Evaluation of late season application of foliar nitrogen's impact of grain yield and milling qualities.

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A result from the 2010 hard red winter wheat harvest was an increase of discussions on protein values across the southern great plains. The crop garnered relatively low protein values for several reasons many of which were directly related to the weather patterns and environmental conditions. The question that many in industry and production were asking was whether protein levels could be economically increased. It has been documented that late season nitrogen (N) applications, pre and post anthesis, can indeed increase protein, a practice that is common in the production of spring wheat. Woolfolk et al., (2002) reported that when UAN and ammonium sulfate was applied to winter wheat pre and post flowering grain N concentration was increased. Agricultural producers are regularly presented with a multitude of products that boast improved yields, protein, or efficiency. One such product is the low-salt, controlled release, specialty N fertilizer. Many of these are sold to be applied at flag leaf with a fungicide in efforts to increase yield but are used elsewhere to increase grain protein. The work performed by Woolfolk did not evaluate N applications prior to pre-anthesis nor did the experiment evaluate N rates as low as what is being recommended. The Woolfolk paper showed increased protein values using traditional fertilizer sources with minimal to no tissue damage; however, treatments were applied in the cool of the morning to ensure minimum burn. This is not practical on a large scale, and reduced leaf burn is one of the selling points of the low-salt products. In addition there has been a great deal of discussion as of recent about the functionality of the additional N present in the grain as a result of post-anthesis applications.

This trial evaluated the use of foliar N applications on winter wheat at two stages, flag leaf and post-flowering using both a traditional and specialty source. Nitrogen rate will also be evaluated to determine impact of N rate on yield and quality. This is important as Woolfolk et al., (2002) reported linear response to N rate up to 34 kg N ha^{-1} and most low salt N fertilizers are not being recommended at rates more than 18 L ha^{-1} or 7.6 kg N ha^{-1}. Liquid UAN will be used as the traditional N source, a caveat however that is both N sources were applied mixed with water to achieve a flow rate of 93.8 L/ha. This was done in an effort to reduce the potential for tissue damage when the N is applied mid-day. The low-salt product used will be a controlled release liquid fertilizer produced for agricultural use that only contains N and is readily available in Oklahoma, in this case, CoRoN 25-0-0.

The trials were established at two locations Lahoma and LCB, and consisted of 14 treatments arranged in a RCBD, Table 1 shows treatment structure. Duster and Okfield were the varieties planted at Lahoma and LCB respectively. At harvest a sub-sample of grain was collected from each plot and sent to the USDA ARS Baking and Milling Lab in Manhattan KS for evaluation of treatment impact on quality.

Treatment	Rate (kg N ha)	Source	Timing
1	Check	Unfertilized Check	
2	Rec Fert $		
3	6.7	UAN	Flag Leaf
4	13.4	UAN	Flag Leaf
5	26.8	UAN	Flag Leaf
6	6.7	CoRoN	Flag Leaf
7	13.4	CoRoN	Flag Leaf
8	26.8	CoRoN	Flag Leaf
9	6.7	UAN	Post Anthesis
10	13.4	UAN	Post Anthesis
11	26.8	UAN	Post Anthesis
12	6.7	CoRoN	Post Anthesis
13	13.4	CoRoN	Post Anthesis
14	26.8	CoRoN	Post Anthesis

Table 1. Treatment Structure for the Impact of Foliar N on Baking and Milling Qualities of Hard Red Winter Wheat. $ Standard Fertility is based on yield goal recommendations and soil test results. The yield goal N rates at Lahoma and LCB waer 112 kg N ha^{-1} and 84 kg N ha^{-1} respectively.

The central great plains experienced a once in a life time weather pattern during the 2010-2011 cropping season. Even though the trial locations witnessed extreme heat and extended periods without rain yields obtained were better than regional averages. Yield levels and quality results differed across locations with just a single year of data no conclusions can be drawn however patterns did develop. Due to site differences each will be discussed independently.

Lahoma

The Lahoma location had been fallowed the previous season which helps explains the extremely high yields compared to the rest of the region. At this location treatment mean yields ranged from 4000-5400 kg ha^{-1}. However there was a great deal of variation across treatments so no significant difference was seen in yields. The coefficient of variation of the yields was 18. No main effects or interactions were significant. Analysis of protein showed no significant difference in protein values across treatments. All treatments receiving foliar N has protein values greater than both the check and standard fertility treatments. The treatments receiving 13.4 kg N ha^{-1} post-anthesis achieved the highest protein values. There was a significant rate*time interaction at p of .095. Yield and Protein results shown in Figure 1.

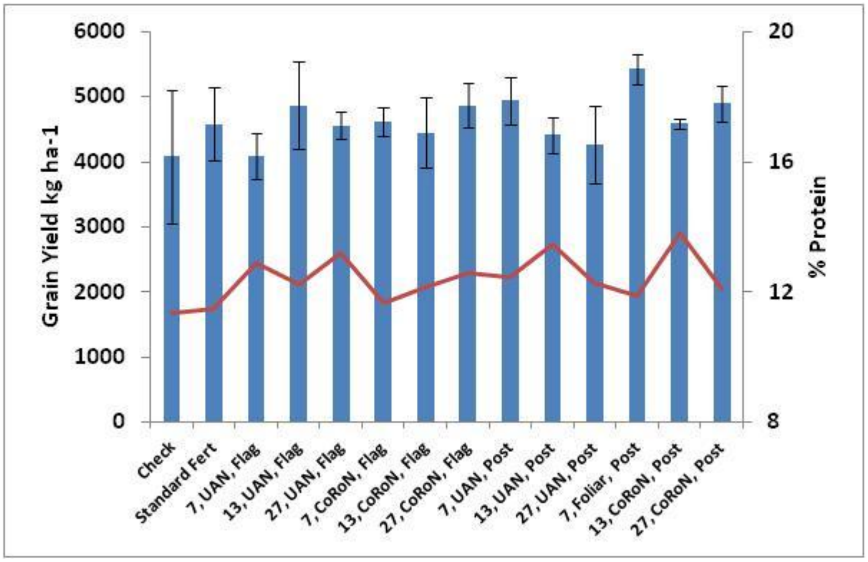

Figure 1. Grain yield (kg ha^{-1}) and protein percentage results from the Lahoma, OK location. Error bars represent standard error of each treatment. Treatment titles shown as nitrogen rate in kg N ha^{-1}, nitrogen source, and application timing.

Mixing tolerance is a ranked value with a score from 0-6, values above 3 are preferred. The results from the Lahoma wheat samples showed significant difference across treatments. Three treatments fell below the industry preference, 27 kg N ha^{-1} CoRoN post-anthesis, 13 kg N ha^{-1} CoRoN flag leaf, and the check. The treatments receiving 13.4 kg N ha^{-1} post-anthesis and the 7 kg N ha^{-1} UAN at flag leaf had the highest mixing tolerance scores, Figure 2. Source was significant at .0013, with UAN at 3.67 and CoRoN at 2.94. Also rate*time interaction was significant at .0091.

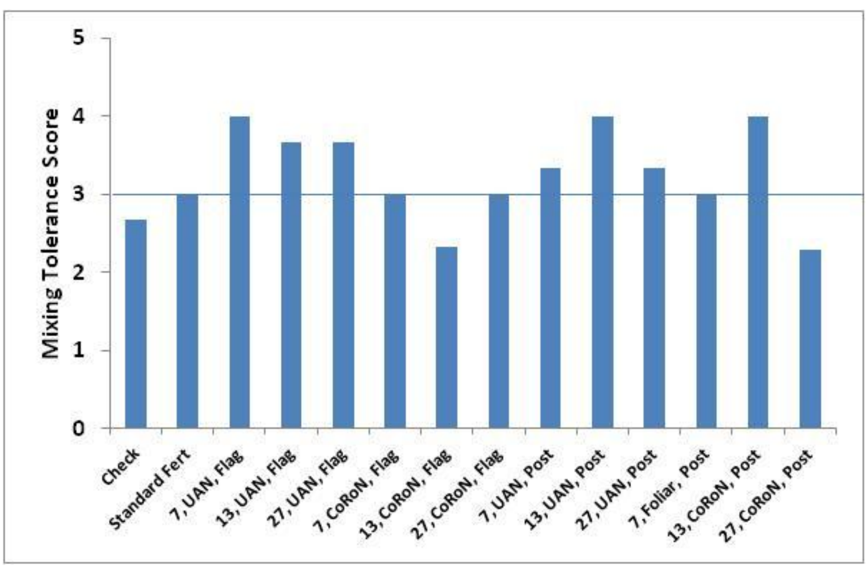

Figure 2. Mixing Tolerance Score results from the grain collected at the Lahoma Ok, location. Hard winter wheat quality targets committee recommends a target value of 3 or greater. The blue horizontal line shows the recommended level. Treatment titles shown as nitrogen rate in kg N ha^{-1}, nitrogen source, and application timing.

The Hard Winter Wheat Quality Targets Committee gives a recommended target Loaf Volume of 850 cc or greater. At the Lahoma location only one treatment yielded a loaf volume sufficient to meet the committee's recommendation, 13 kg N ha^{-1} CoRoN applied post anthesis, Figure 3. There was no significant main effect or interactions with the Loaf Volume data from Lahoma.

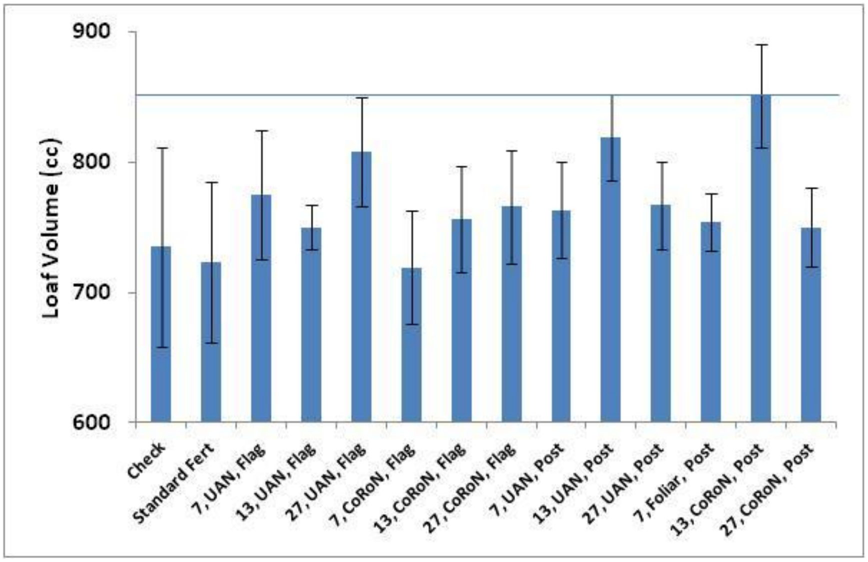

Figure 3. Loaf Volume, measured in cc, results from the grain collected at the Lahoma Ok, location. Error bars represent standard error of each treatment. Hard winter wheat quality targets committee recommends a target value of 850cc or greater. The blue horizontal line shows the recommended level. Treatment titles shown as nitrogen rate in kg N ha^{-1}, nitrogen source, and application timing.

Lake Carl Blackwell (LCB)

The LCB location is located near Stillwater and sets on a lower class of soils that will typically have lower yields than the Lahoma site. The 2011 harvest resulted in a range of yields from 1700 to 2200 kg ha^{-1}. There was no significant difference in yields across treatments however the check and standard fertility treatments did result in the lowest yields Figure 4. The protein data from LCB showed results of which could be considered expected. Standard fertility significantly increased protein above the check while all foliar N treatments increased protein above the level of the standard practice. Five of the six treatments with the highest protein levels were the foliar applications made at post anthesis. The treatment of 27 kg N ha^{-1} UAN post-anthesis resulted in a 1% increase in protein over the standard fertility treatment. Time as a main effect was significant at a .101.

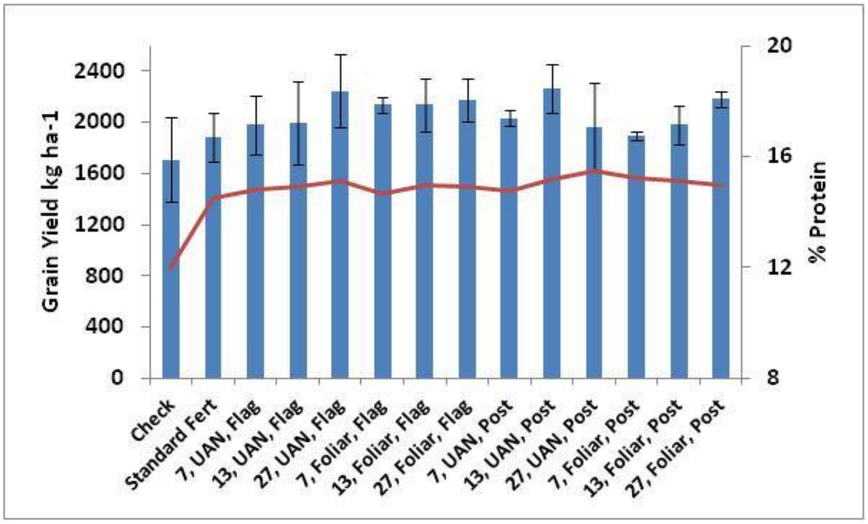

Figure 4. Grain yield and protein percentage results from the LCB, OK location. Error bars represent standard error of each treatment. Treatment titles shown as nitrogen rate in kg N ha^{-1}, nitrogen source, and application timing.

While protein levels at LCB where quite good, 14.5 to 15.5 %, all of the treatments yielded a below par mixing tolerance with scores ranging from 1.3 to 2.0. Neither significant differences nor trends were found across the mixing tolerance data.

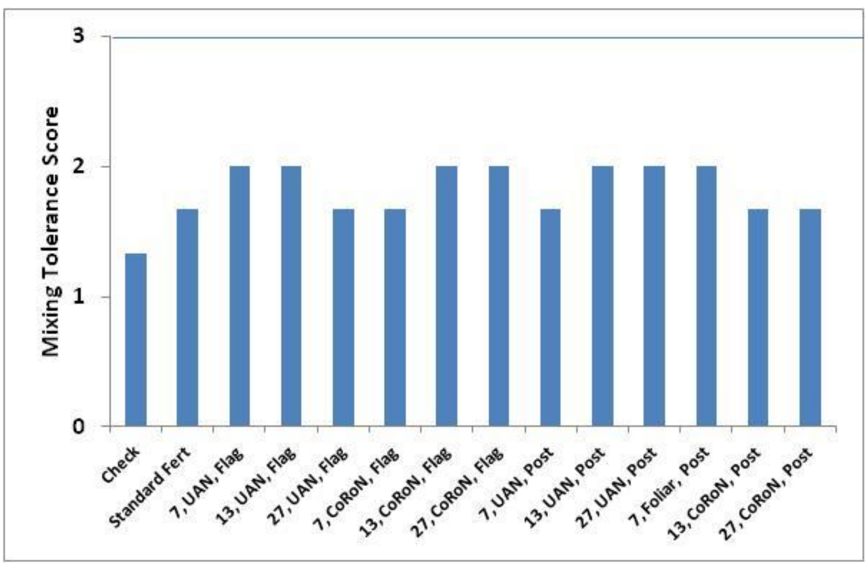

Figure 5. Mixing Tolerance Score results from the grain collected at the Lahoma Ok, location. Hard winter wheat quality targets committee recommends a target value of 3 for greater. The blue horizontal line shows the recommended level. Treatment titles shown as nitrogen rate in kg N ha^{-1}, nitrogen source, and application timing.

As with the protein data 5 of the 6 treatments with the greatest loaf volumes included applied post anthesis. All treatments receiving fertilizer increased the volume above the recommended level of 850 cc. Additionally all treatments receiving foliar N have loaf volumes greater than the standard fertility. While there was no significant difference between the standard fertility and 27 kg N ha^{-1} UAN post-anthesis, the late application did increase volume by 55 cc.

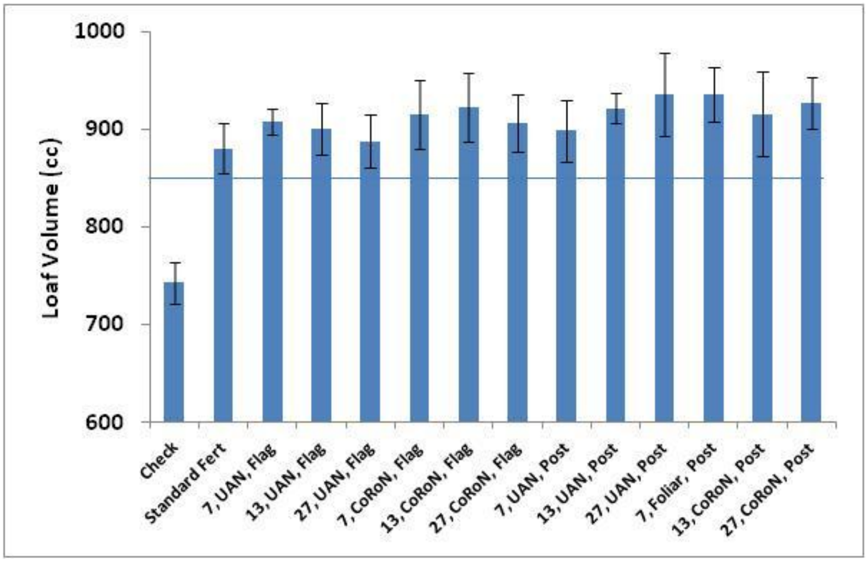

Figure 6. Loaf Volume, measured in cc, results from the grain collected at the Lahoma Ok, location. Hard winter wheat quality targets committee recommends a target value of 850cc or greater. The blue horizontal line shows the recommended level. Error bars represent standard error of each treatment. Treatment titles shown as nitrogen rate in kg N ha^{-1}, nitrogen source, and application timing.

Discussion

A note on procedures is that at both locations all foliar treatments were applied midday. On the day of application daily average temperatures ranged from 60 to 75° F with temperature at application being between 75 to 85° F. Even with the high temperatures no leaf burn was observed from any of the nitrogen applications.

Across both locations no evident trends in grain yields developed but trends where found in the grain protein results. Lack of response in yield due to late season applications of N is not unexpected, especially considering the environment. Extreme heat and drought during the spring and summer drew soil moisture from depth, likely contributing a great deal of additional NO_3 during periods of stem elongation through grain fill. The lack of consistent grain protein results from the Lahoma location tends to support this hypothesis. While there was significant difference in mixing tolerance scores across treatments at Lahoma no conclusions can be drawn on which timing rate or source may lead to an improved score above the standard fertility treatment. Loaf volume results are very positive and indicate a potential increase volume with foliar applied N. While results were not consistent across sites the data does suggest that nitrogen applied post anthesis may lead to a higher likelihood of volume increase.

As is often the case in field experiments no final conclusions can be drawn from a single years worth of data. The extremes of the past cropping season may have lent to even further complicate the results. The 2011-2012 winter wheat crop is in the ground with a good stand at both locations. The 2012 results are highly anticipated as an added year of data will likely lead to a better understanding.

FLUID FERTILIZERS FOR SOD PRODUCTION

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__Project Rationale and Description:__

As nitrogen prices continue to climb sod producers are searching for alternative N sources to the commonly applied granular sources ammonium nitrate (AN), urea (U) and ammonium sulfate (AS). In sod production, the application of N fertilizers is a balancing act between adding sufficient N to push the crop towards timely harvest, and then sustaining regrowth until the next harvest. Unlike a grain crop, which is harvested in a certain time window, with the grain then stored off-site, sod is 'stored' in the field until the market creates a need to harvest. Thus, N fertilizer is often applied for both agronomic and market needs.

Hybrid bermudagrass is a warm season grass that is widely used in the south, west and some areas of the Midwest as a lawn, sports and golf course turf. Because most of the the bermudagrass cultivars are interspecific hybrids (*Cynodon dactylon x C. transvaalensis*) they are sterile, and can only be propagated via sprigs or sod. Hybrid bermudagrass represents a significant portion of the southern sod market, and is grown on the greatest number of sod-production acres in the southeast. The only exception is Florida, which has more acres of Saint Augustinegrass. Hybrid bermudagrass is also prized as a sod crop because it grows quickly, and sod can be harvested more frequently than comparable fields of zoysiagrass.

A typical N fertilization schedule for bermudagrass re-establishment is to apply from 4 to 6 lbs N/1,000 sq. ft (175 - 260 lb N/A) during the months when the grass is actively growing. Consultation with local sod producers revealed the following typical N fertilization plan for their 2008 sod crops: 1 lb N/1,000 sq. ft (44 lb N/A) in April and May, with a late May/early June harvest to follow, 1 lb N in June, after harvest, and 1 lb N in August. That is a total of 4 lb N/1,000 sq. feet for the growing year, with a harvest in the following spring, after winter dormancy. Others plan to push the sod with additional summer N, allowing the crop to be harvested in the fall.

Thus, fertilization issues in sod production include both N rate and N source questions, but the question of N timing also needs to be answered. This is especially true in warm-season grass production, as fall dormancy and spring greenup affect harvest time and N fertilization. The objective of this research proposal was to examine various N fertilizer programs (N source, rate and timing) to determine the best program for production and maintenance of hybrid bermudagrass destined for harvest as a sod crop.

Experiment Design:

The experiment consisted of 4 total N rates and 3 N sources, with all N applied at the rate of 1 lb N/1,000 sq. ft per monthly application. Nitrogen rates were 3, 4, 5, or 6 lb N total/1,000 sq. ft per year (130, 175, 218, or 260 lb N/acre/year), with the N applied as either granular ammonium sulfate, fluid urea-ammonium nitrate (UAN) or fluid slow-release urea-trizone. Specifically, the N Sources were: 1) UAN (32-0-0), 2) ammonium sulfate (21-0-0), 3) 29-2-3 (20.88% urea-triazone and 8.12% urea). The selected N rates bracketed those used by most southern sod growers for bemudagrass production. N applied was 4 split applications of 0.75, 1.0, 1.25 or 1.5 lb N 1,000 ft^{-2} $month^{-1}$. For 2009 the fertilizers were applied in June, July, August, Sept, and in 2010 the fertilizers were applied in April, May, June and July.

The study consisted of 48 plots (4 N rates x 3 N sources x 4 replications, plus a zero N control), each measuring 6 x 8 feet. Ammonium sulfate was applied using a Gandy fertilizer spreader, while UAN and urea-trizone were sprayed applied using a backpack CO_2 sprayer as liquids in a total carrier volume of 4 gal 1,000 ft^{-2}.

The experiment was conducted on an existing stand of Tifway hybrid bermudagrass located at the Auburn University Turfgrass Research Unit (TGRU). In both years the turf was first harvested for sod, simulating typical harvesting procedures. The fertilizer treatments and all data collection were then collected from this tilled area, as the sod was allowed to regrow for the next harvest.

Each week the following data was collected from each plot: 1) phytoxicity using a 1-9 relative scale (1 = none, 9 = complete damage), 24 hr after spraying, with repeated ratings until damage was gone, and, 2) percent establishment as determined via a line-transect method (a string with 50 marks was stretched across each plot in 2 places, and the number of times plant tissue hits a mark was counted towards a measurement of percent establishment). Additional data collection included determinations of shoot density and fall soil analysis (0-3 inch sampling depth) for 2M KCl extractable soil nitrate and ammonium.

One-half of each plot area was used for destructive data collection as the plots matured. Three sections of sod (18 x 24 inches) were randomly collected from the destructive half of each plot, cut using the sod cutter. These sections were used to determine sod strength, using a sod strength machine, which determined the tensile strength (measured as a resistance against a measured pull) of harvested sod.

Results

In both years of the study (2009 and 2010) there was never any evidence of phytotoxicity (turf burn) due to the application of any N sources. Additionally, the interaction of N rate and N source was rarely significant for any of the measured variables. Thus, results discussed in this report will focus on the separate main effects of N rate and N source.

N Source

In 2009 sod which had received 29-2-3 (fluid trizone) as the N source had greater sod strength than that which had been fertilized with UAN or ammonium sulfate. Any fertilized sod was stronger than that which was not fertilized. In 2010 there was no difference in sod strength due to N source, and all fertilized sod was stronger than unfertilized (Table 1, below).

Table 1. Sod strength of harvested hybrid bermudgrass sod as measured by tensile pull, 2009 and 2010, Auburn, AL.

N Source	Harvest Month/Year		
	Foot pounds of force at which the sod tears		
	Oct 19 2009	19 April 2010	
Control	25.3 b	41.9 c	
UAN	49.6 a	73.0 b	
29-2-3	65.4 a	87.5 a	
NH4SO4	47.1 a	74.4 b	
	14 July 2010	17 Aug 2010	18 Nov 2010
Control	0 b	17.6 b	29.6 b
UAN	21.7 a	37.5 a	49.5 a
29-2-3	22.9 a	37.8 a	51.9 a
NH4SO4	23.2 a	36.6 a	51.7 a

Shoot density (2009 data only at this point, 2010 data to be collected this spring) was also unaffected by N source.

N Rate

In both years establishment was maximized at an N rate of between 5.6 and 6.0 lb N/1,000 square feet/year, indicating that the highest N rate of 6 lbs N was often needed to effectively and quickly grow a sod crop. In both 2009 and 2010 sod strength was maximized at an N rate of 4.6 lb N/M/season.

Conclusion – To Date

Use of liquid N sources such as UAN did not negatively affect sod establishment or strength. These sources offer an alternative N source for sod growers, and may be especially useful in fertigation.

Nitrogen Source Effects on Nitrous Oxide Emissions from Irrigated Strip-Till and No-Till Corn Production Systems

Principal Investigator(s): Ardell Halvorson (USDA-ARS)

Problem: Limited information is available on the effects of nitrogen fertilizer sources on greenhouse gas emissions from irrigated cropping systems. Controlled release and stabilized N fertilizers show potential to enhance N fertilizer use efficiency in agricultural systems. Little information is available on how these controlled release and stabilized N fertilizers might affect nitrous oxide emissions from irrigated cropping systems.

Project Objective: Evaluate the effects of controlled release and stabilized N sources on nitrous oxide emissions in irrigated corn systems compared with the commonly used urea and urea-ammonium nitrate fertilizer sources.

Approach: Nitrogen source studies are being conducted near Fort Collins, CO to collect greenhouse gas emissions data from irrigated corn, cropping systems. Several N fertilizer sources [controlled release N sources include a polymer-coated urea (ESN); stabilized urea sources, SuperU or UAN treated with AgrotainPlus; and UAN and urea as conventional sources] will be applied to irrigated, strip-tilled and no-till cropping systems in 2010 with some modification in 2011 depending on 2010 results. Nitrogen rate will be 180 lb N/a as a near optimal N rate for grain yield. The N sources will be hand applied to normal farming practices. Nitrous oxide emissions from each N source treatment and a check (zero fertilizer N applied) treatment will be monitored 1 to 3 times each week during the growing season. Methods used for greenhouse gas measurements will follow those established for the ARS GRACEnet program. Crop yield data, needed soil water and temperature data, and other necessary data needed to interpret the greenhouse gas emissions results will be collected. A scientifically sound experimental design with a minimum of 3 replications will be used.

Expected Results: Data collected will provide information needed to help develop crop and N management systems that can reduce greenhouse gas emissions and enhance environmental quality.

Data Collection:
Needed soil samples will be collected to describe soil chemical and physical characteristics needed for interpreting the greenhouse gas measurement results (such as NO_3-N, NH_4-N, and soil bulk density). Greenhouse gas measurements, which include N_2O as a minimum, will be made one to three times per week during the growing season from selected N treatments. Plant samples will be collected as needed for estimation of crop yield and/or biomass production. USDA-ARS will process the soil and plant materials for N and C content, analyze greenhouse gas data, and prepare scientific publications/reports.

Keywords: Greenhouse gases, nitrous oxide, GRACEnet, nitrogen sources, irrigated systems, corn.

Results from the 2010 and 2011 N Source Studies have been summarized in the publications listed below:

Halvorson, A.D., S.J. Del Grosso, and C.P. Jantalia. 2011. Nitrous oxide emissions from several nitrogen sources applied to a strip-tilled corn field. *In* Proceeding of 2011 Fluid Forum, Feb. 20-23, Scottsdale, AZ. Fluid Fertilizer Foundation, Manhattan, KS. 28:21-27. On-line publication at Fluid Fertilizer Foundation website.

Halvorson, A.D. 2011. Crop management effects on nitrous oxide emissions from irrigated systems. *In* Proc. 2011 Western Nutrient Management Conference, March 3-4, 2011, Reno, NV. International Plant Nutrition Institute, Brookings, SD. 9:16-21.

Halvorson, A.D., S.J. Del Grosso, and C.P. Jantalia. 2011. Nitrogen Source Effects on Soil Nitrous Oxide Emissions from Strip-Till Corn. J. Environ. Qual. 40:1775-1786.

Halvorson, A.D., and S.J. Del Grosso. 2012. Nitrogen source effects on nitrous oxide emissions from irrigated strip-till and no-till corn production systems. *In* Proceedings of 2012 Fluid Forum. Fluid Fertilizer Foundation, Feb 19-21, 2012, Scottsdale, AZ. On-line publication at Fluid Fertilizer Foundation website.

Halvorson, A.D., and S.J. Del Grosso. 2012. Nitrogen fertilizer source and placement effects on nitrous oxide emissions. p. 8-14. *In* A.J. Schlegel and H.D. Bond (Eds.), Great Plains Soil Fertility Conf. Proc. Vol. 14. Denver, CO. 6-7 March 2012, Kansas State University, Manhattan and International Plant Nutrition Institute, Brookings, SD.

Halvorson, A.D. and S.J. DelGrosso. 2012. Nitrogen source effects on soil nitrous oxide emissions from no-till corn. J. Environ. Qual. (in journal review)

This is the final report for this project. All funds received have been spent to support this work. Progress reports were submitted to Fluid Fertilizer Foundation in the form of Proceedings papers for the 2011 and 2012 Fluid Forums held in Scottsdale, AZ. Attached is a pdf copy of the referred journal article published in Journal of Environmental quality. Copies of the JEQ article that is in journal review will be provided when the article is published. If there are any questions, please contact Ardell Halvorson by email at ardell.halvorson@ars.usda.gov.

Nitrogen Source Effects on Soil Nitrous Oxide Emissions from Strip-Till Corn

Ardell D. Halvorson,* Stephen J. Del Grosso, and Claudia Pozzi Jantalia

Nitrogen (N) application to crops generally results in increased nitrous oxide (N_2O) emissions. Commercially available, enhanced-efficiency N fertilizers were evaluated for their potential to reduce N_2O emissions from a clay loam soil compared with conventionally used granular urea and urea-ammonium nitrate (UAN) fertilizers in an irrigated strip-till (ST) corn (*Zea mays* L.) production system. Enhanced-efficiency N fertilizers evaluated were a controlled-release, polymer-coated urea (ESN), stabilized urea, and UAN products containing nitrification and urease inhibitors (SuperU and UAN+AgrotainPlus), and UAN containing a slow-release N source (Nfusion). Each N source was surface-band applied (202 kg N ha^{-1}) at corn emergence and watered into the soil the next day. A subsurface-band ESN treatment was included. Nitrous oxide fluxes were measured during two growing seasons using static, vented chambers and a gas chromatograph analyzer. All N sources had significantly lower growing season N_2O emissions than granular urea, with UAN+AgrotainPlus and UAN+Nfusion having lower emissions than UAN. Similar trends were observed when expressing N_2O emissions on a grain yield and N uptake basis. Loss of N_2O–N per kilogram of N applied was <0.8% for all N sources. Corn grain yields were not different among N sources but greater than treatments with no N applied. Selection of N fertilizer source can be a mitigation practice for reducing N_2O emissions in strip-till, irrigated corn in semiarid areas.

Nitrous oxide is produced in soils mostly from nitrification and denitrification processes with agriculture contributing ~67% of the total U.S. N_2O emissions (USEPA, 2010). Nitrous oxide has a global warming potential (GWP) approximately 298 times greater than that of CO_2 (Solomon et al., 2007), thus the importance of developing methods to reduce N_2O emissions in agricultural systems. Nitrogen fertilization is essential for optimizing crop yields and economic returns in irrigated cropping systems in the U.S. Central Great Plains (Archer et al., 2008; Archer and Halvorson, 2010; Maddux and Halvorson, 2008). Nitrogen fertilizer application generally increases N_2O production from cropping systems (Bouwman et al., 2002; Hao et al., 2001; Dusenbury et al., 2008; Mosier et al., 2006, Halvorson et al., 2008, 2010a; Van Groenigen et al., 2010).

Data available for analyzing N_2O emission impacts on net GWP in irrigated crop production systems is limited (Hao et al., 2001; Mosier et al., 2006; Snyder et al., 2009; Archer and Halvorson, 2010). Snyder et al. (2009) presented an extensive review of greenhouse gas emissions (GHG) from cropping systems but found little information available on the effects of commercially available, controlled-release and stabilized-N sources on N_2O emissions. They suggest that more research on enhanced-efficiency N fertilizers is needed to thoroughly evaluate their agronomic impact and effects on N_2O losses. Olson-Rutz et al. (2009) define enhanced-efficiency fertilizers as “fertilizers that reduce loss to the environment and/or increase nutrient availability compared with conventional fertilizers.” Akiyama et al. (2010) reported N fertilizer containing a nitrification inhibitor reduced N_2O emissions 38% and polymer-coated fertilizer 35% compared with conventionally used N fertilizer. Fertilizers containing urease inhibitor were not effective in reducing N_2O emissions. Halvorson et al. (2010a, b) reported reductions in N_2O emissions from N fertilizers containing both urease and nitrification inhibitors, and with polymer-coated urea fertilizer compared with conventionally used granular urea. Jumadi et al. (2008) and Bronson et al. (1992) also reported reduced N_2O emissions with the use of a nitrification inhibitor added to urea.

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Abbreviations: ANOVA, analysis of variance; CC, continuous corn; CT, conventional-till; DOY, day of year; ESN, polymer-coated urea; ESNssb, ESN subsurface band; GHG, greenhouse gas; GWP, global warming potential; NT, no-till; ST, strip-till; SuperU, stabilized granular urea; UAN, urea-ammonium nitrate; UAN+AP, UAN with AgrotainPlus; UAN+Nf, UAN with Nfusion; WFPS, water-filled pore space.

Venterea et al. (2005, 2010) found N source influenced N_2O emissions from corn production systems in Minnesota with greatest N_2O emissions from anhydrous ammonia application, with significantly lower emissions from urea-ammonium nitrate (UAN) and urea. Hyatt et al. (2010) reported reduced N_2O emissions with a single preplant application of a polymer-coated urea to a potato (*Solanum tuberosum* L.) crop on a loamy sand soil compared with multiple smaller applications (five to six) of urea and ammonium nitrate during the growing season. Venterea et al. (2011b) found lower N_2O emissions from a stabilized urea N source (contained urease and nitrification inhibitors) applied to corn compared with polymer-coated urea but not less than conventional urea from a silt loam soil in southern Minnesota in both conventionally tilled and no-till production systems.

The N source comparison work of Halvorson et al. (2010a) on N_2O emissions involved different tillage and cropping systems, but it did not allow the direct comparison of N_2O emissions from urea, polymer-coated urea (ESN) (registered trademark product of Agrium Advanced Technologies, Loveland, CO), and SuperU (registered trademark product of Agrotain International, St. Louis, MO) under the same experimental conditions. Halvorson et al. (2010b) compared the effects of several enhanced-efficiency N fertilizers on soil N_2O emissions under an irrigated, no-till–(NT), continuous corn (CC) production system, with significant reductions (up to 53%) in N_2O emissions from some enhanced-efficiency N fertilizers when compared with urea. Halvorson et al. (2010a) reported differences in the effectiveness of ESN in reducing N_2O emissions from CT–CC and NT–CC production systems, with no differences in N_2O emissions between ESN and urea in CT–CC but significant reductions with ESN (34%) in the NT–CC compared with urea. Drury et al. (2006) reported that zone tillage or strip tillage and shallow (2-cm depth) N placement are potential management practices that may reduce N_2O emissions from fine-textured soils in cool, humid climates that are cropped to corn. Thus, tillage system can have an effect on N_2O emissions. Strip till has produced irrigated corn yields similar to moldboard plow tillage in the Central Great Plains near Fort Collins, CO, demonstrating its potential to replace moldboard plow tillage (unpublished data, A.D. Halvorson, USDA–ARS, 2008–2010).

The main objective of this study was to evaluate the effects of enhanced-efficiency fertilizer N sources (ESN, stabilized granular urea [SuperU], stabilized UAN [UAN + AgrotainPlus], and slow-release UAN [UAN + Nfusion]) on growing season N_2O emissions compared with those from conventionally used granular urea and liquid UAN applications within an irrigated, strip-till (ST), CC production system. In addition, CO_2 and CH_4 emissions were monitored and reported here for future use but not discussed in detail. A second objective was to evaluate the possible agronomic benefits of the enhanced-efficiency N fertilizers on grain yield and N uptake, and relate N_2O emissions from each N source on a grain yield and N uptake basis.

Materials and Methods

The study was located in a ST, CC field at the Agricultural Research Development and Education Center (ARDEC) in northeastern Colorado, near Fort Collins, CO (40°39′6″ N; 104°59′55″ W; 1535 m above sea level). The region has a semiarid temperate climate with typical mean annual temperature of 8.9°C and rainfall of 383 mm yr^{-1} (average from 1893–2010), with an average of 69, 46, 41, 37, 32, and 29 mm of precipitation in May, June, July, August, September, and October, respectively, or growing season total of 254 mm (May–October). The soil is a Fort Collins clay loam, classified as fine-loamy, mixed, superactive, mesic Aridic Haplustalfs. Selected soil chemical and physical properties of the 0- to 7.6-cm soil depth for the plot area used in this study are: soil pH, 7.6; soil organic C, 12.5 g kg^{-1}; particulate organic C, 4.0 g kg^{-1}; soil electrical conductivity (1:1 water:soil ratio), 0.34 mS cm^{-1}; soil bulk density, 1.39 g cm^{-3}; sand, 403 g kg^{-1}; and clay, 333 g kg^{-1} (Halvorson et al., 2006; Zobeck et al., 2008).

Fertilizer N sources evaluated were granular urea (46% N), liquid UAN (32% N), granular ESN (44% N), SuperU (46% N), stabilized liquid UAN with AgrotainPlus (UAN+AP), and a liquid, slow-release N source of UAN with 20% Nfusion (UAN+Nf) (22% N). All the N sources were surface-band applied by hand next to the corn row (0–10 cm from row, ~5–7 cm band width), shortly after corn emergence (18 May 2009 and 25 May 2010) and watered into the soil with 19 and 16 mm of water with a linear-move sprinkler irrigation system the day after application in 2009 and 2010, respectively. Based on the study of Holcomb et al. (2011), this amount of irrigation water was expected to reduce any NH_3 loss from the applied fertilizers to a very low level (<3%). An additional ESN treatment was included as a subsurface band application (ESNssb) near the corn row (~10 cm from row) at emergence. A hoe was used to make a v-shaped trench ~5 cm deep and ~5 cm wide at the top. The fertilizer was placed in the trench by hand and the trench recovered with soil using the hoe after fertilizer application. A blank treatment (no N applied) was included within the same plot area with the N sources. In addition, a check treatment that had not received N since 2000, but located in separate adjacent plots, was included in the GHG measurements to obtain background N_2O levels without N fertilization. All N source treatments received the same N rate (202 kg N ha^{-1}). The controlled-release, polymer-coated urea, ESN, consists of urea granules coated with a polymer permeable to water that gradually releases N during the growing season, with faster releases with increasing moisture and temperatures. The stabilized urea source SuperU contains urease [N-(n-butyl)-thiophosphoric triamide] and nitrification (dicyandiamide) inhibitors that are uniformly distributed through the granule during the manufacturing process. The AgrotainPlus (registered trademark of Agrotain International, St. Louis, MO) added to UAN contains the same urease and nitrification inhibitors as SuperU. The Nfusion (registered trademark of Georgia Pacific Chemicals, LLC, Atlanta, GA) added to UAN was a slow-release, liquid N made up of slowly available urea polymers in the form of methylene urea plus triazone.

A lateral-move sprinkler irrigation system was used to apply irrigation water as needed during the growing season using Watermark soil moisture sensors (Spectrum Technologies Inc., Plainfield, IL) to estimate soil water depletion before irrigating. The N treatments were arranged in a randomized, complete-block design with three replications. Each N source plot was

3-m long by 4.6-m wide with 0.61-m-wide alleyways between N treatments. The plot area used in this study had been in a CT–CC production system from 1999–2008, with the plot area receiving 202 kg N ha^{-1} in 2007 and 2008. The field operations were: strip-till to a 23-cm depth with a six-row Orthman 1tRIPr (Orthman Manufacturing Inc., Lexington, NE) on 1 Dec. 2008, after corn harvest for the 2009 study and on 31 Mar. 2010, for the 2010 study; plant corn in tilled strip on 30 Apr. 2009 and 4 May 4 2010; spray plots after crop emergence for weed control on 19 June 2009, and on 19 May 2010; and hand harvesting 24 corn plants on 28 Sept. 2009, and 30 Sept. 2010, for grain and stover yield determination at maturity but at high moisture content. Grain yield was estimated by removing the ears and shelling them to determine grain weight at 155 g kg^{-1} water content. Stover yield was also determined and expressed on a dry-weight basis. Grain and stover yields were calculated using established plant stands determined from counts made in two corn rows, 11.8-m long, in adjacent plots to the N-source treatments. Herbicides were used for weed control in all treatments, resulting in the plots being relatively weed free.

Soil samples (0–7.6, 7.6–15.2, 15.2–30.5, 30.5–61.0 cm depths) were collected before spring planting and N fertilization on 10 Apr. 10 2009, and 16 Apr. 2010; during the growing season on 20 May, 3, 16, and 30 June, and 15 and 29 July 2010; and after corn harvest on 29 Nov. 2009, and 2 Nov. 2010, and analyzed for NO_3–N content. Spring residual soil NO_3–N and NH_4–N levels determined on air-dried soil samples are reported in Table 1. Soil NO_3–N levels were higher in the spring of 2009 than 2010 because of the reduced grain yield and N uptake by the corn crop in 2008 caused by a severe hail storm on 14 Aug. 2008, which defoliated (>50%) leaves from corn plants at the early kernel dent stage of growth (Halvorson et al., 2010b). The spring residual soil NO_3–N levels in 2010 follow a high yielding crop in 2009. In 2010, soil samples were collected from the fertilizer band to a depth of 61 cm to assess the effect of N source on soil NO_3–N levels early in the growing season (Table 2). At the 10 May 2010 sampling before fertilizer application, all N source plots and the check treatment had a similar level of available soil NO_3–N in the 0–15.2-, 0–30.5-, and 0–61-cm soil profiles. A weighted average was used to determine the soil NO_3–N content of the treatment using the NO_3–N content measured in the fertilizer band (7-cm width) and soil NO_3–N content of the blank treatment (no N applied) as the unfertilized area (69-cm width) across the entire 76-cm row spacing. The after-harvest soil samples for NO_3–N analyses (Table 3) were collected 10 to 20 cm from the corn row both years. The ESNssb treatment had a significantly higher residual NO_3–N content than the other N treatments at the end of the season in the 0- to 61-cm soil depth.

Measurement of the soil-atmosphere exchange of N_2O, CO_2, and CH_4 were made from 5 May 2009 (day of year [DOY] 125) to 22 Mar. 2010 (DOY 81), and 6 May (DOY 126) to 27 Oct. (DOY 300) 2010, following the procedures reported by Mosier et al. (2006) and Parkin and Venterea (2010). Measurements were made one to three times per week during growing seasons, midmorning of each sampling day. The general gas sampling schedule was to collect gas samples on Monday before irrigation, then on Wednesday following irrigation, and then on Thursday or Friday, with some variation in this schedule. A vented nonsteady state closed chamber technique was used (Livingston and Hutchinson, 1995). A rectangular aluminum chamber (78.6 cm by 39.3 cm by 10 cm height) with a sampling port was placed in a water channel welded onto an anchor that had been inserted 10 cm into the soil at each sampling site. Anchors were set perpendicular to the corn row (76-cm row spacing) so that the corn row and inter-row area were contained within each chamber. Anchors were installed the day of corn planting, with gas sample collection beginning 1 to 5 d later and were not removed until after corn harvest. Duplicate flux measurement sites were included within each plot for a total of six gas measurements per treatment per sampling date. The plants that had been bent over for several weeks were cut off (approximately V-8 growth stage) within each anchor on the following dates, 13 July 2009 (DOY 194) and 23 June 2010 (DOY 174). Air samples from inside the chambers were collected by syringe at 0, 15, and 30 min after the chambers were seated on the anchors. The samples were transported to the laboratory in Fort Collins, CO, where the 25-mL air samples were injected into 12-mL evacuated tubes that were sealed with butyl rubber septa (Exetainer vial from Labco Limited, High Wycombe, Buckinghamshire, UK) for analysis by gas chromatography. The gas chromatograph was a fully automated instrument (Varian model 3800, Varian Inc., Palo Alto, CA) equipped with an electron capture detector to quantify N_2O and thermal conductivity and

Table 1. Spring soil NO_3–N and NH_4–N content before planting the corn crop and N fertilization in 2009 and 2010, with no significant N treatment by year interactions.

Year	N treatment	Soil depth					
		0–15.2 cm		0–30.5 cm		0–61.0 cm	
		NO_3–N	NH_4–N	NO_3–N	NH_4–N	NO_3–N	NH_4–N
		kg N ha^{-1}					
2009	Check	12.0b†	12.9a	17.4b	28.6a	19.7b	46.9a
2009	N source	40.6a	11.2a	60.5a	20.5b	90.5a	34.2b
2010	Check	6.3b	6.6a	13.2b	18.0a	17.7b	28.2a
2010	N source	10.6a	6.6a	26.1a	12.9b	48.9a	21.8b
2-yr avg.	Check	9.1a	9.8a	15.3b	23.3a	18.7b	37.5a
2-yr avg.	N source	25.6a	8.9a	43.3a	16.7a	69.7a	28.0a
2009	Avg.	26.3a	12.0a	39.0a	24.5a	55.1a	40.5a
2010	Avg.	8.5b	6.6b	19.6b	15.4b	33.3a	25.0b

† Values within a column data group followed by the same letter are not significantly different at the α = 0.05 probability level.

flame ionization detectors to quantify CO_2 and CH_4 concentrations, respectively. Fluxes were calculated from the linear or nonlinear (Hutchinson and Mosier, 1981) increase in concentration (selected according to the emission pattern) in the chamber headspace with time as suggested by Livingston and Hutchinson (1995).

Estimates of daily N_2O, CO_2, and CH_4 emissions between sampling days were made using a linear interpolation between adjacent sampling dates. The percent N_2O-N emission resulting from the application of N fertilizer was calculated for each treatment after correction for emission from blank treatment (no N added). The difference between the N_2O-N emission with N applied and the blank treatments was divided by the quantity of fertilizer N applied and then multiplied by 100 to obtain percent.

Soil water content (0- to 10-cm depth) and soil temperature (5- to 7-cm depth) were monitored at each gas sampling event using 2 to 3 EC-TM soil moisture and temperature probes (Decagon Devices Inc., Pullman, WA) located in each replication. Water-filled pore space (WFPS) was calculated according to the soil bulk density (measured by core method) at 0- to 10-cm depth following crop harvest and an assumed particle density of 2.65 Mg m^{-3} (Linn and Doran, 1984). The date and amount of precipitation and irrigation water applied were recorded during the growing season. Precipitation was recorded by an automated weather station located within 200 m of the plot area.

Grain and stover N uptake were evaluated to provide information on the agronomic sustainability of the enhanced-efficiency fertilizers. Grain and stover N content were determined by grinding an oven-dried sample to pass a 150-μm screen and analyzing for N concentration, using an Elementar Vario Macro C-N analyzer (Elementar Americas, Inc., Mt. Laurel, NJ). Grain and stover N uptake were calculated from the N concentration and yield data.

Differences in growing season cumulative N_2O, CO_2, and CH_4 emissions, percentage of fertilizer N lost as N_2O-N, crop yields, and crop N uptake among N treatments and years were determined by analysis of variance (ANOVA), using Analytical Software Statistix9 program (Analytical Software, Tallahassee,

Table 2. Soil NO_3–N levels in three depth increments from 20 May to 29 July 2010, from the N source treatments (significant N treatment × sampling day interaction).

N treatment†	20 May DOY 140‡	3 June DOY 154	16 June DOY 167	30 June DOY 181	15 July DOY 196	29 July DOY 210
			0–15.2 cm soil depth, kg NO_3–N ha^{-1}			
Urea	9.6a§	31.1a	24.2abcd	25.1bc	7.1a	4.8bc
ESNssb	11.7a	13.3bc	11.6cd	14.2cd	9.5a	26.7a
ESN	6.3a	11.4c	8.6d	11.9cd	6.1a	8.2b
SuperU	8.8a	17.5bc	18.2bcd	17.9bcd	15.0a	4.9bc
UAN	8.3a	33.5a	33.9ab	28.9ab	21.0a	8.8b
UAN+Nf	7.8a	37.2a	41.1a	30.7ab	16.4a	6.1bc
UAN+AP	9.2a	24.6ab	30.0abc	40.7a	16.7a	6.3bc
Blank	8.8a	11.4c	7.1d	6.2d	3.7a	4.3bc
Check	7.2a	9.9c	8.0d	5.6d	3.3a	3.5c
			0–30.5 cm soil depth, kg NO_3–N ha^{-1}			
Urea	20.5a	40.9ab	44.3ab	42.5ab	12.0a	10.3b
ESNssb	22.2a	21.0cd	22.1bcd	21.3cd	13.9a	31.7a
ESN	13.9a	19.1d	17.9cd	18.3d	9.2a	11.8b
SuperU	18.8a	27.1cd	31.4ab	29.1bcd	20.6a	8.8b
UAN	19.8a	43.3ab	52.1a	38.5abc	28.5a	15.2ab
UAN+Nf	17.8a	47.4a	52.7a	44.3ab	22.2a	10.3b
UAN+AP	20.8a	33.7bc	42.5ab	50.2a	20.4a	9.7b
Blank	20.4a	18.8d	16.1d	12.0d	6.6a	7.5b
Check	15.2a	18.3d	16.7cd	11.5d	6.7a	7.6b
			0–61.0 cm soil depth, kg NO_3–N ha^{-1}			
Urea	39.8a	57.3ab	65.6ab	70.6a	25.3bcd	25.0a
ESNssb	44.7a	36.6de	38.2bcd	39.1bcd	26.1bcd	37.5a
ESN	27.6a	34.4cde	33.3cd	35.4cd	18.6bcd	16.0a
SuperU	32.9a	43.6bcd	49.7abc	52.8abc	35.0ab	14.3a
UAN	37.9a	60.3a	72.5a	58.6ab	45.4a	24.2a
UAN+Nf	40.4a	66.6a	69.9a	70.1a	36.3ab	16.0a
UAN+AP	44.4a	51.7abc	59.6ab	69.3a	31.6abc	14.0a
Blank	44.1a	34.0de	31.3cd	27.7d	14.7cd	11.2a
Check	26.2a	28.1e	26.6d	21.3d	12.3d	12.4a

† ESNssb = ESN subsurface band; ESN = polymer-coated urea; SuperU = stabilized granular urea; UAN = urea-ammonium nitrate; UAN+Nf = UAN with Nfusion; UAN+AP = UAN with AgrotainPlus.

‡ DOY, day of year.

§ Values within a columns followed by the same lowercase letter are not significantly different at $\alpha = 0.05$ probability level.

FL). A randomized complete block ANOVA was used to evaluate N source differences within a year and a split plot ANOVA to evaluate N source differences between years with N treatment as the main effect and year as subplot. All ANOVA data were checked for normality, and when required, a logarithmic transformation was performed. After mean separation, the logarithmic-transformed means were converted back to their original scale for presentation. All statistical comparisons were made at $\alpha = 0.05$ probability level, using the least significant difference method for mean separation.

Results and Discussion

Environmental Factors

Air and soil temperatures at each GHG sampling date in 2009 and 2010 are shown in Fig. 1. Both years, soil temperatures were cooler during May and early June (DOY 121–160) than the main part of the growing season, with cooler soil temperatures during May 2010 than during May 2009, but warmer temperatures starting in June through most of the growing season in 2010 than in 2009. With crop canopy closure in late June, soil temperatures rose to ~20°C and then declined starting in September. Soil temperature during the December 2009 through February 2010 sampling period were generally <0°C, with an increase in soil temperature starting in early March. Air temperatures in early May were generally cooler in 2010 than in 2009.

Precipitation and irrigation amounts in 2009 and 2010 are shown in Fig. 2. Total 2009 yearly precipitation was 341 mm with May through October corn growing season totaling 259 mm. In 2009, 397 mm of irrigation water was applied to the corn crop with a growing season total (precipitation + irrigation) of 656 mm. Annual precipitation totaled 273 mm in 2010, with a May through October corn growing season total of 129 mm. In 2010, the corn received 396 mm of irrigation water, with a growing season total (precipitation + irrigation) of 525 mm.

Water-filled pore space (Fig. 3) ranged from ~65 to 80% from early May to mid-June in 2009. In 2010, WFPS ranged from ~72 to ~82% in May, then declined to a low of ~50% during June and stabilized between 60 and 70% during the rest of the growing season. During the winter months, WFPS declined to a low of ~35% in December 2009–February 2010. The WFPS tended to increase following precipitation

Table 3. Residual soil NO_3–N in four soil depth increments after corn harvest in 2009 and 2010, and averages over years (no significant interaction between N treatment and years).

Sampling date	N treatment†	Soil depth			
		0–15.2 cm	0–30.5 cm	0–61.0 cm	0–91.5 cm
		kg NO_3–N ha^{-1}			
25 Nov. 2009 (DOY‡ 329)	Urea	9.1a§	29.3bc	53.1bc	88.3ab
	ESNssb	10.6a	62.9a	121.7a	152.0a
	ESN†	11.1a	37.3ab	66.5b	83.9b
	SuperU†	5.1a	15.0bc	34.3bc	52.6bc
	UAN†	6.2a	19.4bc	40.6bc	83.0b
	UAN+Nf†	5.2a	15.0bc	27.3bc	39.8bc
	UAN+AP†	4.6a	13.4bc	27.7bc	57.8bc
	Blank	2.8a	8.4bc	13.9c	16.3c
	Check	2.0a	6.2c	11.7c	14.6c
2 Nov. 2010 (DOY 306)	Urea	10.2a	19.4a	28.9a	39.1a
	ESNssb	36.0a	53.4a	64.4a	73.6a
	ESN	14.6a	24.6a	34.5a	39.8a
	SuperU	14.1a	32.8a	53.1a	66.1a
	UAN	14.7a	26.0a	35.7a	44.2a
	UAN+Nf	18.1a	30.2a	42.2a	50.2a
	UAN+AP	17.3a	28.1a	40.9a	55.5a
	Blank	5.4a	9.2a	12.7a	15.9a
	Check	6.1a	9.6a	14.0a	16.2a
Avg. 2009 and 2010	Urea	9.7b	24.3b	41.0b	63.7ab
	ESNssb	22.6a	63.4a	101.6a	118.7a
	ESN	13.7ab	29.5ab	49.0ab	63.4ab
	SuperU	9.6b	23.9b	43.7b	59.4b
	UAN	10.4ab	22.7b	38.2b	63.6ab
	UAN+Nf	11.6ab	22.6b	34.7b	45.0b
	UAN+AP	10.9ab	20.7b	34.3b	56.5b
	Blank	4.1c	8.8c	13.3c	16.1c
	Check	4.1c	7.9c	12.9c	15.4c

† ESNssb = ESN subsurface band; ESN = polymer-coated urea; SuperU = stabilized granular urea; UAN = urea-ammonium nitrate; UAN+Nf = UAN with Nfusion; UAN+AP = UAN with AgrotainPlus.

‡ DOY = day of year.

§ Values within a columns followed by the same lowercase letter are not significantly different at $\alpha = 0.05$ probability level.

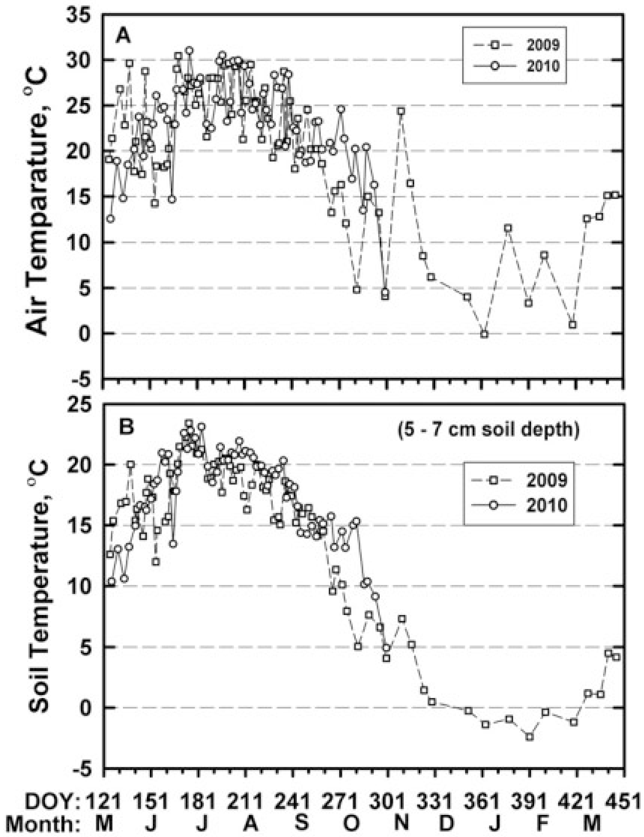

Fig. 1. Air (A) and soil temperature (B) at about the 5- to 7-cm depth measured at the time of gas flux measurement in 2009 and 2010.

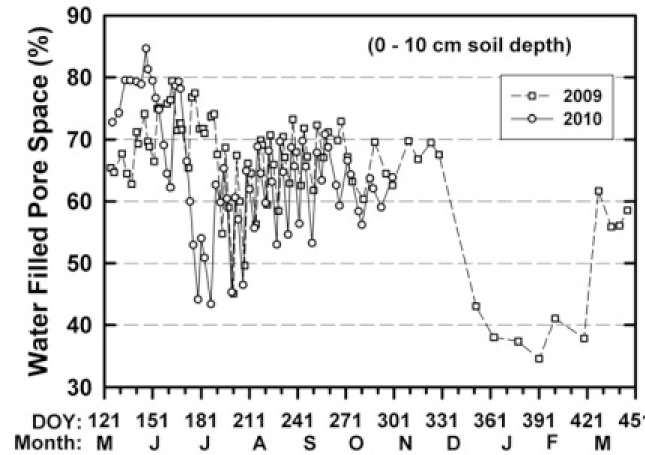

Fig. 3. Water-filled pore space in the 0- to 10-cm soil depth from 5 May 2009 to 22 Mar. 2010 and 6 May 2010 through 31 Oct. 2010.

and irrigation events (Fig. 2) and averaged 67.8 and 65.1% during the 2009 and 2010 growing seasons (May–September), respectively.

Nitrous Oxide Fluxes

Nitrous oxide fluxes increased within days following the application of all N sources except for ESN, which had a delayed release of N_2O in 2009 (Fig. 4) and 2010 (Fig. 5). Nitrous oxide fluxes were highest the first 30 d following N fertilization with urea and UAN when WFPS was highest and then declined to near background levels in ~45 d. Similarly, N_2O-N fluxes from SuperU increased within days following application but were of a smaller magnitude than for urea and UAN, then decreasing down to background levels in ~45 d both years. This trend corresponds to the trend of soil NO_3–N levels being lower for SuperU in 2010 in the 0- to 15.2- and 0- to 30.5-cm soil depths during June than urea and all UAN treatments (Table 2). Also, N_2O-N flux peaks resulting from UAN+Nfusion and UAN+AgrotainPlus application occurred within days of application but were of a much smaller magnitude that those observed for UAN alone, even though the measured soil NO_3–N levels were similar to UAN (Table 2). Nitrous oxide fluxes from ESN and ESNssb followed a different pattern, remaining low until mid-June when N_2O-N fluxes started to increase both years (Fig. 4 and 5). In 2010, the soil NO_3–N levels for the ESN treatments were generally less than for the other N sources during the early part of the growing season following N application. On 29 July, the ESNssb treatment had higher soil NO_3–N levels than the other N treatments (Table 2). The N_2O flux peaks from the ESN treatments during the growing season were greater in 2010 (Fig. 5) than in 2009 (Fig. 4), possibly due to a faster release of the urea N from the polymer-coated granule because of higher soil temperatures in 2010 than in 2009 (Fig. 1). Peaks from ESN application tended to be higher than those from the other N sources during mid-June through August but tended to be smaller and of shorter duration than the peaks observed just after urea or UAN application. The late-season N_2O-N fluxes from the ESN are consistent with the results reported by Halvorson et al. (2010b). The rapid increase in N_2O emissions following N application is consistent with work of Omonode et al. (2011) who reported that 50% of the N_2O emissions occurred shortly after N application, regardless of tillage or crop rotation practices, and with previous work done at this site by Mosier et al. (2006) and Halvorson et al. (2008, 2010a,b).

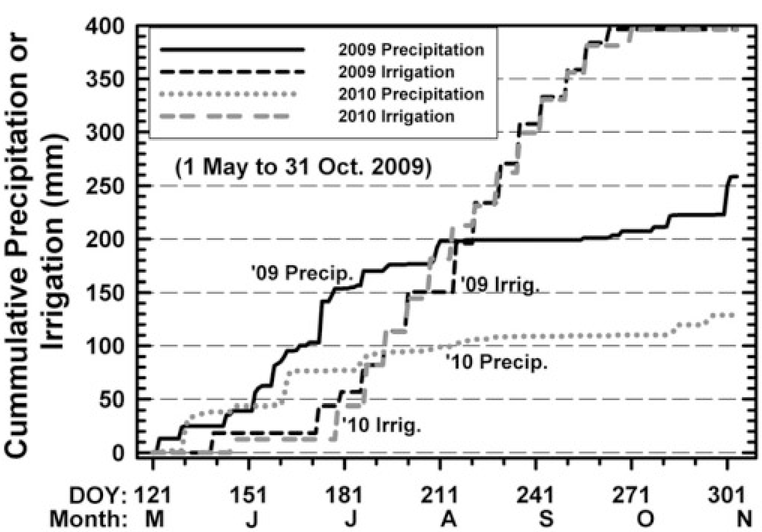

Fig. 2. Cumulative growing season precipitation and irrigation amounts applied in 2009 and 2010.

In 2009, we were able to collect N_2O flux measurements during the noncrop period (1 Oct. 2009–22 Mar. 2010). Nitrous oxide fluxes remained near

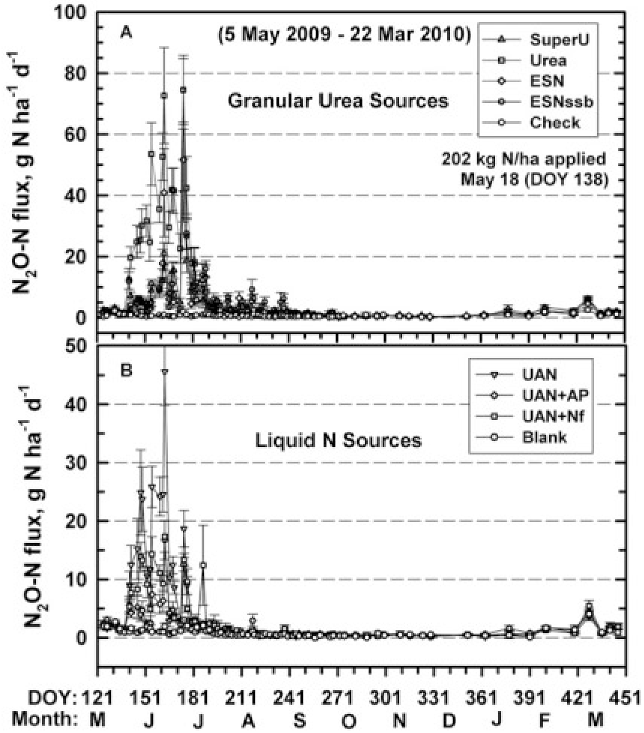

Fig. 4. Daily N_2O-N fluxes with standard error bars at each sampling date in 2009 for (A) SuperU, urea, ESN, ESN subsurface band (ESNssb), and check; and (B) urea-ammonium nitrate (UAN), UAN+AgrotainPlus (AP), UAN+Nfusion (Nf), and blank. Note the different scales on Y axis.

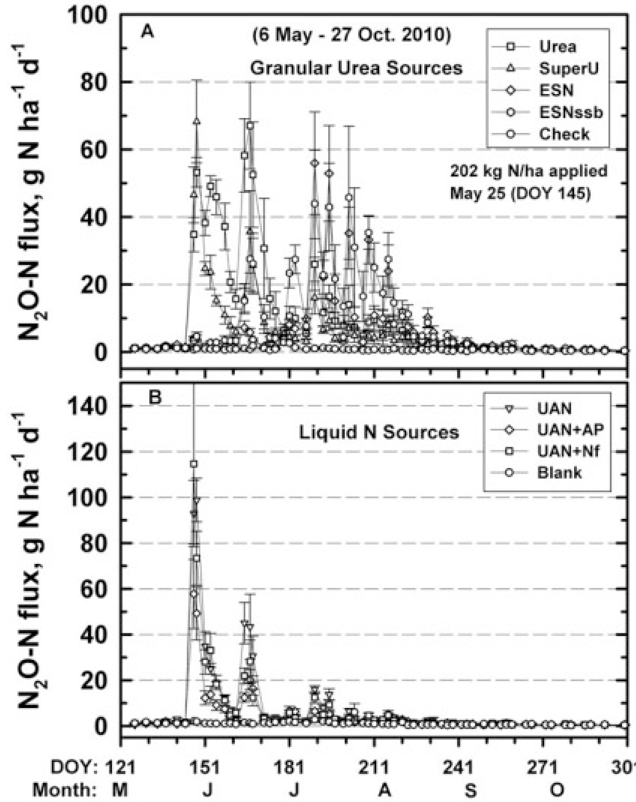

Fig. 5. Daily N_2O-N fluxes with standard error bars at each sampling date in 2010 for (A) SuperU, urea, ESN, ESN subsurface band (ESNssb), and check; and (B) urea-ammonium nitrate (UAN), UAN+AgrotainPlus (AP), UAN+Nfusion (Nf), and blank. Note the different scales on Y axis.

background levels for the entire period for all N treatments, with a slight rise in N_2O emissions on 4 Mar. 2010, as the frozen soil had thawed and soil temperatures increased, with a decline to background levels at the 12 Mar. sampling date. The slight increase in N_2O emissions as the soil thawed out is consistent with the observations of others who reported increased N_2O fluxes at spring thaw (Hao et al., 2001; Dusenbury et al., 2008). Average N_2O-N emissions (174 d) for the noncrop period were: 1.44a, 1.23ab, 1.18ab, 1.13bc, 0.99bcd, 0.88cd, 0.87cd, 0.80d, and 0.79d g N $ha^{-1}d^{-1}$ for ESNssb, ESN, SuperU, urea, UAN+AP, UAN+Nf, check, UAN, and blank, respectively, with significant differences indicated by lowercase letters following the daily emission value. The ESNssb treatment had the highest daily noncrop period emissions and the blank (no N applied) had the lowest emissions. The ESNssb treatment also had the highest level of residual soil NO_3–N in late November 2009 (Table 3), which probably accounts for the slightly higher N_2O emissions during the noncrop period. Nitrification was probably the dominant pathway of soil N_2O loss from applied N fertilizer from this ST, irrigated system based on WFPS being generally <70% both years, except for a short period in early 2010 when WFPS was ~80% before N fertilization (Linn and Doran, 1984). The slightly elevated level of residual soil NO_3–N at the end of the growing season with the ESNssb treatment is consistent with the observations of Venterea et al. (2011a) who reported slightly elevated residual soil N with the polymer-coated urea than with conventional urea in Minnesota.

Cumulative daily N_2O-N fluxes during the corn growing season are shown in Fig. 6 for 2009 and Fig. 7 for 2010. A rapid rise in cumulative daily flux levels for urea and UAN was very apparent both years following N application, with SuperU, UAN+Nfusion, and UAN+AgrotainPlus also showing rapid rises in cumulative N_2O emissions immediately following N application in 2010. Cumulative growing season emissions were greater in 2010 than 2009 for all N treatments, except for urea, which was similar both years but followed similar relative emission patterns both years. The rise in cumulative daily N_2O-N flux was slower for all enhanced-efficiency N sources than for urea and UAN both years. The delayed release of N_2O-N from ESN until about mid-June was very prominent in 2010. The N_2O emissions from the blank (no N applied) treatments that had received 202 kg N ha^{-1} in previous years was very similar to that from the check treatment that had not had any N applied since 1999. The residual soil NO_3–N (Table 1) in the 0- to 15.2-, 0- to 30.5-, and 0- to 61-cm depths were significantly greater in the N source plot area where the blank treatment resided than in the check treatment located in an adjacent plot. Although the residual soil NO_3–N was greater in the blank plot area than in the check plot area before corn planting, we did not observe a significant difference (Table 4) in growing season N_2O emissions between the blank and check treatments. Dobbie et al. (1999) reported a critical soil NO_3–N concentration of 5 mg NO_3–N kg^{-1} below which N_2O emissions may be much reduced, even at high levels of WFPS. This observation has been supported by other researchers (Izaurralde et al., 2004; Dusenbury et al., 2008). In this study, the difference in NO_3–N levels in the 0- to 15.2-cm soil depth had disappeared by 20 May 2010 (DOY 140), between the check

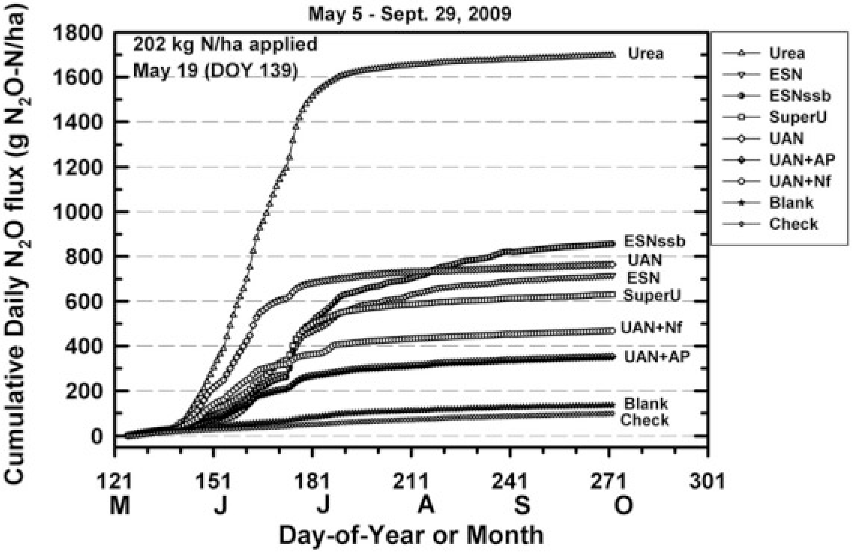

Fig. 6. Cumulative daily N_2O-N emissions during the 2009 growing seasons for each N treatment: urea, urea-ammonium nitrate (UAN), ESN, ESN subsurface band (ESNssb), SuperU, UAN+Nfusion (Nf), UAN+AgrotainPlus (AP), blank, and check.

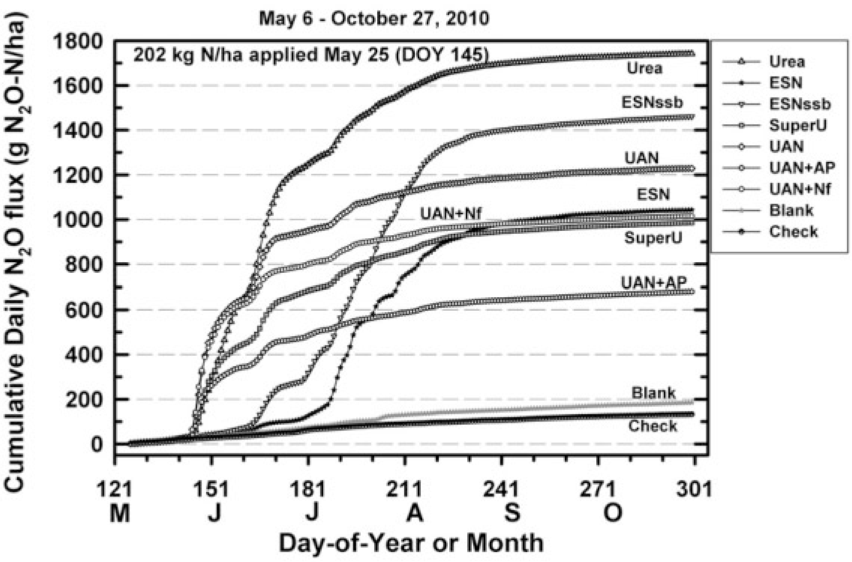

Fig. 7. Cumulative daily N_2O-N emissions during the 2010 growing seasons for each N treatment: urea, urea-ammonium nitrate (UAN), ESN, ESN subsurface band (ESNssb), SuperU, UAN+Nfusion (Nf), UAN+AgrotainPlus (AP), blank, and check.

and blank treatments. A soil NO_3–N concentration of 5 mg NO_3–N kg^{-1} would equate to ~11 kg NO_3–N ha^{-1} in this study, with the blank and check treatments generally having lower NO_3–N levels than 11 kg NO_3–N ha^{-1} during the growing season. This may help explain why there was little difference in N_2O emissions between the blank and check during the growing season. This observation between the blank and check treatments was observed both years. This would tend to indicate in our system that the fresh application of N fertilizer was stimulating microbial activity and the nitrification process resulting in N_2O loss from the N fertilizer applied. The fact that WFPS (Fig. 3) was generally <70% most of the growing season would support the theory that nitrification is the main pathway of N_2O loss at this location (Linn and Doran, 1984).

Nitrous oxide emissions for the two growing seasons (5 May to 29 Sept. 2009 and 6 May to 29 Sept. 2010) are reported in Table 4, with a significant N source × year interaction. This interaction probably resulted from ESNssb, SuperU, UAN, UAN+Nfusion, and UAN+AgrotainPlus having significantly greater N_2O emissions in 2010 than in 2009 but no difference between years for urea, ESN, blank, and the check treatments. Averaged over both years, growing season N_2O-N emissions from all enhanced-efficiency N fertilizers were significantly lower than granular urea, including UAN. The ESNssb treatment had significantly higher N_2O emissions than the UAN+Nfusion, UAN+AgrotainPlus, blank, and check treatments. The UAN+Nfusion and UAN+AgrotainPlus treatments had lower N_2O emissions than UAN. The blank and check treatments had the lowest level of growing season N_2O-N emissions and were not significantly different. Averaged over N sources, growing season N_2O emissions were lower in 2009 than in 2010. The higher WFPS in 2010 during May through mid-June than in 2009 (Fig. 3) may have contributed to the yearly difference, with some denitrification possibly contributing to the increased N_2O loss. The differences between years is consistent with the observations of Mosier et al. (2006) and Halvorson et al. (2008) who reported yearly differences for this site.

Compared with granular urea (averaged over years), UAN+AgrotainPlus reduced N_2O-N emissions 70%, UAN+Nfusion 57%, SuperU 53%, ESN 49%, UAN 42%, and ESNssb 33% in this ST production system. Compared with liquid UAN, UAN+AgrotainPlus reduced N_2O-N emissions 49%, UAN+Nfusion 26%, SuperU 19%, and ESN 12%. These results are thus in good agreement with Halvorson et al. (2010a,b) who showed substantial reductions in N_2O-N emissions with the use of enhanced-efficiency N fertilizers in NT systems.

The N_2O-N emission losses as a percentage of fertilizer N applied are reported in Table 4, with no significant interaction between N source and year. The N_2O-N loss was significantly higher in 2010 than in 2009, with N sources having significant differences in N_2O-N loss. All N sources had significantly lower N_2O-N emission losses than granular urea. This result indicates that the potential for reduction of N_2O-N emissions with the use of controlled-release, slow-release, and stabilized N fertilizer sources in ST systems is substantial. The calculations above show that the fertilizer-induced component of N_2O-N emissions could be reduced up to 70% by using enhanced-efficiency N sources in semiarid, irrigated cropping

Table 4. Cumulative growing season N_2O-N flux (5 or 6 May–29 Sept.) and fertilizer-induced N_2O-N emissions as a percentage of fertilizer N applied (significant N treatment × year interaction for growing season N_2O emission only).

N treatment†	Cumulative growing season N_2O-N emissions			N_2O-N emissions as % of fertilizer N applied		
	2009	2010	Avg.	2009	2010	Avg.
	N_2O-N, g N ha^{-1}			%		
Urea	1698a‡	1726a	1712a	0.77a	0.77a	0.77a
ESNssb	856cde	1439ab	1147b	0.36b	0.63b	0.49b
ESN	716def	1028bcde	872bc	0.29c	0.42bc	0.36cd
SuperU	631ef	972bcd	801bc	0.25cd	0.40bc	0.32cd
UAN	765de	1214abc	989b	0.31bc	0.52b	0.41bc
UAN+Nfusion	468fg	1001bcd	734c	0.16de	0.41bc	0.29de
UAN+AgrotainPlus	352g	665ef	509d	0.11e	0.24c	0.18e
Blank (no N added)	136hi	172h	154e	–	–	
Check (no N added)	99i	123hi	111e	–	–	
Avg.	636B§	927A		0.34B	0.51A	

† ESNssb = ESN subsurface band; ESN = polymer-coated urea; SuperU = stabilized granular urea; UAN = urea-ammonium nitrate; UAN+Nf = UAN with Nfusion; UAN+AP = UAN with AgrotainPlus.

‡ Values within a column followed by the same lowercase letter are not significantly different at α = 0.05 probability level or across 2009 and 2010 columns for N_2O growing season emissions.

§ Values within a row followed by the same uppercase letter are not significantly different at α = 0.05 probability level.

systems. The degree of reduction may vary strongly, depending on cropping system, tillage management, and site-specific conditions as pointed out by Halvorson et al. (2010a). The growing season N_2O-N emissions from the application of a unit of the enhanced-efficiency N fertilizers used in this study were considerably lower (<0.5%) than the default 1% from Tier I methodology of De Klein et al. (2006) used to estimate yearly N_2O-N emissions resulting from N fertilizer application. This indicates the need for source and site-specific N_2O emission data (Adviento-Borbe et al., 2007; Bouwman et al., 2002; Rochette et al., 2008; Snyder et al., 2009). The results presented here may indicate that irrigated soils under semiarid conditions have relatively low N_2O-N losses, provided irrigation is well managed to avoid water-logged conditions and potential for denitrification. In only 1 out of 9 yr have N_2O-N emissions exceeded 1% of N applied at this site (Mosier et al., 2006; Halvorson et al., 2008, 2010a,b), with 1 yr (2003) having very wet soil conditions at fertilization, planting, and during the early growing season.

Carbon Dioxide and Methane Emissions

Growing season CO_2–C emissions varied with N treatment and year, with no significant N source × year interaction. The check with no N applied had higher growing season CO_2–C emissions (2803 kg C ha^{-1}) than SuperU (2434 kg C ha^{-1}), blank (2386 kg C ha^{-1}), Nfusion (2347 kg C ha^{-1}), ESN (2294 kg C ha^{-1}), and urea (2291 kg C ha^{-1}). Differences among N sources in CO_2 emissions were unexpected, with no logical explanation for this difference available. Averaged over years, daily growing season CO_2–C emissions (148 d) did not vary with N treatment, averaging 16.8 kg C ha^{-1} d^{-1}. The average daily CO_2–C emissions in 2010 (17.4 kg C ha^{-1} d^{-1}) was greater than in 2009 (16.1 kg C ha^{-1} d^{-1}). In 2009 during the noncrop period (30 Sept. 2009–22 Mar. 2010), there was no significant difference in daily CO_2–C emissions among N treatments with an average daily emission of 2.4 kg C ha^{-1}d^{-1}.

Growing season daily CH_4–C emissions (148 d) did not vary among N treatments (0.34 g C ha^{-1} d^{-1}), with no significant N source × year interaction. Daily CH_4–C emissions were greater in 2010 (0.41 g C ha^{-1}d^{-1}) than in 2009 (0.28 g C ha^{-1} d^{-1}). Daily CH_4–C emissions for the 174 d noncrop period (30 Sept. 2009 to 22 Mar. 2010) did not vary with N treatment and averaged 0.25 g C ha^{-1}d^{-1}.

Corn Grain and Stover Yield and Nitrogen Uptake

There was a significant increase in grain yield and grain N uptake with application of 202 kg N ha^{-1} when compared with the blank and check treatments both years (Table 5), with a significant N treatment × year interaction. Both years, there was no significant grain yield differences among N sources, however, grain yields with N application were greater in 2010 than in 2009 for all N source treatments but lower in 2010 than 2009 for the blank and check treatments, which resulted in significant interaction. Cahill et al. (2010), Halvorson et al. (2010b), Nelson et al. (2009), and Venterea et al. (2011b) also reported no or small corn yield differences among N sources applied at similar N rates. Similarly, grain N uptake (Table 5) for the blank and check treatments were lower in 2010 than in 2009, with no differences in N uptake between N sources in 2009 or 2010, thus causing significant interaction. Averaged over both years, enhanced-efficiency fertilizers did not affect grain yields, with all alternative N sources not significantly different from urea and UAN. The grain yield of the blank and check treatments averaged (2 yr) 70 and 46% of the highest grain yield, respectively. The check treatment had not been fertilized since 1999, so the resulting yield is primarily from mineralization of soil organic matter plus N applied with the irrigation water (14 and 25 kg N ha^{-1} in 2009 and 2010, respectively). Based on the grain yield and N uptake data over both years, the enhanced-efficiency fertilizers did not have any grain yield advantage over granular urea or liquid UAN in our study.

Stover yields did not vary among N sources with a significant N treatment × year interaction (Table 6). The significantly lower stover yields in 2010 compared with 2009 for the blank and check treatments probably caused the interaction. Stover yields with N application were significantly greater than with no N applied, with the check treatment being significantly lower than the blank treatment (Table 6). Stover yields did not vary with year. Stover N uptake was greater with urea than with UAN+AgrotainPlus, with no other differences among N sources (Table 6). Stover N uptake was greater with N application than without N application, with the blank having a greater N uptake than the check treatment. There was no difference in N uptake between years.

Nitrous Oxide Emissions as a Function of Grain Yield and Nitrogen Uptake

Van Groenigen et al. (2010) suggested that N_2O emissions need to be assessed as a function of crop N uptake and grain yield to provide an agronomic assessment of N_2O emissions. They also pointed out that to minimize N_2O emissions and maintain or increase crop yield, N uptake by the crop must be maximized. Nitrous oxide emissions per megagram of grain yield for each N treatment in this study are presented in Table 7. When analyzed over both years, there was no significant N treatment × year interaction. Averaged over years, all enhanced-efficiency N sources, including UAN, had lower N_2O-N emission levels per megagram of grain yield than urea. The ESNssb treatments had greater N_2O emissions per megagram grain than UAN+Nfusion, UAN+AgrotainPlus, blank, and check treatments. The UAN+AgrotainPlus had lower N_20 emissions per megagram grain than UAN. The blank and check treatments had the lowest level of N_2O emissions per megagram grain, but these are not economically sustainable management practices (Archer et al., 2008; Archer and Halvorson, 2010). The N_2O emissions per megagram grain were slightly higher in 2010 than in 2009, consistent with the higher level of N_2O emissions in 2010 than in 2009 (Table 7). These data show that the enhanced efficiency fertilizers have potential to reduce

Table 5. Grain yield (at 155 g kg^{-1} water content) and grain N uptake for each N treatment in 2009 and 2010, and averages for both years (significant N treatment × year interactions).

N treatment†	Grain yield			Grain N uptake		
	2009	2010	Avg.	2009	2010	Avg.
	Mg ha^{-1}			kg N ha^{-1}		
Urea	13.11bc‡	15.44a	14.28a	142ab	138ab	140a
ESNssb	13.76b	15.79a	14.78a	154a	157a	155a
ESN	13.56bc	15.43a	14.50a	147a	139ab	143a
SuperU	13.70b	16.24a	14.97a	150a	147a	149a
UAN	12.97bc	16.64a	14.81a	141ab	150a	145a
UAN+Nfusion	13.21bc	16.05a	14.63a	145a	135ab	140a
UAN+AgrotainPlus	13.22bc	15.33a	14.27a	144a	136ab	140a
Blank (no N added)	12.11c	8.80d	10.45b	120b	59c	90b
Check (no N added)	8.43d	5.47e	6.95c	61c	43c	52c
Avg.	12.68B§	13.91A		134A	123B	

† ESNssb = ESN subsurface band; ESN = polymer-coated urea; SuperU = stabilized granular urea; UAN = urea-ammonium nitrate; UAN+Nf = UAN with Nfusion; UAN+AP = UAN with AgrotainPlus.

‡ Values within a column followed by the same lowercase letter are not significantly different at $\alpha = 0.05$ probability level or across 2009 and 2010 columns for grain yield and grain N uptake interactions.

§ Values within a row followed by the same uppercase letter are not significantly different at $\alpha = 0.05$ probability level.

Table 6. Stover yield (dry weight basis) and N uptake for each N treatment in 2009 and 2010, and averages for both years (significant N treatment × year interaction for stover yield only).

N treatment†	Stover yield			Stover N uptake		
	2009	2010	Avg.	2009	2010	Avg.
	Mg ha^{-1}			kg N ha^{-1}		
Urea	9.39a‡	9.07ab	9.23a	60a	60a	60a
ESNssb	9.44a	9.45a	9.44a	63a	56a	59ab
ESN	9.28a	9.07ab	9.17a	58a	60a	59ab
SuperU	9.30a	9.50a	9.40a	55ab	57a	56ab
UAN	8.80ab	9.71a	9.26a	50ab	58a	54ab
UAN+Nfusion	8.58ab	9.27ab	8.93a	51ab	59a	55ab
UAN+AgrotainPlus	8.58ab	9.14ab	8.86a	51ab	51a	51b
Blank (no N added)	8.16b	5.92c	7.04b	44b	25b	35c
Check (no N added)	6.45c	4.19d	5.32c	27c	18b	23d
Avg.	8.67A§	8.37A		51A	49A	

† ESNssb = ESN subsurface band; ESN = polymer-coated urea; SuperU = stabilized granular urea; UAN = urea-ammonium nitrate; UAN+Nf = UAN with Nfusion; UAN+AP = UAN with AgrotainPlus.

‡ Values within a column followed by the same lowercase letter are not significantly different at $\alpha = 0.05$ probability level or across 2009 and 2010 columns for stover yield interaction.

§ Values within a row followed by the same uppercase letter are not significantly different at $\alpha = 0.05$ probability level.

N_2O-N emissions per unit of grain production at this semiarid, irrigated corn production site in the Central Great Plains.

Following the examples of Venterea et al. (2011b) and Van Groenigen et al. (2010) for evaluating agronomic N use efficiencies, we also expressed growing season N_2O emissions on a per kilogram of grain and total aboveground biomass (grain + stover) N uptake basis for each N treatment. Growing season emissions per unit of grain N uptake are reported in Table 7. Urea had significantly higher N_2O-N emissions per kilogram grain N uptake than the enhanced-efficiency N sources, including UAN. The UAN+AgrotainPlus had significantly lower emissions per kilogram of grain N uptake than UAN and was not significantly different from the blank and check treatments receiving no N fertilizer. The N treatment × year interaction was not significant. Consistent with the grain N uptake data (Table 5), grams N_2O-N emissions per kilogram grain N uptake were greater in 2010 (6.9) than in 2009 (4.5). These emission levels were similar to the range (4.0–10.7 g N_2O-N kg^{-1} grain N) reported by Venterea et al. (2011b) in Minnesota. Izaurralde et al. (2004) similarly reported a lower N_2O emission loss as a percentage of grain N harvested for a zero N applied treatment than for a high N application treatment in a spring wheat (*Triticum aestivum* L.) system.

Growing season N_2O-N emissions per kilogram of total biomass N uptake (Table 7) showed the same trends in treatment differences as observed for grain N uptake above. Urea had the highest level of N_2O-N emissions per kilogram total biomass N uptake with UAN+AgrotainPlus, blank, and check treatments being the lowest. Based on an N surplus analysis (N fertilizer applied – total aboveground biomass N uptake), the N surplus averaged over both years in this study was 1.2 kg N ha^{-1}, which would make this an N_2O-efficient cropping system as projected by the meta-analysis of Van Groenigen et al. (2010). Averaged over the 2 yr, the N fertilizer recovery efficiency ([total biomass N uptake with N applied – total biomass N uptake with no N applied]/N fertilizer applied) (Noellsch et al., 2009) was 38%, with no differences among N sources but significant yearly differences—18% in 2009 and 57% in 2010, when using the blank as the no N applied treatment. Using the check as the no N applied treatment resulted in a 73% N fertilizer recovery efficiency, with significant yearly differences, 56% in 2009 and 90% in 2010. The N fertilizer recovery efficiency was lower in 2009 as a result of the relatively high yield and N uptake of the blank treatment in 2009 compared with 2010. The higher yield and N uptake of the blank and check treatments in 2009 was probably due to the higher level of residual soil NO_3–N levels (Table 1) in 2009 than 2010. These N fertilizer recovery efficiencies are similar to those reported by Venterea et al. (2011b) and Noellsch et al. (2009).

Conclusions

Controlled-release, slow-release, and stabilized N sources reduced N_2O-N emissions from an irrigated, ST, CC cropping system when compared with granular urea. Nitrous oxide fluxes resulting from urea, UAN, SuperU, UAN+Nfusion, and UAN+AgrotainPlus applications peaked within days after application, whereas N_2O flux peaks from ESN and ESNssb occurred 4 to 6 wk after application but with flux peaks generally of lower magnitude than with conventional urea. All enhanced-efficiency fertilizers and UAN reduced growing season N_2O emissions when compared with urea, and UAN+Nfusion and UAN+AgrotainPlus did so in comparison to UAN. Nitrification was probably the main pathway of soil N_2O loss from applied N fertilizer from this ST, irrigated system throughout most of the growing season, except for possibly some loss due to denitrification in early May 2010 when WFPS reached 80% for a short period. Growing season N losses as N_2O-N were consistently <0.5% of N applied for all enhanced-efficiency N sources, including UAN, with urea having a loss of <0.8%. Expressing N_2O emissions as a function of grain yield and N uptake showed greater agronomic N use efficiency for the enhanced-efficiency N fertilizers than for urea. This study shows that N source can affect N_2O-N emissions following N fertilizer application. Choice of N source can be a valid management alternative for reducing N_2O emissions to the environment in the semiarid western United States. Additional work is needed to verify the effectiveness of these fertilizer sources in reducing N_2O emissions in other rainfed and irrigated cropping systems, especially in humid areas with large amounts of untimely spring rainfall, which can contribute to N_2O losses through denitrification.

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Table 7. Average (2009–2010) growing season N_2O-N emissions as a function of corn grain yield, grain N uptake, and total aboveground N uptake (grain + stover) for each N Treatment (no significant N treatment × year interaction).

N treatment†	g N_2O-N Mg^{-1} grain yield	g N_2O-N kg^{-1} grain N uptake	g N_2O-N kg^{-1} total N uptake
Urea	121a‡	12.2a	8.5a
ESNssb	78b	7.3b	5.3b
ESN	61bc	6.1bc	4.3bc
SuperU	54bcd	5.6bc	4.0bcd
UAN	66bc	6.8b	5.0bc
UAN+Nfusion	49cd	5.3bc	3.8cd
UAN+AgrotainPlus	36de	3.8cd	2.7de
Blank (no N added)	15e	2.2d	1.6e
Check (no N added)	17e	2.0d	1.4e
Avg. 2009	48B§	4.5B	3.2B
Avg. 2010	62A	6.9A	4.9A

† ESNssb = ESN subsurface band; ESN = polymer-coated urea; SuperU = stabilized granular urea; UAN = urea-ammonium nitrate; UAN+Nf = UAN with Nfusion; UAN+AP = UAN with AgrotainPlus.

‡ Values within a columns followed by the same lowercase letter are not significantly different at α = 0.05 probability level.

§ Values within a column followed by the same uppercase letter are not significantly different at α = 0.05 probability level.

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Nutrient Removal Estimates for Major Fruits and Vegetable Crops Grown on Calcareous Soils in South Texas

Research Summary

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SUMMARY

Nutrient Removal by Major Vegetable Crops Grown on Calcareous Soils in Texas

The impacts of fertilizer input on crop productivity and quality are well documented. For many high-value fruits and vegetable crops (e.g. melons, tomatoes, citrus), fertilizer requirements for peak yields can differ from the requirements for optimal quality traits such as taste, texture and shelf-life. Currently, there are no nutrient management guidelines for optimizing produce quality even though certain nutrient elements such as potassium (K) are known to influence quality development. The objective of this long-term project is to determine nutrient removal values for major fruits and vegetable crops grown on calcareous soils in South Texas, and to use the information to refine fertilizer recommendations for yield, quality. During the spring growing season of 2011, nutrient removal amounts were estimated for muskmelons (*Cucumis melo* L. Var. *Reticulatus*) and onions from fields that were previously investigated in 2009. Removal rates by grapefruits from commercial orchards were also estimated. Pre-plant soil N, P_2O_5 and K_2O test levels were slightly lower in 2011 than in previous years. Melon yields ranged from 11-19 $t \cdot acre^{-1}$ and were generally greater than those recorded in 2009. Estimated nutrient removal amounts in 2011 ranged from 45-84 lbs N/acre, 7-17 lbs P/acre, and 60-128 lbs K/acre compared to 18-37 lbs N/acre, 7-11 lbs P/acre, and 44-90 lbs K/acre respectively in 2009. Nutrient removal estimates for sweet onion were also higher in 2011 than in 2009, consistent with higher yields in 2009. Grapefruit yields averaged 311 80lb-boxes per acre (12.4 ton/acre fresh fruit) and nutrient removal estimates ranged from 24-31 lbs N/acre, 6-9 lbs P/acre, and 60-71 lbs K/acre.

Keywords: Nutrient removal; fertilization; quality; muskmelon; onion; grapefruit

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INTRODUCTION

The impacts of fertilizer use on crop productivity and basic nutritional quality parameters (proteins, minerals, vitamins and essential oils) are well documented (FAO, 1981; Marschner, 1995; Havlin et al., 2005; Stewart et al., 2005). Relatively high levels of fertilizer applications are required to ensure adequate yields and quality of many high-value crops. During the course of the growing season, crops take up and accumulate various nutrients in biomass, some of which are eventually removed from the site with harvested products. Crop nutrient uptake is influenced by soil and climatic conditions. Low soil moisture, poor aeration due to compaction or excessive moisture, low soil temperatures, high lime in the root zone, nutrient imbalances, and other factors may restrict uptake of plant nutrients. Nutrient imbalances, especially inadequate K supply, often contribute significantly to poor crop yields and quality even though most soil tests commonly indicate sufficient levels (>150ppm) of soil K (Jifon et al., 2009; Lester et al., 2006). This is often the case in the predominantly calcareous soils in South Texas and other major vegetable production regions where high levels of soil calcium (Ca) and magnesium (Mg) typically exacerbate the apparent K deficiency problem. Accurate estimates of crop nutrient requirements (amounts) as well as timely supply and placement of the appropriate nutrient sources is essential for improving yields, quality, and profitability while protecting the environment. Nutrients in crop residues that are left in the field can partially add to soil nutrient reserves as the residues decompose. Information regarding crop nutrient removal amounts is essential in determining the amounts that must be reapplied to sustain yields and quality while maintaining soil fertility. The objective of this long-term project is to obtain nutrient removal values for major fruits and vegetable crops grown on calcareous soils in South Texas, and to use this information in developing guidelines for nutrient management to assure yield and quality as well as in selecting varieties for specific sites based on their nutrient accumulation/removal capacities.

MATERIALS AND METHODS

Commercial vegetable fields (melons and onions) in the Lower Rio Grande Valley, TX (annual rainfall ~22 inches) were sampled in 2009, 2010 and 2011; more recently, grapefruit orchards were also sampled during the 2010-2011 harvest season. Soils are predominantly calcareous (Table 1). In 2011, commercial melons (cantaloupe) and sweet onions field that were initially sampled in 2009 were used for fruit and bulb sampling. Soils in these fields are predominantly calcareous (average pH 7.6) and heavy-textured (Harlingen clay). Onions were planted in mid-October 2010 and harvested in April 2011. Melon fields were direct-planted in early spring (February-March) and harvested in late May. All fields were managed following standard commercial practices including irrigation, nutrient management, and pest control. Soil samples were collected from each site from the top 30 cm soil layers for residual nutrient analysis prior to planting.

Vegetative tissues (leaves/petioles and stems) were sampled before and after fruit set/bulb initiation for chemical analysis. Samples were rinsed with distilled water, dried (70 °C for 48 h), ground in a Wiley mill to pass a 40-µm screen and ashed (500 °C, 5 h), before tissue analysis. At harvest, vegetative tissues and marketable fruits and onion bulbs were sampled, weighed and analyzed for mineral contents. Total nitrogen (N) concentration of tissues was analyzed by the Kjeldahl method. Mineral nutrient concentrations (P, K, Ca, Mg,) were analyzed by inductively coupled plasma (ICP) emission spectroscopy, following tissue digestion with nitric acid and hydrogen peroxide. Nutrient removal amounts were estimated from fruit/bulb yields, dry matter, and mineral nutrient concentrations.

RESULTS AND DISCUSSION

Soil mineral nutrient concentrations determined prior to planting in 2011were generally lower than those found in 2009 (Table 1) however, these levels (except for nitrogen) were substantially higher than sufficiency ranges. Mineral nutrient concentrations in vegetative tissues measured just prior to harvest were significantly lower than sufficiency levels for each of the three crops (melons, onions and grapefruit) as developing fruits and bulbs became stronger sinks for nutrients and assimilates. Tissues sampled in 2011 also had slightly lower nutrient concentrations than those sampled in 2009 (Table 2).

Average melon fruit yields in 2011 ranged from 15-20 $t \cdot acre^{-1}$ and were slightly higher compared to 2009. Fruit soluble solids ranged from 9.6 to 11.9% and were highly correlated with fruit potassium concentrations. This is consistent with previous greenhouse and field observations on melons (Jifon et al., 2009; Lester et al., 2006). Estimates of nutrient removal amounts for melons in 2011 ranged from 26-39 lbs/acre for nitrogen, 10-14 lbs/acre for phosphorus, and 66-82 lbs/acre for potassium and were significantly higher than estimates for 2009. The 2011 removal estimates were also slightly higher than the averages reported for muskmelons in other regions under ideal growing conditions (IPNI, 2001; Maynard and Hochmuth, 2007). These differences may be due to poor weather conditions (freeze events) during the growing season in 2009 and the generally low yields that year; favorable weather conditions during the growing season in 2011 and the associated higher fruit yields likely contributed to the higher removal rates.

Sweet onion bulb yields ranged from 17 to 22 tons/acre and were also higher in 2011 than in 2009. Average nutrient removal estimates in 2011 for sweet onion (61.3, 19.4, 75 lbs/acre for nitrogen, phosphorus, and potassium respectively) were however, not significantly different from those observed in 2009 due in part to low mineral concentrations in bulbs.

Grapefruit yields ranged from 290 to 321 boxes per acre (average 311 boxes/acre or 12 ton/acre fresh fruit). At the time of grapefruit harvest, leaf mineral nutrient concentrations were significantly lower than recommended levels (table 2). Calculated nutrient removal rates with marketable fruits ranged from 28.9, 8.1, and 66.1 lbs/acre of marketable fresh fruit for nitrogen, phosphorus and potassium respectively.

Even though pre-plant soil macronutrient (especially K, Ca, Mg) reserves were high in both years, a clear decline in tissue macronutrient contents during the late fruit developmental stages was observed, indicating that nutrient supply from the soil via root uptake was insufficient. This is plausible if competition for assimilates between roots and maturing fruits limits root activity and water/nutrient uptake. For fields that were sampled in 2009 and again in 2011, there was a slight decline in average values of pre-plant soil nutrient concentrations. For macronutrients (K, Ca, Mg) with typically high levels, it is customary in this region not to apply supplemental fertilizers. However, high yields, high crop removal rates, and the declining trends in soil reserve levels over time highlight the need for a reassessment of fertilizer management practices, especially those aimed at achieving superior fruit quality. Continued sampling over multiple years, and locations with varying weather conditions, soil types and yield scenarios will be needed to establish realistic nutrient removal values that can be used to develop improved fertilizer management guidelines.

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Table 1: Average values of pre-plant soil mineral concentrations for each crop (from the 0–30 cm soil depth.

Crop	Soil Organic Matter (%)	pH	NO_3-N	P	K	Ca	Mg
			(mg·kg^{-1})				
			2009				
Melon	2.3	8.2	71.0	57.4	524	16300	646
Onions	1.7	7.1	49.2	48.3	788	12802	502
Grapefruit	-	-	-	-	-	-	-
			2011				
Melon	1.1	7.7	44.2	75.2	719.4	17834.9	699.2
Onions	1.2	8.6	36.1	67.3	801.6	12602.7	584.2
Grapefruit	1.9	7.8	104.6	40.2	416.2	3628	417

Table 2: Average whole leaf macro- and micronutrient concentrations at early vine development and pre-harvest growth stages of melon (‘Cruiser’) plants at two commercial field sites.

	N %	P %	K %	Ca %	Mg %	S %	Fe ppm	Mn ppm	Zn ppm	B ppm	Cu ppm
					Melons						
2009	2.6	0.28	2.7	4.2	0.51	0.49	188	52.3	48.2	61.1	7.3
2011	2.1	0.26	1.3	3.4	0.39	0.38	129	46.4	38.3	42.3	6.9
Sufficiency range	3-5.5	0.3-0.6	3-5	2-5	0.3-0.8	0.2-0.5	40-100	20-200	7-30	50-200	25-60
					Onions						
2009	3.0	0.28	2.3	2.8	0.40	0.49	181	65.2	51.6	51.1	8.0
2011	2.4	0.20	1.9	1.9	0.31	0.38	167	59.9	37.4	48.6	7.1
Sufficiency range	3-6	0.3-0.5	2-5	2-5	0.3-0.5	0.5-1.0	60-300	50-65	20-60	30-50	5-10
					Grapefruit						
2009	-	-	-	-	-	-	-	-	-	-	-
2011	2.1	0.09	0.7	1.5	0.2	0.14	36	18	18	21	3.1
Sufficiency range	2.5-2.7	0.12-0.16	1.2-1.7	3.0-4.9	0.30-0.49	0.20-0.39	60-120	25-100	25-100	36-100	5-16

Table 3: Average yields and estimates of macronutrients removed with muskmelon fruit harvests at several locations with contrasting soil types.

Yield	Yield tons/acre	N	P	K lbs/acre	Ca	Mg	S
				Melons			
2009	15.2a	79.7b	15.2a	98.8b	32.2b	5.1b	
2011	19.8a	92.3a	18.2a	121.4a	43.5a	7.9a	
				Onions			
2009	10.2b	44.2b	15.3b	55.0b	26.9b	3.7a	
2011	13.8a	61.3a	19.4a	74.6a	31.9a	4.9a	27.2a
				Grapefruit			
2009	-	-	-	-	-	-	-
2011	12.2a	28.9	8.1	66.1	15.6	5.0	2.5

Proximal Sensing for Early Detection of Nitrogen Deficiency in Corn for In-season Precision Nitrogen Management

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ABSTRACT

Early detection of nitrogen deficiency is essential to site-specific nitrogen management for practical and physiological reasons. Current proximal sensing techniques based on reflectance do not allow reliable detection of nitrogen deficiency prior to V8 growth stage of corn. Another technique based on fluorescence also offers the possibility to detect nitrogen deficiency of plants. The objective of this project was to assess the possibility to detect nitrogen deficiency prior to V8 growth stage of corn based on fluorescence readings. Our results acquired from greenhouse grown plants indicate that fluorescence sensing provide a good indication of corn nitrogen deficiency from V6 growth stage of corn.

Keywords: site-specific nitrogen management, chlorophyll fluorescence, corn

INTRODUCTION

The global nitrogen use efficiency (NUE) is less than 40 % globally (Cassmann, 2002). The growing amount of nutrients from agriculture activities that leaches in the environment and the higher price of nitrogen (N) fertilizers constitute serious concerns for public and farmers (Roberts, 2008). One way of improving NUE is by targeting N-fertilizer when and where the plant will absorb it and turn it into yield (Shanahan et al., 2008). Corn plants do not need the same quantity of N across the season. The maximum N uptake period starts around V6 to V8 growth stages and last up to V16 to V18 growth stage and it is at the beginning of this period that N should be available for the plant in sufficient quantity (Scharf et al., 2006). Nitrogen under the form of nitrates (best form for plant absorption) is very soluble and mobile and N fertilizer applied before the maximum N uptake period have greater chances to leach in the environment, especially in spring conditions when precipitation events are more frequent. On the other hand, if the N fertilizers are applied after the beginning of the maximum N uptake period, the plant will absorb sub-optimal quantity of N and yield will be lower. Thus, to better manage N fertilizer and increase NUE, temporal heterogeneity in N needs should be taken into account and N should be applied around V6 to V8 growth stages of corn. Accordingly, spatial heterogeneity of N-needs should also be taken into account for optimal N use.

The soil fertility varies from one location of the field to the other and N-fertilizer application can be spatially modulated according to soil fertility. Based on the maximum N uptake period, the appropriate N rate should be decided between V6 and V8 growth stage of corn. However, current proximal canopy sensing tools using normalized difference vegetation index (NDVI) provide a poor correlation with yield prior to V8 growth stage of corn (Elwadie et al., 2005; Teal et al., 2006; Martin et al., 2007). Using leaf reflectance sensors, plants with N deficiency seems to be detected too late for practical implementation of site-specific N management. Another emerging approach for the detection of N deficiency in corn is the use of fluorescence sensor.

Fluorescence is a property of certain pigments, the fluoreophores, which re-emit light after being exposed to light. Chlorophyll is a fluorescent pigment that emits fluorescence in the red to far-red (690 nm to 740 nm) regions of the light spectrum after light excitation (Buschmann et al., 2000). Fluorescence emitted in the red to far-red region of the spectrum is often referred to as chlorophyll fluorescence (ChlF) and can be used to assess plant chlorophyll content (Lorenzen, 1966). Chappelle et al. (1984) observed significantly different ChlF emission between corn plants with complete nutrient supply and corn plants with N-deficiency at both 690 nm and 740 nm. A fluorescence based index, called the nitrogen balance index (NBI), exploit the ratio of far-red fluorescence excited by UV light to red fluorescence excited by either green or red light to detect nitrogen deficiency pf green plants (Cartelat et al., 2005).

The hypothesis of this study was that the sensing of fluorescence has the potential to detect N-deficiency in corn earlier than V8 growth stage. The specific objective was to determine if fluorescence sensing can detect differences in corn plants treated with four different N rates before V8 growth stage of corn.

MATERIALS AND METHODS

This experiment was conducted in a greenhouse at Colorado State University from October 2010 to February 2011. The soil used for this experiment was collected at Colorado State University’s Agricultural Research Development and Education Center, located in Fort Collins, Colorado (40° 40’ 38.24” N, 104° 58’ 44.76” W). In this field, soil was sampled in five locations and was sent for nitrogen content analysis. Among the five locations, the one with the lowest residual nitrogen content was chosen to take the soil used for the greenhouse study. The soil was sieved at 5 mm. A composite sample from the soil collected at this location was sent for analysis. Soil texture was classified as a sandy clay loam and residual NO_3-N content was 1.7 mg/kg.

Corn (*Zea maize* L.) plants (variety DKC45-79) were grown in 11 liters plastic pots. Each pot contained 8 kg of soil. Four nitrogen treatments were used: control (0 kg/ha), low (75 kg/ha), intermediate (150 (kg/ha) and high (225 kg/ha). For each nitrogen rate, 20 pots were prepared, giving a total of 80 pots. Prior to planting, reagent grade fertilizer was added to each pot. Nitrogen was added under the form of ammonium nitrate (NH_4NO_3) at the rate of 0 mg/pot for control pots, 583 mg/pot for low N pots, 1167 mg/pot for intermediate N pots and 1750 mg/pot for high N pots. For each of the eighty pots, 2899 mg of potassium phosphate (KH_2PO_4) and 53 mg of zinc sulfate ($ZnSO_4$) were added. There were three corn plants per pots. Weeds were hand removed every other day. Water was supplied by drip irrigation every day.

The sensor used for this study was the Mutiplex®3 hand-held multi-parameter optical sensor (FORCE-A, Orsay, France). The sensing area is about 10 cm in diameter. The Multiplex®3 was set to make an average over 500 induction/detection cycles for each reading (Table1). The four induction channels are UV, blue, green and red and the three detection channels are yellow (YF), red (RF) and far-red (FRF). The flash induces the emission of fluorescence and filters allow the selection of the wavebands of interest. The Multiplex®3 automatically computes two nitrogen balance indexes (NBI), the green NBI (NBI_G) and the red NBI (NBI_R; Table 1).

Readings were taken twice a week from V4 to V8 growth stage of corn by holding the sensor 10 cm above the top leaves of each pot. This process was repeated for each of the four sets of pot (different N treatment). At tasseling, plants were cut, dried and weighted.

For each selected parameter and for each growth stage, an ANOVA was used to detect significant difference among fluorescence reading (α = 0.05). In the case of significant difference, a Tukey's HSD test was used to compare treatments. The same analysis was done for corn plants dry weights. All statistical analysis was done using the statistical software R with the functions "aov" and "TukeyHSD" (R Development Core Team 2010).

Table 1. Parameters used for this study along with their description and formula.

Parameter	**Description**	**Formula***
NBI_R	Nitrogen balance index (red)	$\frac{1}{500}\sum_{i=1}^{500}\frac{FRF_{UV_i}}{RF_{R_i}}$
NBI_G	Nitrogen balance index (green)	$\frac{1}{500}\sum_{i=1}^{500}\frac{FRF_{UV_i}}{RF_{G_i}}$

*Fluorescence waveband is indicated as FRF for far-red fluorescence and RF for red fluorescence and induction waveband is in subscript. UV=Ultra-violet; G=Green; R=Red.

RESULTS

<u>Nitrogen treatment effect:</u> The different nitrogen treatments had a significant effect on dry weight (Fig. 1). Dry weight resulting from 150 kg/ha N rate and 225 kg/ha N rate were not significantly different from each other's. All other treatments resulted in significantly different dry weights.

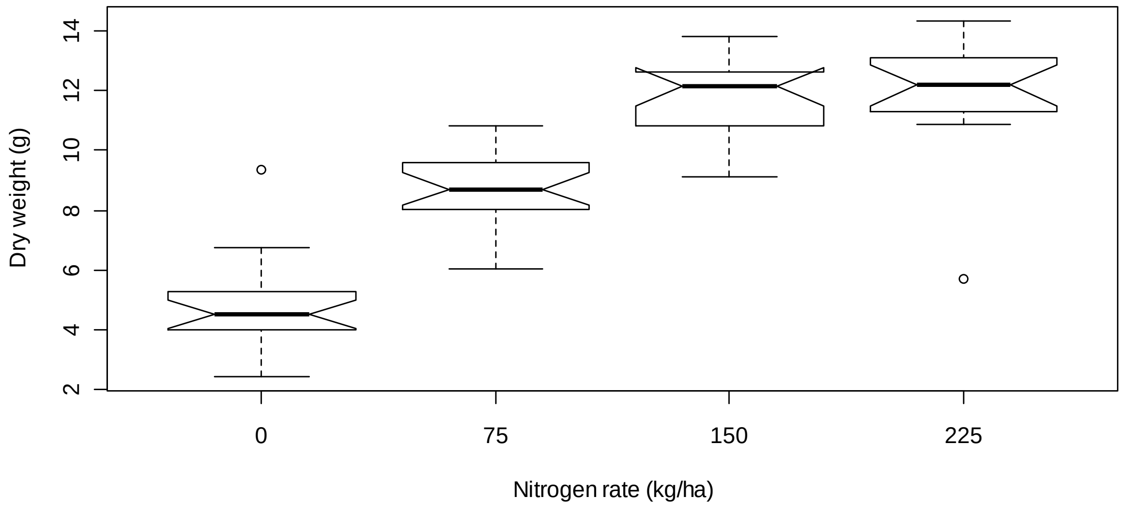

Figure 1. Boxplots of the difference in dry weights for the four N rate treatments. Boxplots with notches that do not overlap are significantly different (α = 0.05).

Fluorescence: Two parameters were investigated to detect corn N-deficiency. The first parameter was the nitrogen balance index measured with red excitation (NBI_R) and it presented good potential for N-deficiency detection from V5 growth stage of corn (Fig. 2). From V7, all four N-rate treatments were significantly different. The second parameter was the nitrogen balance index measured with green excitation (NBI_G) and it presented good potential for N-deficiency detection from V6 growth stage of corn (Fig. 2). From V7, all four N treatments were significantly different.

DISCUSSION

The main outcome of these results is the fact that induced fluorescence, as measured by Mutiplex®3, enabled the detection of N deficiency prior to V8 growth stage of corn (Fig. 2). Both NBI_R and NBI_G enabled the distinction between the lowest N rate (0 kg/ha) and the highest N rate (225 kg/ha) from V4 growth stage of corn. Previous studies have observed the potential of induced fluorescence to detect N deficiency (Chappelle et al., 1984; Cartelat et al., 2005; Zhang & Tremblay, 2010). However, no paper in the literature has mentioned the potential for induced fluorescence to detect N deficiency at such early growth stages.

Our results indicate that induced fluorescence is a promising approach to detect nitrogen deficiency in corn at early growth stages opening new possibilities for the practical implementation of site-specific nitrogen management. These results were obtained in a greenhouse experiment and field experiment should be implemented to evaluate the potential of this technology in a real corn field.

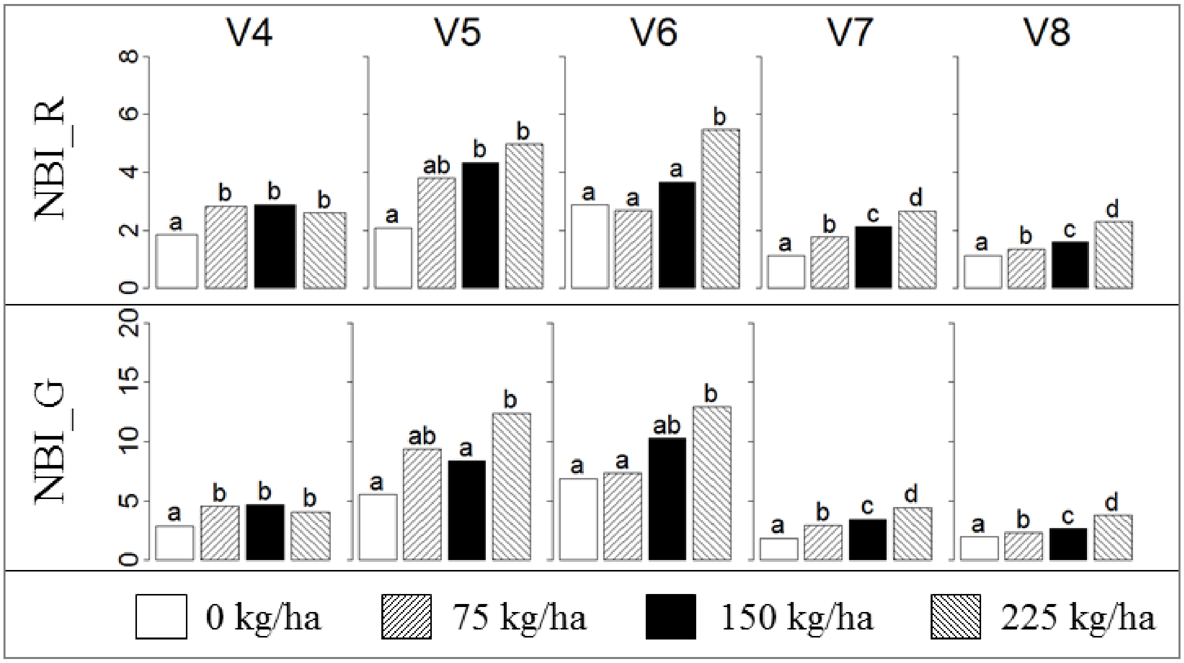

Figure 2. Bar graphs of the average value of each parameter (mentioned on the left axis), for each growth stages from V4 to V8 (mentioned on the top of the figure) and for each nitrogen rate (legend at the bottom of the figure). Different letters indicate significant difference (α=0.05) within the same growth stage and the same fluorescence parameter.

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FLUID FERTILIZER'S ROLE IN SUSTAINING SOILS USED FOR BIO-ENERGY FEEDSTOCK PRODUCTION

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ABSTRACT

The use of corn (*Zea mays* L.) as a bio-energy feedstock has attracted the attention of many producers. Recently, the focus has shifted from grain-based to cellulose-based ethanol production. In addition to biological conversion of corn stover to ethanol, thermal conversion (pyrolysis) of stover is being explored. Regardless of post-harvest processing, the short- and long-term effects of both increasing grain yields and removing stover on soil nutrient cycling, physical properties, and biological activity must be understood to ensure that soil productivity and ecosystem services are maintained. Our objectives for 2011 were to evaluate: (i) the use of surface or subsurface bands of N-P-K-S fluid fertilizers to optimize positional and temporal availability of nutrients; and (ii) the effect of biochar application on P availability and cycling in Clarion-Nicollet-Webster soils. Corn was grown in a field trial under a variety of management systems including 30-inch row spacing with standard fertility management and a twin-row, high-population treatment with increased nutrient additions applied in split-applications. Analysis of whole plants at V6 and ear leaves at mid-silk showed adequate levels of all macronutrients, which suggests that nutrient management was balanced for the two planting scenarios and the amount of stover removed from the field with the 2010 harvest. Management scenario, tillage, and previous stover removal did not affect corn grain yields, which varied from 172 to 182 bu/ac in 2011. In addition, biochar application and cover crop growth had no effect on grain and stover yields. As expected, the amount of dry stover collected was higher for the 90% removal (low cut) treatments of all management scenarios. In 2011, the intensively managed (twin row) plots did not produce more grain or dry stover than the conventional plots. In a separate controlled-climate chamber study, biochar and P fertilizer amendments affected soil P supply and corn seedling growth during five consecutive production and harvest cycles. Plants grown in soil with only 100 lb. P_2O_5/A had the highest shoot and root dry matter values, while those grown in soil amended with biochar in 2007 (legacy) without P fertilizer had the lowest values. Addition of 100 lb. P_2O_5/A numerically increased shoot and root dry matter values regardless of legacy or fresh biochar amendment. Although cumulative shoot dry matter production tended to be higher for treatments without biochar, the overall agronomic efficiency of the P fertilizer was improved by biochar application. Further statistical analysis of plant growth and nutrient uptake data should provide a clearer picture of the fertilizer value of the biochar, any biochar-fertilizer interactions, and whether legacy or fresh biochar affect the nutrition of juvenile corn in different ways.

INTRODUCTION

The use of corn as a bio-energy feedstock has attracted the attention of many producers, especially in the Cornbelt states. Recently, the focus has shifted from grain-based to cellulose-based ethanol production, with corn stover (stalks and cobs) being an important feedstock material (Bridgwater, 2006). In addition to biological conversion of corn stover to ethanol, thermal conversion (pyrolysis) of stover to bio-oil, syngas, and biochar is being explored as an alternative platform (Laird, 2008). Regardless of post-harvest processing, the short- and long-term effects of both increasing grain yields and removing stover on soil nutrient cycling, physical properties, and biological activity must be understood to ensure that soil productivity and ecosystem services are maintained. Up to this point, the bio-energy industry has been forced to use estimates, such as those offered by Johnson et al. (2006), to determine the amount of crop residues that must remain in the field. Research has shown that the use of no-tillage production can reduce the rate of residue decomposition, thus offering a mechanism to maintain soil organic carbon after removing some portion of the stover (Perlack et al., 2005). A significant amount of research has addressed fertility requirements and nutrient cycling in conventional grain production systems, but only recently has information on bio-energy feedstock systems become available (Heggenstaller et al., 2008; Blanco-Canqui and Lal, 2009). To provide more quantitative fertility guidelines, soil management studies focusing on cropping systems, tillage, fertilizer rates and placement, use of cover crops, and controlled wheel traffic are needed. Because it would be difficult to address all of these variables in a single project, our research focuses on nutrient requirements, specifically phosphorus (P), potassium (K) and sulfur (S), for no-till corn bio-energy production systems.

There is also significant interest in the use of biochar as a soil amendment for sequestering carbon and improving agricultural soil quality. Crop yield increases and improvements in soil physical and chemical properties have been reported, but variability among the responses has been significant (Glaser et al., 2002; McHenry, 2009). Biochars have some plant nutrient content, but nutrient availability can vary widely (Chan et al., 2007; McHenry, 2009). Biochars cannot be considered a substitute for fertilizers, although Chan et al. (2007) reported that yields of radish (*Raphanus sativus*) increased with increasing rates of biochar in combination with N fertilizer, suggesting that biochar played a role in improving N-use efficiency. Application of biochar to soils may also enhance P availability and improve P-use efficiency. Preliminary research has shown that additions of biochar tend to increase Mehlich 3-extractable P and reduce P leaching when applied in combination with animal manures (D.A. Laird, unpublished data).

The overall goal of this project is to evaluate the use of N-P-K-S fluid fertilizers to enhance corn grain and stover productivity. A secondary goal is to determine the role biochar application may have in nutrient cycling. This project is part of a long-term corn grain and stover removal study that focuses on standard and intensive fertility management, tillage, biochar additions to test the “charcoal vision” (Laird, 2008) for sustaining soil quality while producing bio-energy products, and use of cover crops to build soil carbon and help off-set potential negative impacts of stover removal. Our specific objectives for 2011 were to evaluate (i) the use of surface or subsurface bands of N-P-K-S fluid fertilizers to optimize positional and temporal availability of nutrients, and (ii) the effect of previous and recent biochar application on P availability and cycling in Clarion-Nicollet-Webster soils.

METHODS AND MATERIALS

Biomass Removal Study

The 25-acre field study established in 2008 on the Clarion-Nicollet-Webster soil association at the Iowa State University Agronomy & Agricultural/Biosystems Engineering Research Center (AAERC), southwest of Ames in Boone County, Iowa, was continued. This study currently focuses on rates of residue removal (0, ~50%, and ~90%), tillage (chisel plow versus no-tillage), a one-time biochar addition (4.32 and 8.25 tons/A), benefits of an annual cover crop, and effectiveness of a corn-soybean crop rotation. The rotation treatment was established in 2011 to replace a perennial cover crop treatment. One set of plots (40 x 280 ft.) is managed with standard production practices, and a second set of plots is managed in a twin-row configuration with higher inputs. Conventional weed and insect control practices are being followed. The study includes 22 treatments that are replicated four times. Soil samples (0-2 and 2-6 inches) were collected with a hand probe from each plot 9 November 2010, and analyzed for pH, organic matter content, available P, exchangeable K, Ca, and Mg, extractable SO^{4-}, and CEC (Table 1). Pioneer Brand P0461xr corn was planted 2-3 May 2011. With the exception of N, fertilizer applications in 2011 (Table 2) were based on 2010 grain and stover removals and fall soil test results. In 2011, the total N applied to conventional treatments was 200 lb/A, and to twin-row treatments was 225 lb/A. Early-season whole-plant samples at the V6 growth stage (15 June 2011) and ear-leaf samples at the mid-silk stage (22 July 2011) were collected and analyzed to determine the nutritional status of the crop. Beginning 1 November, corn grain and stover were harvested with an experimental, single-pass, dual-stream harvester, based on a John Deere 9750 STS combine equipped with an 8-row head. Sub-samples of stover and grain are being analyzed for nutrient content so that a more complete nutrient balance can be calculated.

Table 1. Average soil test levels for two depth increments within a Clarion-Nicollet-Webster soil association prior to imposing treatments for 2011. The range indicates plot variability within the study site.

Soil Test Parameter	Composite	Range	Composite	Range
	0-2 inch		2-6 inch	
Bray-1 P, ppm	40	13 – 72	29	11 – 62
Exch. K, ppm	171	114 – 278	115	79 – 198
Exch. Ca, ppm	2723	1954 – 3903	2935	1962 – 4041
Exch. Mg, ppm	285	186 – 424	313	185 – 504
Extract. S, ppm	6	4 – 7	4	2 – 10
pH	5.8	5.2 – 6.4	6.0	5.2 – 6.6
O. M., %†	3.3	2.5 – 4.9	3.1	2.4 – 4.0
CEC, cmol(+)/kg	20.2	14.2 – 28.1	20.6	15.2 – 28.3

† Ignition method.

Table 2. Fertilizer management for the conventional and high-input (twin row) systems in 2011.

System	Stover Removal, %	Timing	Source
Conventional		Fall 2010	11-52-0 + 0-0-60
200+68+49+20S	0	Starter	32-0-0 (UAN)
200+79+124+20S	50		12-0-0-26S (ATS)
200+88+188+20S	90	Sidedress	32-0-0 (UAN)
Twin-Row		Fall 2010	11-52-0 + 0-0-60
225+65+46+30S	0	Starter	32-0-0 (UAN)
225+76+118+30S	50		12-0-0-26S (ATS)
225+82+165+30S	90	Sidedress	32-0-0 (UAN)

Biochar Study

Surface soil (0-6 inches) was collected from two adjacent plots within the bio-energy field trial site at the Iowa State University AAERC in April 2010. One plot was a control that had standard management, chisel plow tillage, and 90% residue removal. The second was a biochar plot (8.25 ton/ac., fall 2007) that also had standard management, chisel plow tillage, and 90% residue removal. The soil for both plots is classified as Clarion loam (fine-loamy, mixed, mesic Typic Haplaquolls). Initial soil physical and chemical properties (Table 3) were measured.

To determine effects of previous (2007) biochar, fresh biochar, and liquid P fertilizer applications on soil P supply, a laboratory/climate chamber experiment was initiated. Commercially available hardwood-based biochar was added at rates equivalent to 0 or 8 tons/acre to subsamples of unamended soil. Ammonium polyphosphate (APP, 10-34-0) was then applied to provide the equivalent of 100 lb. P_2O_5 per acre. Nitrogen, K, and S fertilizers were also applied to ensure adequate amounts of those nutrients. The biochar and fertilizer were thoroughly mixed with the soil. Unamended soil served as a control treatment. After the amendments were added, the soils were incubated in a moist condition for four weeks. Following incubation, soil solution was displaced and analyzed for total P and Bray 1-P was determined for the treated and untreated soils. Relative changes in these soil P supply parameters are being used to quantify legacy and fresh biochar amendment effects on P.

Table 3. Initial soil test levels for Clarion loam collected in 2010. Legacy biochar refers to an 8 ton/acre application to this soil in the fall of 2007.

Soil Test Parameter	Control Soil	Legacy Biochar Soil
Bray-1 P, ppm	65 (VH)	50 (VH)
Exchangeable K, ppm	159 (VH)	119 (L)
Exchangeable Ca, ppm	2034	1981
Exchangeable Mg, ppm	206	213
Extractable S, ppm	4	4
pH	5.6	5.7
Organic Matter, %	2.8	2.8
CEC, cmol(+)/kg	15.1	14.8

A pot experiment was then initiated. Pre-germinated corn (Pioneer Brand 36V75) seedlings were planted two per pot, and pots were placed in a controlled-climate chamber with

16 hours of light and 22°C/12°C day/night temperature. Each treatment combination was replicated four times. After 20 days, plants were harvested. Corn roots were separated from soil, and after fertilizing with replacement N (but not P), the same soil was returned to each pot. New corn seedlings were planted and allowed to grow another 20 days. In order to investigate the effect of biochar addition on depletion of plant-available P, the treatment soils were subjected to five growth cycles. At this point, measurements are complete, but data analyses are incomplete. Total dry matter production and nutrient uptake from each treatment are being compared. The agronomic efficiency of the P fertilizer and P uptake efficiency are being calculated for the various treatments. These data are being used to determine: i) the P fertilizer value of the biochar, ii) if biochar-P fertilizer interactions occurred, and iii) the differences between legacy and fresh biochar as it relates to the P nutrition of the corn. Because of the time and effort involved in carrying out this study, concurrent measurements of K and S uptake efficiency will also be evaluated. In addition, we monitored water-use efficiency.

RESULTS AND DISCUSSION

Biomass Removal Study

Plant Nutrition

Management scenario, tillage, and the amount of residue removed from the field with the 2010 harvest did not affect early plant growth and nutrient content of whole plants at the V6 stage. Levels of all primary and secondary macro-nutrients were adequate for optimal growth (Table 4). Nitrogen concentrations were well above the published critical value of 3.5% (Mills and Jones, 1996), suggesting that pre-plant N fertilizer and soil N were sufficient to support the corn crop before additional N was sidedressed six weeks after planting.

At mid-silk in 2011, no differences in ear-leaf nutrient concentrations were detected among the treatments (Table 5). Unlike previous years, N concentrations in the tissue were above the critical value. Phosphorus and K concentrations in ear leaves were also within the sufficiency ranges of 0.25% to 0.50% for P and 1.7% to 3.0% for K for all treatments (Mills and Jones, 1996). In addition, S concentrations were within the sufficiency range of 0.10% to 0.30% (Jones et al., 1990).

The plant analysis results suggest that fertilizer inputs and nutrient removals are more balanced than in previous years, although since the hybrid was changed, that could have also affected nutrient uptake and use efficiency. During the first growing season of the trial in 2008, N, K, and S deficiencies were recorded (Kovar and Karlen, 2010), and N deficiencies persisted in 2009. These deficiencies were not a problem with the P0461xr hybrid in 2011.

Corn Grain and Stover Yield

In 2011, management scenario, tillage, and previous stover removal had little effect on corn grain yield (Table 6). In addition, the biochar and cover crop treatments had no effect on grain and stover yields, so data were pooled with the conventional treatments. In 2009 and 2010, grain yields tended to be lower when corn stover was not removed than when ~50% or ~90% was removed, but this was not the case in 2011. These results lend support to previous work

Table 4. Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) critical values and concentrations in whole plants at the V6 growth stage for five management scenarios in 2011. Values (%) are means of 8 to 16 replications depending on treatment. Standard deviations are in parentheses below each mean.

Nutrient	Critical Value	Control	Biochar 1†	Biochar 2‡	Twin-Row	Annual CC§
N	3.50	3.82 (0.25)	3.69 (0.16)	3.66 (0.21)	3.93 (0.27)	4.00 (0.18)
P	0.30	0.44 (0.04)	0.42 (0.04)	0.45 (0.05)	0.45 (0.03)	0.47 (0.04)
K	2.50	3.94 (0.30)	3.82 (0.35)	4.15 (0.28)	4.01 (0.31)	4.14 (0.28)
Ca	0.30	0.53 (0.04)	0.52 (0.04)	0.54 (0.04)	0.53 (0.04)	0.54 (0.03)
Mg	0.15	0.38 (0.05)	0.36 (0.04)	0.36 (0.04)	0.37 (0.04)	0.40 (0.03)
S	0.20	0.29 (0.02)	0.28 (0.02)	0.29 (0.02)	0.30 (0.02)	0.29 (0.01)

†4 tons biochar/A; ‡8 tons biochar/A; §CC = cover crop.

Table 5. Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) critical values and concentrations in ear leaves at mid-silk stage for five management scenarios in 2011. Values (%) are means of 8 to 16 replications depending on treatment. Standard deviations are in parentheses below each mean.

Nutrient	Critical Value	Control	Biochar 1†	Biochar 2‡	Twin-Row	Annual CC§
N	2.70	3.06 (0.13)	3.07 (0.12)	2.99 (0.11)	3.01 (0.13)	3.11 (0.13)
P	0.25	0.44 (0.03)	0.45 (0.03)	0.47 (0.03)	0.44 (0.03)	0.45 (0.03)
K	1.70	1.80 (0.11)	1.83 (0.09)	1.90 (0.14)	1.81 (0.15)	1.82 (0.09)
Ca	0.21	0.49 (0.04)	0.50 (0.04)	0.51 (0.04)	0.47 (0.04)	0.52 (0.04)
Mg	0.20	0.33 (0.03)	0.33 (0.03)	0.33 (0.03)	0.32 (0.03)	0.34 (0.03)
S	0.10	0.19 (0.01)	0.19 (0.01)	0.19 (0.01)	0.19 (0.01)	0.19 (0.01)

†4 tons biochar/A; ‡8 tons biochar/A; §CC = cover crop.

demonstrating yield decreases when plant residues are removed (Blanco-Canqui and Lal, 2009). Although greater N immobilization related to the residues remaining in the soil would negatively affect mid-season corn growth and subsequent grain yields, fertilizer N rates for the 2011 crop appear to have been sufficient to offset decreased N availability. The warm and humid weather in central Iowa during the late spring/early summer (Hillaker, 2012) provided ideal growing conditions for the corn crop, although high humidity kept overnight low temperatures persistently higher than usual, which may have negatively impacted corn pollination. Precipitation was greater than normal for five of the first six months of the year, which continued the very wet pattern of the previous three years. However, dry conditions quickly developed during late July and continued into August and September (Hillaker, 2012). These conditions during grain fill likely decreased final yield of the crop.

As expected, the amount of dry stover collected was higher for the 90% removal (low cuts) treatments of all management scenarios. Similar to 2009 and 2010, the intensively managed (twin row) plots did not produce more dry stover than the conventional plots. Whole plants collected at physiological maturity and residue samples from the machine harvest are being analyzed to determine elemental composition, so that the total amount of nutrients removed can be calculated. These values will be used to guide fertilizer recommendations for 2012.

Table 6. Management system, tillage, and residue removal effects on corn grain and stover yields in 2011. Values are means of 4 to 12 replications depending on treatment. Standard deviations are given in parentheses.

Treatment	Tillage	Percent Removal	Grain[†] (bu/ac)	Stover (t/ac)
Conventional	No-tillage	0	178 (6.1)	0
Conventional	No-tillage	50	177 (5.9)	1.63 (0.57)
Conventional	No-tillage	90	178 (2.8)	2.68 (0.28)
Conventional	Chisel Plow	0	173 (2.8)	0
Conventional	Chisel Plow	50	182 (2.9)	1.74 (0.19)
Conventional	Chisel Plow	90	176 (3.7)	2.94 (0.65)
Twin-Row	No-tillage	0	177 (6.1)	0
Twin-Row	No-tillage	50	182 (4.4)	1.86 (0.23)
Twin-Row	No-tillage	90	175 (10.6)	3.22 (0.96)
Twin-Row	Chisel Plow	0	172 (2.7)	0
Twin-Row	Chisel Plow	50	179 (5.8)	1.90 (0.24)
Twin-Row	Chisel Plow	90	170 (7.0)	2.69 (0.35)

[†] Grain yields adjusted to 15.5% moisture.

Biochar Study

Both biochar and P fertilizer amendments affected soil P supply and corn seedling growth during five consecutive production and harvest cycles. Relative differences in shoot and root dry matter production observed at Harvest 1, 20 days after planting, tended to hold throughout the trial (Table 6). Plants grown in soil amended with 100 lb. P_2O_5/A alone had the highest shoot and root dry matter values, while those grown in soil amended with biochar in 2007 (legacy biochar) without P fertilizer had the lowest values. Addition of 100 lb. P_2O_5/A, numerically increased shoot and root dry matter accumulation, regardless of biochar amendment. This result was somewhat unexpected, given the initial high levels of available soil P (Table 3). Higher root:shoot dry weight ratios were recorded for the legacy biochar treatments, suggesting that the plants were partitioning more resources to root growth, rather than shoot growth. Without plant nutrient content data, however, it is difficult to speculate on the reason for this result. Although cumulative shoot dry matter production tended to be higher for the treatments without biochar, the overall agronomic efficiency of the P fertilizer was improved by biochar application (Table 6). Further statistical analysis of plant growth and nutrient uptake data should provide a clearer picture of the fertilizer value of the biochar, any biochar-fertilizer interactions, and whether legacy or fresh biochar affect the nutrition of juvenile corn in different ways.

Table 6. Corn shoot and root dry matter accumulation, root:shoot ratios, and agronomic efficiency of phosphorus (P) fertilizer as affected by legacy (2007) and fresh (2010) biochar application. Plants were harvested after 20 days of growth in a controlled-climate chamber. Data represent dry matter accumulation after one harvest and after five harvests. Values are means of four replications. Standard deviations are shown in parentheses.

Treatment	P Fertilizer	Shoot Dry Weight	Root Dry Weight	Root:Shoot Ratio	Agronomic Efficiency
	lb. P_2O_5/A	G	g		g shoot DM/g P
Harvest 1					
Control	0	2.97 (0.17)	1.68 (0.14)	0.57	
	100	3.22 (0.10)	2.08 (0.08)	0.65	5.8
2007 Biochar†	0	1.90 (0.10)	1.49 (0.08)	0.78	
	100	2.16 (0.15)	1.60 (0.06)	0.74	6.2
2010 Biochar†	0	2.33 (0.16)	1.51 (0.05)	0.65	
	100	2.46 (0.14)	1.57 (0.18)	0.64	3.1
Cumulative‡					
Control	0	10.13 (0.81)	7.40 (1.11)	0.73	
	100	10.87 (0.30)	8.03 (0.72)	0.74	17.1
2007 Biochar†	0	7.71 (0.10)	6.57 (0.42)	0.85	
	100	8.93 (0.52)	5.81 (0.23)	0.65	28.3
2010 Biochar†	0	9.10 (0.31)	6.14 (0.35)	0.67	
	100	10.08 (0.29)	6.17 (0.56)	0.61	22.7

†8 tons biochar/A; ‡ Values are cumulative for five harvests of dry matter.

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Visualization of phosphorus diffusion from granular and fluid fertilizers in non-calcareous highly phosphorus-fixing soils

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INTRODUCTION

Low phosphorus (P) availability is an important constraint for plant growth in soils with high P-fixing capacities. In these soils, large amounts of fertilizer are necessary to counteract low efficiency of P, as P can be rapidly and irreversibly converted to forms not available for plant uptake. There is an increasing interest in the improvement of fertilizer efficiency through reducing P fixation in soils. However, improvements can only be achieved when the behaviour of fertilizers in soils are clearly understood. Work in this regard has been undertaken in the calcareous alkaline soils of Australia where the chemical behaviour of granular and fluid P fertilizers has been investigated using direct methods (isotopic dilution with radiotracers) and non-destructive spatially resolved spectroscopic techniques. Results from these studies have led to the conclusion that fluid fertilizers outperform granular sources on these types of soils, due to a greater diffusion of P from the point of fluid P application (Lombi et al., 2004a; Lombi et al., 2006). It is not clear yet whether fluid fertilizers have beneficial effects in non-calcareous soils. The aim of this study was to investigate the diffusion of P from granular and fluid fertilizers applied to slightly acidic high-P fixing soils through the utilization of a simple and quick visualization method. Also a calcareous and a non-fixing soil were included for comparison.

MATERIALS AND METHODS

Visualization of P diffusion

Five surface (0-10 cm) soils (Table 1) from the following soil orders (U.S. Soil Taxonomy Classification): an Andisol from New Zealand (North-NZ), two Oxisols, one from Western Australia (Greenwood) and one from Queensland (Redvale), a calcic Inceptisol from South Australia (Pt. Kenny), and an Alfisol from South Australia (Monarto). Soils from the orders Andisol and Oxisol were selected because of their large content of minerals with high P affinities (e.g. Fe/Al oxides, hydroxides, and allophane). The calcic Inceptisol was included because of its high calcium carbonate content, which promotes P fixation through precipitation reactions of P with Ca. The Alfisol is a non-fixing soil and was included for comparison.

The soil samples were air dried and ground to pass a 2-mm sieve. Soil pH was measured in a 1:5 soil/deionized water suspension. Oxalate extractable Al (Al_{ox}) and Fe (Fe_{ox}) were determined using a 1:100 soil/oxalate extract, following the procedure described by Rayment and Higginson (1992). Diffusive gradient in thin films (DGT) devices assembly and deployment was performed according to the methodology of Mason et al. (2010). Total soil carbon content was measured using the procedure of Matejovic (1997). The $CaCO_3$ content of the Pt. Kenny and Monarto soils was determined following the Martin and Reeve (1955) method. Soil texture was determined using the pipette method (McKenzie et al., 2002) after oxidation of organic matter by hydrogen peroxide and destruction of carbonate by acetic acid. The sorption of P by the soils was determined using different P equilibrating solutions as described by Rayment and Lyons (2011).

Table 1. Selected chemical and physical properties of the soils used in the visualization study.

	North-NZ	Greenwood	Redvale	Pt Kenny	Monarto
Soil order	Andisol	Oxisol	Oxisol	Inceptisol	Alfisol
pH (H_2O)	5.7	5.9	6.4	8.7	7.9
Al_{ox}, mg/kg	42000	17300	2340	241	345
Fe_{ox}, mg/kg	8190	4140	2220	98	325
P_{DGT}, µg/L	16	6	b.d.l.†	33	11
Total C, %	8.5	4.4	1.0	2.8	1
$CaCO_3$, %	<0.2	<0.2	<0.2	28	< 0.2
Clay, %	6.6	13.1	61.3	3	8.3
Freundlich *k* parameter ‡	2515	1402	983	92.7	8.64
Freundlich *n* parameter ‡	0.79	0.76	0.32	0.57	0.59

† b.d.l., below detection limit
‡ Freundlich equation: $s = k.c^n$, with s (mg/kg) the P concentration on the solid phase and c (mg/l) the solution concentration in a water extract at L:S 10 l/kg. k is a measure of soils affinity to sorb P while n relates to the change in affinity with concentration.

Plastic Petri dishes (5.5 cm diameter and 1.1 cm height) were filled to obtain a bulk density of 0.7, 1.0, 1.2, 1.1 and 1.3 g/cm^3 for the North-NZ, Greenwood, Redvale, Pt Kenny, and Monarto soils, respectively and were wetted to field capacity using deionized water. The Petri dishes were closed, sealed with Parafilm and left to equilibrate overnight. The following day the Petri dishes were opened and fertilizer was placed at the exact centre of each Petri dish 3 mm from the surface. Fertilizer treatments included five granular and three fluid fertilizer sources. Three and four replicates were prepared for the granular and fluid treatments, respectively.

- Granular fertilizers: the granular products evaluated were the calcium phosphates: single super phosphate (SSP; 9% P), and triple super phosphate (TSP; 20% P), and the ammonium phosphates: monoammonium phosphate (MAP; 22% P), diammonium phosphate (DAP; 20% P), and MES-10 which is a product that contains 17.5% P in the form of monoammonium phosphate and 10% S (half as ammonium sulphate and half as elemental sulphur). The granules of each fertilizer were selected based on their weight in order to add 9.24 mg of P per Petri dish.
- Fluid fertilizers: 200 and 100 µL of a solution of technical grade MAP (TG-MAP), and 100 µL ammonium polyphosphate (APP; 16% P) were injected in the middle of each Petri dish. The rate of P added was the same as for the granular treatments (9.24 mg P per Petri dish).

After the application of the fertilizers the Petri dishes were closed, sealed with Parafilm, and incubated in dark conditions and room temperature. The Petri dishes were opened at days 7 and 35 after the fertilizer application, in order to carry out the visualization.

The visualization of P diffusion was performed following the method developed by Degryse et al. (in preparation). On the day of the visualization, previously prepared

Fe oxide impregnated filter papers (Chardon et al. 1996) (Whatman, No. 1, and 5.5 cm diameter) were wetted and immediately put in contact with the soil. After a 30 min deployment time the papers were removed from the soil and rinsed with deionized water to remove adhering soil particles. The P on the paper was visualized using a method modified from Cutting and Roth (1973). The papers were left to air dry before being scanned. The scanned images were analyzed with GIMP (v. 2.6.11) software for image processing. The images were converted to black-white binary images, based on a threshold colour value. The area of the black (high-P) zone was quantified using the histogram command, from which the radius was derived.

Statistical analysis

The radius of P diffusion was analyzed using the PROC GLM procedure Statistical Analysis System software (SAS Institute, 2003). Additionally, the Tukey's multiple comparison procedure was used to identify differences among treatment means at the 0.05 level.

RESULTS AND DISCUSSION

Visualization of P diffusion

The Andisol and Oxisol used in the present study were classified as slightly acidic, with a pH (in water) ranging from 5.7 to 6.4; whereas the calcic Inceptisol is an alkaline soil with a pH of 8.7. The strength of P sorption decreased in the order of North>Greenwood>Pt. Kenny>Monarto but was also concentration dependent (Figure 1).

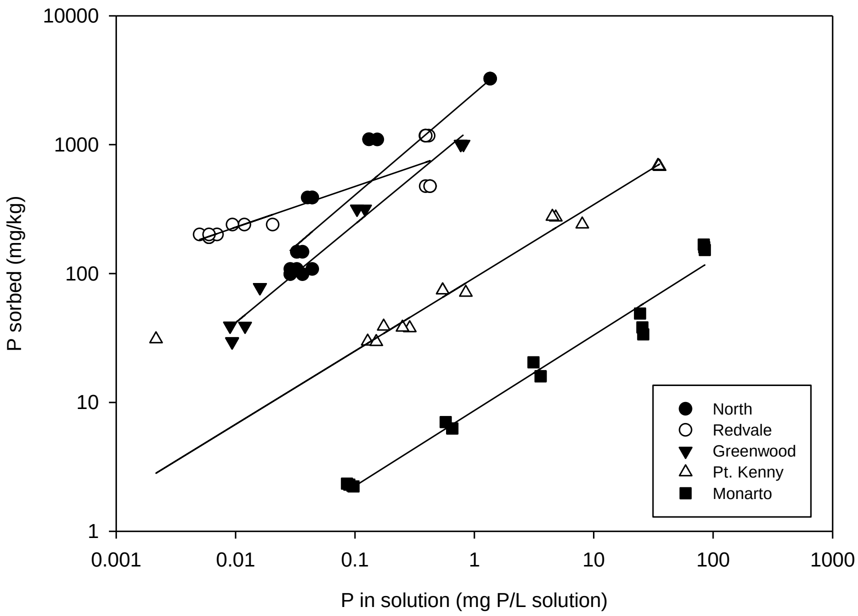

Figure 1. Sorption data for P applied as KH_2PO_4 for the five soils, showing agreement with the Freundlich model (parameter values in Table 1), except for the North NZ soil.

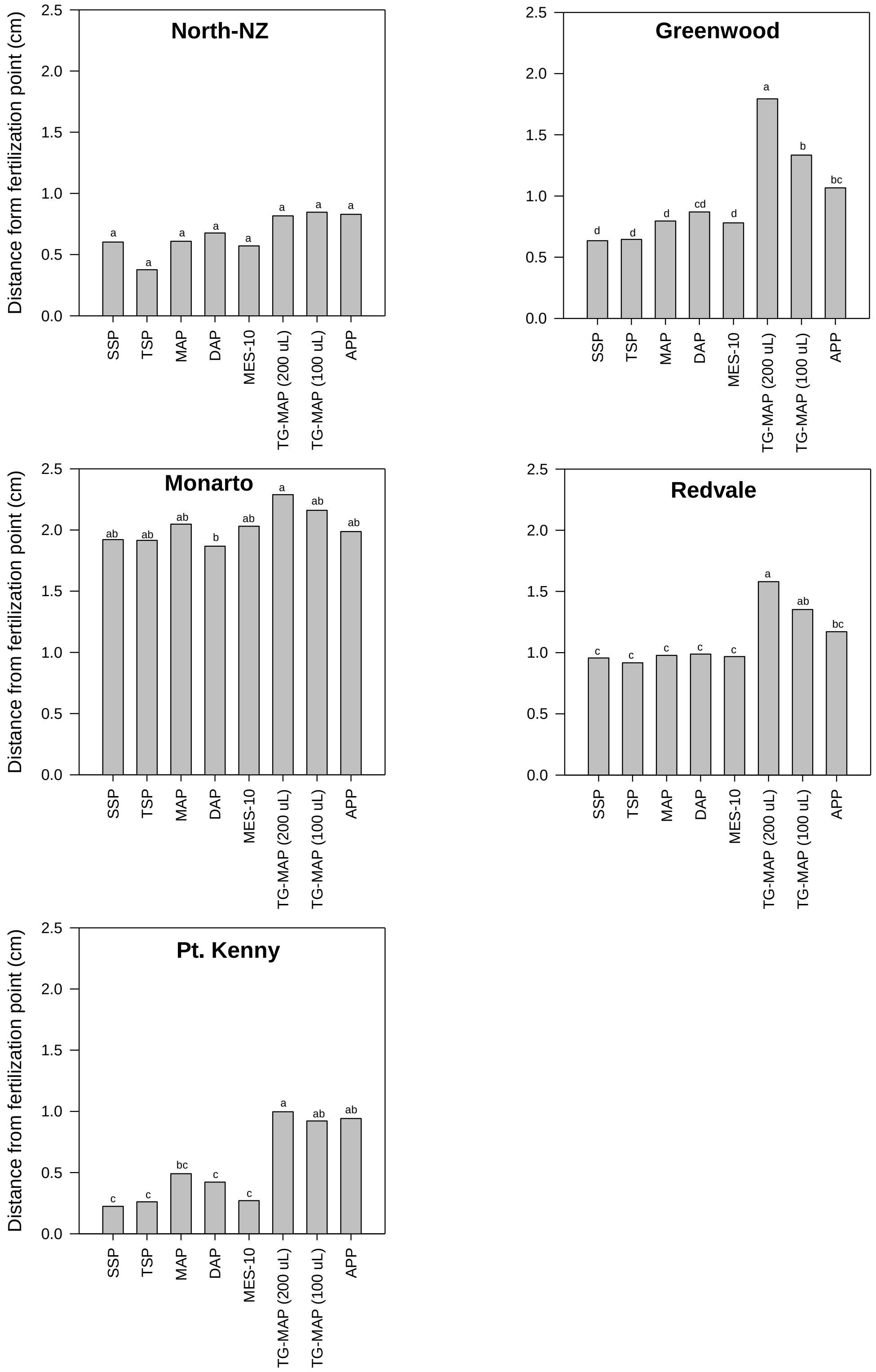

Figure 2. Diffusion of P from granular and fluid fertilizers as measured by the visualization technique.

The radius of diffusion of P from the point of fertilizer application at day 7 is shown in Figure 2. The faster diffusion of P in the Monarto soil (2.04 cm) compared to that of the other soils can be explained by the weaker P sorption in this soil. The calcic Inceptisol (Pt. Kenny) had the smallest radius of diffusion despite having a P sorption strength lower than the Oxisols and the Andisol.

A significantly greater diffusion was observed for the fluid fertilizers than for the granular fertilizers in the two Oxisols (Redvale and Greenwood) and in the calcic Inceptisol (Pt. Kenny), but not in the Andisol (North) and Alfisol (Monarto) soils.

The greater mobility of fluid P in a calcareous soil was previously observed by Lombi et al. (2004a), and was found to be related to the flow of soil moisture toward the hygroscopic fertilizer granule, limiting the diffusion of P outward which in turn favours precipitation of Ca-P species (Hettiarachchi et al., 2006; Lombi et al., 2006). The same physical and chemical processes may have limited the diffusion of P from the granular fertilizers in the Oxisols; however it is likely Al and Fe, and not Ca, were the key elements in these acidic soils limiting P diffusion.

Diffusion of P from the fluid fertilizers in the Andisol was not significantly better than the granular products, despite this soil having a highest P sorption capacity.

CONCLUSIONS

Previously, fluid fertilizer P has been found to diffuse better through calcareous soils and lability of the fertilizer P is higher than for equivalent granular formulations (Lombi et al., 2004b), leading to higher agronomic efficiency for crop production (Holloway et al., 2001). The visualization experiment indicated that diffusion of P from fluid fertilizers may also be greater that equivalent granular fertilizers in non-calcareous soils. The two Oxisols used here exhibited strong P sorption and fluid P was more effective in diffusing through these soils than granular P. However, fluid P was not more effective in terms of diffusion in the Andisol, despite the strong P sorption in this soil – this is under further investigation.

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IMPROVING THE EFFICIENCY OF FOLIAR FERTILIZATION WITH UREA USING UREASE INHIBITORS

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SYNOPSIS

Urea is the most recommended foliar N source due to its relatively low toxicity, quick absorption, and low cost. However, in the literature reports of yield increases with foliar urea application are inconsistent. The objectives of this research were to study foliar urea assimilation in cotton and to test the effect of the urease inhibitor N-butyl thiophosphoric triamide (NBPT) with foliar urea application. The study consisted of a growth chamber experiment with the treatments: (1) control; (2) foliar urea; (3) foliar urea+NBPT; and (4) foliar NBPT, and a field experiment with the treatments: (A) full recommended N soil rate with no foliar N application; (B) 75% of recommended N soil rate with no foliar application; (C) 75% of recommended N soil rate with two foliar Urea applications; (D) 75% of recommended N soil rate with two foliar Urea+NBPT applications. Each foliar urea application was calculated to supply 11.2 kg of N per hectare. In the growth room study the addition of NBPT to foliar urea inhibited urease activity. In addition, NBPT exhibited a trend for increased leaf urea content and improved cell membrane integrity. In the field study the addition of NBPT to foliar urea resulted in an increase in seedcotton yield. In conclusion, NBPT was effective in inhibiting cotton leaf urease, and in improving nitrogen use efficiency and yield in field grown cotton.

JUSTIFICATION

Foliar N application has been studied as a supplement to meet cotton N requirements (Oosterhuis, 1999). Cotton root capacity for absorbing nutrients declines when the plants are developing fruit (Maples and Baker, 1993), and therefore at this stage it is reasonable to supply N to the plants by foliar application. Foliar application of N has the advantages of low cost and rapid response of the plant, and the disadvantages of possible foliar burn, compatibility problems with other chemicals and limitations on the amount of nutrient that can be applied (Oosterhuis, 1999). Many studies have been done testing the use of foliar urea in cotton; however results in yield have been inconsistent (Maples and Barker, 1993; Oosterhuis and Bondada, 2001; Wilborn et al., 2006).

Once in the plant urea is converted to ammonia, by the enzyme urease, and ammonia is incorporated to glutamate, by the enzyme glutamine synthetase (Sirko and Brodzik, 2000). In the literature it is still not clear whether leaf burn resulted from foliar urea application is caused by toxic accumulation of urea or ammonia. In soybean, foliar urea leaf burn is mainly associated with urea accumulation (Bremmer 1995; Krogmeier et al., 1989). However; to our knowledge in the literature there is no research done in cotton. Use of urease inhibitor with foliar urea application could be an effective method to help elucidate the fate of urea in cotton leaves. A well known urease inhibitor is N-(n-butyl) thiophosphoric triamide (NBPT) applied in the soil with urea, NBPT has been proved to have high efficiency in inhibiting urease at low concentration in a wide variety of soils (Vittori et al., 1996; Rawluk et al., 2001).

Preliminary data indicated that addition of NBPT to foliar urea application increased cotton yield, with values significantly higher than urea alone. Furthermore, seedcotton yield of NBPT + foliar urea treated plots that received only 75% of the full recommended N rate was statistically equivalent to the plots that had 100 % of the N rate. Thus, the use of urease inhibitor with foliar urea fertilization could have the potential of enhance N assimilation in plant leaves, which could help improve foliar N management in crops.

OBJECTIVES

The main objective is to study foliar urea assimilation in cotton plants and how the use of the urease inhibitor NBPT will affect the efficiency of foliar urea application. An additional objective is to understand if cotton leaves treated with urea, suffers from toxicity of urea or ammonia. With a better understanding of the physiological effects of foliar urea application and the use of a urease inhibitor, we expect to improve foliar N management in crops.

MATERIAL AND METHODS

Growth room and field tests were conducted to determine if use of the urease inhibitor NBPT will affect the efficiency of foliar urea application.

Growth Room Study:

Cotton (*Gossypium hirsutum* L.) cultivar ST4554B2RF was planted in 1.5-liter pots filled with soil from a representative cotton growing area in Marianna, AR (Memphis silt loam - fine-silty, mixed, active, thermic Typic Hapludalfs). The pots was arranged in a large walk-in growth chamber (Model PGW36, Conviron, Winnipeg, Canada) with day/night temperatures of 30/20^{o}C, relative humidity of 70% and 14 hour photoperiods at 500 µmol m^{-2} s^{-1} of photosynthetically active radiation (PAR). The P_2O_5 and K_2O fertilization rates were 45 and 73 kg ha^{-1} calculated using a soil volume of 1 ha and 0.15 m furrow slice. No soil N fertilization was applied in this experiment and pots were watered daily only with double deionized water. The treatments consisted of: (T1) untreated control with no foliar urea application; (T2) foliar urea application; (T3) foliar urea applications with NBPT (T4) foliar NBPT without urea. Each foliar urea application was calculated to supply 11.2 kg of N per hectare. The treatment with urea plus

NBPT was applied using the commercial fertilizer Agrotain (Agrotain Int. LLC) and the foliar NBPT rate was calculated based on reports that Agrotain contains 0.84% of NBPT. Treatments were applied at 8:00 AM, 4 weeks after planting. Spraying was carried with a CO_2 backpack sprayer regulated to deliver 93.22 l ha^{-1}. Photosynthesis and chlorophyll fluorescence were measured 2 and 24 hours after application. Leaf discs for membrane leakage were collected 2 and 24 hours after application, and immediately after, leaves were sample for subsequent biochemical measurements. Leaves were kept in a -80^{o}C freezer for protein, glutathione reductase, glutamine synthetase, urea and urease determination. The experiment was repeated twice in 2010 and a complete randomized design with 5 replications was used to conduct the experiment.

Measurements included: Leaf photosynthesis was recorded using a Licor 6200 photosynthesis portable system; Chlorophyll fluorescence was done using a Modulated Fluorometer OS1-FL; Membrane leakage was measured as a percent injury method; Malondialdehyde (MDA) extraction procedure followed the method of Goel & Sheoran (2003); Glutathione Reductase (GR) Activity was measured using the method of Gomez et al. (2004); Leaf protein content was measure using the method of Bradford (1976); Glutamine Synthetase (GS) with a modified leaf extraction method of Yajun et al. (2008); Urea measured using a modified method of hot water extraction of Lang and Kaiser (1994); and Urease measured using the method of Gerendas and Sattelmacher (1997.

Field Study:

A field study was conducted at the University of Arkansas Lon Mann Cotton Branch Station at Marianna, AR in a Memphis silt loam (Fine-silty, mixed, active, thermic Typic Hapludalfs) soil. The experiment was uniformly fertilized following preseason soil tests and state extension recommended rates, except for N, which was applied according to the treatments. Treatments consisted of: (T1) full recommended N soil rate with no foliar N application; (T2) 75% of recommended N soil rate with no foliar application; (T3) 75% of recommended N soil rate with two foliar urea applications (at first flower and two weeks later); (T4) 75% of recommended N soil rate with two foliar urea plus NBPT applications (at first flower and two weeks later). Each foliar urea application was calculated to supply 11.2 kg of N per hectare. The treatment with urea plus NBPT was applied using the commercial fertilizers Agrotain (Agrotain Int. LLC). The full recommended N rate consisted 125 kg N ha^{-1} and 93.7 kg N ha^{-1} was used for 75% of the recommended N rate treatment. Soil-applied N fertilization was side-dressed at planting and at the pinhead-square stage using urea. Weed, insect control and irrigation were performed according to state extension recommendations. The experiment was conducted using a plot size of 4 rows spaced 0.96 m apart by 15 m length. A randomized complete block design with 5 replications was used to conduct the experiment. Seedcotton yield was measured from the two middle rows using a mechanical harvester.

Statistical Analyses: In the growth chamber study a three factor factorial analysis was used, with the factors being treatment application, time of measurement and experiment. The objective of this analysis was to observe the interaction effect between treatment and time of measurement and the main effect of treatment. For the field study a two factor factorial analysis was used, in which the factors consisted of treatment application and year of the study. The software JMP version 8.1 (SAS Institute Cary, NC) was used to perform the statistical analyses. Mean and standard error values were calculated to assemble graphs using the Sigma Plot software version 10 (MMIV Systat Software, Inc., San Jose, CA). Analysis of Variance and LSD test (α=0.05) were used to analyze statistical significance between means. A probability less than 0.05 was considered significant.

RESULTS

<u>Growth Room Study:</u>

There was a significant main treatment effect was observed for membrane leakage (*P=0.*0031) and MDA (*P=0.0270*). There was a significant decrease in membrane leakage and MDA for the NBPT treatment. For example compared with the control, the NBPT treatment had a decrease of 20% (*P=0.0051*) in membrane leakage and 18% (*P=0.0070*) in MDA content. The treatment Foliar Urea+NBPT (58.59±7.41 % injury) had only a numerical decrease (*P=0.0827*) in membrane leakage (Fig. 1A) compared to the Foliar Urea treatment (61.65±6.38 % injury). Similarly, data of MDA (Fig. 1B) also indicated only a numerical (*P=0.1761*) decrease in the values of the Foliar Urea+NBPT (20.38±1.17 mmol g^{-1} FW) compared to the Foliar Urea (22.44±1.24 mmol g^{-1} FW) treatment.

Glutathione reductase data (Fig. 1C) did not have any significant interaction or treatment effect (*P=0.1191)*. The Foliar Urea+NBPT treatment had a numerical increase in GR values compared to the rest of the treatments; however due to the high variability in the measurements the data were not significantly different.

Data of urease activity (Fig. 2) had a significant (*P=0.0349*) interaction effect between the parameters treatment and time of measurement. The analysis indicated that no significant treatment effect (*P=0.7913*) was observed in the measurements made a 2 h after foliar application (Fig. 2A). However measurements collected at 24 h after foliar application (Fig. 2B) showed a significant (*P=0.0114)* treatment effect, in which the foliar urea treatment exhibited significantly higher urease activity values than the rest of the treatments. In comparison to the Foliar Urea+NBPT (0.007±0.0001 units g^{-1} FW) treatment, the Foliar urea (0.011 ±0.0001 units g^{-1} FW) treatment had a 42% increase in urease activity (*P=0.02335*) when measurement were made 24 h after foliar application. Furthermore, the Foliar Urea+NBPT treatment did not exhibit increased urease activity; its values were not significantly different than the control treatment (*P=0.4909)*.

Leaf urea content (Fig. 3) measurement also indicated a significant (*P=0.0382*) interaction effect between the parameters treatment and time of measurement. In the measurement made 2h after foliar application (Fig. 3A) a significant treatment effect was observed (*P=0.0200*); however, the only statistical differences observed were when the Foliar NBPT treatment was compared with the treatments Foliar Urea (*P=0.*0129) and Foliar Urea+NBPT (*P=0.*0034). At the measurement made at 24h after foliar application (Fig. 3B), also a significant treatment effect was observed (*P<0.0001*). Compared to the Control treatment a significant increase in leaf urea content was observed in the treatments Foliar Urea (*P=0.*0013) and Foliar Urea+NBPT (*P=0.*0006). In this case, the treatments Foliar Urea (3.15±0.18 mM g^{-1}FW) and Foliar Urea+NBPT (3.57±0.44 mM g^{-1}FW) had respectively, a 48% and 68% increase in leaf urea content compared to the Control treatment (2.12±0.11 mM g^{-1}FW). Significant differences were also observed when the Foliar NBPT treatments was compared with the treatments Foliar Urea (*P=0.*0003) and with Foliar Urea+NBPT (*P=0.*0002). On the otherhand, comparative analysis of the Foliar Urea with Foliar Urea+NBPT (*P=0.*4780) and of the Control with Foliar Urea (*P=0.*5887) were not significant.

The data of GS (Table 1) and leaf protein (Table 1) content did not have any significant interaction or treatment effect. The treatment effect P values for GS and protein were respectively 0.4354 and 0.1193. Similarly the measurement of photosynthesis (Table 2 and chlorophyll fluorescence (Table 2) had no statistical effect of interaction or treatment. In this case the treatment effects P-values for photosynthesis and chlorophyll fluorescence were 0.1961 and 0.8531, respectively.

Field Study:

A significant (*P=0.*0012) interaction effect between treatment and year of the experiment was observed in the data of seedcotton yield. There was a significant (*P=0.0029*) treatment effect (Fig. 4A) with the treatments 100% N Soil–No Foliar and 75% N Soil–Urea+NBPT Foliar exhibiting the highest yields. Significant differences were observed between the treatments 100% N Soil–No Foliar and 75% N Soil–No Foliar (*P=0.0013)*, between 100% N Soil–No Foliar and 75% N Soil–Urea Foliar (*P=0.0167*), between 75% N Soil–No Foliar and 75% N Soil–Urea+NBPT Foliar (*P=0.0017*), and between 75% N Soil–Urea Foliar and 75% N Soil–Urea+NBPT Foliar (*P=0.0221*). No differences were observed between the treatments 100% N Soil–No Foliar and 75% N Soil–Urea+NBPT Foliar (*P=0.8831*), and between 75% N Soil–No Foliar and 75% N Soil–Urea Foliar (*P=0.1901*). Comparative analysis of the treatments indicated that 75% N Soil–Urea+NBPT Foliar (1997.10±108.25 kg ha^{-1}) exhibited a 20%, and 12% increase in seedcotton yield compared to the treatments 75% N Soil–No Foliar (1660.05±61.52 kg ha^{-1}) and 75% N Soil–Urea Foliar(1776.60±62.68 kg ha^{-1}), respectively. In 2010 (Fig. 4B), the treatment effect on seedcotton yield was not significant (*P=0.0951*). Differences were expected between the treatments 100% N Soil–No Foliar and 75% N Soil–No Foliar, but the comparison was not significant (*P=0.1106*).

In the measurement of leaf burn (Fig. 5A) collected in the 2010 experiment, a significant treatment effect was observed (*P<0.0001*). However the comparative analysis only indicated that higher values of leaf burn occurred in the plots that received foliar urea application. No significant differences were observed between the treatments 75% N Soil–Urea Foliar and 75% N Soil–Urea+NBPT Foliar (*P=0.2639*).

Measurement of leaf N (Fig. 5B) and petiole nitrate (Fig. 5C) content indicated no significant interaction or treatment effect. The P-values for the treatment effect were respectively 0.4197 and 0.2955 for leaf N and petiole nitrate data.

Discussion

The summary of the growth chamber study was that: application of only NBPT decreased membrane leakage and MDA; addition of NBPT-to-foliar-urea decreased urease activity measured at 24 h after application; and had no effect in the measurements of GS, GR, protein, photosynthesis, and chlorophyll fluorescence. In the field study, addition of NBPT to foliar urea resulted in a yield increase. Furthermore, addition of NBPT to foliar urea application had no significant effect on leaf burn, leaf N, and petiole nitrate content.

In the literature, foliar urea application with the urease inhibitor phenylphosphorodiamde (PPD) has been reported to have a negative effect on soybean leaves (Krogmeier et al., 1989). The authors of this study hypothesized that soybean leaf–tip injury caused by foliar urea application was attributed to ammonia formation from urea hydrolysis; however they reported that the leaf necrosis was attributed to toxicity of urea rather than of ammonia. On the otherhand Rawluk et. al. (1999) did not observe any negative effect from NBPT with foliar applied urea in wheat. In our study the negative effect of adding the urease inhibitor to foliar urea was not evident. We observed that addition of NBPT to foliar urea was effective in inhibiting leaf urease activity measured at 24 h after application. The mode of action of NBPT is carried by a binding and deactivation of the urease receptor site for urea (Mobiley, 1989; Manuza et al., 1999). The efficacy of NBPT in inhibiting urease in the soil is well documented (Watson et al., 1994; Antisari et al., 1996; Rawluk et al., 2001); however to our knowledge there is no report of NBPT effect on leaf urease activity. Since the addition of NBPT to foliar urea decreased urease activity it was expected that NBPT would result in increased leaf urea content. However, urea measurement collected at 24h after treatment application showed no significant differences between the treatments Foliar Urea and Foliar Urea+NBPT. There was a numerical increase in leaf urea content with addition of NBPT, thus it is possible that a statistical difference could be detected if the measurements were done after the 24h period. The data of urease and urea in cotton indicated that the total hydrolization and assimialtion of the foliar applied urea is not completed in the period of 24 h. The data of membrane leakage and MDA had identical results, indicating that application of Foliar NBPT improved the cell membrane integrity of cotton leaves. The treatment Foliar Urea+NBPT showed statistically equal values compared to the Foliar NBTP treatment; however its values were not significantly different than the Foliar Urea treatment. The process involved in the role of NBPT on cell membrane integrity is not clear; however since NBPT binds to Ni urease receptor sites, it is possible that NBPT has a Ni chelating effect in the plant. Ros et al. (1992) reported that Ni affected the cell plasma membrane properties and ATPase activity of rice plants. Furthermore, in the review of Seregin and Kozhevnikova (2006), there are reports of Ni causing oxidative stress in a variety of plants, thus NBPT in the plant could be resulting in a protective mechanism against Ni. In this experiment, no evidence of a negative effect of urea and/or NBPT was observed in the measurements of GR, GS, protein, photosynthesis and chlorophyll fluorescence. However it is possible that an effect of NBPT could occur in a measurement collected after the 24 h sampling, since a significant NBPT effect was observed in urease and membrane integrity data. Additional research is needed to address this hypothesis.

The yield data of the field experiment showed a significant interaction effect between treatment and year of the experiment. This indicated that the values of seedcotton yield responded differently to foliar treatment applications depending on the year of the experiment. We observed a significant seedcotton yield increment with addition of NBPT to foliar urea. Addition of NBPT increased yield compared to application of foliar urea alone and it resulted in equivalent seedcotton yield to the 100% N Soil application treatment. However data of leaf burn, leaf N, and petiole nitrate content did not show any significant effect of addition of NBPT to foliar urea application. The significant influence on NBPT on cotton yield could result from the NBPT effect on the inhibition of urease and improvements of cell membrane integrity indicated in the growth chamber study.

In conclusion in the growth chamber study the use of NBPT to foliar urea application decreased urease activity and it showed trends for increasing leaf urea content and improving cell membrane integrity. In the field study seedcotton yield improvements were observed with addition of NBPT to foliar urea.

Table 1: Effect of foliar treatments on glutamine synthetase and leaf protein content (Growth Room Study).

Foliar Treatment	Glutamine Synthetase (mM glutamyl hydroxamate g^{-1}FW hr^{-1})	Leaf Protein mg g^{-1} FW
Control	0.070 ± 0.005	11.48 ± 0.21
Urea	0.064 ± 0.003	11.81 ± 0.18
Urea+NBPT	0.066 ± 0.004	11.37 ± 0.19
NBPT	0.063 ± 0.002	11.33 ± 0.21
P-Value	0.4354	0.1193

Table 2: Effect of foliar treatments on leaf photosynthesis and chlorophyll fluorescence (Growth Room Study).

Foliar Treatment	Leaf Photosynthesis µmol m^{-2} s^{-1}	Chlorophyll Fluorescence Yield (Fv/Fm)
Control	12.46 ± 0.60	708.06 ± 14.98
Urea	13.00 ± 0.47	703.98 ± 9.17
Urea+NBPT	13.36 ± 0.50	698.98 ± 6.64
NBPT	13.58 ± 0.34	702.65 ± 7.00
P-Value	0.1961	0.8531

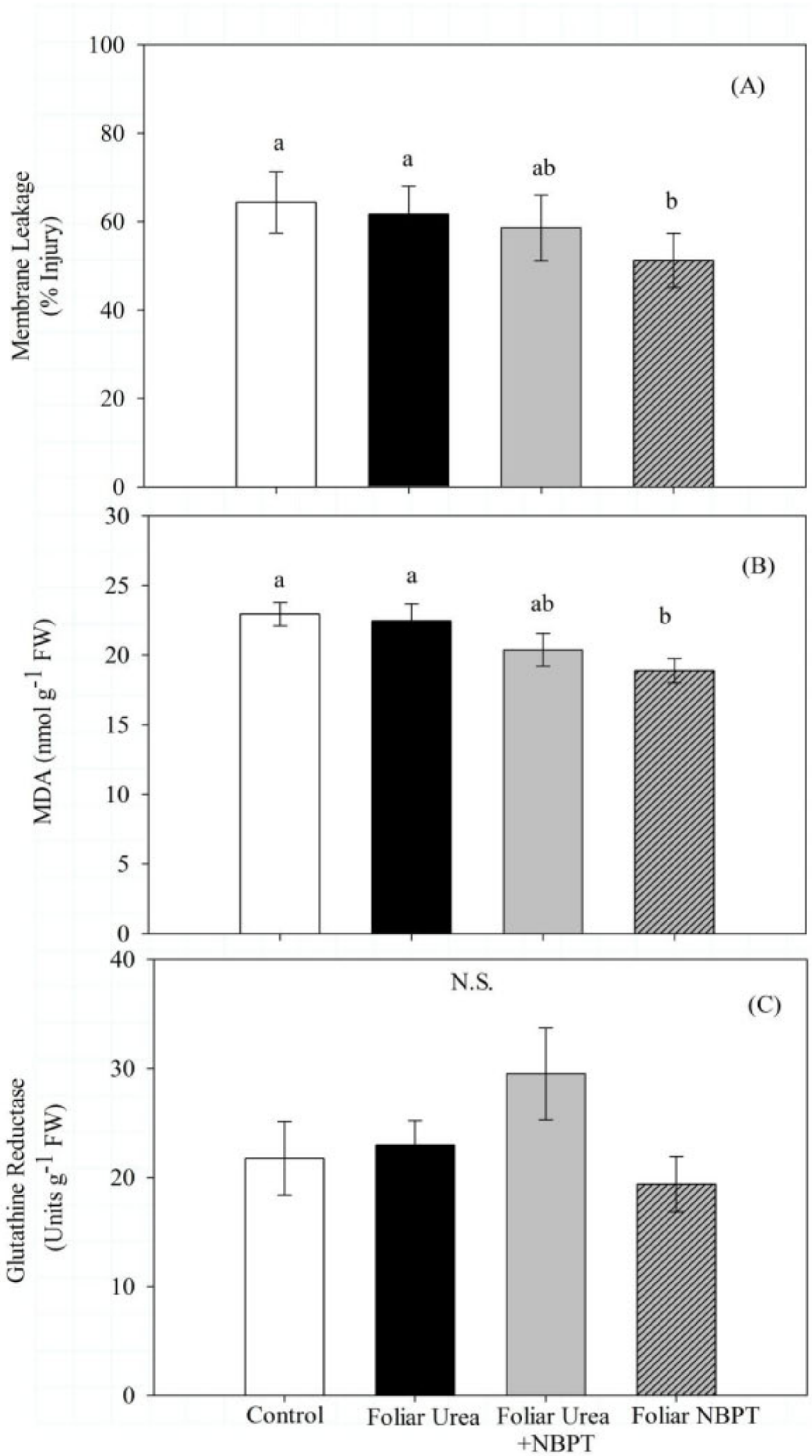

Figure 1: Effect of foliar treatments on membrane leakage (A), MDA (B), and glutathione reductase (C) in cotton grown in growth room conditions. N.S. = not significant ($P \leq 0.05$).

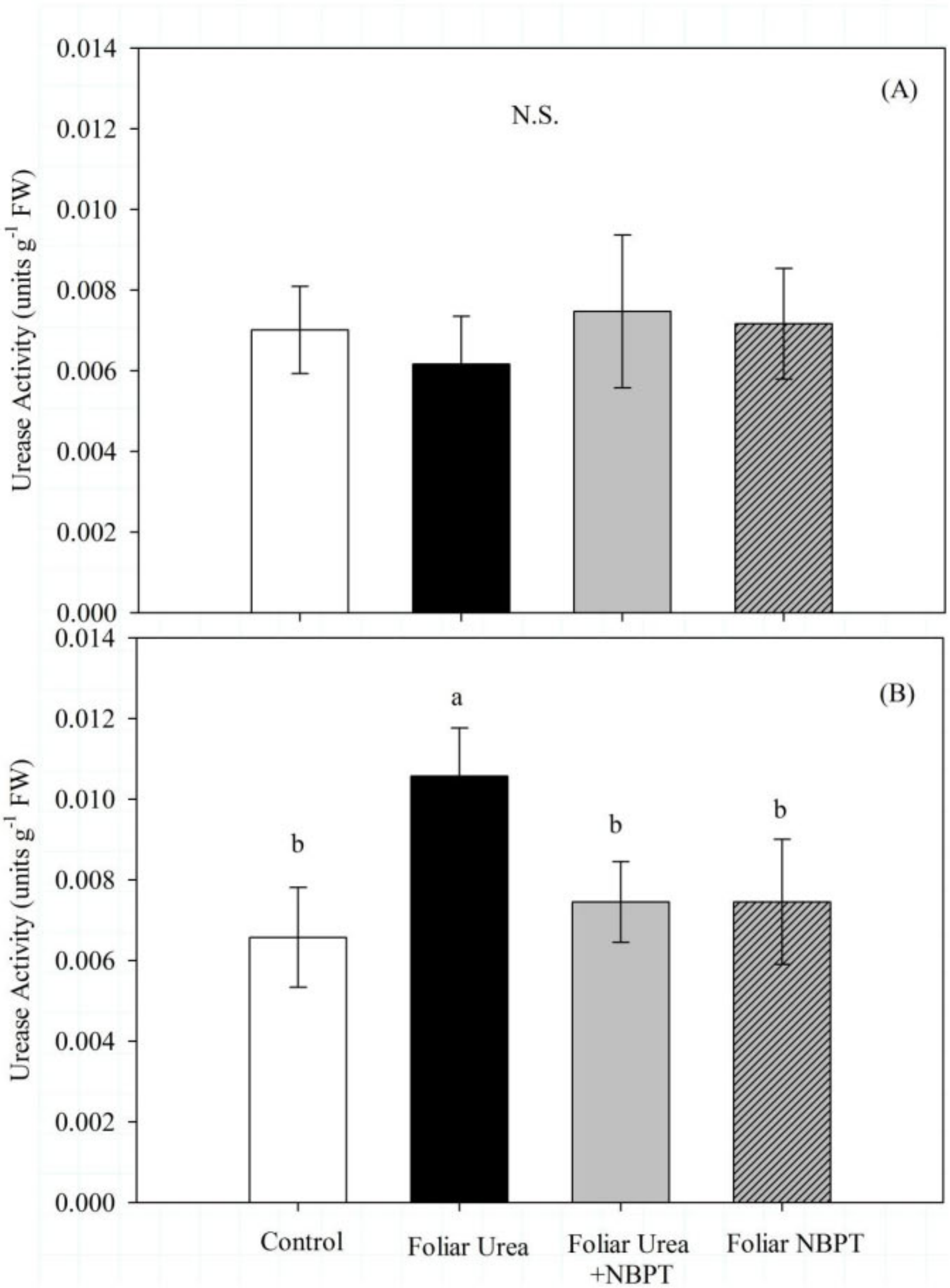

Figure 2: Effect of foliar treatments on leaf urease activity measured at 2h (A) and 24 h (B) after application in cotton grown in growth room conditions. N.S. = not significant (P≤0.05).

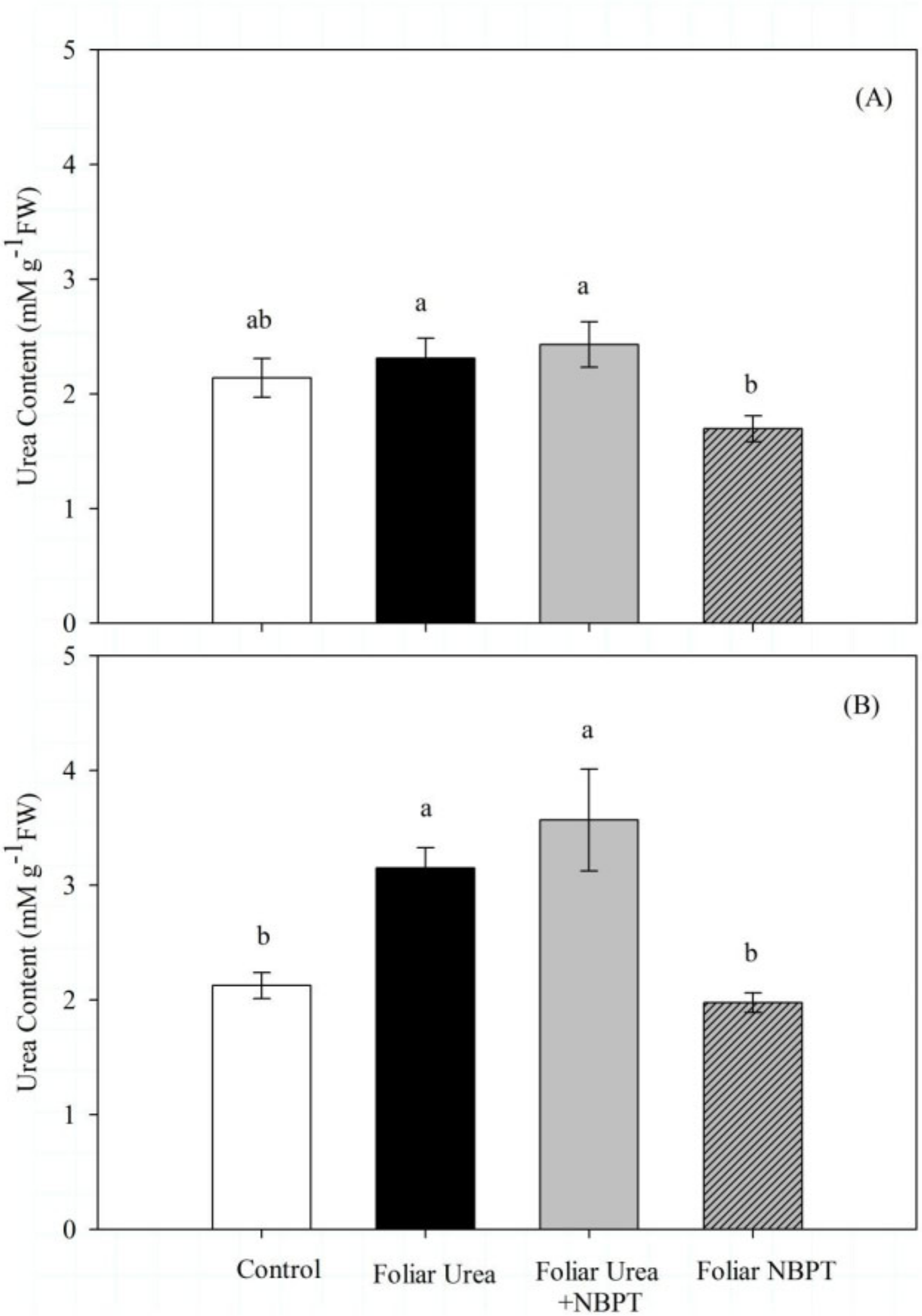

Figure 3: Effect of foliar treatments on leaf urea content measured at 2h (A) and 24 h (B) after application in cotton grown in growth room conditions.

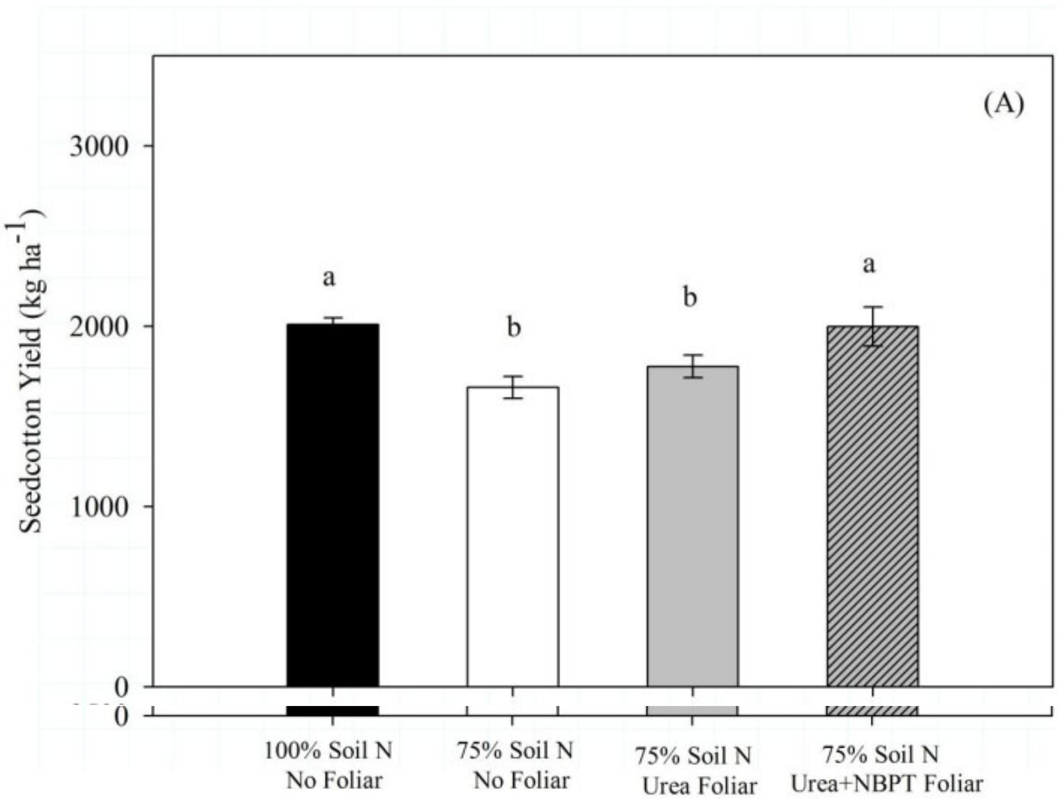

Figure 4: Effect of foliar treatments on seedcotton yield of field grown . N.S. = not significant ($P \leq 0.05$).

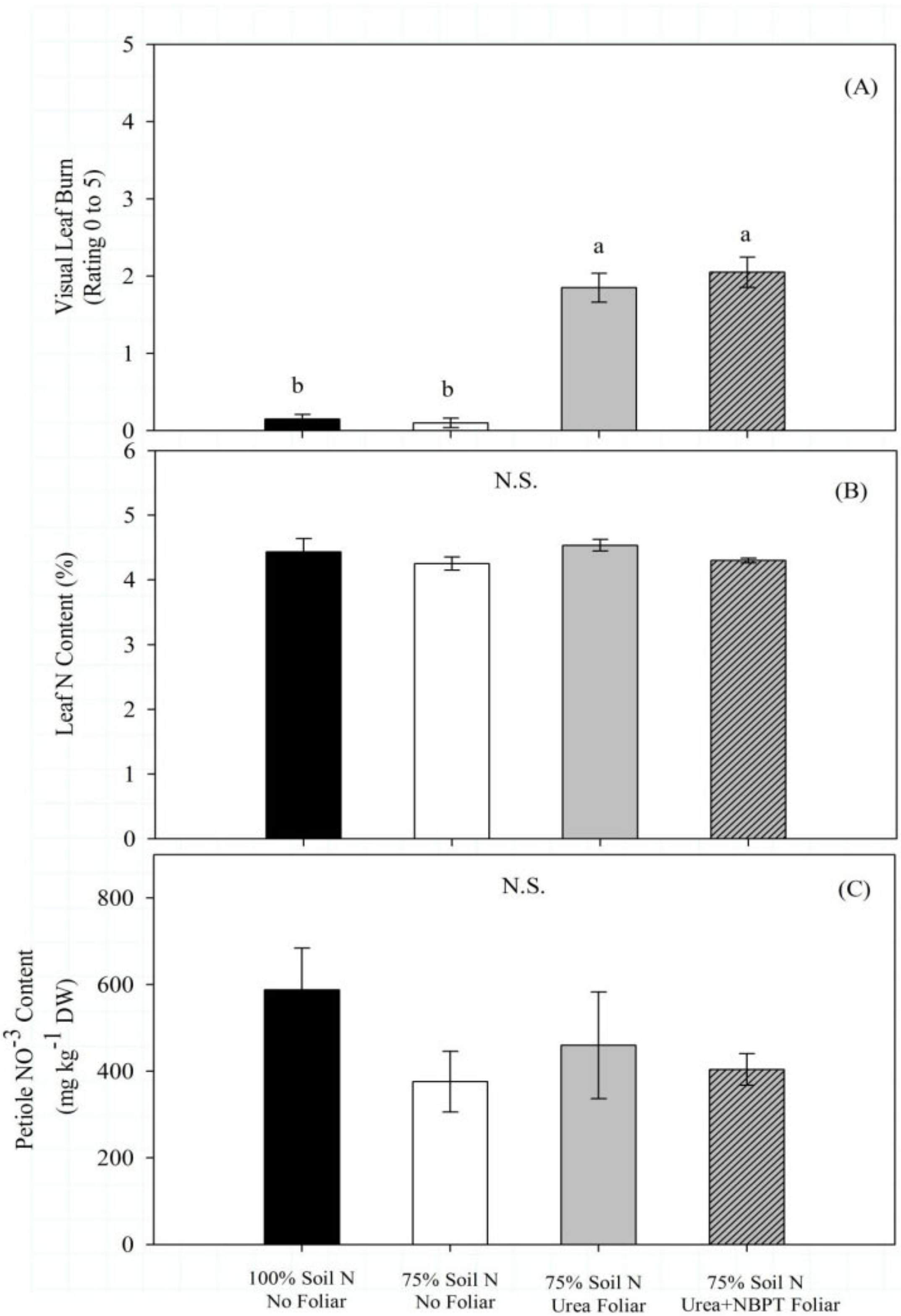

Figure 5: Effect of foliar treatments on leaf burn (A), leaf N (B), and petiole nitrate (C) of a field grown cotton (2010). N.S. = not significant ($P \leq 0.05$).

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Improving Corn and Soybean Yields with Starter and Foliar Fluid Fertilizers[1]

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ABSTRACT

Corn and soybean production under high yield environments can benefit from the combined use of starter and foliar fertilization, including macro and micronutrients. The objective of this study was to evaluate corn and soybean response to starter fluid fertilizers in combination with foliar application of macro and micronutrients to maximize yields. Experiments were conducted in 2010 and 2011 at four locations for corn and soybean under irrigation. Starter and foliar fertilizer treatments were applied in a factorial arrangement with combinations of N, P, K and micronutrients Fe, Mn, Zn, B, and Cu. Soil samples were collected from each location with samples from each experimental unit. Tissue samples were collected from each plot before foliar fertilizer application and analyzed for the macro and micronutrients included in this study. Plant population, plant height, and grain yield were measured. Changes in soybean tissue concentration due to starter fertilizers were observed for B and Mn when compared to the control. Average soybean yield was slightly higher when micronutrients were included in the starter fertilizer, however this different was not statistically significant for combined analysis across sites. Corn plant tissue concentration (V6) was increased for Fe. Early growth was significantly increased over the control with starter fertilizer, however no additional biomass was observed with the addition of micronutrients.

INTRODUCTION

The use of alternative fertilizer application strategies to achieve maximum yields and enhance nutrient use efficiency has been proposed for decades. Often a combination of broadcast and band applications can provide optimum nutrient uptake in low fertility/low soil test conditions. However, under current reduced tillage systems with high yield potential, broadcast nutrients can remain on the soil surface, limiting root contact, or where the soil surface may have been compacted through wheel traffic. When these conditions become more severe, alternative action must be considered.

With the increase in corn and soybean yields due to important genetic improvements, demand for nutrients has also increased. It is likely that the increased utilization of reduced tillage systems and some soil conditions such as high soil pH found in large areas of the Great Plains may decrease the plant-availability of some macro and micronutrients. This may be corrected through

[1] Second year, 2012

some combination of starter and foliar fertilizer application, fertilizer rate adjustment of both macro and micronutrients.

Previous work by Gordon (2008) showed that direct application of P and K to soybeans can have a significant impact on soybean yield, with average increases as high as 34 bu/acre. However, further studies are needed to investigate starter and foliar applications with other nutrients to maximize yields in soybean. On the other hand, in corn, fluid fertilizer placed in a band near the seed at planting has frequently shown positive effects on yield (Rehm and Lamb, 2009). Furthermore, this approach can be especially valuable under conditions of reduced tillage (Kovar and Mallarino, 2001; Haq and Mallarino 2000). In addition, foliar fertilization could in some cases increase nutrient supply at early growth stages when the root system is not well developed. Thus, foliar application of nutrients to corn and soybean in addition to starter fertilizer can help to overcome possible limitations in crop nutrient uptake and increase nutrient use efficiency and yields.

Some soil conditions such as high soil pH and low organic matter may contribute to decrease the supply of micronutrients to crops. Increased nutrient demands from more intensive cropping practices and high yielding potential crops may also require additional micronutrient for optimum yield. Supplementary foliar application of N, P, K, and micronutrients can help to enhance crop yields under these conditions. Consequently, there is an increasing interest from producers about the potential benefits of foliar application of nutrients as complement of their fertilization programs to maximize yields.

The overall objective of this study was to evaluate crop response to starter fluid fertilizers in combination with foliar application of macro and micronutrients to maximize corn and soybean yields. Specific objectives include (1) assessment of corn and soybean grain yield and early growth response to starter application of fluid fertilizers and (2) compare responses with and without additional foliar fertilizers. (3) Verify potential soil parameters that could be related to responses to starter and foliar applied macro and micronutrients. (4) Evaluate tissue testing as a diagnostic tool to explain responses to foliar and starter macro and micronutrient application.

MATERIALS AND METHODS

The experiment was conducted in 4 locations for corn and 4 locations for soybean during 2010 and 2011 in Kansas. Studies were located under high yield potential irrigated conditions. The field studies consisted of small-plot field research of six rows wide by 50 feet in length. Macronutrients treatments included N, P, and K, and micronutrients included Fe, Mn, Zn, B, and Cu. Starter fluid fertilizer treatments and foliar treatments were applied in various combinations in a factorial arrangement. Three starter treatments (none, N,P,K only, and N,P,K + micros) were combined with three foliar treatments (none, N,P,K only, and N,P,K + micros) for a total of nine treatment combinations.

Starter fluid fertilizers were applied near the seed using a dribble band placement. The foliar fertilizer application was made before the plant begins the rapid increase in nutrient and dry weight accumulation. For corn, foliar application was around the 6-8 leaf grown stage, and for soybean around the 5-7 trifoliate. The procedure for fluid fertilizer application simulated procedures commonly used by producers. Foliar fertilizer was diluted into water and applied with a hand-held CO2-powered sprayer. Fertilizer used for starter application was a 4-10-10 formulation, micronutrients Zn, Cu, and Mn were chelated EDTA. Iron was a chelated HEDTA, and B was derived from boric acid. Foliar N,P,K was applied using a 10-10-10 fertilizer formulation.

Soil samples at the 0-6 inch depth were collected from each individual plot and analyzed for routine soil properties and soil properties that can help identify the likelihood of response to foliar and starter treatments. Analysis included soil organic matter, soil test phosphorus, soil test potassium, and soil pH by standard methods in addition to micronutrients Fe, Mn, Zn, B, and Cu. Tissue samples were collected 1-3 days before foliar treatment for total N, P, K, and micronutrients. At harvest, yield was recorded for each plot and a grain samples were collected. Statistical analysis was completed with the GLIMMIX procedure in SAS 9.2 (SAS Institute, 2000). Plant population was used as covariate in the analysis.

RESULTS AND DISCUSSION

Average soil test levels are presented in Table 1. Soybean tissue analysis showed a significant increase in B concentration with the addition of micronutrients in the starter fertilizer. Concentration of Fe and Zn were similar to the control. Manganese concentration was decreased with the addition of Mn in the starter fertilizer (Fig 1). A decrease in Mn concentration in soybean with the use of chelated (EDTA) source has been observed in previous studies (Randall et al 1975). Average soybean yield was slightly higher when micronutrients were added to the starter fertilizer (Fig 2). This suggests that a lower Mn tissue concentration may not be necessarily indicative of yield response in this case.

Plant tissue analysis in corn showed an increase in Fe concentration with the addition of micronutrients in the starter, other nutrients show no clear difference (Fig 3). However, early growth in corn was significantly increased with starter fertilizers compared to the control (Fig 4). The addition of micronutrients in the starter fertilizer did not contribute to additional early growth, and is likely that the effect in early growth is contributed by N and P. Foliar application of N (derived from methylene ureas and triazone) in corn showed average yield increase at all locations in addition to pre-plant N application. This suggests a possible additional benefit of foliar applications, and additional studies should evaluate different rates and application timing.

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Table 1. Average soil test values for study locations in 2011 and 2012. Loc. 1 and 2 are in 2011.

Crop	Location	pH	P (ppm)	K (ppm)	OM (%)	Soil texture
Soybean	Loc 1	7.1	34	255	1.6	Fine sandy loam
	Loc 2	6.4	28	135	0.9	Loamy fine sand
	Loc 3	7.0	22	480	2.9	Silt Loam
	Loc 4	6.5	14	510	2.1	Silt Loam
Corn	Loc 1	7.4	114	388	1.8	Silt Loam
	Loc 2	6.4	19	242	1.8	Silt Loam
	Loc 3	6.7	21	460	2.9	Silt Loam
	Loc 4	6.3	16	655	2.3	Silt Loam

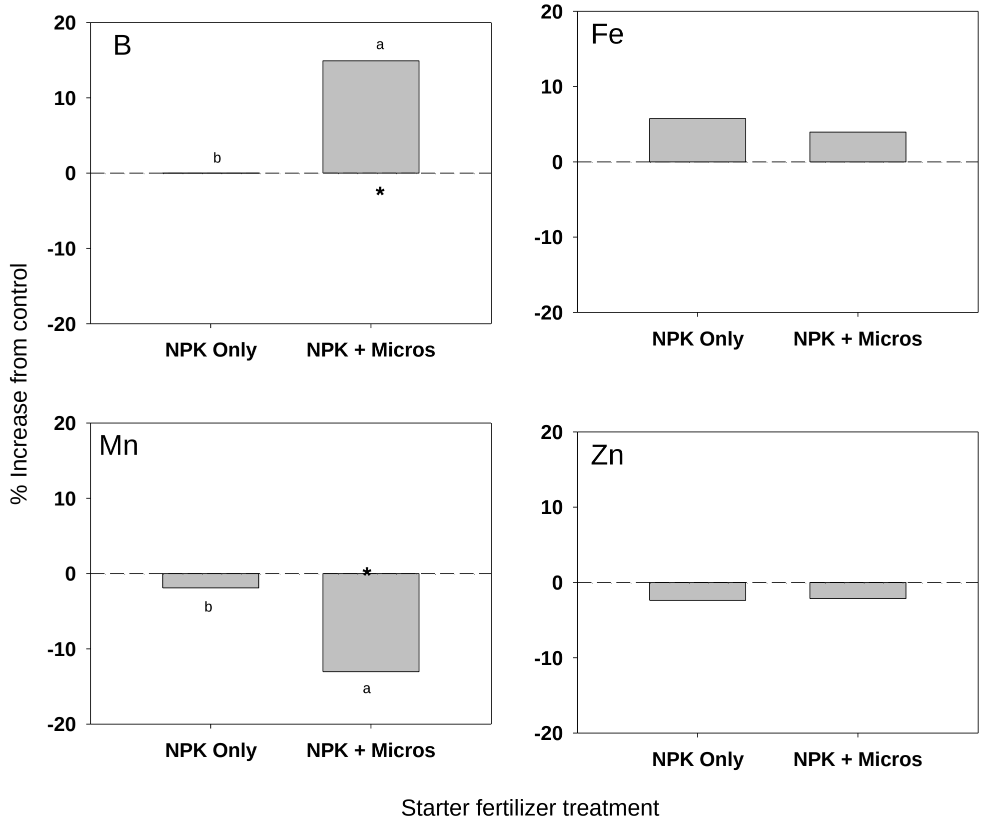

Figure 1. Effect of starter fertilizer application on tissue nutrient concentration in soybean compared to the control. Asterisk (*) indicate statistically significant difference from zero at $p \leq 0.05$. Letters indicate statistically significant difference between treatments at $p \leq 0.05$

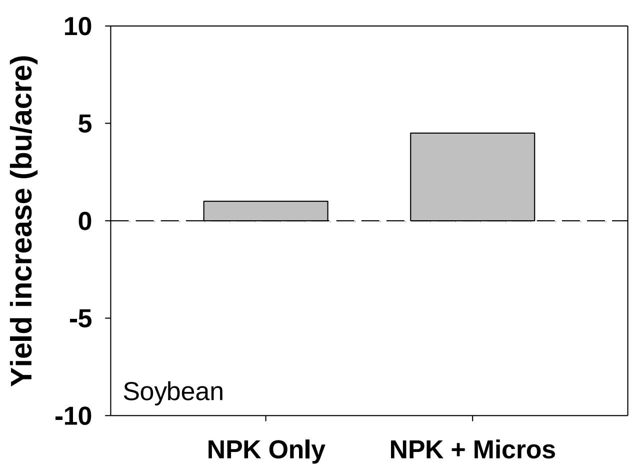

Figure 2. Effect of starter fertilizers with and without micronutrient application on soybean yield increase compared to the control.

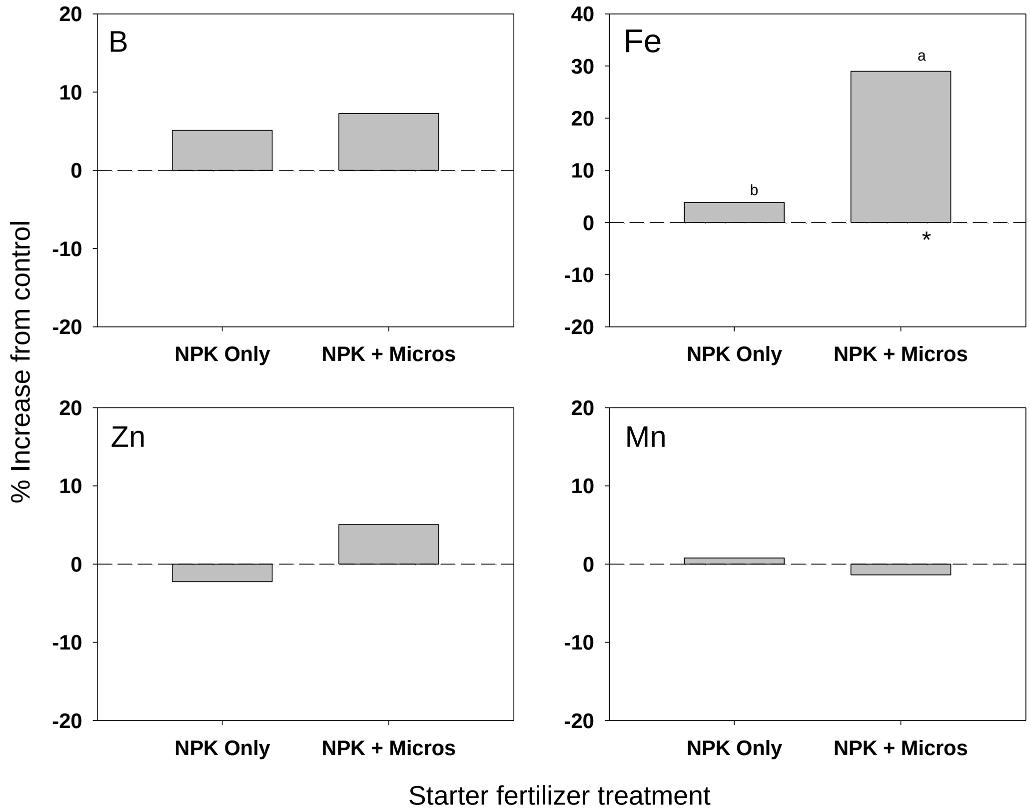

Figure 3. Effect of starter fertilizer application on tissue nutrient concentration in corn compared to the control. Asterisk (*) indicate statistically significant difference from zero at $p \leq 0.05$. Letters indicate statistically significant difference between treatments at $p \leq 0.05$

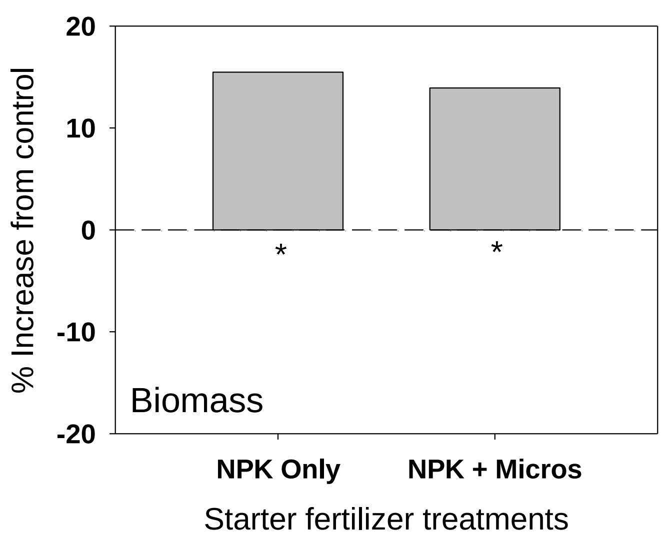

Figure 4. Increase in corn early growth biomass (V6) as affected by starter fertilizer treatments compared to the control. Asterisk (*) indicates statistically significant difference from zero at $P \leq 0.05$.

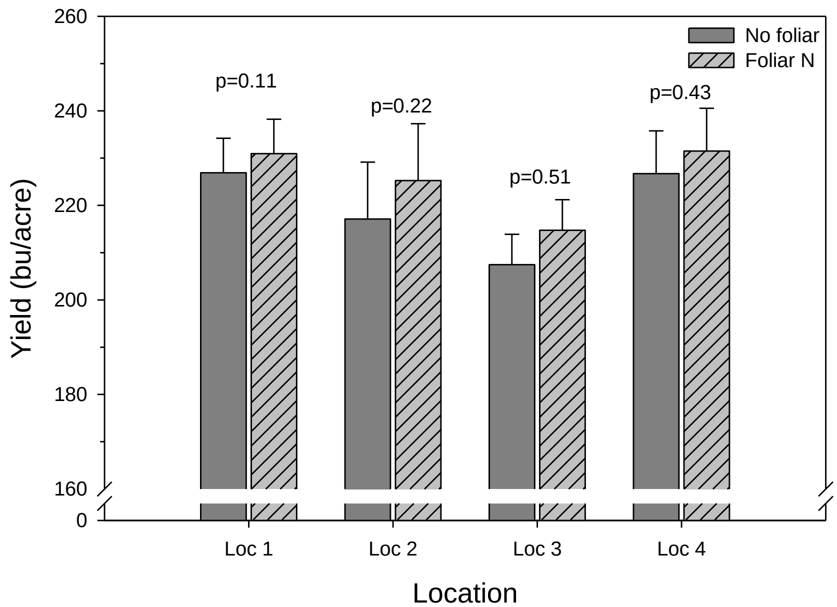

Figure 5. Foliar fertilizer application to corn at 4 locations during 2010 and 2011. Probably values for mean comparisons are included for each site. Pre-plant N rates were: Loc 1: 180 lbs; Loc 2: 180 lbs; loc 3: 200 lbs; loc 4: 200 lbs N/acre.

Enhancing Continuous Corn Production under High-Residue Conditions With Starter Fluid Fertilizer Combinations and Placements

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ABSTRACT

Continuous corn production using conservation tillage often results in less uniform and smaller early season growth along with lower grain yields and profitability. This is especially true on fine-textured and poorly drained soils in the northern part of the Corn Belt where decomposition of surface residues is slower and soil temps are colder. The primary objective of this study was to determine the effects of fluid starter fertilizer combinations and placement of 10-34-0 (APP), 28-0-0 (UAN), and 12-0-0-26 (ATS) on second-year corn production in reduced tillage/high-residue conditions. Two field experiments, one on a Webster clay loam soil at Waseca and another on an Mt Carroll silt loam near Rochester, were established in April of 2011. Twelve of the 14 total treatments comprised a factorial arrangement of rates of three fluid starter fertilizers: 0 or 4 gal/ac of APP, 0 or 8 gal/ac of UAN, and 0, 2, and 4 gal/ac of ATS. The APP was applied in-furrow with the seed while UAN and ATS were applied as a dribble band on the soil surface within 2" of the seed row. Corn was planted at 35,000 seeds/ac on May 17 at Waseca and May 19 at Rochester. At the V2 to V3 growth stage UAN was injected 3" deep midway between the rows to give a total (at planting + V2-3) N rate of 200 lb/ac on all plots. At V7 stage corn plants were harvested from each plot to determine dry matter yield, and the plant tissue was analyzed for N, P, K and S concentration. Grain yield and moisture content were determined by combine harvesting. Grain samples were analyzed for N, P, K and S concentration. A wet June and July followed by a dry August and September stressed corn and may have reduced yield potential. Crop response to treatments varied between locations. Early plant growth (plant heights and dry matter yields) were enhanced when N, P and S starter fertilizers as APP, UAN and ATS were applied at both sites. At Rochester, grain moisture was reduced 1.4 percentage points and grain yields were increased 4 bu/ac with 4 gal/ac of APP (16 lb P_2O_5/ac) applied in-furrow at planting, when averaged across UAN and ATS treatments. A 4 gal/ac rate of ATS (11.5 lb S/ac) increased corn yields 8 bu/ac compared with 0 gal/ac of ATS at Rochester. No grain yield responses to N, P, and S starter fertilizer treatments were found at Waseca.

INTRODUCTION

Crop rotations in the Midwest have changed from the traditional corn-soybean rotation to more corn-intensive rotations. Due to the expanding demand for corn to supply the ethanol industry and the increasing insect and disease challenges facing soybean producers, some farmers are switching to a corn-corn-soybean rotation or for some, continuous corn. These rotations produce large amounts of biomass (corn stover) that often remain on the soil surface with present day tillage systems. This is good in terms of erosion control, but can be a significant problem from the standpoint of seedbed preparation, early corn growth, and yield.

Corn dominated crop rotations present a huge tillage challenge to corn producers on many poorly drained, colder soils of the northern Corn Belt because corn yields following corn are generally reduced significantly when conservation tillage practices are used. Research by Randall and Vetsch (2010) has shown many of the early growth and yield problems associated with corn after corn could be eliminated by using conventional tillage (i.e. moldboard plow) in combination with fluid starter fertilizers. Generally, for most northern Corn Belt farmers the moldboard plow is not an option, because of increased potential for erosion, lack of equipment, or the labor/time needed to plow large acreages. This research also showed fluid starter fertilizers [APP (10-34-0) applied in furrow or APP and UAN (28-0-0) dribbled on the soil surface] significantly increased early growth of corn by 13 to 43% and corn yield by 5 to 7 bu/ac. This study did not address a commonly asked question, would dual placement (APP in furrow and UAN dribbled on the soil surface) further enhance corn production.

Continuous corn generally shows slow early growth, pale spindly plants, and reduced yields with reduced tillage systems. Sulfur deficiency in corn has contributed to some of these pale looking plants. Corn yield responses to sulfur have been reported on medium and fine-textured soils in Minnesota and Iowa. In Minnesota we have very little data on the optimum rate and placement of sulfur containing fluid starter fertilizers for corn. With increased costs and price volatility of fertilizers, farmers have questions about what products, placements, and rates give them the most "bang for their buck".

The objectives of this study were to: 1) determine the effects of fluid starter fertilizer combinations and placement of 10-34-0 (APP), 28-0-0 (UAN), and 12-0-0-26 (ATS) on second-year corn production in reduced tillage/high-residue conditions and 2) provide management guidelines on placement and rates of UAN, APP, and ATS combined as a starter for crop consultants, local advisors, and the fertilizer industry as they serve corn producers trying to meet the growing needs for corn grain by the ethanol industry and livestock producers.

EXPERIMENTAL PROCEDURES

Two field experiments were established in April of 2011. One on a Webster clay loam soil at the Southern Research and Outreach Center, Waseca, MN and another on a Mt Carroll silt loam six miles northeast of Rochester, Minnesota. Both sites were planted to corn in 2010 and were fall chisel plowed after harvest. Fourteen total treatments were arranged in a randomized, complete-block design with four replications. Twelve of the 14 treatments comprised a factorial combination of sources and rates of three fluid starter fertilizers: 0 or 4 gal/ac of APP (5+16+0, lb/ac of N, P_2O_5, and S, respectively); 0 or 8 gal/ac of UAN (24+0+0); and 0, 2, and 4 gal/ac of ATS (2 gal = 3+0+5.8 and 4 gal = 5+0+11.5). The APP fluid starter was applied in-furrow with the seed while UAN and ATS were applied as a dribble band on the soil surface within 2" of the seed row. Two additional treatments were included to measure crop response when adding 1 gal/ac of ATS in-furrow with 4 gal/ac of APP with and without 8 gal/ac of UAN dribbled on the soil surface. Each plot was 10' wide (4 30-inch rows) by 50' long. Soil samples (0-6" depth) were taken from each rep to characterize the research plot areas. Soil tests at Waseca averaged: pH = 5.9, organic matter = 7.2%, Bray P_1 = 47 ppm (very high) and exchangeable K = 264 ppm (very high) and at Rochester pH = 6.3, organic matter = 3.4%, Bray P_1 = 13 ppm (medium) and exchangeable K = 68 ppm (low).

Corn (DeKalb 52-43 at Waseca and 51-85 at Rochester) was planted at 35,000 seeds/ac on May 17 (Waseca) and May 19 (Rochester). Weeds were controlled with a combination of pre (Surpass and Callisto) and post emergence (glyphosate) herbicide applications. Surface residue accumulation after planting averaged 39 and 12% at Waseca and Rochester, respectively. In early June stand counts were taken on the center two rows of each plot and were thinned to a uniform plant population. At V2 to V3 on June 9, UAN was injected 3" deep midway between the rows to give a total (at planting + at V2-3) N rate of 200 lb/ac on all plots. Because of low soil test K, 120 lb K_2O/ac was injected mid-row at Rochester on June 9. On June 30 at Waseca and June 29 at Rochester (V7 stage) 8 random plants from each plot were cut at ground level, dried, weighed to determine dry matter yield, ground, and analyzed for N, P, K and S concentration in plant tissue. On the same dates extended leaf plant heights from 10 random plants per plot were also measured. At R1 (July 29 at Waseca and August 3 at Rochester) SPAD meter readings were taken from the ear leaf of 30 plants in each plot. Relative leaf chlorophyll content was calculated from these measurements. Grain yield and moisture content were determined on October 3 (Waseca) and 21 (Rochester) by harvesting the center two rows of each plot with a research plot combine equipped with a weigh cell and moisture sensor. Grain yields were calculated at 15.5% moisture. Grain samples were saved, dried, ground, and analyzed for N, P, K and S.

RESULTS AND DISCUSSION

Waseca site

The 2011 growing season started out cool and wet at Waseca (Table 1). A wet April and May resulted in delayed planting and slow early growth of corn. Over 3 inches of rain occurred in the two week period after planting, which resulted in standing water on ½ of one of the four replications in the study. The standing water slowed germination, reduced stands, resulted in N loss, and generally increased variability in some plots. These plots were removed from the data set as outliers after an initial statistical evaluation of the data was completed. The months of May, June and July all had greater than normal precipitation. July was very warm, air temperatures averaged 5° greater than normal (data not shown). August and September were dry with precipitation for the two months totaling 6.64 inches below normal. The dry conditions in the latter part of the growing season probably reduced yields and increased variability in the data. Growing degree units (GDU) from May 1 through September 15 (first frost) were near normal.

Plant heights and whole plant dry matter yields were affected by all three of the treatment main effects in the factorial analysis of treatments 1-12 (Table 2). Heights and yields were increased when APP was applied in-furrow and when UAN and ATS were applied as a surface band. Plant heights were greatest with the 4 gal/ac rate of ATS. However, yields were not different among the 2 and 4 gal/ac rates of ATS, when averaged across APP and UAN treatment main effects. A significant APP×UAN×ATS interaction for plant height showed a large increase in plant height with increasing rates of ATS, when APP and UAN were not applied. Whereas, when APP and/or UAN were applied the plant height response to ATS was inconsistent. The significant APP×UAN×ATS interaction for dry matter yield was similar to what was found for plant height. One gal/ac of ATS plus 4 gal/ac or APP applied in-furrow did not affect V7 plant heights or yields compared with 4 gal/ac of APP alone. The application of fluid fertilizers at planting resulted in dramatic visual (early growth, vigor, and color) differences.

Nutrient concentrations and uptakes in V7 corn plants were affected by the treatment main effects in this study, however the data were quite variable probably due to the cool and wet conditions in late May and June (Table 2). Four gal/ac of APP increased uptake of N, P, K and S, whereas nutrient concentrations in V7 corn plants were not affected by APP. Eight gal/ac of UAN applied as a surface band reduced N, P and S concentrations (likely due to the dilution effect), when averaged across APP and ATS treatments. The dilution effect occurs when early growth increases dramatically, thus causing concentrations of some nutrients to decline. Nutrient uptakes were not affected by UAN application. Potassium concentration in V7 plants decreased slightly at the 2 gal/ac rate of ATS compared with the control. Sulfur concentrations were very low, significantly less than established critical level of 0.20%, but were not affected by ATS application. A significant APP×ATS interaction for S concentration showed S concentration was least with the 4 gal/ac of APP and 0 gal/ac of ATS treatment (data not shown). Phosphorus, K, and S uptakes were increased when ATS was applied as a surface band. The nutrient uptake responses to treatment main effects found in this study were generally a result of increased plant dry matter (yield responses) and not to increased nutrient concentration. Several significant two and three way interactions were found for nutrient uptake in V7 corn plants. Generally, the APP×UAN×ATS interactions for N, P and S uptake were explained by the response found for dry matter yield discussed earlier. However, the unusual response observed with treatment # 6 (low dry matter yield and very low S concentration and uptake), which cannot be explained by the authors, may have caused some of these interactions. Adding 1 gal/ac of ATS to 4 gal/ac of APP applied in-furrow, did not affect nutrient concentrations and uptakes in V7 corn plants, compared with 4 gal/ac of APP alone.

Treatment effects on grain moisture, grain yield, and relative leaf chlorophyll content (RLC) are presented in Table 3. Grain was quite dry at harvest (October 3) considering the later than normal planting date (May 17). Application of APP or UAN at planting did not affect grain moisture at this site. Grain moisture increased 1.0 percentage point with 4 gal/ac of ATS compared with 0 gal/ac, when averaged across APP and UAN treatments. Corn grain yields were not affected by the application of APP, UAN or ATS at planting and there were no significant interactions. The wet spring followed by a dry August and September increased yield variability at this site. Yields ranged from 184 to 201 bu/ac. An *analysis of all 14 treatments found no significant differences for grain moisture and/or yield. Relative leaf chlorophyll content at R1 was not affected by any of the treatments at this site.*

Initial plant stand and final plant population were reduced 1200-1300 plants/ac with ATS fertilization, when averaged across APP and UAN treatments (Table 3). The cool and wet period after planting likely contributed to the stand reductions observed in these data. Highly significant APP×ATS and UAN×ATS interactions were found for initial stand and final plant population. When averaged across UAN rate, plant populations were greatest when APP and ATS were not applied. When APP was not applied, populations decreased linearly as the ATS rate increased; whereas, when APP was applied plant populations decreased with 2 gal/ac of ATS but not at the 4 gal/ac rate. These data showed under difficult climatic conditions ATS applied as a surface dribble band can reduce stand, however applying APP (in-furrow) plus ATS (dribble) did not reduce stand further. When averaged across APP rate, surface dribble banding UAN and ATS reduced plant populations compared with ATS alone (Figure 2b). Strangely, applying UAN without ATS increased populations. This interaction showed, unlike the response found with APP, applying UAN and ATS may increase the potential for stand reductions.

Treatment effects on the concentration and uptake of N, P, K and S in corn grain are presented in Table 4. Applying 4 gal/ac of APP at planting increased grain N concentration and uptake, but did not affect P, K and S on this very high P testing site. Grain N, P, K and S concentrations and uptakes were not affected by UAN applied as a surface dribble band at planting, when averaged across APP and ATS rates. Four gal/ac of ATS increased grain S concentration and uptake, when averaged across APP and UAN rates. Application of ATS did not affect grain N, P and K concentration and uptake. There were no highly ($P \leq 0.05$) significant interactions found for grain nutrient concentration and uptake.

Rochester site

The early part of the 2011 growing season at Rochester was cool but not as wet as Waseca (Table 1). Although the amounts were not great, frequent rains delayed planting and field operations in the area. July was warm and wet; precipitation totaled 4.66 inches greater than normal. August was dry, but September had near normal precipitation which aided late season grain fill and enhanced yields. Growing season precipitation totaled one inch below normal.

Generally, plant heights and whole plant dry matter yields were affected by all three of the treatment main effects in the factorial analysis of treatments 1-12 (Table 5). Heights and yields were increased when APP was applied in-furrow and when UAN was applied as a surface band. When averaged across APP and UAN rates, dry matter yields were greater with 4 gal/ac of ATS applied as a surface band compared with 0 or 2 gal/ac of ATS, although plant heights were not significantly greater (P-value = 0.105). No significant interactions were found for plant height and dry matter yield. These data were similar to the Waseca site and showed a consistent early growth and plant vigor advantage when fluid starter fertilizers were placed in or near the seed row at planting. Adding 1 gal/ac of ATS to 4 gal/ac of APP applied in-furrow had no affect on plant heights or dry matter yields compared with 4 gal/ac of APP alone.

Nutrient concentrations and uptakes in V7 corn plants were affected by the treatment main effects in this study (Table 5). An application of 4 gal/ac of APP at planting increased P concentration about 8% and decreased K concentration about 10%, when averaged across UAN and ATS rates. Moreover, APP application increased whole plant N, P, K and S uptake. Surface banding UAN increased N and P concentration and reduced K concentration, when averaged across APP and ATS treatments. Nitrogen, P and S uptake in V7 plants were increased by UAN application at planting. Sulfur concentration increased as the rate of ATS increased in the starter fertilizer, when averaged across APP and UAN treatments. Similar to APP and UAN application, ATS applied at planting decreased K concentration slightly. ATS application increased N, P and S uptake in V7 corn plants. No significant interactions were found for nutrient concentration and uptake. Applying 1 gal/ac of ATS and 4 gal/ac of APP in-furrow increased S concentration in whole plants compared with 4 gal/ac of APP alone.

Treatment effects on grain moisture, grain yield, initial plant stand, final plant population and relative leaf chlorophyll content (RLC) are presented in Table 6. Grain moisture was reduced 1.4 percentage points when APP was applied at planting. A significant APP×ATS interaction for grain moisture showed when APP was not applied ATS reduced grain moisture slightly. However when APP was applied grain moisture was considerably less and applying ATS did not further reduce moisture (data not shown). Corn grain yield increased 4 bu/ac with 4 gal/ac of APP compared with 0 gal/ac of APP, when averaged across UAN and ATS treatments. Yield was greater (202 bu/ac) with 4 gal/ac of ATS compared with 2 gal/ac (196 bu/ac) and 0 gal/ac (194 bu/ac) of ATS, when averaged across APP and UAN treatments. Applying 1 gal/ac of ATS and 4 gal/ac of APP in-furrow had no affect on grain yields compared with 4 gal/ac of APP alone. Initial plant stand and final plant populations were reduced slightly (≤600 plant/ac) with APP application. The 4 gal/ac rate of ATS also reduced initial stand about 500 plants/ac. These small reductions would not have affected grain yields. No Significant interactions were found for corn grain yield, initial plant stand and final plant population. Relative leaf chlorophyll content at R1 was greater with 2 and 4 gal/ac of ATS compared with 0 gal/ac of ATS. A highly significant APP×UAN interaction for RLC showed when APP was not applied, UAN application reduced RLC. However when APP was applied, UAN application increased RLC (data not shown). A significant APP×ATS interaction for RLC showed when APP was not applied, 2 and 4 gal/ac of ATS increased RLC compared with 0 gal/ac of ATS; Whereas when APP was applied, RLC increased as the rate of ATS increased (data not shown).

Treatment effects on the concentration and uptake of N, P, K and S in corn grain are presented in Table 7. Sulfur uptake in corn grain increased slightly with 4 gal/ac of APP applied at planting, when averaged across UAN and ATS treatments. Grain N concentration increased slightly when UAN was applied as a surface dribble band at planting, when averaged across APP and ATS rates. Sulfur concentration and uptake in corn grain increased as the rate of ATS increased, when averaged across APP and UAN rates. Nitrogen concentration in corn grain was reduced with 4 gal/ac of ATS compared with 2 gal/ac of ATS. Several significant interactions were found for grain nutrient concentration and uptake. Generally, these differences were small and of little agronomic importance.

2011 SUMMARY

A cool and wet spring delayed planting and slowed early growth and development of corn. Warm and wet conditions in July produced rapid growth, which allowed for the crop to "catch up" after a slow start to the growing season. Less than normal late summer rainfall, especially at Waseca, probably reduced yield potential. Crop response to the treatments varied between locations. At Waseca early growth and vigor were enhanced with fluid starter fertilizers but grain yields were not affected; Whereas, at Rochester early growth and grain yield were enhanced by starter treatments. Key observations from the second year of this 3-year study include:

1) *Early plant growth (plant heights and dry matter yields) were enhanced when N, P and S starter fertilizers as APP, UAN and ATS were applied at Waseca and Rochester sites.*
2) *Grain moisture was reduced 1.4 percentage points when APP was applied at Rochester. At Waseca grain moisture at harvest was very low and responses to treatments were inconsistent.*
3) *At Rochester on a medium testing P soil, corn grain yields increased 4 bu/ac with APP (phosphorus fertilization) compared with no APP.*
4) *Corn grain yields increased 8 bu/ac with the 4 gal/ac rate of ATS (sulfur fertilization) at Rochester compared with 0 gal/ac of ATS.*
5) *No grain yield responses to N, P and S starter fertilizers were found at Waseca in 2011. Cool and wet conditions early, followed by a very dry August and September increased variability and likely limited yields at this site.*
6) *For results from the 2010 study see Vetsch et al., 2011 (available online).*

2010–2011 SUMMARY

Treatment effects on corn grain moisture, grain yield and plant height by location (Waseca and Rochester) and year (2010 and 2011) are summarized in Table 8. Applying 4 gal/ac of APP in-furrow: 1) reduced grain moisture at three of four location-years; 2) increased grain yield at one of four location-years (4 bu/ac increase at Rochester in 2011); and 3) increased plant height at the V7 growth stage in all four location-year comparisons. Applying 8 gal/ac of UAN as a surface band: 1) reduced grain moisture in two of four location-years; 2) did not affect corn grain yield; and 3) increased plant height in three of four location-year comparisons. Applying ATS as a surface band: 1) reduced grain moisture in one of four location-years; 2) increased grain yield at two of four location-years (6-9 bu/ac at Waseca in 2010 and an 8 bu/ac with 4 gal/ac of ATS at Rochester in 2011); and 3) increased plant height in two of four location-year comparisons. A combination of N, P and S fluid starter fertilizers as APP, UAN and ATS increased plant height by 21% compared with the control (data not shown).

During this study period, applying APP and ATS independently or in combination had the greatest likelihood for increasing corn grain yields. Applying UAN as a nitrogen starter fertilizer did not affect grain yield in this study. Generally, APP, ATS and UAN applied as starter fertilizers increased early growth and vigor of continuous corn under reduced tillage and may reduce grain moisture at harvest.

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Table 1. Precipitation at Waseca and Rochester and growing degree units (GDUs) at Waseca.

		Precipitation					
		Waseca		Rochester		Waseca GDUs	
Month	Year	2011	Normal[1/]	2011	Normal[1/]	2011	Normal[1/]
		- - - - - inches - - - - -		- - - - - inches - - - - -			
May	2011	4.67	3.93	2.72	3.66	299	332
June	2011	5.19	4.69	3.24	4.34	538	538
July	2011	7.21	4.42	9.19	4.53	790	655
Aug.	2011	0.92	4.75	1.89	4.66	617	597
Sept.	2011	0.86	3.67	2.82	3.66	238	348
May-Sept.	Total	18.85	21.46	19.86	20.85	2482	2470

[1/] 30-Yr normal, 1971-2010.

Table 2. Early growth, yield, nutrient concentration and uptake of V7 corn plants at Waseca.

				V7	Whole Plant Samples at V7 (June 30)								
	Fertilizer rate			Plant		Concentration				Uptake			
Trt	APP	UAN	ATS	height	Yield	N	P	K	S	N	P	K	S
#	---- gal/ac -----			inch	lb/ac	-------------- % --------------				---------- lb/ac -----------			
1	0	0	0	30.2	577	3.53	0.398	4.82	0.177	20.4	2.30	27.8	1.02
2	0	0	2	32.0	675	3.36	0.419	4.57	0.179	23.1	2.86	31.1	1.22
3	0	0	4	37.2	828	3.45	0.436	5.10	0.174	29.3	3.59	44.3	1.43
4	0	8	0	35.4	729	3.56	0.375	4.87	0.167	25.9	2.73	35.5	1.21
5	0	8	2	36.0	791	3.26	0.402	4.42	0.171	27.4	3.20	35.5	1.41
6	0	8	4	35.4	716	2.75	0.368	5.07	0.148	19.9	2.61	36.4	1.06
7	4	0	0	35.5	742	3.46	0.417	4.82	0.166	25.8	3.05	35.6	1.23
8	4	0	2	38.3	863	3.47	0.420	4.81	0.169	30.2	3.63	41.5	1.47
9	4	0	4	37.0	822	3.47	0.416	4.97	0.179	28.3	3.41	40.9	1.46
10	4	8	0	37.3	837	2.78	0.366	4.95	0.135	25.1	3.21	43.1	1.21
11	4	8	2	35.4	822	3.32	0.406	4.72	0.170	27.3	3.33	38.8	1.39
12	4	8	4	39.0	876	3.13	0.391	4.74	0.168	27.6	3.42	41.4	1.48
13	4	0	1*	36.9	755	3.35	0.412	4.78	0.172	25.2	3.10	36.0	1.30
14	4	8	1*	34.8	811	2.90	0.410	4.75	0.153	23.5	3.32	38.6	1.24
Stats for RCB design (all 14 treatments)													
P > F:				0.001	0.001	0.024	0.038	0.205	0.022	0.040	0.001	0.001	0.028
Average LSD(0.10):				2.0	103	0.39	0.034	NS	0.020	5.2	0.46	5.1	0.24
Stats for a Factorial Design (Treatments 1-12)													
APP (10-34-0) applied in-furrow													
None				34.3	719	3.32	0.400	4.81	0.169	24.3	2.88	35.1	1.22
4 gal/ac				37.1	827	3.27	0.403	4.84	0.164	27.4	3.34	40.2	1.37
P > F:				0.001	0.001	0.895	0.731	0.765	0.347	0.027	0.001	0.000	0.022
UAN (28-0-0) applied as a surface dribble band													
None				35.0	751	3.46	0.418	4.85	0.174	26.2	3.14	36.9	1.30
8 gal/ac				36.4	795	3.13	0.385	4.80	0.160	25.5	3.08	38.4	1.29
P > F:				0.010	0.083	0.006	0.001	0.554	0.008	0.602	0.618	0.171	0.860
ATS (12-0-0-26) applied as a surface dribble band													
None				34.6	721	3.33	0.389	4.86	0.161	24.3	2.82	35.5	1.17
2 gal/ac				35.4	787	3.35	0.412	4.63	0.172	27.0	3.25	36.7	1.37
4 gal/ac				37.1	810	3.20	0.403	4.97	0.167	26.3	3.26	40.8	1.36
P > F:				0.001	0.014	0.240	0.112	0.013	0.212	0.194	0.004	0.001	0.014
Average LSD (0.10):				1.0	51	NS	NS	0.19	NS	NS	0.23	2.3	0.12
Interactions (P > F)													
APP×UAN				0.042	0.818	0.781	0.724	0.908	0.922	0.582	0.854	0.753	0.853
APP×ATS				0.272	0.547	0.097	0.991	0.088	0.033	0.964	0.496	0.026	0.691
UAN×ATS				0.016	0.041	0.208	0.343	0.549	0.364	0.042	0.019	0.001	0.150
APP×UAN×ATS				0.001	0.031	0.225	0.263	0.780	0.345	0.023	0.014	0.023	0.058

* One gal/ac rate of ATS applied in-furrow with seed and 10-34-0.

Table 3. Grain moisture and yield, plant stand, final plant population, and relative leaf chlorophyll at Waseca.

						Initial	Final	VT-R1
	Fertilizer rate			Grain	Grain	Plant	Plant	Leaf
Trt	APP	UAN	ATS	H_2O	Yield	Stand	Pop.	Chloro
#	-------	gal/ac	-------	%	bu/ac	plants×10^3/A		%
1	0	0	0	18.1	194	32.8	32.8	98.1
2	0	0	2	18.6	194	31.7	31.7	97.6
3	0	0	4	18.7	191	30.8	30.8	98.4
4	0	8	0	17.4	199	33.2	33.1	96.4
5	0	8	2	18.3	192	31.4	31.4	97.4
6	0	8	4	19.9	194	30.5	30.5	97.4
7	4	0	0	17.7	197	31.4	31.4	97.1
8	4	0	2	17.9	197	32.6	32.5	97.5
9	4	0	4	18.6	199	32.3	32.3	97.8
10	4	8	0	17.7	194	32.8	32.8	97.4
11	4	8	2	17.6	203	29.9	29.9	99.1
12	4	8	4	18.1	201	31.8	31.8	96.0
13	4	0	1*	18.2	197	31.0	31.0	99.0
14	4	8	1*	17.8	184	30.1	30.1	97.4
Stats for RCB design (all 14 treatments)								
P > F:				0.270	0.181	0.001	0.001	0.198
Average LSD (0.10):				NS	NS	1.3	1.3	NS
Stats for a Factorial Design (Treatments 1-12)								
APP (10-34-0) applied in-furrow								
None				18.5	194	31.7	31.7	97.6
4 gal/ac				17.9	198	31.8	31.8	97.5
P > F:				0.108	0.170	0.708	0.735	0.796
UAN (28-0-0) applied as a surface dribble band								
None				18.3	195	31.9	31.9	97.8
8 gal/ac				18.2	197	31.6	31.6	97.3
P > F:				0.785	0.662	0.300	0.314	0.301
ATS (12-0-0-26) applied as a surface dribble band								
None				17.8	196	32.6	32.5	97.3
2 gal/ac				18.1	197	31.4	31.4	97.9
4 gal/ac				18.8	196	31.3	31.3	97.4
P > F:				0.046	0.824	0.005	0.004	0.494
Average LSD (0.10):				0.7	NS	0.6	0.6	NS
Interactions (P > F)								
APP×UAN				0.649	0.685	0.409	0.459	0.238
APP×ATS				0.519	0.156	0.011	0.010	0.301
UAN×ATS				0.642	0.768	0.015	0.018	0.178
APP×UAN×ATS				0.333	0.212	0.088	0.094	0.368

* One gal/ac rate of ATS applied in-furrow with seed.

Table 4. Nutrient concentration and uptake in the corn grain at Waseca.

Trt	Fertilizer rate APP	UAN	ATS	Grain concentration N	P	K	S	Nutrient uptake in grain N	P	K	S
#	------- gal/ac		-------	-------------- %			--------------	------------- lb/ac			-------------
1	0	0	0	1.15	0.25	0.38	0.079	105	23.3	34.5	7.3
2	0	0	2	1.15	0.27	0.39	0.082	105	24.6	35.6	7.5
3	0	0	4	1.20	0.26	0.38	0.084	109	23.8	34.1	7.6
4	0	8	0	1.15	0.26	0.38	0.079	108	24.3	35.6	7.4
5	0	8	2	1.19	0.27	0.39	0.079	108	24.6	35.6	7.1
6	0	8	4	1.09	0.26	0.40	0.085	100	24.2	36.8	7.8
7	4	0	0	1.21	0.25	0.37	0.080	113	23.3	34.6	7.4
8	4	0	2	1.20	0.26	0.37	0.081	111	23.8	34.5	7.5
9	4	0	4	1.20	0.26	0.38	0.085	112	24.1	35.3	7.9
10	4	8	0	1.16	0.26	0.38	0.079	104	23.5	33.5	7.0
11	4	8	2	1.20	0.27	0.38	0.081	115	25.8	36.8	7.8
12	4	8	4	1.17	0.27	0.38	0.085	111	25.2	36.2	8.1
13	4	0	1*	1.15	0.28	0.39	0.081	107	26.1	35.8	7.6
14	4	8	1*	1.12	0.26	0.37	0.083	97	22.6	32.6	7.3
Stats for RCB design (all 14 treatments)											
P > F:				0.062	0.943	0.848	0.161	0.017	0.705	0.409	0.020
Average LSD (0.10):				0.06	NS	NS	NS	8	NS	NS	0.5
Stats for a Factorial Design (Treatments 1-12)											
APP (10-34-0) applied in-furrow											
None				1.15	0.26	0.39	0.081	106	24.1	35.4	7.4
4 gal/ac				1.19	0.26	0.38	0.082	111	24.3	35.2	7.6
P > F:				0.042	0.610	0.203	0.768	0.018	0.848	0.807	0.107
UAN (28-0-0) applied as a surface dribble band											
None				1.18	0.26	0.38	0.082	109	23.8	34.8	7.5
8 gal/ac				1.16	0.26	0.39	0.081	108	24.6	35.7	7.5
P > F:				0.117	0.307	0.232	0.713	0.443	0.225	0.172	0.993
ATS (12-0-0-26) applied as a surface dribble band											
None				1.17	0.26	0.38	0.079	107	23.6	34.5	7.3
2 gal/ac				1.18	0.27	0.38	0.080	110	24.7	35.6	7.5
4 gal/ac				1.16	0.26	0.38	0.085	108	24.3	35.6	7.9
P > F:				0.540	0.548	0.513	0.001	0.558	0.393	0.369	0.001
Average LSD (0.10):				NS	NS	NS	0.002	NS	NS	NS	0.2
Interactions (P > F)											
APP×UAN				0.959	0.558	0.862	0.640	0.758	0.638	0.631	0.925
APP×ATS				0.969	0.912	0.800	0.964	0.491	0.791	0.693	0.198
UAN×ATS				0.078	0.987	0.807	0.769	0.242	0.974	0.537	0.533
APP×UAN×ATS				0.149	0.995	0.718	0.790	0.128	0.684	0.362	0.127

* One gal/ac rate of ATS applied in-furrow with seed and 10-34-0.

Table 5. Early growth, yield, nutrient concentration and uptake of V7 corn plants at Rochester.

				V7	Whole Plant Samples at V7 (June 24)								
	Fertilizer rate			Plant		Concentration				Uptake			
Trt	APP	UAN	ATS	height	Yield	N	P	K	S	N	P	K	S
#	---- gal/ac -----			inch	lb/ac	-------------- % --------------				---------- lb/ac -----------			
1	0	0	0	27.3	375	3.54	0.226	2.90	0.200	13.3	0.85	10.9	0.75
2	0	0	2	27.5	413	3.50	0.247	2.62	0.220	14.5	1.02	10.9	0.90
3	0	0	4	28.9	461	3.60	0.250	2.64	0.216	16.6	1.16	12.1	1.00
4	0	8	0	28.1	423	3.62	0.253	2.64	0.207	15.2	1.07	11.2	0.87
5	0	8	2	30.2	575	3.49	0.264	2.48	0.208	20.0	1.51	14.2	1.19
6	0	8	4	30.2	556	3.64	0.259	2.39	0.218	20.1	1.46	13.2	1.21
7	4	0	0	32.1	632	3.47	0.258	2.57	0.194	21.9	1.64	16.2	1.23
8	4	0	2	32.6	551	3.53	0.263	2.44	0.210	19.5	1.45	13.4	1.15
9	4	0	4	33.3	746	3.49	0.266	2.30	0.210	26.0	1.98	17.1	1.56
10	4	8	0	33.4	651	3.64	0.289	2.42	0.199	23.6	1.87	15.7	1.29
11	4	8	2	34.0	693	3.61	0.265	2.12	0.208	25.0	1.84	14.7	1.44
12	4	8	4	33.1	731	3.74	0.287	2.17	0.222	27.4	2.10	16.2	1.63
13	4	0	1*	31.4	608	3.55	0.276	2.31	0.211	21.6	1.70	14.2	1.28
14	4	8	1*	33.4	693	3.68	0.298	2.12	0.211	25.5	2.07	14.8	1.47
Stats for RCB design (all 14 treatments)													
P > F:				0.001	0.001	0.095	0.004	0.006	0.020	0.001	0.001	0.023	0.001
Average LSD(0.10):				1.9	102	0.15	0.026	0.32	0.013	3.2	0.36	3.2	0.23
Stats for a Factorial Design (Treatments 1-12)													
APP (10-34-0) applied in-furrow													
None				28.7	467	3.57	0.250	2.61	0.211	16.6	1.18	12.1	0.99
4 gal/ac				33.1	667	3.58	0.271	2.34	0.207	23.9	1.81	15.6	1.38
P > F:				0.001	0.001	0.720	0.001	0.002	0.156	0.001	0.001	0.001	0.001
UAN (28-0-0) applied as a surface dribble band													
None				30.3	530	3.52	0.252	2.58	0.208	18.6	1.35	13.4	1.10
8 gal/ac				31.5	605	3.62	0.269	2.37	0.210	21.9	1.64	14.2	1.27
P > F:				0.011	0.007	0.011	0.005	0.015	0.523	0.001	0.002	0.358	0.007
ATS (12-0-0-26) applied as a surface dribble band													
None				30.2	520	3.57	0.256	2.63	0.200	18.5	1.36	13.5	1.03
2 gal/ac				31.1	558	3.53	0.260	2.41	0.211	19.7	1.46	13.3	1.17
4 gal/ac				31.4	623	3.62	0.265	2.37	0.217	22.5	1.68	14.6	1.35
P > F:				0.105	0.009	0.186	0.459	0.028	0.001	0.005	0.016	0.375	0.001
Average LSD (0.10):				NS	54	NS	NS	0.17	0.006	1.9	0.18	NS	0.12
Interactions (P > F)													
APP×UAN				0.419	0.321	0.091	0.994	0.943	0.340	0.669	0.594	0.337	0.583
APP×ATS				0.484	0.159	0.507	0.204	0.999	0.741	0.244	0.123	0.230	0.237
UAN×ATS				0.407	0.127	0.416	0.395	0.976	0.148	0.239	0.493	0.409	0.369
APP×UAN×ATS				0.628	0.739	0.789	0.612	0.698	0.661	0.882	0.909	0.940	0.874

* One gal/ac rate of ATS applied in-furrow with seed and 10-34-0.

Table 6. Grain moisture and yield, plant stand, final plant population, and relative leaf chlorophyll at Rochester.

						Initial	Final	VT-R1
	Fertilizer rate			Grain	Grain	Plant	Plant	Leaf
Trt	APP	UAN	ATS	H_2O	Yield	Stand	Pop.	Chloro
#	------	gal/ac	-------	%	bu/ac	plants×10^3/A		%
1	0	0	0	21.8	193	35.2	34.7	97.4
2	0	0	2	21.4	194	35.6	34.8	98.3
3	0	0	4	20.8	198	34.9	34.4	98.0
4	0	8	0	22.0	188	35.8	34.7	94.7
5	0	8	2	20.6	194	35.6	34.7	97.2
6	0	8	4	21.0	205	34.5	34.4	96.9
7	4	0	0	19.8	197	34.8	34.6	96.7
8	4	0	2	20.4	198	34.7	34.2	96.6
9	4	0	4	19.7	203	34.4	34.3	98.1
10	4	8	0	19.8	196	34.7	34.4	96.0
11	4	8	2	19.7	199	35.1	34.7	98.4
12	4	8	4	20.0	204	34.7	34.5	99.4
13	4	0	1*	20.6	199	35.1	34.5	98.1
14	4	8	1*	19.9	196	34.4	34.3	98.7
Stats for RCB design (all 14 treatments)								
P > F:				0.001	0.011	0.244	0.430	0.001
Average LSD (0.10):				0.8	7	NS	NS	1.4
Stats for a Factorial Design (Treatments 1-12)								
APP (10-34-0) applied in-furrow								
None				21.3	195	35.3	34.6	97.1
4 gal/ac				19.9	199	34.7	34.4	97.5
P > F:				0.001	0.011	0.025	0.086	0.167
UAN (28-0-0) applied as a surface dribble band								
None				20.6	197	34.9	34.5	97.5
8 gal/ac				20.5	198	35.1	34.6	97.1
P > F:				0.501	0.718	0.570	0.596	0.200
ATS (12-0-0-26) applied as a surface dribble band								
None				20.9	194	35.1	34.6	96.2
2 gal/ac				20.5	196	35.2	34.6	97.6
4 gal/ac				20.4	202	34.6	34.4	98.1
P > F:				0.117	0.001	0.083	0.216	0.001
Average LSD (0.10):				NS	3	0.5	NS	0.6
Interactions (P > F)								
APP×UAN				1.000	0.908	0.673	0.275	0.001
APP×ATS				0.027	0.624	0.513	0.649	0.141
UAN×ATS				0.084	0.179	0.794	0.517	0.026
APP×UAN×ATS				0.908	0.435	0.523	0.219	0.817

* One gal/ac rate of ATS applied in-furrow with seed.

Table 7. Nutrient concentration and uptake in the corn grain at Rochester.

	Fertilizer rate			Grain concentration				Nutrient uptake in grain			
Trt	APP	UAN	ATS	N	P	K	S	N	P	K	S
#	------ gal/ac -------			-------------- % --------------				------------- lb/ac -------------			
1	0	0	0	1.18	0.23	0.37	0.072	108	21.3	33.4	6.6
2	0	0	2	1.19	0.22	0.35	0.073	109	20.1	32.2	6.7
3	0	0	4	1.18	0.22	0.34	0.076	110	20.1	31.8	7.1
4	0	8	0	1.21	0.24	0.38	0.068	108	21.5	33.4	6.0
5	0	8	2	1.21	0.25	0.38	0.073	111	23.3	35.2	6.7
6	0	8	4	1.15	0.24	0.37	0.076	111	23.2	35.4	7.3
7	4	0	0	1.17	0.27	0.40	0.070	109	25.4	37.7	6.5
8	4	0	2	1.17	0.22	0.35	0.074	109	20.4	33.1	6.9
9	4	0	4	1.17	0.25	0.38	0.078	112	24.4	36.5	7.5
10	4	8	0	1.21	0.23	0.35	0.065	113	20.8	32.1	6.0
11	4	8	2	1.23	0.23	0.36	0.073	115	21.6	33.6	6.9
12	4	8	4	1.18	0.23	0.37	0.082	114	22.2	35.2	7.9
13	4	0	1*	1.17	0.25	0.37	0.076	110	23.2	35.2	7.2
14	4	8	1*	1.19	0.24	0.36	0.070	110	21.8	33.0	6.5
Stats for RCB design (all 14 treatments)											
P > F:				0.235	0.286	0.203	0.001	0.856	0.255	0.159	0.001
Average LSD (0.10):				NS	NS	NS	0.004	NS	NS	NS	0.5
Stats for a Factorial Design (Treatments 1-12)											
APP (10-34-0) applied in-furrow											
None				1.18	0.23	0.36	0.073	109	21.6	33.6	6.7
4 gal/ac				1.19	0.24	0.37	0.074	112	22.5	34.7	7.0
P > F:				0.829	0.588	0.578	0.412	0.131	0.245	0.141	0.060
UAN (28-0-0) applied as a surface dribble band											
None				1.18	0.24	0.37	0.074	110	22.0	34.1	6.9
8 gal/ac				1.20	0.24	0.37	0.073	112	22.1	34.1	6.8
P > F:				0.050	0.876	0.992	0.238	0.157	0.861	0.968	0.498
ATS (12-0-0-26) applied as a surface dribble band											
None				1.19	0.24	0.37	0.069	109	22.3	34.1	6.3
2 gal/ac				1.20	0.23	0.36	0.073	111	21.4	33.5	6.8
4 gal/ac				1.17	0.23	0.36	0.078	112	22.5	34.7	7.5
P > F:				0.075	0.412	0.438	0.001	0.476	0.433	0.442	0.001
Average LSD (0.10):				0.02	NS	NS	0.002	NS	NS	NS	0.2
Interactions (P > F)											
APP×UAN				0.177	0.011	0.008	0.647	0.367	0.010	0.008	0.750
APP×ATS				0.742	0.310	0.293	0.040	0.969	0.317	0.353	0.253
UAN×ATS				0.174	0.113	0.131	0.030	0.726	0.068	0.045	0.015
APP×UAN×ATS				0.863	0.674	0.611	0.348	0.923	0.633	0.685	0.810

* One gal/ac rate of ATS applied in-furrow with seed and 10-34-0.

Table 8. Corn grain moisture, yield and plant height as affected by treatment main effects by location and year.												
	Waseca location						Rochester location					
	Grain moisture		Grain yield		Plant height		Grain moisture		Grain yield		Plant height	
Main effect	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011	2010	2011
	%		bu/ac		inch		%		bu/ac		inch	
APP (10-34-0) in-furrow												
None	18.6a	18.5a	214a	194a	32.7a	34.3a	17.4a	21.3a	208a	195a	36.8a	28.7a
4 gal/ac	17.7b	17.9a	214a	198a	35.3b	37.1b	16.5b	19.9b	210a	199b	40.0b	33.1b
UAN (28-0-0) surface dribble-band												
None	18.6a	18.3a	216a	195a	32.4a	35.0a	17.1a	20.6a	209a	197a	38.2a	30.3a
8 gal/ac	17.7b	18.2a	212a	197a	35.5b	36.4b	16.8b	20.5a	209a	198a	38.6a	31.5b
ATS (12-0-0-26) surface dribble-band												
None	19.5a	17.8a	209a	196a	32.5a	34.6a	17.1a	20.9a	209a	194a	38.2a	30.2a
2 gal/ac	18.0b	18.1a	218b	197a	34.6b	35.4a	17.0a	20.5a	209a	196a	38.3a	31.1a
4 gal/ac	17.0c	18.8b	215b	196a	34.8b	37.1b	16.8a	20.4a	210a	202b	38.7a	31.4a

In-Season Precision Applications of Fluid Fertilizer to Optimize Cotton Productivity and Nitrogen Use Efficiency

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Abstract

Current nitrogen (N) fertility recommendations should possibly be modified because of the significant yield increases resultant from new cotton cultivars and improved management practices. On the other hand, it is essential to develop innovative approaches that can manage N fertilizer more efficiently to increase grower profitability due to substantially increased N prices. The objectives of this study for 2011 were to estimate the spatial variations in lint yield, normalized difference vegetation index (NDVI), leaf N concentration, and soil nitrate within a field, and to evaluate the relationships among cotton lint yield, canopy NDVI, and leaf N under Tennessee production environments. A field experiment was conducted on a private farm in Gibson County, west Tennessee in 2011. Five N application rate treatments of 0, 40, 80, 120, and 160 lb N/acre were evaluated as side dress N in large strip plots (38-ft wide running the length of the field) in a randomized complete block design with three replicates. Each strip plot was divided into eight 100-ft long sub plots. Soil nitrate and ammonium prior to cotton planting and after harvest, canopy NDVI readings and leaf N concentrations at the early square and early, mid, and late bloom growth stages, and lint yields at harvest were measured on a sub plot basis. The 2011 results showed statistically significant but weak correlations of lint yield with canopy NDVI readings no matter when NDVI values were collected. Canopy NDVI was not a strong indicator of plant N nutrition during early square to late bloom. There was significant global spatial autocorrelation of residual lint yields (N treatment effects on yields excluded) within the test field based on Moran's I statistic. The LISA cluster map showed that there were some significant local clusters of residual lint yields within this test field. Overall, there was significant global and some significant local spatial dependence of lint yields relating to the characteristics of this test field.

In-Season Precision Applications of Fluid Fertilizer to Optimize Cotton Productivity and Nitrogen Use Efficiency

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Introduction

Presently, nitrogen (N) fertilizers are recommended to be applied at 30-60 lb N/acre on bottom soils and 60-80 lb N/acre on upland soils before or at cotton planting in Tennessee. These recommendations have been used for decades without any major modifications. Because of the significant yield increases resultant from new cotton cultivars and improvements in management practices, there is a need to re-evaluate the current N recommendations to see whether N application rates are adequate for new cultivars to reach their optimal yield potentials.

On the other hand, there is an urgent need to develop innovative approaches that can manage N fertilizer more efficiently to increase grower profitability due to substantially increased N prices during the last several years. Overall, there are two major factors limiting N use efficiency in the current cotton N management systems. Firstly, the current N management systems were developed based on a state or regional scale, and they have no capability to cope with spatial variability within individual fields. Under the current systems, cotton producers use a uniform N fertilizer rate for the entire field or even the entire farm, which often results in under- and over-applications of N. Secondly, large doses of N are usually applied early in the season (pre-planting or at planting) before cotton plants can effectively uptake and utilize it; this puts the applied N at high risk to environmental losses. In order to solve these two problems, there is a need to develop new N management systems that can generate variable-rate N recommendations for different areas within a field and emphasize the application of N in the mid-season.

Measuring crop N nutrition status during the season by optically sensing crop canopy seems to be a viable precision N management tool for variable-rate N applications within the field, emphasizing N application in the mid-season, and minimizing the cost of N application. Researchers have utilized on-vehicle, real-time optical sensing of crop canopy to generate Normalized Differential Vegetation Index (NDVI) to assess crop N nutrition status. This approach enables on-the-go diagnoses of crop N deficiency, real-time applying N fertilizer at variable rates, and precisely treating each area sensed without processing data or determining location within a field beforehand. Research on wheat and corn has shown an about 15% increase in N use efficiency and some significant yield increases with this approach. So far, precision N research has been focused on wheat and corn. Little investigation has been documented on cotton.

The objectives of this study were to: 1) determine the optimal N fertilizer application rates for high-yielding cotton production systems in Tennessee; 2) estimate the spatial variations in lint yield, NDVI, leaf N concentration, and soil nitrate within a field; 3) investigate the relationships between lint yield and NDVI, and between NDVI and crop N nutrition status; and 4) if there is a significant relationship between cotton yield and canopy NDVI, then algorithms will be developed for variable-rate N applications within a field, based on the relationship between lint yield and NDVI. The algorithms for variable-rate N applications will be compared with the uniform-rate N application system in terms of N fertilizer consumption and lint yield. In 2011, our work focused on the Objectives 2 & 3.

Overall, if this project has been carried out successfully, it will provide accurate N fertilizer recommendations for high-yielding cotton production systems. It will also generate appropriate algorithms for in-season variable-rate N applications within a field on cotton. All these can significantly reduce N fertilizer consumption and improve cotton productivity, and thus increase grower profitability.

Materials and Methods

A field experiment was conducted on a private farm in western Tennessee in 2011. The cooperative farmer was Jeff Dodd in Gibson County. The experiment in 2011 was conducted on the same field with the same plot layout as in 2009 and 2010. This producer applied 40 lb/a N across the test field as pre-plant N in the form of calcium nitrate (27% N) before cotton planting in 2011.

Five N application rate treatments of 0, 40, 80, 120, and 160 lb N/acre were evaluated as side dress N in large strip plots (38-ft wide strips running the length of the field) in a randomized complete block design with three replicates. The dates of cotton planting and N treatment implementation are presented in Table 1. Cotton was planted in 38” rows. This test was managed using the recommended best management practices except the N treatments (Table 1).

Each strip plot in this test was divided into eight 100-ft long sub plots. A composite soil sample was taken at a depth of 2-ft. for nitrate and ammonium in the soil profile on a sub plot basis prior to treatment initiation. Canopy NDVI data were collected from each sub plot at the early square and early, mid, and late bloom growth stages using the GreenSeeker® (NTech Industries, Inc., CA) RT 200 Data Collection and Mapping System (Table 1). A composite leaf sample (10 blades + petioles) was collected on a sub plot basis for four times at about the same dates when NDVI data were taken (Table 1). All leaf samples were analyzed for N concentrations using our own LECO Tru-Spec Analyzer. Cotton harvest was completed on a sub plot basis in early October by harvesting the central six rows of cotton. A post-harvest soil sample was collected for soil nitrate and ammonium at a 2-ft depth from each sub plot.

Correlations of lint yield with canopy NDVI and leaf N concentrations and the coefficient of variation (CV) for each strip plot were estimated using SAS Statistical Software v.9.1. Spatial variations in lint yield, canopy NDVI, leaf N, and post-harvest soil N within the experiment were visualized in GIS maps using ArcView v.9.3. A quadratic regression of lint yield was conducted using the classic and spatial error models in GeoDa 0.9.5-i (Beta) with a weight matrix created using a 2nd order queen's contiguity model that includes all lower contiguity orders. In order to evaluate the spatial dependence of lint yield relating to the characteristics of the test field (not to N treatments), we removed the effects of side dress N treatments on lint yields from the lint yields data using the spatial error model, and we used the residual lint yields (which were obtained in the spatial error model in GeoDa and in which N treatment effects on lint yields had been excluded) to make Moran's I statistic and scatter plot and the Localized Indicators of Spatial Autocorrelation (LISA) cluster map. Moran's I statistics and scatter plot and the LISA cluster map of residual lint yields were created in GeoDa using the 2nd order queen's contiguity model that includes all lower contiguity orders.

Results and Discussion

Correlations of Lint Yields with Canopy NDVI and Leaf N

The correlations of lint yield with canopy NDVI were statistically significant at early square and early, mid, and late bloom stages (Table 2). The correlations of lint yield with leaf N were significant at mid and late bloom stages (Table 2). There was significant correlation of leaf N with canopy NDVI at mid and late bloom stages (Table 2). Overall, the determination coefficient (R^2) values for the above correlations in 2011 were similar to those in 2010, but lower than those in 2009; which suggests that the correlations of lint yields with canopy NDVI and leaf N vary with years.

Spatial Analyses

ArcView GIS maps of canopy NDVI, leaf N, lint yields, and post-harvest soil N at Gibson are presented in Fig. 1 to 10, respectively. The lint yield map shows that spatial variations in lint yield did exist within most strip plots. Visually, it seemed lint yield had a better correlation with canopy NDVI at late bloom (August 17) than the other growth stages. The post harvest soil N map indicates that the side dress N treatments implemented early in the season did not show evident impacts on soil nitrate and ammonium after cotton harvest, which suggests that residual nitrate and ammonium from the N treatments was ignorable in the soil after harvest.

In order to examine the spatial dependence of lint yields within the test field, we conducted a quadratic regression of lint yields with side dress N application rates using the classic model in the GeoDa software, and we observed significant spatial dependence of lint yields within the test field (data not presented). Then, the spatial error model in GeoDa was used to conduct the quadratic regression of lint yields with side dress N rates; the output was presented in Table 3.

In order to visualize the spatial dependence of lint yield relating to the characteristics of the test field (not to N treatments), we used the residual lint yields (which were obtained in the spatial error model in GoeDa and in which N treatment effects on lint yields had been excluded) to make Moran's I statistic and scatter plot and LISA cluster map. Moran's I statistic and scatter plot and LISA cluster map are presented in Fig. 11, and 12, respectively.

Moran's I and scatter plot evaluates global spatial autocorrelation. Moran scatter plot provides a visual exploration of global spatial autocorrelation. The four quadrants in the Moran scatter plot provide a classification of four types of spatial autocorrelation: high-high and low-low for positive autocorrelation; low-high and high-low for negative spatial autocorrelation. The value listed at the top of the graph is the Moran's I statistic. Fig. 11 shows that there was significant ($p = 0.001$)

spatial autocorrelation of residual lint yields (N treatment effects on yields excluded) within the tested field.

The LISA cluster map estimates local spatial autocorrelation. It contains information on only those locations that have significant spatial autocorrelation. Four types of spatial autocorrelations are colored in four different colors: dark red for high-high, dark blue for low-low, pink for high-low, and light blue for low-high. The LISA cluster map in Fig. 12 shows that there were some significant local clusters of residual lint yields (N treatment effects on yields excluded) within this tested field. Specifically, there were eighteen sub plots with high residual yields surrounded by high residual yield neighbors, sixteen low residual yield sub plots were surrounded by low residual yield neighbors, four sub plots with low residual yields were surrounded by high residual yield neighbors, and two high residual yield sub plots were surrounded by low residual yield neighbors.

Spatial Variations within Each Strip Plot

Coefficients of variation (CV) were generally low for canopy NDVI and leaf N within each strip plot at the early square and early, mid, and late bloom stages (Table 4). The CV values were greater with lint yields and postharvest soil nitrate and ammonium (Table 4). Since all the sub plots within a strip plot received the identical N treatment, the CV value for each strip plot in Table 4 reflects the spatial variations within that strip plot. The CV results of 2011 showed the same trends as those of 2009 and 2010.

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Table 1. Major operations performed at Gibson in 2011.

List of operations performed	Date performed
Cotton planting	5/21/11
Side dress liquid nitrogen treatments	6/15/11
Collected early square leaf samples	7/5/11
Collected early bloom leaf samples	7/27/11
Collected mid-bloom leaf samples	8/4/11
Collected late bloom leaf samples	8/17/11
Recorded canopy NDVI at early square	7/5/11
Recorded canopy NDVI at early bloom	7/27/11
Recorded canopy NDVI at mid-bloom	8/4/11
Recorded canopy NDVI at late bloom	8/17/11
Dried and ground all leaf samples & shipped them for analyses	10/14/11
Harvested center 6 rows of each 12-row plot	10/1/11
Collected seed cotton samples for lint quality	10/1/11
Collected 2 ft. post-harvest soil samples	11/10/11
Dried and ground all soil samples & shipped them for analysis	12/6/11

Table 2. Correlations among lint yield, canopy NDVI, and leaf N concentration at Gibson in 2011.

Dependent variable (Y)	Independent variable (X)	R^2	R	P
Lint yield	NDVI_7-5-11	0.13	0.36	<0.0001
Lint yield	NDVI_7-27-11	0.18	0.42	<0.0001
Lint yield	NDVI_8-4-11	0.29	0.54	<0.0001
Lint yield	NDVI_8-17-11	0.26	0.51	<0.0001
Lint yield	Leaf N_7-5-11	0.02	0.14	0.1143
Lint yield	Leaf N_7-27-11	0.01	0.10	0.1934
Lint yield	Leaf N_8-4-11	0.05	0.22	0.0243
Lint yield	Leaf N_8-17-11	0.04	0.20	0.0213
Leaf N_7-5-11	NDVI_7-5-11	0.01	0.10	0.1954
Leaf N_7-27-11	NDVI_7-27-11	0.00	0.00	0.9943
Leaf N_8-4-11	NDVI_8-4-11	0.05	0.22	0.0183
Leaf N_8-17-11	NDVI_8-17-11	0.08	0.28	0.0024

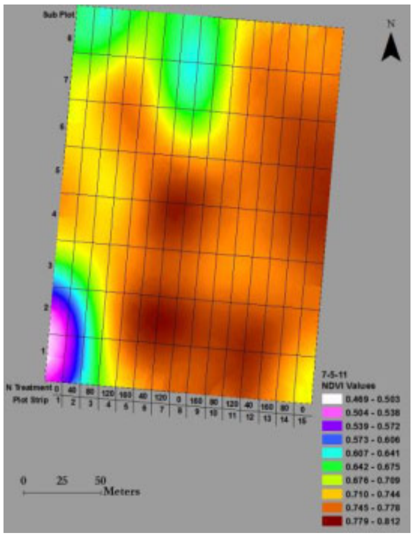
Table 3. Regression summary of output using spatial error model at Gibson in 2011.

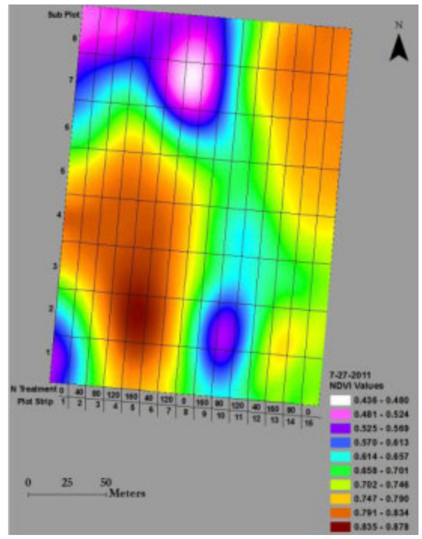
Variable	Coefficient	Std. Error	z-value	Probability
CONSTANT	66.80268	6.4063	10.42765	0.0000000
N	0.2812453	0.1199682	2.344331	0.0190612
N*N	-0.0008253423	0.0006874219	-1.200634	0.2298932
LAMBDA	0.6661434	0.09001163	7.400636	0.0000000

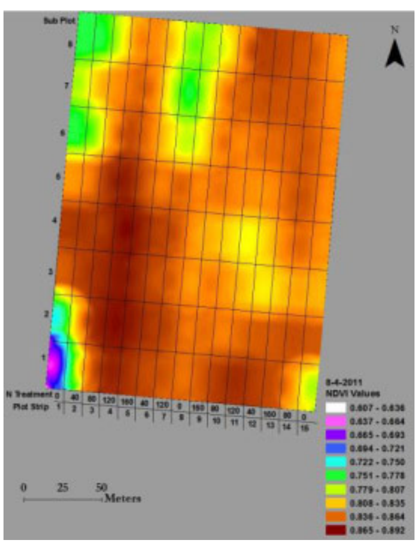
Table 4. Coefficient of variation (%) in canopy NDVI, leaf N, lint yield, and post-harvest soil N within each strip plot at Gibson in 2011.

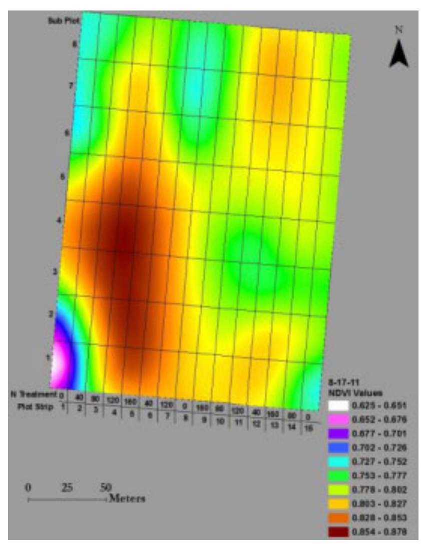
Strip plot	N rate	NDVI 7-5-11	NDVI 7-27-11	NDVI 8-4-11	NDVI 8-17-11	Leaf N 7-5-11	Leaf N 7-27-11	Leaf N 8-4-11	Leaf N 8-17-11	Yield	Post-harvest soil N
1	0	19.2	10.1	11.3	9.3	8.3	13.1	14.8	18.1	5.6	79.7
2	40	10.3	7.5	5.6	3.6	5.4	8.2	16.3	11.3	23.2	37.5
3	80	4.3	4.2	3.2	2.7	5.3	7.0	7.5	5.1	17.5	34.9
4	120	6.1	7.0	1.5	1.0	7.5	4.7	6.7	6.4	13.7	58.7
5	160	2.8	2.2	1.7	1.4	2.4	5.8	4.3	3.3	9.6	60.3
6	40	5.8	8.6	2.9	2.1	4.3	3.8	3.7	6.6	29.3	51.1
7	120	18.0	13.8	6.8	5.3	6.3	3.1	3.1	5.7	27.0	49.9
8	0	6.1	5.1	2.4	1.2	5.6	6.1	7.7	8.7	19.5	59.8
9	160	5.1	4.0	3.0	1.9	3.9	5.5	3.0	4.5	20.1	103.2
10	80	4.4	19.7	2.2	1.9	3.2	9.2	2.2	4.7	20.3	53.9
11	120	1.6	3.4	3.0	1.9	3.2	8.6	3.9	3.9	13.4	79.3
12	40	3.8	3.9	2.8	2.3	4.4	10.5	2.6	8.3	36.3	59.2
13	160	2.1	1.8	1.5	1.3	4.5	4.8	3.6	4.9	24.0	40.8
14	80	3.4	4.9	1.0	1.0	2.9	3.5	4.2	5.0	19.0	72.8
15	0	7.6	5.4	2.9	3.0	4.0	7.0	3.9	9.4	9.1	22.0

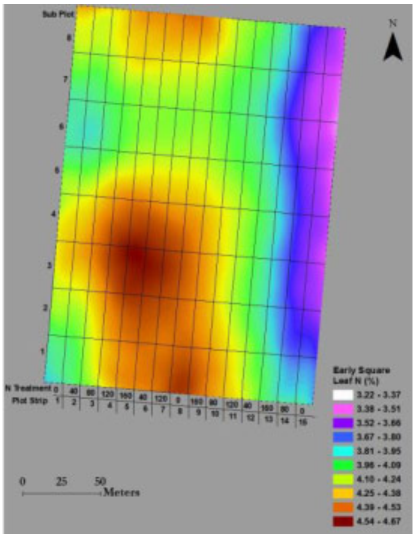
Fig. 1 to 10. ArcView GIS Maps of canopy NDVI, leaf N, lint yield, and post-harvest soil N at Gibson in 2011.

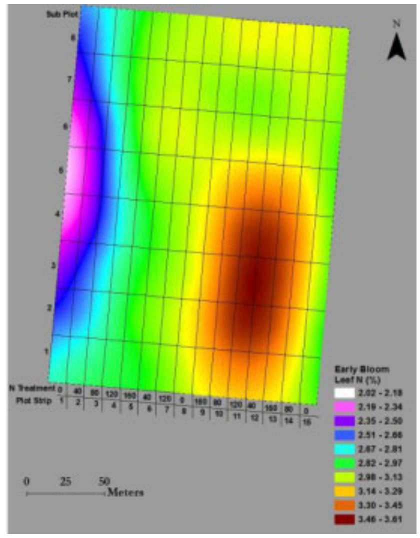


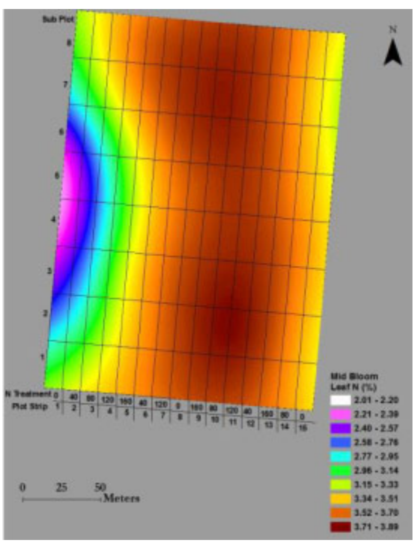


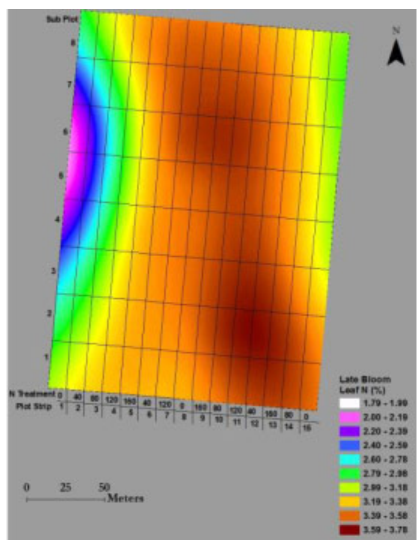


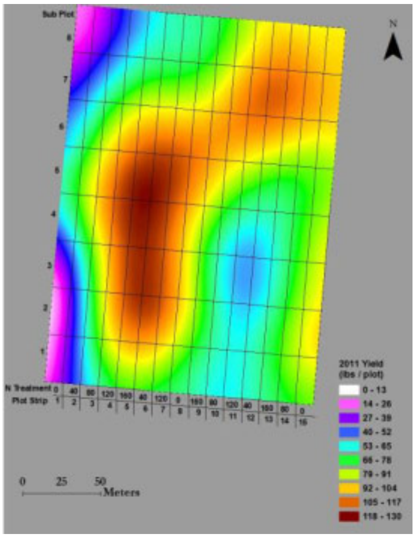



Sub Plot
N
N Treatment
Plot Strip
Early Square
Leaf N (%)
3.22 - 3.37
3.38 - 3.51
3.52 - 3.66
3.67 - 3.80
3.81 - 3.95
3.96 - 4.09
4.10 - 4.24
4.25 - 4.38
4.39 - 4.53
4.54 - 4.67
0 25 50
Meters


Sub Plot
N
N Treatment
Plot Strip
Early Bloom
Leaf N (%)
2.02 - 2.18
2.19 - 2.34
2.35 - 2.50
2.51 - 2.66
2.67 - 2.81
2.82 - 2.97
2.98 - 3.13
3.14 - 3.29
3.30 - 3.45
3.46 - 3.61
0 25 50
Meters


Sub Plot
N
N Treatment
Plot Strip
Mid Bloom
Leaf N (%)
2.01 - 2.20
2.21 - 2.39
2.40 - 2.57
2.58 - 2.76
2.77 - 2.95
2.96 - 3.14
3.15 - 3.33
3.34 - 3.51
3.52 - 3.70
3.71 - 3.89
0 25 50
Meters


Sub Plot
N
N Treatment
Plot Strip
Late Bloom
Leaf N (%)
1.79 - 1.99
2.00 - 2.19
2.20 - 2.39
2.40 - 2.59
2.60 - 2.78
2.79 - 2.98
2.99 - 3.18
3.19 - 3.38
3.39 - 3.58
3.59 - 3.78
0 25 50
Meters


Sub Plot
N
N Treatment 0 40 80 120 160 40 120 0 160 80 120 40 160 80 0
Plot Strip 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
0 25 50 Meters
2011 Yield (lbs / plot)
0 - 13
14 - 26
27 - 39
40 - 52
53 - 65
66 - 78
79 - 91
92 - 104
105 - 117
118 - 130

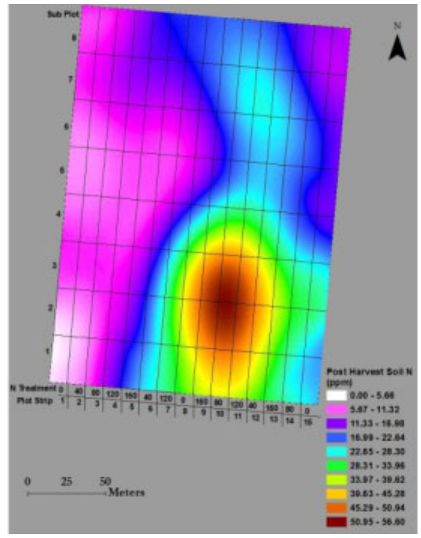

Sub Plot
N
N Treatment 0 40 80 120 160 40 120 0 160 80 120 40 160 80 0
Plot Strip 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
0 25 50 Meters
Post Harvest Soil N (ppm)
0.00 - 5.66
5.67 - 11.32
11.33 - 16.98
16.99 - 22.64
22.65 - 28.30
28.31 - 33.96
33.97 - 39.62
39.63 - 45.28
45.29 - 50.94
50.95 - 56.60

Fig. 11. Moran's I and scatter plot of residual lint yield (N treatment effects on yields excluded) at Gibson in 2011.

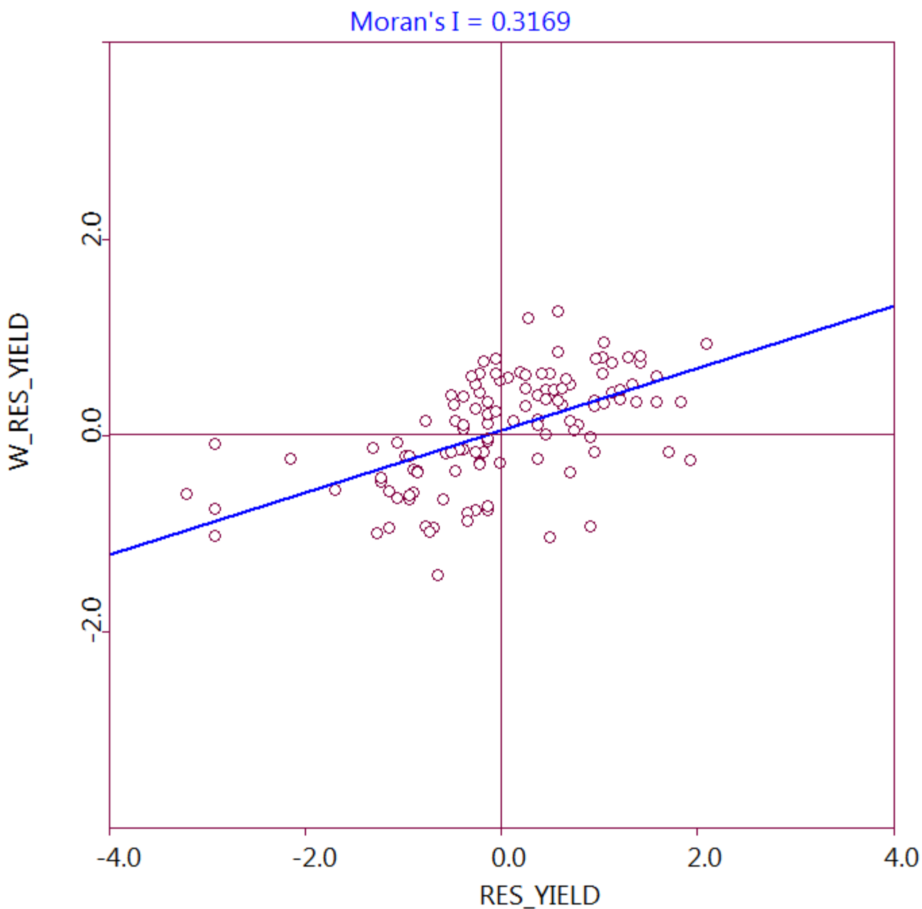


Fig. 12. LISA cluster map of lint yield (N treatment effects on yields excluded) at Gibson in 2011.