 | NS |

† Means derived from all treatments receiving respective adjuvant regardless of droplet size.

‡ Means derived from all treatments receiving respective droplet size regardless of adjuvant.

§ Urea ammonium nitrate (28-0-0).

¶ Methylated seed oil.

# Petroleum oil concentrate.

†† Nonionic surfactant.

‡‡ Methylated seed oil organisilicone surfactant.

§§ LSD comparing adjuvant treatments to control.

¶¶ LSD comparing droplet treatments to control.

Table A.10. Means for test weight and yield influenced by all treatments combined across all environments in 2016 and 2017 in experiment two.

| | TW | Yield |
|---|---|---|
| | kg m$^{-3}$ | kg ha$^{-1}$ |
| 1) Control, No Treatment | 766 a | 5397 abc |
| 2) UAN† Medium Droplet | 766 a | 5526 a |
| 3) UAN Coarse Droplet | 765 ab | 5426 ab |
| 4) UAN + MSO‡ Medium Droplet | 760 bcd | 5360 abc |
| 5) UAN + MSO Coarse Droplet | 761 abcd | 5247 bcd |
| 6) UAN + POC§ Medium Droplet | 758 d | 5339 abc |
| 7) UAN + POC Coarse Droplet | 759 cd | 5182 cd |
| 8) UAN + NIS¶ Medium Droplet | 761 abcd | 5093 d |
| 9) UAN + NIS Coarse Droplet | 758 d | 5173 cd |
| 10) UAN + MSOOS# Medium Droplet | 764 abc | 5256 bcd |
| 11) UAN+ MSOOS Coarse Droplet | 761 abcd | 5310 abcd |
| 12) UAN 60:40 Dilution Ratio†† | 762 abcd | 5479 ab |
| 13) UAN 75:25 Dilution Ratio | 763 abcd | 5446 ab |
| 14) UAN + NBPT‡‡ | 758 d | 5330 abc |
| 15) Urea Solution + NBPT | 762 abcd | 5498 a |
| Mean | 762 | 5334 |

† Urea ammonium nitrate (28-0-0).
‡ Methylated seed oil.
§Petroleum oil concentrate.
¶ Nonionic surfactant.
# Methylated seed oil organisilicone surfactant.
†† Dilution ratio of nitrogen solution (UAN:Water)
‡‡ N-n-butyl thiophosphoric triamide, urease inhibitor

Table A.11. Grain protein content influenced by all treatments for individual and combined environments in experiment two.

| | Casselton | | Prosper | | Fargo | Ada | Combined |
|---|---|---|---|---|---|---|---|
| | 2016 | 2017 | 2016 | 2017 | 2016 | 2017 | 2016-2017 |
| | ---------------------------------g kg$^{-1}$---------------------------- | | | | | | |
| 1) Control, No Treatment | 132 | 129 | 126 | 134 | 132 | 129 | 130 |
| 2) UAN† Medium Droplet | 140 | 139 | 133 | 139 | 136 | 136 | 137 |
| 3) UAN Coarse Droplet | 138 | 138 | 133 | 141 | 130 | 134 | 136 |
| 4) UAN + MSO‡ Medium Droplet | 140 | 138 | 130 | 138 | 132 | 135 | 136 |
| 5) UAN + MSO Coarse Droplet | 140 | 136 | 132 | 138 | 134 | 133 | 136 |
| 6) UAN + POC§ Medium Droplet | 140 | 136 | 135 | 138 | 129 | 135 | 135 |
| 7) UAN + POC Coarse Droplet | 138 | 142 | 136 | 138 | 132 | 134 | 137 |
| 8) UAN + NIS¶ Medium Droplet | 138 | 136 | 130 | 140 | 134 | 134 | 135 |
| 9) UAN + NIS Coarse Droplet | 139 | 137 | 132 | 138 | 134 | 135 | 136 |
| 10) UAN + MSOOS# Medium Droplet | 138 | 132 | 132 | 139 | 132 | 136 | 135 |
| 11) UAN+ MSOOS Coarse Droplet | 138 | 138 | 133 | 138 | 133 | 136 | 136 |
| 12) UAN 60:40 Dilution Ratio†† | 141 | 135 | 134 | 139 | 135 | 135 | 136 |
| 13) UAN 75:25 Dilution Ratio | 143 | 139 | 135 | 140 | 135 | 136 | 138 |
| 14) UAN + NBPT‡‡ | 141 | 138 | 133 | 139 | ## | 135 | 137 |
| 15) Urea Solution + NBPT | 138 | 132 | 131 | 138 | ## | 136 | 135 |
| §§Range | 11 | 13 | 10 | 7 | 7 | 7 | 8 |
| Mean | 139 | 136 | 132 | 138 | 133 | 135 | 136 |
| LSD$_{0.05}$ | 4 | NS | 4 | NS | 4 | 4 | 2 |

† Urea ammonium nitrate (28-0-0).
‡ Methylated seed oil.
§Petroleum oil concentrate.
¶ Nonionic surfactant.
# Methylated seed oil organisilicone surfactant.
†† Dilution ratio of nitrogen solution (UAN:Water).
‡‡ N-n-butyl thiophosphoric triamide, urease inhibitor.
§§ Difference between maximum and minimum values across all treatments for that location.

Table A.12. Test weight, yield, and grain protein content influenced by all treatments for individual and combined environments in 2017 in experiment two.

| | Protein | | | | TW | | | | Yield | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ada | Cass. | Pros. | Comb. | Ada | Cass. | Pros. | Comb. | Ada | Cass. | Pros. | Comb. |
| | ---------------g $kg^{-1}$-------------- | | | | --------------kg $m^{-3}$-------------- | | | | --------------kg $ha^{-1}$------------- | | | |
| 1) Control, no Fertilizer | 127 | 123 | 131 | 127 | 778 | 755 | 765 | 766 | 3819 | 4728 | 4723 | 4423 |
| 2) Control, with Fertilizer | 129 | 129 | 134 | 131 | 801 | 758 | 762 | 774 | 6175 | 5907 | 4712 | 5598 |
| 3) UAN† Medium Droplet | 136 | 139 | 139 | 138 | 797 | 761 | 766 | 775 | 6458 | 6225 | 4684 | 5789 |
| 4) UAN Coarse Droplet | 134 | 138 | 141 | 138 | 800 | 756 | 757 | 771 | 6235 | 5788 | 4225 | 5416 |
| 5) UAN + MSO‡ Medium Droplet | 135 | 138 | 138 | 137 | 794 | 754 | 764 | 771 | 6130 | 5686 | 4606 | 5474 |
| 6) UAN + MSO Coarse Droplet | 133 | 136 | 138 | 136 | 796 | 757 | 761 | 771 | 6020 | 5531 | 4409 | 5320 |
| 7) UAN + POC§ Medium Droplet | 135 | 136 | 138 | 136 | 788 | 757 | 757 | 767 | 6129 | 5755 | 4604 | 5496 |
| 8) UAN + POC Coarse Droplet | 134 | 142 | 138 | 138 | 793 | 741 | 764 | 766 | 6028 | 5156 | 4652 | 5278 |
| 9) UAN + NIS¶ Medium Droplet | 134 | 136 | 140 | 136 | 794 | 755 | 762 | 770 | 6045 | 5556 | 4074 | 5225 |
| 10) UAN + NIS Coarse Droplet | 135 | 137 | 138 | 137 | 787 | 753 | 761 | 767 | 6101 | 5484 | 4421 | 5335 |
| 11) UAN + MSOOS# Medium Droplet | 136 | 132 | 139 | 135 | 795 | 754 | 765 | 771 | 5992 | 5390 | 4612 | 5331 |
| 12) UAN+ MSOOS Coarse Droplet | 136 | 138 | 138 | 137 | 793 | 755 | 763 | 770 | 6285 | 5516 | 4393 | 5398 |
| 13) UAN 60:40 Dilution Ratio†† | 135 | 135 | 139 | 136 | 796 | 759 | 760 | 772 | 6443 | 5819 | 4563 | 5608 |
| 14) UAN 75:25 Dilution Ratio | 136 | 139 | 140 | 138 | 793 | 761 | 758 | 771 | 6257 | 5973 | 4428 | 5553 |
| 15) UAN + NBPT‡‡ | 136 | 138 | 139 | 138 | 796 | 750 | 759 | 769 | 6253 | 5570 | 4288 | 5370 |
| 16) Urea Solution + NBPT | 136 | 132 | 138 | 135 | 796 | 762 | 759 | 773 | 6529 | 5838 | 4759 | 5709 |
| 17) UAN Streamer Bars at ZGS 65 | 135 | 128 | 135 | 133 | 797 | 761 | 767 | 775 | 6317 | 5696 | 4349 | 5454 |
| 18) UAN Streamer Bars at ZGS 65 | 138 | 128 | 136 | 134 | 796 | 758 | 765 | 773 | 6181 | 5465 | 4419 | 5355 |
| $LSD_{0.05}$ | 4 | 9 | 4 | 4 | 10 | 12 | 6 | 7 | 369 | 815 | 506 | 577 |

† Urea ammonium nitrate (28-0-0).

‡ Methylated seed oil.

§ Petroleum oil concentrate.

¶ Nonionic surfactant.

# Methylated seed oil organisilicone surfactant.

†† Ratio of UAN:Water.

‡‡ N-n-butyl thiophosphoric triamide, urease inhibitor.