STRATEGIES FOR OPTIMIZING NITROGEN USE IN CORN WITH AND WITHOUT SUBSURFACE DRAINAGE

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Strategies for Optimizing Nitrogen Use in Corn

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Evan Twedt

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

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ABSTRACT

Twedt, Evan Jacob, M.S., Department of Plant Sciences, College of Agriculture, Food Systems, and Natural Resources, North Dakota State University, April 2011. Strategies for Optimizing Nitrogen Use in Corn With and Without Subsurface Drainage. Major Professor: Dr. Joel K. Ransom.

Excessive soil moisture can impact planting date, plant establishment, and N availability, resulting in reduced yields and N use efficiency. Nitrogen management practices such as use of urease and nitrification inhibitors, and split applications may be used to reduce N lost during the growing season, improving N use efficiency and crop productivity. The objective of this study was to determine whether N management practices could improve corn (*Zea mays* L.) productivity with or without subsurface drainage on a fine-textured clay soil in eastern North Dakota. Five field trials were conducted in 2009 and 2010 in eastern North Dakota. Treatments consisted of a factorial combination of N management practices [urease inhibitor n-(n-butyl) thiophosphoric triamide (NBPT), starter fertilizer, nitrification inhibitor 2-Chloro-6-(trichloromethyl) pyridine (nitrapyrin), and split applications], N rates (56, 112, 168, and 224 kg N ha^{-1}), and the presence of subsurface drainage (two environments). In both 2009 and 2010 there was no grain yield differences among drainage treatments. Differences in grain yield were observed with different N rates. Nitrogen management practices also affected grain yield. The interactions between N management practices and drainage were not significant. End of season stalk nitrate content showed differences in N availability with different N rates, but not N management practices. Neither NBPT nor the starter fertilizer significantly increased yield over the untreated check in any environment. Nitrapyrin significantly increased yield over the untreated check at Fargo in 2010. Increased N rates resulted in greater corn grain protein.

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"Trust in the Lord" Proverbs 3:5-6

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INTRODUCTION

The Red River Valley of the North is known for its agriculture because of the productive soils that are common throughout the area. These deep, fine-textured soils were formed from the sediments of Lake Agassiz that occupied the area starting about 11,700 years ago to as recently as approximately 7,500 years ago (North Dakota Geological Survey, 2007). The soils of the Red River Valley are not only fertile but are often high (40-60%) in clay content, have low infiltration rates, and a flat topography. As a result of these characteristics, saturated soils and aeration stress can be very troublesome to producers that farm these soils.

In recent years, corn has become increasingly popular in the Red River Valley. In 1995, there were 664,000 hectares of corn planted for grain in Grand Forks, Traill, Cass, and Richland counties. In 2009, those same counties grew 1,470,000 hectares of corn (USDA, 2011a).

Corn is very sensitive to saturated soils (Ritter and Beer, 1969). Consequently, subsurface drainage has been installed in many areas of the United States where corn is grown to help minimize the stress caused by excess water during the growing season. Subsurface drainage is also referred to as tile drainage, because the drainage structures used were made from clay tiles when it was first developed. Tile drainage also serves purposes other than just minimizing plant stress caused by excess water. It also allows farmers to access their fields earlier in the growing season, practice timelier in-season field work, and minimize harvest delays due to rain (Fore, 2003).

Reducing nitrogen (N) losses and maximizing N use efficiency in corn is also very important to producers because of the increase in input prices in the past decade especially fertilizers. In 2000, $10 billion was spent in the United States on fertilizers, including lime and soil conditioners (USDA, 2011b). In 2009, that number more than doubled to $20.9 billion.

Reducing N loss may be achieved through the use of fertilizer additives. One such additive inhibits the enzyme urease which breaks down $CO(NH_2)_2$ (urea) to NH_3 (ammonia). Other fertilizer additives are nitrification inhibitors, which restrict NH_4^+ (ammonium) conversion to NO_3^- (nitrate), and the use of banded fertilizers with or near the seed, called 'starter fertilizers', which provide plant nutrients early in the growing season (Niehues et al., 2004). These fertilizer additives may improve N use efficiency especially in non-drained fields where greater N losses can be anticipated due to denitrification.

Many of the benefits of subsurface drainage, such as the lengthening of the growing season by allowing earlier planting, decreasing soil salinity, or increasing ease of field work by reducing the risk of causing soil compaction, were not tested in this experiment. Agronomic traits associate with corn production were the only factors used to determine differences in treatments.

RESEARCH OBJECTIVES

The objectives of this research were to determine differences in corn yield due to subsurface drainage and N management treatments and to explore optimum fertilizer timing and type with and without subsurface drainage. The hypotheses tested by this research were:

- Subsurface drainage improves yields across N management practices.
- Corn yield is improved with nitrification and urease inhibitors by reducing N loss and improving the availability of N under drained and un-drained environments.
- Split applications of N improve N use efficiency.
- Adding fertilizer to the seed row at planting helps improve yield and N use efficiency.

LITERATURE REVIEW

Drainage

Plant stresses due to saturated soils can decrease the growth and metabolism of plants. Some of the physiological and biochemical effects caused by saturated soils include changes in respiratory metabolism, root permeability, water and mineral uptake, N fixation in legumes, and changes in levels of endogenous hormones (Bradford and Yang, 1981). Ashraf and Rehman (1999) showed that saturated soils significantly lowered total N in leaves and roots of corn plants. As N levels in leaves decline below a critical value, corn grain yield is reduced.

The effect of too much water in the soil is known as aeration stress. Too much water in the soil can occur following intense rainfall or rain falling on already saturated soil. These factors can result in standing water in the field if there is inadequate surface drainage either in depressions or on a soil surface that is uniformly flat and drains slowly. Saturated soil conditions can stress plants and may limit plant growth and yield (Scott et al.,1989). The harmful effects of prolonged flooding on plant growth are usually due to an insufficient supply of oxygen, which arrests root respiration. In a study on the effects of flood duration on the growth and yield of soybean (*Glycine max* (L.) Merr.), Scott et al. (1989) found that grain yield was reduced with increased length of soil saturation. Results showed that prolonged flooding on poorly drained, slowly permeable soils significantly decreased the plant canopy height, plant dry matter, and seed yield. Seed yield decrease was linearly related to flood duration.

In areas such as the Red River Valley of the North, where the topography is flat and low lying areas are routinely flooded, problems with saturated soils and aeration stress can be very troublesome to producers. Also, since many of the soils within the Red River Valley have a high clay content, infiltration rates into and water movement through the soil are very slow (National Cooperative Soil Survey, 2005). Producers that have a history of wet fields due to drainage problems, especially in the spring of the year, might benefit from subsurface drainage. Not only would it allow a producer to be able to conduct field work earlier, it could also increase corn grain yields by decreasing the amount of damage to the crop from saturated soil conditions during the season.

Research has shown the benefits of subsurface drainage in many areas of the United States (Wilson, 2000), but none of this research has been conducted on the fine-textured soils of eastern North Dakota. Subsurface drainage is accomplished by installing perforated pipes at a depth of about one meter and widths of pre-determined distances depending upon location. Water drainage control structures can be used to manage the amount of water that is drained and therefore affect the subsurface water table during different times of the year (Drury et al., 2009). Subsurface drainage can relieve unwanted water that is in the field without drying the soil past field capacity, the point at which soil moisture is held in the soil and excess water has drained away by gravity.

Improved crop production resulting from subsurface drainage is in a large part due to better physical conditions for field operations, but also is due to a deeper unrestricted root zone that allows for greater crop rooting, and thus better nutrient uptake and greater yields. Removal of excess water by subsurface drainage reduces the potential for anaerobic conditions and, as a result, decreases the potential for nitrate to be lost from the soil profile through the process of denitrification (Randall and Sawyer, 2008).

Nitrogen loss potential by means of leaching or denitrification is greater with heavy rainfall and highly saturated soils. Nitrogen loss potential is also directly related to the amount of N in the soil in the nitrate form. Nitrate is the form of N most readily taken up by the plant, but it is also the form with the greatest risk for loss from the soil (Mathesius and Luce, 2009) through leaching and/or denitrification. Most fertilizer N in North Dakota is applied as anhydrous ammonia or as urea (which is readily converted to ammonium in moist conditions). Ammonium is not prone to leaching or denitrification but can quickly be converted to nitrate, through a process termed nitrification. Nitrate is vulnerable to leaching due to its high water solubility and negative charge.

Nitrogen makes up 78% of the earth's atmosphere and yet it is the most commonly deficient nutrient in non-legume plants. Nitrogen is an important component of many important structural, genetic, and metabolic compounds in plant cells. It is a major component of chlorophyll, which is needed for photosynthesis, and amino acids, the building blocks of proteins. Some proteins act as structural units in plant cells while others act as enzymes, making many of the biochemical reactions in plants possible. Nitrogen is also a component of energy-transfer compounds, such as ATP which allows cells to conserve and use the energy released in metabolism. Lastly, N is a significant component of nucleic acids such as RNA and DNA (Eckert, 2008).

Plants absorb N as both nitrate and ammonium and both move into plant roots by mass flow and diffusion. Plant growth is often improved when the plant is nourished by both nitrate and ammonium (Below and Gentry, 1987).

When plants are N deficient their older leaves appear yellow. Some of the leaf yellowing is due to the translocation of N from the chloroplasts of older leaves to younger tissues. When N is deficient, proteins in the older plant tissue are converted to soluble N, translocated to the new tissues and reused in the synthesis of new protein (Havlin et al., 2005). The tendency of newer growth to remain green as the lower leaves yellow is due to the mobility of N in the plant.

Nitrogen losses

Only about 50% of the applied N is typically taken up by corn during the year following fertilizer addition. About 25% is immobilized during residue decomposition or remains in the soil as nitrate. The remaining 25% is lost from the plant rooting zone by leaching and/or denitrification (Nelson and Huber, 1992).

Denitrification

Denitrification is the process whereby inorganic N is returned to the atmosphere in the gas phase after nitrate is converted to nitrous oxide (N_2O) in the soil. Denitrification commonly occurs when soils are saturated sufficiently long so that O_2 is depleted and anaerobic conditions occur. When anaerobic conditions occur, anaerobic organisms obtain oxygen from NO_2^- (nitrite) and nitrate present in the soil. The most common organisms involved in denitrification are organisms in the bacteria genera *Pseudomonas*, *Bacillus*, and *Paracoccus* (Havlin et al., 2005). Different agricultural practices can inhibit the amount of N lost through denitrification. One of these practices is through the use of subsurface drainage, by improving soil aeration and reducing saturated soil occurrences. Another one of these practices is through the use of nitrification inhibitors (Thompson, 1989).

Since the soils in the Red River Valley are dense silty clays, it is likely that denitrification accounts for a greater portion of the N lost compared with leaching. This is especially evident in the spring of the year when conditions are wet and plant water use is minimal. The fact that denitrification is responsible for more N loss than leaching can be explained by the low amounts of water being slowly moved vertically through the soil. The slow movement of water is due to the capillary pores in the soil holding water tightly (Mathesius and Luce, 2009). In this situation, saturated soils and anaerobic conditions may result in nitrate being lost to the atmosphere through denitrification. Nitrification inhibitors can be effective in slowing the conversion of ammonia or ammonium to nitrate and in doing so potentially reducing the amount of N that can be lost into the atmosphere through denitrification (Lee et al., 2007).

Nitrate leaching

Since nitrate is very soluble in water and is not strongly adsorbed to the soil's cation exchange sites it is subject to leaching losses. Some of the factors that influence the magnitude of nitrate leaching losses are the rate, time, source, and method of N fertilization; intensity of cropping and crop N uptake; soil profile characteristics that affect percolation; and quantity, pattern, and time of precipitation (Havlin et al., 2005). Managing factors known to affect nitrification in soils can reduce nitrate leaching.

Leaching occurs when the moisture content of the soil exceeds the capacity of the soil to hold the water in defiance of the gravitational pull of the earth. When this happens, gravity causes water to move down through the soil profile. Nitrate is the primary form of N that is leached. The amount of nitrate leached is directly proportional to the amount of water the soil can hold. A sandy soil cannot hold as much water as a clay soil, which would suggest that leaching of nitrate will take place much more easily in a sandy soil compared with a fine-textured clay soil (Troeh and Thompson, 2005).

One way to decrease the amount of nitrate leached through the soil is by managing the time of application of N fertilizers. When all the N is applied in the fall of the previous growing season, or at the beginning of the current growing season, the N has a greater opportunity to be leached because the plant is not able to access or utilize much of the N early in the growing season. The plant's roots are still small and unable to reach most of the N that is available. Also, plant growth is minimal early in the growing season and N requirements are minimal (Olson and Kurtz, 1982).

The application of fertilizer into the soil alongside plants during the growing season, known as sidedressing, may be a way to supply N to corn when it is needed while reducing losses caused by early spring rains (Mathesius and Luce, 2009).

Nitrification

Nitrification is the process in which ammonium (NH_4^+) in the soil is converted to nitrate (NO_3^-) through microbial oxidation. Nitrification is a two-step process where ammonium is converted to nitrite (NO_2^-) by *Nitrosomonas* bacteria which is then converted to nitrate by *Nitrobacter* bacteria. Both of these autotrophic bacteria obtain their energy from the oxidation of N. The nitrification process also requires O_2. Gas exchange and adequate supply of O_2 to nitrifying bacteria is maximized in coarse textured soils or soils with developed soil structure. The amount and rate of ammonia converted to nitrate is influenced by the supply of ammonia in the soil as well as the population of nitrifying organisms, the soil pH (*Nitrosomonas*, 7.8-8.0, *Nitrobacter*, 7.3-7.5), soil aeration, soil moisture, and soil temperature. Nitrification rates are generally highest when soil moisture is at field capacity and optimum temperatures for nitrification are from 25 to 35°C (Emmer and Tietema, 2008).

Nitrification inhibitors

Nitrification inhibitors have been shown to be most beneficial with fall applied N. Randall et al. (2008) showed that fall applied anhydrous ammonia with nitrapyrin had a 942 kg ha^{-1} grain yield increase in corn compared with fall applied anhydrous ammonia alone. Malzer et al. (1989) also recorded a corn grain yield increase with the optimum N rate with fall anhydrous ammonia application with nitrapyrin.

A study of nutrient source effects on corn grain yield on a flat landscape showed that nitrate levels were higher in plots treated with urea than plots with manure treatments (Thomas et al., 2005). It was speculated that even though the N application rates from manure and urea were similar, the slow release of the organic N from manure may have allowed the N to be taken up more efficiently by the crop. This resulted in fewer nitrates in the manure treated soils after the fall harvest when the soil tests were conducted.

Walters and Malzer (1990) demonstrated that the use of nitrification inhibitors (in years when corn growing degree days were relatively high, compared with years when the corn growth was reduced due to fewer heat units) reduced leaching load by approximately 10%. The reduction was measured during the time period between planting and silking of corn, when 60% of the total annual leaching load occurs.

Zacherl and Amberger (1990) found that ammonium oxidation and respiration of *Nitrosomonas europea* cells were reduced by up to 93% compared to the control when treated with nitrapyrin at a rate of 10 mg kg^{-1} in suspension. Ammonium N carries a positive charge (NH_4^+) which allows ammonium to be held in place by negatively charged soil and organic matter. When N is 'stabilized' in the ammonium form it is less susceptible to losses from leaching and denitrification. Nitrapyrin can increase yield in corn from 126 to 1257 kg ha^{-1} when conditions are favorable for N losses (Havlin et al., 2005).

Volatilization

Ammonia volatilization is much greater with broadcast urea fertilizer compared to subsurface or surface band applications. The amount of ammonia volatilization losses are greater when soil pH is greater than 7.5. The soil buffering capacity, environmental conditions during the application of fertilizer, and the amount of crop residues present at the soil surface also influence ammonia volatilization rate. Surface crop residues, along with containing a larger quantity of urease enzymes compared to bare soil, increase potential ammonia volatilization by maintaining wet, humid conditions at the soil surface and by reducing the quantity of urea diffusing into the soil (Fox and Hoffman, 1981).

Urease inhibitors

Volatilization of ammonia occurs when urea comes in contact with moisture and urease, an enzyme that occurs naturally in the soil which catalyzes the reaction that converts urea into carbon dioxide and ammonia. Urease inhibitors can delay the conversion of urea to ammonia and thus delay the conversion of ammonia to nitrate in the soil. The most common commercial urease inhibiter, Agrotain – [NBPT, n-(n-butyl) thiophosphoric triamide], works by blocking the enzyme urease by locking onto the urease enzyme binding sites, preventing the enzyme from reacting with the urea (Manunza et al., 1999). The primary purpose of this urease inhibitor is to reduce the loss of ammonia by volatilization when urea is surface applied (Nelson and Huber, 1992).

NBPT decreases in the rate of ammonia volatilization from urea applied to the surface as dry urea or urea-ammonium nitrate solutions. Ammonia volatilization losses from urea at Brandon, MB, decreased from 40 mg to 2 mg and from 88 mg to 12 mg with NBPT in two separate studies for a seven-day period after application (Grant, 2004). Eberhar et al. (2010) showed in a study in southern Illinois that urea with NBPT provided a 690 kg ha^{-1} yield advantage over urea alone when surface applied in no-till corn in 4 years out of the 14-year study. Havlin et al. (2005) reported corn grain yield increases of 314 kg ha^{-1} up to 1257 kg ha^{-1} with applications of NBPT in corn.

Starter fertilizers

Pop-up fertilizer (liquid ammonium polyphosphate) is an in-furrow starter fertilizer used to enhance seedling vigor. Starter fertilizers often enhance crop growth primarily because it places a readily available supply of plant nutrients (especially P) in a position where nutrients are easily accessible to the limited root system of a seedling. Even though a soil may have high fertility, a seedling's root system may not be able to obtain the necessary nutrients due to lack of root mass and density within the soil (Beegle et al., 2003). Since the fertilizer is applied directly with the seed at planting (in-furrow), the plant may experience improved early development that could increase potential crop yield and allow for better subsequent N use. On the other hand, in-furrow placement of fertilizer almost always decreases plant population. For that reason, many growers apply banded fertilizer 2.5 to 5 cm away for the seed and 2.5 to 5 cm below the seed placement depth.

Nitrogen fertilizer additives can be added, either directly to the N fertilizer, or to the soil to inhibit the breakdown of N fertilizers by microorganisms, increasing the availability of N to the plant. Nitrogen fertilizer applied with the corn seed at planting may allow the plant to have access to fertilizer early in the growing season while its roots are still small and unable to access fertilizer outside of its root zone, thereby avoiding deficiencies that are common in the wet cool soils in the spring in North Dakota.

MATERIALS AND METHODS

General

Field experiments were conducted at the North Dakota State University (NDSU) experimental farm, Northwest 22, near Fargo, ND, (Latitude = 46.93°, Longitude = -96.86°) and at the NDSU research fields near Prosper, ND, (Latitude = 47.00°, Longitude = -97.11°) in 2009 and 2010. A field experiment was also conducted in 2010 at the Mark Brodshaug Farm (Latitude =46.80°, Longitude =-96.94°) located north east of Horace, ND, this location will be referred to as 'Horace'.

The soil at Northwest 22 (Fargo) is a Fargo (fine, smectitic, frigid Typic Epiaquerts)-Ryan (fine, smectitic, frigid Typic Natraquets) silty clay. The Fargo series consists of deep, poorly drained, slowly permeable soils formed from calcareous, clayey lacustrine soils. This soil generally has a slope of 0 to 1%. The Ryan series consists of very deep, poorly drained, very slowly permeable soils that formed from high sodium clayey sediments. This soil generally has a slope of zero to one percent.

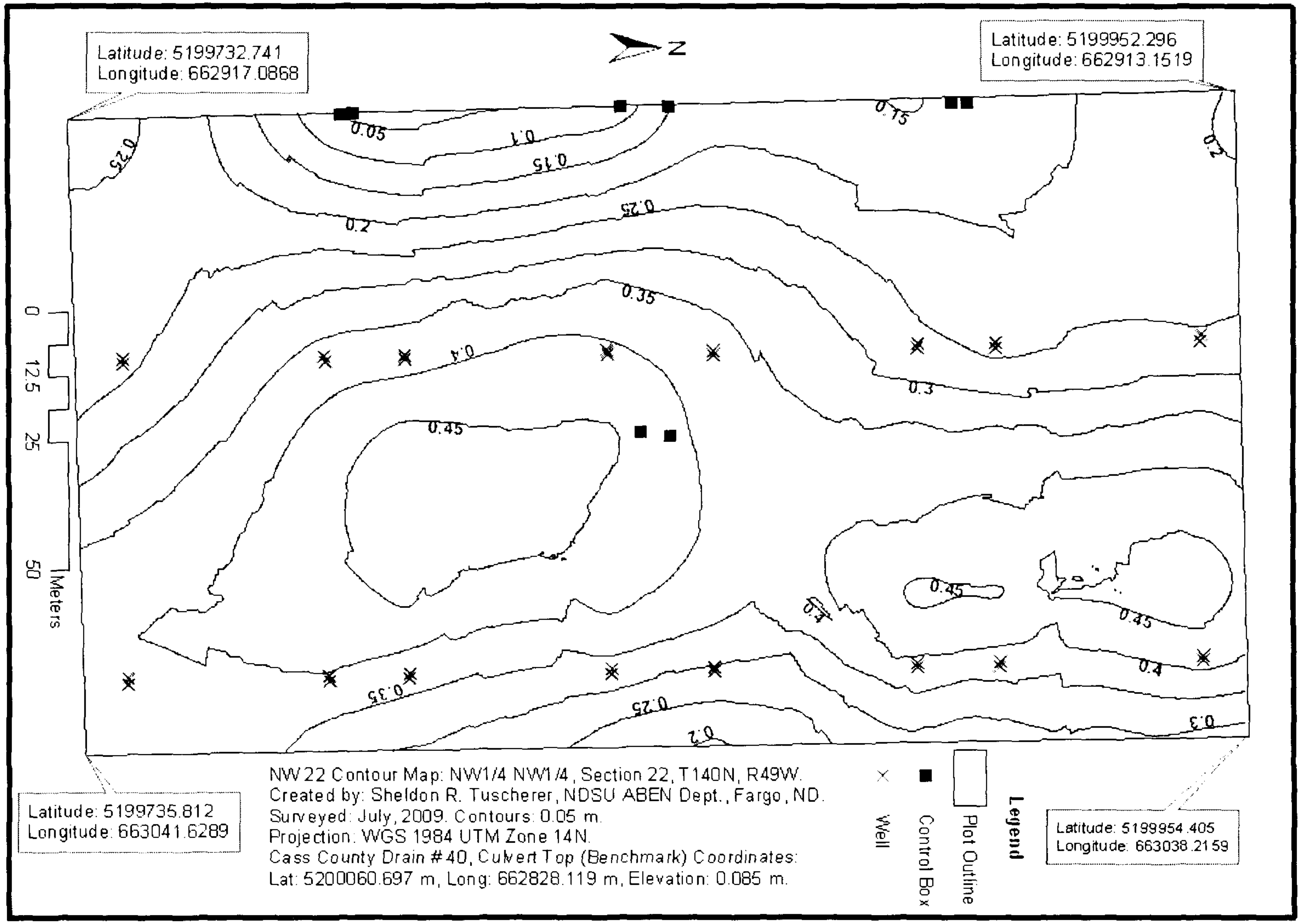
The soil at Prosper is a Bearden (fine-silty, mixed, superactive, frigid Aeric Calciaquolls)- Lindass (fine, smectitic, frigid Typic Argiaquolls) silty clay loam. The soil at Horace is a Fargo (fine, smectitic, frigid Typic Epiaquerts)-Hegne (fine, smectitic, frigid Typic Calciaquets) silty clay loam (USDA-NRCS, 2009). Weather related information was obtained from the North Dakota Agriculture Weather Network (NDAWN, 2011) website. Fargo weather was obtained from the Fargo NDAWN station which is approximately 5 km from the Fargo research site, the Horace weather data was also obtained from this weather station as it was the closest site to the location at 20 km away. Prosper weather was obtained from the Prosper NDAWN station, about 1 km from the Prosper research site. All historical and normal averages were obtained from the NDAWN website which consist of values from 1971-2000.

Tile drain lines were installed at the Fargo site in 2008 at 1-m depth and 7.6-m between lines. At this site, subsurface drainage was included as a factor in the experiment. The tile drainage pipes are 10 cm in diameter in this particular study. The plot area was split into eight units, all of which contain subsurface drain tile. There are seven tile lines in each unit. Each of the eight units has its own water table control structure (Agri-Drain Corp, Adair, IA). Four of the control structures were open, allowing these units to be subsurface drained (drained). Four of the control structures were closed, precluding subusurface drainage (undrained).

Water table depth measurements were taken once a week using the Solinst Water Level Meter Model 101 (Solinst, Georgetown, ON, Canada). The water table depth was measured using the eight control boxes that control the subsurface drainage lines for each unit as well as the 32 wells (four in each unit) that were located throughout the Fargo location (Figure 1).

Measurements were made from the top of the pipe to the depth of the water and then corrected for the height of the pipe above the adjacent ground surface. The wells were installed in May of 2009 using a soil probe. A schedule 40 PVC pipe (diameter 5.1 cm) was inserted into the hole created by the soil probe and sand was filled-in around the pipe. The water level was monitored in order to observe differences between the subsurface drained and undrained units.

Fig 1. Soil contour and well locations for Fargo, ND research site. (Source: Sheldon R. Tuscherer).



Treatments at the Fargo site consisted of a factorial combination of subsurface drainage, N fertilizer practices, and N rates arranged in a randomized complete-block design with a split-split plot arrangement with four replicates. The main plot treatments were subsurface drainage (with and without). The four sub-plots treatments were N fertilizer practices. The five sub-sub-plot treatments were rates of N.

At Prosper and Horace, where subsurface drainage was not a factor, treatments consisted of a combination of N fertilizer practices and N rates arranged in a randomized complete-block design with a split-plot arrangement with four replicates. The four main plot treatments were N fertilizer practices. The five sub-plot treatments were rates of N. These sites allowed us to expand our inference on N rate and N fertilizer management practices in the absence of any controlled subsurface drainage.

The N fertilizer practices consisted of the following: 1) urea broadcast and incorporated before planting with no additive, 2) as previous treatment with the addition of nitrapyrin, at 4.68 L ha^{-1}, 3) as the first treatment with the addition of NBPT, a urease inhibitor, at 5.21 L active ingredient Mg^{-1} of urea, and 4) as the first treatment with the addition of liquid ammonium polyphosphate 10-34-0 (Pop-up), an in-furrow starter fertilizer, at a rate of 28 kg ha^{-1} providing a rate of N of 2.8 kg ha^{-1} and phosphorus of 9.84 kg ha^{-1}. The rate of urea was adjusted in plots treated with the in-furrow starter fertilizer additive so the total N rate would be equal to all other treatments.

The N rates were: 56, 112, 168, 224 kg N ha^{-1}, and a split application of 56 kg N ha^{-1} at planting followed by 56 kg N ha^{-1}. Fertilizer was spread by hand and incorporated pre-planting with the exception of the in-furrow starter fertilizer and the second half of the split application which was applied to the corn as a side dressing when the corn was at about the V8 growth stage (McWilliams et al., 1999). The sidedress application treatment was not incorporated but always preceded significant rain. N fertilizer rates were chosen in order to make inferences over a large range of fertilizer rates. Individual sub-sub-plots were 6.1 m long and 3.0 m wide. Each plot consisted of four rows of corn with a 76 cm row spacing. The two outside rows served as border rows, as only the two inside rows were used for data collection.

Corn was planted with a John Deere 7000/7100 Maxemerge planter (Deere and Company, Moline, IL) with 76-cm row spacing at a population of 81,500 seeds ha^{-1}. The Roundup Ready® corn hybrid, Peterson 56J86, was the same throughout all locations. Weeds were controlled with Roundup WeatherMax® (glyphosate) at 540 g ae ha^{-1} as needed throughout the season. Persistent weeds were removed by hand prior to row closure.

The timing of various standard practices and measurements for all years and locations are summarized in Table A9.

2009

In 2009, corn was planted on 11 May at Fargo. The crop the previous year was wheat. Corn emergence was poor and not uniform so corn was tilled and replanted 4 June. Corn was planted on 29 May at Prosper with the previous year crop being wheat. Pre-season soil tests are presented in Table 1; there were no recorded preseason soil tests for Fargo, ND in 2009.

Table 1. Pre-season soil test averages for Fargo, Prosper, and Horace.

Location	Year	Previous crop	N	P	K
			kg ha-1	mg kg-1	mg kg-1
Fargo	2009	Wheat	-	-	-
	2010	Soybean	49	0.017	0.401
Prosper	2009	Wheat	25	0.024	0.330
	2010	Wheat	33	0.017	0.253
Horace	2010	Corn	9	0.004	0.296

Nitrapyrin was applied to soil with a backpack sprayer and then incorporated with a rotovator. Corn plant height was measured for each plot after corn had tasseled. Heights were measured in cm from the ground to the top of the tassel. Heights were the average of two plants in the sub-sub-plot.

Harvesting was done by hand. In each plot, a 4.6 m section from one of the inside rows was harvested. The number of harvested ears and plants were counted and recorded. The ears were then weighed. A sub-sample of 10 ears were weighed and then shelled by running the ears through an Almaco HP5 combine (Almaco, Nevada, IA). The grain was weighed again to determine the shelling percentage. Corn weight was multiplied by the shelling percentage to get the yield per plot.

Once the corn had been shelled and weighed, the corn was tested within 24 hours of harvest, for moisture using a moisture meter (Dickey-John GAC 2100, DICKEY-John Corp., Minneapolis, MN). Grain yield was determined by weighing the harvested corn seed and dividing by the harvested area. Yields were adjusted to 155 g kg^{-1} moisture. Grain protein and starch were measured on a dry weight basis using a 0.5 kg sub-sample of seed on a Diode Array 7200 NIR Analyzer (Perten Instruments, Springfield, IL). Thousand kernel weights were taken for each sample on a dry weight basis using a Model 850-3 seed counter (International Marketing and Designer Corp., San Antonio, TX).

Corn basal stalk nitrate sampling and analysis was conducted after harvest on two replicates of the following treatments: the five no additive N rates and also the 168 kg N ha^{-1} N rate for the nitrapyrin, pop-up, and NBPT treatments. Samples from 10 plants in each treatment were taken from the same row that was harvested. Each sample consisted of a 20-cm section of the stalk starting at 15 cm above the soil surface and continuing upwards to 35 cm above the soil surface (Blackmer and Mallarino, 1996). Stalk samples were obtained in both the drained and undrained portions of each replicate.

2010

In 2010, corn was planted on 22 April at Fargo. The crop the previous year was soybean. Corn was planted on 22 April at Prosper with the previous year crop being wheat. Corn was planted 26 May at Horace. The crop the previous year was corn. Pre-season soil samples can be found in Table 1.

Nitrapyrin was applied to soil with backpack sprayer and then incorporated immediately with a disk. Corn height was measured for each plot after corn had tasseled. Heights were measured in centimeters from the ground to the highest leaf node. Heights were averaged between two plants in each plot.

Harvesting was done by hand. In each sub-sub-plot, a 3.05-m length from two of the inside rows was collected. The number of plant ears harvested were counted and recorded. All ears were then run through an Almaco PMC 20-A combine (Almaco, Nevada, IA) for shelling.

Corn moisture, grain yield, grain protein, starch, and thousand kernel weight was determined in the same way as in 2009. Nitrate stalk sampling and analysis was conducted similar to methods used in 2009. Soil cores were also obtained from the 112 kg N ha^{-1} rate treatment and the 56 kg N ha^{-1} followed by 56 kg N ha^{-1} split rate treatment in all of the N fertilizer practices. These samples were taken pre-planting, at the V6 stage prior to the side-dress application, approximately three weeks after side-dressing, and post-harvest. Samples taken at pre-planting and post-harvest were taken from 0 to 15 cm and also 15 to 46 cm. In-season samples were only taken at the 0 to 15 cm depth. Four sub-samples were taken from inside the two border rows in each plot and then combined to increase accuracy.

All plots were measured for Normalized Difference Vegetative Index (NDVI) activity using a Greenseeker® Model 505 Optical Sensor Unit (Greenseeker®, Ukiah, CA). Readings were taken once at the V10 stage and again seven days later. The Greenseeker® sensor head was placed 1 m above a corn row and walking speed was kept at a pace of 1.34 meter sec^{-1}.

NDVI is used to measure plant health and vigor by using light emitting diodes (LED) to generate red and near infrared (NIR) light that is reflected off of the crop and measured by a photodiode located at the front of the sensor's head. Red light is absorbed by plant chlorophyll as an energy source during photosynthesis. Plants that are greener are usually assumed to be healthier and will absorb more red light and reflect larger amounts of near infrared light than plants that are less green. This phenomenon allows the Greenseeker® to provide a relationship between N status reading, if plant stages and plant biomass are similar (Gupta et al., 2008).

Statistical analysis

Data were subjected to an analysis of variance by each location separately. Homogeneity of variances was tested with an F-test at the 95% confidence level. Each location/year combination was considered an environment. Environment was random, drainage, additive, and rate were fixed effects. A combined analysis across environments was conducted when variance was homogeneous for each character (Carmer et al., 1989). Since a practice difference occurred in the type and timing of incorporation for the nitrapyrin additive in 2009 compared to 2010, results are presented by each location separately. At Fargo, an ANOVA for a randomized complete block design with a split-split plot arrangement was used. At Prosper and Horace an ANOVA for a randomized complete block design with a split plot arrangement was used. An F-protected LSD for fixed effects was used at the 95% confidence level (Steel et al., 1997). For continuous independent variables such as N rates, regression analysis was conducted for significant effects. The regression test with four degrees of freedom with two individual variables was used. Continuous independent variable values that were not significant can be found in the appendix.

ANOVA tables with expected mean squares for the statistical analysis used in the experiments conducted can be found in the appendix, Tables A1-A8.

RESULTS AND DISCUSSION

Climatic information

2009 - The 2009 growing season mean air temperature at Fargo for the growing season (4 June – 17 November 2009) was 15°C and at Prosper (29 May – 8 October 2009) it was 17°C as compared to the historical average air temperatures for these locations of 15°C and 18°C, respectively. Although mean air temperatures for the growing season were at or near historical averages, monthly mean air temperatures were below historical temperature averages for every month of the growing season except for September and November at both Fargo and Prosper (Table 2). Growing degree days (GDD) for corn in the 2009 growing season were also below normal at Fargo and Prosper (Table 3). At Fargo, the accumulated corn GDD for the growing season were 1093 [°C] below the normal corn accumulated GDD of 1161 [°C]. Accumulated corn GDD for the growing season at Prosper were 1042 [°C] which were well below 1194 [°C], the normal for that location (NDAWN, 2011).

Rainfall during 2009 the growing season was 462.5 mm and 409.2 mm for Fargo and Prosper, respectively (NDAWN, 2011). Rainfall for both locations was lower than the historical average in every month except October (Table 4). For both Fargo and Prosper, July received the lowest rainfall of the growing season with only 15.9 and 24.6 mm of rainfall, respectively.

2010 - For the 2010 growing season (22 April – 8 October 2010) at Fargo, the mean air temperature was 18°C and the total rainfall was 500.9 mm (NDAWN, 2011). At Prosper (21 April – October 10 2010) the mean air temperature was 17°C and the total rainfall was 499.9 mm (NDAWN, 2011).

Table 2. Mean air temperature for Fargo and Prosper, in 2009 and 2010, and historical means (1971-2000) for the months of April to November.

	Fargo			Prosper		
Month	2009	2010	Historical	2009	2010	Historical
	°C					
April	5	11	6	5	10	6
May	12	15	14	12	14	13
June	18	19	19	17	19	18
July	19	22	21	18	21	21
August	19	22	21	18	21	20
September	19	14	14	17	13	14
October	5	10	7	4	9	8
November	4	-1	-3	3	-2	-3

Table 3. Growing degree days (GDD) for Fargo and Prosper, in 2009 and 2010, for the months of April to November.

	Fargo			Prosper		
Month	2009	2010	Normal	2009	2010	Normal
	°C					
April	42	115	46	36	114	51
May	148	168	172	144	174	181
June	253	275	273	248	268	256
July	288	380	361	269	340	336
August	285	365	328	253	322	326
September	265	140	171	237	136	188
October	12	108	58	12	110	74
November	15	20	0	17	16	0
Total GDD	*1308*	*1571*	*1409*	*1216*	*1480*	*1412*

Corn growing degree days for the 2010 growing season at Fargo were 1428 [°C], above the normal of 1359 [°C] for that same period. Similarly, the corn GDD for the 2010 growing season at Prosper were 1326 [°C] compared to the normal of 1343 [°C] (NDAWN, 2011). The 2010 growing season rainfall was much closer to historical averages in both the Fargo and Prosper locations with the exception of September which was at least twice the historical average in both locations (Table 4).

Table 4. Total rainfall for the months of April to October in Fargo and Prosper in 2009 and 2010, and historical means (1971-2000).

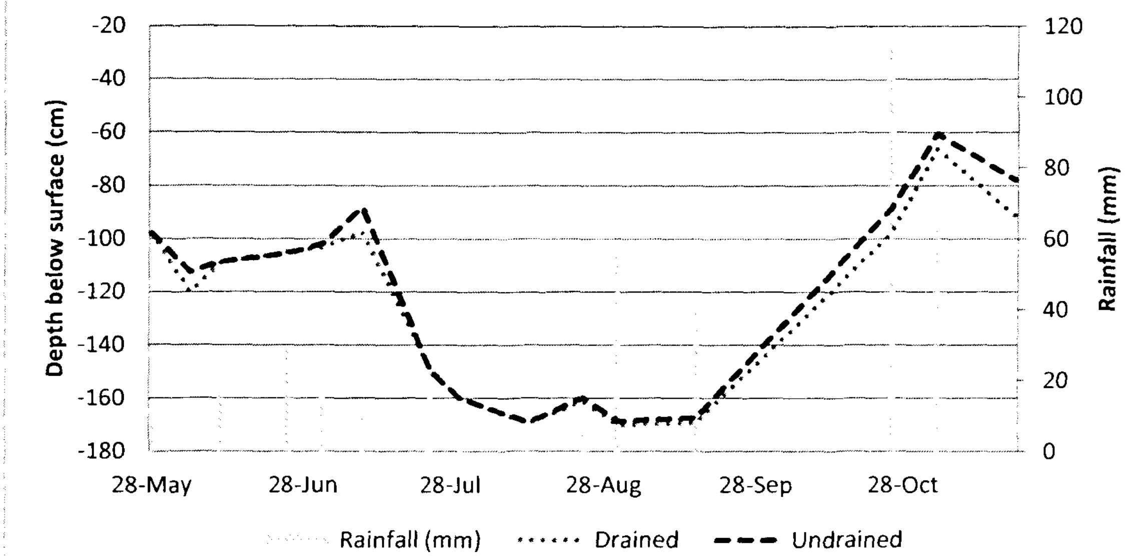
	Fargo			Prosper		
Month	2009	2010	Historical	2009	2010	Historical
	mm					
April	16.4	36.8	34.8	26.4	29.5	36.3
May	44.2	68.1	66.3	23.1	69.9	67.8
June	81.7	86.1	89.2	66.5	80.8	91.4
July	15.9	105.1	73.2	24.6	103.4	82.3
August	46.8	67.7	64.0	57.4	89.4	68.1
September	49.8	151.4	55.4	53.1	134.6	54.1
October	137.4	60.6	50.0	127.8	36.1	48.0
Total	392.3	575.8	432.9	378.9	543.7	448.0

2009 Yield and crop performance

In 2009, generally grain yield was very low compared to the 5 year average of 8.16 Mg ha^{-1} for the county (Cass) (USDA, 2011c), because of the combination of late planting dates and low accumulated GDD for the season. Averaged over all rates and additives there were no significant differences between drainage treatments for any of the crop related variables at Fargo in 2009. The lack of difference was probably due to below average rainfall during the growing season, and especially in June when most yield potential was developing. The only period of excessive moisture was in October after senescence (Table 2). Furthermore, there was little difference between the water table levels in the undrained and drained treatments throughout the season (Figure 2), suggesting similar soil water levels between the two drainage treatments.

Fargo, ND - In 2009, there was an interaction between drainage and additives for yield ($P \leq 0.10$) at Fargo, ND (Table 5).

Fig 2. Water table depth below the soil's surface and rainfall in Fargo in 2009.



This interaction resulted because the yield of the nitrapyrin and NBPT additive treatments were relatively less in the undrained main plots compared to the drained main plots while the no additive and pop-up treatments had opposite responses with their yield being higher in the undrained main plots than in the drained.

Table 5. Mean squares for the analysis of variance for agronomic traits Fargo, 2009.

Source of variation	df	Mean Squares							
		PP†	PH†	M†	Y†	KPE†	TKW†	PC†	SC†
Rep	3	206	129.9**	1180*	1.30‡	4645	19114	464**	8
A (drainage)	1	1	59.4	1600	0.02	4907	42	4	11
Error (a)	3	266	681.7	2715	10.66	98086	1410	968	138
B (Additive)	3	76	135.1	3066**	8.64**	7421	10614	347**	112‡
A x B	3	30	50.7	144	1.31‡	12199	12041	8	21
Error (b)	18	298	69.1	550	0.62	15984	9332	45	37
C (Rate)	4	174	26.8	1065*	2.88**	13639	7047	2359**	292**
A x C	4	85	8.3	338	0.29	4653	11621	35	5
B x C	12	85	34.6	435	0.42	8968	9430	48	22
A x B x C	12	94	29.9	692	0.36	11593	8746	52	39
Error (c)	96	113	28.2	434	0.58	10397	10040	35	26
CV,%		12	2.2	6	13.7	17	82	7	1

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

† PP= Plant population, PH= Plant height, M= Moisture, Y= Yield, KPE= Kernels per ear, TKW= 1000 kernel weight, PC= Protein content, SC= Starch content.

‡ Significant at ($P \leq 0.10$).

55

In Fargo, corn with nitrapyrin was lower in yield than all other treatments (Table 5). This was due to the fact that the ground had been worked with a rotovator after the nitrapyrin was applied which caused the soil to clump and made the seed bed sub-optimal for plant emergence and plant establishment. Nafziger et al., (1991) showed that sub-optimal seed bed conditions that delayed germination and emergence resulted in 6 to 9 percent yield loss when the delayed corn plants emerged around 10 days after earlier plants.

The nitrapyrin treatment also had lower protein which was probably associated with uneven emergence.

Significant differences were seen in some of the variables at differing N rates. At Fargo in 2009, the 56 kg N ha^{-1} rate was lower than all other rates for grain yield, except the 224 kg N ha^{-1} rate (Table 6). The 112 kg N ha^{-1} and the split application rate were not significantly different for grain yield suggesting that there was no advantage to a split application of N in this season. More of a difference may have shown up between N rates if the yields had been higher, but because of the low yields associated with poor growth, the 112 kg N ha^{-1} rate was adequate. Lang et al., (1956) showed that grain yield and protein both increased as N rate increased.

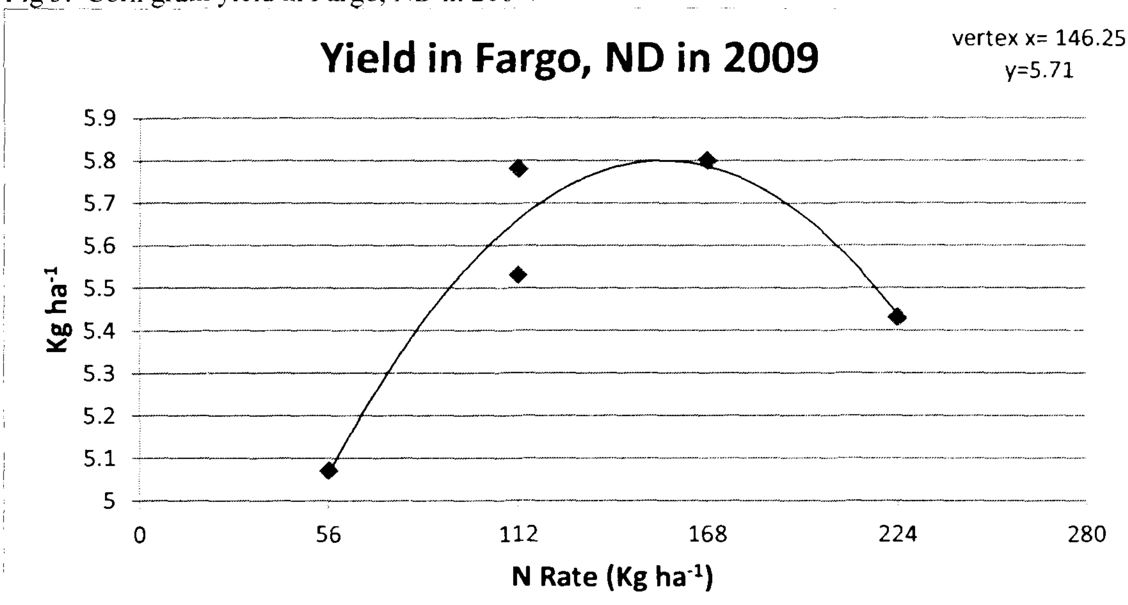
Corn grain protein showed a significant quadratic relationship between rate and protein ($R^2 = 0.88$; $y = 68.9 + 0.13x$) (Figure 3). Corn grain protein increased as the N rate increased. Sauberlich et al. (1953) showed that N fertilization could increase the protein and amino acid content of corn significantly in the absence of a yield response. There was no difference between the 112 kg N ha^{-1} and the split application rate for protein.

Table 6. Plant population, height, grain moisture, yield, thousand kernel weight, protein, and starch in corn as affected by subsurface drainage, N additives, and N rates in Fargo, ND, in 2009.

Variables	Population	Height	Moisture	Yield	KPE†	TKW†	Protein	Starch
	pl ha^{-1}‡	cm	g kg^{-1}	Mg ha^{-1}		g	g kg^{-1}	g kg^{-1}
Drainage								
Undrained	91.1	236	356.6	5.51	584	122	85.8	630.9
Drained	91.0	238	362.9	5.53	593	123	86.1	631.4
F-test	NS	NS	NS	NS	NS	NS	NS	NS
Additive								
No additive	92.0	235	350.9	5.78	586	114	87.9	629.0
NBPT§	91.3	238	353.8	5.65	591	136	85.2	631.7
Nitrapyrin	89.0	239	369.1	4.83	570	104	82.1	633.0
Pop-up	91.8	236	365.2	5.82	603	137	88.5	630.7
Mean	*91.0*	*237*	*359.8*	*5.52*	*588*	*123*	*85.9*	*631.1*
LSD (0.05)	NS	NS	11.0	0.37	NS	NS	3.2	NS
Rate								
kg N ha^{-1}								
56	93.2	237	365.1	5.07	554	109	72.8	636.2
56-56	93.2	238	361.4	5.78	587	136	84.6	630.5
112	91.0	236	351.2	5.53	590	112	84.8	631.1
168	90.0	237	356.8	5.80	609	114	93.3	628.7
224	87.7	237	364.2	5.43	597	141	94.1	629.1
Mean	*91.0*	*237*	*359.7*	*5.52*	*587*	*122*	*85.9*	*631.1*
LSD (0.05)	NS	NS	10.3	0.38	NS	NS	3.0	2.6

† KPE= Kernels per ear, TWK = thousand kernel weight.
‡ pl ha^{-1}= 1000 plants ha^{-1}.
§NBPT = n-(n-butyl) thiophosphoric triamide.

Fig 3. Corn grain yield in Fargo, ND in 2009.



Prosper, ND - At the Prosper location in 2009, protein content was the only measured agronomic trait that was significantly different between additives at $P \leq 0.10$ (Table 7). Urea broadcast and incorporated prior to seeding with no additive had the lowest protein of the four N management practices, numerically. This suggests that perhaps N availability was lowest with no additive and that there was more nitrification, denitrification or leaching when no additive was added compared with the other practices.

Table 7. Plant population, height, grain moisture, yield, thousand kernel weight, protein, and starch in corn as affected by N additives and N rates in Prosper, ND, in 2009.

Variables	Population	Height	Moisture	Yield	KPE†	TKW†	Protein	Starch
	pl ha^{-1}‡	cm	g kg^{-1}	Mg ha^{-1}		g	g kg^{-1}	g kg^{-1}
Additive								
No additive	75.7	194	301.9	8.49	634	180	69.4	640.4
NBPT§	72.1	203	287.9	8.83	648	190	76.6	637.0
Nitrapyrin	75.0	194	297.4	8.50	634	184	71.9	638.0
Pop-up	77.9	202	285.6	9.18	619	185	72.0	638.9
Mean	*75.2*	*198*	*293.2*	*8.75*	*634*	*185*	*72.5*	*638.6*
LSD (0.05)	NS	NS	NS	NS	NS	NS	5.1¶	NS
Rate								
kg N ha^{-1}								
56-56	76.1	194	306.7	8.62	622	184	72.0	637.9
112	74.3	203	279.7	8.88	646	186	72.9	639.2
LSD (0.05)	NS	8	10.1	NS	NS	NS	NS	NS

† KPE= Kernels per ear. TWK = thousand kernel weight.
‡ pl ha^{-1}= 1000 plants ha^{-1}.
§ NBPT = n-(n-butyl) thiophosphoric triamide.
¶ Significant at ($P \leq 0.10$).

Application timing was significant for plant height and moisture. The plants with 112 kg N ha^{-1} rate were taller than those with the split application, suggesting that there may have been more N available during the vegetative part of plant growth but this was not reflected as a difference in grain yield. Although both rates were high in moisture, the split application had significantly higher moisture than the 112 kg N ha^{-1} rate; this fosters the idea that the split application of urea at the V8 stage allowed plant growth later in the season, thus increasing moisture at harvest. There were no significant interactions measured between N practices at Prosper in 2009 (Table 8).

Table 8. Mean squares for the analysis of variance for agronomic traits Prosper, 2009.

Source of variation	df	Mean Squares							
		PP†	PH†	M†	Y†	KPE†	TKW†	PC†	SC†
Rep	3	53	94	196	0.5	1110	55	44	78
A (Additive)	3	45	193	476	0.9	1440	132	73‡	16
Error (a)	9	52	112	239	1.1	3248	163	23	29
B (Rate)	1	26	626*	5832**	0.5	4464	55	7	13
A x B	3	97	20	290	0.1	5829*	20	53	42
Error (b)	12	37	107	173	0.4	1593	143	41	53
CV,%		8	5	4	6.9	6	6	9	1

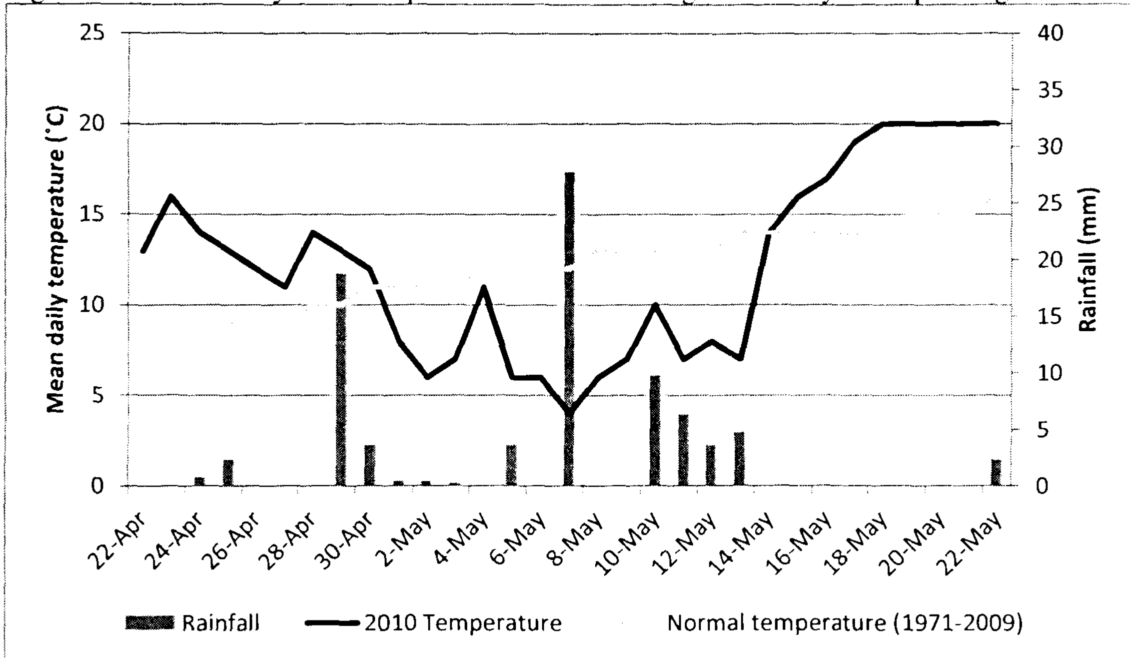
*,** Significant at ($P \leq 0.05$), and ($P \leq 0.01$), respectively.
† PP= Plant population, PH= Plant height, M= Moisture, Y= Yield, KPE= Kernels per ear, TKW= 1000 kernel weight, PC= Protein content, SC= Starch content.
‡ Significant at ($P \leq 0.10$).

2010 Yield and crop performance

Fargo, ND - At Fargo, in 2010, drainage did not significantly impact any of the variables measured except for population ($P \leq 0.10$) and grain moisture at harvest ($P \leq 0.09$) (Table 9). There were periods during the growing season in which water table depths between drained and undrained varied greatly (Figure 5). The higher water table in the undrained treatment early in the growing season may have impacted establishment. Similarly, the higher water table in the undrained treatment towards harvest may have resulted in more grain moisture at harvest.

There was a significant difference for additives for all variables measured, except for height and moisture. Plant population establishment was difficult in 2010 because of the prevailing cool, wet weather after planting (Figure 4).

Fig 4. Rainfall and daily mean temperature in 2010 for Fargo for 30 days after planting.



The plant population was substantially lower than the 81,510 plants ha^{-1} that was planted, regardless of the additive. The lower population was assumed to be due to chilling injury that took place during the cold period that occurred after corn planting. Chilling injury can occur when the corn seed imbibes water at cold temperatures. Soil temperature is critical during imbibition by seeds as cold temperatures can affect the integrity of cell membranes and consequently affect emergence (Bedi and Basra, 1993).

With the cold weather, the germination process was also slowed. There were 29 days between planting and emergence for the corn planted in Fargo, ND in 2010. The significantly poorer plant population associated with the pop-up additive may have been caused by the additional stress on the corn seed associated with the liquid fertilizer being placed directly with the seed during planting. Normally this addition is not harmful, but it appears that when some imbibitional damage has already occurred, salt injury is amplified.

Salt injury occurs when the fertilizer concentration in soil solution surrounding the seed is so high that water moves out of the seed and into the soil (Alley et al., 2010).

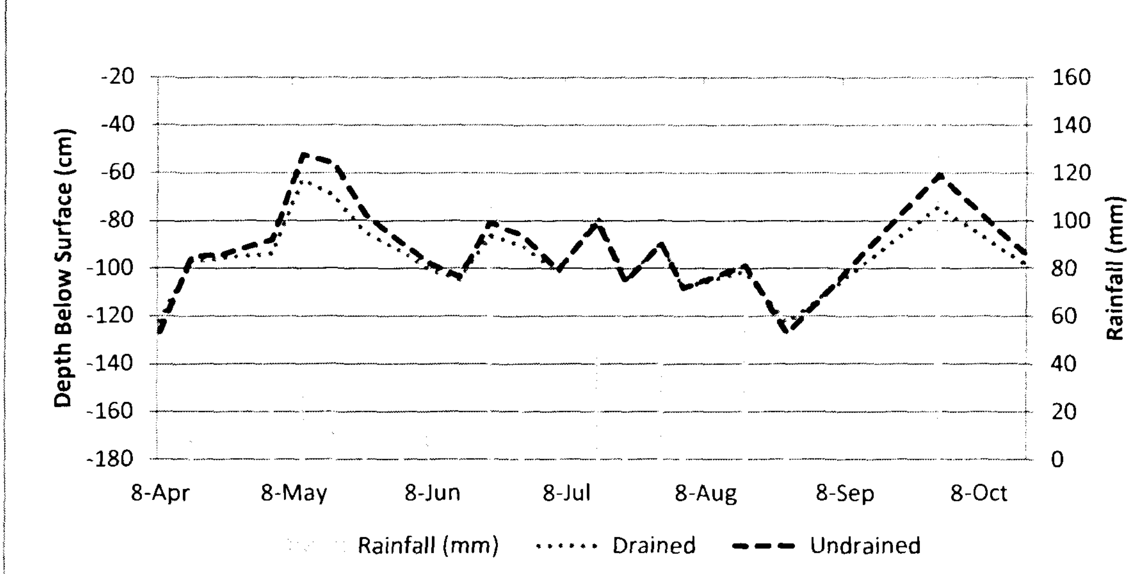
Table 9. Plant population, height, grain moisture, yield, thousand kernel weight, protein, and starch in corn as affected by subsurface drainage, N additives, and N rates Fargo, ND, in 2010.

Variables	Population	Height	Moisture	Yield	KPE†	TKW†	Protein	Starch
	pl ha^{-1}‡	cm	g kg^{-1}	Mg ha^{-1}		g	g kg^{-1}	g kg^{-1}
Drainage								
Undrained	55.6	208	181.9	9.88	590	284	76.2	645.7
Drained	60.2	207	175.5	10.50	581	285	76.4	647.0
F-test	§	NS	§	NS	NS	NS	NS	NS
Additive								
No		207	179.0	9.97	564	282	75.2	
additive	60.5							648.2
NBPT¶	62.3	208	176.4	10.75	591	285	76.5	645.8
Nitrapyrin	64.6	207	179.0	11.13	581	281	74.4	648.2
Pop-up	44.2	205	180.3	8.90	606	291	79.0	643.3
Mean	*57.9*	*207*	*178.7*	*10.19*	*586*	*285*	*76.3*	*646.4*
LSD (0.05)	6.7	NS	NS	0.88	23	7	2.5	2.4
Rate								
kg N ha^{-1}								
56	54.4	207	181.5	8.71	583	270	70.5	648.7
56-56	58.3	205	175.6	10.48	602	287	76.2	646.0
112	58.4	207	176.5	10.49	602	283	75.1	646.5
168	60.1	207	179.0	10.61	570	290	79.4	644.4
224	58.3	208	181.0	10.65	571	293	80.0	646.2
Mean	*57.9*	*207*	*178.7*	*10.19*	*586*	*285*	*76.2*	*646.4*
LSD (0.05)	NS	NS	NS	0.73	NS	7	3.1	2.7

† KPE= Kernels per ear. TWK = thousand kernel weight.
‡ pl ha^{-1}= 1000 plants ha^{-1}.
§ Significant at ($P \leq 0.10$).
¶ NBPT = n-(n-butyl) thiophosphoric triamide.

The starter fertilizer was significantly lower than all other additives including the untreated check for yield. The reduced grain yield could be directly related to the significantly lower plant population. Starter was significantly greater than the untreated check for thousand kernel weight. With the significantly lower plant population, each plant had greater access to resources thus producing larger kernels. Starter fertilizer was higher for protein than the untreated check. Lang et al. (1956) showed that grain protein levels increased with lower plant populations. In addition to more plant space, the amount of N per plant was higher with the starter fertilizer compared to other additives, which may also explain the increased thousand kernel weight, higher moisture content, and lower starch.

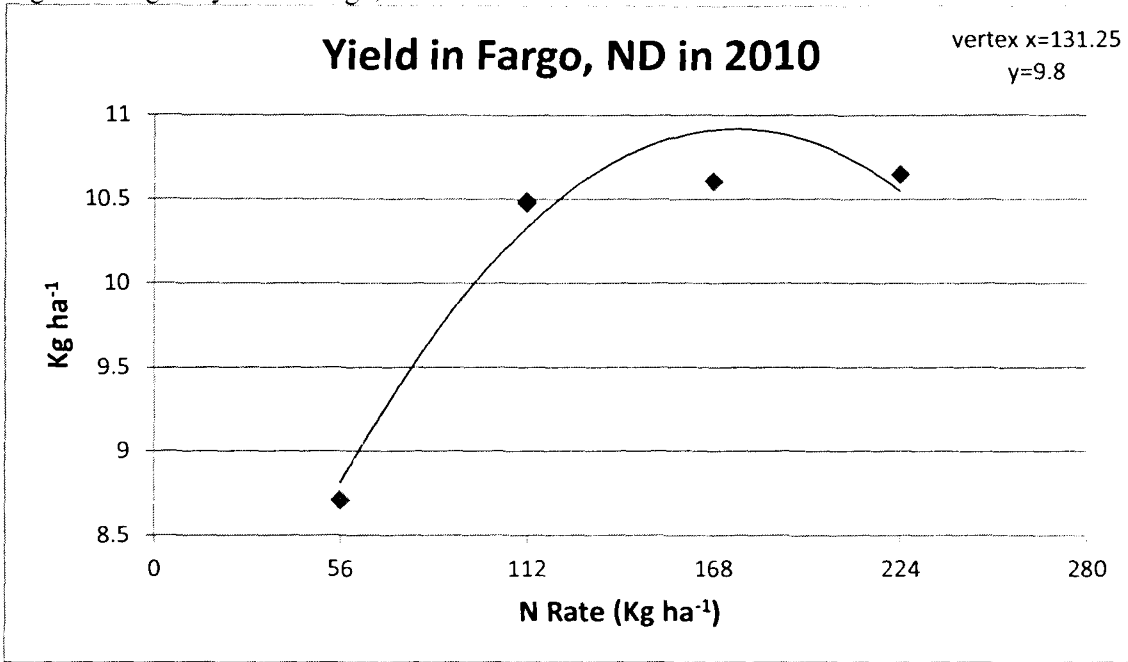
Fig 5. Water table depth below surface and rainfall in Fargo in 2010.



Adding nitrapyrin significantly increased yield compared to the untreated check, suggesting that N efficiency was improved by nitrapyrin. For starch, NBPT was significantly lower than the untreated check.

Corn grain yield increased quadratically with increasing rates of N at the $P \leq 0.10$ level ($R^2 = 0.94$; $y = 6.3 + 0.053x - 0.0002x^2$) (Figure 6). There was a significant linear relationship between N rate and thousand kernel weight at $P \leq 0.01$ ($R^2 = 0.96$; $y = 250.4 + 0.42x - 0.001x^2$).

Fig 6. Corn grain yield in Fargo, ND in 2010.



Thousand kernel weight was significantly lower for the 56 kg N ha^{-1} rate than all other rates and appears to be the yield component most affected by the low amounts of N.

The trend for protein was similar to that in 2009 at Fargo, with higher N rates producing higher protein. There was a significant linear relationship between N rate and protein ($R^2 = 0.99$, $y = 62.8 + 0.16x - 0.0003x^2$). Just like in 2009 at Fargo there was no significant difference for protein between the split application rate and the 112 kg N ha^{-1} rate.

In 2010, there were interactions for moisture between drainage by additive, drainage by rate, and additive by rate at Fargo, ND (Table 10). These results were possibly related to the poor plant population in the starter fertilizer additive. Starch for the 56 kg N ha^{-} rate was significantly higher than with the 168 kg N ha^{-1} rate.

Table 10. Mean squares for the analysis of variance for agronomic traits Fargo, 2010.

Source of variation	df	Mean Squares PP†	PH†	M†	Y†	KPE†	TKW†	PC†	SC†
Rep	2	103**	127**	633**	9.0	1265	756**	63	127**
A (drainage)	1	643‡	1	1242‡	11.5	1999	25	2	48
Error (a)	2	78	513	134	3.0	7526	88	34	71
B (Additive)	3	2582**	44	81	29.2**	9333**	639*	121**	165**
A x B	3	116	116	396**	0.8	2380	13	6	11
Error (b)	12	142	21	98	2.5	1617	143	20	18
C (Rate)	4	108	28	165	16.5**	6080	1969**	350**	57**
A x C	4	99	60	64*	2.0	1183	102	14	29
B x C	12	84	38	40*	1.0	2750	181	15	25
A x B x C	12	53	13	107	1.2	4206	128	11	6
Error (c)	64	56	17	87	1.6	3864	144	29	22
CV,%		13	2	5	12.0	11	4	7	1

*,** Significant at ($P\leq0.05$), and ($P\leq0.01$), respectively.
† PP= Plant population, PH= Plant height, M= Moisture, Y= Yield, KPE= Kernels per ear, TKW= 1000 kernel weight, PC= Protein content, SC= Starch content.
‡ Significant at ($P\leq0.10$).

Interactions were seen in 2010 at Prosper, ND (Table 12) for additive by rate in plant height ($P\leq0.10$), moisture ($P\leq0.10$), and thousand kernel weight ($P\leq0.05$). The reasoning for these interactions is uncertain. There were no definite trends for any one of the additive treatments, thus resulting in a significant interaction in these traits.

Prosper, ND - In 2010, at the Prosper site, there were significant differences in plant population between additive treatments (Table 11). The starter fertilizer treatment was significantly lower in population, similar to what was seen in the starter fertilizer additive in 2010, at Fargo (Table 9). There was again 29 days between planting and emergence for the corn planted at Prosper in 2010. The reason for the low population in the starter treatment could possibly be attributed to the combination of chilling (Figure 7) and salt injury as previously described. The low population in the starter treatment had an effect on grain yield. There were no significant differences in grain yield between the other three additives used.

Fig 7. Rainfall and daily mean temperature in 2010 for Prosper for 30 days after planting.

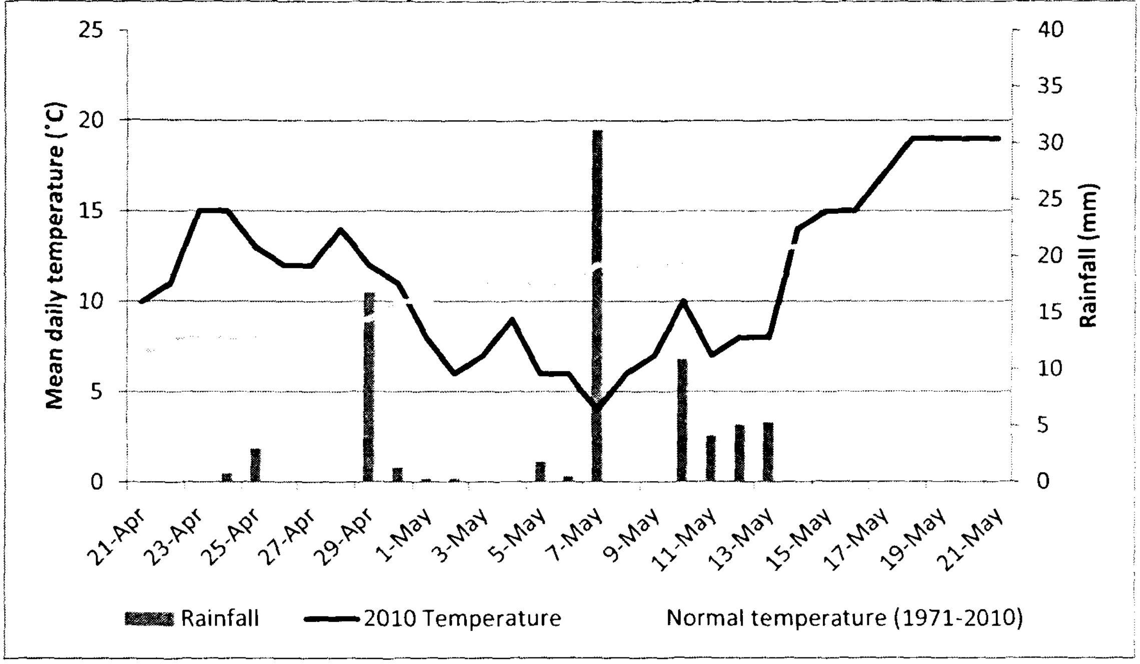


Table 11. Plant population, height, grain moisture, yield, thousand kernel weight, protein, and starch in corn as affected by N additives and N rates in Prosper, ND, in 2010.

Variables	Population	Height	Moisture	Yield	KPE†	TKW†	Protein	Starch
	pl ha^{-1}‡	cm	g kg^{-1}	Mg ha^{-1}		g	g kg^{-1}	g kg^{-1}
Additive								
No additive	58.3	225	198.9	11.65	599	301	72.0	645.9
NBPT§	62.9	225	201.4	11.98	608	291	71.2	650.8
Nitrapyrin	58.6	225	199.8	11.88	602	302	74.0	647.8
Starter	43.8	224	204.5	10.40	593	301	79.2	644.6
Mean	*58.6*	*225*	*201.2*	*11.48*	*601*	*299*	*74.1*	*647.3*
LSD (0.05)	6.4	NS	NS	1.09	NS	NS	2.6	2.0
Rate								
kg N ha^{-1}								
56	55.3	223	196.0	10.76	616	291	71.0	648.4
56-56	57.2	223	197.9	11.51	576	304	74.1	646.2
112	57.5	225	199.3	11.47	622	294	74.6	648.0
168	54.8	226	204.2	11.60	570	310	76.3	646.6
224	68.2	226	208.3	12.04	619	295	74.3	647.1
Mean	*58.6*	*225*	*201.1*	*11.48*	*601*	*299*	*74.1*	*647.3*
LSD (0.05)	NS	3	6.1	0.70	38	11	NS	NS

† KPE= Kernels per ear. TWK = thousand kernel weight.
‡ pl ha^{-1}= 1000 plants ha^{-1}.
§ NBPT = n-(n-butyl) thiophosphoric triamide.

The starter fertilizer treatment produced a significantly higher protein than the other additive practices, like in the Fargo location, and was accredited to fact that the plant population for the starter was lower, thus more plant space and N was available to each plant therefore increasing protein content. MacGregor et al. (1961) showed that additional increments of N resulted in further increases in protein content and that N fertilization produced an increase in total amino acids.

There was also a significant difference between rates at Prosper in 2010. Height and moisture both increased as rate increased with no significant difference between the 112 kg N ha^{-1} rate and the split application rate. There was a significant quadratic relationship at $P \leq 0.10$ between rate and height ($R^2 = 0.72$; $y = 221.0 + 0.036x - 0.00006x^2$) and at $P \leq 0.01$ between rate and moisture ($r = 0.98$; $y = 193.4 + 0.034x + 0.0002x^2$). There was also a significant quadratic relationship at $P \leq 0.01$ between rate and corn grain yield ($R^2 = 0.93$; $y = 10.1 + 0.015x - 0.00003x^2$) (Figure 8).

Fig 8. Corn grain yield in Prosper, ND in 2010.

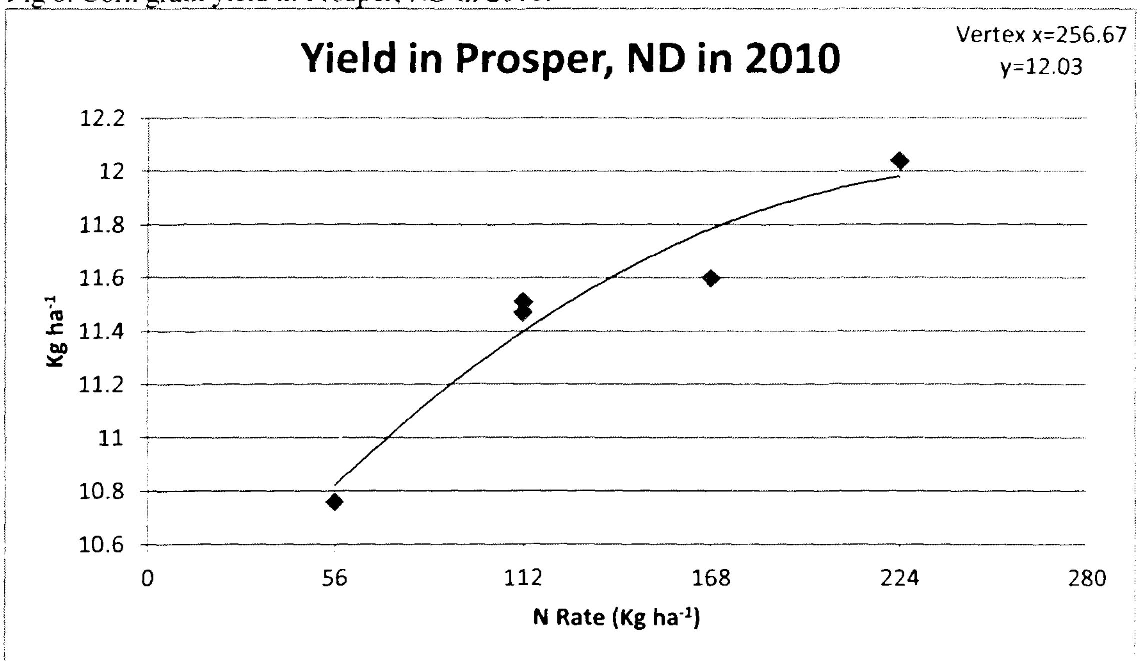


Table 12. Mean squares for the analysis of variance for agronomic traits Prosper, 2010.

Source of variation	df	Mean Squares							
		PP†	PH†	M†	Y†	KPE†	TKW†	PC†	SC†
Rep	3	394**	87**	49	6.7**	5705	252	113**	15
A (Additive)	3	1384**	1	119	10.8*	884	527	259**	147**
Error (a)	9	81	40	222	2.3	4240	208	13	8
B (Rate)	4	28	45*	405**	3.4*	10219**	1042**	58‡	13
A x B	12	30	30‡	134‡	0.7	2463	530*	28	15
Error (b)	48	44	17	73	1.0	2853	242	26	27
CV,%		12	2	4	9.0	9	5	7	8

*,** Significant at ($P \leq 0.05$), and ($P \leq 0.01$), respectively.
† PP= Plant population, PH= Plant height, M= Moisture, Y= Yield, KPE= Kernels per ear, TKW= 1000 kernel weight, PC= Protein content, SC= Starch content.
‡ Significant at ($P \leq 0.10$).

Horace, ND - In Horace, ND in 2010, interactions were also seen for additive by rate (Table 13) for thousand kernel weight ($P \leq 0.05$). The differences in these agronomic traits were also similar to Fargo, ND, attributed to the significantly low plant population in the starter fertilizer additive.

Table 13. Mean squares for the analysis of variance for agronomic traits Horace, 2010.

Source of variation	df	Mean Squares							
		PP†	PH†	M†	Y†	KPE†	TKW†	PC†	SC†
Rep	3	263**	367	3741**	3.0**	1965	133	34*	411‡
A (Additive)	3	1503*	425	3360	3.0	49602	1181**	8	75
Error (a)	9	334	214	2510	2.9	25739	143	20	257
B (Rate)	4	47	1983**	509	25.2**	79031**	386**	192**	146
A x B	12	40	243	283	0.5	635	162*	7	108
Error (b)	48	55	189	490	0.6	1455	81	11	160
CV,%		12	6	9	13.0	10	4	5	2

*,** Significant at ($P \leq 0.05$), and ($P \leq 0.01$), respectively.
† PP= Plant population, PH= Plant height, M= Moisture, Y= Yield, KPE= Kernels per ear, TKW= 1000 kernel weight, PC= Protein content, SC= Starch content.
‡ Significant at ($P \leq 0.10$).

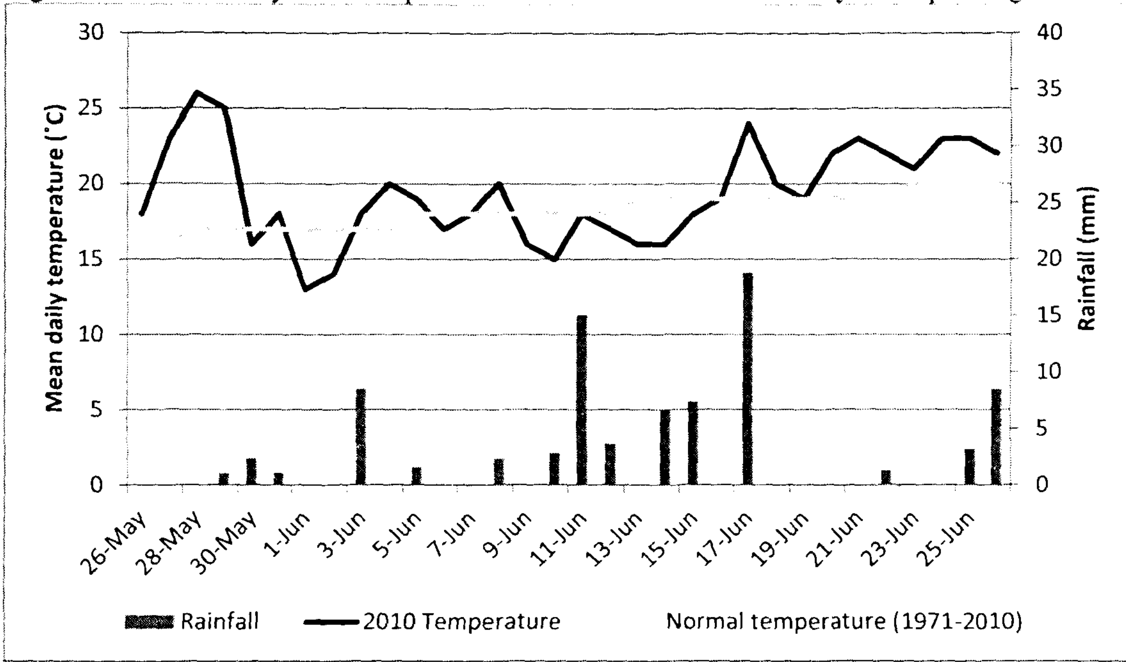
Although the planting date at Horace was later in 2010 than at both Prosper and Fargo sites, which lends to the idea that chilling injury would be less likely (Figure 3 & 9), there was still a significant population decrease with the starter fertilizer additive (Table 8). Since lower plant population was not attributed directly to chilling injury, the low population (Table 14) in the starter fertilizer additive is most likely related to salt injury. Alley et al., (2010) stated that seed-placed starter fertilizer rate should not exceed a rate of 94 kg ha^{-1} for clay loam soils to avoid salt injury. Considering that the rate applied of 28 kg ha^{-1} is a third of the maximum recommended rate it would be assumed that salt injury alone would be unlikely, under most circumstances. The lower plant population for the pop-up starter fertilizer may be accredited, again, to the combination of both the chilling and salt injury. The difference between planting and emergence was 12 days. Grain yield was not affected by the decreasing plant population with starter.

Table 14. Plant population, height, grain moisture, yield, thousand kernel weight, protein, and starch in corn as affected by N additives and N rates at Horace, ND in 2010.

Variables	Population	Height	Moisture	Yield	KPE†	TKW†	Protein	Starch
	pl ha^{-1}‡	cm	g kg^{-1}	Mg ha^{-1}		g	g kg^{-1}	g kg^{-1}
Additive								
No additive	65.2	220	236.3	5.81	369	247	60.6	645.6
NBPT§	66.2	212	249.4	5.24	320	250	61.3	644.7
Nitrapyrin	74.1	221	234.8	6.18	336	249	60.8	643.2
Pop-up	53.1	213	217.8	5.77	433	264	62.0	647.8
Mean	*64.6*	*216*	*234.6*	*5.75*	*365*	*252*	*61.2*	*645.3*
LSD (0.05)	13.1	NS	NS	NS	NS	9	NS	NS
Rate								
kg N ha^{-1}								
56	62.8	205	240.3	3.79	257	252	57.6	640.4
56-56	65.8	205	238.2	5.65	361	249	59.9	644.7
112	67.0	219	228.9	5.65	350	247	59.5	646.1
168	64.1	224	237.4	6.56	415	253	62.1	647.7
224	63.5	229	228.1	7.08	438	260	66.6	647.7
Mean	*64.6*	*216*	*234.6*	*5.75*	*364*	*252*	*61.1*	*645.3*
LSD (0.05)	NS	10	NS	0.54	27	6	2.4	NS

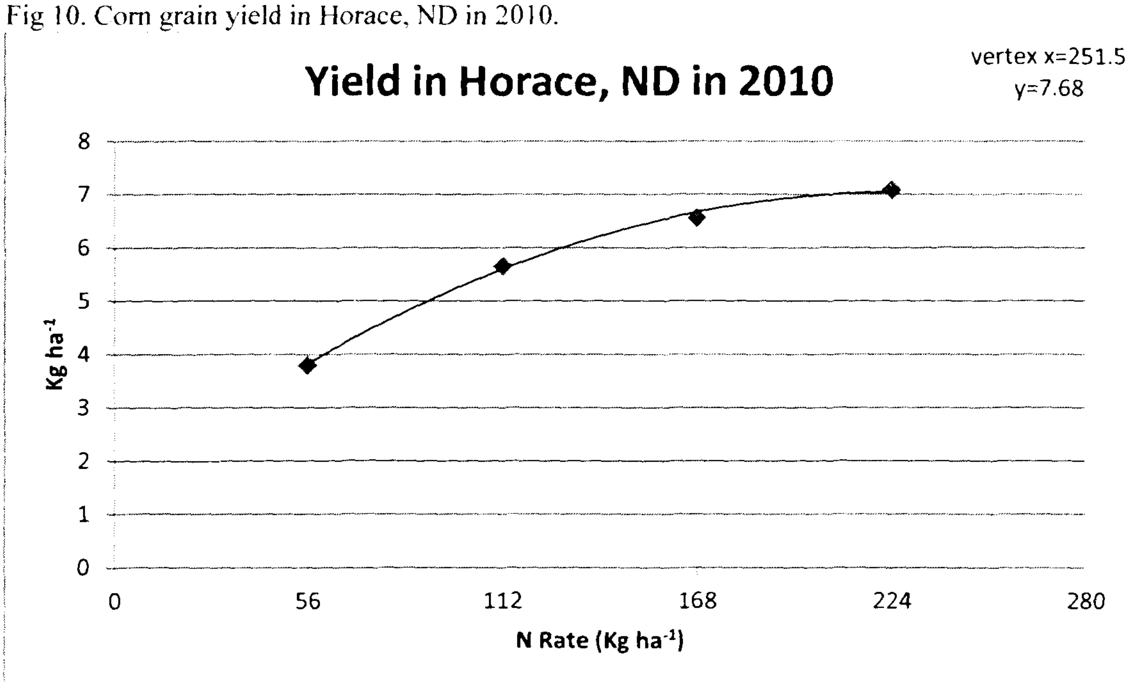
† KPE= Kernels per ear. TWK = thousand kernel weight.
‡ pl ha^{-1}= 1000 plants ha^{-1}.
§ NBPT = n-(n-butyl) thiophosphoric triamide.

Fig 9. Rainfall and daily mean temperature in 2010 for Horace for 30 days after planting.



There was a significant quadratic relationship between rate and height in 2010 at Horace at $P \leq 0.05$ ($R^2 = 0.78$; $y = 194.9 + 0.17x - 0.00007x^2$) (Figure 10).

Fig 10. Corn grain yield in Horace, ND in 2010.



Both the 56 kg N ha^{-1} rate and the split application rate were significantly lower than all other rates for height, suggesting that N was limiting during the part of the season when the vegetative growth rate was highest. There was also a significant quadratic relationship at $P \leq 0.01$ between rate and yield ($R^2 = 0.997$; $y = 1.36 + 0.05x - 0.0001x^2$) and rate and protein ($R^2 = 0.99$; $y = 57.0 + 0.0025x + 0.0002x^2$). There was no difference between the 112 kg N ha^{-1} rate and the split application for yield, but both rates were significantly lower than the 168 and 224 kg N ha^{-1} rates, which indicates that N was limiting at rates below 168 kg N ha^{-1} at this location.

Nitrate stalk tests

There were no interactions between drainage, additives, or rates for any of the nitrate stalk tests (Tables A15-A18).

The nitrate stalk test (Blackmer and Mallarino, 1996) is used to evaluate the amount of N taken up by the plant that remains unutilized by plant metabolism and structure at the end of the season. Our test results are related to the relative amount of N available in the soil and therefore any differences between treatments should be a measure of N-use efficiency. When corn is insufficient in N late in the season during the grain filling period the plant will acquire N from the lower leaves and stalk to provide adequate N for seed development (corn grain). Plants that have excessive N availability, i.e. more than what is needed to achieve their grain yield potential, will have more N in the lower stalk at the end of the season. Blackmer and Mallarino (1996) categorized basal stalk nitrate concentrations into four ranges: low (less than 250 mg kg^{-1} NO_3^-), marginal (250 to 700 mg kg^{-1} NO_3^-), optimal (700 to 2000 mg kg^{-1} NO_3^-), and excess (greater than 2000 mg kg^{-1} NO_3^-).

There were no significant differences between additives (Tables 15 and 16) in any of the years or locations included in this study for stalk NO_3 level. There were, however, significant differences between rates (Tables 15 and 17). The rates in 2010 at the Prosper location (Table 15) were significantly different with both the 56 kg N ha^{-1} rate and the split application rate being categorized in the optimal category (700 to 2000 mg kg^{-1} NO_3^-), all other rates had a stalk NO_3^--N content greater than 2000 mg kg^{-1}, which is classified as excess. Table 11 showed that there was a difference in grain yield between N rates in 2010 at the Prosper site as well and that the 56 kg N ha^{-1} rate was significantly lower than all other rates.

Table 15. Nitrate stalk test means for Nitrogen and NO_3^--N for additive and rate at Prosper and Horace, ND in 2010.

	Prosper		Horace	
Variable	N	NO_3^--N	N	NO_3^--N
	mg g^{-1}	mg kg^{-1}	mg g^{-1}	mg kg^{-1}
Additive				
No additive	6.69	2554	2.15	844
NBPT†	6.33	3727	2.88	774
Nitrapyrin	8.37	4611	2.43	956
Pop-up	8.93	5443	2.60	818
Mean	*7.58*	*4084*	*2.52*	*848*
LSD(0.05)	NS	NS	NS	NS
Rate				
kg N ha^{-1}				
56	4.51	1547	2.41	967
56-56	4.77	1767	2.41	773
112	4.98	2317	2.44	1020
168	6.69	2554	2.15	844
224	7.94	3980	2.71	647
Mean	*5.78*	*2433*	*2.42*	*850*
LSD (0.05)	1.97	1643	NS	NS

†NBPT = n-(n-butyl) thiophosphiroic triamide.

There was a significant quadratic relationship between rate and NO_3^--N level at $P \leq 0.01$ ($R^2 = 0.94$; $y = 1676.6 - 5.05x + 0.067x^2$) as well as between rate and total N ($R^2 =$

0.97; y = 4.23 - 0.0223x + 0.00009x^2) at Prosper in 2010. The correlation between yield and nitrate content in the stalk may show that at the 56 kg N ha^{-1} rate N was limiting. Thus, the 56 kg N ha^{-1} rate is lower than a rate that would give maximum yield potential at the Prosper location.

A significant difference between drained and undrained at $P \leq 0.10$ occurred in Fargo in 2010 for mg g^{-1} of N in the stalks (Table 16). The drained was slightly higher than the undrained.

Table 16. Nitrate stalk tests means for Nitrogen and NO_3^--N for Fargo in 2009 and 2010 as affected by subsurface drainage and N additives.

	2009		2010	
Variables	N	NO_3^--N	N	NO_3^--N
	mg g^{-1}	mg kg^{-1}	mg g^{-1}	mg kg^{-1}
Drainage				
Undrained	6.23	2148	5.13	2314
Drained	6.22	1774	6.23	3233
F-test	NS	NS	†	NS
Additive				
No additive	6.68	2150	6.86	3810
NBPT‡	6.28	2067	6.77	3305
Nitrapyrin	6.63	2438	6.29	3292
Pop-up	6.80	2030	6.35	3423
Mean	*6.60*	*2172*	*6.57*	*3458*
LSD (0.05)	NS	NS	NS	NS

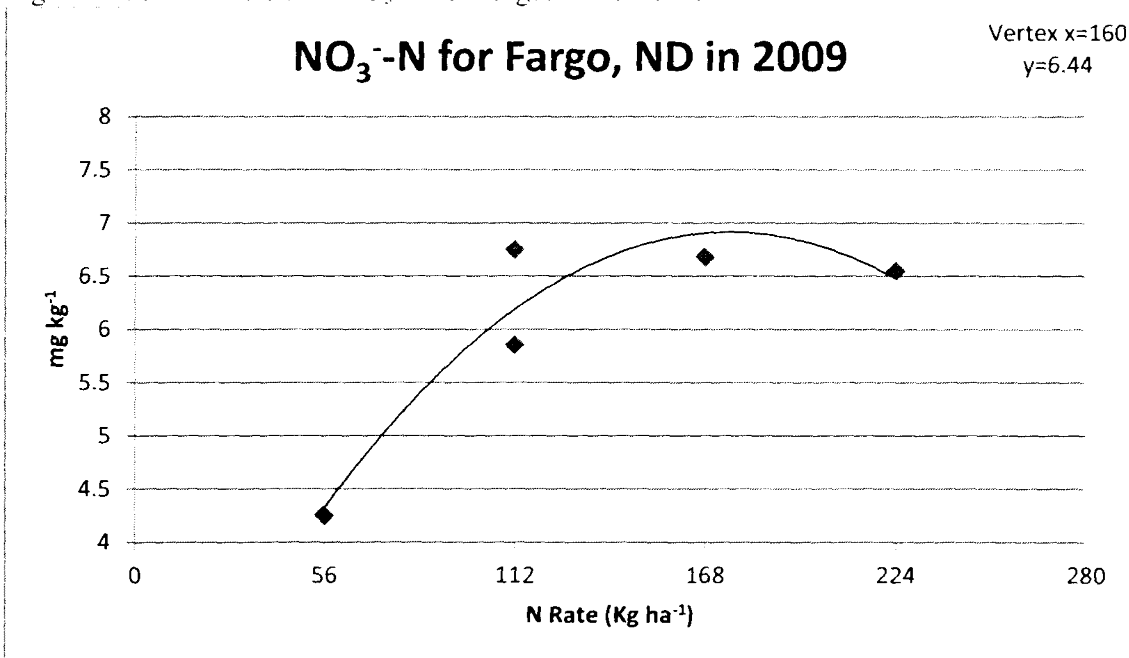
† Significant at ($P \leq 0.10$).
‡ NBPT = n-(n-butyl) thiophosphiroic triamide.

There was a significant quadratic relationship between rate and stalk NO_3^--N at $P \leq 0.05$ (R^2 = 0.90; y = -318 + 16.17x – 0.0012x^2) for Fargo in 2009 (Figure 11). There was also a significant quadratic relationship between rate and NO_3^--N at $P \leq 0.01$ (R^2 = 0.89; y = -388 + 22.14x – 0.0073x^2) and between rate and N at $P \leq 0.05$ (R^2 = 0.84; y = 1.6 + 0.033x – 0.00004x^2) at for Fargo in 2010 (Table 17). There was no significant difference in stalk nitrate between the split application rate and the 112 kg N ha^{-1} rate at any location in any year. Although the difference was not significant, the 112 kg N ha^{-1} rate had a higher concentration of N at all sites and years except Fargo in 2010 (Table 17). This did not result in significant differences between grain yields between the two rates.

Table 17. Nitrate stalk tests means for Nitrogen and NO_3^--N for Fargo in 2009 and 2010 as affected by N rates.

	2009		2010	
Rate	N	NO_3^--N	N	NO_3^--N
kg N ha^{-1}	mg g^{-1}	mg kg^{-1}	mg g^{-1}	mg kg^{-1}
56	4.25	512	3.64	1057
56-56	5.85	1166	4.78	1790
112	6.75	2006	4.06	1529
168	6.68	2150	6.86	3810
224	6.55	3317	6.70	3980
Mean	*6.02*	*1830*	*5.21*	*2433*
LSD (0.05)	1.47	948	1.76	1542

Fig 11. Nitrate stalk tests for NO_3^--N for Fargo, ND in 2009.



Greenseeker® measurements

There were no interactions between drainage, additives, or rates for NDVI obtained with the Greenseeker® (Table 18).

Table 18. Mean squares for the analysis of variance for Greenseeker® NDVI measured in 2010 at Fargo, ND.

Source of variation	df	Date 7-8-10	7-15-10
Rep	2	0.0159**	0.0028**
A (drainage)	1	0.0157†	0.0023
Error (a)	2	0.0014	0.0003
B (Additive)	3	0.0106**	0.0013**
A x B	3	0.0005	0.0003
Error (b)	12	0.0012	0.0001
C (Rate)	4	0.0025*	0.0006*
A x C	4	0.0010	0.0002
B x C	12	0.0011	0.0001
A x B x C	12	0.0011	0.0002
Error (c)	64	0.0009	0.0002
CV,%		3.57	1.70

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

NDVI differences between drainage at the 8 July date were probably associated with the differences in population between drained and undrained at this location (Table 9). There was a significant difference for the NDVI between additives (Table 19) for both dates measured in Fargo, ND. This difference was attributed to the difference in population among plants with different additives. The pop-up additive had significantly fewer plants than the other additives, so there was less green biomass in these plots. The untreated check, nitrapyrin, and NBPT additives were not significantly different from each other which shows that the N additives did not have an effect on greenness or biomass at the time when the Greenseeker® readings were taken. The difference for NDVI between rates (Table 19) in the first reading showed that the 56 kg N ha^{-1} rate was significantly lower than all other rates, except for the 112 kg N ha^{-1} rate applied as a split. This suggests that the plant biomass or greenness at the 56 kg N ha^{-1} rate was less than all other rates and indicates that plants at the 56 kg N ha^{-1} rate were showing some deficiencies relative to the higher rates. There was also no significance at either date between the 112 kg N ha^{-1} rate, and the 56-56 kg N ha^{-1} rate for NDVI.

Table 19. Normalized Difference Vegetative Index (NDVI) using Greenseeker® at Fargo on two different dates as affected by subsurface drainage, N additives, and N rates in 2010.

	8 July	15 July
Drainage		
Undrained	0.810	0.848
Drained	0.833	0.857
F-test	0.019†	NS
Additive		
No additive	0.822	0.855
NBPT‡	0.835	0.858
Nitrapyrin	0.834	0.854
Pop-up	0.794	0.843
LSD (0.05)	0.019	0.006
Rate		
kg N ha^{-1}		
56	0.807	0.845
56-56	0.815	0.854
112	0.828	0.853
168	0.832	0.858
224	0.823	0.852
LSD (0.05)	0.017	0.008

† Significant at ($P \leq 0.10$).
‡ NBPT = n-(n-butyl) thiophosphiroic triamide.

Soil N tests

A significant drainage by additive interaction was seen in the post-split soil tests for soil NO_3^--N at the 15 cm-depth, in 2010, at Fargo (Table 21).

Soil nitrate-N tests were not significantly different at Fargo between drained and undrained at any time during the season (Table 20-21). Furthermore, there were no significant differences between N additives. However, the split application treatment (50.1 mg kg^{-1} of NO_3^--N) had greater soil nitrate-N at the 15 cm depth compared to the 112 kg N ha^{-1} rate (37.1 mg kg^{-1} of NO_3^--N). The split application (18.5 mg kg^{-1} of NO_3^--N) was also significantly higher than the 112 kg N ha^{-1} (15.9 mg kg^{-1} of NO_3^--N) at the 15 cm depth at the end of season measurement time. This indicates that there was more N in the top profile of the soil in the split application after the second application and at the end of season than the 112 kg N ha^{-1} rate. There was no difference in the 45 cm depth at these dates between the two treatments. This could be due to differences in plant use, N not leaching to the 45 cm depth, or to denitrification.

Table 20. Pre-split mean squares for soil tests measured in 2010 at Fargo, ND.

Source of variation	df	Pre-split 15.24	Pre-split 45.72
Rep	1	827*	2756**
A (Drainage)	1	248	441
Error (a)	1	14	182
B (Additive)	3	9	123
A x B	3	96	87
Error (b)	6	107	206
CV,%		31	22

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

Table 21. Post-split and end of season mean squares for soil tests measured in 2010 at Fargo, ND.

Source of variation	df	Post-split	End of Season	
		15.24	15.24	45.72
Rep	1	14	621.3**	3916**
A (drainage)	1	95	5.3	72
Error (a)	1	259	9.0	28
B (Additive)	3	74	11.4	274
A x B	3	117*	6.8	50
Error (b)	6	52	16.8	170
C (Rate)	1	1365**	52.5*	41
A x C	1	3	0.3	113
B x C	3	13	8.2	80
A x B x C	3	43	8.6	65
Error (c)	8	27	7.7	113
CV,%		12	16.1	33

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

CONCLUSIONS

Subsurface drainage treatments, did not significantly improve yields across any of the N management practices. Subsurface drainage will not always provide an agronomic response, and conditions were such during the two years of this study that excessive soil moisture did not limit agronomic crop performance.

Nitrapyrin, a nitrification inhibitor, significantly increased yield over the untreated check at Fargo in 2010 when conditions favored denitrification. Franzen (2010) stated that grain yield increases with the use of a nitrification inhibitor have been inconsistent due to the variability of rainfall necessary to lead to nitrate leaching in sandier soils or denitrification in high clay soils.

Urease inhibitor, NBPT, did not significantly increase any agronomic trait over the untreated check in any year or location except for a significant increase in corn grain starch in Prosper, ND in 2010.

Adding fertilizer to the seed row at planting did not significantly increase corn grain yield. In fact, the addition of fertilizer to the seed row at planting reduced plant populations which resulted in significantly lower corn grain yields in 2010. Conditions were unfavorable for emergence and when the added salt of this treatment was combined with poor environmental conditions for emergence, poor plant populations resulted. However, in one location pop up was superior to other N management practices. Chilling and salt injury were not measured but only observed.

Corn grain yield was shown to be less in instances when N was limiting, in lower yielding environments optimal yield was seen at the higher rates of N. In most cases minimal yield increases were seen beyond the 112 kg N ha^{-1}.

A trend towards higher grain protein in corn when more N was available to the plant was recorded in some environments. In some environments, height was affected by N rate as was grain moisture at harvest, with both traits increasing as N rates increased. Shorter plant height and increased corn grain moisture content also occurred with the split application of N in some environments. Grain yield was not significantly affected by timing of N application.

More research is needed to conclude if the factors tested hold potential to improve N use efficiency and corn productivity in the variable environments of eastern North Dakota.

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Table A1. Combined analyses of variance for a randomized complete block design with a split-split plot arrangement where drainage, nitrogen fertilizer practices, and nitrogen rates are fixed effects and replication and experiments are random effects.

Source of variation	Combined df	Mean Square: Observed	Mean Square: Expected	F-test
Experiments	e-1 = 1	M1		-
Rep/Exp	e(r-1) = 4	M2		-
A (drainage)	(a-1) = 1	M3	$\sigma^2 + c\sigma^2_\theta + bc\sigma^2_\gamma + rbc\sigma^2_{AE} + rbce_{\theta A}$	M3/M4
A x Exp	(a-1)(e-1) = 1	M4	$\sigma^2 + c\sigma^2_\theta + bc\sigma^2_\gamma + rbc\sigma^2_{AE}$	M4/M5
Pooled error A	e(a-1)(r-1) = 4	M5	$\sigma^2 + c\sigma^2_\theta + bc\sigma^2_\gamma$	-
B (Additive)	(b-1) = 3	M6	$\sigma^2 + c\sigma^2_\theta + rac\sigma^2_{BE} + race\sigma^2_{\theta B}$	M6/M7
B x Exp	(b-1)(e-1) = 3	M7	$\sigma^2 + c\sigma^2_\theta + rac\sigma^2_{BE}$	M7/M10
A x B	(a-1)(b-1) = 3	M8	$\sigma^2 + c\sigma^2_\theta + rc\sigma^2_{ABE} + rce\sigma^2_{\theta AB}$	M8/M9
A x B x Exp	(a-1)(b-1)(c-1) = 3	M9	$\sigma^2 + c\sigma^2_\theta + rc\sigma^2_{ABE}$	M9/M10
Pooled error B	ae(r-1)(b-1) = 24	M10	$\sigma^2 + c\sigma^2_\theta$	-
C (Rate)	c-1 = 4	M11	$\sigma^2 + rab\sigma^2_{CE} + rabe_{\theta AB}$	M11/M12
C x Exp	(c-1)(e-1) = 4	M12	$\sigma^2 + rab\sigma^2_{CE}$	M12/M19
A x C	(a-1)(c-1) = 4	M13	$\sigma^2 + rb\sigma^2_{ACE} + rbe_{\theta AC}$	M13/M14
A x C x Exp	(a-1)(c-1)(e-1) = 4	M14	$\sigma^2 + rb\sigma^2_{ACE}$	M14/M19
B x C	(b-1)(c-1) = 12	M15	$\sigma^2 + ra\sigma^2_{BCE} + rae_{\theta BC}$	M15/M16
B x C x Exp	(b-1)(c-1)(e-1) = 12	M16	$\sigma^2 + ra\sigma^2_{BCE}$	M16/M19
A x B x C	(a-1)(b-1)(c-1) = 12	M17	$\sigma^2 + r\sigma^2_{ABCE} + re_{\theta ABC}$	M17/M18
A x B x C x Exp	(a-1)(b-1)(c-1)(e-1) = 12	M18	$\sigma^2 + r\sigma^2_{ABCE}$	M18/M19
Pooled error C	abe(r-1)(c-1) = 128	M19	σ^2	-
Total	rabce-1 = 239			

Table A2. Combined analyses of variance for a randomized complete block design with a split-split plot arrangement where drainage, nitrogen fertilizer practices, and nitrogen rates are fixed effects and replications are random effects.

Source of variation	2009 Fargo df	2010 Fargo df	Mean Square		F-test
			Observed	Expected	
Rep	(r-1) = 3	(r-1) = 2	M1	$\sigma^2 + c\sigma^2_\theta + bc\sigma^2_\gamma + abcr\sigma^2_R$	-
A (drainage)	(a-1) = 1	(a-1) = 1	M2	$\sigma^2 + c\sigma^2_\theta + bc\sigma^2_\gamma + r\sigma^2_{ABC} + rb\sigma^2_{AC} + rc\sigma^2_{AB} + rbc\sigma^2_A$	M2/M3
Error (a) = RepxA	(r-1)(a-1) = 3	(r-1)(a-1) = 2	M3	$\sigma^2 + c\sigma^2_\theta + bc\sigma^2_\gamma$	-
B (Additive)	(b-1) = 3	(b-1) = 3	M4	$\sigma^2 + c\sigma^2_\theta + r\sigma^2_{ABC} + ra\sigma^2_{BC} + rc\sigma^2_{AB} + rac\sigma^2_B$	M4/M6
A x B	(a-1)(b-1) = 3	(a-1)(b-1) = 3	M5	$\sigma^2 + c\sigma^2_\theta + r\sigma^2_{ABC} + rc\sigma^2_{AB}$	M5/M6
Error (b) = RepxB(A)	a(r-1)(b-1) = 18	a(r-1)(b-1) = 12	M6	$\sigma^2 + c\sigma^2_\theta$	-
C (Rate)	c-1 = 4	c-1 = 4	M7	$\sigma^2 + r\sigma^2_{ABC} + ra\sigma^2_{BC} + rb\sigma^2_{AC} + rab\sigma^2_C$	M7/M11
A x C	(a-1)(c-1) = 4	(a-1)(c-1) = 4	M8	$\sigma^2 + r\sigma^2_{ABC} + rb\sigma^2_{AC}$	M8/M11
B x C	(b-1)(c-1) = 12	(b-1)(c-1) = 12	M9	$\sigma^2 + r\sigma^2_{ABC} + ra\sigma^2_{BC}$	M9/M11
A x B x C	(a-1)(b-1)(c-1) = 12	(a-1)(b-1)(c-1) = 12	M10	$\sigma^2 + r\sigma^2_{ABC}$	M10/M11
Error (c) = RepxC(AxB)	ab(r-1)(c-1) = 96	ab(r-1)(c-1) = 64	M11	σ^2	-
Total	rabc-1 = 159	rabc-1 = 119			

Table A3. Combined analyses of variance for a randomized complete block design with a split plot arrangement where nitrogen fertilizer practices and nitrogen rates are fixed effects and replications are random effects.

Source of variation	2010 Horace df	2010 Prosper df	2009 Prosper df	Mean Square		F-test
				Observed	Expected	
Rep	r-1 =3	r-1 =3	r-1 = 3	M1	$\sigma^2 + b\sigma^2\gamma + ab\sigma^2_R$	-
A (Additive)	a-1 = 3	a-1 = 3	a-1 = 3	M2	$\sigma^2 + b\sigma^2_\gamma + r\sigma^2_{AB} + rb\sigma^2_A$	M2/M3
Error (a) RepxA	(r-1)(a-1) = 9	(r-1)(a-1) = 9	(r-1)(a-1) = 9	M3	$\sigma^2 + b\sigma^2_\gamma$	-
B (Rate)	b-1 = 4	b-1 = 4	b-1 = 1	M4	$\sigma^2 + r\sigma^2_{AB} + ra\sigma^2_B$	M4/M6
A x B	(a-1)(b-1) = 12	(a-1)(b-1) = 12	(a-1)(b-1) = 3	M5	$\sigma^2 + r\sigma^2_{AB}$	M5/M6
Error (b) = RepxB(A)	a(b-1)(r-1) = 48	a(b-1)(r-1)= 48	a(b-1)(r-1) = 12	M6	σ^2	-
Total	rab-1 = 79	rab-1 = 79	rab-1 = 31			

Table A4. Combined analyses of variance for a randomized complete block design with a split plot arrangement. Nitrogen fertilizer practices and Nitrogen rates are fixed effects. Replication and experiments are random effects.

Source of variation	Combined df	Mean Square Observed	Mean Square Expected	F-test
Experiments	3	M1		-
Rep(Exp)	10	M2		-
A (Additive)	3	M3	$\sigma^2 + b\sigma^2_{\gamma} + rb\sigma^2_{AE} + rbe_{OA}$	M3/M4
A x Exp	9	M4	$\sigma^2 + b\sigma^2_{\gamma} + rb\sigma^2_{AE}$	M4/M5
Pooled Error (a)	30	M5	$\sigma^2 + b\sigma^2_{\gamma}$	-
B (Rate)	4	M6	$\sigma^2 + ra\sigma^2_{BE} + rae_{OB}$	M6/M7
B x Exp	12	M7	$\sigma^2 + ra\sigma^2_{BE}$	M7/M10
A x B	12	M8	$\sigma^2 + r\sigma^2_{ABE} + re_{OAB}$	M8/M9
AxBxExp	36	M9	σ^2	-
Pooled error (b)	160	M10		
Total	279			

Nitrate stalk N tests

Table A5. Stalk nitrate expected mean squares for a randomized complete block design with a split plot arrangement where drainage and rate are fixed effects and replications are random effects.

Source of variation	2009 Fargo df	2010 Fargo df	Mean Square Observed	Mean Square Expected	F-test
Rep	r-1 = 1	r-1 = 1	M1	$\sigma^2 + b\sigma^2\gamma + ab\sigma^2_R$	-
A (Drainage)	a-1 = 1	a-1 = 1	M2	$\sigma^2 + b\sigma^2_\gamma + r\sigma^2_{AB} + rb\sigma^2_A$	M2/M3
Error (a) RepxA	(r-1)(a-1) = 1	(r-1)(a-1) = 1	M3	$\sigma^2 + b\sigma^2_\gamma$	-
B (Rate)	b-1 = 4	b-1 = 4	M4	$\sigma^2 + r\sigma^2_{AB} + ra\sigma^2_B$	M4/M6
A x B	(a-1)(b-1) = 4	(a-1)(b-1) = 4	M5	$\sigma^2 + r\sigma^2_{AB}$	M5/M6
Error (b) = RepxB(A)	a(b-1)(r-1) = 8	a(b-1)(r-1) = 8	M6	σ^2	-
Total	rab-1 = 19	rab-1 = 19			

Table A6. Stalk nitrate expected mean squares for a randomized complete block design with a split plot arrangement where drainage and treatments are fixed effects and replications are random effects.

Source of variation	2009 Fargo df	2010 Fargo df	Mean Square Observed	Mean Square Expected	F-test
Rep	r-1 = 1	r-1 = 1	M1	$\sigma^2 + b\sigma^2\gamma + ab\sigma^2_R$	-
A (Drainage)	a-1 = 1	a-1 = 1	M2	$\sigma^2 + b\sigma^2_\gamma + r\sigma^2_{AB} + rb\sigma^2_A$	M2/M3
Error (a) RepxA	(r-1)(a-1) = 1	(r-1)(a-1) = 1	M3	$\sigma^2 + b\sigma^2_\gamma$	-
B (Additive)	b-1 = 3	b-1 = 3	M4	$\sigma^2 + r\sigma^2_{AB} + ra\sigma^2_B$	M4/M6
A x B	(a-1)(b-1) = 3	(a-1)(b-1) = 3	M5	$\sigma^2 + r\sigma^2_{AB}$	M5/M6
Error (b) = RepxB(A)	a(b-1)(r-1) = 6	a(b-1)(r-1) =6	M6	σ^2	-
Total	rab-1 = 15	rab-1 = 15			

Table A7. Stalk nitrate expected mean square for a randomized complete block design where treatment is fixed effects and replications are random effects.

Source of variation	2009 Fargo df	Mean Square		F-test
		Observed	Expected	
Rep	r-1 =1	M1	$\sigma^2 + \sigma^2_R$	-
A (Rate)	a-1 = 4	M2	$\sigma^2 + \sigma^2_A$	M2/M3
Error (a) RepxA	(r-1)(a-1) = 4	M3	σ^2	-
Total	rab-1 = 9			

Soil Tests

Table A8. Soil nitrate expected mean squares measured in 2010 at the Fargo location for a randomized complete block design with a split plot arrangement where treatments and rate are fixed effects and replications are random effects.

Source of variation	df	Mean Square		F-test
		Observed	Expected	
Rep	r-1 = 1	M1	$\sigma^2 + b\sigma^2\gamma + ab\sigma^2_R$	-
A (Additive)	a-1 = 1	M2	$\sigma^2 + b\sigma^2_\gamma + r\sigma^2_{AB} + rb\sigma^2_A$	M2/M3
Error (a) RepxA	(r-1)(a-1) = 1	M3	$\sigma^2 + b\sigma^2_\gamma$	-
B (Rate)	b-1 = 3	M4	$\sigma^2 + r\sigma^2_{AB} + ra\sigma^2_B$	M4/M6
A x B	(a-1)(b-1) = 3	M5	$\sigma^2 + r\sigma^2_{AB}$	M5/M6
Error (b) = RepxB(A)	a(b-1)(r-1) = 6	M6	σ^2	-
Total	rab-1 = 15			

Table A9. Soil nitrate expected mean squares measured in 2010 at the Fargo location for a randomized complete block design with a split plot arrangement where treatments and rate are fixed effects and replications are random effects.

Source of variation	Fargo df	Mean Square		F-test
		Observed	Expected	
Rep	(r-1) = 1	M1	$\sigma^2 + c\sigma^2_\theta + bc\sigma^2_\gamma + abcr\sigma^2_R$	-
A (drainage)	(a-1) = 1	M2	$\sigma^2 + c\sigma^2_\theta + bc\sigma^2_\gamma + r\sigma^2_{ABC} + rb\sigma^2_{AC} + rc\sigma^2_{AB} + rbc\sigma^2_A$	M2/M3
Error (a) = RepxA	(r-1)(a-1) = 1	M3	$\sigma^2 + c\sigma^2_\theta + bc\sigma^2_\gamma$	-
B (Additive)	(b-1) = 3	M4	$\sigma^2 + c\sigma^2_\theta + r\sigma^2_{ABC} + ra\sigma^2_{BC} + rc\sigma^2_{AB} + rac\sigma^2_B$	M4/M6
A x B	(a-1)(b-1) = 3	M5	$\sigma^2 + c\sigma^2_\theta + r\sigma^2_{ABC} + rc\sigma^2_{AB}$	M5/M6
Error (b) = RepxB(A)	a(r-1)(b-1) = 6	M6	$\sigma^2 + c\sigma^2_\theta$	-
C (Rate)	c-1 = 1	M7	$\sigma^2 + r\sigma^2_{ABC} + ra\sigma^2_{BC} + rb\sigma^2_{AC} + rab\sigma^2_C$	M7/M11
A x C	(a-1)(c-1) = 1	M8	$\sigma^2 + r\sigma^2_{ABC} + rb\sigma^2_{AC}$	M8/M11
B x C	(b-1)(c-1) = 3	M9	$\sigma^2 + r\sigma^2_{ABC} + ra\sigma^2_{BC}$	M9/M11
A x B x C	(a-1)(b-1)(c-1) = 3	M10	$\sigma^2 + r\sigma^2_{ABC}$	M10/M11
Error (c) = RepxC(AxB)	ab(r-1)(c-1) = 8	M11	σ^2	-
Total	rabc-1 = 31			

Greenseeker®

Table A10. Mean squares for soil tests measured in 2010 at the Fargo location.

Source of variation	Fargo df	Mean Square		F-test
		Observed	Expected	
Rep	(r-1) = 2	M1	$\sigma^2 + c\sigma^2_\theta + bc\sigma^2_\gamma + abcr\sigma^2_R$	-
A (drainage)	(a-1) = 1	M2	$\sigma^2 + c\sigma^2_\theta + bc\sigma^2_\gamma + r\sigma^2_{ABC} + rb\sigma^2_{AC} + rc\sigma^2_{AB} + rbc\sigma^2_A$	M2/M3
Error (a) = RepxA	(r-1)(a-1) = 2	M3	$\sigma^2 + c\sigma^2_\theta + bc\sigma^2_\gamma$	-
B (Additive)	(b-1) = 3	M4	$\sigma^2 + c\sigma^2_\theta + r\sigma^2_{ABC} + ra\sigma^2_{BC} + rc\sigma^2_{AB} + rac\sigma^2_B$	M4/M6
A x B	(a-1)(b-1) = 3	M5	$\sigma^2 + c\sigma^2_\theta + r\sigma^2_{ABC} + rc\sigma^2_{AB}$	M5/M6
Error (b) = RepxB(A)	a(r-1)(b-1) = 12	M6	$\sigma^2 + c\sigma^2_\theta$	-
C (Rate)	c-1 = 4	M7	$\sigma^2 + r\sigma^2_{ABC} + ra\sigma^2_{BC} + rb\sigma^2_{AC} + rab\sigma^2_C$	M7/M11
A x C	(a-1)(c-1) = 4	M8	$\sigma^2 + r\sigma^2_{ABC} + rb\sigma^2_{AC}$	M8/M11
B x C	(b-1)(c-1) = 12	M9	$\sigma^2 + r\sigma^2_{ABC} + ra\sigma^2_{BC}$	M9/M11
A x B x C	(a-1)(b-1)(c-1) = 12	M10	$\sigma^2 + r\sigma^2_{ABC}$	M10/M11
Error (c) = RepxC(AxB)	ab(r-1)(c-1) = 64	M11	σ^2	-
Total	rabc-1 = 31			

Day Log

Table A11. Important dates for the 2009 and 2010 growing seasons at Fargo, Prosper, and Horace, ND.

Location/Date	Action	Details	
Fargo 2009			
11 May	Soil sampling	Pre-plant	
11 May	Spread urea	No additive	For all rates
		Nitrapyrin	For all rates
		NBPT	For all rates
		Pop-up	For all rates
11 May	Applied nitrapyrin	4.67 L ha^{-1}	
11 May	Planted corn	81,500 seeds ha^{-1} with 76-cm row spacing	
11 May	Applied pop-up	28 kg ha^{-1}	
4 June	Re-planted corn	81,500 seeds ha^{-1} with 76-cm row spacing	
4 June	Applied pop-up	28 kg ha^{-1}	
15 June	Corn emergence		
25 June	Sprayed corn	Glyphosate at 540 g ae ha^{-1}	
13 July	Split application	56 kg N ha^{-1}	
24 July	Sprayed corn	Glyphosate at 540 g ae ha^{-1}	
17 November	Corn harvested	4.6 m from one inside row	
19 November	Stalk N testing	10 stalks from harvested row	
Prosper 2009			
29 May	Soil sampling	Pre-plant	
29 May	Spread urea	No additive	For all rates
		Nitrapyrin	For all rates
		NBPT	For all rates
		Pop-up	For all rates
29 May	Applied nitrapyrin	4.67 L ha^{-1}	
29 May	Planted corn	81,500 seeds ha^{-1} with 76-cm row spacing	

Table A11(continued)

29 May	Applied pop-up	28 kg ha^{-1}	
6 June	Corn emergence		
2 July	Split application	56 kg N ha^{-1}	
24 July	Sprayed corn	Glyphosate at 540 g ae ha^{-1}	
9 November	Corn harvested	4.6 m from one inside row	
Fargo 2010			
22 April	Soil sampling	Pre-plant	
22 April	Spread urea	No additive	For all rates
		Nitrapyrin	For all rates
		NBPT	For all rates
		Pop-up	For all rates
22 April	Applied nitrapyrin	4.67 L ha^{-1}	
22 April	Planted corn	81,500 seeds ha^{-1} with 76-cm row spacing	
	Applied pop-up	28 kg ha^{-1}	
21 May	Corn emergence		
27 May	Sprayed corn	Glyphosate at 540 g ae ha^{-1}	
22 June	Sprayed corn	Glyphosate at 540 g ae ha^{-1}	
24 June	Soil sampling	Rep 3 + 4 Pre-split	
24 June	Split application	56 kg N ha^{-1}	
8 July	Greenseeker®		
15 July	Greenseeker®		
16 July	Soil sampling	Rep 3 Post-split	
19 July	Soil sampling	Rep 4 Post-split	
17 August	Corn heights	Two plants from inside rows	
8 October	Corn harvest	3.05 m from two inside rows	
12 October	Soil sampling	Rep 3 End of season	
13 October	Soil sampling	Rep 4 End of season	
18 October	Stalk N testing	10 stalks from harvested rows	

Table A11(continued)

Prosper 2010			
21 April	Soil sampling	Pre-plant	
21 April	Spread urea	No additive	For all rates
		Nitrapyrin	For all rates
		NBPT	For all rates
		Pop-up	For all rates
22 April	Applied nitrapyrin	4.67 L ha^{-1}	
22 April	Planted corn	81,500 seeds ha^{-1} with 76-cm row spacing	
22 April	Applied pop-up	28 kg ha^{-1}	
21 May	Corn emergence		
22 June	Sprayed corn	Glyphosate at 540 g ae ha^{-1}	
25 June	Soil sampling	Pre-split	
25 June	Split application	56 kg N ha^{-1}	
8 July	Greenseeker®		
15 July	Greenseeker®		
19 July	Soil sampling	Post-split	
19 August	Corn heights	Two plants from inside rows	
6 October	Corn harvest	3.05 m from two inside rows	
15 October	Stalk N testing	10 stalks from harvested rows	
Horace 2010			
26 May	Soil sampling	Pre-plant	
26 May	Spread urea	No additive	For all rates
		Nitrapyrin	For all rates
		NBPT	For all rates
		Pop-up	For all rates
26 May	Applied nitrapyrin	4.67 L ha^{-1}	
26 May	Planted corn	81,500 seeds ha^{-1} with 76-cm row spacing	
26 May	Applied pop-up	28 kg ha^{-1}	
6 June	Corn emergence		

Table A11(continued)

16 July	Soil sampling	Pre-split blocks 2+3
16 July	Split application	56 kg N ha^{-1}
20 July	Sprayed corn	Glyphosate at 540 g ae ha^{-1}
3 August	Soil sampling	Post-split blocks 2+3
21 September	Corn heights	Two plants from inside rows
19 October	Corn harvest	3.05 m from two inside rows
19 October	Stalk N testing	10 stalks from harvested rows
19 October	Soil sampling	Post-harvest blocks 2+3

Mean Square Tables

Nitrate stalk N tests

Table A12. Mean squares for the analysis of variance for nitrogen stalk nitrate tests between additives in 2009 and 2010 at Fargo, ND.

Source of variation	df	2009		2010	
		N	N-NO_3	N	N-NO_3
Rep	1	0.7	357891	1.8	3577375
A (Drainage)	1	1.2	619227	9.0†	6100505
Error (a)	1	3.5	3373687	0.7	141899
B (Additive)	3	0.2	135864	0.3	234781
A x B	3	1.4	244620	1.3	2317839
Error (b)	6	1.2	496599	1.1	1335850
CV,%		16.6	32	16.0	33

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

Table A13. Mean squares for the analysis of variance for nitrogen stalk nitrate tests between rates in 2009 and 2010 at Fargo, ND.

Source of variation	df	2009		2010	
		N	N-NO_3	N	N-NO_3
Rep	1	3.44†	16673	1.1	1557004
A (Drainage)	1	0.26	726422	2.7	3554771
Error (a)	1	0.01	2121232	0.6	2564103
B (Rate)	4	4.40*	4524729**	8.9**	7411741**
A x B	4	1.97	911389	0.2	562362
Error (b)	8	0.81	337871	1.2	894886
CV,%		15.0	32	20.7	39

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

Table A14. Mean squares for the analysis of variance for nitrogen stalk nitrate tests between treatments in 2010 at Prosper, ND and Horace, ND.

Source of variation	df	Horace		Prosper	
		N	N-NO_3	N	N-NO_3
Rep	1	0.5†	5306	0.5	1071772
A (Additive)	3	0.2	12109	3.2	3061903
Error (a)	3	0.1	36425	1.8	835013
CV,%		11.2	23	17.8	22

*,** Significant at ($P\leq0.05$), and ($P\leq0.01$), respectively.

† Significant at ($P\leq0.10$).

Table A15. Mean squares for the analysis of variance for nitrogen stalk nitrate tests between rates in 2010 at Prosper, ND and Horace, ND.

Source of variation	df	Horace		Prosper	
		N	N-NO_3	N	N-NO_3
Rep	1	0.2	5615	11.2**	4654964*
A (Rate)	4	0.1	44806	4.4*	1824104†
Error (a)	4	0.2	43271	0.5	350136
CV,%		17.3	25	12.3	24

*,** Significant at ($P\leq0.05$), and ($P\leq0.01$), respectively.

† Significant at ($P\leq0.10$).