ABSTRACT

Title of Document: **CORN RESIDUAL NITRATE AND ITS IMPLICATIONS FOR FALL NITROGEN MANAGEMENT IN WINTER WHEAT**

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Corn (*Zea mays*, L.) production typically requires supplemental nitrogen (N) to optimize yields. In dryland corn production systems, where N is applied during the early to mid-vegetative growth stages, inappropriate N applications or limited moisture during the growing season can result in large disparities between optimum and applied N rates. This leads to variable post-harvest residual nitrate (NO_3-N) accumulation, which is susceptible to loss. However, this NO_3-N could provide the starter N requirement of the subsequent winter wheat (*Triticum aestivum*, L.) crop. Accounting for residual NO_3-N present at wheat planting is important to avoid compounding N loss potential due to corn residual NO_3-N accumulation. The objectives of this study were to 1) examine plant based tools for assessing soil NO_3-N; 2) to examine post-harvest residual NO_3-N accumulation patterns following corn production; 3) to determine optimum fall starter N rates for winter wheat production; and 4) to identify a soil NO_3-N level above which starter N could be forgone without negative agronomic effect. This study found that plant canopy measurements are useful tools for assessing corn N management and for

identifying drought sites, which had the greatest NO_3-N accumulations. The corn stalk nitrate test was significantly (p<0.001) and positively correlated with soil residual NO_3-N (r^2=0.41). Greatest soil residual NO_3-N accumulation occurred where drought conditions reduced production. The agronomic optimum fall starter N rate for winter wheat in Maryland is 17 to 34 kg N ha^{-1} where soil NO_3-N concentration to 15 cm depth is less than 15 mg kg^{-1}. However, the fall starter N response was highly variable and declined significantly (p<0.01) as fall precipitation after planting increased. The results of this study indicate that residual NO_3-N levels at planting should be considered before applying fall starter N to winter wheat.

CORN RESIDUAL NITRATE AND ITS IMPLICATIONS FOR FALL NITROGEN MANAGEMENT IN WINTER WHEAT

by

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Professor Robert Kratochvil, Chair
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Dedication

To my family for their love and encouragement

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Chapter 1: Introduction

Background and problem definition

In the Mid-Atlantic, winter wheat (*Triticum aestivum*, L.) is frequently grown following corn (*Zea mays*, L.), which is the largest crop in hectarage in Maryland. Corn production typically requires supplemental nitrogen (N) either as commercial fertilizer or manure to optimize yields. This N loading can lead to accumulation of post-harvest soil residual nitrate (NO_3-N) where N supplementation exceeds crop requirements. In dryland corn production, large variation in optimum N rates has been reported (Spargo, 2008; Hong *et al*., 2007; Roth and Fox, 1990) and at some sites the economically optimum nitrogen rate (EONR) was zero. Moisture stress, especially during the reproductive growth stages, causes a corn crop to not meet its yield potential (Nielsen *et al*., 2010). This potential for dramatic yield reduction due to drought compounds N management challenges for dryland corn production. In corn production, fertilizer N is typically applied during the early to mid-vegetative growth stages, a time when knowledge of growing season precipitation is absent. This feature of corn N management periodically results in mismatches between applied and optimum N rates due to growing season moisture stress. This can lead to post-harvest residual NO_3-N accumulation, which can leach to groundwater flow pathways during the winter water-recharge period. These pathways are the dominant link to surface waters on the Mid-Atlantic Coastal Plain (Boesch *et al*., 2001). Consequently, accumulation and subsequent loss of NO_3-N following corn production can degrade water quality in water bodies such as the Chesapeake Bay. Improving water quality in the Chesapeake Bay is the subject of intense focus by the Environmental Protection Agency. Maryland is imposing mandatory N loss restrictions through implementation of total maximum daily loads for N inputs to waterbodies (Maryland Department of Environment, 2010). Corn N management practices have an important role to play in curtailing losses from corn production systems. However, when post-harvest residual NO_3-N accumulation does occur, N management in the following crop is important to limit loss. Winter wheat or other small grains planted following corn can potentially act as cover crops and sequester residual NO_3-N (Coale *et al*., 2001). To increase hectares planted to cover crops, the state of Maryland provides a financial incentive for producers to not apply fall starter N to small grains (Maryland Department of Agriculture, 2010). However, application of starter fertilizer N to winter wheat is a recommended practice in the region (Sammons *et al*., 1989; Alley *et al*., 2009; Walker and Taylor, 1998). At sites where N availability exceeds wheat requirements applying fall starter N may compound the N leaching problem.

Justification for research

Sporadic post-harvest NO_3-N accumulation and loss due to variable precipitation patterns are inherent in the dryland corn production system. To minimize mismatches between the optimum and applied N rate, management practices such as application of the EONR, should be examined for their potential to curtail losses. However, when NO_3-N accumulation occurs, tools which allow producers or policy makers to identify sites or regions likely to have elevated residual NO_3-N would be useful to guide remediation strategies such as targeted cover crop plantings and N management in the subsequent winter wheat crop. Additionally, the soil profile distribution of post-harvest residual NO_3-N may affect its availability within the root zone of subsequent crops, such as winter wheat. The distribution pattern affects the potential for NO_3-N recovery in plant biomass before leaching pressure moves it to groundwater flow. In winter wheat, fall tillers will generally produce heads with more kernels (Alley *et al*., 2009). However, inadequate N availability can delay or inhibit tiller initiation (Longnecker *et al*., 1993); this may lead to agronomically unfavorable consequences, such as reduced grain yields. Consequently, application of fall starter N is recommended in the region. However, in the context of reducing N losses to the Chesapeake Bay, there is an urgent need to assess the level of residual NO_3-N which is adequate to forgo fall starter N for the wheat crop and, thus, reduce system N loading. Application of starter N based on soil NO_3-N levels at planting will be critical to avoid compounding fall-winter N loss potential from the corn production system with further losses from the following wheat crop.

General research approach

From May 2005 to July 2010, 23 field experiments were conducted on the Maryland Coastal Plain and Piedmont at University of Maryland Research and Education Centers (UMRECs) and at producer field sites. The experimental design was a randomized complete block split plot with four replicates at UMRECs. For producer field sites, the experimental design was a randomized complete block with six replicates. At each UMREC site, the study cycle lasted from May, when corn was planted and the main plot factor (corn N fertilization) applied, through October when wheat was planted following corn harvest and the split plot factor (wheat starter N fertilization) applied.

Wheat was harvested the following June. At the producer field sites, wheat was planted in October and harvested at maturity the following June.

At UMRECs, late-season corn measurements, including green leaf counts, chlorophyll meter readings, normalized difference vegetation index (NDVI), and the corn stalk nitrate test (CSNT) were examined as tools for assessing corn N management and for predicting post-harvest soil residual NO_3-N accumulation. Green leaf, chlorophyll meter, and NDVI measurements were collected three times during reproductive growth of the corn crop at six site years (ten site years for NDVI). Corn stalk samples were collected at or close to maturity (ten site years).

Prior to wheat planting, all sites were soil sampled. Sampling was to a maximum depth of 60 cm at UMRECs and all sites were sampled to a minimum depth of 30 cm. During the mid to late winter period and prior to application of spring green-up fertilizer N, soil samples were collected to a 60 cm depth. Ammonium and/or NO_3-N were measured in each soil sample to examine the post-corn harvest accumulation, soil profile distribution, and fall-winter retention patterns at the sites. All wheat plots received uniform spring fertilizer N on or as soon as possible following 1 March. Prior to application of this fertilizer N, tiller density and NDVI were assessed. Wheat was harvested at maturity and grain yield recorded.

General research objectives and hypothesis

Objective 1: To examine the utility of late-season corn measurements including green leaf number, chlorophyll meter readings, NDVI, and the CSNT as tools for assessing post-harvest soil residual NO_3-N accumulation and N management in corn production.

Hypotheses:

1. Measurements collected from the corn canopy will predict post-harvest residual NO_3-N accumulation and assess the appropriateness of prior N management.
2. The CSNT will predict soil residual NO_3-N accumulation and assess the appropriateness of prior N management.

Objective 2. To assess the effects of corn N management on post-harvest residual NO_3-N accumulation and soil profile distribution over a range of Maryland soil types.

Hypotheses:

1. Application of the economically optimum nitrogen rate (EONR) will reduce N loading and accumulation compared with yield maximizing rates.
2. Deviation in applied N rate from the EONR will predict post-harvest soil residual NO_3-N accumulation in Maryland.
3. Nitrogen fertilization for corn will affect post-harvest NO_3-N accumulation and its distribution within the soil profile.

Objective 3. To determine winter wheat response to fall starter N and how this response is influenced by pre-plant soil NO_3-N.

Hypotheses:

1. Carryover residual NO_3-N from the preceding crop will reduce the fall starter N requirement of winter wheat.
2. Where pre-plant soil residual NO_3-N is less than 15 mg kg^{-1} in the surface 15 cm, application of fall starter N will increase late-winter wheat tiller density.
3. Where pre-plant soil residual NO_3-N is less than 15 mg kg^{-1} in the surface 15 cm, application of fall starter N will increase wheat grain yield.

Objective 4. To determine whether corn residual NO_3-N and fall starter N present at winter wheat planting remains in the surface 60 cm soil until the mid to late winter.

Hypotheses:

1. A portion of residual NO_3-N from the preceding corn crop present at wheat planting will remain in the surface 60 cm until the mid- to late-winter.
2. Fall starter N application will increase mid to late winter soil NO_3-N in the surface 60 cm.
3. Carryover NO_3-N will be concentrated deeper in the soil profile due to leaching pressure.

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Chapter 2: Literature Review

Introduction

In Mid-Atlantic States such as Maryland, soft red winter wheat (*Triticum aestivum*, L.) hectarage is exceeded only by corn (*Zea mays*, L.) and soybean [*Glycine max* (L.) Merr.]. Unlike those two crops, however, winter wheat is planted in the fall and grows through the fall-winter-spring groundwater recharge period. This presents both an environmental and an economic opportunity. By using wheat to sequester residual nitrate (NO_3-N), which is readily leached from the root zone (Endelman *et al*., 1974; Hahne *et al*., 1977), losses during the groundwater recharge period can be curtailed. This is especially important on the Mid-Atlantic Coastal Plain, where groundwater flow provides the main link to surface waters (Boesch *et al*., 2001); including the Chesapeake Bay, where improved water quality is at the forefront of political and regulatory efforts. However, coupled with these opportunities is the challenge of starter fertilizer nitrogen (N) management for the winter wheat crop. Choosing a starter N rate which optimizes wheat N use efficiency and minimizes losses will require site specific information on the contribution of soil residual N.

Plants demonstrate measurable symptoms of their growing conditions, including N availability. Utilizing these symptoms to identify sites which may have adequate soil residual NO_3-N following corn would help to improve fall starter N management for winter wheat. The use of green leaf counts (Binford and Blackmer, 1993), chlorophyll meter readings (Piekielek *et al*., 1995), and the normalized difference vegetative index (NDVI) (Clay *et al*., 2006) during the reproductive growth stages of corn have proven to be useful indicators of plant N status. Additionally, the end of season corn stalk nitrate test (CSNT) (Binford *et al*., 1990) can identify plants with excessive N availability. These measurements might also provide useful information regarding site residual NO_3-N levels, which could guide starter N management for the following winter wheat crop.

This literature review will focus on the use of plant based measurements to determine corn nitrogen status and residual N, factors which effect fall residual N accumulation in corn production and subsequent loss or carryover during the fall-winter period. Additionally, the potential for using residual NO_3-N to provide for the establishment requirements of winter wheat will be examined, along with the current recommendations regarding starter N management in the Mid-Atlantic.

Using plant based measurements to determine corn nitrogen status and yield

The chlorophyll meter

Leaf chlorophyll concentration provides a strong indication of plant N status. Wolfe *et al*. (1988) reported that the correlation between leaf chlorophyll and N concentration was strong (r^2=0.80). Chlorophyll meters, such as the handheld SPAD-502 (Konica Minolta, New Jersey, USA), can provide a rapid, non-destructive estimate of extractable chlorophyll. The meter is clamped onto the leaf surface and measures light transmittance through a 2 by 3 mm test area. The device generates two specific wavelengths (650 nm for absorption by chlorophyll and 940 nm to allow adjustment for leaf thickness) that are selected for determination of leaf chlorophyll content. The output is recorded in dimensionless SPAD units (Spectrum Technologies, 2009). These units are highly correlated with chlorophyll concentration. Markwell *et al*. (1995) reported that the relationship between chlorophyll and SPAD units for soybean and corn was non-linear (r^2=0.94). Earl and Tollenaar (1997) reported a strong relationship between corn leaf absorbance of photosynthetically active radiation and chlorophyll meter readings; they attributed these results to the strong relationship between chlorophyll content and spectral properties of corn leaves.

Due to their strong relationship with leaf chlorophyll, the chlorophyll meter can also provide a useful indicator of plant N status. Schepers *et al*. (1992) and Ziadi *et al*. (2008) reported that meter readings increase as N fertilization rate increases, and the relationship was generally quadratic where a wide range of N rates (0-300 and 20-250 kg N ha^{-1}, respectively) was used. In contrast, Varvel *et al*. (1997) reported that the relationship was nearly linear; however, the range of N fertilization rates was less (0-200 kg N ha^{-1}) compared with those studies mentioned previously. Similar responses have been observed when comparing chlorophyll meter readings and leaf N to relative grain yield in corn. Cerrato and Blackmer (1991) reported that grain yield increased linearly as leaf N concentrations increased. However, optimal and above optimal N rates resulted in similar leaf N concentrations. The SPAD chlorophyll meter has been used in a wide variety of crops, including corn, to assess crop N status and to aid in fertilizer N management (Piekielek *et al*., 1992; Varvel *et al*., 1997; Scharf *et al*., 2006). Rapid data collection without the requirement of sample drying, grinding and analysis is a major advantage of these meters. For this reason, they may have greater practical utility for N management compared with tools which require sample processing, such as the CSNT (Binford *et al*., 1990) and the pre-sidedress nitrate test (PSNT) (Magdoff *et al*., 1984). Indeed, Piekielek *et al*. (1992) reported that the SPAD chlorophyll meter had similar accuracy compared with the PSNT for determining sites which would respond to sidedress N applications.

A limitation of the chlorophyll meters is that readings are influenced by many factors. It has been reported that lower temperatures and increased precipitation reduce readings or chlorophyll concentrations (Piekielek *et al*., 1995; Schlemmer *et al*., 2005; Ziadi *et al*., 2008). Corn hybrid and site characteristics also affect readings (Blackmer and Schepers, 1995; Hawkins *et al*., 2007; Ziadi *et al*., 2008). Additionally, plant density (Blackmer *et al*., 1993), insect damage, disease (Piekielek *et al*., 1995), and plant growth stage (Scharf *et al*., 2006; Hawkins *et al*., 2007) influence readings. Many of these factors also affect visual leaf ratings and NDVI. Consequently, the use of relative measurements is recommended to adjust for localized factors (Blackmer and Schepers, 1994; Piekielek *et al*., 1995). Relative measurements are calculated by dividing the measurement from each plot by the measurement from a high-N reference plot, where N fertility is not limiting plant growth. The use of relative grain yields which are calculated in a similar fashion is advocated when examining the relationship between relative chlorophyll meter readings across sites. Relative yields provide a common index of N sufficiency across sites, whereas absolute yields do not (Cerrato and Blackmer, 1991). Ziadi *et al*. (2008) reported that chlorophyll meter readings were significantly related to relative yield, but the intercepts varied by site-year. They also showed that the relative readings are more strongly correlated with relative yield than absolute readings (r^2=0.67 compared with 0.45, respectively). Piekielek *et al*. (1995) reported that using relative chlorophyll meter readings helped to remove prediction error associated with sampling at different growth stages. They also reported, that the chlorophyll content of corn ear leaves from N-deficient plants at the ¼ milk line growth stage, are more dependent on the effects of N deficiency than differences in hybrid characteristics, such as the stay-green trait.

Much of the early research involving the chlorophyll meter focused on identifying sites which would respond to N application, rather than predicting the appropriate N rate to apply. It was concluded that absolute chlorophyll meter readings were not useful for making N rate recommendations (Piekielek *et al*., 1992; Bullock and Anderson, 1998). However, Scharf *et al.* (2006) reported that chlorophyll meter readings were excellent indicators of corn yield response to N over a wide range of soil types, geography, weather, hybrids, and management practices. Researchers have reported a weaker relationship between chlorophyll meter measurements collected at early corn growth stages, i.e., from V6 to V10 (Ritchie *et al*., 1997) and grain yield. In contrast, the relationship was stronger for measurements collected at later growth stages (from R3 to R5) (Blackmer and Schepers, 1995; Bullock and Anderson, 1998). Ziadi *et al*. (2008) reported that early season measurements were not significantly affected by N treatment rates, observing that N deficiency was unlikely at these early growth stages. This is in agreement with Argenta *et al*. (2004), who reported similar results and suggested that the lack of N deficiency in early stages of corn development was probably due to residual soil N or starter N at planting.

Piekielek *et al*. (1995) examined use of the SPAD chlorophyll meter as a tool for assessing corn N management practices late in the growing season at the ¼ milkline stage. They collected readings from the ear leaf 1 to 2 cm from the edge of the leaf close to the middle of the leaf length. Based on their results, they suggested 52.0 SPAD units as a critical value for separating N-deficient from N-sufficient sites. Using relative SPAD units helped to remove error caused by earlier sampling, i.e., at the R3 or R4 growth stages. A critical level of 0.93 relative SPAD units separated N-deficient and N-sufficient sites with an 8.1% error rate. When readings are taken at the ¼ milk line stage, SPAD units were nearly as accurate as relative SPAD units in identifying N-deficient and N-sufficient corn. Using the meter to assess end of season N sufficiency levels can provide a tool for refinement of fertilizer N recommendations in future years (Piekielek *et al*., 1995; Varvel *et al*., 1997; Scharf *et al*., 2006).

Luxury consumption occurs when the addition of a nutrient results in an increase in the concentration of that nutrient without an increase in yield (Macy, 1936). As described in the previous paragraph, normalizing measurements by expressing them relative to a non-N limited reference plot is recommended. However, this practice is based on the assumption that chlorophyll meter measurements are the same whether N supply is optimum or excessive. Zhang *et al*. (2008a) reported that increased applications of N often promoted an increased production of chlorophyll that is not accompanied by an increase in grain yields. They suggested that N application above sufficiency levels causes luxury chlorophyll production. Thus, the common practice of expressing chlorophyll meter measurements as a percentage of the measurements collected from high N reference plots could result in overestimation of fertilizer N requirement. Additionally, little attention has been given to the sensitivity or ability of the meter to identify small N deficiencies with reasonable certainty. The underlying problem is the difficulty in determining “the critical concentration,” which distinguishes plants having deficient N from plants having sufficient N. For these reasons Zhang *et al*. (2008b) suggested that the chlorophyll meter has limited utility for sites with moderate N stress.

Both relative grain yield and relative chlorophyll meter readings plateau at excessive N rates (Blackmer and Schepers, 1994; Piekielek *et al*., 1995). Readings which reach plateau levels at corn growth stages V8 to VT indicate that fertilizer N is adequate for maximum yield (Varvel *et al*., 1997). However, the N rate adequate to attain a plateau in chlorophyll meter readings may not be desirable, as plateau initiation has been reported to be above the economically optimal N rate (EONR) (Piekielek *et al*., 1995). This suggests that N rates adequate to produce readings at some level below plateau values would be economically optimal.

Green leaf counting

The leaf yellowing that occurs when plants are senescing is associated with a decrease in foliar N concentration, as this N is translocated to the grain. The remobilization of N from vegetative tissues to the grain is extremely important for the N economy of plants (Yang *et al*., 2004). As a consequence of this process, only a minor fraction of the N in harvested grain is taken up from the soil during the period between anthesis and plant maturity. Leaf senescence is often associated with plants grown under N deficient conditions, as plants remobilize N for reproductive growth (Thomas and Stoddart, 1980). This process is commonly referred to as "firing" in corn.

Binford and Blackmer (1993) developed a visual rating system that involves quantifying the number of green leaves at and below the primary ear of corn plants. When this numerical rating was converted to an adjusted rating by comparing it to a high N reference strip, the relationship with grain yield was positive (r^2=0.74 to 0.80). They concluded that use of visual leaf rating was similarly effective for assessing corn N status compared with use of leaf N concentration, but required less time, effort and expense. Visual ratings collected from corn growth stage R3 to R5 provided slightly greater sensitivity to N stress compared with those taken at R1. In Pennsylvania, Fox *et al*. (2001) reported that a relative visual rating at the ¼ milk line growth stage better identified N sufficient sites compared with unadjusted visual ratings. Similarly, Binford and Blackmer (1993) reported that adjusted visual ratings were more strongly correlated with relative yield (r^2=0.80) compared with unadjusted ratings (r^2=0.52) at R4. Since visual ratings can be affected by drought stress, hybrid stay-green rating, high plant population and disease, using a relative rating may remove some of the error associated with these environmental and/or genetic factors (Fox *et al*., 2001). They reported a critical relative rating of 0.73 across all sites separating N sufficiency from deficiency. However, a relative rating of 0.83 would have been a better critical level under drought conditions. This indicates that relative ratings did not remove all the drought stress effect. A disadvantage of relative ratings is the requirement for high N reference strips. Fox *et al*. (2001) examined the possibility of establishing a critical number of green leaves to separate N deficient from N sufficient sites. They reported that leaf counts may be useful in identifying N-sufficient sites. In their study, 96% of assessments with a visual rating >4.0 green leaves plant^{-1} were N sufficient. However, 54% of assessments below this level were also N sufficient.

Optical sensors and the normalized difference vegetative index

A drawback to using either the chlorophyll meter or visual ratings is that plant-to-plant variation will require many measurements to obtain a representative average.

Handheld optical sensors, such as the Crop Circle 210 (Holland Scientific, Lincoln, NE) are alternative tools which rapidly collect data across a large canopy area. The Crop Circle 210 emits its own modulated light and measures canopy reflectance in the visible (VIS) band at 590 nm and in the near infra-red (NIR) band at 880 nm. Light reflected back from the crop canopy is captured by two photodiodes on the sensor unit, and reflectance is measured and recorded by the onboard data collection system. The NDVI, which was developed to assess plant greenness by Rouse *et al*. (1974), is calculated as follows:

$$NDVI = (NIR - VIS)/(NIR + VIS)$$

Where NIR is the fraction of emitted NIR radiation returned from the sensed area (reflectance), and VIS is the fraction of emitted VIS radiation returned from the sensed area.

Nitrogen stress reduces the production rate of chlorophyll. Thus, reflectance of photosynthetically active light is increased. NDVI has been shown to be a useful predictor of grain yield in a number of crops. Raun *et al*. (2001) reported that NDVI measurements collected from winter wheat at Feekes growth stages 4 and 6 (Large, 1954) could be used for non-destructive estimation of yield potential. Teal *et al*. (2006) reported a strong positive relationship between corn yield and NDVI at V8 (r^2=0.77). Similarly, Martin *et al*. (2007) reported that the correlation between corn grain yield and NDVI was highest at the V7 to V9 growth stages. Teal *et al*. (2006) also observed that readings taken at later growth stages did not accurately determine yield potential and attributed this outcome to the influence of canopy closure on the sensor field of view. Solari *et al*. (2008) demonstrated that chlorophyll meter readings and NDVI readings had better correlation during corn vegetative growth stages and attributed the poorer relationship during reproductive growth stages to interference from tassels which reduced sensor ability to detect canopy variation. Similarly, Martin *et al*. (2007) observed a trend for the correlation between NDVI and grain yield to increase as the growing season progressed but only up to the V8 growth stage. They reported correlations between grain yield and NDVI of 0.12, 0.00, 0.05, 0.29, 0.26, 0.66, 0.61, 0.56, 0.64 for growth stages V3-V12 (no V11 reading was reported) to r^2=0.40 at VT. In contrast, Clay *et al*. (2006) reported that the correlation between NDVI and grain yield increased as the growing season progressed: r^2=0.24, 0.29, and 0.65 for the V8-V9, V11-VT, and R1-R2 measurements, respectively.

The corn stalk nitrate test

Plants take up N as NO_3-N or ammonium (NH_4-N) which they must either utilize or store, as high levels of unassimilated NH_4-N can be toxic. As a result, plants assimilate NH_4-N near the site of absorption/generation and rapidly store any excess in their vacuoles. Plants can, however, translocate relatively high levels of NO_3-N from cell to cell without negative effect. The forms of N transported vary between plants. Pate (1983) examined this issue and reported that the total N in the xylem for cocklebur, corn, and radish was 95%, 65% and 15% NO_3-N, respectively. Hanway and Englehorn (1958) reported NO_3-N accumulation in the stalks or stems of field crops, including corn, sorghum, and soybean, increased especially as they matured. In corn, NO_3-N tended to be more concentrated in the lower portion of the stalk compared with the upper portion. For their study, corn grain yields ranged from 1.9 to 6.8 Mg ha^{-1}, and a drought effect on NO_3-N accumulation was observed with NO_3-N concentrations highest in non-irrigated plots. Stalk NO_3-N concentrations decreased with increasing water application. A fertilizer N effect was also observed, very little NO_3-N was present in plants that received no fertilizer N compared with those that received higher fertilizer N rates. For example, mature stalks sampled in October contained 2.4% and 8.8% NO_3-N where zero and 168 kg ha^{-1} fertilizer N was applied. In addition, they also observed an effect of previous crop and manure application on stalk NO_3-N. They observed slightly elevated stalk NO_3-N content for corn following legume meadow compared with continuous corn. Application of 36 Mg ha^{-1} manure almost doubled the NO_3-N content of the lower stalks in the first and second year for their study.

The corn stalk NO_3-N test was proposed (Binford *et al*., 1990) as a post-mortem tool for characterizing the degree of unwarranted N used in corn production. They collected stalk 20 cm sections cut from 15 cm above the ground within 10 days of black layer formation. Dried leaves were removed from the stalk segments which were dried, ground, and analyzed to determine stalk NO_3-N concentration. They reported that above maximum corn grain yields stalk NO_3-N concentrations increased linearly in response to additional fertilizer N. Binford *et al*. (1992) reported an optimal CSNT range of 450 to 2180 mg NO_3-N kg^{-1}, which is in close agreement with the range of 250 to 1800 mg NO_3-N kg^{-1} proposed by Binford *et al*. (1990) in their original study. Pooling of data from the two studies produced an optimal range of 350 to 2050 mg NO_3-N kg^{-1}. However, iterative calculations performed on the pooled data indicated that 700 mg kg^{-1} stalk NO_3-N concentration was the lowest level at which relative yields were not significantly ($p \leq 0.05$) different from the plateau yields (Binford *et al*., 1992). Given the 5.5% increase in yields which Binford *et al*. (1990) observed within the optimal range, they suggested that selection of the higher critical level may have merit, and that application of "inexpensive" fertilizer N could be profitable up to the 700 mg NO_3-N kg^{-1} level.

Fox *et al*. (2001) examined expanding the sampling window for the CSNT in Pennsylvania. A critical level of 250 mg NO_3-N kg^{-1} predicted N adequacy with an error rate of only 5.7% for samples collected at the ¼ milkline stage. There was a strong linear correlation between samples collected at the ¼ milkline stage and stalk NO_3-N concentrations at black-layer (r^2=0.96); across 209 treatments no trend for change in stalk NO_3-N between the two sampling times was observed. Thus, they suggested that the sample window for the CSNT could be from the ¼ milk-line stage to three weeks after black-layer formation. Hooker and Morris (1999) also examined corn stalk NO_3-N sampling earlier than the black layer stage proposed by Binford *et al*. (1992). They reported that a stalk NO_3-N concentration of 500 mg kg^{-1} at the "corn silage stage" (total plant dry matter ranged from 25 to 43% at sample collection) resulted in an error rate of only 6.1% for predicting N adequacy. They suggested an optimal range of 500 to 1000 mg kg^{-1} stalk NO_3-N. These reports indicate that sites with CSNT values below 2000 mg kg^{-1} may have excessive N availability.

Using plant based measurements to predict soil residual nitrogen

As discussed above, plant based measurements are useful indicators of plant N status. This suggests potential to use these measurements to glean information regarding soil N availability. It has been reported that chlorophyll meter readings in corn generally increase during the growing season up to a maximum and then gradually decrease (Scharf *et al*., 2006; Ziadi *et al*., 2008). Similarly, Varvel *et al*. (1997) reported that chlorophyll meter readings reach a plateau at N sufficiency, making it impossible to distinguish areas which have adequate soil N from those which have excessive levels. Piekielek *et al*. (1995) reported that relative chlorophyll meter readings at the ¼ milkline stage accurately separated N-deficient from N-sufficient treatments. They attempted to determine if chlorophyll meter readings from the ear leaf could predict the amount of excess N that had been applied to N-sufficient sites. However, there was little correlation (r^2=0.08) between readings and excess N. They concluded that chlorophyll meter readings cannot be used to predict the presence of excess N on N-sufficient treatments and that, by definition, relative readings cannot be used to predict amounts of excess N applied. However, they did report a 70% probability that >50 kg N ha^{-1} excess N was applied where chlorophyll meter readings were above the suggested sufficiency level of 52.0 to 56.0 SPAD units. Blackmer and Schepers (1994) reported that the meter showed little sensitivity to luxury consumption, indicating that it has little utility as a tool for detecting excess N consumption. In contrast, Zhang *et al*. (2008a) reported that increased applications of N often promote an increased production of chlorophyll which is not accompanied by grain yield increase. They suggested that such N application increases could be considered to cause luxury production of chlorophyll. These findings are given credence by the reports of Piekielek *et al*. (1995) that chlorophyll meter readings above the sufficiency level (52.0 to 56.0 SPAD units) were observed where N availability was high.

Visual green leaf ratings have been observed to plateau at N rates above N sufficiency (Binford and Blackmer, 1993; Fox *et al*., 2001). Variation in the rate of green leaf loss with varying N availability was observed by Binford and Blackmer (1993), who reported a significant N rate by time interaction for leaf ratings at 17 of 21 sites. Regression analysis showed that leaf ratings declined by one leaf every 12 days in unfertilized plots, by one leaf every 13.7 days in plots receiving 168 kg N $ha^{-1,}$ and by one leaf every 13.4 days for plots receiving 336 kg N ha^{-1}. However, they concluded that leaf ratings lacked the ability to detect excessive N availability. This indicates that they will have poor ability to quantify soil NO_3-N accumulation

Unlike the chlorophyll meter and green leaf readings which have limited utility for distinguishing N sufficiency from N excess, the CSNT is more effective at distinguishing between sufficient and excessive N levels. Varvel *et al*. (1997) reported that end-of-season corn stalk NO_3-N increased as fertilizer N rate increased. Their results demonstrate that using the chlorophyll meter and CSNT concurrently provides additional criteria to partition and separate fields into areas with potentially different levels of residual N. Binford *et al*. (1992) reported that the CSNT has the ability to complement soil tests due to its ability to detect N deficiencies and excesses. They demonstrated that corn stalk NO_3-N concentrations increased as fertilizer N application rates increased, especially at N levels greater than those adequate for yield optimization. This is an important relationship because the level of N fertilization has been linked to post-harvest residual NO_3-N accumulation (Hong *et al*., 2007; Jolley and Pierre, 1977).

Residual nitrogen accumulation, loss and movement in corn

Corn nitrogen management effects on corn performance and soil residual nitrate

Application of fertilizer N is an important yield enhancing practice of modern agricultural production. It is applied to the majority of the corn production area in the

United States. However, utilization of that N, described as N use efficiency, has been reported to be poor. Raun and Johnson (1999) estimated worldwide N removal by cereal grain to be only 33% of total N supplied from soil, rainfall and fertilizer N. The majority of the N not removed in the grain is likely to be accounted for by N retained in the crop stover and roots, N immobilized, and N lost from the soil system through leaching and denitrification. Jokela and Randall (1989) reported that increasing the N rate for corn increased grain yield, N uptake (five of six sites), and soil residual NO_3-N (all six sites). Similarly, Vanotti and Bundy (1994) reported soil NO_3-N levels measured in the spring to 90 cm depth were significantly influenced by the corn fertilizer N rate used the preceding growing season. The influence of corn N management was also noted by Roth and Fox (1990). They observed that as N rates increased, fall-measured residual NO_3-N levels increased in either linear or curvilinear patterns, depending on site. Jolley and Pierre (1977) reported similar patterns and concluded that residual NO_3-N accumulations increased rapidly when fertilizer N rates are above optimum.

In Maryland, residual mineral N in the surface 80 cm averaged 87 and 114 kg ha^{-1} when 168 and 336 kg ha^{-1} fertilizer N was applied to the corn at silt loam sites (Shipley *et al*., 1992). Jokela and Randall (1989) reported soil residual NO_3-N levels in the surface 150 cm ranging from 150 to 400 kg N ha^{-1} for most treatments at silt and clay loam sites in Minnesota. At silt loam sites in Pennsylvania, Roth and Fox (1990) reported the accumulation of 34 to 295 kg ha^{-1} post-harvest residual NO_3-N in the surface 122 cm for corn N rates ranging between 0 and 200 kg ha^{-1}. For the Pennsylvania study, sites with manure history generally had the largest NO_3-N accumulations. During the period of the study conducted by Jokela and Randall (1989), all sites were affected by unusually dry mid-summer periods, which may explain why residual N levels were higher than those reported by Roth and Fox (1990) and Shipley *et al*. (1992).

Hong *et al*. (2007), in a large plot study conducted in producer fields, reported that exceeding the EONR increased residual NO_3-N at all six sites. The average producer N rate was 187 kg N ha^{-1}, and at four of six sites producer N rate exceeded the EONR. At these four sites, the producer fertilizer N rate exceeded the EONR by 7 to 112 kg N ha^{-1} (64 kg N ha^{-1} on average). Across all six sites, N application using the EONR compared with producer practice would have reduced N loading to the production system by 39 kg N ha^{-1} without reducing profitability. Application of the EONR reduced residual NO_3-N by at least 12 kg ha^{-1} in the surface 90 cm. They reported residual NO_3-N levels which increased with increasing positive ΔEONR (change in applied N rate relative to the EONR). A linear increase in soil residual NO_3-N accumulation began between 65 kg N ha^{-1} below the EONR and 20 kg N ha^{-1} above the EONR when residual NO_3-N and ΔEONR data for each site was modeled using a plateau-linear function. A similar trend for increasing residual NO_3-N was noted by Olsen *et al*. (1970), who found that total soil NO_3-N was directly related to the rate of N application. However, they reported that limiting N applications to approximately the corn requirements was an effective strategy for reducing residual NO_3-N accumulation. In Pennsylvania, Roth and Fox (1990) reported estimated soil residual NO_3-N levels that ranged from 41 to 135 kg ha^{-1} in the surface 120 cm at the EONR. Jaynes *et al*. (2001) reported that when fertilizer N rate exceeds crop N requirement, NO_3-N can accumulate in the soil profile. However, Hong *et al*. (2007) reported that fertilizer N rates less than EONR resulted in little fertilizer derived post-harvest residual NO_3-N, and this was the case even when the

EONR was high. Additionally, their results showed that at negative ΔEONR residual NO_3-N accumulation was not significantly different from the check plots, indicating that where the EONR is not exceeded, there will be little potential for fertilizer N derived loss to local water-bodies in corn production.

Corn nitrogen management effects on soil residual ammonium

In contrast to reports of corn N management strongly influencing soil residual NO_3-N accumulation, there is less evidence of a similar trend in post-harvest soil NH_4-N accumulation. Liang *et al*. (1991) reported that NH_4-N levels in the soil were generally very low compared with NO_3-N levels and for that reason did not discuss them. Their study examined the impact of corn N rate and moisture availability in corn production. Similarly, in a study which examined the impact of cropping system and N rates on residual inorganic N, Varvel and Peterson (1990) observed few, if any, differences in residual NH_4-N concentrations in the surface 150 cm. They did observe differences between treatments for NO_3-N. Similarly, Vanotti and Bundy (1994) observed that NH_4-N levels were unaffected by previous corn N treatments. Additionally, other studies which examined the impact of corn N management on residual N do not discuss NH_4-N (Hong *et al*., 2007; Jokela and Randall, 1989). However, earlier in the growing season NH_4-N may be more important. Meisinger *et al*. (1992) reported that total soil inorganic N when corn is 15 to 30 cm high was a better predictor of grain yield than NO_3-N alone. They suggested that early in the corn growing season, the microbial driven nitrification process which converts NH_4-N to NO_3-N is still actively converting spring NH_4-N to NO_3-N, while late in the season this conversion is virtually complete leaving only small concentrations of NH_4-N in the soil. High loadings of organic N, such as those present in their study, may also provide a large NH_4-N pool that causes elevated soil NH_4-N levels over a longer period of time compared to sites with low organic N inputs. This indicates that the contribution of NH_4-N is more important early in the growing season, due to the activity of ammonium producing organisms vs. nitrifying organisms, than during the late-summer and fall months at the end of the growing season.

Corn nitrogen management effects on subsurface nitrogen loss

Jaynes *et al*. (2001) examined NO_3-N loss in leachate under a corn-soybean rotation and reported that, even following the low corn N treatment (57 or 67 kg N ha^{-1}), leachate NO_3-N exceeded the Environmental Protection Agency's maximum contaminant level for drinking water of 10mg NO_3-N L^{-1}. They reported leachate losses of 35 and 29 kg NO_3-N ha^{-1} following the medium and low corn N rates, respectively, stating that those loss amounts were not significantly different. However, the leachate NO_3-N loss at the high corn fertilizer N rate (48 kg N ha^{-1}) was significantly greater compared with the low fertilizer N rate. In this study, the EONR fell between the medium and high N rates, indicating that the greatest N loss potential to groundwater can occur when the EONR is exceeded. For example, in a study where corn was grown in rotation with either oat or soybean on a silt loam site in Iowa, increasing the corn N rate from 100 to 250 kg ha^{-1} doubled the NO_3-N concentration in water samples collected from tile drainage from 20 to 40 mg N L^{-1} (Baker and Johnson, 1981). They also observed a 2 month delay (100 mm of flow) from the time of N application to detection of a fertilizer N effect in the tile drainage. In Maryland, Staver and Brinsfield (1995) reported that fertilizing for realistic yield goals combined with management practices, such as splitting N application and installing grass waterways, reduced surface N runoff losses to <5 kg ha^{-1}. However, even when yield goals were met in their study, annual NO_3-N leaching losses were approximately 30 kg ha^{-1}, which caused groundwater NO_3-N leachate concentrations to exceed 10 mg L^{-1}. Andraski *et al*. (2000) reported that soil NO_3-N concentrations at 120 cm increased as the total N application increased above the EONR. At the predicted EONR for this study, soil water NO_3-N concentration was 18 mg L^{-1}. At fertilizer rates >50 kg N ha^{-1} below the EONR, average leachate NO_3-N concentration was <10 mg L^{-1}. In contrast, the average leachate NO_3-N concentration where fertilizer N rates were >50 kg N ha^{-1} in excess of the EONR was >20 mg L^{-1}. They reported a direct relationship between NO_3-N leaching loss and N application rates exceeding crop needs.

Challenges in applying optimal nitrogen rates to corn

The findings discussed above indicate that accumulation of excessive levels of post-harvest residual NO_3-N can be minimized by not exceeding crop N requirements (Andraski *et al*., 2000; Hong *et al*., 2007; Olsen *et al*., 1970). However, substantial amounts of NO_3-N in leachate were detected as applied N rates approached the EONR (Andraski *et al*., 2000; Staver and Brinsfield, 1995). Nevertheless, careful N management, including application of the EONR, can reduce N loading to agricultural systems. Unfortunately, application of appropriate fertilizer N rates is a major challenge in dryland corn production due to erratic precipitation patterns, which cause yields to vary widely between sites and years. Hong *et al*. (2007) found EONR to be widely variable (49 to 228 kg N ha^{-1}) both between and within fields. Similarly, Roth and Fox (1990) reported wide variability (51 to 179 kg N ha^{-1}) in the EONR at sites with no history of manure application. In the same study, the EONR for sites with manure history was typically lower: two sites did not respond to N application, and at the three sites that did respond the EONR ranged from 48 to 100 kg N ha^{-1}. Furthermore, in Virginia, the EONR for corn ranged from 0 to 277 kg N ha^{-1}(Spargo, 2008). Andraski *et al*. (2000) also observed fluctuating EONR, 130 to 150 kg N ha^{-1}, for two continuous corn sites without manure history. For sites with alfalfa and/or manure history that also responded to N application, the EONR ranged from 80 to 120 kg N ha^{-1}. However, similar to the findings of Fox and Roth (1990), the Andraski *et al.* (2000) study had two sites with manure history that did not respond to N application; these were the highest yielding sites in the study.

The annual variability in the EONR caused by fluctuating corn yields, poses a challenge for producers. Additionally, Hong *et al*. (2007) urged caution in interpreting the EONR. They cited the inevitable uncertainty associated with accuracy of yield monitoring, variation in non-treatment factors (e.g., soil-water redistribution and organic matter content), and spatial variability in soil N availability within the measurement area. They suggested that the error in their EONR estimation was probably plus or minus 10 kg N ha^{-1}.

The wide variability in EONR between sites (Roth and Fox, 1990; Andraski *et al*., 2000) and within fields (Hong *et al*., 2007) indicates that factors other than precipitation are influencing N requirement. Factors such as the temporal variability in soil N supply and moisture holding capacity may be important at individual sites. Many studies have shown great variability in corn check yields for sites with and without manure history, which suggests that large variability is inherent in the soil N supply. Meisinger *et al*. (1992) reported corn grain yields ranging from 1.2 to 6.1 Mg ha^{-1} for plowed sites and from 1.3 to 4.8 Mg ha^{-1} for no-till sites in Maryland, which received no N application during the study or in the preceding year. Additionally, cover crop history may influence N availability. Meisinger *et al*. (1992) observed corn yields which ranged from 4 to 9 Mg kg^{-1} for a silt loam site; the lowest and highest yields followed grass and leguminous cover crops, respectively. Check yields (zero N application) following application of varying rates of composted sludge in the previous year ranged from 5.5 to 7.5 Mg ha^{-1}. Similarly, in Pennsylvania, Roth and Fox (1990) reported variable check yields which ranged from 4.3 to 8.1 Mg ha^{-1} for sites without manure history and from 6.6 to 11 Mg ha^{-1} where manure had been applied. In Minnesota, over a three year period, check yields ranged from 5 to 7.3 Mg ha^{-1} at a silt loam site and from 1.7 to 5.6 Mg ha^{-1} at a clay loam site (Jokela and Randall, 1989). In Wisconsin, Andraski *et al*. (2000) reported check yields ranging from 4.7 to 8.9 Mg ha^{-1} for continuous corn without manure history. At sites where alfalfa and/or manure history was a factor, check yields ranged from 6.5 to 12.9 Mg ha^{-1}.

Matching N availability to corn N uptake by applying the majority of N later in the season rather than at planting is considered a good management practice. However, Jokela and Randall (1989) examined N rate and timing and found that delaying N application from the planting date to V8 did not increase grain yield, increase total dry matter accumulation, or improve fertilizer nitrogen use efficiency. Delayed N application did increase soil residual NO_3-N at sites which experienced sub-optimal mid-summer precipitation. They suggested that this may be linked to the reduced period for which fertilizer N was available for denitrification, leaching or immobilization during the growing season and that the practice of sidedressing fertilizer N may increase post-harvest NO_3-N leaching potential.

Fertilizer nitrogen to grain yield ratio at the economic optimum nitrogen rate

An average fertilizer N to corn grain ratio of 9 kg Mg^{-1} at the EONR, for sites with manure history, was calculated from the data of Roth and Fox (1990). The two sites in their study that did not respond to application of fertilizer N were not used in this calculation. At six sites with no manure history, this ratio was 15 kg Mg^{-1}, but it was quite variable, ranging from 6 to 23 kg Mg^{-1}. Similarly, Andraski *et al*. (2000) reported this ratio was 13 and 15 kg Mg^{-1} for two silt loam sites in continuous corn production. At four sites with a history of manure and/or alfalfa use, it ranged from 7 to 12 kg Mg^{-1} (on average 9 kg Mg^{-1}). Two of the six sites (Andraski *et al*., 2000) with a history of alfalfa and/or manure application did not respond to N application, i.e., the EONR was zero. These two sites produced the highest grain yields recorded during the study, which indicates that moisture limitation was not the factor that caused the EONR to be zero.

Impact of corn production frequency and site history on residual nitrogen accumulation

Olsen *et al*. (1970) reported that the frequency of corn production within the rotation is directly related to total soil NO_3-N accumulation. They observed a large accumulation of residual NO_3-N to a depth of 150 cm after 4 years of continuous corn production. In the Mid-Atlantic region, corn production may result in greater residual N accumulation compared with the region's other major field crop, soybean, due to corn's relatively high fertilizer N requirement. Hong *et al*. (2007) reported that following application of the EONR, residual NO_3-N in the surface 90 cm, which was estimated based on applied N rates, ranged from 12 to 57 kg ha^{-1} (33 kg ha^{-1} on average) for corn following soybean. In comparison, Andraski *et al*. (2000) reported much higher mean residual NO_3-N levels of 108 kg ha^{-1} for corn following corn. However, if fertilizer applied N rates are low to moderate, such elevations in residual NO_3-N linked to corn production may not occur. Varvel and Peterson (1990) reported residual NO_3-N concentrations following continuous soybean receiving 34 kg N ha^{-1} were equal to or greater than concentrations following continuous corn receiving low fertilizer N rates (0 and 90 kg N ha^{-1}). However, at higher fertilizer N rates (68 and 180 kg N ha^{-1} for soybean and corn, respectively) residual NO_3-N levels were significantly higher for the corn. They suggested that inclusion of soybean in the rotation could act either as a N source or sink depending on soil residual N status. The ability of soybean to consume and deplete excess residual N from the preceding crop would give credence to the suggestion of Olsen *et al*. (1970) that rotations with legumes could reduce soil NO_3-N accumulation. Using spring collected soil samples, Meisinger *et al*. (1992) showed that soil NO_3-N levels to 30 cm depth trended higher when soybean, rather than corn, was the preceding crop.

Roth and Fox (1990) reported that field history has a large impact on soil residual NO_3-N; sites with manure history had higher NO_3-N accumulation. At sites where N response was observed in the corn crop NO_3-N accumulation following application of the EONR averaged 74 kg ha^{-1} for non-manured sites, and 94 kg ha^{-1} for manured sites. Andraski *et al*. (2000) also found that manure history decreased the EONR for sites but increased post-harvest soil residual NO_3-N. Similarly, the results of Meisinger *et al*. (1992) showed that spring soil NO_3-N concentrations were elevated by applications of animal manure and composted sludge made in the preceding year. This increased accumulation of NO_3-N was likely the result of increased mineralization from organic residues between the end of N uptake by the preceding crop and the time of sampling at the manured sites.

Influence of soil texture and water percolation on soil profile nitrogen distribution

Soil texture is an important factor that affects NO_3-N loss via leaching during the growing season, and soil texture variability within fields can influence NO_3-N leaching patterns (Gehl *et al*., 2006). They found elevated residual NO_3-N in the surface 90 cm where silt and clay content of the surface soil was higher. However, elsewhere in the field, where the sand content was uniform throughout the profile, no corresponding elevation in residual NO_3-N was detected within the 240 cm soil depth that was sampled. They proposed that this NO_3-N had likely moved below the 240 cm depth during the growing season. This suggestion is supported by the findings of Endelman *et al*. (1974), who found that on a loamy sand soil, 2.5 cm of water applied daily moved NO_3-N 15 to 20 cm day^{-1}, indicating that on sandy textured soils, rainfall could have moved NO_3-N out of the sampled zone over the growing season. Hahne *et al*. (1977) measured NO_3-N movement in the surface 315 cm and reported that soil type is an important factor influencing the amounts and vertical distribution of NO_3-N. They observed the lowest accumulations and highest losses of NO_3-N in a fine sandy loam soil, while no change was observed for the silt loam soil. Levels of NO_3-N actually increased for the clay loam soil. They attributed the elevated losses from the fine sandy loam site to be the result of more leaching loss caused by greater internal drainage.

The accumulation of residual NO_3-N and its distribution within the soil profile at the end of the corn growing season is affected by both rainfall and irrigation (Hahne *et al*., 1977). Smika *et al*. (1977) examined water percolation and NO_3-N movement under irrigation on a loamy sand in Colorado; they found a strong negative correlation between residual NO_3-N retained in 180 cm soil depth and the amount of water that percolated to a 150 cm depth (r^2=0.95). When sites were managed for 10% water percolation, residual NO_3-N levels were 20 kg ha^{-1} to 180 cm. In contrast, sites managed for <5% water percolation had residual NO_3-N levels of 250 kg ha^{-1} to 180 cm. They also reported that annual dry matter production was negatively correlated with NO_3-N percolation to 150 cm (r=-0.99). Gehl *et al*. (2006) found that post-harvest NO_3-N distributions within the 240 cm soil depth following normal and 1.25 times the normal irrigation were variable among sites, within a site, and sometimes between years at the same site. They concluded that elevated post-harvest residual NO_3-N is an indicator that the fertilizer N rate applied exceeded corn N demand. However, relatively low post-harvest NO_3-N accumulation does not always indicate that N and water management practices did not affect leaching. Typically, under dryland corn production there is limited downward movement of water through the soil profile during the growing season, but Gehl *et al.* (2006) demonstrated that periods of irrigation or rainfall which led to substantial percolation may cause such movement. Under such circumstances, sandy textured soils are particularly susceptible to NO_3-N leaching, as shown by Endelman *et al.* (1974). Roth and Fox (1990) determined that silt loam sites in Pennsylvania with high leaching potential due to NO_3-N accumulation can be identified, in most cases, using a 30 cm soil sample. They suggested that identification and subsequent management of these sites should be a top priority to reduce post-harvest NO_3-N losses to groundwater.

The influence of precipitation on corn performance and residual nitrogen

The variable nature of growing season precipitation causes crop moisture limitations. This limitation causes reductions in corn yield and crops which do not meet their yield potential (Nielsen *et al*., 2010). This study found that precipitation totals between July 16 and August 26 (the period corresponding with reproductive growth stages of pre-tassel through mid-grain fill) is critical for minimizing water stress effects on corn yield. When soil moisture level at planting time was also considered, precipitation during the referenced period was positively and strongly correlated with grain yields (r^2=0.87 and 0.91, where available moisture at planting was less than or greater than 250 mm, respectively). In years when available soil moisture at planting was less than 250 mm in the surface 180 cm, the probability of achieving breakeven yield (2.5 Mg ha^{-1}) ranged from 20 to 53%. When early season moisture availability was greater than 250 mm, the probability of attaining breakeven yield ranged from 93 to 97%. They suggested that assessing moisture availability at planting could reduce the risk associated with dryland corn production in the central Great Plains.

Moisture limitation is a significant problem for dryland corn production on the Atlantic Coastal Plain, where summer droughts can often lead to large scale crop yield reductions and very high residual NO_3-N levels where crops were fertilized to attain normal yields (Shipley *et al*., 1992). Consequently, excess N supply for the corn crop is likely to occur during moisture limited seasons. This is significant, as the amount of excess fertilizer N applied is a major factor affecting residual NO_3-N (Olsen *et al*., 1970; Meisinger *et al*., 1987; Hong *et al*., 2007). Moisture limitation was also linked to elevated residual NO_3-N in Wisconsin by Vanotti and Bundy (1994). Soil sample collection to a 90 cm depth in the spring following corn production showed significant increases in soil profile NO_3-N, even following low corn N rates (56 to 112 kg N ha^{-1}), where the preceding corn crop was moisture limited. However, under optimal corn growing conditions, significant increases in residual NO_3-N were observed only following higher N rates.

Growing season precipitation can also influence residual NO_3-N distribution. Jaynes *et al*. (2001) found that residual NO_3-N tended to be most concentrated in the surface 30 cm except for one year out of four, when growing season precipitation was considerably greater. During that growing season, there was one event where more than 150 mm precipitation accumulated in one day, more than double any other daily total recorded during the four year study. Following this high precipitation growing season, the surface 90 cm was NO_3-N depleted, and the deeper layers from 90 to 120 cm had relatively greater mass of NO_3-N compared with other years. This was especially the case following the high fertilizer N treatment (202 kg N ha^{-1}). Similarly, Gehl *et al*. (2006) reported that where less than average water was received, post-harvest soil NO_3-N levels for fertilizer N rates >180 kg N ha^{-1} often exceeded 60 kg N ha^{-1} in the surface 30 cm. Olsen *et al.* (1970) suggested the most effective methods of reducing NO_3-N movement through the soil profile to ground water are: 1) limiting fertilizer N rates to approximately crop requirements; 2) reducing the acreage and frequency of high N input crops, such as corn, in rotations; and 3) using cover crops.

Soil profile distribution of residual nitrate

The soil profile distribution of residual NO_3-N will influence root zone availability for the following crop. Jaynes *et al*. (2001) reported that in three of four growing seasons studied, more than half the post-harvest residual NO_3-N detected in the surface 120 cm was concentrated in the upper 30 cm. They attributed this to the contribution from mineralized organic residues concentrated in the surface layers of soil. In contrast, at two sandy clay loam sites with alfalfa history in Canada, Liang *et al*. (1991) found that distribution of soil profile NO_3-N remained similar throughout the surface 100 cm, ranging from 20 to 40 kg N ha^{-1} 20 cm^{-1}. Varvel and Peterson (1990) found relatively low NO_3-N accumulation in the surface 150 cm for sites under continuous corn production, and further sampling to a 750 cm depth indicated no excess N present.

Nitrogen retention and loss during winter

Elevated post-harvest residual NO_3-N levels suggest a potential for N carryover for subsequent crop production exists (Jokela and Randall, 1989). However, their study found a 50 to 70% reduction in soil profile NO_3-N by the following spring on silt and clay loam soils in Minnesota. Also, no yield advantage was observed in the following year's crop as a result of treatments which increased fall residual NO_3-N. In contrast, Meisinger *et al*. (1987) reported that both wheat yield and N uptake were significantly affected by preceding corn N applications. The main factors effecting spring carryover of residual N were the level of excess N applied to the preceding corn crop and winter precipitation. Similarly, Liang *et al*. (1991) observed that over winter changes in root zone NO_3-N concentration are dependent on the amount present in the fall and on winter precipitation patterns.

Olsen *et al.* (1970) determined that greater leaching of NO_3-N in Wisconsin generally occurs between fall and spring, rather than during the corn growing season, and NO_3-N retention can be influenced by factors such as soil texture, depth to the water table, and precipitation or irrigation. They found that the amount of carryover N in the spring was generally a function of corn N rates and climatic conditions and was highly variable. Similarly, Vanotti and Bundy (1994) reported that the amount of carryover residual NO_3-N likely to be found in a specific year varies greatly. Carryover amounts in their study following the 85 kg ha^{-1} corn fertilizer N rate were uniformly low, averaging 18 kg N ha^{-1}, or 21%, of applied N. Average carryover for higher fertilizer rates of 168 and 224 kg N ha^{-1} were 41 and 48%, respectively. Additionally, they found carryover levels to be highly variable, with 80% probability that N carryover would be 32 to 106 kg N ha^{-1} and 63 to 151 kg N ha^{-1}, respectively, for the two higher N rates. They suggested that accurately predicting N carryover for the following spring based on a previous corn N rate was not possible in the humid Midwest. In Pennsylvania, Roth and Fox (1990) observed significant NO_3-N present at the spring sampling time (24 March to 20 April). They attributed this to carryover through the winter and/or mineralization and nitrification before sampling which replaced NO_3-N lost through the winter period. However, similar to the reports of others, there was significant over winter NO_3-N depletion and differences within the soil profile due to N rates used in the preceding corn crop were diminished by spring. The effect of corn N rate on soil residual NO_3-N was significant at two and five out of five sites in the spring and fall, respectively. Smaller fall to spring changes in NO_3-N corresponded to lower precipitation levels, an outcome that is consistent with the reports of Olsen *et al*. (1970). In the Pennsylvania study the largest difference in NO_3-N between fall and spring was observed following the highest corn N rate, indicating that high to excessive rates will be the largest contributors to leaching loss. Over-winter, N loss is more likely to be the result of leaching rather than denitrification, as substantial downward NO_3-N movement is generally observed over winter. In contrast, during the summer months when soil temperatures are relatively high and moisture availability is good to excellent, such as the case for irrigated corn, the potential for greater loss from denitrification exists (Liang *et al*., 1991).

Consequences of residual nitrogen accumulation

Hong *et al*. (2007) reported that average residual NO_3-N in the surface 90 cm of soil for corn check plots (zero N applied) was 16 kg ha^{-1} compared with 64 kg ha^{-1} for the average of the fertilized treatments. The average amount of fertilizer N applied in excess of the EONR was 95 kg N ha^{-1}. This indicated that about half of the excess fertilizer N was recovered as residual NO_3-N, while the rest was likely subject to immobilization in soil organic matter, luxury accumulation by the corn crop, canopy NH_3 volatilization, denitrification, and in-season leaching below the 90 cm depth. Similarly, Varvel and Peterson (1990) suggested that immobilization by crop residues and soil organic matter, rather than leaching, was probably responsible for most of the apparent N losses they observed in a continuous corn cropping system. Removal of N by the crop accounted for 50% of applied N for their low N application rate (90 kg N ha^{-1}), but only 20% was removed by the crop for the high rate (180 kg N ha^{-1}). When high levels of residual NO_3-N remain in the soil profile following corn harvest, it will be subject to leaching loss and may move to surface and ground waters (Hahne *et al*., 1977).

It may take many years for the polluting effects of residual NO_3-N accumulation and leaching on water quality to be evident. Olsen *et al*. (1970) reported that it would take 10 to 13 years following N application for NO_3-N to move through 4 m of the soil profile at silt loam or finer textured sites in Wisconsin. They based this estimation on the rate of movement observed at a Plano silt loam site. Similarly, Boesch *et al*. (2001) noted that lag time of up to 10 years for movement of NO_3-N through ground water flow makes it difficult to determine clear links between changes in crop N management and changes in surface water quality on the Delmarva Peninsula. While loss of NO_3-N during or at the end of the growing season has negative implication for ground water, loss during the growing season could cause an economic loss through reduced yields.

Starter nitrogen for winter wheat

In the Mid-Atlantic region, variable summer precipitation makes N management for dryland corn production challenging. Highly variable residual NO_3-N following corn harvest is a common occurrence (Roth and Fox, 1990; Vanotti and Bundy, 1994; Hong *et al*., 2007). Residual NO_3-N levels tend to be higher following corn than the other main summer crop in the region: soybean (Scharf and Alley, 1994). This residual NO_3-N is subject to loss, primarily by leaching during the region's fall-winter-spring groundwater recharge period (Roth and Fox, 1990; Scharf and Alley, 1994; Jaynes *et al*., 2001). Sequestration of residual NO_3-N by grass (Shipley *et al*., 1992), cereal (Coale *et al*., 2001) and brassica (Dean and Weil, 2009) winter cover crops has been shown to reduce winter N loss in Maryland.

Rye (*Secale cereale* L.) is frequently cited as a benchmark cover crop species for N scavenging and sequestration in Maryland (Shipley *et al*., 1992; Staver and Brinsfield, 1998; Dean and Weil, 2009). When compared with a rye cover crop, winter wheat grown for commodity purposes has been shown to exhibit similar ability to sequester soil N (Fisher *et al*., 2011; Coale *et al*., 2001). Mid-March typically marks the beginning of rapid N uptake by winter wheat in the Mid-Atlantic (Baethgen and Alley, 1989a). Uptake of N by winter wheat during the fall-winter period is often moderate. In Virginia, Baethgen and Alley (1989a) reported above ground N uptake at Zadoks growth stage 25 (Zadoks, 1974) ranging from approximately 5 kg ha^{-1} where 17 kg ha^{-1} fall starter N was applied (1983-84 two sites) to 30 kg ha^{-1} where 34 kg ha^{-1} starter was applied (1984-85 two sites). Similarly, Fisher (2010) reported N uptakes of approximately 14 to 21 kg N ha^{-1} by late January to late February (three sites). Higher N uptake of approximately 74 kg ha^{-1} by late February was observed for winter wheat planted in late September (earlier than typical for commodity purposes) at one site. Residual N at this site was thought to have been very high due to severe drought conditions experienced by the preceding corn crop. Also in Maryland, above ground N uptake was 29 to 41 kg ha^{-1} at growth stage 30 for 25 wheat cultivars which received 20 kg ha^{-1} fall starter N (Costa *et al*., 2000). Such moderate N uptake indicates that residual N may be sufficient to forgo starter N applications for winter wheat. Coale *et al*. (2001) suggested that winter wheat for grain production could be managed as a winter cover crop. This could provide significant additional cover crop hectarage, as the area of winter wheat planted for grain production averaged 86,600 hectares in Maryland for the period 2006-2010 (USDA, 2010).

Management of winter wheat as a cover crop would involve forgoing fall starter N. However, adequate N availability in soil during germination and early plant development is important for good wheat establishment and tillering. Longnecker *et al.* (1993) examined the impact of N deficiency on wheat leaf and tiller emergence, tiller initiation, and apical development. Wheat was grown with complete nutrient solution in sand and was provided four levels of N [50, 300, 800 and 1600 *M* N (N_{50}, N_{300}, N_{800} and N_{1600})] by hourly irrigation. Shoot N at the two leaf stage was 33, 50, 58, and 64 g N kg^{-1} for the N_{50}, N_{300}, $N_{800,}$ and N_{1600} treatments, respectively. Dry matter was also reduced for the lower N treatments with accumulation of the N_{50}, N_{300}, N_{800} treatments being 10%, 50%, and 80% of the N_{1600} treatment, respectively. They found that leaf emergence was decreased in all N_{50} and some N_{300} treatments compared with the N_{1600} control. Tiller bud initiation also decreased in the N_{50} treatment. The growth of those tiller buds present was also delayed or completely inhibited by N deficiency. To add some field perspective a soil NO_3-N concentration of 10 mg kg^{-1} to 15 cm depth at wheat planting is approximately equivalent to 3500 *M* N assuming the gravimetric water content is 30%. The requirement for adequate N availability in the fall is reflected in regional winter wheat recommendations (Sammons *et al*., 1989; Weisz and Heiniger, 2004; Walker and Taylor, 1998). Additionally, Virginia's recommendations state that N is required to establish the crop and promote the production of fall tillers. Fall tillers will begin growth first in the spring and will generally produce heads with more kernels (Alley *et al*., 2009). Additionally, a protracted or intense N deficiency has been shown to reduce grain number and yield regardless of growth stage (Jeuffroy and Bouchard, 1999).

Despite the potential for winter wheat to act as a cover crop, few studies have specifically examined the impact of residual NO_3-N and fall starter fertilizer N responsiveness for that crop. Spring N management for winter wheat tends to receive more focus. Little information is published detailing the consequences of foregoing starter N in the Mid-Atlantic. However, many studies have shown a strong link between carryover of residual NO_3-N and spring fertilizer N response in winter wheat (Scharf and Alley, 1994; Cui *et al.,* 2008), corn (Bundy and Malone, 1988; Schmitt and Randall, 1994; Halvorson *et al*., 2005) and grain sorghum (*Sorghum bicolor* L.) (Bagayoko *et al*., 1992). These studies showed that cropping and N management history affects soil NO_3-N amounts and availability. When an elevated amount of residual soil N is present, it can increase yields and reduce N requirement for the following crop. This indicates that a similar link may exist between fall starter fertilizer N responsiveness in winter wheat and residual NO_3-N from the preceding crop.

Regional fall nitrogen recommendations

Carryover N from the previous crop frequently occurs in the Mid-Atlantic region (Meisinger *et al*., 1987; Sammons *et al*., 1989; Scharf and Alley 1994; Walker and Taylor, 1998). However, regional fall fertilizer N recommendations for winter wheat give only limited guidance regarding when residual N is adequate to forego starter N. Soil NO_3-N testing before wheat planting is rarely practiced in the Mid-Atlantic, and only Virginia provides recommendations based on residual NO_3-N levels at planting. The use of fall starter N rates from 0 to 45 kg ha^{-1} at planting is permitted practice in Maryland (Maryland Department of Agriculture, 2005). In North Carolina, application of 17 to 34 kg ha^{-1} starter N is recommended to promote maximum growth and tillering (Weisz and

Heiniger, 2004). The recommendation in Virginia is similar for sites where residual N availability is less than 30 mg kg^{-1} (Alley *et al*., 2009). In Delaware, up to 23 kg ha^{-1} is recommended (Walker and Taylor, 1998); this is similar to recommendations in Maryland of 11 to 23 kg ha^{-1} by Sammons *et al*. (1989).

The influence of residual nitrate on small grains

Vanotti and Bundy (1994) examined N carryover following corn and found that oat yields in Wisconsin were influenced by the residual effects of the previous corn crop's N rates in 21 out of 25 years. They suggested that soil testing is necessary to adjust N recommendations for the varying and significant post corn harvest residual NO_3-N that occurs in most years. Similarly, Cui *et al*. (2008) reported that residual NO_3-N levels can be variable and that NO_3-N moves readily out of the root zone. To account for the contribution of soil NO_3-N, they suggested that it should be determined at the beginning of each growing season. According to Scharf and Alley (1994), winter wheat N response across several Virginia soils is heavily influenced by the amount of inorganic N in the surface 120 cm. In the Mid-Atlantic, only Virginia provides guidance regarding the soil NO_3-N level at planting which may be adequate to reduce or forego starter N. Alley *et al*. (2009) state that where soil NO_3-N levels are greater than 30 mg kg^{-1} in the surface 15 cm, N availability is high, and no starter fertilizer N application is required. They consider sites with residual NO_3-N levels less than 10 mg kg^{-1} in the surface 15 cm of soil likely to result in N deficiency in newly emerged seedlings. In Colorado, Vaughan *et al*. (1990a) suggested that when all N is spring applied on soils with very low residual NO_3-N levels (< 5 mg kg^{-1} in surface 30 cm), winter wheat could be predisposed to winterkill and poor plant development, which may lead to reduced grain yields.

However, the results of Knapp and Knapp (1978) do not support this theory, as they reported no yield or winter survival benefit to applying fall N to wheat in New York where residual inorganic N at planting was low (<18 kg ha^{-1}, no sampling depth mentioned).

Olson *et al*. (1976) reported no yield response to fertilizer N in winter wheat grown in semi-arid Nebraska (annual rainfall 580 to 840 mm) where residual NO_3-N in the surface 180 cm exceeded 90 kg ha^{-1}. Daigger and Sander (1976) found that winter wheat plants easily obtained N at a depth of 150 cm and that wheat root systems are mainly established during the fall growing season in Nebraska. Cui *et al*. (2008) reported that the N response of winter wheat on the North China Plain was significantly influenced by soil NO_3-N levels at both planting and during tiller development. They reported that no fertilizer N response (fall or spring application) was likely where soil NO_3-N exceeded 72 kg ha^{-1} (equivalent to approximately 16 mg kg^{-1}) in the surface 30 cm at planting. It is worth noting, however, that soil organic matter content at these study sites ranged from 9.5 to 20.7 percent, much higher than typical soil organic matter content in the Mid-Atlantic.

Use efficiency of fall fertilizer nitrogen

Worldwide N use efficiency in cereal production, including wheat, is approximately 33% (Ruan and Johnson, 1999). Similarly, Olson and Swallow (1984) reported 27 to 33% of fertilizer N rates (56 to 112 kg ha^{-1}) applied to conventional tillage winter wheat were recovered in the grain. Fall fertilizer N has lower utilization efficiency than spring-applied N in winter wheat (Stanford and Hunter, 1973; Boquet and Johnson, 1987; Howard and Lessman 1991). Stanford and Hunter (1973) reported, in a study conducted at five sites in Pennsylvania, that the average whole plant recoveries from fall and spring applied N were 48 and 56%, respectively. Soil sampling to measure soil residual NO_3-N or N mineralization was not reported in this study.

Agriculture accounts for approximately 38% of N loading to the Chesapeake Bay, with about half of this N loading attributed to animal manures (Environmental Protection Agency, 2010). Urban point and non-point sources are the other major contributors to loss. The fate of fall N is of particular concern in Maryland, where at the 2009 Chesapeake Bay Executive meeting, a strategic action plan set a two year goal to reduce (compared with 2008 levels) the amount of N reaching the Chesapeake Bay by 1,700,000 kg (Maryland Department of Agriculture, 2010). It has been reported that NO_3-N leaching is largely influenced by the amount of soil residual NO_3-N after harvest (Roth and Fox 1990; Sogbedji *et al*., 2000; Dinnes *et al*., 2002). When N supply from soil NO_3-N and N fertilizer exceed wheat N demand, N accumulation in the soil profile and loading from the field to the environment is significantly increased (Cui *et al*., 2008). Significant reduction in total N losses depends on effective strategies to reduce NO_3-N leaching to groundwater (Boesch *et al*., 2001). For these reasons, fall N management for crops such as winter wheat and barley which grow during the ground water recharge period requires additional attention.

Fall starter nitrogen rates used as standard practice in regional wheat trials

To determine if fall starter N use on winter wheat is justifiable in the environmentally sensitive Chesapeake Bay watershed, data which demonstrates its agronomic contribution is important. However, studies which specifically examine fall starter N fertilization are not common in the Mid-Atlantic region. Spring N fertility studies are more common and often use fall starter N as a standard practice. In winter wheat management trials in Pennsylvania, Stanford and Hunter (1973), Roth *et al*. (1984), and Fredrick and Marshall (1985) used 22 kg ha^{-1} starter N. Baethgen and Alley (1989a) conducted spring N management trials in Virginia using standard fall N rates of 17 and 34 kg ha^{-1} in different years. In spring N optimization studies in North Carolina, Weisz *et al*. (2001) used a standard starter N rate of 34 kg ha^{-1} at Coastal Plain sites and 34 kg ha^{-1} (one year) or 0 kg ha^{-1} (two years) at Piedmont sites. Also in North Carolina, Flowers *et al*. (2004) applied a standard application of 22 and 0 kg ha^{-1} fall starter N at sites planted early and late, respectively. Weisz *et al*. (2001) reduced the Piedmont site fall starter N rate, as they expected a greater likelihood of residual N at these sites. However, soil sampling data was not reported.

Limited information has been published from trials in the Mid-Atlantic which employed multiple fall N rates, and those which have been published show variable fall starter N responses. Data from N management trials (four site years) conducted in Maryland by Kratochvil *et al*. (2005) on hard red winter wheat showed that yield responses to application of 28 kg ha^{-1} fall starter N ranged from negative 0.01 Mg^{-1} (-0.2%) to positive 0.63 Mg^{-1} ha^{-1} (+10.5%). Twelve of fourteen comparisons in that study showed a positive response (three were considered significant $p \leq 0.05$). The influence of residual N on fall N responsiveness is unknown, as no soil sample data was reported. In New York, Knapp and Knapp (1978) examined the effect of N fertilization on wheat yields and winter survival across a range of planting dates. They reported no increase in either wheat survival rates or yields at sites with relatively low inorganic N levels (18 kg ha^{-1} and 8 kg ha^{-1}) in response to application of 22 kg ha^{-1} starter N (no sampling depth mentioned). When spring N was applied in April, soil inorganic N levels were 14 and 7 kg ha^{-1} for the two sites regardless of fall N rate.

Beyond the Mid-Atlantic, Stanford and Hairston (1984) reported that, in Oklahoma, splitting N fertilizer by applying part of it at planting was no better than applying all N in the spring. They suggested that much of the fall applied N was lost through runoff and/or denitrification. Vaughan *et al*. (1990a) found that wheat yields in Colorado increased incrementally in response to both fall and spring N splits up to 68 kg ha^{-1}. However, no yield disadvantage was incurred when all N was applied in the spring where total rates were less than 68 kg ha^{-1}. Nevertheless, when the maximum spring N rate (68 kg ha^{-1}) was applied, corresponding increases in fall N rate resulted in incremental grain yield increases.

Vaughan *et al*. (1990b) applied fall N rates of 0, 22, 44, and 66 kg ha^{-1} to examine spring plant critical N levels in the western Great Plains. Across 19 site years, they reported that tissue N concentrations were very similar for all treatments just after breaking dormancy at Feekes growth stage 3, indicating that residual N had provided adequate N up to that growth stage.

Frequently, in humid climate locations, residual N at planting was not measured in the N management trials that examined wheat response to fall and spring N fertilization (Stanford and Hairston, 1984; Kratochvil *et al*., 2005) and in those that examined spring N fertilization only (Fredrick and Marshall, 1985; Baethgen and Alley, 1989a; Baethgen and Alley, 1989b). Such omission of residual N contribution is not surprising. Although residual mineral N has proven a good indicator of wheat N response in climates where leaching of NO_3-N from the root zone is minimal (Olson *et* *al*., 1976; Olson and Swallow, 1984), in humid climates the winter inorganic N content of the soil is considered too variable to act as a good indicator of crop N requirements (Fox and Piekielek, 1978). However, elevated residual N levels have been shown to influence wheat fertilizer N responsiveness in the Mid-Atlantic (Meisinger *et al*., 1987; Scharf and Alley 1994) and beyond the region (Daigger and Sander, 1976; Olson *et al*., 1976; Cui *et al*., 2008). This suggests that baseline residual N data could prove useful in examining fertilizer N responsiveness in N fertility studies.

Conclusion

Canopy measurements collected during the corn reproductive growth stages, such as visual ratings, chlorophyll meter readings, and NDVI, are useful indicators of plant N status. These measurements also have a strong positive correlation with corn grain yield. However, their usefulness for quantifying soil N is limited by their inability to identify distinct symptoms of luxury N accumulation; symptoms which might allow for the quantification of soil residual N. Nevertheless, these measurements are good methods for identifying both N deficiency and sufficiency, requiring less labor and processing compared with other assessment methods. This indicates that they could perform a dual purpose as tools to assess both in-season corn N management and residual N potential. Visual ratings are particularly attractive from a practical perspective due to their simplicity and lack of expense. Assessing NDVI remotely is possible, which also makes it attractive. As application of fertilizer N rates in excess of crop requirements is linked to residual N accumulation, sites deemed N deficient are likely to have low residual N levels. Sites at which N availability is sufficient could be selected for further N management assessment, such as use of the CSNT. The CSNT is based on the luxury accumulation of NO_3-N that is exhibited by corn in situations with above optimal N availability. The test has proven an effective tool for identifying excessive N availability. The test's ability to gain insight into corn N status above sufficiency shows potential for predicting soil residual N levels.

In the Mid-Atlantic, optimum N rates and yields for dryland corn grown without N are extremely variable. Factors such as seasonal and site-to-site variation in N mineralization, precipitation patterns, and prices make applying optimum N rates for corn extremely challenging. These factors frequently contribute to mismatches between applied and optimum nitrogen rates. Nitrogen escape from agricultural production systems to the Chesapeake Bay is contributing to water quality degradation. The fate of excess N is extremely important in the context of limiting the environmental impact of corn production systems in the region. Sites with coarse textured soils and/or sites with substantial water percolation will have the most rapid soil profile NO_3-N movement and loss. The timing of this movement has implications for remediation efforts using cover crops. Understanding the fate of excess N will be crucial for implementing site specific stewardship to minimizing future N losses to the Chesapeake Bay, losses which are now subject to mandatory federally enforced limits.

Cover crops and crops grown for commodity purposes will sequester N, thus reducing loss. The relatively large area of winter wheat grown in Maryland provides potential to sequester residual N by foregoing fall starter N. However, little information is published which details the consequences of foregoing fall starter N for winter wheat. Nitrogen deficiency early in plant development has been linked to a host of agronomically unfavorable symptoms; therefore, application of fall starter N is generally recommended in the region. However, due to the variable nature of residual N pools and to intense efforts to minimize N losses to the Chesapeake Bay, there is an urgent need to assess soil N status before application of fall fertilizer N to winter wheat.

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Chapter 3: Late-season corn measurements to assess residual nitrate and corn nitrogen management in the Chesapeake Bay watershed

Abstract

Evaluation of corn (*Zea mays* L.) nitrogen (N) management practices and soil residual nitrate (NO_3-N) late in the growing season provides critical management information that can be used for a future corn crop, subsequent small grain crop, and about potential N loss to ground water flow. Although late-season corn based measurements have been advocated to assess corn N management, there has been little examination of their potential to identify sites with elevated residual NO_3-N. In this study, normalized difference vegetative index (NDVI), the corn stalk nitrate test (CSNT), and post-harvest soil residual NO_3-N were measured at 10 site years. The number of green leaves (ear-leaf and below) and chlorophyll meter readings (measured in SPAD units) were measured at six site years. Corn fertilizer N rates ranged from 0 to 269 kg N ha^{-1}. The CSNT was positively (p<0.001) correlated with residual NO_3-N (r^2=0.41). Significantly, values less than 2.0 g NO_3-N kg^{-1}, commonly accepted as the upper limit of the optimal range, did not imply that residual NO_3-N would be low where drought reduced production. Substantially increased residual NO_3-N occurred mainly where there was drought stress. This indicates that drought stress is at least as important as N rate in determining soil NO_3-N accumulation. All canopy measurements at growth stages R3 to R4 were effective indicators of drought stress. The NDVI is particularly useful because it

can be measured remotely and can detect drought stressed sites with potentially elevated residual NO_3-N levels. Thus, it could be used to target these sites for cover cropping, which would maximize statewide N retention. Grain yield was positively correlated with green leaf number, SPAD units, and NDVI between the R2 and R5 growth stages where drought stress did not occur. Across sites, relative readings were most useful for predicting relative grain yield when collected at R3 to R4 (r^2=0.83, 0.86, and 0.79, for green leaf number, SPAD units, and NDVI, respectively). Measurements from the canopy can identify drought sites, which in this study had the highest post-harvest soil residual NO_3-N accumulation. Use of NDVI particularly would allow policy makers to identify drought sites in the late summer and target them for cover crop planting, thus minimizing N losses to groundwater flow.

Introduction

Nitrogen accumulation and subsequent movement from agricultural fields has negative implications for water quality and represents an economic loss to producers. Federally mandated efforts to improve water quality in the Chesapeake Bay have emphasized N loss reduction from agricultural production systems within the watershed. Corn production requires relatively high N supplementation compared with other crops, such as soybean. This has significant implications for controlling N losses, as soil profile N accumulation (Jolley and Pierre, 1977; Jokela and Randall, 1989; Hong *et al*., 2007) and groundwater NO_3-N levels (Baker and Johnson, 1981; Jaynes *et al*., 2001) are elevated by increasing fertilizer N application, particularly above optimum N rates. Groundwater NO_3-N levels exceeding 10 mg L^{-1} NO_3-N (the EPA drinking water standard) is a health concern for infants. Staver and Brinsfield (1995) reported this level was exceeded in corn field leachate, even where corn was fertilized to attain reasonable yield goals. As groundwater flow is the dominant link between agricultural systems and the surface waters on the Atlantic Coastal Plain (Boesch *et al*., 2001), leachate NO_3-N concentrations directly impact N inputs to the Chesapeake Bay. Curtailing these losses will be important for Maryland to meet its N loss reduction goals: 23% reduction by 2017 (Maryland Department of Environment, 2010).

Ongoing research has provided N management aids for field crop production. The pre-sidedress nitrate test (Magdoff *et al*., 1984) has proven a useful tool for N management in Maryland for sites with manure or legume history (Meisinger *et al*., 1992). The use of both the chlorophyll meter (Hawkins *et al*., 2007) and NDVI (Teal *et al*., 2006; Dellinger *et al*., 2008) during the vegetative growth stages has given significant relationships with N requirement in corn. However, prediction accuracy tends to be lower for early to mid-vegetative growth stage measurements (V4 to V6) (Ritchie *et al*., 1997), the stages at which side-dress N applications are commonly made, compared with delayed (V8 to V10) measurements. Additionally, in dryland corn production, low summer moisture availability and site specific factors may contribute to discrepancies between the N rate applied and the optimum rate. Late season assessments can provide useful evaluations of corn N management practices. Such tools include the chlorophyll meter, green leaf number, NDVI, and the CSNT.

Piekielek *et al*. (1995) found that a critical level of 52.0 SPAD units at the ¼ milk line growth stage separated N deficient from N sufficient sites with 93% accuracy. Timing was less important when readings were normalized by expressing them relative to a high-N reference treatment. A critical level of 0.93 relative SPAD units distinguished N deficient from N-sufficient sites with 92% accuracy. Binford and Blackmer (1993) developed a visual rating system involving counting the number of green leaves below the ear leaf. Adjusted green leaf number (each plot rating subtracted from the high N reference) was positively correlated (r^2=0.74 to 0.80) with relative grain yield. Ratings provided slightly greater sensitivity when taken at growth stages R3 to R5 compared with R1. The requirement to establish a high N reference strip, which producers are often reluctant to do, is a disadvantage for relative or adjusted readings (Fox *et al*., 2001). Fox *et al*. (2001) examined using the absolute green leaf number at the ¼ milkline growth stage. They reported that this had only limited value as a screening tool for N sufficiency. Although 96% of treatments with a visual rating >4.0 green leaves per plant were N sufficient, 54% of treatments below this level were also sufficient. When relative readings were used, a critical value of 0.73 separated N sufficiency from N deficiency with 7.4% error. Thus, a high N reference strip should be an important component of these types of N management assessments. In the current era of heightened environmental concerns and expensive N, producers may be more willing to utilize tools which demonstrate whether their N management was appropriate. The NDVI can be assessed either on site using handheld optical sensors or by remote sensing using aerial or satellite imagery. Corn grain yield and NDVI are positively correlated (Clay *et al*., 2006; Martin *et al*., 2007; Teal *et al*., 2006).

While all of the measurements discussed previously appear to have limited sensitivity to N status above sufficiency, the CSNT has been advocated because of its ability to distinguish between sufficient and excessive N availability. Binford *et al*.

(1992) reported that levels in the range 0.7 to 2.0 g NO_3-N kg^{-1} indicated sufficiency in Iowa. However, in Pennsylvania, Fox *et al*. (2001) reported that a critical level of 0.25 g NO_3-N kg^{-1} separated N deficiency from sufficiency with 93% accuracy. They suggested that, above the 2.0 g NO_3-N kg^{-1} CSNT threshold, polluting levels of post-harvest soil residual NO_3-N are likely to be present. However, there is little published data detailing this relationship. Hooker and Morris (1999) suggested an optimal range of 0.5 to 1.0 g NO_3-N kg^{-1} for corn silage. Indeed, if stalk NO_3-N levels as low as 0.25 g NO_3-N kg^{-1} can indicate sufficiency, the potential exists that elevated soil residual NO_3-N may occur at a site with CSNT levels below 2.0 g NO_3-N kg^{-1}.

Cropland with elevated post-harvest residual NO_3-N poses a critical risk for N escape to ground water. Currently, intensive efforts are being made to reduce N inputs to the Chesapeake Bay, an endeavor deemed essential to improving water quality (Maryland Department of Environment, 2010). Dryland corn production frequently suffers localized or regional drought conditions. Using tools which help producers and/or policy makers identify regions, areas, or individual fields that are primed for above average N loss would be useful for targeting N loss control measures from dryland corn. The study objective was to examine green leaf counts, chlorophyll meter readings, NDVI, and the CSNT as tools for identifying sites with elevated residual NO_3-N and thus expanding options for assessing corn N management. In the past, the potential of these tools to identify or quantify site residual NO_3-N has received little attention. In the context of increasing N loss reduction pressures within the Chesapeake Bay watershed, these tools could guide remediation efforts, such as cover crops or fall N management adjustments to winter wheat, to sites with elevated residual NO_3-N.

Materials and Methods

Ten field experiments were established at University of Maryland Research and Education Centers located in both the Coastal Plain and Piedmont regions of Maryland between 2006 and 2008 (Table 3.1). The experimental design was a randomized complete block with four replications. Two corn hybrids, Pioneer '33B51' (2006 and 2007) and Pioneer '33B54' (2008) were used; both are full season hybrids (113 day relative maturity). All sites were planted during late April to mid-May at a seeding rate of 73 000 seeds ha^{-1} using a no-till drill at 76 cm spacing. Plot length was 12.2 in 2006 and 2007 and 15.2 in 2008. All plots were 9.1 m wide (12 corn rows) except at Clarksville where plots were 6.1 m wide (eight corn rows). Four corn fertilizer N rates: 0 (67 in 2006), 135, 202, and 269 kg ha^{-1} were applied at each site. At all sites, 34 kg N ha^{-1} was applied as starter and the balance was provided as side-dress in a surface band during V4 to V6 growth stages, except for the zero N treatment which received no N. The fertilizer N source was liquid N (30% N as urea-ammonium nitrate solution).

Green leaf counts, chlorophyll meter readings, and NDVI measurements were collected from the corn canopy at three times (the R2, R3 to R4, and R5 growth stages). Green leaf number was determined by counting the number of green leaves below and including the ear leaf following the procedure described by Binford and Blackmer (1993). Chlorophyll meter readings were collected from a point midway along the ear leaf using a Minolta SPAD 502 chlorophyll meter (Minolta, Ramsey, NJ) as described by Piekielek *et al*. (1995). The meter produces an output in SPAD units, which have been shown to be highly correlated with leaf chlorophyll concentration (Markwell *et al*., 1995). Both green leaf counts and chlorophyll meter readings were collected from a total of 10 (2006) and 20 (2007) randomly selected plants out of rows 3, 4, 9, and 10. A Crop Circle optical sensor (Holland Scientific, Lincoln, NE), which senses at 590 nm in the visible and 880 nm in the infrared light spectrum was used to collect NDVI measurements from the rows noted above in at all sites except Clarksville where measurements were collected from rows 2, 3, 6, and 7 of each plot. Relative ratings for green leaf number, SPAD units, and NDVI were calculated by dividing the respective readings from each plot by the average reading from the highest N treatment (269 kg N ha^{-1}).

Sample collection for the CSNT followed the procedure of Binford *et al*. (1990). A 20 cm stalk section was cut from a total of 10 plants in each plot by cutting the stalk at 15 and 35 cm above the ground at or close to corn growth stage R6. Stalk sections were randomly collected from rows 2, 5, 8, and 11 except at Clarksville where sections were collected from rows 2, 3, 6, and 7. The stalk segments were stripped of leaves, dried at 60°C and ground in a Wiley mill to pass a 2 mm sieve. The ground samples were further ground to a fine consistency using a coffee grinder. Nitrate concentration was determined by shaking 0.25 g of sample in 100 ml of 2 *M* KCl solution for 30 minutes using a reciprocating shaker (Eberbach Corp., Ann Arbor, Michigan). Samples were allowed to settle for 30 minutes and supernatant liquid was filtered through grade 42 filter paper (Whatman Inc., Buckinghamshire, U.K.). Corn stalk NO_3-N concentrations in extract solutions were determined by colorimetric analysis using a continuous-flow ion analyzer [Lachat, 1987 (2007 and 2008) and Technicon Industrial Systems, 1977 (2006)]. Corn stalk samples were not collected from the center two rows of each plot, as these rows were used to determine corn grain yield. The same rows described earlier from which NDVI measurements were collected were harvested at maturity, and yield was recorded using a Massey Ferguson 8XP plot combine (Kincaid Manufacturing, Haven, KS) equipped with a HarvestMaster data collection system (Juniper Systems, Logan, UT) that recorded grain weight and moisture content as it was harvested. At Clarksville yields were adjusted for removal of corn stalk sections from the harvested rows. Corn grain yields were adjusted to 155 g kg^{-1} moisture content. Relative yields were calculated by dividing the grain yield from each plot by the average yield from the highest corn N treatment at each site.

Following corn harvest, eight soil cores $plot^{-1}$ were collected to a 30 cm depth. Soil samples were air dried at room temperature immediately following collection and ground to pass through a 2 mm sieve. Soil NO_3-N analysis followed the same procedure described above for corn stalks, except soil was extracted at a ratio of 1:10 in 1 *M* KCl solution. The mass calculation of soil profile NO_3-N was conducted using the assumption that 15 cm x 1 ha soil weighs 2.24 x 10^6 Mg (i.e. assuming a soil bulk density of 1.49 g cm^{-3}).

Correlation analysis to determine the relationship between the plant measurements collected and corn grain yield at individual sites was conducted using the PROC REG procedure of SAS version 9.2 (SAS Institute, Cary, NC). This procedure was also used to examine the relationship between relative plant measurements and relative grain yield pooled across site years which did not experience drought conditions. Using the PROC NLIN procedure of SAS, a quadratic-plateau model was fitted to corn yield response data for each site year. These functions were used to determine the nitrogen sufficient yield nitrogen rate (NSYNR) (i.e., the rate at which the crop had sufficient N to maximize grain yield) and the economically optimum nitrogen rate (EONR). A price ratio of fertilizer N to corn of 7.2 kg kg^{-1} (\$1.062 kg^{-1} N, \$0.147 kg^{-1} corn) was used to calculate EONR. These prices represented average Maryland corn prices and national fertilizer N prices during the study period (2005-2009) (USDA, 2010a; USDA, 2010b). At sites which did not respond to application of fertilizer N, zero was assigned as EONR and NSYNR.

Results and Discussion

Late-season corn measurements to assess post-harvest soil residual nitrate

The use of corn canopy measurements as predictors of post-harvest soil residual NO_3-N has received limited attention. This may be because they are minimally useful for identifying excessive N availability to the corn crop. Green leaf counts have been shown to plateau at levels above N sufficiency (Binford and Blackmer, 1993; Fox *et al*., 2001) and, for this reason, are unable to detect excess N. Chlorophyll meter readings have also generally been observed to plateau above sufficiency and to show little sensitivity to luxury consumption (Blackmer and Schepers, 1994; Piekielek *et al*., 1995; Varvel *et al*., 1997), indicating they have little utility for detecting excess N consumption. However, Zhang *et al*. (2008) reported that increased N applications often promote increased production of chlorophyll not accompanied by grain yield increase. Sensitivity to such luxury chlorophyll production may provide some information regarding excess N. Binford and Blackmer (1993) suggested that, in light of the inability of green leaf counts to detect excess N, the CSNT should be used at sites which show no sign of N deficiency.

Summer droughts are commonplace in the Mid-Atlantic region and are frequently localized due to the variable nature of summer precipitation. For instance, during the study period, Beltsville and Wye experienced drought in 2007, while Poplar Hill did not. In 2008, only Clarksville suffered from drought conditions, while the other three sites did not. Due to the range of growing conditions during the study period, examination of late-season corn measurements as tools for identifying residual NO_3-N at both normal and drought affected sites was possible.

Green leaf measurements

The highest corn N rate applied (269 kg N ha^{-1}) exceeded the EONR at all sites (data not shown). The plots with the highest green leaf number tended to correspond to the highest corn N rates. However, little elevation in soil residual NO_3-N was observed for any of the four sites unaffected by drought during 2006 and 2007 (Fig. 3.1). The lack of NO_3-N accumulation at these sites may be attributable to the highest fertilizer N rate only moderately exceeding the NSYNR (by 33 kg N ha^{-1} on average; data not shown). Additionally, increased CSNT values corresponding to increasing fertilizer N rate were observed (Fig. 3.4). This, combined with the lack of substantially increased soil residual NO_3-N when green leaf number is high, suggests that the corn stover is acting as a sink for excessive N.

The results of this study indicate that green leaf number is useful for identifying sites which suffered from drought conditions (Fig. 3.1). These sites typically had the highest residual NO_3-N levels. Even following the low corn N rate (135 kg N ha^{-1}), residual NO_3-N generally exceeded 50 kg ha^{-1} to 30 cm depth. Green leaf number at the R3 to R4 growth stage was most effective for identifying sites with elevated residual

NO_3-N caused by drought. Sites with less than 3.5 green leaves at this stage were likely to have elevated residual NO_3-N (Fig. 3.1). Similarly, green leaf number at the R5 growth stage also identified the sites with elevated residual NO_3-N due to drought. However, there was substantial overlap between green leaf number and soil NO_3-N concentration for non-drought affected sites which had low residual NO_3-N levels. This overlap is attributed to the effects of maturity driven senescence. Counts collected at the R2 growth stage were not effective for identifying sites with elevated residual NO_3-N due to drought stress. This is attributed to the symptoms of drought being less pronounced at this growth stage.

The chlorophyll meter

Absolute SPAD units produced by the Minolta chlorophyll meter have been proposed as a more accurate predictor of relative grain yield compared with green leaf number (Fox *et al*., 2001). This suggests that the chlorophyll meter may also be a better predictor of residual NO_3-N. As was observed with green leaf number, SPAD units collected at the R3 to R4 growth stage appear to be useful for identifying sites likely to have elevated residual NO_3-N caused by drought conditions (Fig. 3.2). However, separation between these sites at the R3 to R4 growth stage was better for the green leaf counts compared with SPAD units. The SPAD units were more effective for separating drought sites compared with green leaf number at the R2 growth stage, which indicates that the chlorophyll meter is more sensitive to drought stress than green leaf number. In the current study, neither SPAD units nor green leaf counts were useful for quantifying post-harvest residual NO_3-N in normal growing seasons.

The normalized difference vegetation index

Producers will know that drought is occurring without collecting the measurements previously discussed. However, for policy makers and agencies striving to incentivize programs to limit annual N loss, tools to identify localized drought conditions would be useful. Identification of these sites before the beginning of the fall-winter-spring groundwater recharge period could allow for remediation efforts, such as use of cover crops, to be targeted to high risk areas, perhaps by increasing the incentive for planting a cover crop on the basis of N loss risk. To be used for this purpose, green leaf number and SPAD unit collection would require visiting sites and collecting measurements. However, NDVI can be measured remotely, which would be a more practical option for assessing N loss potential at either a regional or local level.

The data in this study, collected from 10 site years in Maryland, indicate NDVI has potential to screen for sites likely to have elevated residual NO_3-N resulting from drought conditions. Similar to green leaf number and SPAD units, NDVI collected at the R3 to R4 growth stage best distinguished between drought and normal sites (Fig. 3.3). This is important for N loss risk assessment, as drought sites tended to have residual NO_3-N levels exceeding 50 kg N ha^{-1} in the surface 30 cm, while levels for sites unaffected by drought were typically lower (Fig. 3.3). Interestingly, in an outcome also observed with green leaf number, NDVI at the R2 growth stage did not produce a distinct separation between sites affected by drought and those that had normal precipitation. The NDVI measurements collected later in the growing season (R5) separated sites with drought from those with normal precipitation. However, similar to the other canopy measurements, a greater number of sites with low NDVI would have been incorrectly identified as having elevated residual NO_3-N risk compared with low NDVI at the R3 to R4 growth stage (Fig. 3.3). Again, this was attributed to the equalizing effect of maturity driven canopy properties at the later growth stage.

Measurements of NDVI were collected at a greater number of sites compared with the other canopy measurements. Across these sites, at the R3 to R4 growth stage, some evidence of increasing residual NO_3-N at the highest NDVI values was observed (Fig. 3.3). This reflects the fact that NDVI, like the other canopy measurements, reaches a plateau at or above N sufficiency and does not increase beyond this level regardless of soil or plant N status.

The corn stalk nitrate test

The ability of the corn stalk to luxury accumulate NO_3-N indicates that the CSNT may be a useful tool to assess soil residual NO_3-N. Fox *et al*. (2001) suggested that CSNT levels above 2.0 g NO_3-N kg^{-1} may be a sign that potentially polluting levels of residual NO_3-N will be present following harvest. However, there is little published data detailing this relationship. This is significant, as the CSNT is advocated as a tool for improving corn N management and reducing environmental losses in the region (Anon, 2009). Where grain yield optimization is the goal, 2.0 g NO_3-N kg^{-1} is considered the upper boundary of the optimal range of CSNT values (Binford *et al*., 1992). However, in the context of N loss reduction efforts within the Chesapeake Bay watershed, residual NO_3-N, and not solely grain yield, will need to be considered to identify whether corn N management was appropriate.

The data in this study (Fig. 3.4) demonstrate a significant ($p<0.001$) positive correlation between the CSNT and soil residual NO_3-N in the surface 30 cm. However, this relationship is quite variable, as evidenced by the relatively low coefficient of determination observed (r^2=0.41). For this reason, the CSNT does not make a good quantitative indicator of residual NO_3-N. Nevertheless, because the CSNT is widely used, these values could be used as a qualitative indicator of residual NO_3-N levels for a region. Such information may provide a useful assessment of progress in reducing N loading and loss. Although CSNT values up to 2.0 g NO_3-N kg^{-1} are considered optimum for grain production (Binford *et al*., 1992), the data presented in Fig. 3.4 demonstrate that soil residual NO_3-N can be elevated at CSNT values below this level. This illustrates, as other researchers have found (Binford *et al*., 1992; Morris and Hooker, 1999), that there is uncertainty associated with identifying the optimal stalk NO_3-N concentration. In the present study, elevated residual NO_3-N at CSNT values below 2.0 g NO_3-N kg^{-1} were observed mainly at sites affected by drought. Drought conditions have been shown to increase NO_3-N in corn stalks (Hanway and Englehorn, 1958). The highest CSNT values were observed for the high N rates at drought sites, and these corresponded to high levels of residual NO_3-N (Fig. 3.4). However, some plots, especially those at Wye in 2007, had relatively low CSNT values despite having elevated residual NO_3-N. This can be attributed to spatial separation between surface applied fertilizer N and the root system due to moisture limitations at this site. Unlike the other two drought sites, significant grain yield response to N was observed at Wye site in 2007 (data not shown), and this outcome may have contributed to the depleted CSNT values observed at this site.

Late-season corn measurements to assess nitrogen management and grain yield

Green leaf measurements

The green leaf number was significantly correlated with grain yields between corn growth stages R2 and R5 at all locations, with the exception of Beltsville in 2007 (all three growth stage measurements) and Wye in 2007 (last two growth stage measurements) (Table 3.2). Both of these sites experienced severe drought stress during 2007. At Beltsville, no yield response to fertilizer N was observed, and grain yields were substantially below average at Wye (data not shown). The poor (Wye 2007 at R2) and non-significant relationships (Beltsville 2007 and Wye 2007 at R3-R4 and R5) with grain yield observed (Table 3.2) may be partially attributable to altered leaf senescence patterns, which are linked to drought conditions (Wolfe *et al*., 1988). Nitrogen limited plants exhibit more rapid leaf senescence compared with plants which have sufficient N available (Binford and Blackmer, 1993; Wolfe *et al*., 1988). A similar divergence in N driven leaf senescence was observed in this study, as evidenced by the slope of the regression line which universally declined between collection of the first and second leaf counts (Table 3.2.). Although maturity driven senescence is simultaneously occurring, N driven senescence speeds up the process in N limited crops. Thus, there is greater separation between plants with varying N status later in the growing season compared with earlier in the season.

While the green leaf number is an excellent predictor of grain yield at individual sites not affected by drought ($0.71 \leq r^2 \geq 0.93$), its ability to be reliable across sites is also important. To examine this relationship, relative green leaf number and yields were used. Relative yields provide a common index of N sufficiency across sites, whereas absolute yields do not (Cerrato and Blackmer, 1991). The 2007 Wye and Beltsville sites were excluded due to drought conditions, as relative readings are unable to completely correct for the drought effect (Fox *et al*., 2001). The slope of the regression line between relative green leaf number and relative yield decreased as the growing season progressed. Thus, the relative green leaf number at R5 showed the greatest separation between plants of varying N status (Fig. 3.6). However, the relationship was poor (r^2=0.62) compared with the relationship at the R3 to R4 growth stage (r^2=0.83). Similarly, Binford and Blackmer (1993) observed the highest correlation between adjusted leaf ratings (which were calculated by subtracting the green leaf count for each plot from the mean of the two highest treatments) and grain yields collected at R4 (r^2=0.80) in Iowa. The relatively poor relationship at R5 in the present study may be attributable to the effects of maturity driven senescence, which were more pronounced at this growth stage compared with earlier growth stages. Relative green leaf number at R2 was also significantly correlated with relative grain yield. However, the steeper slope of the regression line provides evidence that N deficiency driven senescence is less pronounced at this timing. Thus, it may be more difficult to identify crops with marginal N deficiency at this growth stage compared with later growth stages (Fig. 3.6).

The chlorophyll meter

Chlorophyll meter derived SPAD units collected between the R2 and R5 growth stages were significantly correlated with grain yield ($0.70 \leq r^2 \geq 0.93$), except for Beltsville in 2007, which experienced severe drought (Table 3.3). However, at Wye in 2007, which also experienced drought conditions, the chlorophyll meter readings were a better predictor of grain yield than green leaf number. The slope of the regression line between SPAD units and grain yield declined as the crop matured (except at Wye in 2007).

The strong relationship between relative SPAD units and relative yield observed (Fig. 3.7) is in agreement with the findings of Piekielek *et al*. (1995) that the chlorophyll meter is a useful tool for the assessment of N sufficiency. The slope of the regression line declined between R2 and R5, indicating greatest separation between plants of differing N status at R5 (Fig. 3.7). Similarly, Fox *et al*. (2001) reported a strong correlation (r^2=0.80) between relative SPAD units at the ¼ milk line stage and relative grain yield. However, in the present study the coefficient of determination was relatively low at this growth stage (r^2=0.64). Relative SPAD units collected at R2 were highly correlated with grain yield (r^2=0.81), but the relationship was strongest at the R3 to R4 stage (r^2=0.86).

The normalized difference vegetation index

Measurement of NDVI has the potential for greater application compared with the canopy measurements previously discussed because it can be measured, not only from the ground at each site, but also by airplane or satellite. Due to its potential for wider application, it was measured at the greatest number of sites (Table 3.4). Additionally, optical sensors rapidly collect NDVI measurements across a large canopy area, and Ma *et al*. (1996) reported that NDVI was well correlated with "field greenness" (a product of plant leaf area and chlorophyll meter reading). This indicates that it may be a more useful measure of crop vigor than chlorophyll meter readings alone. Measurements of NDVI collected between the R2 and R5 growth stages were significantly correlated with grain yield (Table 3.4). With the exception of the three sites which experienced severe drought stress (Beltsville and Wye in 2007 and Clarksville in 2008), the relationship was strong ($0.72 \leq r^2 \geq 0.97$) for measurements collected between R2 and R4. The relationship was also strong at R5 for most sites, yet it was more variable ($0.33 \leq r^2 \geq 0.91$). The relationship had poorer reliability ($0.44 \leq r^2 \geq 0.90$) or was non-significant at the three drought sites.

Relative NDVI was evaluated as a predictor of relative yield for seven site years which did not experience drought conditions. Exclusion of the drought sites improved the coefficient of determination substantially (data not shown). Relative NDVI and relative grain yield were significantly correlated, and the correlation was highest for measurements collected at R2 (Fig. 3.8). However, only data from five site years was available at this growth stage, which may have accounted for the higher correlation observed. As was the case for the other relative canopy measurements, NDVI collected at the R3 to R4 growth stage was significantly and strongly (r^2=0.79) correlated with relative grain yield (Fig. 3.8).

All canopy measurements collected were well correlated with both absolute grain yield at individual sites and relative grain yield across sites. The low-tech green leaf count approach performed similarly to more high tech and expensive methods, such as the chlorophyll meter or optical sensor derived NDVI. However, Fox *et al*. (2001) pointed out that absolute number of green leaves at and below the ear leaf is not an accurate indicator of N adequacy, whereas absolute SPAD units are accurate. Use of relative readings improves the predictive accuracy of these tests but does require the establishment of a high N reference strip.

The corn stalk nitrate test

The measurements discussed above are useful indicators of N sufficiency on a site by site basis, especially if a high N reference strip is used. However, producers may not wish to establish such strips (Fox *et al*., 2001). The CSNT proposed by Binford *et al*. (1990) is a reliable tool for identifying sites with excessive N application; they suggested an optimal range of 0.25 to 1.80 g NO_3-N kg^{-1} based on research conducted in Iowa. In that study, the upper value for the optimal range was set as the mean stalk NO_3-N concentration at the EONR. Binford *et al*. (1992) later revised the optimal stalk NO_3-N concentration to 0.7 to 2.0 g N kg^{-1} based on iterative calculations and net returns which combined the original data with a further 30 site years. In the present study, the regression line plotted for the relationship between CSNT levels and ΔEONR indicates a stalk NO_3-N level of 0.57 g kg^{-1} at the EONR across study sites (Fig. 3.5), considerably lower than the upper bound of 1.80 g NO_3-N kg^{-1} reported in Iowa by Binford *et al*. (1990). This suggests that the upper bound for N sufficiency may be lower for Maryland. This is supported by the findings of Hooker and Morris (1999) that 0.5 to 1.0 g N kg^{-1} indicated N adequacy for corn silage in Connecticut. Additionally, Fox *et al*. (2001) reported that CSNT values greater than 0.25 g NO_3-N kg^{-1} identified N sufficiency in Pennsylvania with an error rate of only 5.7%. Thus, there is a degree of uncertainty in establishing an optimal range. The data from the present study presented in Fig. 3.9 also indicates that establishment an optimum range is difficult. However, these data support the lower bound of the sufficiency range identified by Fox *et al*. (2001) and indicate potential to reduce the upper bound of the sufficiency range for CSNT recommendations in Maryland.

Conclusions

The green leaf number, SPAD units, and NDVI have utility for identifying sites with elevated residual NO_3-N associated with drought. Collecting these measurements at the R3 to R4 growth stage can potentially identify sites where drought occurred. Thus, there is promise that these tools can be utilized for purposes other than predicting yield potential. The ability of remotely sensed NDVI to distinguish drought affected sites at the R3 to R4 stage is significant, as these sites were observed to be most likely to have elevated post-harvest residual NO_3-N levels. Thus, it is these sites which are likely to have the greatest N loss potential, even when fertilizer N application rate is close to the average optimal rate. The CSNT was positively ($p<0.001$) correlated with soil residual NO_3-N ($r^2=0.41$). The prevalence of drought appears to be at least as important as fertilizer N rate in contributing to elevated post-harvest residual NO_3-N pools in the region. For this reason, identifying and targeting these sites for either cover or commodity cover crop planting to sequester the excessive residual N pool will be crucial to maximizing N loss reductions to the Chesapeake Bay.

All corn canopy measurements examined performed well as predictors of grain yield when collected between the R2 and R4 growth stages, both at individual sites ($0.71 \leq r^2 \geq 0.97$) and across sites ($0.79 \leq r^2 \geq 0.86$) unaffected by drought. While SPAD units and NDVI were better predictors of grain yield compared with green leaf number at sites affected by drought, all measurements had reduced grain yield prediction reliability under drought conditions. Measurements collected at the R3 to R4 stage were typically the most highly correlated with grain yield, indicating that N deficiency symptoms are well expressed at this growth stage without the overbearing influence of maturity driven senescence. A significant advantage for green leaf counts is that producers can do this without purchasing equipment. These plant based measurements require establishment of a high N reference strip, which is often considered a disadvantage. There is increasing pressure for agricultural input regulation within the Chesapeake Bay watershed. In this context the use of voluntary practices which assess and demonstrate the appropriateness of N management on a year and site specific basis may become necessary. The CSNT is an effective tool for identifying excessive N applications; however, the data in this study support findings that a degree of uncertainty is associated with the setting of an optimal range. Soil sample data indicated that values within what Binford *et al*. (1992) identified as the CSNT sufficiency range in Iowa (0.7 to 2.0 g NO_3-N kg^{-1}) may not imply that residual soil NO_3-N is low, where drought reduced production occurs. Additionally, the results for this study support findings in eastern states that a sufficiency range lower than 0.7 to 2.0 g NO_3-N kg^{-1} may be appropriate. In the context of N loss reduction commitments for states within the Chesapeake Bay, some reassessment of the CSNT sufficiency range which also considers soil residual NO_3-N risk may be appropriate.

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Table 3.1: Site locations, soil characteristics and precipitation.

Location	Year	Latitude	Longitude	Soil taxonomy	Soil series and surface soil texture†	Precipitation 1 May to 31 Aug.
Upper Marlboro	2006	38° 51' 39" N	76° 46' 29" W	Aquic Hapludults	Adelphia-Holmdel fsl	397
Beltsville	2006	39° 01' 31' N	76° 50' 26" W	Aquic Hapludults	Russett-Christiana fsl	420
Beltsville	2007	39° 01' 33" N	76° 50' 31" W	Aquic Hapludults	Hammonton ls	220
Beltsville	2008	39° 00' 45" N	76° 49' 43" W	Typic Hapludults-Aquic Hapludults	Downer-Hammonton ls	505
Clarksville	2008	39° 15' 53" N	76° 55' 49" W	Aquic Fragiudults	Glenville sl	308
Wye	2006	38° 54' 38" N	76° 08' 48" W	Typic Hapludults	Nassawango sl	495
Wye	2007	38° 54' 42" N	76° 08' 38" W	Typic Hapludults	Nassawango sl	251
Wye	2008	38° 54' 45" N	76° 08' 42" W	Typic Hapludults	Nassawango sl	439
Poplar Hill	2007	38° 21' 28" N	75° 46' 51" W	Typic Hapludults	Nassawango sl	430
Poplar Hill	2008	38° 21' 26" N	75° 46' 52" W	Typic Hapludults	Nassawango sl	335

† Texture: fsl, fine sandy loam; ls, loamy sand; sl, silt loam; l, loam.

Table 3.2: Parameters for within site year models describing the relationship between green leaf number and corn grain yield.

		R2 growth stage			R3 to R4 growth stage			R5 growth stage		
Site	Year	Slope	Intercept	r^2	Slope	Intercept	r^2	Slope	Intercept	r^2
		——Mg ha^{-1}——			——Mg ha^{-1}——			——Mg ha^{-1}——		
Beltsville	2006	1.5	-0.70	0.93	1.2	2.7	0.86	1.19	4.94	0.87
Upper Marlboro	2006	1.20	0.27	0.83	0.84	3.85	0.83	0.95	5.39	0.78
Wye	2006	1.24	3.52	0.71	1.10	4.90	0.83	0.98	7.88	0.77
Beltsville	2007	NS†	-	-	NS	-	-	NS	-	-
Wye	2007	-3.45	2.56	0.57	NS	-	-	NS	-	-
Poplar Hill	2007	1.77	-0.55	0.89	1.64	0.58	0.90	1.74	1.21	0.86

† NS: not significant ($p \leq 0.05$).

Table 3.3: Parameters for within site year models describing the relationship between chlorophyll meter readings (SPAD units) and corn grain yield.

		R2 growth stage			R3-4 growth stage			R5-6 growth stage		
Site	Year	Slope	Intercept	r^2	Slope	Intercept	r^2	Slope	Intercept	r^2
		——Mg ha^{-1}——			——Mg ha^{-1}——			——Mg ha^{-1}——		
Beltsville	2006	0.35	-1.11	0.84	0.23	-3.77	0.90	0.14	2.31	0.91
Upper Marlboro	2006	0.28	-8.48	0.86	0.17	-1.18	0.93	0.09	4.00	0.70
Wye	2006	0.28	-6.18	0.82	0.17	0.37	0.83	0.09	6.67	0.79
Beltsville	2007	NS†	-	-	NS	-	-	NS	-	-
Wye	2007	0.30	-7.44	0.86	0.26	-5.38	0.78	0.29	-5.25	0.71
Poplar Hill	2007	0.25	-5.18	0.88	0.21	-3.77	0.91	0.18	-1.71	0.86

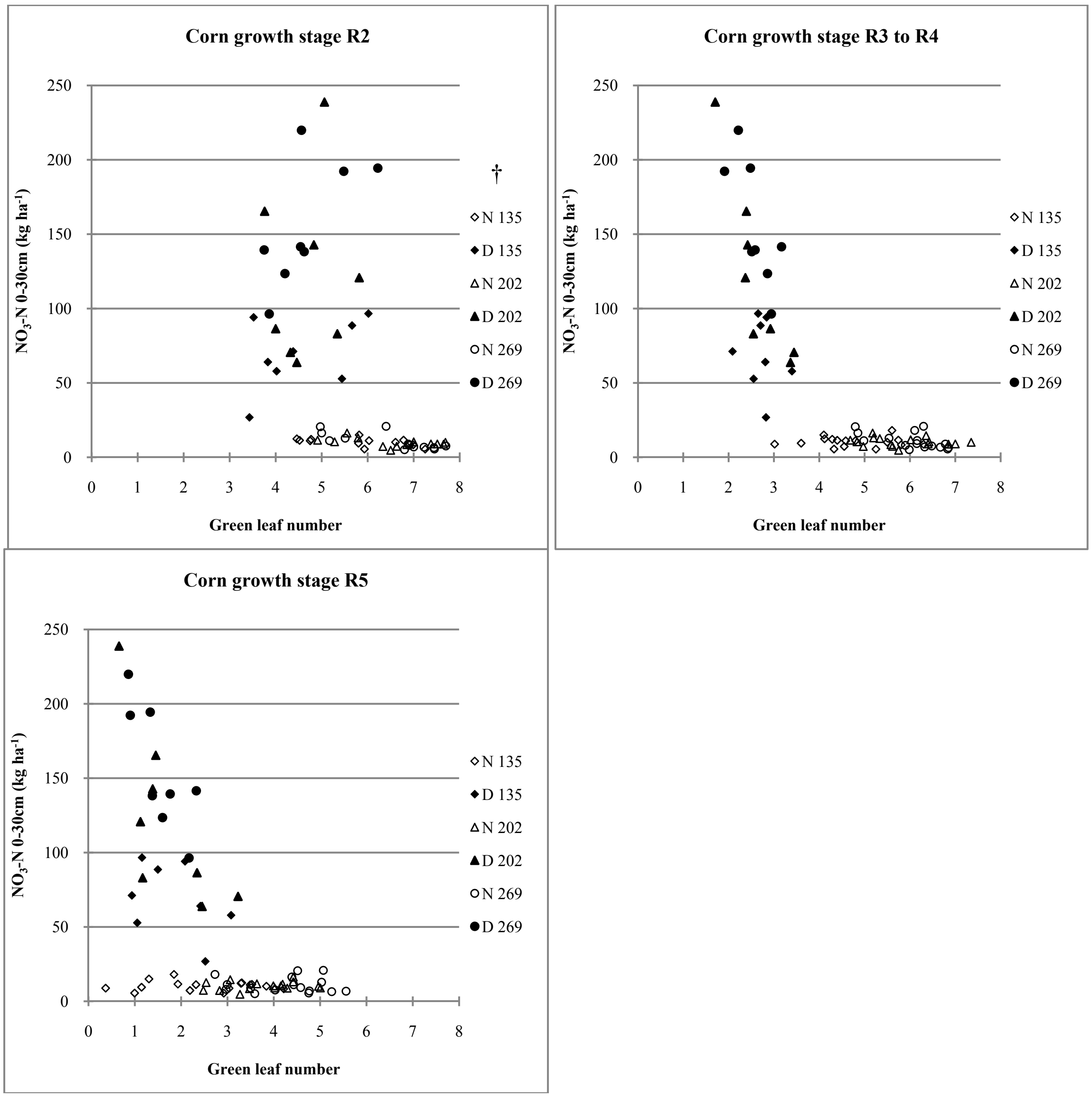
† NS: not significant ($p \leq 0.05$).

Table 3.4: Parameters for within site year models describing the relationship between normalized difference vegetation index (NDVI) and corn grain yield.

		R2 growth stage			R3-4 growth stage			R5 growth stage		
Site	Year	Slope	Intercept	r^2	Slope	Intercept	r^2	Slope	Intercept	r^2
		——Mg ha^{-1}——			——Mg ha^{-1}——			——Mg ha^{-1}——		
Beltsville	2006	ND†	ND	ND	45.17	-20.86	0.91	31.74	-8.37	0.91
Upper Marlboro	2006	ND	ND	ND	34.12	-13.70	0.86	29.77	-8.82	0.76
Wye	2006	42.09	-18.77	0.75	26.84	-6.81	0.78	17.60	1.38	0.75
Beltsville	2007	NS‡	-	-	NS	-	-	NS	-	-
Wye	2007	34.05	-11.14	0.86	36.88	-10.61	0.52	NS	-	-
Poplar Hill	2007	46.96	-21.52	0.97	40.36	-18.11	0.93	37.78	-13.32	0.84
Beltsville	2008	38.49	-16.32	0.80	33.10	-12.70	0.88	33.36	-8.37	0.81
Wye	2008	79.19	-44.88	0.92	47.81	-21.44	0.97	32.15	-10.66	0.90
Poplar Hill	2008	35.37	-15.37	0.93	6.80	3.62	0.72	24.71	-4.31	0.33
Clarksville	2008	28.92	-14.01	0.44	28.36	-8.16	0.90	30.59	-7.52	0.77

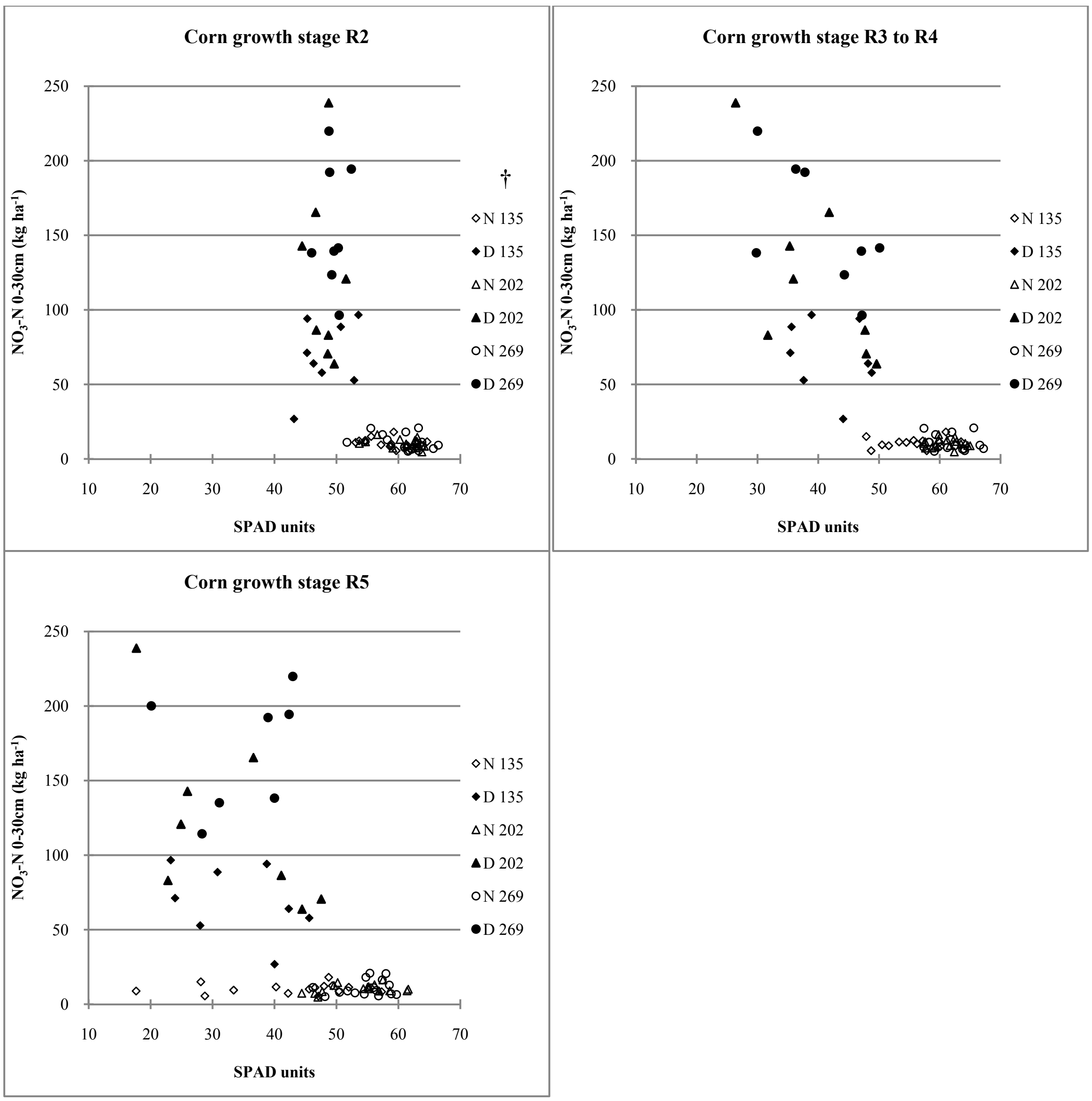
† ND: not determined, no measurements collected at this timing.
‡ NS: not significant ($p \leq 0.05$).

Fig. 3.1: Relationship between corn green leaf number at and below the ear leaf and post-harvest soil residual nitrate (NO_3-N) in the surface 30 cm. Data presented is for green leaf counts collected at three times during reproductive growth (R2, R3 to R4, and R5) at six site years where fertilizer nitrogen rates of 135, 202, and 269 kg N ha^{-1} were applied.



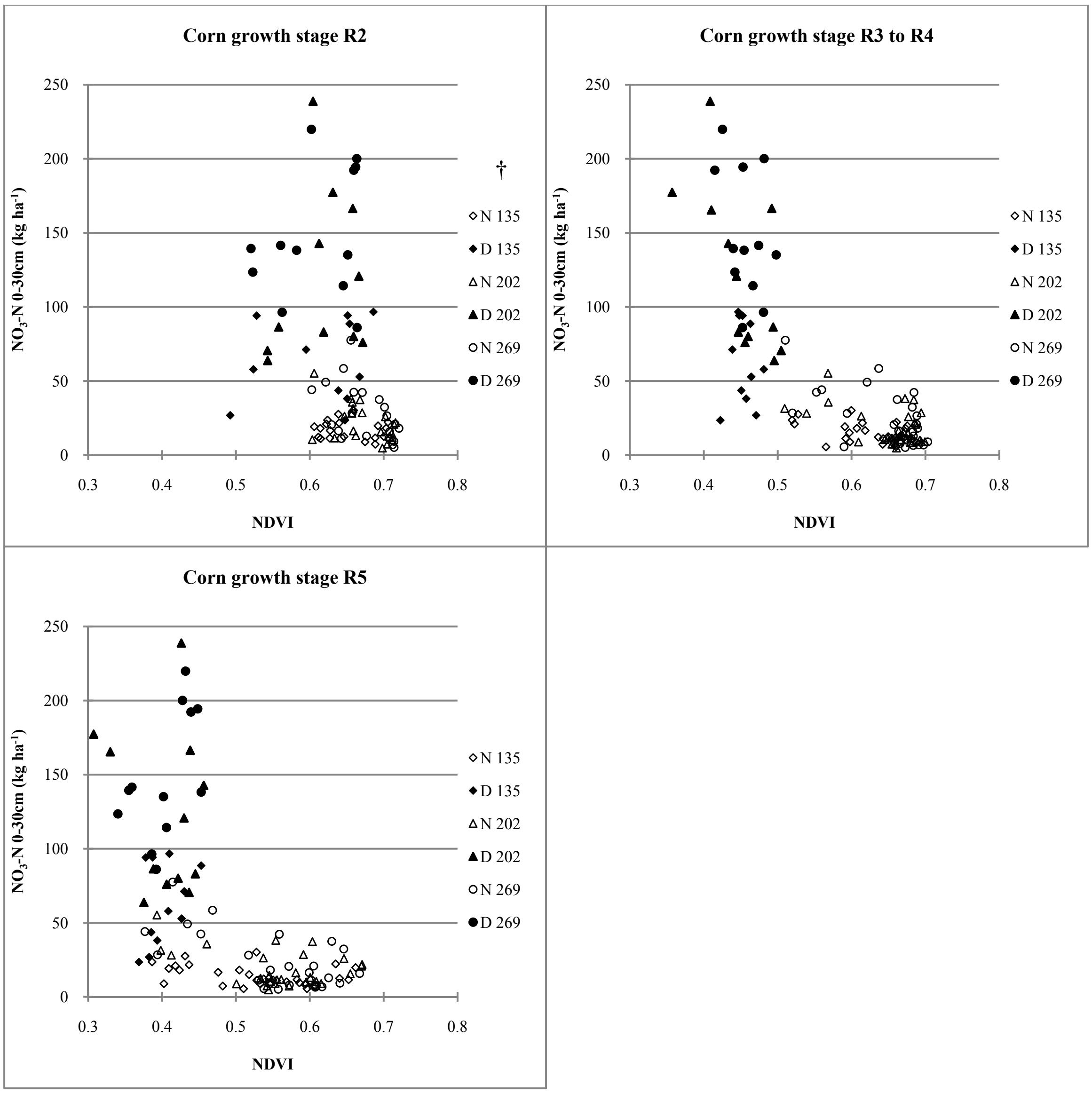
† Letters designates whether drought conditions prevailed N: normal growing season; D: drought. Numbers designates corn fertilizer nitrogen rate (kg N ha^{-1}).

Fig. 3.2: Relationship between chlorophyll meter readings (SPAD units) collected from the corn the ear leaf and post-harvest soil residual nitrate (NO_3-N) in the surface 30 cm. Data presented is for SPAD units collected at three times during reproductive growth (R2, R3 to R4, and R5) at six site years where fertilizer nitrogen rates of 135, 202, and 269 kg N ha^{-1} were applied.



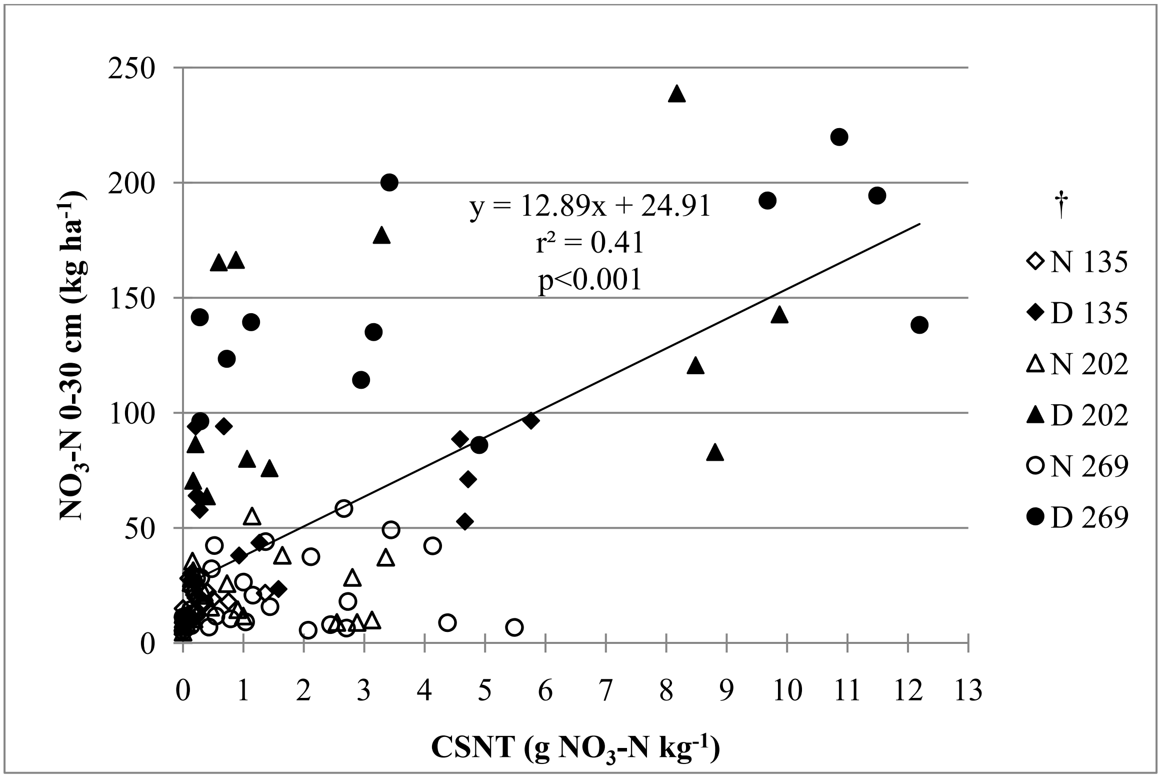
† Letters designates whether drought conditions prevailed; N: normal growing season; D: drought. Numbers designates corn fertilizer nitrogen rate (kg N ha^{-1}).

Fig. 3.3: Relationship between the normalized difference vegetation index (NDVI) collected from the corn canopy and post-harvest soil residual nitrate (NO_3-N) in the surface 30 cm. Data presented is for NDVI collected at three times during reproductive growth (R2, R3 to R4, and R5) at 10 site years (R2 eight site years) where fertilizer nitrogen rates of 135, 202, and 269 kg N ha^{-1} were applied.



† Letters designates whether drought conditions prevailed; N: normal growing season; D: drought. Numbers designates corn fertilizer nitrogen rate (kg N ha^{-1}).

Fig. 3.4: Relationship between the corn stalk nitrate test (CSNT) and soil residual nitrate (NO_3-N) in the surface 30 cm at 10 site years where fertilizer nitrogen (N) rates of 135, 202, and 269 kg N ha^{-1} were applied.



† Letters designates whether drought conditions prevailed; N: normal growing season; D: drought. Numbers designates corn fertilizer nitrogen rate (kg N ha^{-1}).

Fig. 3.5: Relationship between the corn stalk nitrate test (CSNT) and change in applied nitrogen (N) rate compared with the economically optimum nitrogen rate (ΔEONR) and post-harvest soil residual nitrate (NO_3-N) in the surface 30 cm at 10 site years.

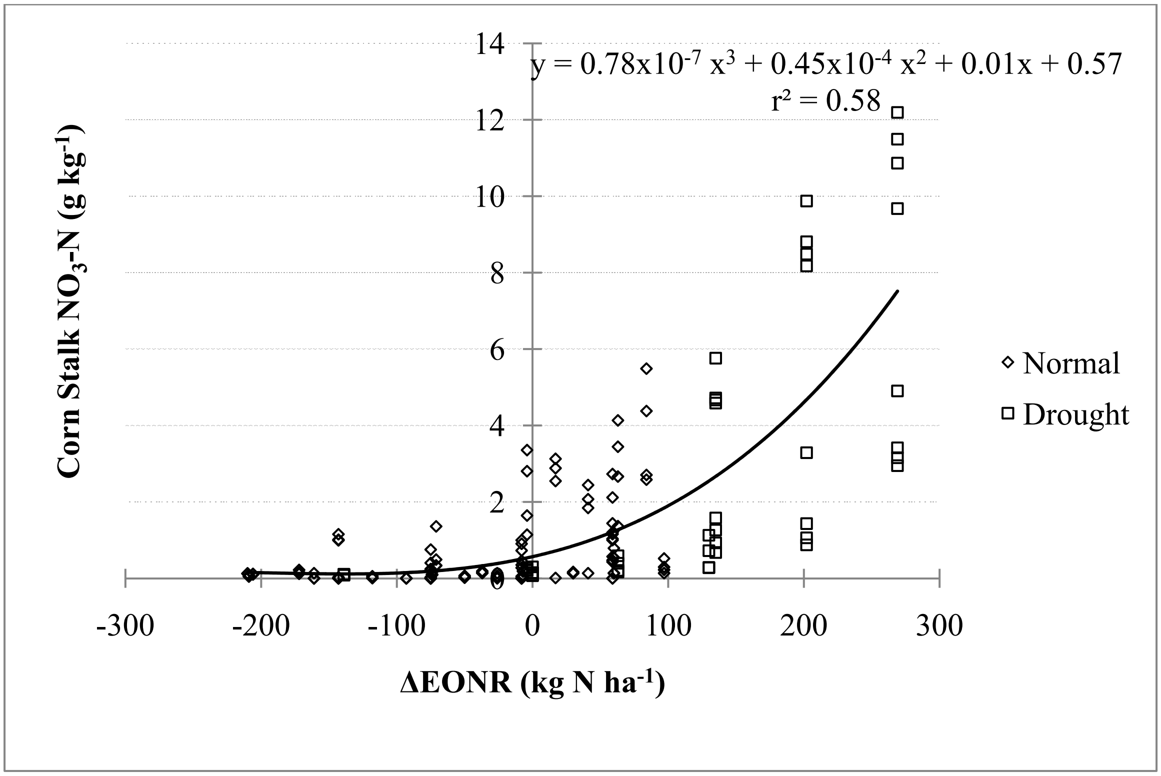


Fig. 3.6: Relationship between relative corn grain yield and relative green leaf number at and below the ear leaf collected at three times during reproductive growth (R2, R3 to R4, and R5) at four site years which did not suffer drought stress. The term relative indicates that measurements for each plot were expressed as a percentage of the average measurement from the highest fertilizer nitrogen treatment (269 kg N ha^{-1}) at each site.

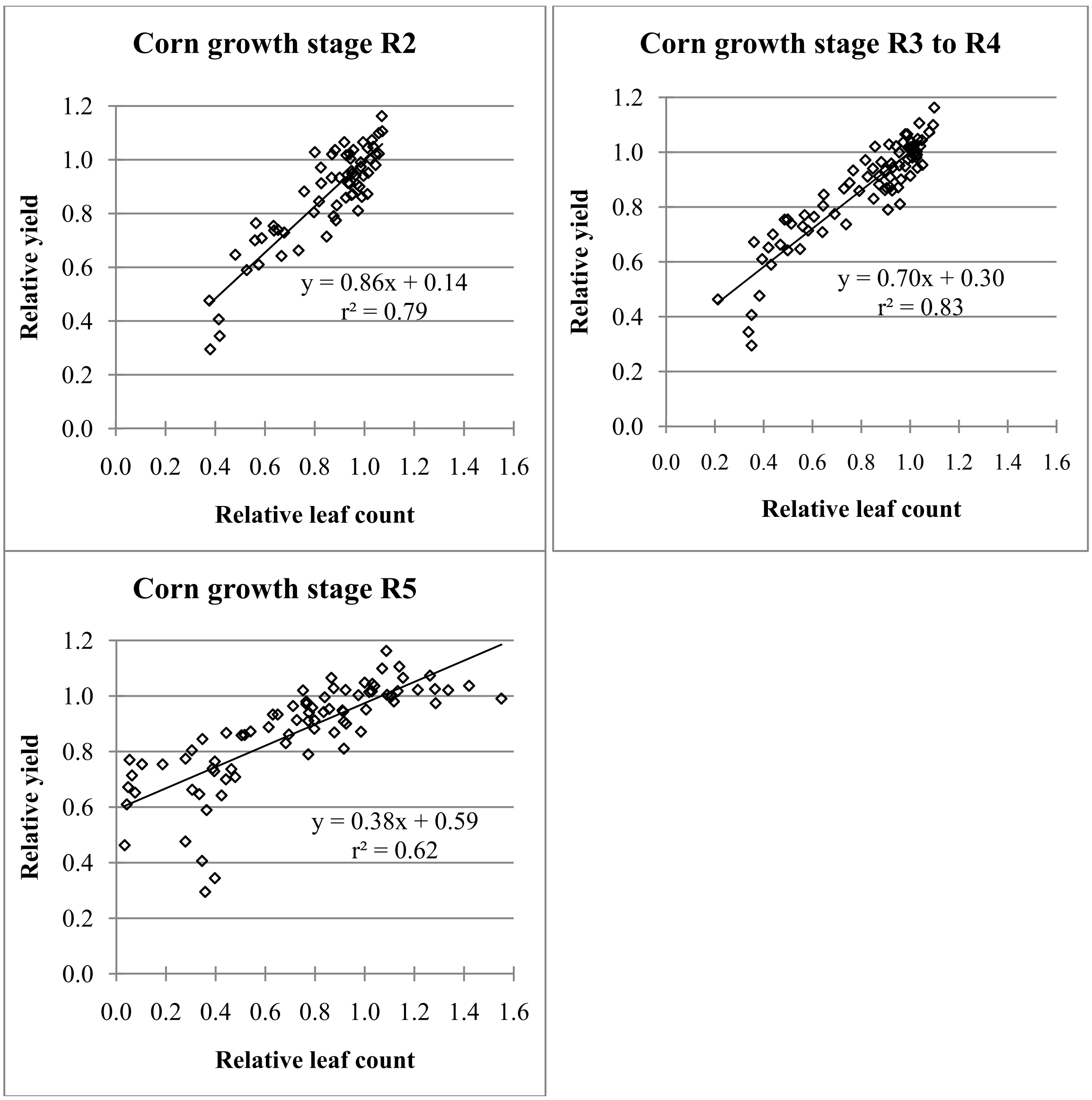


Fig. 3.7: Relationship between relative corn grain yield and relative chlorophyll meter reading (SPAD units) collected at three times during reproductive growth (R2, R3 to R4) at four site years where drought stress did not occur. The term relative indicates that measurements for each plot were expressed as a percentage of the average measurement from the highest fertilizer nitrogen treatment (269 kg N ha^{-1}) at each site.

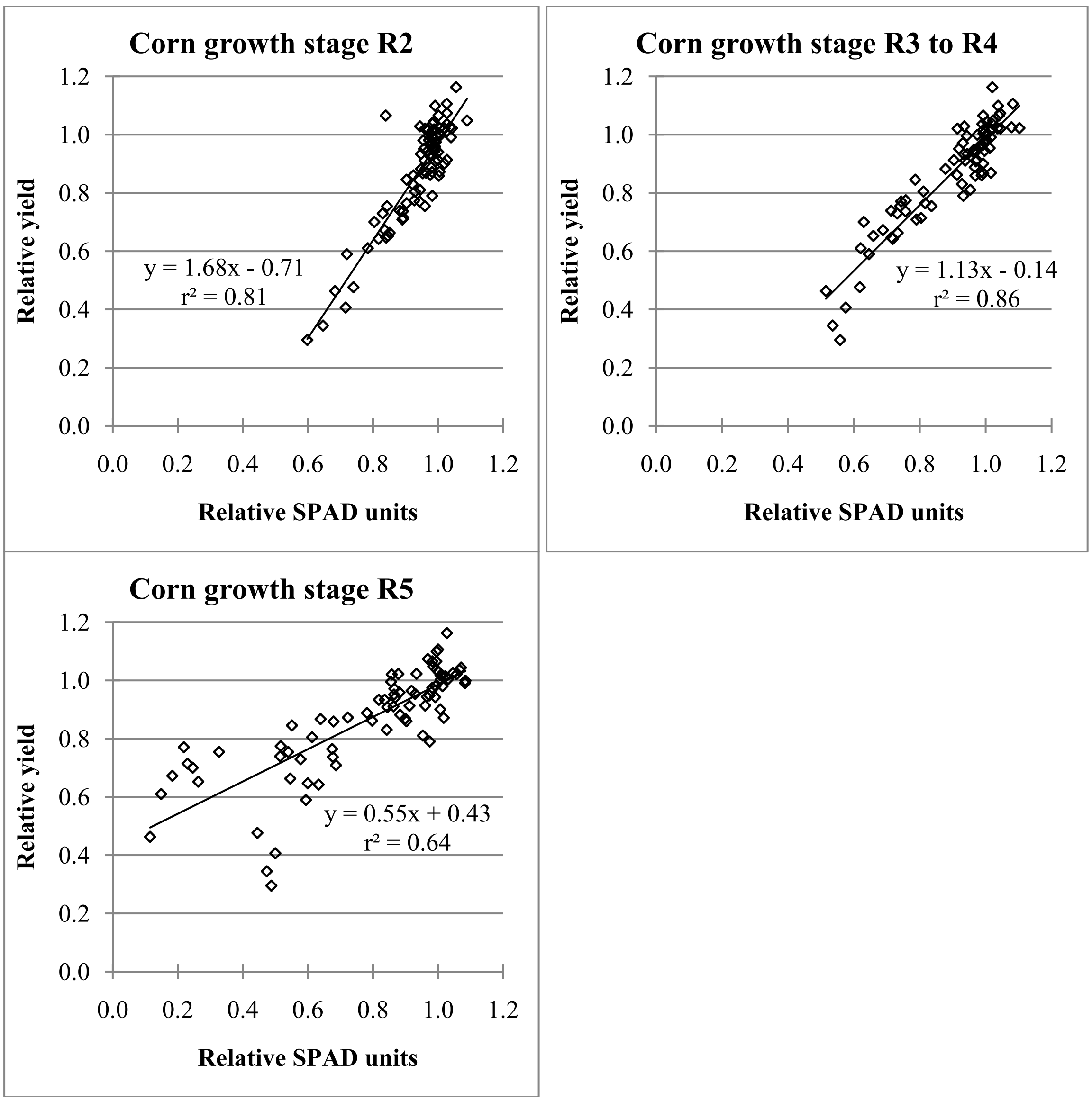


Fig. 3.8: Relationship between relative corn grain yield and relative normalized difference vegetation index (NDVI) collected at three times during reproductive growth (R2, R3 to R4, and R5) at seven site years (R2 at five site years). The term relative indicates that measurements for each plot were expressed as a percentage of the average measurement from the highest fertilizer nitrogen treatment (269 kg N ha^{-1}) at each site.

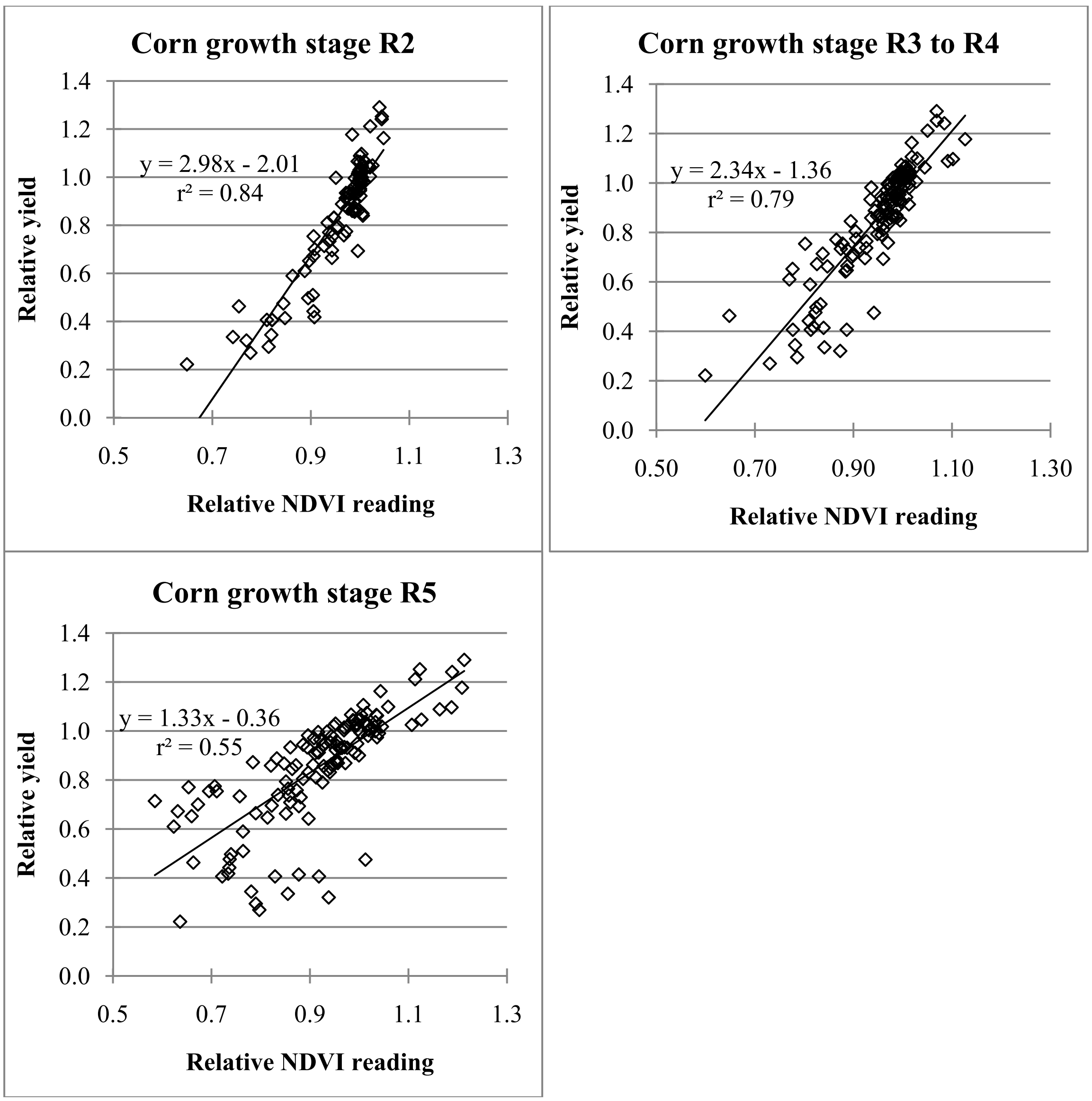
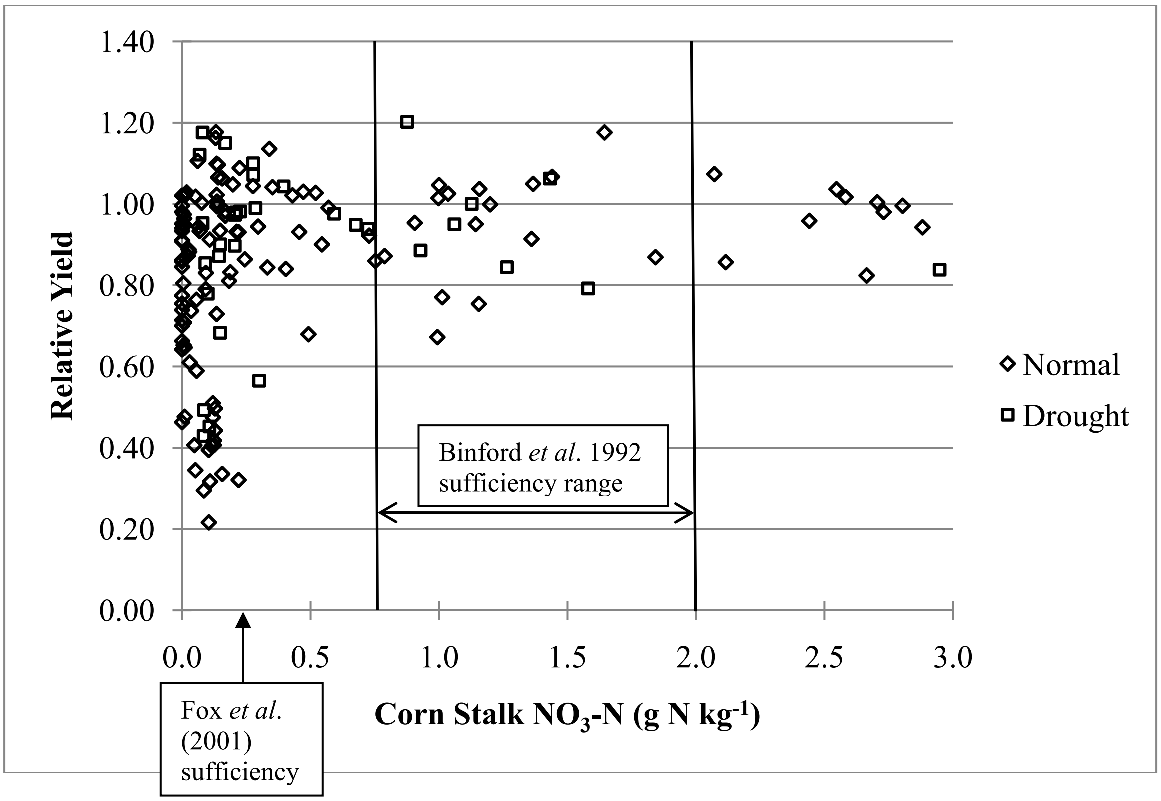


Fig. 3.9: Relationship between the corn stalk nitrate test (CSNT) and relative corn grain yield at ten site years. Relative yields were derived by expressing the yields for each plot as a percentage of the average yield from the highest fertilizer nitrogen (N) rate (269 kg N ha^{-1}) at each site.



Chapter 4: Post harvest soil residual nitrate and soil profile distribution following Mid-Atlantic corn production

Abstract

Practices which minimize nitrogen (N) loading to corn (*Zea mays* L.) have potential to reduce post-harvest N accumulation and loss. When accumulation does occur, identifying and understanding soil profile nitrate (NO_3-N) distribution patterns will be important for implementation of successful remediation strategies. The study objectives were to examine both system N loading and accumulation when applying the economic optimum nitrogen rate (EONR); to examine change from this rate (ΔEONR) as a tool for aiding NO_3-N accumulation management; and to examine soil profile distribution of residual NO_3-N. Research was conducted at sixteen site years on the Maryland Coastal Plain and Piedmont. Fertilizer N rates from 0 to 269 kg ha^{-1} were applied at the sites; grain yield was recorded; and the nitrogen sufficient yield nitrogen rate (NSYNR), the rate which maximized grain yield, and the EONR were determined. Soil NO_3-N to 30 cm depth was measured at all sites, and total inorganic N to a 60 cm depth at 10 site years. On average application of the EONR reduced fertilizer N loading by 24 kg ha^{-1}, post-harvest residual NO_3-N accumulation to 30 cm depth by 6 kg ha^{-1} (10 site years), and post-harvest residual inorganic N accumulation to 60 cm depth by 10 kg ha^{-1} (16 site years) compared with the NSYNR. However, EONR was variable across site years ranging from 0 to 256 kg N ha^{-1}. There was a strong positive correlation (r^2=0.79; n=61) between ΔEONR and residual NO_3-N present in the surface 30 cm. When fertilizer N was surface applied, residual NO_3-N accumulations tended to be most

concentrated in the surface 15 cm. However, following injection, the distribution was more uniform to 60 cm. My data demonstrates that applying the EONR can reduce system N loading, and using ΔEONR post-harvest residual N accumulation can be semi-quantitatively estimated. Residual NO_3-N was most commonly concentrated close to the surface, especially were fertilizer N is surface applied at silt loam sites. This depth distribution is helpful for post-harvest N utilization by cover crops or winter small grains.

Introduction

Corn is an important crop grown in the Mid-Atlantic States, including Maryland, where the annual corn hectarage exceeds that of any other field crop. This is significant, as corn is a high N demanding crop, frequently requiring more N to produce optimal yields than the region's soils mineralize during a growing season. Producers make up the shortfall in soil N supply by applying supplemental N as either fertilizer or manure, hence increasing system N loading. States within the Chesapeake Bay watershed have given increased emphasis to increasing N-use efficiency in corn, which will concurrently reduce N losses to the Chesapeake Bay. Each state is developing watershed management plans to implement the total maximum daily loads for N inputs to the Bay.

Nitrogen escape from agricultural systems is under focus as part of efforts to meet loss reduction goals. Maryland is to reduce its N losses from agriculture by 23% by 2017 compared with 2009 levels (Maryland Department of Environment, 2010). Applying the correct level of supplemental N to field crops will be critical to meeting this goal. Excessive N application has been linked to elevated post-harvest soil residual NO_3-N (Jokela and Randall, 1989; Vanotti and Bundy 1994; Roth and Fox, 1990; Jolley and

Pierre, 1977; Hong *et al*., 2007) and increased NO_3-N concentration in leachate (Jaynes *et al*., 2001; Baker and Johnson, 1981; Andraski *et al*., 2000). Additionally, the frequency of corn in crop rotations has been linked to residual NO_3-N accumulation (Olsen *et al*., 1970). Given the intensive N management required for corn, it has the potential to be a larger contributor to NO_3-N losses compared with soybean [*Glycine max* (L.) Merr.] (Scharf and Alley, 1994; Jaynes *et al*., 2001), the other major Mid-Atlantic field crop. Unlike soybean, corn does not have the ability to supply its N requirements. Soybean can act as a N source through biological N_2 fixation if available soil N is limited, or as a N sink if soil available N is high (Varvel and Peterson, 1990).

Growing season precipitation, particularly during the reproductive growth stages, is critical for achieving optimum corn yield (Nielsen *et al*., 2010) and consequently for total crop N uptake. Without supplemental N, wide variation in corn yields has been reported across sites and years (Meisinger *et al*., 1992; Roth and Fox, 1990; Jokela and Randall, 1989; Andraski *et al*., 2000). Variable precipitation and soil N mineralization were considered the major contributing factors to this yield variability. When producers apply fertilizer N, typically early in the vegetative corn growth stages, they do so without knowledge about moisture availability for the rest of the season. This is problematic for predicting appropriate fertilizer N rates to optimize yield and minimize N loss.

The movement of excessive N through ground water flow to surface waters, such as the Chesapeake Bay, can take many years. Residency times of water collected from springs within the Chesapeake Bay watershed ranged from modern (0-4 years) to more than 50 years (Phillips *et al*., 1999). For intensive cropping systems, such as those found on the Atlantic Coastal Plain, ground water flow is the main hydrological link to surface waters. Lag times for movement of NO_3-N through this pathway complicates efforts to assess the effects of N management practices (Boesch *et al*., 2001). However, elevated post-harvest soil residual NO_3-N levels can provide a good indicator of practices which result in excessive N availability. Roth and Fox (1990) reported that potentially polluting soil profile NO_3-N accumulations can be identified, in most cases, using a 30 cm soil sample.

Corn N management practices which minimize the pool of post-harvest residual NO_3-N are the goal. However, low post-harvest NO_3-N does not preclude the possibility of in-season leaching having occured (Gehl *et al*., 2006). In dryland corn production, however, there tends to be little NO_3-N leaching in most soils during normal corn growing seasons (Magdoff, 1991). The majority of N loss occurs during the winter recharge period. The changes in root zone NO_3-N concentration during the recharge period are dependent upon the amount of NO_3-N present in the fall and the amount of winter precipitation (Liang *et al*., 1991). Consequently, implementation of corn N management practices which minimize post-harvest residual NO_3-N accumulation reduces fall-winter NO_3-N movement into the groundwater flow system. Application of N rates to corn which approximately meet crop N demands (Olsen *et al*., 1970) and the EONR (Hong *et al*., 2007; Andraski *et al*., 2000) have been shown to minimize post-harvest NO_3-N accumulation. If NO_3-N accumulation is to be avoided completely, it may be necessary to apply less than EONR. Hong *et al*. (2007) reported that linear increases in soil residual N were initiated between 65 kg N ha^{-1} below and 20 kg N ha^{-1} above the EONR. When applied N rates are less than EONR, there is minimal N accumulation (Hong *et al*., 2007) or loss (Jaynes *et al*., 2001) compared with check treatments. However, a crucial issue in dryland corn production systems is that the determination and application of EONR, which occurs during the vegetative growth stages, is challenging due to uncertainties about precipitation during the remainder of the growing season and fluctuating corn and N prices. Many researchers have reported wide fluctuation in EONR between sites and years (Roth and Fox, 1990; Spargo, 2008; Hong *et al*., 2007; Andraski *et al*., 2000). Inevitably, even when the target is to apply the EONR, mismatches between applied N rate and the EONR will periodically occur. Therefore, corn production in the region will require additional strategies to reduce NO_3-N losses to groundwater. Planting of cover crops has been shown to be an effective tool for sequestering residual N in the Mid-Atlantic (Shipley *et al*., 1992; Coale *et al*., 2001; Dean and Weil, 2009). Corn post-harvest soil profile NO_3-N distribution may affect recovery potential by influencing the period for which NO_3-N remains within the root zone of a subsequent cover crop. Previous researchers have reported diverse soil profile distribution of post-harvest residual NO_3-N. At some sites, NO_3-N decreased with depth (e.g. Jaynes *et al*., 2001; Varvel and Peterson, 1990; Roth and Fox, 1990), was uniform throughout the profile (e.g. Liang *et al*., 1991; Roth and Fox, 1990), or was concentrated deeper in the profile (e.g. Roth and Fox, 1990).

The current study evaluates the effect of fertilizer N application amounts to corn on post-harvest residual NO_3-N pools and their distribution in the soil profile. Improving Chesapeake Bay water quality is a priority, and some of the most intensive cropping within the watershed is found on the Piedmont and Coastal Plain regions of Maryland. An assessment of corn N management practices on residual NO_3-N quantity and distribution is warranted if further N loss reduction goals are to be met.

Materials and Methods

This study was conducted at University of Maryland research and education centers located within the Coastal Plain and Piedmont regions of Maryland during five growing seasons (Table 4.1). The experimental design was a randomized complete block with four replications. The corn hybrids Pioneer '33B51' (2005 to 2007) and Pioneer '33B54' (2008 to 2009) were planted during May; both have a 113 day relative maturity. All sites were planted using a no-till drill at a seeding rate of 73 000 seeds ha^{-1} and 76 cm row spacing in late April to mid-May. In 2005, three fertilizer N rates of 84, 169, and 253 kg ha^{-1} were applied, and during the subsequent years four fertilizer N rates of 0 (67 in 2006), 135, 202, and 269 kg ha^{-1} were applied. During all years, 34 kg N ha^{-1} was applied as starter and the balance was provided as a side-dress application between corn growth stages V4 and V6 (Ritchie *et al*., 1997), except for the zero N treatment which received no fertilizer N. The fertilizer N source was liquid N (30% N as urea-ammonium nitrate solution). Fertilizer N was applied as a surface band except at Beltsville and Clarkesville in 2009 where N was injected to a 10 cm depth.

Grain yields were determined following physiological maturity by harvesting plots using a Massey Ferguson 8-XP plot combine (Kincaid Equipment Manufacturing, Haven, KS). Grain weight and moisture content were recorded by the onboard HarvestMaster data collection system (Juniper Systems, Logan, UT) as each plot was harvested. Following corn harvest, eight soil cores were collected from each plot to a depth of 60 cm (30 cm in 2005 and 2006) and divided into increments (Table 4.1) to measure the quantity and distribution of NO_3-N within the sampled soil profile. Samples were air dried at room temperature immediately following collection and were crushed to pass through a 2 mm sieve. Soil inorganic N was extracted at a ratio of 1:10 in 1 *M* KCl solution by shaking for 30 minutes using an reciprocating shaker (Eberbach Corp., Ann Arbor, Michigan), settling for 30 minutes, and filtering of supernatant liquid through grade 42 filter paper (Whatman Inc., Buckinghamshire, United Kingdom). Ammonium (NH_4-N) and NO_3-N in soil extract solutions were determined by colorimetric analysis using a continuous-flow ion analyzer (Lachat, 1986; Lachat, 1987). In 2005 and 2006, NO_3-N concentration only was determined. For those two years, NO_3-N concentration in soil extract solutions was determined using the same procedures detailed above, except the analysis was by continuous flow-ion analyzer (Technicon Industrial Systems, 1977). The mass calculation of soil profile NO_3-N and NH_4-N was conducted using the assumption that 15 cm x 1 ha soil weighs 2.24 x 10^6 Mg (i.e. assuming a soil bulk density of 1.49 g cm^{-3}).

Using the PROC NLIN procedure of SAS version 9.2 (SAS Institute, Cary, NC), a quadratic-plateau model was fitted to describe corn yield response to fertilizer N at each site year individually. These functions were used to determine the NSYNR and the EONR for each site. A price ratio of fertilizer N to corn of 7.2 kg kg^{-1} (\$0.147 kg^{-1} corn, \$1.062 kg^{-1} N) was used to calculate EONR. These prices represented average Maryland corn prices and national fertilizer N prices during the study period (USDA, 2010a; USDA, 2010b). At sites that did not respond to application of fertilizer N, as determined by analysis of variance using the mixed models procedure of SAS, zero was assigned as the EONR and the NSYNR. A quadratic-plateau model could not be fitted to the yield data from the Beltsville site in 2009 (Table 4.4). For this site fertilizer rates greater than 135 kg N ha^{-1} did not increase grain yields so the 135 kg N ha^{-1} rate was selected as

NSYNR and EONR. To determine the effect of corn N fertilization and depth on post-harvest soil residual NO_3-N at each site, repeated measures analysis was conducted using the mixed models procedure of SAS. The default error covariance structure (variance components) which assumes independent and identically distributed errors was used. In all cases means were determined using the lsmeans option of the mixed model procedure.

Results and Discussion

Corn grain yield

Corn grain yields increased significantly in response to fertilizer N application at all sites in 2005 and 2006 (Tables 4.2 and 4.3). From 2007 to 2009, a check treatment (0 kg N ha^{-1}) was included (Table 4.4). At the majority of sites, grain yield responded positively to application of fertilizer N, indicating that N fertilization was generally required to optimize yields. However, at two sites (Beltsville 2007 and Clarksville 2008), no significant yield response to fertilizer N application was detected (Table 4.4). The lack of yield response is attributable to growing season drought stresses (Figs. 4.2 and 4.4) that coincided with the period prior to tassel initiation through grain fill, which commonly occurs in mid-July in Maryland. Precipitation during this period is highly correlated with corn grain yield (Nielsen *et al*., 2010). As evidenced by data from the present study, drought conditions in the region result in corn grain yield reductions and, in some years and sites, optimum N rates of zero. Reduced or poor yield response to fertilizer N under drought conditions indicate potential for large mismatches between applied fertilizer N rates and optimum rates for grain yield in the Mid-Atlantic. Fertilizer

N not taken up by the corn crop will increase the potential for post-harvest residual NO_3-N accumulation and loss.

In 2007, precipitation patterns and totals were similar at the Beltsville and Wye sites (Figs. 4.1 and 4.2). However, at Wye, corn grain yield responded to application of fertilizer N but at Beltsville no response was observed. This outcome is important for efforts to closely match applied N rates to corn N demand, as it indicates potential for larger mismatches between optimum and applied corn fertilizer N rates at sites with coarser soil texture. This may be related to lower water holding capacity at coarser textured sites.

Corn grain yields where no N was applied were variable, ranging 1.9 to 5.2 Mg ha^{-1} (Table 4.4) for sites without manure history. Such fluctuation is consistent with variability in check yields reported by other researchers (Meisinger *et al*., 1992; Jokela and Randall, 1989). Only the Clarksville site in 2009 had previous manure history (although none was applied in the study year), and at this site the yield for the check (10.6 Mg ha^{-1}) was more than double the highest check yield for any other site. Higher check yields due to manure history have also been reported by others (Roth and Fox, 1990; Andraski *et al*., 2000). At sites such as these, use of the pre-sidedress nitrate test has been advocated in Maryland to account for higher N mineralization (Meisinger *et al*., 1992).

Environmental benefit of applying the economically optimum nitrogen rate

Application of the EONR reduced N loading compared with the rate which maximized grain yield, the NSYNR. On average, the EONR was 27 kg ha^{-1} lower than the NSYNR for sites which responded to fertilizer N (24 kg N ha^{-1} for all sites). This indicates that applying the EONR can reduce N loading to corn production systems within the Chesapeake Bay watershed without negatively affecting profitability. Reduced fertilizer N loading to the production system suggests that the pool of post-harvest residual NO_3-N will also be reduced compared with yield maximizing N rates. Across sites, applying the EONR reduced residual inorganic N in the surface 60 cm by 10 kg N ha^{-1} (2007 to 2009) and residual NO_3-N in the surface 30 cm by 6 kg N ha^{-1} (2005 to 2009) compared with applying the NSYNR (Figs. 4.5, 4.6, 4.7 and 4.8). Similarly, Hong *et al*. (2007) reported that application of the EONR in Missouri reduced residual NO_3-N by at least 12 kg N ha^{-1} in the surface 90 cm compared with producer N rates, which in some instances substantially exceeded the NSYNR.

Residual inorganic N to 60 cm depth was on average 18 kg N ha^{-1} greater than the check treatments following application of the EONR (data not shown). However, where the applied N rate was less than the EONR (ΔEONR < 0), residual NO_3-N levels were typically less than 30 kg ha^{-1} to 30 cm depth (Fig. 4.8). This is consistent with high N use efficiency at ΔEONR < 0. As the applied fertilizer N rate approached the EONR variability in residual NO_3-N levels increased (Fig. 4.8). When ΔEONR exceeded zero, both residual NO_3-N level and variability increased, an outcome that has also been observed by others (Hong *et al*., 2007; Andraski *et al*., 2000). The data presented in Figs. 4.6 and 4.8 indicates that sites where ΔEONR < 0 tend to have lower residual N levels compared with sites where ΔEONR > 0. Similarly, other researchers (Roth and Fox, 1990; Jolley and Pierre, 1977) reported that N accumulation increased rapidly at higher N rates. This is important because the amount of fertilizer N applied, the amount of fall residual NO_3-N, and the amount of winter precipitation are important factors which influence NO_3-N carryover or loss (Liang *et al*., 1991; Jokela and Randall, 1989; Meisinger *et al*., 1987). Therefore, practices which minimize residual N accumulation, such as application of N rates that are not excessive (a result that can occur using the EONR), can limit N loading to corn production systems. This approach will minimize the post-harvest soil residual inorganic N pool, which otherwise may be lost to ground water flow pathways that link to the Chesapeake Bay.

While applying the EONR is both economically and environmentally beneficial, fluctuating corn yields caused by variable precipitation inevitably lead to mismatches between applied N rate and EONR in dryland corn production. In this study, the EONR was variable across sites and years ranging from 0 to 256 kg N ha^{-1} (Tables 4.2, 4.3, and 4.4). At two sites, drought reduced the EONR to zero. Under such conditions, elevated post-harvest soil residual NO_3-N levels are likely, even when N is applied conservatively. Similarly, other researchers in the region (Roth and Fox 1990; Spargo 2008) have reported wide fluctuation in EONR. Additional variability in the EONR arises from seasonal variability and imperfect forecasts of corn and fertilizer prices, while research studies typically examine the EONR using previously observed average prices. The average ratio of corn price to fertilizer N price was 7.2 kg kg^{-1} during the present study period, and this was used to calculate EONR. The ratios reported by other researchers during their study periods are variable, and provide evidence of common price fluctuation. For example, the corn price to fertilizer N ratios were 5.6 kg kg^{-1} for Roth and Fox, 1990; 3.4 kg kg^{-1} for Andraski *et al*., 2000; 6.9 kg kg^{-1} for Hong *et al*., 2007; 7.4 kg kg^{-1} for Spargo, 2008).

Given the observed variability in the EONR for dryland corn production systems, it is almost inevitable that optimum N rates will be exceeded in some growing seasons, as N applications are completed during the early-mid vegetative growth stages. Exceeding the NSYNR and/or the EONR is a strong indication of increased post-harvest residual N accumulation (Figs. 4.5, 4.6, 4.7, and 4.8). Such residual N is at risk of movement through subsurface flow to the Chesapeake Bay. Maryland has proposed to increase to fall plantings of commodity small grains and traditional cover crops to sequester N, which is aimed at reducing over winter N losses (Maryland Department of Environment, 2010). Fisher (2010) reported N uptake by no-till winter wheat (*Triticum aestivum*, L.) was highest following corn where yields were reduced by drought conditions. They attributed this to substantial residual N availability because of poor N recovery by the corn crop. This suggests that identification and targeting of sites with elevated post-harvest residual N for mitigation practices could play a critical role in reducing N leaching to ground water flow pathways that feed the Chesapeake Bay.

Identifying sites with elevated post-harvest residual nitrogen

Targeting cover crop plantings, to include sites which have high residual NO_3-N, could reduce N losses from corn cropping systems. Roth and Fox (1990) reported that in most cases excess soil profile N accumulation can be detected using a 30 cm post-harvest soil sample. However, sampling and analysis is time consuming, requiring considerable labor input and is expense on a large scale. Using ΔEONR as an indicator of site residual N could provide a less labor intensive alternative. In this study, ΔEONR provided a strong indication of post-harvest soil residual inorganic N to a depth of 60 cm [r^2=0.81, n=40 (Fig. 4.6)] and of soil NO_3-N quantity in the surface 30 cm [r^2=0.79, n=61 (Fig.

4.8)]. Similarly, Andraski *et al*. (2000) reported ΔEONR to be a strong predictor of residual NO_3-N in the surface 90 cm in Wisconsin (r^2=0.88) but with considerably fewer data points (n=16). These data indicate that ΔEONR could be used as an indicator of residual NO_3-N. Most producers have ready access to site N application rate and grain yield information. This information could be used to calculate ΔEONR, which has been shown in this study to be highly correlated with post-harvest residual N across a range of soil textures and growing seasons in Maryland. Using ΔEONR may provide a more attractive and efficient method of identifying sites with elevated post-harvest residual N compared with soil sampling.

Identifying the economically optimum nitrogen rate at producer sites

A drawback to using the ΔEONR approach for predicting residual NO_3-N is the requirement to identify the EONR for each site annually, which would require the establishment of fertilizer N response strips. Although producers can easily vary N rates, they do not universally harvest using combines with yield monitoring capabilities. This may limit the ability to glean yield data from N response test strips. Producers do, however, generally know the fertilizer N rate they are applying and a field's grain yield. This information can be used to calculate the fertilizer N to grain yield ratio (kg Mg^{-1}). During this study the ratio was remarkably stable for N response sites which did not have a history of manure application (Tables 4.2, 4.3, and 4.4). On average, this ratio was similar for medium (silt loam) and lighter (sandy) textured sites (20.2 kg Mg^{-1} and 20.8 kg Mg^{-1}, respectively). This is similar to the University of Maryland recommendation of approximately 17.9 kg Mg^{-1} for corn production (Coale, 2002). The ratio was slightly more variable for sandy textured sites, ranging from 15.8 to 24.8 kg Mg^{-1}, compared with to silt loam sites where the ratio ranged from 17.0 to 24.0 kg Mg^{-1}.

The Clarksville 2009 site had a history of manure application, although none was applied in the study year. At this site, the ratio of fertilizer N applied to achieve economically optimal corn grain yield was 10.3 kg Mg^{-1}, much lower than for the other sites. This was likely due to increased growing season N mineralization from organic residues. The ratio ranged from 0 to 9.3 kg Mg^{-1} for non-drought sites with manure history in Pennsylvania when calculated from the data of Roth and Fox (1990) and was, on average, higher where no manure had been applied (15.1 kg Mg^{-1}). This indicates that site manure history is an important factor influencing N requirement. Lower ratio values may be expected at sites with manure history compared with those without.

Two study sites did not respond to application of fertilizer N (Table 4.4) due to drought conditions. Consequently, the ratio of fertilizer N to grain yield at EONR was 0 kg Mg^{-1}. As corn is rarely grown without fertilizer N (Spargo, 2008), the lack of fertilizer N response is likely to lead to significant mismatches between optimum and applied N rates. At the Beltsville site, if the average EONR from the four N response seasons (173 kg N ha^{-1}) was applied, the ratio would have been 48 kg Mg^{-1}. At the Clarksville site that experienced drought conditions, if the lowest N rate (135 kg ha^{-1}) was the application amount, the ratio would have been 30 kg Mg^{-1}. Both of these ratios are above the optimal ratio range discussed above, and thus would indicate elevated potential for residual NO_3-N accumulation. Post-harvest fertilizer N to corn grain yield ratios which exceed the University recommended ratio (17.9 kg Mg^{-1}) indicated increased potential for elevated post-harvest residual NO_3-N accumulation (Fig. 4.9)

For N response sites without manure history, a fertilizer N rate to corn grain yield ratio ranging from 16 to 25 kg Mg^{-1} indicated that EONR was applied at these study sites. However, tighter ranges for this ratio may be appropriate for individual producer sites or regions. For instance, the ratio at Wye (silt loam) ranged from 17 to 20.3 kg Mg^{-1} at the EONR over 5 growing seasons. The lower ratio observed at the Clarksville site in 2009 indicates that manure history is an important factor affecting supplemental N requirements for corn, a conclusion supported by the data of Roth and Fox (1990). More research is needed to ascertain if it is possible to determine an appropriate guideline ratio for fertilizer N to grain yield at the EONR for these sites.

Depth distribution of post-harvest soil residual nitrate

Sandy textured Coastal Plain sites (Beltsville)

At the 2007 and 2008 Beltsville sites, a significant depth by N rate interaction for soil NO_3-N concentration was detected reflecting the varying magnitude of the change in soil NO_3-N concentration with increasing depth for the applied corn N rates (Fig. 4.10). Fertilizer N was surface applied in both years. In contrast, in 2009, no depth effect was detected, and soil NO_3-N concentration was similar throughout the sampled soil profile (Fig. 4.10). Here, the surface soil texture was a loamy sand, and fertilizer N was injected to a 10 cm depth. Injection of fertilizer N may have contributed to relatively uniform NO_3-N concentrations within the sampled soil profile in 2009, as precipitation totals were similar to those received in 2008 (Fig. 4.2). Sandy textured sites have been shown to be susceptible to downward NO_3-N movement in the soil profile during the growing season (Hahne *et al.,* 1977; Endelman *et al*., 1974; Gehl *et al*., 2006). In the present study, post-harvest residual NO_3-N tended to be concentrated close to the surface when fertilizer N, which is a positive finding for efforts to sequester N using cover crops.

At the Beltsville sites, application of fertilizer N significantly increased residual NO_3-N concentration, particularly close to the surface (Fig. 4.10). No fertilizer N response was observed at the Beltsville site in 2007 (Table 4.1). Consequently, the EONR was zero, and high levels of post-harvest residual NO_3-N were present, particularly following the high fertilizer N rates (Fig. 4.9). This difference was attributed to the lack of fertilizer N yield response caused by severe drought in 2007 (Fig. 4.2). In both 2008 and 2009, the N fertilization effect was also significant at all sampling depths. However, the levels were much lower compared with 2007 when drought reduced production.

Silt loam textured Coastal Plain sites (Wye and Poplar Hill)

At both the Wye and Poplar Hill sites, fertilizer N was surface applied in all cases. At Wye, a significant depth by N rate interaction for soil NO_3-N concentration was detected in both 2007 and 2008 (Fig. 4.11). The depth effect was significant at each site and year for some or all of the corn N treatments (Fig. 4.11). These data collected over growing seasons with a range of precipitation totals (Figs. 4.2 and 4.3) demonstrate that post-harvest residual NO_3-N is concentrated close to the surface, which indicates that little downward movement of NO_3-N occurs during the corn growing season at silt loam sites. The tendency for post-harvest residual NO_3-N to be concentrated close to the surface, even when present at high concentration, is consistent with the reports of others (Shipley *et al*., 1992; Jaynes *et al.*, 2001; Roth and Fox, 1990). Jaynes *et al*. (2001) reported that more than half of the residual NO_3-N recovered post-harvest to a 120 cm depth was present in the surface 30 cm. Roth and Fox (1990) reported that for nine of eleven sites in Pennsylvania, soil NO_3-N decreased with depth regardless of manure history.

With the exception of Wye in 2007, corn grain yield response to fertilizer N was good (Tables 4.2, 4.3, and 4.4). As a result, the EONR was relatively high, ranging from 172 to 256 kg ha^{-1} (Table 4.4). Nevertheless, a significant N fertilization effect on post-harvest residual NO_3-N levels in the surface 30 cm was observed at all these sites except for Wye in 2009; here, N fertilization only had an effect on soil NO_3-N in the surface 15 cm (Fig. 4.11). Unlike the sandy textured sites discussed above, N fertilization had no significant effect on post-harvest residual NO_3-N levels from 30 to 60 cm depth at the silt loam sites. Although Poplar Hill and Wye in 2007 were very similar in terms of soil characteristics (Table 4.1), the levels of post-harvest residual NO_3-N in the surface 30 cm were dramatically different. This is attributable to the season-long moisture stress conditions which were experienced at Wye but not at Poplar Hill; Wye received 44% less rainfall compared with Poplar Hill (Figs. 4.2 and 4.3).

A significant N fertilization effect was observed in the surface 30 and/or 15 cm soil depth at these sites (Fig. 4.10). However, with the exception of Wye in 2007, where grain yields were reduced due to drought, the increases tended to be minor, especially for the 135 kg N ha^{-1} rate. This rate was in all cases below the EONR, indicating that yield response to the applied rate is an important factor determining residual NO_3-N accumulation.

Silt loam textured Piedmont sites (Clarksville)

The Clarksville site experienced drought conditions in 2008. Although May to September rainfall was 437 mm at Clarksville (Fig. 4.4), only 149 mm fell from June to August. As a result, the corn crop suffered moisture limitation during the most sensitive period: tasseling through grain fill, which was shown by Nielsen *et al*. (2010) to be critical for grain yield. As a result, no yield response to fertilizer N application was observed (Table 4.4); consequently, the EONR was zero. A significant depth by N rate interaction for soil NO_3-N concentration was detected (Fig. 4.12). This interaction was also detected at Coastal Plain sites which suffered drought conditions. At Clarksville in 2009, no depth effect on residual soil NO_3-N concentration was observed. No other silt loam or sandy textured site exhibited this trend, with the exception of the Beltsville site in 2009. The lack of a depth effect at these sites is attributed to injection of fertilizer N to a 10 cm depth.

In 2008 at Clarksville, a significant N fertilization effect was detected but only in the surface 30 cm, despite relatively large NO_3-N accumulation. This pattern of accumulation is similar to that observed at Wye in 2007. A significant fertilizer N effect was observed in 2009, but in this year the effect was significant throughout the sampled soil profile. This site was the only silt loam site in the study at which a significant N fertilization effect was detected at the 30 to 60 cm depth, which may be linked to injection of fertilizer N.

No significant corn N fertilization effect on soil NO_3-N concentration (30 to 60 cm depth) was detected at the silt loam sites where N was surface applied (Figs. 4.11 and 4.12). This was the case even when surface soil NO_3-N concentration was high, such as at Wye in 2007. However, at the sandy textured soils of Beltsville, a significant corn N fertilization effect on soil NO_3-N concentration was detected at all sampling depths (Fig. 4.9). This supports the findings of Hahne *et al*. (1977), who reported that vertical accumulation of residual NO_3-N is highly dependent on soil type. They reported greater NO_3-N losses from a fine sandy loam compared with either silt loam or clay loam soils. They suggested that NO_3-N movement to ground water as a result of continuous corn production is likely, with increasingly pronounced effects at higher N rates on sandy textured sites. Endelman *et al*. (1974) also reported that sandy textured sites were susceptible to rapid downward movement of NO_3-N at modest water percolation rates. Data from the present study indicates greater potential for NO_3-N migration out of the root zone during the growing season at sandy textured sites compared with silt sites in Maryland. This, combined with greater drought susceptibility due to lower moisture holding capacity, indicates that annual N loss risk may be higher at sandy textured sites compared with finer textured sites. Nevertheless, a greater proportion of residual NO_3-N was generally concentrated close to the surface. This is important because NO_3-N located closer to the surface may remain within the root zone of subsequent cover crops for a longer period compared with NO_3-N concentrated deeper in the soil profile.

Conclusions

Application of corn fertilizer N rates less than the EONR minimized accumulation of residual N. However, in the Mid-Atlantic, the EONR for dryland corn production is variable, and because N is applied during the early vegetative growth stages, mismatches between EONR and applied N rate will occur periodically. At sites where fertilizer N was surface applied, residual N was concentrated closer to the surface, which is positive for sequestration by subsequent commodity or cover crops. However, greater downward migration of NO_3-N was observed by the end of the growing season at sandy textured sites compared with silt loam sites. This, combined with the greater drought susceptibility of sandy textured sites, indicates greater annual N loss potential. Consequently, the use of tools and practices to improve N management and sequester residual N will be particularly important in reducing N losses to the Chesapeake Bay at coarser textured sites.

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Table 4.1: Study locations, soil characteristics, and sampling increments for the 16 site years at which this research was conducted.

Site	Year	Latitude	Longitude	Soil taxonomy	Soil series and surface soil texture†	Soil sampling increments (cm)	Plot size (m)
Upper Marlboro	2005	38° 51' 29" N	76° 46' 30" W	Aquic Hapludults	Donlonton fsl	0-30	12.2 x 9.1
Upper Marlboro	2006	38° 51' 39" N	76° 46' 29" W	Aquic Hapludults	Russett-Christiana fsl	0-15, 15-30	12.2 x 9.1
Beltsville	2005	39° 01' 30" N	76° 50' 29" W	Aquic Hapludults	Adelphia-Holmdel fsl	0-30	12.2 x 9.1
Beltsville	2006	39° 01' 31' N	76° 50' 26" W	Aquic Hapludults	Russett-Christiana fsl	0-15, 15-30	12.2 x 9.1
Beltsville	2007	39° 01' 33" N	76° 50' 31" W	Aquic Hapludults	Hammonton ls	0-15, 15-30, 30-60	12.2 x 9.1
Beltsville	2008	39° 00' 45" N	76° 49' 43" W	Typic Hapludults-Aquic Hapludults	Downer-Hammonton ls	0-15, 15-30, 30-60	15.2 x 9.1
Beltsville	2009	39° 00' 35" N	76° 49' 46" W	Aquic Hapludults	Russett-Christiana fsl	0-15, 15-30, 30-60	18.3 x 9.1
Clarksville	2008	39° 15' 53" N	76° 55' 49" W	Aquic Fragiudults	Glenville sl	0-15, 15-30, 30-60	15.2 x 6.1
Clarksville	2009	39° 15' 03" N	76° 55' 50" W	Typic Hapludults	Glenelg l	0-15, 15-30, 30-60	15.2 x 6.1
Wye	2005	38° 54' 41" N	76° 08' 48" W	Typic Hapludults	Nassawango sl	0-30	12.2 x 9.1
Wye	2006	38° 54' 38" N	76° 08' 48" W	Typic Hapludults	Nassawango sl	0-15, 15-30	12.2 x 9.1
Wye	2007	38° 54' 42" N	76° 08' 38" W	Typic Hapludults	Nassawango sl	0-15, 15-30, 30-60	12.2 x 9.1
Wye	2008	38° 54' 45" N	76° 08' 42" W	Typic Hapludults	Nassawango sl	0-15, 15-30, 30-60	15.2 x 9.1
Wye	2009	38° 54' 34" N	76° 08' 49" W	Aquic Hapludults-Typic Hapludults	Mattapex Nassawango sl	0-15, 15-30, 30-60	18.3 x 9.1
Poplar Hill	2007	38° 21' 28" N	75° 46' 51" W	Typic Hapludults	Nassawango sl	0-15, 15-30, 30-60	12.2 x 9.1
Poplar Hill	2008	38° 21' 26" N	75° 46' 52" W	Typic Hapludults	Nassawango sl	0-15, 15-30, 30-60	15.2 x 9.1

† Texture: fsl, fine sandy loam; ls, loamy sand; sl, silt loam; l, loam.

Table 4.2: Corn grain yields, the economic optimum nitrogen rate (EONR), the nitrogen sufficient yield nitrogen rate (NSYNR) which maximized grain yield, and the fertilizer N to grain yield ratio at EONR for 2005 sites.

	Fertilizer N kg ha^{-1}							Fertilizer N : Grain yield at EONR
Site	75	168	252	EOY†	NSY‡	EONR	NSYNR	
	Mg ha^{-1}					kg N ha^{-1}		kg Mg^{-1}
Beltsville	7.3b§	9.7a	10.0a	9.9	10.0	185	204	18.7
Upper Marlboro	7.6c	11.1b	12.2a	12.2	12.2	228	248	18.7
Wye	8.3b	10.6a	10.9a	10.8	10.9	188	210	19.4

† EOY: Economically optimal yield.
‡ NSY: Nitrogen sufficient yield.
§ Means in each row with different lettering are significantly different at $p \leq 0.05$.

Table 4.3: Corn grain yields, the economic optimum nitrogen rate (EONR), the nitrogen sufficient yield nitrogen rate (NSYNR) which maximized grain yield, and the fertilizer N to grain yield ratio at EONR for 2006 sites.

Site	68	135	202	269	EOY†	NSY‡	EONR	NSYNR	Fertilizer N : Grain yield at EONR
	——Fertilizer N kg ha^{-1}——								
	——Mg ha^{-1}——						——kg N ha^{-1}——		kg Mg^{-1}
Beltsville	6.8b§	9.4a	10.4a	10.5a	10.4	10.4	164	176	15.8
Upper Marlboro	6.2c	7.8b	9.2a	8.9b	8.9	9.0	202	236	22.7
Wye	7.9c	10.0b	11.3a	11.8a	11.6	11.8	235	275	20.3

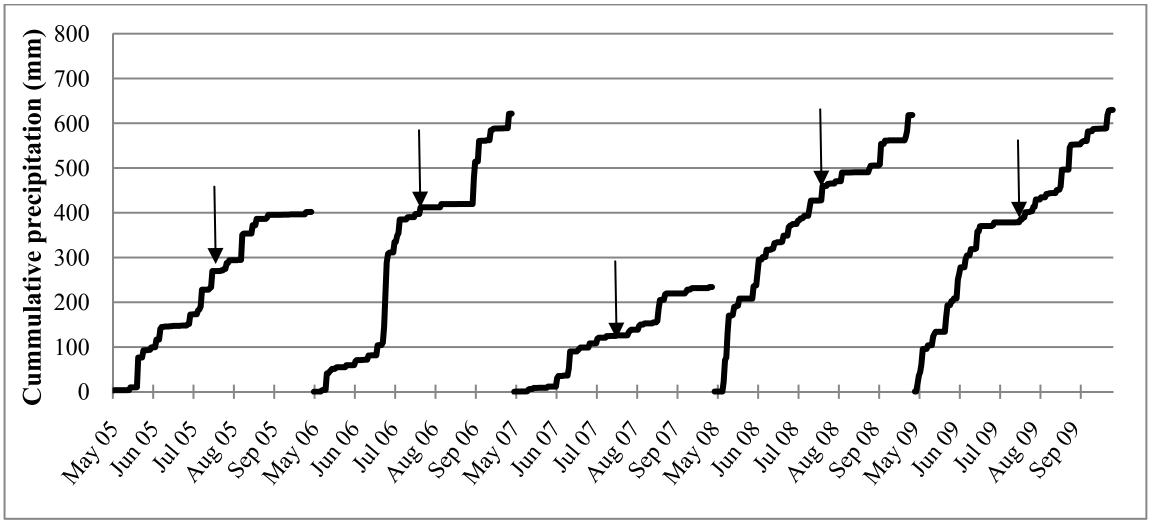
† EOY: Economically optimal yield.
‡ NSY: Nitrogen sufficient yield.
§ Means in each row with different lettering are significantly different at $p \leq 0.05$.

Table 4.4: Corn grain yields, the economic optimum nitrogen rate (EONR), the nitrogen sufficient yield nitrogen rate (NSYNR) which maximized grain yield, and the fertilizer N to grain yield ratio for 2007 to 2009 sites.

Site and year	0	135	202	269	EOY†	NSY‡	EONR	NSYNR	Fertilizer N:Grain yield at EONR
	Fertilizer N kg ha^{-1}								
	Mg ha^{-1}						kg N ha^{-1}		kg Mg^{-1}
Beltsville ‘07	3.6a§	3.9a	3.7a	3.5a	3.6	3.6	0	0	0
Beltsville ‘08	2.9b	6.7a	9.7a	7.9a	8.4	8.5	206	243	24.5
Beltsville ‘09	1.9b	5.6a	4.7a	4.5a	5.6	5.6	135	135	24.1
Wye ‘07	3.8b	7.0a	7.3a	7.1a	7.1	7.2	139	168	19.6
Wye ‘08	5.2b	10.0a	11.0a	11.2a	11.1	11.2	210	246	18.9
Wye ‘09	4.2c	12.4b	14.1a	15.2a	15.1	15.2	256	281	17.0
Poplar Hill ‘07	3.7b	7.8a	8.5a	8.9a	8.7	8.9	209	254	24.0
Poplar Hill ‘08	2.9b	7.3a	8.0a	7.7a	7.7	7.8	172	202	22.3
Clarksville ‘08	3.9a	4.5a	4.6a	5.1a	3.9	3.9	0	0	0
Clarksville ‘09	10.6b	13.5a	13.7a	13.7a	13.6	13.7	140	175	10.3

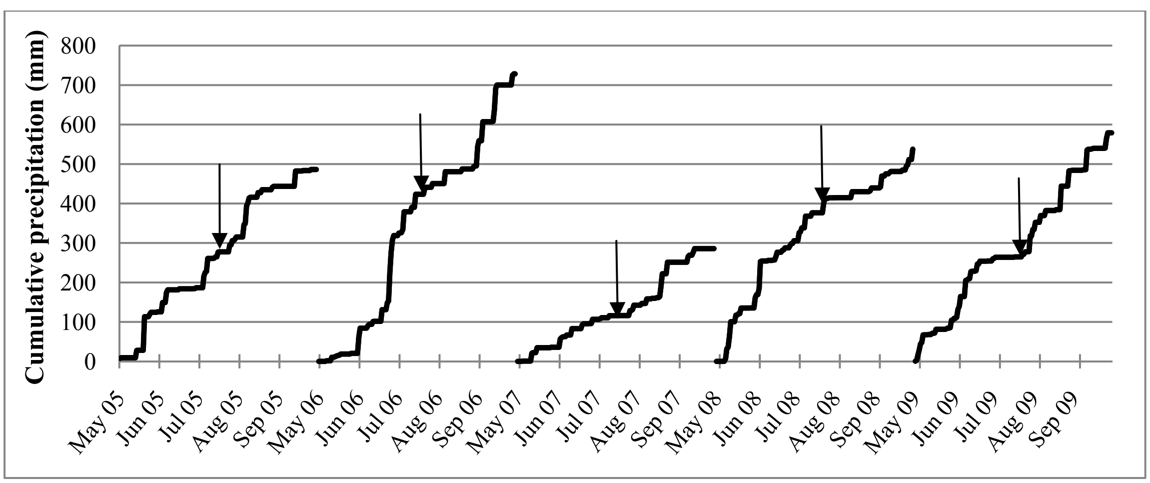
† EOY: Economically optimal yield.
‡ NSY: Nitrogen sufficient yield.
§ Means in each row with different lettering are significantly different at $p \leq 0.05$.

Fig. 4.1: Cumulative growing season precipitation (May-September) by year at Beltsville during the study period.



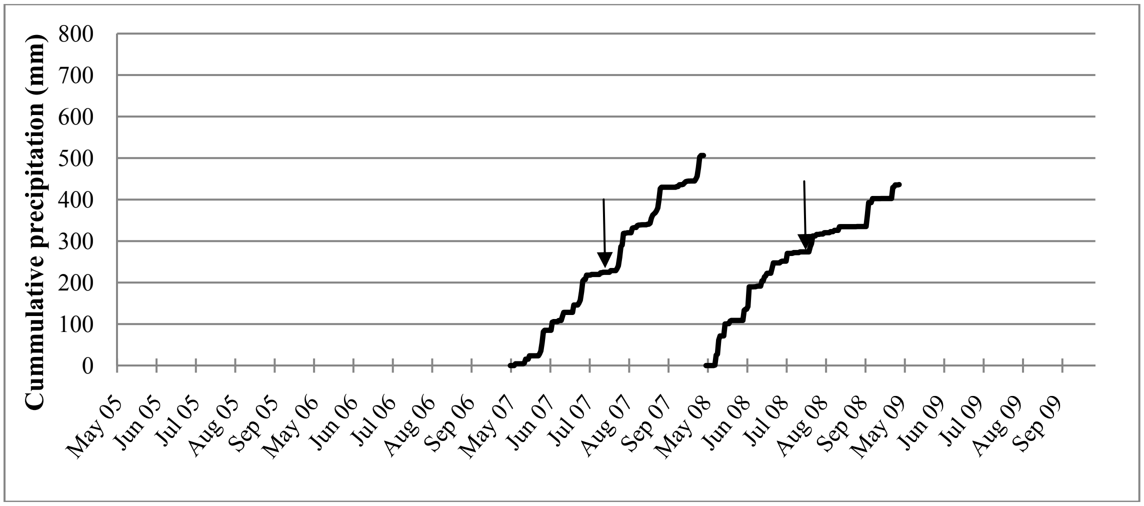
Arrows indicate the approximate timing of tasseling and pollination of corn.

Fig. 4.2: Cumulative growing season precipitation (May-September) by year at Wye during the study period.



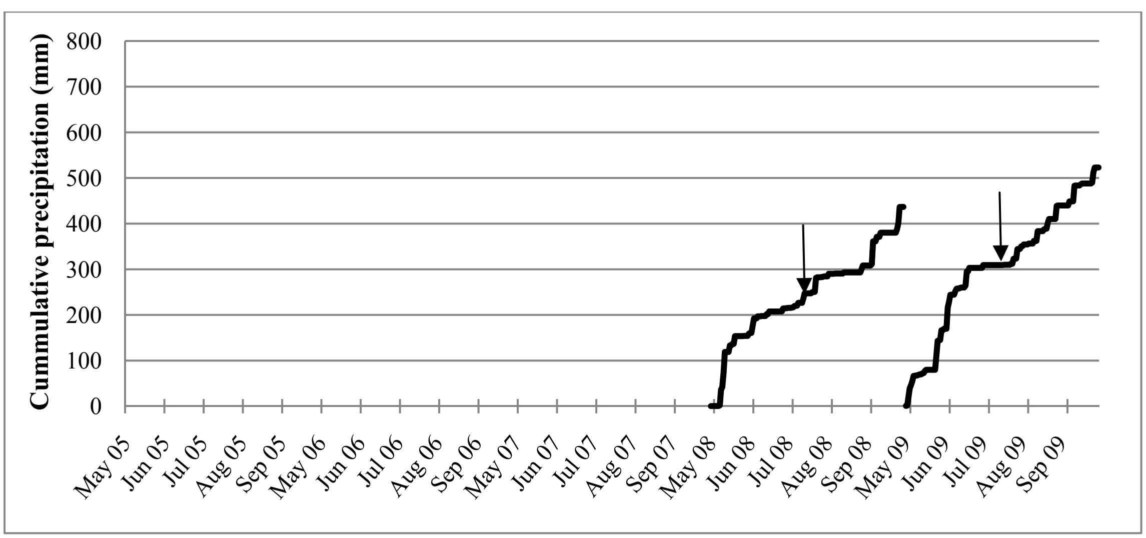
Arrows indicate the approximate timing of tasseling and pollination of corn.

Fig. 4.3: Cumulative growing season precipitation (May-September) by year at Poplar Hill during the study period.



Arrows indicate the approximate timing of tasseling and pollination of corn.

Fig. 4.4: Cumulative growing season precipitation (May-September) by year at Clarksville during the study period.



Arrows indicate the approximate timing of tasseling and pollination of corn.

Fig. 4.5: The relationship between post-corn harvest soil residual inorganic N in the surface 60 cm and applied fertilizer nitrogen (N) change relative to the nitrogen sufficient yield nitrogen rate (ΔNSYNR), which maximized corn grain yield, for 2007 to 2009 sites.

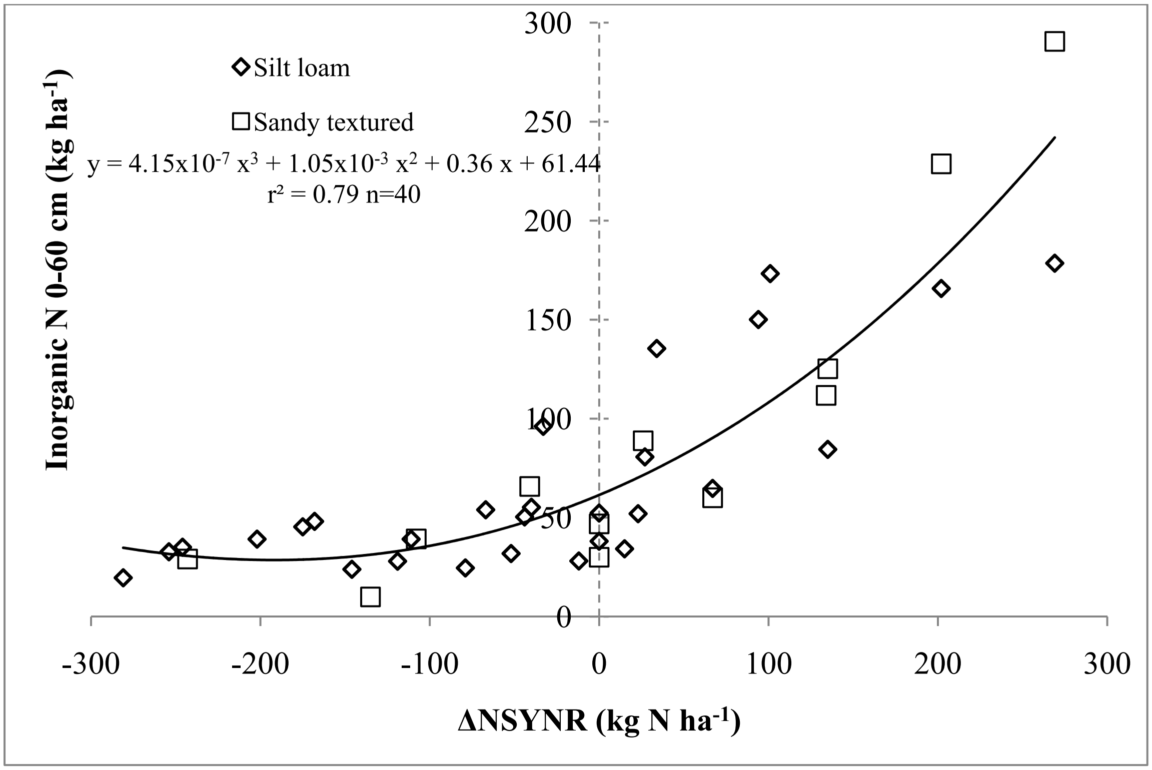


Fig. 4.6: The relationship between post-corn harvest soil residual inorganic N in the surface 60 cm and applied fertilizer nitrogen (N) change relative to the economically optimal nitrogen rate (ΔEONR) for 2007 to 2009 sites.

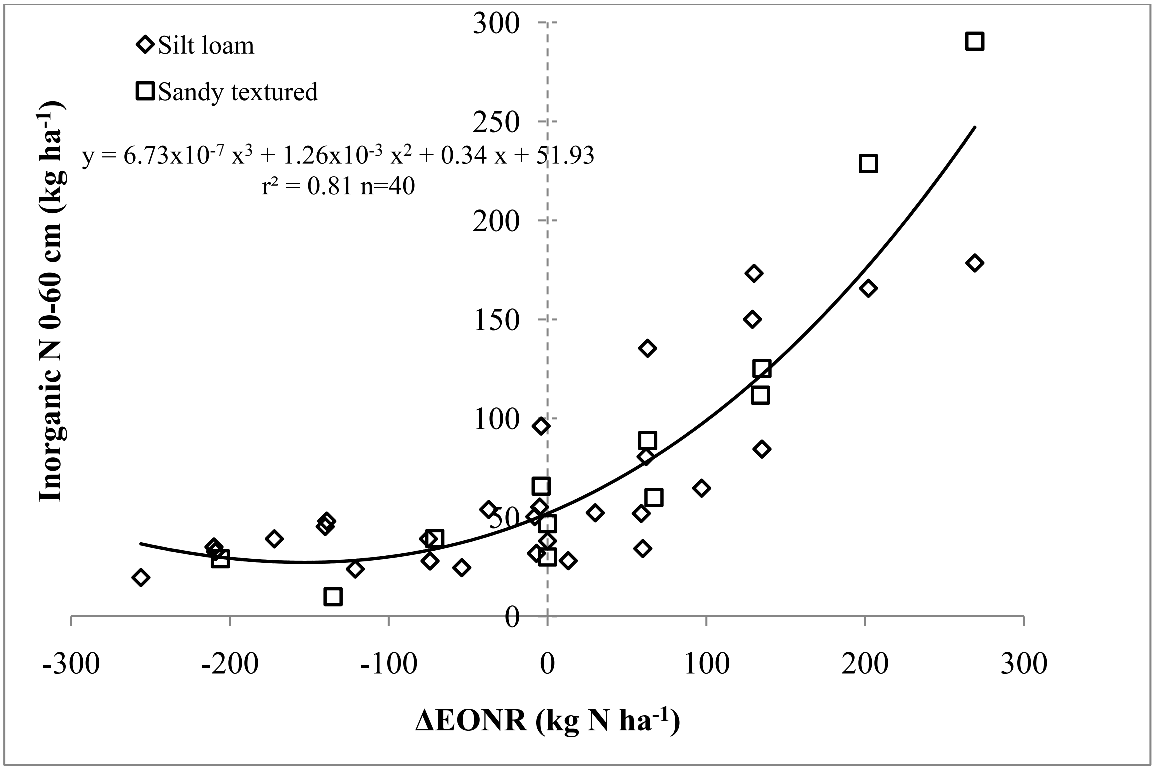


Fig. 4.7: The relationship between post-corn harvest soil residual nitrate (NO_3-N) in the surface 30 cm and applied fertilizer nitrogen (N) change from the nitrogen sufficient yield nitrogen rate (ΔNSYNR), which maximized corn grain yields, for 2005 to 2009 sites.

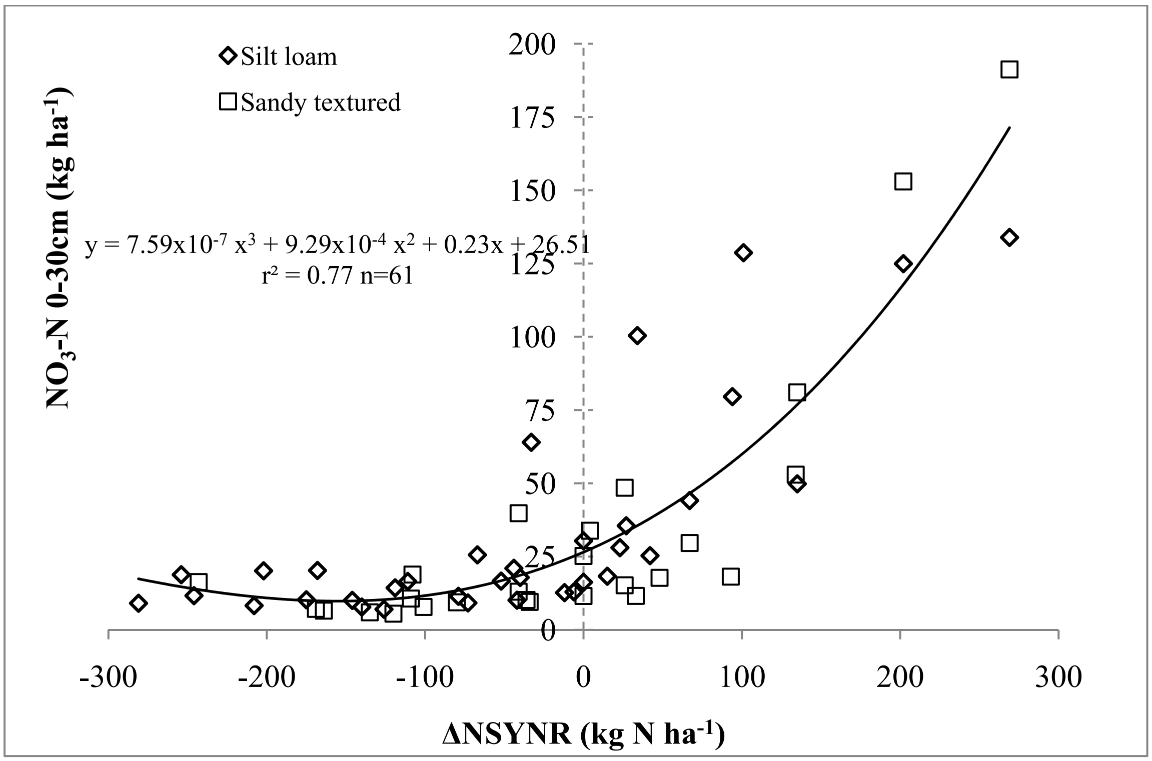


Fig. 4.8: The relationship between post-corn harvest soil residual nitrate (NO_3-N) in the surface 30 cm and applied fertilizer nitrogen (N) change from the economically optimal nitrogen rate (ΔEONR) for 2005 to 2009 sites.

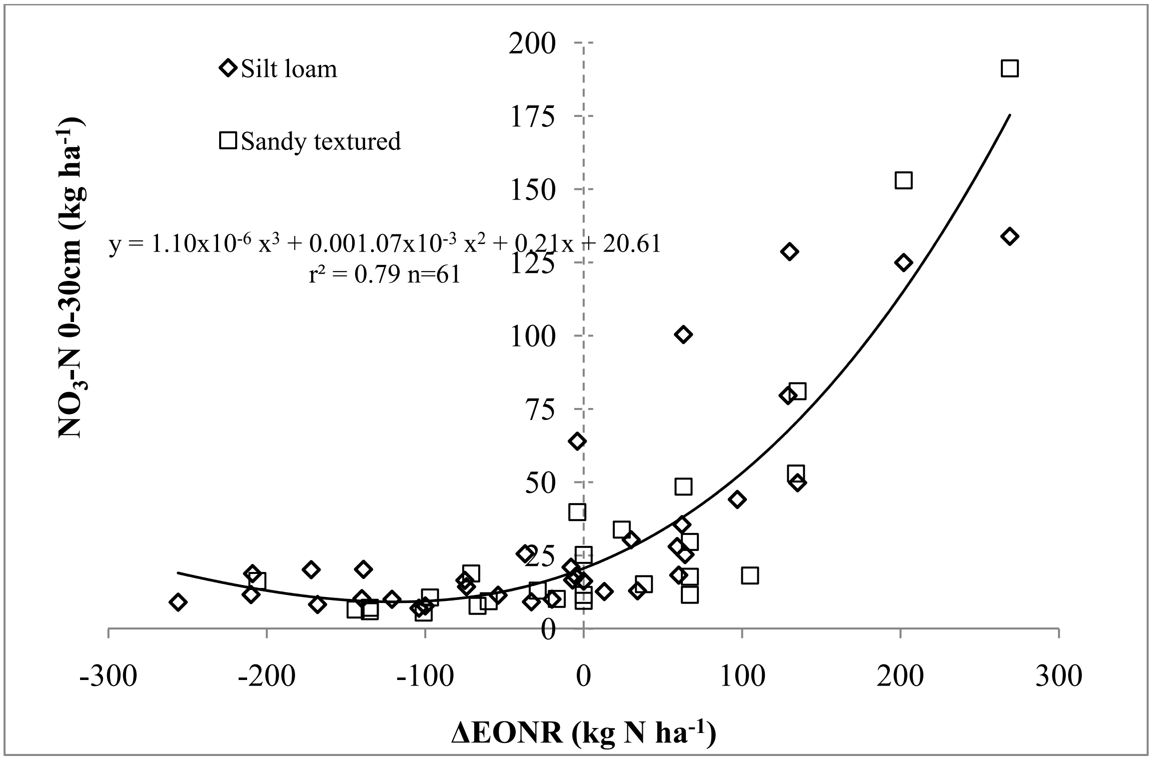


Fig. 4.9: Relationship between soil residual nitrate (NO_3-N) and change in the fertilizer N to grain yield ratio from the University of Maryland fertilizer N recommended ratio (17.9 kg Mg^{-1}, which represents the zero point on the x-axis)

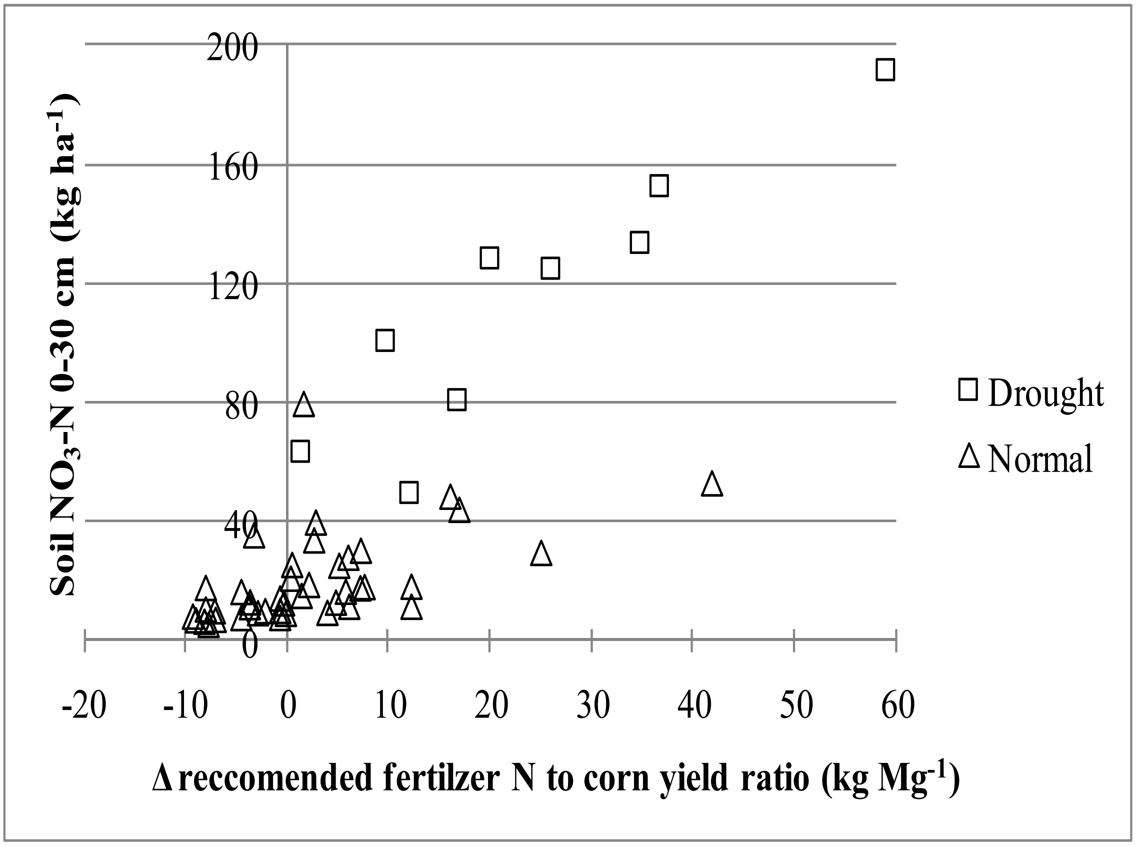
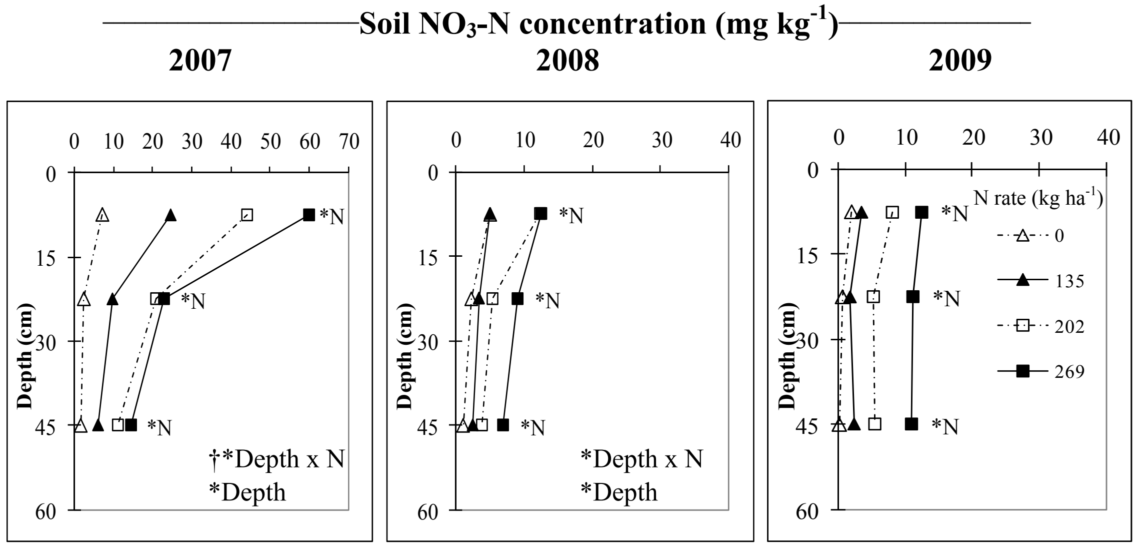
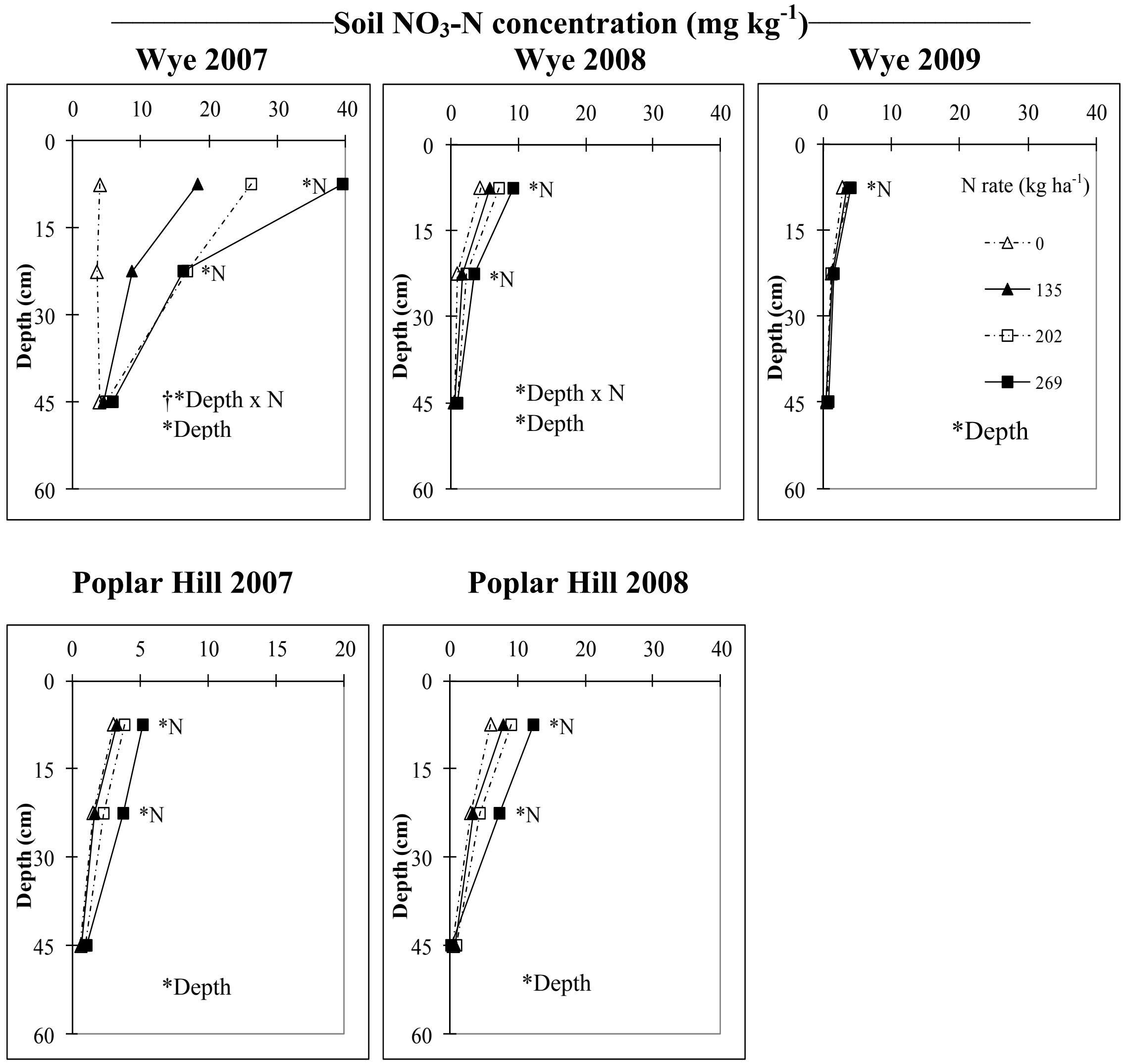


Fig. 4.10: Effects of corn nitrogen (N) fertilization and depth on soil profile nitrate (NO_3-N) concentration and distribution following corn harvest at sandy textured sites (Beltsville).



† * indicates that the effect was significant ($p \leq 0.05$).

Fig. 4.11: Effects of corn nitrogen (N) fertilization and depth on soil profile nitrate (NO_3-N) concentration and distribution following corn harvest at Coastal Plain silt loam sites (Wye and Poplar Hill).

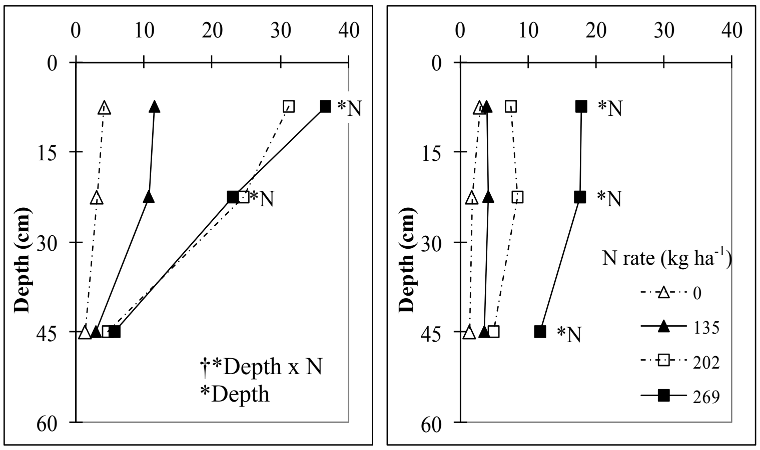


† * indicates that the effect was significant ($p \leq 0.05$).

Fig. 4.12: Effects of corn nitrogen (N) fertilization and depth on soil profile nitrate (NO_3-N) concentration and distribution following corn harvest at Piedmont sites (Clarksville).

Soil NO_3-N concentration (mg kg^{-1})

2008 **2009**



† * indicates that the effect was significant ($p \leq 0.05$).

CH 5: Fall starter nitrogen management for winter wheat

Abstract

Fall starter fertilizer nitrogen (N) recommendations, which account for the seasonally variable soil residual nitrate (NO_3-N) contribution, can optimize winter wheat (*Triticum aestivum*, L.) yields and minimize losses to water-bodies, including the Chesapeake Bay. The objective of this study was to develop fall starter N recommendations for winter wheat based on soil NO_3-N present at planting. Replicated plots receiving fall starter N rates ranging 0 to 68 kg N ha^{-1} were established at 22 site years in Maryland. At 15 site years, wheat followed three or four corn (*Zea mays*, L.) N treatments in a split plot design, which resulted in a range of pre-wheat planting soil residual NO_3-N at each site. At seven site years, the preceding crop received only one N rate. All plots were soil sampled to a minimum depth of 30 cm before planting, and NO_3-N was measured. Standard spring N management was applied across all fall starter N treatments. Wheat yield, late winter tiller density, and normalized difference vegetation index (NDVI) increased significantly in response to application of 34 kg N ha^{-1} starter (pre-plant soil NO_3-N levels ≤15 mg kg^{-1} in the surface 15 cm). Even where pre-plant soil residual NO_3-N levels were ≤15 mg kg^{-1} in the surface 15 cm, the yield response was highly variable, declining significantly ($p<0.01$) as post planting fall precipitation totals increased. No response in any of the parameters measured was detected where soil NO_3-N levels were >15 mg kg^{-1} in the surface 15 cm. These data indicate that fall starter N rates of 17 to 34 kg N ha^{-1} are agronomically appropriate where soil nitrate NO_3-N are ≤15 mg kg^{-1} at planting.

Introduction

Optimizing soil nitrogen (N) availability for winter wheat establishment is crucial, both agronomically and environmentally, especially in sensitive areas such as the Chesapeake Bay watershed. Inadequate plant available N is associated with a host of factors considered negative for optimizing crop yield. Limited soil N availability increases the likelihood of N deficiency in emerging seedlings (Alley *et al*., 2009). Such N deficiency reduces the rate of tiller emergence, decreases tiller bud emergence, and delays or completely inhibits the growth of tiller buds that are present (Longnecker *et al*., 1993). Loss of fall tillers is problematic for yield optimization, as these generally produce heads with more kernels (Alley *et al*., 2009). Additionally, protracted or intense N deficiency can reduce grain number and yield regardless of growth stage (Jeuffroy and Bouchard, 1999). Vaughan *et al*. (1990) suggested that deficient plants may also be predisposed to winter kill and poor development. To avoid these negative effects on wheat establishment, starter fertilizer rates up to 45 kg N ha^{-1} are recommended in the Mid-Atlantic (Coale, 2002; Weisz and Heiniger, 2004; Alley *et al*., 2009; Sammons *et al*., 1989; Walker and Taylor, 1998). The applications of fall starter N supplements the pool of residual/mineralized N which remains following the preceding crop. This is significant environmentally, as soil NO_3-N levels during the fall, along with winter precipitation, are important factors influencing root zone N loss (Vanotti and Bundy, 1994; Liang *et al*., 1991).

Agronomically, applications of fertilizer N which result in excessive N availability may also reduce yields due to lodging or reduced grain test weights (Bundy and Andraski, 2004). In Maryland, another factor which producers must consider is the availability of the commodity cover crop program (Maryland Department of Agriculture, 2010), which pays farmers \$62 ha^{-1} not to apply any fall N to small grains and not to apply spring N before 1 March. With the continued availability of this program, the additional grain yield value due to applying fall N must exceed the cost of fertilizer and application plus the cost of sacrificing this payment to be economical.

In Maryland and other states within the Chesapeake Bay watershed, efforts to improve water quality are focusing on the establishment of stronger nutrient management policies. Water quality in the Chesapeake Bay is listed as impaired, which means it does not meet Clean Water Act standards (Environmental Protection Agency, 2006). Reductions in N, phosphorous, and sediment inputs to the Chesapeake Bay have been identified as the solutions to improving water quality. States within the watershed are being implementing total maximum daily loads for nutrient and sediment inputs to the Bay which meet mandatory loss reduction goals. Maryland is to reduce N losses from agriculture by 23% by 2017 (Maryland Department of Environment, 2010). The Natural Resource Conservation Service (2010) reported that 65 percent of cropped acres within the Chesapeake Bay watershed require additional nutrient management to address excessive N loss through subsurface flow pathways. Farmers have implemented best management practices for controlling N losses from agriculture since the 1980s. Updating N management recommendations is required for further N reductions.

Fall N fertilizer applied close to the beginning of the groundwater recharge period may be lost from the root zone over the winter if not taken up by the wheat crop. On the Maryland Coastal Plain, which represents the most intensively cropped area within the Chesapeake Bay watershed, examination of the fall N requirement is especially important. Here, groundwater is the dominant link between agricultural systems and surface waters and ultimately the Chesapeake Bay (Boesch *et al*., 2001). To minimize negative environmental effects caused by N losses, the contribution of residual NO_3-N from the preceding crop should be considered before applying fall starter N. Winter wheat is commonly grown following both soybean and corn in the Mid-Atlantic. The residual N pool following corn can be greater than the pool following soybean (Scharf and Alley, 1994) and highly variable (Roth and Fox, 1990; Vanotti and Bundy, 1994; Hong *et al*., 2007). The application of standard fall starter N rates to sites with variable residual NO_3-N pools creates potential for excess fall N availability and increases the potential for N loss. Little information is available detailing the link between residual NO_3-N and optimum fall starter N rate for wheat in the Mid-Atlantic. However, many studies have developed the general principle that a strong link exists between increasing residual NO_3-N and diminished spring fertilizer N response in winter wheat (Bundy and Andraski, 2004; Scharf and Alley 1994; Cui *et al.,* 2008; Meisinger *et al*., 1987), in corn (Bundy and Malone, 1988; Schmitt and Randall, 1994; Halvorson *et al*., 2005) and in grain sorghum (*Sorghum bicolor* L.) (Bagayoko *et al*., 1992). These data raise the question of whether this general principle might be extended to fall starter N responsiveness in winter wheat to fall residual NO_3-N. In Virginia, no starter N is recommended for wheat when residual NO_3-N exceeds 30 mg kg^{-1} (equivalent to approximately 68 kg N ha^{-1}) in the surface 15 cm (Alley *et al*., 2009). Limited information is available relating the appropriate starter N rate to residual NO_3-N in Maryland or other Mid-Atlantic states. Significant reduction in total N losses depends on effective strategies to reduce NO_3-N leaching to groundwater (Boesch *et al*., 2001). In light of the above, fall starter N requirements in the region require closer examination. The study objectives were to determine whether soil residual NO_3-N levels affect fall starter N responsiveness in winter wheat and to determine optimum fall starter N rates.

Materials and Methods

Twenty-two field experiments were established at University of Maryland Research and Education Centers (UMRECs) (2005-2009) and at producer field sites (2008-2009) in the Coastal Plain and Piedmont regions of Maryland. Sites were chosen to represent the wide range of soils (Table 5.1), and climates under which winter wheat is commonly grown. At UMRECs, the experimental design was a randomized complete block split plot, with corn N fertilization as the main plot factor and wheat fall starter N fertilization the split plot factor. At producer field sites, the experimental design was a randomized complete block. At UMRECs, N rates ranging deficient through excessive were applied to the corn to generate a range of pre-wheat planting soil residual NO_3-N at each site. The corn N rates applied were 0, (67 in 2006), 135, 202, and 270 kg N ha^{-1}, except in 2005, when the rates applied were 84, 168, and 253 kg N ha^{-1}. The N source used was urea-ammonium nitrate (UAN); 34 kg N ha^{-1} was applied at planting and the balance at as a side-dress application between corn growth stages V4 and V6 (Ritchie *et al.*, 1997). Corn N was applied as a surface band except at Beltsville and Clarksville in 2009 where side-dress N was injected to 10 cm depth. At producer field sites, the producers' standard N management practice was applied preceding the wheat crop.

Following corn harvest, but before wheat planting, six or eight 2.5 cm soil cores were collected $plot^{-1}$ to depths of either 30 or 60 cm and divided into increments (Table

5.1). Soil samples were air dried at room temperature immediately following collection and ground to pass through a 2 mm sieve. Soil inorganic N was extracted at a ratio of 1:10 in 1 *M* KCl solution by shaking for 30 minutes using reciprocating shaker (Eberbach Corp. Ann Arbor, Michigan), settling for 30 minutes, and filtering supernatant liquid through grade 42 filter paper (Whatman Inc. Buckinghamshire, United Kingdom). Nitrate in soil extract solutions were determined by colorimetric analysis using a continuous-flow ion analyzer [(Technicon Industrial Systems, 1977 (2005 and 2006); Lachat, 1987 (2007 to 2009)].

Wheat was planted following soil sample collection and the Hessian fly (*Mayetiola destructor* Say)-free recommended dates. All wheat was planted between 13 October and 25 October, dates considered within the optimal wheat planting window, and establishment was either by no-till (twenty sites) or conventional tillage (two sites) (Table 5.1). Full-sized farm equipment was used to plant sites, with seeding rate adjusted for a target emerged population of approximately 310 emerged seedlings m^{-2}. Corn was the crop preceding wheat at all sites, except for one producer field site (Table 5.1). At UMRECs, one wheat cultivar 'USG 3209' was planted at all sites, except in 2009, when 'Pioneer 25R62' was used. At producer field sites, cultivar was selected by the producer, and farm practice was used for wheat seeding rate. Fall starter fertilizer N treatments were applied using surface applied UAN at wheat planting. Trials at UMRECs received starter fertilizer N rates of 0, 17, 34, and 68 kg ha^{-1} at planting (fall 2008 and 2009) or two starter fertilizer N rates of 0 and 34 kg ha^{-1} (2005 through 2007). Producer field sites received starter fertilizer N rates of 0, 17, 34, and 51 kg ha^{-1}. Farm standard herbicide, insecticide, and fungicide applications were applied in a timely fashion and as required using farm equipment. Standard spring management, including N management, was applied across all fall starter N treatments at all sites. At both UMRECs and producer sites, spring fertilizer N applications were applied as early as ground conditions permitted following green-up but not before 1 March. Not applying spring N before 1 March is a requirement for participation in the Maryland commodity cover crop program. Spring fertilizer N rates at UMRECs were applied as a split application of 56 kg N ha^{-1} at Zadoks growth stage 23 to 30 (Zadoks *et al*., 1974) and 56 kg N ha^{-1} at growth stage 31 to 32. At producer field sites, spring N rates were applied per the producer's standard practice but not before 1 March. Plots were harvested at maturity and yield recorded using a Massey Ferguson 8XP plot combine (Kincaid Manufacturing, Haven, KS) equipped with a HarvestMaster data collection system (Juniper Systems, Logan, UT) that records the grain weight and moisture content of each plot as it is harvested. In addition, tillers with three or more visible leaves were counted in five 0.3 m row segments prior to application of green-up N at seven site years during 2008 and 2009. From 2008 to 2010, measurements of NDVI were collected from fourteen site years prior to application of spring fertilizer N using a Crop Circle ACS-210 optical sensor (Holland Scientific, Lincoln, NE).

The PROC REG procedure of SAS version 9.2 (SAS Institute, Cary, NC) was used to examine the correlation between soil NO_3-N concentration in the surface 15 cm and the NO_3-N concentration to both 30 and 60 cm depth. This procedure was also used to examine the correlation between wheat yield response to fall fertilizer N and both fall precipitation and soil NO_3-N concentration at planting. Using the mixed model procedure of SAS, a pooled ANOVA was conducted to determine the effect of applying fall N on wheat grain yield, spring tiller density, and NDVI. For this analysis, the 0 and 34 kg N ha^{-1} fall N treatments (which were common to all 22 site years) were used. To determine the appropriate fall N rate, a second pooled ANOVA analysis was conducted using data from 13 site years, at which four fall fertilizer N treatments were applied. At UMRECs and producer field sites the applied starter N rates were the same except for the highest rate. The highest rate was considered adequate to provide greater N availability to the crop than would be required to maximize fall-winter growth at all sites. For the purposes of analysis, the highest rate was designated as the 51/68 kg N ha^{-1} rate. In both the analysis of pooled data from 13 and 22 site years, data was divided into two separate categories based on soil residual NO_3-N at wheat planting: 1) main plots or sites where mean soil NO_3-N concentration at wheat planting was ≤15 mg kg^{-1} in the surface 15 cm; 2) main plots or sites where mean soil NO_3-N concentration at planting was >15 mg kg^{-1} in the surface 15 cm. At 21 of 22 total sites at least one preceding N management treatment resulted in soil residual NO_3-N level ≤15 mg kg^{-1} (Table 5.2). At five of 22 total sites at least one preceding N management treatment resulted in soil residual NO_3-N level >15 mg kg^{-1} (Table 5.2). Due to the large imbalance between these two categories, separate ANOVA was conducted for data from each category. Fall fertilizer N treatment and soil texture were considered fixed effects; site year and block were considered random. When statistical difference ($p \leq 0.05$) was detected between treatments by ANOVA, mean comparisons were by Tukey's mean comparison test ($p \leq 0.05$). In all cases, means were determined using the lsmeans option of the mixed model procedure.

Results and Discussion

Sampling depth and pre-wheat planting soil residual nitrate

To incorporate the contribution of the residual NO_3-N pool into fall starter N recommendations, it will be necessary to soil sample because companion studies comparing late-season crop monitoring vs. soil sampling (Forrestal, 2011) have shown that soil sampling provides the most reliable estimate of residual NO_3-N. Determining an appropriate soil sampling depth is important. Recommendations based on shallow soil sampling allow for more intense sampling and require less labor which is more attractive to producers. However, leaching pressure during the corn growing season may move NO_3-N downward into the soil profile, thus limiting the usefulness of shallow sampling. To examine whether shallow sampling is an accurate predictor of soil NO_3-N deeper in the profile, samples were collected in increments (Table 5.1). Data from 19 site years indicated soil samples collected to a 15 cm depth prior to wheat planting are excellent predictors (r^2=0.96) of soil NO_3-N concentration to 30 cm depth (Fig. 5.1). Based on this strong relationship, soil NO_3-N concentration for the surface 15 cm was estimated from the 0 to 30 cm sample in 2005 using the equation $y=1.2452x-0.2234$ derived from data collected at 19 sites from 2006 through 2009. Estimated soil NO_3-N concentrations in the surface 15 cm for the three sites in 2005 low (<10 mg kg^{-1}) (Table 5.2). Data from 11 site years indicates that soil samples collected to a 15 cm depth are also strong predictors (r^2=0.89) of soil NO_3-N concentration in the surface 60 cm (Fig. 5.2). Similarly, Roth and Fox (1990) reported NO_3-N accumulation in the surface 30 cm was highly correlated (r^2=0.90) with total NO_3-N in the surface 120 cm. Herron *et al*. (1968) also found a strong correlation between NO_3-N in the surface 30 cm with the total NO_3-N concentration to 180 cm depth. These results are consistent with the suggestion by Magdoff (1991) that there is little NO_3-N leaching in most soils during the corn growing season. This is also consistent with Scharf and Alley (1994), who reported that the majority of NO_3-N leaching occurs during the fall-winter-spring groundwater recharge period in humid regions. The strong relationship observed (Figs. 5.1 and 5.2) indicates that soil sampling to 15 cm depth provides an adequate basis for establishing residual soil NO_3-N availability for a winter wheat crop. As a result, subsequent analysis and discussion will focus on soil NO_3-N concentration in the surface 15 cm and its relationship with fall starter fertilizer N responsiveness in winter wheat.

Following the low corn fertilizer N rate, which ranged 0 to 84 kg N ha^{-1}, soil residual NO_3-N levels were consistently low (<8 mg kg^{-1}) prior to wheat planting. As corn fertilizer N rate increased, soil residual NO_3-N levels tended to increase (Table 5.2). Large variations in residual soil NO_3-N levels were observed across sites and years (Table 5.2), confirming the variable pattern reported in other states (Roth and Fox, 1990; Vanotti and Bundy, 1994; Hong *et al*., 2007). If present at wheat planting, this residual NO_3-N is available for uptake while it remains within the wheat root zone. The variability in residual NO_3-N observed following corn reinforces the concept that standard rates of wheat starter N are inappropriate. This residual NO_3-N may provide for the modest fall-winter N uptake of the wheat crop, which has been reported to be less than 30 kg N ha^{-1} by Baethgen and Alley (1989).

In Virginia, no fall starter N is recommended at soil NO_3-N concentrations >30 mg kg^{-1} in the surface 15 cm (Alley *et al*., 2009). My study shows that on average grain yield response to starter N declines as soil residual NO_3-N level increases (Fig. 5.3).

These data could be used to support the extension of the Virginia recommendation to Maryland. However, in light of efforts to minimize N losses to the Chesapeake Bay, and the diminished average yield response as the 30 mg kg^{-1} residual NO_3-N level is approached a lower upper limit may be appropriate in Maryland. Moderate fall-winter N uptake by the wheat crop (Baethgen and Alley 1989) suggests that a lower upper limit may have minimal influence on adequacy of N availability at wheat planting.

Effects of pre-plant soil nitrate and fall precipitation on wheat yield response to application of starter nitrogen

Even at low levels soil NO_3-N levels wheat yield response to fall starter fertilizer N was quite variable (Figs. 5.3 and 5.4). Some of this response variability may be linked to fall precipitation patterns, which affect root zone fertilizer N retention. In this study, wide variation in fall precipitation totals was observed, with greater than a threefold difference in precipitation totals across sites (Fig. 5.5). For site where pre-plant NO_3-N availability was ≤15 mg kg^{-1} wheat yield response to application of 34 kg ha^{-1} fall starter N declined significantly ($p<0.01$) with increasing post-planting fall precipitation (Fig. 5.5). The trend observed was similar for both sandy and silt loam textured sites. Precipitation patterns cannot be controlled. However, nitrification inhibitors which extend root zone N availability by limiting leaching loss (Bengtson, 1979) or controlled release urea which can increase wheat nitrogen use efficiency (Yang *et al*., 2011), may be beneficial where fall N is applied.

Effects of applying 34 kg ha^{-1} fall starter fertilizer nitrogen on wheat tiller density, normalized difference vegetation index, and grain yield

The majority of corn N treatments resulted in post-harvest residual NO_3-N levels ≤15 mg kg^{-1} (Fig. 5.3), suggesting that the majority of producer field sites will also be below this level where drought conditions or manure history are not factors. For this reason, sites were examined separately from those with residual NO_3-N levels >15 mg kg^{-1}. Fertilizer N management in the preceding crop resulted in twenty one site years where soil NO_3-N concentration was ≤15 mg kg^{-1} to 15 cm depth following at least one preceding corn N treatment (Table 5.2). At five site years, soil NO_3-N concentration exceeded 15 mg kg^{-1} following at least one preceding corn N treatment (Table 5.2).

Tiller density, NDVI, and wheat grain yield increased significantly in response to application of 34 kg ha^{-1} fall starter N at sites where soil NO_3-N levels ≤15 mg kg^{-1} in the surface 15 cm (Table 5.3 and 5.4). Measurements of NDVI were collected at 13 site years (six silt loam and seven sandy textured), and a significant interaction between fall fertilizer N and soil texture was detected. Although application of fall starter N increased NDVI for sites in both textural classes, this increase was larger at the silt loam sites. Measurements of NDVI have been shown to be a reliable predictor of tiller density in both Virginia (Philips *et al*., 2004) and in North Carolina (Flowers *et al*., 2001). Therefore, increases in NDVI observed in the present study may indicate positive effects of fall N application on tiller density. The greater response observed at silt loam sites indicates possible greater fertilizer N retention within the root zone, compared with retention at sandy textured sites. This is consistent with greater soil profile drainage in sandy textured sites (Hahne *et al*., 1977), which increases leaching potential. In addition, at the 13 site years where NDVI was measured, average fall precipitation totals were higher for the sandy textured sites (180 mm) compared with the silt loam sites (130 mm). Increased leaching potential combined with higher precipitation totals at the sandy textured sites may have reduced root zone fertilizer retention relative to silt loam sites.

At the seven site years (five silt loam and two sandy textured) where spring tiller density was measured, application of 34 kg ha^{-1} fall starter N significantly increased tiller density where residual NO_3-N level was ≤15 mg kg in the surface 15 cm. On average, tiller density was increased by 94 tillers m^{-2} (15.6%), [tiller density was above the 550 tillers m^{-2} identified the critical level by Weisz *et al*., (2001) even where no starter was applied] and the trend was similar at sandy textured and silt loam sites. Reduced tiller density due to not applying fall N may reduce yields; however, forgoing this response may not reduce yields dramatically. Wheat has the ability to compensate for reduced winter tiller survival by increasing spring tillering (Weisz *et al*., 2001). In addition, wheat exhibits compensation of the other yield components during the growing season where tiller density is reduced (Chen *et al*., 2008). In the present study, uniform spring N management was applied to all fall N treatments, with 56 kg ha^{-1} green-up N being applied as soon as ground conditions permitted following 1 March at UMRECs. These spring N applications complied with the conditions of the Maryland commodity cover crop program (Maryland Department of Agriculture, 2010). Spring tillering can be encouraged and optimum yields achieved, even where winter tiller density is sub-optimal, by manipulating the timing of spring N application (Weisz *et al*., 2001). However, when temperatures permit initiation of spring growth before the first permitted N application date (1 March), limited N availability may hinder spring tiller promotion. Applying spring N later than optimal due to program restrictions, along with possible further delays caused by ground conditions that preclude equipment movement, may increase the chances for yield depressions associated with not applying fall N. Optimizing spring N availability would require splitting of spring N applications. This is the University of Maryland recommended practice but one that is not universally practiced by producers in the region. Logistical and equipment limitations can cause producers to apply single rather than split applications (Murdock *et al*. 1997).

When site year was examined as a random effect application of 34 kg ha^{-1} fall N significantly increased wheat grain yields where soil residual NO_3-N level was ≤15 mg kg^{-1} (Table 5.4). No interaction between fall N and soil texture was detected and average yield response across 21 site years was 0.19 Mg ha^{-1} (4.2%). However, across sites this response was variable, ranging from negative 0.17 to positive 0.66 Mg ha^{-1} (Fig. 5.4). This is similar to response ranges of negative 0.01 to positive 0.63 Mg ha^{-1} to application of 28 kg ha^{-1} starter N reported by Kratochvil *et al*. (2005) for hard red winter wheat at four site years in Maryland. In New York, Knapp and Knapp (1978) reported responses ranging from negative 0.27 to positive 0.02 Mg ha^{-1} at two site years where residual NO_3-N at planting was low.

At sites where residual NO_3-N levels exceeded 15 mg kg^{-1} in the surface 15 cm prior to wheat planting, no significant response to 34 kg ha^{-1} starter N was detected for the response variables measured (Table 5.5). This suggests that forgoing fall starter N at sites which have soil NO_3-N >15 mg kg^{-1} is unlikely to have negative agronomic effects in Maryland.

Choosing the fall starter nitrogen rate for winter wheat

As previously discussed, where residual NO_3-N was ≤15 mg kg^{-1} in the surface 15 cm, yields increased significantly in response to the application of 34 kg ha^{-1} starter N. This rate was chosen for examination because it was applied at all study sites. However, to more closely examine the propriety of this rate, a range of fall N rates were needed. At 13 site years, four fall starter fertilizer N treatments (0, 17, 34, and what was considered an excessive rate of 51/68 kg ha^{-1}) were applied. Similar to when 0 and 34 kg ha^{-1} fall N rates were examined, a significant interaction between soil texture and fall N rates was detected for NDVI when all N rates were examined. Silt loam sites demonstrated larger NDVI response to fall N compared with sandy textured sites. This is attributed the effect of internal drainage characteristics and precipitation totals on fertilizer N retention for the respective soil textures. When examined across a range of fall N rates, application of 34 kg ha^{-1} increased NDVI significantly compared with the 0 kg N ha^{-1} treatment (sandy textured) and compared with both the 0 and 17 kg ha^{-1} N rates (silt loam). Further increasing the N rate to the excessive rate (51/68 kg ha^{-1}), which exceeds the highest fall N rate recommended in Maryland, did not increase NDVI significantly. Based on the strong correlation reported between NDVI and tiller density in winter wheat ($0.67 \geq r^2 \leq 0.99$ by Philips *et al*., 2004) and vegetative coverage ($0.81 \geq r^2 \leq 0.98$ by Lukina *et al*., 2000), the data from the present study demonstrate positive growth response but variable yield response to application of fall starter N in Maryland at sites where residual NO_3-N ≤15mg kg^{-1} in the surface 15 cm.

Data from 21 of 22 site years where soil residual NO_3-N was ≤15 mg kg^{-1} at planting showed positive wheat grain yield response to fall starter N application and no interaction with soil texture was detected (Table 5.3). This may be due to the equalizing effects of spring yield component compensation. However, the yield response trend was similar to that observed for NDVI (Table 5.7). Significantly, higher yields were observed where 34 kg ha^{-1} fall starter N was applied compared with the 0 kg ha^{-1} starter N treatment, but not compared with the 17 kg N ha^{-1} treatment. Application of the highest N rate did not increase wheat grain yield compared with the application of 34 kg ha^{-1}. When giving consideration to both spring NDVI and yield response, these data suggest that 17 to 34 kg ha^{-1} is an appropriate fall starter N rate at sites where residual NO_3-N ≤15 mg kg^{-1} in the surface 15 cm. This is similar to recommendations of 17 to 34 kg ha^{-1} in Virginia (Alley *et al*., 2009) and North Carolina (Weisz and Heiniger, 2004). Sammons *et al*. (1989) recommended slightly lower rates of 11 to 23 kg N ha^{-1} in Maryland.

Although application of fall starter N resulted in increased yields (soil NO_3-N at planting ≤15 mg kg^{-1}), such applications may not be desirable if they are not economical and/or result in environmental degradation. During the five year period of 2005 to 2009, wheat grain prices in Maryland ranged from \$115 to \$216 Mg^{-1}; the average was \$162 Mg^{-1} (USDA, 2010a). During the same period, fertilizer N prices ranged from \$0.72 to \$1.34 kg^{-1} N; the average was \$0.96 kg^{-1} (USDA, 2010b). Average yield response to application of 34 kg ha^{-1} was 0.18 Mg ha^{-1} at 13 site years (Table 5.7) and 0.19 Mg ha^{-1} at 21 site years (Table 5.4). Additional grain yield in response to application of 34 kg ha^{-1} fall starter N at 21 site years was valued at \$31 ha^{-1} using the average prices; this was slightly less than the cost of 34 kg fertilizer N (\$33 ha^{-1}), which does not include the application cost. However, the largest wheat yield response observed (0.66 Mg ha^{-1}) is valued at \$117 ha^{-1}. The Maryland commodity cover crop program currently pays producers \$62 ha^{-1} not to apply fall starter N. This payment is equivalent to the value of 0.38 Mg^{-1} grain at average prices. At the majority of site years in this study, wheat grain yield benefit to application of fall starter N was below this threshold, even where residual NO_3-N at planting was low (≤15 mg kg^{-1}) (Fig. 5.4). Therefore, participation in the Maryland commodity cover crop program provides a significant economic incentive to forgo application of fall N even on sites were soil NO_3-N levels to 15 cm depth are (≤15 mg kg^{-1}.

Conclusions

Soil NO_3-N concentration to 15 cm depth was strongly correlated with NO_3-N concentration in the surface 30 cm (r^2=0.96) and surface 60 cm (r^2=0.89). This indicates that pre-plant soil sampling to 15 cm depth and NO_3-N analysis will provide a useful indicator of residual soil NO_3-N availability to 60 cm depth for wheat establishment. Where soil NO_3-N levels ≤15 mg kg^{-1} late-winter NDVI, tiller density and wheat yield increased significantly in response to application of 34 kg N ha^{-1} fall starter. The probability of attaining yield response to 34 kg N ha^{-1} fall starter N which covered the fertilizer cost greatest where soil residual N was low (<5 mg NO_3-N kg^{-1}). At sites where residual NO_3-N was ≤15 mg kg^{-1}, average yield response to 34 kg N ha^{-1} starter was 0.19 Mg $ha^{-1.}$ However, this response was quite variable. Positive yield response to fall starter N was not guaranteed, even where pre-plant soil NO_3-N was low. Sites where post-planting fall precipitation amounts were lower tended to provide the greatest yield response, and this response declined with increasing precipitation totals, which is consistent with fall starter N being susceptible to leaching losses especially on coarse textured soils. Based on late-winter NDVI, tiller density, and grain yield response, application of 17 to 34 kg ha^{-1} fall starter N is agronomically optimal at sites where residual NO_3-N ≤15 mg kg^{-1} in the surface 15 cm. In this study, spring N was split applied close to initiation of spring growth (but after 1 March). Where starter N is forgone at sites with low residual NO_3-N, providing adequate N at initiation of spring growth to promote tillering may assume increased importance to reduce the chances for reduced yield. Early application of spring fertilizer N may be advisable where fall starter N is not applied compensate for potentially reduced fall-winter tiller survival. Early spring N applications should be form part of a two split N application schedule which increases the chances for optimizing N availability to the crop while minimizing loss potential to water resources.

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Table 5.1: Site locations, soil characteristics, preceding management and soil sampling.

Farm	Fall wheat planted	Latitude	Longitude	Soil taxonomy	Soil series and surface soil texture†	Tillage system & preceding crop	Fall soil sampling increment (cm)
Upper Marlboro	2005	38° 51' 29" N	76° 46' 30" W	Aquic Hapludults	Donlonton fsl	No-till Corn	0-30
Beltsville	2005	39° 01' 30" N	76° 50' 29" W	Aquic Hapludults	Russett-Christiana fsl	No-till Corn	0-30
Upper Marlboro	2006	38° 51' 39" N	76° 46' 29" W	Aquic Hapludults	Adelphia-Holmdel fsl	No-till Corn	0-15, 15-30
Beltsville	2006	39° 01' 31' N	76° 50' 26" W	Aquic Hapludults	Russett-Christiana fsl	No-till Corn	0-15, 15-30
Beltsville	2007	39° 01' 33" N	76° 50' 31" W	Aquic Hapludults	Hammonton ls	No-till Corn	0-15, 15-30, 30-60
Beltsville	2008	39° 00' 45" N	76° 49' 43" W	Typic Hapludults-Aquic Hapludults	Downer-Hammonton ls	No-till Corn	0-15, 15-30, 30-60
Beltsville	2009	39° 00' 35" N	76° 49' 46" W	Aquic Hapludults	Russett-Christiana fsl	No-till Corn	0-15, 15-30, 30-60
Clarksville	2008	39° 15' 53" N	76° 55' 49" W	Aquic Fragiudults	Glenville sl	No-till Corn	0-15, 15-30, 30-60
Clarksville	2009	39° 15' 03" N	76° 55' 50" W	Typic Hapludults	Glenelg l	No-till Corn	0-15, 15-30, 30-60
Wye	2005	38° 54' 41" N	76° 08' 48" W	Typic Hapludults	Nassawango sl	No-till Corn	0-30
Wye	2006	38° 54' 38" N	76° 08' 48" W	Typic Hapludults	Nassawango sl	No-till Corn	0-15, 15-30
Wye	2007	38° 54' 42" N	76° 08' 38" W	Typic Hapludults	Nassawango sl	No-till Corn	0-15, 15-30, 30-60
Wye	2008	38° 54' 45" N	76° 08' 42" W	Typic Hapludults	Nassawango sl	No-till Corn	0-15, 15-30, 30-60
Poplar Hill	2007	38° 21' 28" N	75° 46' 51" W	Typic Hapludults	Nassawango sl	No-till Corn	0-15, 15-30, 30-60
Poplar Hill	2008	38° 21' 26" N	75° 46' 52" W	Typic Hapludults	Nassawango sl	No-till Corn	0-15, 15-30, 30-60
Poplar Hill	2009	38° 21' 20" N	75° 46' 26" W	Aquic Hapludults	Mattapex sl	No-till Corn	0-15, 15-30, 30-60
Denton dryland	2008	38° 54' 52" N	75° 46' 37" W	Typic Hapludults	Hambrook sl	Conventional Cucumbers	0-15, 15-30
Denton irrigated	2008	38° 55' 13" N	75° 44' 36" W	Typic Hapludults	Hambrook sl	Conventional Corn	0-15, 15-30
Marydel	2008	39° 07' 07" N	75° 48' 29" W	Typic Endoaquults-Aquic Hapludults	Fallsington-Woodstown sl	No-till Corn	0-15, 15-30
Greensboro	2008	38° 58' 16" N	75° 50' 26" W	Typic Hapludults	Ingleside-Hambrook	No-till Corn	0-15, 15-30

					sl-l		
Cordova irrigated	2009	38º 51’ 02” N	75º 57’ 15” W	Typic Hapludults	Hambrook-Sassafras sl	No-till Corn	0-15, 15-30
Cordova dryland	2009	38º 50’ 57” N	75º 57’ 04” W	Typic Hapludults	Hambrook-Sassafras sl	No-till Corn	0-15, 15-30

† Texture: fsl, fine sandy loam; ls, loamy sand; sl, silt loam; l, loam.

Table 5.2: Summary of pre-wheat planting soil residual NO_3-N concentrations in the surface 15 cm (mg kg^{-1}) at 16 site years at University of Maryland Research and Education Centers (UMREC) and six site years at producer field sites (PFS).

			Preceding N management			
Site	Year wheat planted	Site type	Low†	Optimum‡	High Optimum§	Excessive¶
			Soil NO_3-N 0-15 cm (mg kg^{-1})			
Beltsville	2005	UMREC	1	3	-	5
Beltsville	2006	UMREC	3	4	4	4
Beltsville	2007	UMREC	7	25	44	60
Beltsville	2008	UMREC	5	5	12	13
Beltsville	2009	UMREC	2	3	8	13
Upper Marlboro	2005	UMREC	2	3	-	9
Upper Marlboro	2006	UMREC	2	2	2	3
Clarksville	2008	UMREC	2	14	31	37
Clarksville	2009	UMREC	3	4	7	18
Wye	2005	UMREC	2	2	-	7
Wye	2006	UMREC	2	2	2	2
Wye	2007	UMREC	4	18	26	40
Wye	2008	UMREC	4	6	7	9
Poplar Hill	2007	UMREC	3	3	4	5
Poplar Hill	2008	UMREC	6	8	9	12
Poplar Hill	2009	UMREC	2	-	-	-
Denton irrigated	2008	PFS	-	-	45	-
Denton dryland	2008	PFS	-	-	5	-
Marydel	2008	PFS	-	-	11	-
Greensboro	2008	PFS	-	-	11	-
Cordova irrigated	2009	PFS	-	-	5	-
Cordova dryland	2009	PFS	-	-	7	-
<u>Mean</u>			3.13	6.80	13.33	15.80
Std. dev.			1.67	6.85	13.65	16.73
CV			0.53	1.01	1.02	1.06

†Low: 2005 84 kg N ha^{-1}, 2006 68 kg N ha^{-1}, 2007-2009 0 kg N ha^{-1}.
‡Optimum: 2005 168 kg N ha^{-1}, 2006-2009 135 kg N ha^{-1}.
§High Optimum: 2005 no treatment, 2006-2009 202 kg N ha^{-1}, farmer sites rate assigned to high optimum column.
¶Excessive: 2005 253 kg N ha^{-1}, 2006-2009 269 kg N ha^{-1}.

Table 5.3: Effect of applying 34 kg ha^{-1} fall starter fertilizer nitrogen (N) on winter wheat normalized difference vegetation index (NDVI), and tiller density in the late winter, and grain yield, at sites where pre-plant soil residual nitrate (NO_3-N) was: a) ≤15 mg kg^{-1} to 15 cm depth; b) >15 mg kg^{-1} to 15 cm depth.

	NDVI	Spring Tiller Density	Wheat Grain Yield
	——Site years for effect——		
a) Pre-plant soil NO_3-N ≤15 mg kg^{-1} to 15 cm depth			
	13	7	21
Effect			
Fall starter N	***	**	***
Soil texture	ns†	ns	ns
Fall starter N x soil texture	**	ns	ns
b) Pre-plant soil NO_3-N >15 mg kg^{-1} to 15 cm depth			
	5	3	5
Effect			
Fall starter N	ns	ns	ns
Soil texture	ns	ns	ns
Fall N x soil texture	ns	ns	ns

* Significant at 0.05 level.
** Significant at 0.01 level.
*** Significant at 0.001 level.
† not significant ($p \leq 0.05$).

Table 5.4: Effect of applying 34 kg ha^{-1} fall starter fertilizer nitrogen (N) on winter wheat normalized difference vegetation index (NDVI), and tiller density in the late winter, and grain yield, at sites where pre-plant soil residual nitrate (NO_3-N) was ≤15 mg kg^{-1} in the surface 15 cm.

Soil texture	Fall starter N	NDVI	Spring tillers	Grain yield
	kg N ha^{-1}		tillers m^{-2}	Mg ha^{-1}
		Site years for effect		
		13	7	21
All	0		601b	4.53b
All	34		695a	4.72a
Sandy	0	0.4570b†		
Sandy	34	0.4684a		
Silt loam	0	0.3930c		
Silt loam	34	0.4246b		

†Values within each column followed by the same letter are not significantly different using Tukey's test ($p \leq 0.05$).

Table 5.5: Effect of applying 34 kg ha^{-1} fall starter fertilizer nitrogen (N) on winter wheat normalized difference vegetation index (NDVI), and tiller density in the late winter, and grain yield, at sites where pre-plant soil residual nitrate (NO_3-N) was >15 mg kg^{-1} in the surface 15 cm.

Soil texture	Fall starter N	NDVI	Spring tillers	Grain yield
	kg ha^{-1}		tillers m^{-2}	Mg ha^{-1}
		Site years for effect		
		5	3	5
All	0	0.4942a†	619a	5.32a
All	34	0.5052a	627a	5.38a

†Values within each column followed by the same letter are not significantly different using Tukey's mean comparison test ($p \leq 0.05$).

Table 5.6: Effect of fall starter fertilizer nitrogen (N) rate on late winter normalized difference vegetation index (NDVI) and grain yield of winter wheat at silt loam (6 site years) and sandy textured (7 site years) sites where pre-plant soil residual NO_3-N was ≤15 mg kg^{-1} in the surface 15 cm.

Soil texture	Fall starter N	NDVI	Grain yield
	kg ha^{-1}		Mg ha^{-1}
All	0		4.60c
All	17		4.65bc
All	34		4.78ab
All	51/68		4.86a
Sandy textured	0	0.4607b†	
Sandy textured	17	0.4709ab	
Sandy textured	34	0.4723a	
Sandy textured	51/68	0.4771a	
Silt loam	0	0.3898e	
Silt loam	17	0.4033d	
Silt loam	34	0.4191c	
Silt loam	51/68	0.4233c	

†Values within each column followed by the same letter are not significantly different using Tukey's mean comparison test ($p \leq 0.05$).

Fig. 5.1: Relationship between soil nitrate (NO_3-N) concentration to 15 cm depth and soil NO_3-N concentration to 30 cm depth for samples collected at nineteen site years.

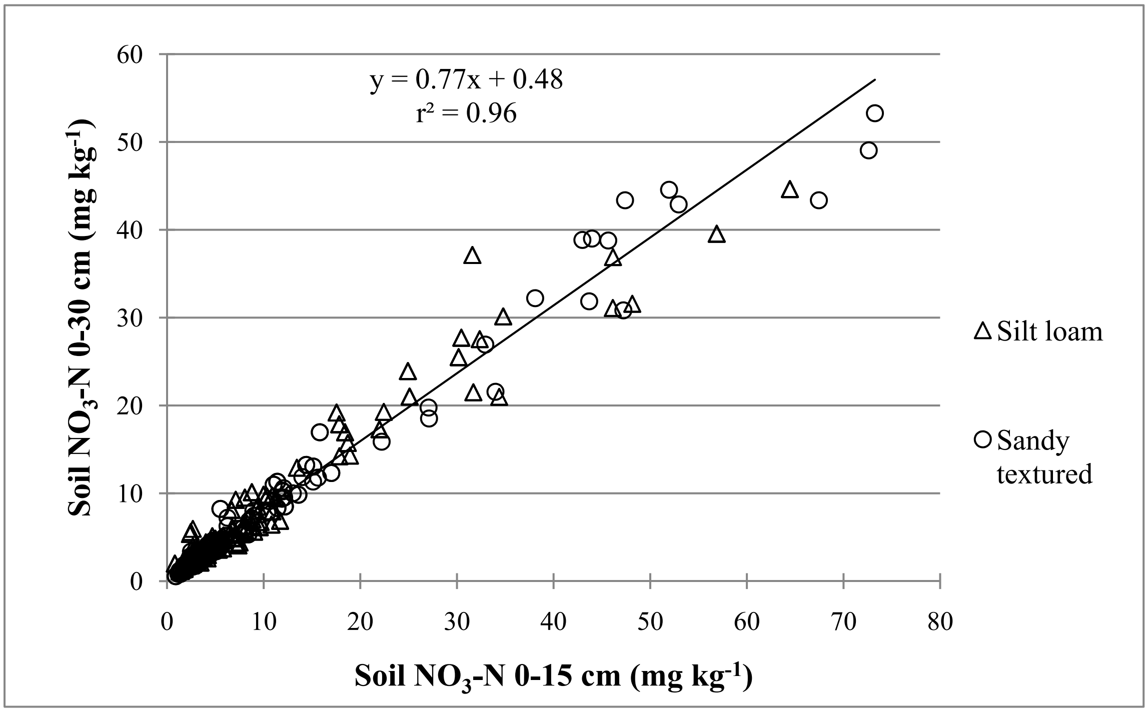


Fig. 5.2: Relationship between soil nitrate (NO_3-N) concentration to 15 cm depth and soil NO_3-N concentration to 60 cm depth for samples collected at eleven site years.

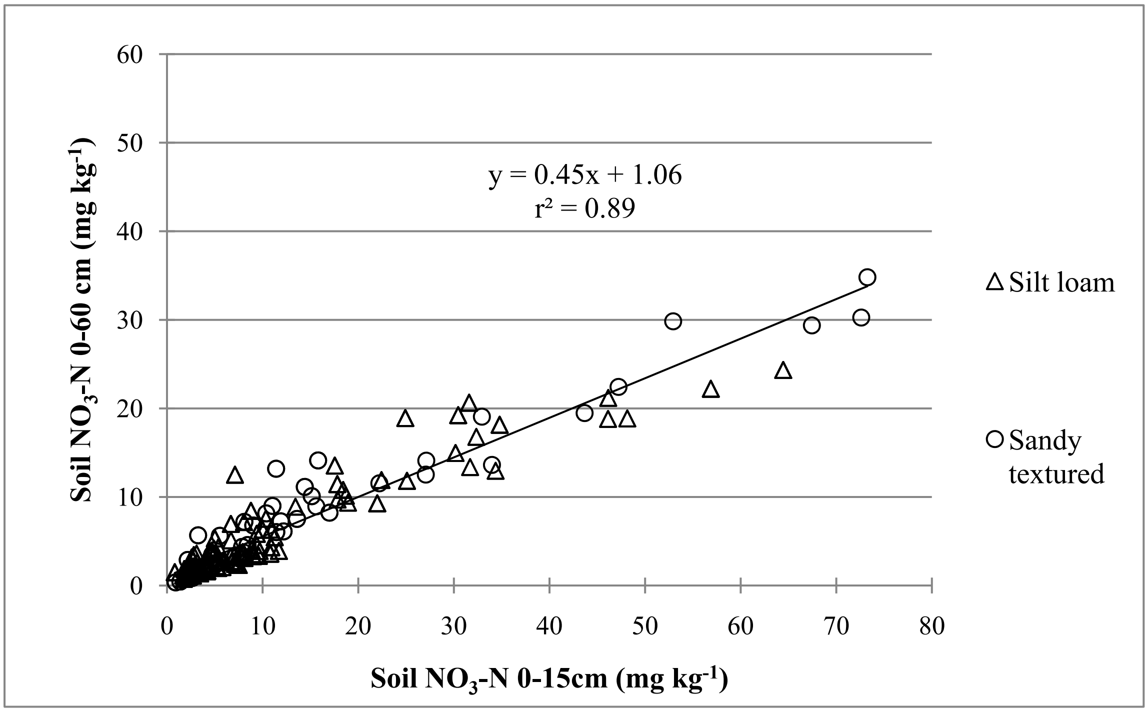
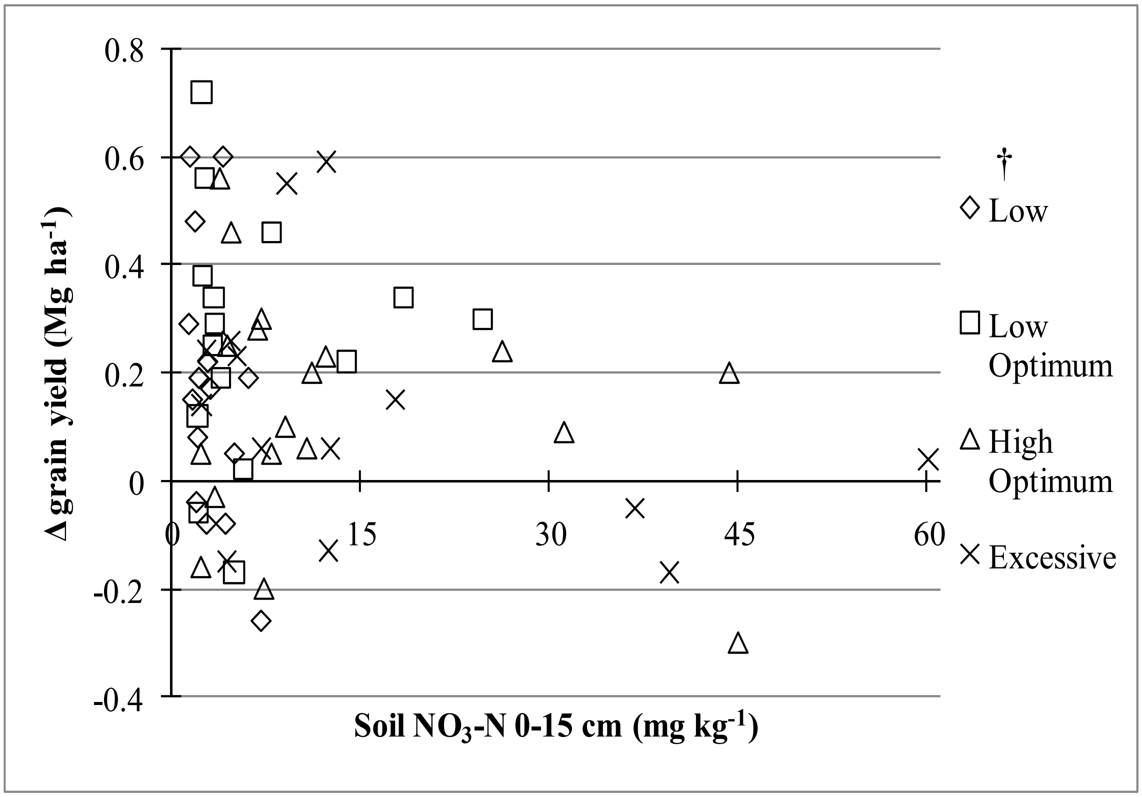


Fig. 5.3: Relationship between soil pre-wheat planting soil nitrate (NO_3-N) concentration to 15 cm depth and change in grain yield (Δgrain yield) at 22 site years. Δgrain yield is defined as grain yield for the 34 kg ha^{-1} fall starter fertilizer N treatment minus the grain yield for the zero starter N treatment.



	Soil NO_3-N 0-15 cm (mg kg^{-1})			
	0-5	5-10	10-15	>15
n	32	14	7	10
	Percentage			
Negative yield response	22	21	14	30
Positive yield response	78	78	86	70
Paid for N ‡	50	36	37	30

† Legend refers to preceding corn N management according to:
Low: 2005 84 kg N ha^{-1}, 2006 68 kg N ha^{-1}, 2007-2009 0 kg N ha^{-1}.
Optimum: 2005 168 kg N ha^{-1}, 2006-2009 135 kg N ha^{-1}.
High Optimum: 2005 no treatment, 2006-2009 202 kg N ha^{-1}, farmer sites rate assigned to high optimum column.
Excessive: 2005 253 kg N ha^{-1}, 2006-2009 269 kg N ha^{-1}.
‡ A 0.204 Mg ha^{-1} grain yield response paid for 34 kg ha^{-1} fertilizer N (N cost \$0.96 kg^{-1}, wheat grain value \$162 Mg^{-1})

Fig. 5.4: Average change in grain yield (Δgrain yield) in response to application of 34 kg ha^{-1} fall starter N at 21 site years where pre-plant soil nitrate (NO_3-N) was ≤15 mg kg^{-1} to 15 cm depth. Δgrain yield is defined as mean grain yield for the 34 kg ha^{-1} fall starter fertilizer N treatment at each site minus the mean grain yield for the zero starter N treatment at the same site. Change in grain yield listed in ascending order.

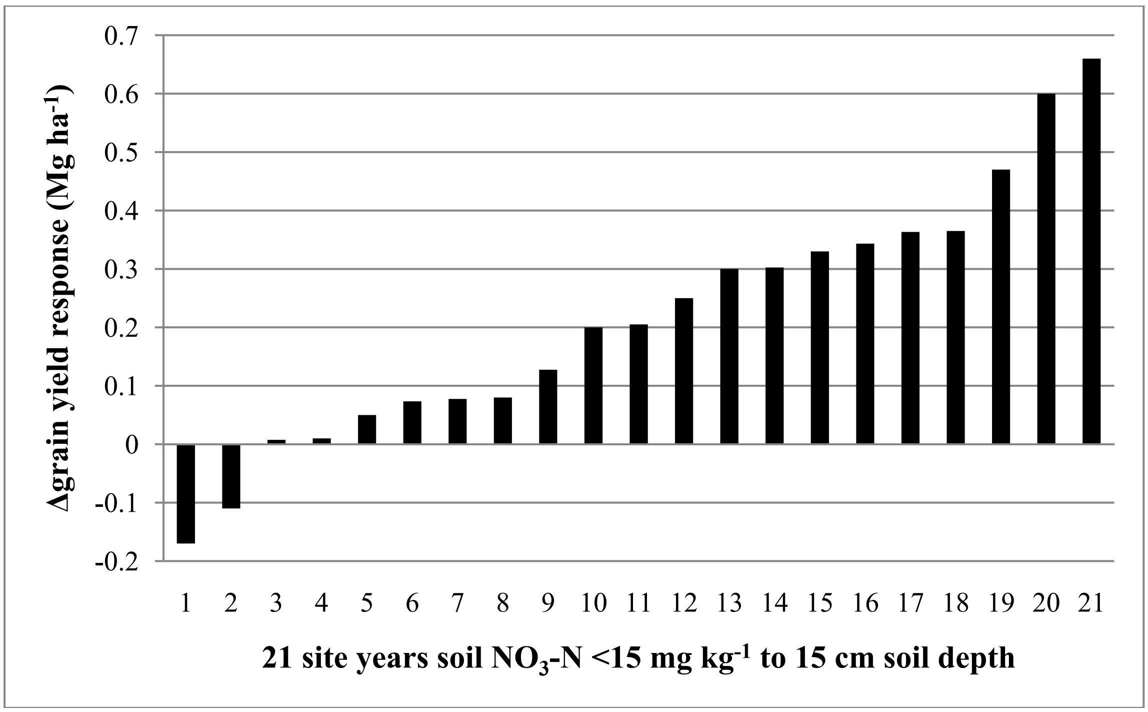
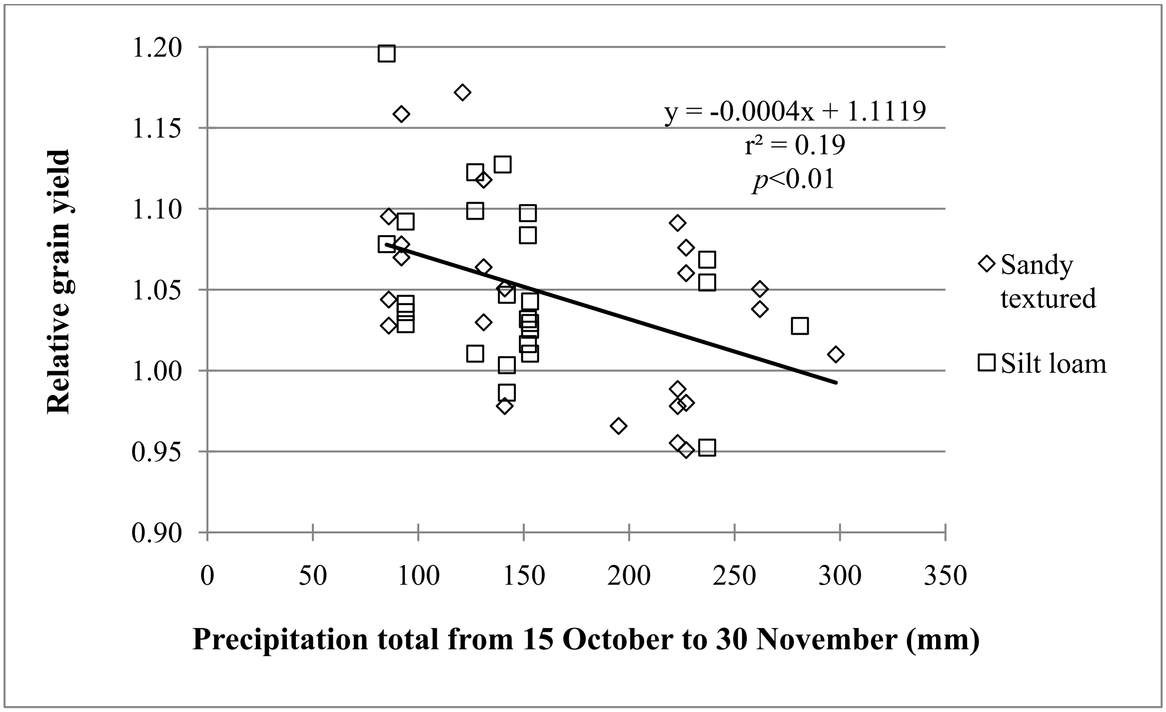


Fig. 5.5: Relationship between post-wheat planting fall precipitation and relative wheat yield (where grain yield for 34 kg N ha^{-1} fall N treatment is expressed relative to yield from the 0 kg ha^{-1} fall starter N treatment) for sites where pre-plant soil residual nitrate (NO_3-N) was ≤15 mg kg^{-1} to 15 cm depth.



Chapter 6: Fall to winter soil nitrate retention and profile distribution in winter wheat: effects of starter and preceding corn nitrogen applications

Abstract

Winter carryover of residual nitrate (NO_3-N) can contribute to the spring nitrogen (N) requirements of winter wheat (*Triticum aestivum*, L.). Nitrogen management in the preceding corn (*Zea mays*, L.) crop and fall starter N applied at wheat planting are potential sources of such carryover NO_3-N. This study examined the effects of preceding corn N and wheat fall starter N applications on mid- to late-winter soil NO_3-N pools and NO_3-N soil profile distribution. Replicated field studies using a randomized complete block split-plot design were established at nine site years on the Maryland Coastal Plain and Piedmont regions. Corn plots that received corn N rates (the main plot factor) of 0, 135, 202, and 269 kg ha^{-1} were established in the spring. Following harvest, residual NO_3-N was measured and wheat was planted. Wheat starter N rates (the split-plot factor) of 0 and 34 kg ha^{-1} were applied, and winter soil samples were collected to assess NO_3-N retention. Corn N fertilization was found to have a significant impact on soil NO_3-N at both fall and winter sampling dates. However, soil NO_3-N levels diminished between fall and late winter, particularly at sandy textured sites. Typically, application of 34 kg ha^{-1} fall starter N did not significantly increase soil NO_3-N levels in the surface 60 cm. Where significantly increased winter NO_3-N was detected, it was concentrated at the deeper sampling increment (30 to 60 cm), with the surface 15 cm being NO_3-N depleted

at all sites. These data indicate potential for carryover NO_3-N contribution to spring wheat growth where NO_3-N remains within the root zone; however, fall starter N should not be applied with the expectation of a significant carryover benefit.

Introduction

The soil profile distribution and retention of carryover NO_3-N in the mid- to late-winter period has important environmental and agronomic implications for winter wheat as well as other crop systems. Application of fall starter fertilizer N to winter wheat is a recommended practice in the Mid-Atlantic (Alley *et al*., 2009; Walker and Taylor, 1998; Sammons *et al*., 1989). The level of soil NO_3-N from the preceding corn crop present at wheat planting is variable. When fall starter N and/or residual soil NO_3-N levels exceed the fall-winter N uptake by the wheat crop, it is subject to leaching. However, where NO_3-N is retained within the root zone it has the potential to affect spring fertilizer N requirements for the wheat.

Residual N levels are a good indicator of whether wheat will respond to application of fertilizer N in climates where NO_3-N leaching from the root zone is minimal. In these situations, sites with low soil residual N levels result in the greatest fertilizer N response (Olson *et al*., 1976; Olson and Swallow, 1984). However, in humid climates, the winter inorganic soil N content is considered more variable and is influenced by total winter precipitation (Meisinger *et al*., 1987). Nevertheless, significant carryover of residual NO_3-N from fall to spring can occur in humid climates (Roth and Fox, 1990; Vanotti and Bundy, 1994; Wall *et al*., 2010). In Wisconsin, Bundy and

Andraski (2004) reported that pre-plant soil NO_3-N in the surface 90 cm was correlated (r^2=0.53) to the economically optimum nitrogen rate (EONR) for wheat.

Adequate spring N availability is important to promote tiller development and to overcome initial yield depressions associated with conversion no-till systems (Weisz *et al*., 2001; Rasmussen *et al*., 1997). Weisz *et al*. (2001) recommended applying fertilizer N at mid-tillering. Similarly, Kratochvil *et al*. (2005) found that the greatest returns for hard red winter wheat in Maryland occurred when the first split of spring fertilizer N was applied at green-up. However, the total spring N requirement may be reduced if significant amounts of carryover NO_3-N are present in the root zone. This is an important consideration given the current N loss reduction goals within the Chesapeake Bay watershed (Maryland Department of Environment, 2010). Failure to consider the soil N supplying capacity when determining N fertilizer rates may lead to inefficient N use and increased pollution potential (Fox and Piekielek, 1978).

Late winter to early spring N applications occur within the groundwater recharge period; thus, they may increase N loss potential to ground-water flow pathways. On the Coastal Plain, these pathways form the dominant link between agricultural systems and surface waters (Boesch *et al*., 2001). Therefore, N losses represent a threat to the Chesapeake Bay. Additionally, the Maryland commodity cover crop program (Maryland Department of Agriculture, 2010), a program that pays producers to not apply fall starter N to small grains, does not permit spring N application before 1 March. The agronomic consequences of adhering to this date will be influenced by how early spring green-up occurs, but, they also may be influenced by the availability of carryover NO_3-N to meet crop requirements. Several researchers have reported that spring N requirements for winter wheat may be influenced by carryover NO_3-N (Scharf and Alley, 1994; Bundy and Andraski, 2004). Furthermore, Meisinger *et al*. (1987) reported that wheat yields and N uptake were significantly influenced by N additions to the preceding corn crop. In an era of increasing regulatory pressure on N usage within the Chesapeake Bay watershed, further examination of mid- to late-winter carryover of NO_3-N for winter wheat is warranted. This mid- to late-winter period precedes the time of rapid N uptake by winter wheat (Baethgen and Alley, 1989). The amount of NO_3-N carryover to this time could reduce spring N requirements for winter wheat.

One of the objectives of this study was to determine if fall soil residual NO_3-N following corn is retained in the soil profile during the fall to winter period. The effect of fall starter N application on mid- to late-winter soil NO_3-N availability was also examined. Additionally, this study examined the mid to late winter soil profile distribution of soil NO_3-N and how this was affected by preceding corn and wheat fertilizer N management.

Materials and Methods

This study was conducted at University of Maryland Research and Education Centers (UMRECs) located on the Maryland Coastal Plain and Piedmont during three wheat production seasons (Table 6.1). The experimental design was a randomized complete block with a split plot arrangement of treatments and four replications. Corn was planted during late April to mid-May at a seeding rate of 73 000 seeds ha^{-1} using a no-till drill at 76 cm row spacing. The main plot factor was corn fertilization, four rates of 0, 135, 202, and 269 kg N ha^{-1} were applied; treatments that were intended to create a range of residual NO_3-N levels post-harvest. All plots, with the exception of the zero N treatment, received 34 kg N ha^{-1} as starter at corn planting with the balance applied as side-dress during corn growth stages V4 to V6 (Ritchie *et al*., 1997). The fertilizer N source was liquid N (30% N as urea-ammonium nitrate solution). Side-dress fertilizer N was applied as a surface band, except at Beltsville and Clarksville in 2009 fertilizer N was injected to 10 cm depth. Corn plots were harvested and wheat was planted using a no-till drill between 13 and 25 October, dates considered within the optimal wheat planting window in Maryland. Seeding rate for wheat was adjusted for a target emerged population of approximately 310 seedlings m^{-2}. One wheat cultivar ('USG 3209') was planted at all sites, except in 2009, when 'Pioneer 25R62' was used. The split plot factor was the wheat fall starter N fertilization. Two N rates (0 and 34 kg ha^{-1}) were applied to wheat split plots within each corn main plot treatment.

Soil sampling occurred twice: once following corn harvest but before wheat planting and once during mid-to late-winter (Table 6.1). Eight 2.5 cm soil cores $plot^{-1}$ were collected in the fall and four soil cores $plot^{-1}$ in the winter. In both cases, sampling depth was 60 cm. Soil cores were divided into 0 to 15, 15 to 30, and 30 to 60 cm increments; air dried at room temperature immediately following collection; and ground to pass through a 2 mm sieve. Soil NO_3-N for each sample was extracted at a ratio of 1:10 in 1 *M* KCl solution by shaking for 30 minutes using an reciprocating shaker (Eberbach Corp., Ann Arbor, Michigan); settling for 30 minutes; and filtering supernatant liquid through grade 42 filter paper (Whatman inc., Buckinghamshire, United Kingdom). Nitrate concentration in soil extract solutions was determined by colorimetric analysis using a continuous-flow ion analyzer (Lachat, 1987). The mass calculation of soil profile

NO_3-N was conducted using the assumption that 60 cm x 1 ha of soil weighs 8.94 x 10^6 Mg (i.e., assuming a soil bulk density of 1.49 g cm^{-3}).

To determine how the soil profile NO_3-N in the surface 60 cm changed between fall and winter sampling, and the effect of corn and wheat N fertilization, repeated measures analysis was conducted. The mixed models procedure of SAS version 9.2 (SAS Institute, Cary, NC) was used to conduct this analysis. This procedure was also used to determine how soil NO_3-N concentration changed with depth due to corn and wheat N fertilization at the winter sampling time. The default error covariance structure (variance components) which assumes independent and identically distributed errors was used for both analyses. When statistical difference ($p \leq 0.05$) was detected by ANOVA, mean comparisons were made using Fisher's protected least significant difference test ($p \leq 0.1$). In all cases means were determined using the lsmeans option of the mixed model procedure.

Results and Discussion

Fall residual nitrate at wheat planting

The amount of N applied to the corn crop resulted in a large variation in fall residual NO_3-N levels at wheat planting (Tables 6.2, 6.3, and 6.4). At all sites, the highest corn N rate (269 kg N ha^{-1}), which was considered excessive, had significantly ($p \leq 0.1$) greater residual NO_3-N levels compared with the 0 kg N ha^{-1} check treatment. However, where manure history (Clarksville 2009) or drought (Clarksville 2008, Beltsville and Wye 2007) were not factors (Tables 6.2, 6.3, and 6.4), there was no significant difference in residual NO_3-N levels between the lowest corn N rate (135 kg N ha^{-1}) and the check treatment. The highest fall residual NO_3-N levels were present at sites with manure history or which were affected by drought. Fall residual NO_3-N levels (Vanotti and Bundy, 1994) influence root zone N loss. Additionally, Fisher *et al*., (2011) reported greatest N uptake by a winter wheat cover crop in Maryland which followed corn where drought reduced production, attributing this to elevated residual NO_3-N in the fall. This suggests that the greatest potential for over-winter sequestration by the wheat crop and loss to groundwater occurs at sites that have high levels of residual NO_3-N due to manure history and/or drought reduced production.

Fall to winter soil profile nitrate change: no wheat starter nitrogen

During the winter of 2007 to 2008, soil residual NO_3-N present in the surface 60 cm tended to decrease between fall and winter sampling dates where no fall starter N was applied (Table 6.2). At Poplar Hill, fall NO_3-N levels were considerably lower compared with the other two sites, and apparent loss and/or sequestration by the wheat was small (3 to 12 kg NO_3-N ha^{-1}). At Poplar Hill, the decrease in NO_3-N levels between fall and winter sampling was significant only following the highest corn N rate (269 kg N ha^{-1}). In contrast, at Beltsville and Wye fall NO_3-N levels were much higher, except for the zero corn N treatment; this was due to drought conditions during summer of 2007 (Table 6.2). At these two sites, a significant decrease in residual NO_3-N in the surface 60 cm was observed between fall and winter where fertilizer N was applied to the corn (Table 6.2). Uptake of NO_3-N by winter wheat is unlikely to have accounted for all of the large decreases observed. Baethgen and Alley (1989) and Fisher (2010) measured fall through winter N uptake by winter wheat and reported that uptake for above ground vegetation was generally in the range of approximately 5 to 30 kg N ha^{-1}. Using the NO_3-N uptake values observed by Baethgen and Alley (1989) and Fisher (2010), it is likely that significant NO_3-N moved below the sampling depth at Beltsville and Wye during the winter of 2007 to 2008, as the fall to winter NO_3-N decrease in the surface 60 cm was unlikely to have been completely sequestered in the wheat biomass. Thus, significant loss to ground water flow systems is likely to occur when fall residual NO_3-N levels are high, even when a wheat crop is present.

Greater reduction in NO_3-N levels during the winter of 2007 to 2008 at Beltsville, compared with Wye, was at least partially due to higher fall NO_3-N levels and more fall-winter precipitation (Table 6.2). In addition, soil texture had a role. Where fertilizer N had been applied to the corn, the percentage of NO_3-N retention in the surface 60 cm of soil in late winter was lower at Beltsville (22 to 25%) compared with Wye (33 to 55%). This is consistent with Hahne *et al*. (1977), who observed greater NO_3-N losses in fine sandy loam soil compared with a silt loam soil and attributed this to greater internal drainage and leaching in coarse textured soil.

Following corn harvest in 2008, fall NO_3-N accumulations were largest at Beltsville and Clarksville (Table 6.3). A significant decrease in soil NO_3-N to 60 cm depth was observed between the two sampling dates at both sites (Table. 6.3). At Beltsville (a loamy sand soil), the significant corn N effect on residual NO_3-N present in the fall was no longer present at the winter sampling date; this outcome was attributed to NO_3-N movement below the 60 cm sampling depth. At Clarksville (a silt loam textured soil), NO_3-N to 60 cm depth also declined significantly between sampling dates. However, contrary to what was observed at Beltsville, a corn N treatment effect was observed at both the fall and winter sampling dates, indicating potential for fall residual

NO_3-N to provide a contribution to the spring N requirement of winter wheat. Both the Wye and Poplar Hill sites had relatively modest fall NO_3-N accumulations in 2008, although a significant corn N fertilization effect was observed. Soil NO_3-N levels remained unchanged at Wye between sampling dates. In contrast, by the winter sampling date at Poplar Hill, soil NO_3-N levels had decreased significantly where no corn N was applied (Table 6.3), to the extent that the corn N treatment effect was not observed at the winter sampling date. This was similar to the findings of Roth and Fox (1990) who reported that differences in soil NO_3-N accumulations due to corn N treatments were diminished between fall and spring sampling dates.

In the fall of 2009, a significant corn N treatment effect on residual NO_3-N levels was observed at both sites (Table 6.4). Due to snow cover in early 2010, the winter sampling occurred in March, which was later than in the two previous years. Soil NO_3-N in the surface 60 cm decreased significantly between fall and winter sampling dates at both sites following the highest corn N rate and following the 202 kg N ha^{-1} corn N rate at Beltsville. At both Beltsville and Clarksville, the corn N treatment effect on soil NO_3-N present in the fall was not detected in March (Table 6.4). Soil NO_3-N concentration in the surface 60 cm increased significantly between the fall and winter sampling dates at Clarksville where no corn N was applied. Since large declines in NO_3-N levels to 60 cm depth were observed following the highest corn N treatments (Table 6.4), it is likely that NO_3-N present in the fall following the zero corn N treatment was depleted over the winter. This suggests that spring N mineralization and nitrification in the surface 15 cm accounts for the increase in NO_3-N levels at the March sampling date. Similarly, Roth and Fox (1990), in a study conducted in Pennsylvania, suggested that mineralization and nitrification prior to spring sampling (24 March to 20 April) may have replaced some NO_3-N lost during the winter.

Across sites and years, the largest decreases in soil profile NO_3-N levels between fall and winter sampling dates occurred where soil residual NO_3-N levels were highest in the fall. Similarly, other researchers have observed winter NO_3-N reductions to be largest where fall levels were high (Bundy and Malone, 1988; Roth and Fox, 1990). However, the winter wheat crop will sequester a portion of the fall NO_3-N, thus reducing environmental loss compared with a winter fallow situation. Data from the present study suggests that significant NO_3-N carryover during the fall through winter period can occur in this region where fall NO_3-N levels are elevated; this is especially the case at silt loam sites, where retention potential appears greater compared with sandy textured sites. This is in agreement with Meisinger *et al*. (1987), who reported that wheat yield and N uptake were significantly affected by preceding corn N fertilizer rates.

Effect of 34 kg ha^{-1} fall starter nitrogen on mid-late winter soil nitrate

When 34 kg N ha^{-1} fall starter was applied, rarely were winter NO_3-N levels significantly higher compared with the no starter treatment (Tables 6.2, 6.3, 6.4), which suggests that little starter-derived NO_3-N is retained over the winter. This is consistent with reports that N use efficiency for winter wheat is low when fertilizer N is applied in the fall compared with spring application (Stanford and Hunter, 1973; Howard and Lessman, 1991). As winter sampling dates generally preceded spring green-up, the fate of this starter N may be accounted for by fall through winter uptake by the wheat crop and/or loss below the 60 cm soil profile sampled. No wheat N uptake measurements were collected in the present study. However, other studies in the region have demonstrated that wheat vegetative uptake (above ground tissue) generally will be from 5 to 30 kg N ha^{-1} by the mid- to late-winter (Baethgen and Alley, 1989; Fisher, 2010). When fall NO_3-N levels were high, such as was observed following the highest corn N rates at several sites (Tables 6.2, 6.3 and 6.4), over winter reductions in soil profile NO_3-N exceeded the reported wheat uptake values, even when no starter N was applied. The change in NO_3-N in the surface 60 cm between fall and winter dates for corn that received fertilizer N ranged from negative 47 to negative 188 kg NO_3-N ha^{-1} when drought affected the crop (Beltsville 2007, Wye 2007 and Clarksville, 2008) (Table 6.2 and 6.3). This amount of change is substantially greater than the highest wheat N uptake of 30 kg N ha^{-1} observed by Baethgen and Alley (1989). As application of fall starter N rarely increased winter soil NO_3-N levels it is likely that it increased NO_3-N losses from the surface 60 cm particularly at sites where losses were greater than wheat N sequestration potential. Thus, application of starter N at sites with high levels of fall residual NO_3-N, and where complete sequestration of this NO_3-N by the wheat crop is unlikely, will serve to compound N losses.

Fall soil NO_3-N levels tended to be relatively low, ranging from 15 to 34 kg N ha^{-1},when the preceding corn N rate was 135 kg ha^{-1} and drought did not occur (Tables 6.2, 6.3, and 6.4). At these sites, N loss potential was relatively low: changes in NO_3-N ranging from negative 26 to positive 3 kg NO_3-N ha^{-1} were observed where no fall starter was applied. When the 34 kg N ha^{-1} starter contribution to the fall N pool is considered, the changes ranged from negative 48 to negative 23 kg NO_3-N ha^{-1}. Thus, at sites where fall residual NO_3-N levels are low, there may be a reasonable expectation that fall starter N will be sequestered in the wheat biomass. At these sites, changes in soil NO_3-N observed between fall and winter were similar to the uptake values reported for winter wheat in the region by Baethgen and Alley (1989) and Fisher (2010). To minimize the environmental impact of applying starter N to winter wheat, pre-plant soil NO_3-N should be measured and starter N applied only based on the reasonable expectation of wheat N uptake exceeding the levels present.

These data indicate that application of fall fertilizer N results in little additional soil NO_3-N availability under winter wheat by mid to late winter. This suggests that fall starter N will provide little contribution to the spring green-up N requirements of the winter wheat crop in the Mid-Atlantic. In the absence of significantly increased levels of soil NO_3-N resultant from starter N application, this N may have moved below the sampling depth, been denitrified, or been sequestered by the wheat crop. It is likely that a combination of retention, leaching loss, denitrification, and additional N sequestration by the wheat crop accounts for the changes observed.

Mid- to late-winter soil profile nitrate distribution

At the winter sampling dates soil NO_3-N concentrations in the surface 15 cm were consistently low (<5 mg kg^{-1}) across sites and years (Fig. 6.1). At Poplar Hill in 2008, residual NO_3-N levels were low and relatively uniform throughout the 60 cm soil profile (Fig. 6.1). Even though treatment effects were observed, they are likely to be agronomically insignificant for spring N availability to the wheat crop. At Beltsville and Wye in 2008, a significant interaction between corn N rate and depth was observed (Fig. 6.1). At these sites, NO_3-N concentrations remained relatively stable throughout the profile following the low corn N rates but increased with depth for the high corn N rates.

There was no significant wheat starter N effect, which suggests that residual effects from the preceding crop are most important in determining carryover NO_3-N levels.

At the winter sampling date in 2009, soil NO_3-N levels were extremely low throughout the soil profile at Poplar Hill, Beltsville, and Wye. At Poplar Hill, a significant corn N by fall starter N interaction was detected. Application of starter N increased soil NO_3-N following the highest corn N rate but not following the other corn N rates (Fig. 6.1). At Clarksville, significant amounts of NO_3-N remained in the surface 60 cm at the winter sampling date. This NO_3-N was concentrated mainly at the deeper sampling increments, which is similar to the pattern observed at the Wye and Beltsville in 2007. The interaction between corn N rate and depth observed at these sites is due to soil NO_3-N concentration either decreasing or remaining stable with depth following the two lower corn N rates but increasing with depth following the two higher corn N rates. This outcome is attributed to little fall NO_3-N being present in the fall to leach through the profile following the 0 and 135 kg N ha^{-1} corn N rates.

In 2010, winter sampling was completed later than in previous years and precipitation amounts between fall and winter sampling were much greater than for the previous years (Table 6.4). This indicates that greater leaching pressure was applied to residual NO_3-N between fall and winter sampling dates. Nevertheless, a significant depth effect was observed at Beltsville, with NO_3-N declining with depth (Fig. 6.1), however, levels were low at all sampling depths. Similarly, at Clarksville, a significant depth effect was detected (Fig. 6.1), with NO_3-N levels in the surface 15 cm higher compared with levels from 15 to 30 cm. Some evidence of increased NO_3-N at the surface was also observed at Beltsville and Wye in 2009 (Fig. 6.1). Higher NO_3-N at the surface is attributed to initiation of mineralization and nitrification close to the surface.

These data demonstrate that little effect of preceding corn or wheat N application is present in the surface 15 cm following winter. This is attributed to leaching and wheat N uptake that occurs during the fall-winter period. Typically, surface 15 cm of soil depleted (< 5 mg kg^{-1}) of NO_3-N between the sampling dates. When carryover NO_3-N attributable to preceding N treatments was present, it consistently declined with depth, which suggests that significant downward migration of fall NO_3-N occurs over the winter period in the region. Given this pattern of NO_3-N migration, the ability of winter wheat to sequester this mobile nutrient during the fall, winter, and particularly spring will depend on the depth of wheat rooting systems. Fortunately, and promising from an environmental perspective, winter wheat establishes a deep rooting system. Kmoch *et al*. (1957) reported that winter wheat roots had reached at least a 90 cm depth by November and that root weight increased in response to additional N availability. Similarly, Daigger and Sander (1976) found that wheat root systems are established mainly during the fall and wheat easily obtained N placed at depths of up to 150 cm. This indicates that winter wheat grown for commodity purposes may provide a significant environmental benefit by sequestering NO_3-N which has moved deep in the soil profile in the spring. This warrants consideration for applying spring N particularly in the context of minimizing environmental loss from the cropping system.

Conclusions

The results of this study indicate that changes in soil profile NO_3-N between fall and winter can be large for a winter wheat crop in the Mid-Atlantic. These changes will be greatest where high levels of soil residual fall NO_3-N are present. Also of importance is the soil texture with sandy textured soils having greater loss potential than finer textured soils. Nevertheless, high or excessive fertilizer N applications made to corn can affect NO_3-N levels in the mid to late winter. Carryover amounts may be large enough to provide a significant contribution to the spring N requirements of the winter wheat crop, especially where fall residual NO_3-N levels are high and winter precipitation is below average. The application of fall starter N provided little additional NO_3-N availability by mid- to late-winter when compared with the zero fall starter N treatment. For this reason, site specific decisions should be made regarding whether fall N availability at planting is adequate for wheat establishment. My results demonstrate that starter N is unlikely to provide a significant contribution to NO_3-N availability to 60 cm depth by the mid- to late-winter. Thus, fall starter N application should not be considered a substitute for careful N management at spring green-up.

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Table 6.1: Details of site characteristics and soil sampling dates for experiments at nine University of Maryland Research and Education Centers.

Farm	Year of study	Latitude	Longitude	Soil taxonomy	Soil series and surface soil texture†	Fall soil sampling date	Winter soil sampling date
Beltsville	’07-‘08	39º 01’ 33” N	76º 50’ 31” W	Aquic Hapludults	Hammonton ls	12 Oct.	23 Jan.
Beltsville	’08-‘09	39º 00’ 45” N	76º 49’ 43” W	Typic Hapludults-Aquic Hapludults	Downer-Hammonton ls	13 Oct.	2 Feb.
Beltsville	’09-‘10	39º 00’ 35” N	76º 49’ 46” W	Aquic Hapludults	Russett-Christiana fsl	25 Oct.	10 Mar.
Clarksville	’08-’09	39º 15’ 53” N	76º 55’ 49” W	Aquic Fragiudults	Glenville sl	17 Oct.	23 Jan.
Clarksville	’09-‘10	39º 15’ 03” N	76º 55’ 50” W	Typic Hapludults	Glenelg l	22 Oct.	18 Mar.
Wye	’07-‘08	38º 54’ 42” N	76º 08’ 38” W	Typic Hapludults	Nassawango sl	11 Oct.	25 Jan.
Wye	’08-‘09	38º 54’ 45” N	76º 08’ 42” W	Typic Hapludults	Nassawango sl	9 Oct.	21 Jan.
Poplar Hill	’07-‘08	38º 21’ 28” N	75º 46’ 51” W	Typic Hapludults	Nassawango sl	16 Oct.	7 Feb.
Poplar Hill	’08-’09	38º 21’ 26” N	75º 46’ 52” W	Typic Hapludults	Nassawango sl	1 Oct.	20 Jan.

† Texture: fsl, fine sandy loam; ls, loamy sand; sl, silt loam; l, loam.

Table 6.2: Soil nitrate (NO_3-N) to 60 cm depth at the fall and winter soil sampling, and change (Δ) as influenced by fall fertilizer nitrogen (N) application under winter wheat cropping 2007-2008 sites.

Site	year	Corn fertilizer N rate	Fall	Winter 0 kg ha^{-1} fall N	Winter 34 kg ha^{-1} fall N	Precipitation 1 May to 31 Aug.	Precipitation 1 Oct. to 31 Jan.
		kg N ha^{-1}	———NO_3-N (kg ha^{-1})———			———mm———	
Beltsville	'07-'08	0	29 a j†	6 a h	6 a h	220	334
		135	105 a i	23 b gh	23 b h		
		202	196 a h	41 b gh	34 b h		
		269	251 a g	63 b g	92 b g		
Poplar Hill	'07-'08	0	13 a h	10 a g	13 a h	335	189
		135	15 a h	11 a g	14 a h		
		202	19 a gh	15 a g	19 a g		
		269	25 a g	13 c g	19 b g		
Wye	'07-'08	0	35 a j	9 b h	15 ab i	251	286
		135	81 a i	27 b h	44 b hi		
		202	119 a h	55 b gh	60 b gh		
		269	152 a g	84 b g	93 b g		

† Means followed by different letters are significantly different according to: a, b, c – means compared within the row; g, h, i, j – means compared within the column for each location ($p<0.1$, F-protected LSD).

Table 6.3: Soil nitrate (NO_3-N) to 60 cm depth at fall and winter soil sampling, and change (Δ) as influenced by fall fertilizer nitrogen (N) application under winter wheat cropping 2008-2009 sites.

Site	year	Corn fertilizer N rate	Fall	Winter 0 kg ha^{-1} fall N	Winter 34 kg ha^{-1} fall N	Precipitation 1 May to 31 Aug.	Precipitation 1 Oct. to 31 Jan.
		kg N ha^{-1}	———NO_3-N (kg ha^{-1})———			———mm———	
Beltsville	'08-09	0	22 a j†	7 b g	8 b g	505	232
		135	34 a i	9 b g	6 b g		
		202	56 a h	10 b g	11 b g		
		269	78 a g	9 b g	15 b g		
Poplar Hill	'08-09	0	22 a h	12 ab g	10 b h	494	285
		135	29 a gh	11 b g	13 b h		
		202	34 a gh	12 b g	17 b gh		
		269	50 a g	12 b g	27 b g		
Wye	'08-09	0	16 b h	19 ab h	22 a h	439	329
		135	20 b h	23 ab h	26 a h		
		202	24 a g	23 a h	25 a h		
		269	29 b g	29 b g	40 a g		
Clarksville	'08-09	0	22 a i	14 a h	21 a h	189	219
		135	65 a h	18 b gh	24 b gh		
		202	146 a g	38 b gh	46 b gh		
		269	159 a g	51 b g	64 b g		

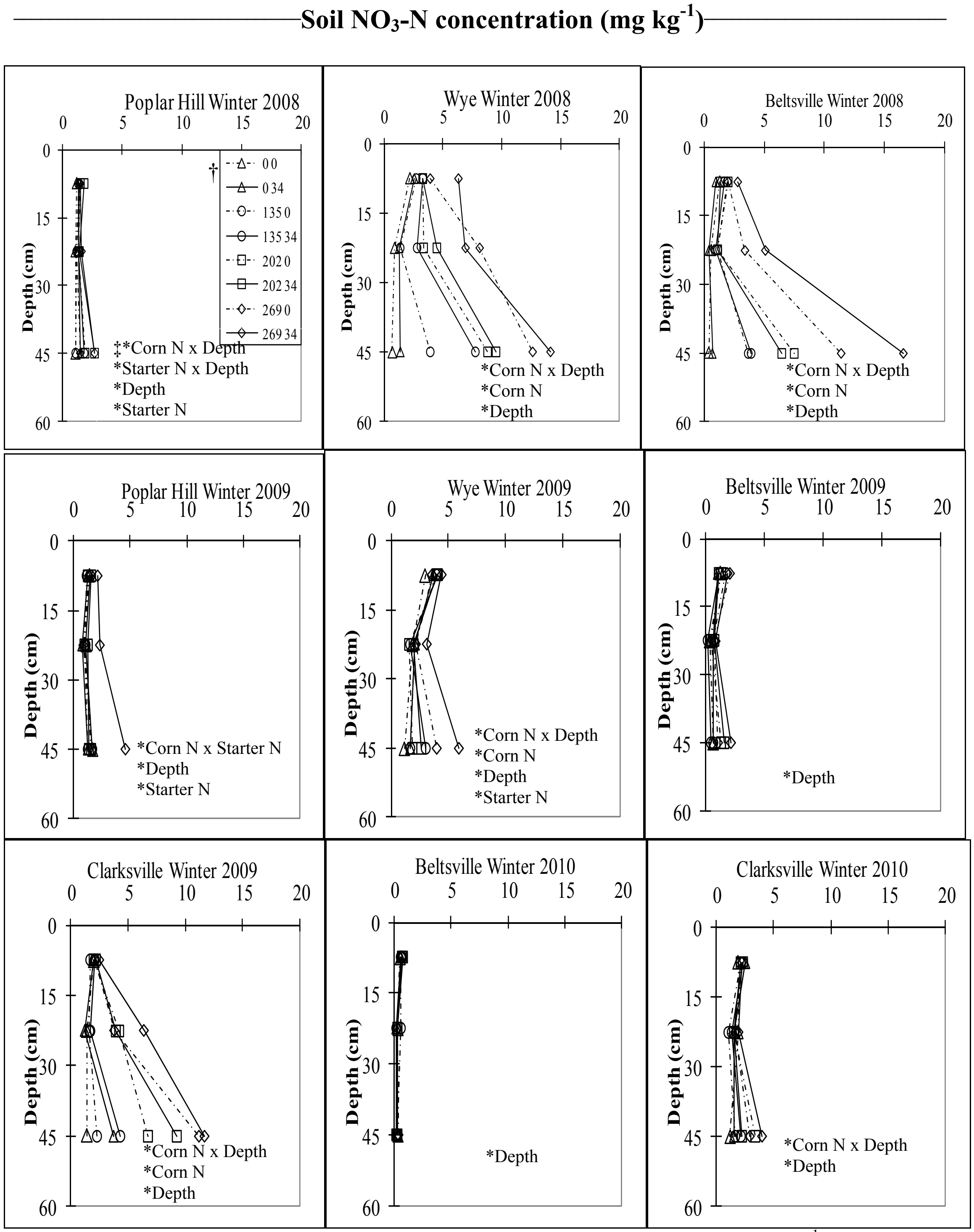
† Means followed by different letters are significantly different according to: a, b, c – means compared within the row; g, h, i, j – means compared within the column for each location ($p<0.1$, F-protected LSD).

Table 6.4: Soil nitrate (NO_3-N) to 60 cm depth at fall and winter soil sampling, and change (Δ) as influenced by fall fertilizer nitrogen (N) application under winter wheat cropping 2009-2010 sites.

Site	year	Corn fertilizer N rate	Fall	Winter 0 kg ha^{-1} fall N	Winter 34 kg ha^{-1} fall N	Precipitation 1 May to 31 Aug.	Precipitation 1 Oct. to 31 Jan.
		kg N ha^{-1}	———NO_3-N (kg ha^{-1})———			———mm———	
Beltsville	'09-'10	0	7 a i†	11 a g	8 a h	552	639
		135	22 a i	15 ab g	8 b h		
		202	54 a h	9 b g	12 b gh		
		269	102 a g	11 b g	15 b g		
Clarksville	'09-'10	0	16 b i	35 a g	35 a g	367	542
		135	34 a hi	34 a g	45 a g		
		202	57 a h	49 a g	41 a g		
		269	132 a g	42 b g	55 b g		

† Means followed by different letters are significantly different according to: a, b, c – means compared within the row; g, h, i, j – means compared within the column for each location (p<0.1, F-protected LSD).

Fig. 6.1: Soil nitrate (NO_3-N) concentration prior to spring green-up under winter wheat as affected by depth, preceding corn nitrogen (N), and fall starter N fertilization.



† The first number is the corn N rate and the second number is fall starter N rate (kg N ha^{-1}).
‡ * Indicates that the effect is significant ($p \leq 0.05$).

CH 7: Conclusions

Using late-season corn measurements to assess residual nitrate and corn nitrogen management

The results observed in this study concur with others who have found that late-season green leaf ratings, chlorophyll meter readings, and the normalized difference vegetative indices (NDVI) collected from the corn (Zea mays, L.) canopy are useful for assessing corn nitrogen (N) management. However, prior studies did not examine the relationship of these measurements with post-harvest soil residual nitrate (NO_3-N) accumulation. Although none of the corn canopy measurements were effective for quantifying residual NO_3-N accumulation, they were useful for identifying sites where drought reduced production. This is significant because the drought sites typically had post-harvest soil residual NO_3-N accumulations > 50 kg ha^{-1} compared with < 50 kg ha^{-1} where drought did not occur. Thus, drought sites pose the greatest N loss risk.

The corn stalk nitrate test (CSNT) is a post-mortem test used as a tool to identify whether N availability to the corn crop was excessive. It is commonly accepted that CSNT values >2.0 g NO_3-N kg^{-1} indicate that excessive N was available during the growing season. However, the results of this study were found to concur more closely with findings in Pennsylvania that determined a CSNT value of 0.25 g NO_3-N identifies N sufficiency. Furthermore, although the test is advocated as a tool for reducing N losses from corn production, little information is available detailing the relationship between CSNT values and soil residual NO_3-N. That relationship was examined in this study and it was determined that these two variables were positively correlated (r^2=0.41).

Post-corn harvest soil residual nitrate and its soil profile distribution in Mid-Atlantic corn production

Practices which minimize N loading to corn, such as applying the economically optimum nitrogen rate (EONR), have potential to reduce post-harvest soil NO_3-N accumulation and loss. Across study sites the EONR ranged from 0 to 256 kg N ha^{-1}. On average, the EONR reduced fertilizer N loading by 24 kg ha^{-1} compared with the yield maximizing N rate. Additionally, the EONR reduced post-harvest soil residual NO_3-N to 30 cm by 6 kg ha^{-1} (16 sites) and soil inorganic N to 60 cm depth by 10 kg ha^{-1} (10 sites) compared with the yield maximizing N rate. Application of EONR is a good strategy for maximizing profitability and minimizing N accumulation and loss. Variable precipitation, however, makes choosing the EONR for dryland corn during the early to mid corn vegetative growth stages extremely challenging. The occurrence of drought was an important factor in determining post-harvest soil NO_3-N accumulation and loss potential.

When the EONR was exceeded, post-harvest soil residual NO_3-N levels tended to be elevated. The University of Maryland Extension service recommends application of 18 kg N Mg^{-1} grain yield. Exceeding this ratio also proved to be a useful indicator of elevated post-harvest soil residual NO_3-N. Post-harvest soil residual NO_3-N tended to be most concentrated in the surface 15 cm when fertilizer N was surface applied, especially at silt loam sites. This outcome is positive in terms of availability of N either for subsequent fall planted small grains or for recovery by cover crops in a system where optimum N rates are exceeded periodically.

Fall starter nitrogen management for winter wheat

Farmers frequently ask whether it is economical to forgo application of fall starter N to winter wheat. This study revealed that wheat yield response to fall starter N is highly variable. The probability of attaining an economic yield response to application of 34 kg ha^{-1} fall starter N tended to decrease with increasing soil NO_3-N. Pooled data from sites where soil NO_3-N levels were >15 mg kg^{-1} in the surface 15 cm had no yield response to application of 34 kg N ha^{-1}.

Even when soil NO_3-N levels in the surface 15 cm were low (≤15 mg kg^{-1}), yield response was quite variable, ranging between negative 0.17 to positive 0.66 Mg ha^{-1}. Additionally, yield response decreased with increasing post-planting fall precipitation. Pooled data from 21 sites where soil NO_3-N levels were ≤15 mg kg^{-1} in the surface 15 cm revealed a significant grain yield response (0.2 Mg ha^{-1}) to application of 34 kg ha^{-1} fall starter N.

Increasing the fall starter N rate above 34 kg N ha^{-1} did not increase grain yield. Application of 17 to 34 kg fall starter N was agronomically optimal where soil NO_3-N levels were ≤15 mg kg^{-1} to 15 cm depth. However, the Maryland commodity cover crop program provides a significant economic incentive to forgo application of fall N. Consequently, fall starter N application was not economical at the majority of sites in this study.

Fall to winter soil nitrate retention and profile distribution in winter wheat: effects of starter and preceding corn nitrogen applications

Between fall and winter, large decreases in soil profile NO_3-N to 60 cm depth were observed to occur for the winter wheat crop. These decreases were greatest for sites with coarse textured soils and where fall soil residual NO_3-N levels were high. Nevertheless, high or excessive fertilizer N application to the corn crop affected NO_3-N levels in the mid to late winter. It is surmised that these carryover amounts at sites where fall residual NO_3-N levels are high and winter precipitation is below average, may be large enough at times to provide a contribution to the spring N requirements of the winter wheat crop.

The application of fall starter N, compared with no fall starter N, provided little additional NO_3-N availability to 60 cm depth by mid- to late-winter. For this reason, site specific decisions should be made regarding whether fall N availability at planting is adequate for wheat establishment. This research demonstrated that fall starter N application is unlikely to provide a significant contribution to NO_3-N availability to 60 cm depth by the mid- to late-winter. Fall starter N may have been subject a combination of uptake by the wheat, leaching below the sampled depth, and denitrification.

Recommendations

Typically, when drought reduces corn production, a significant amount of post-harvest soil NO_3-N accumulation will occur. To maximize N retention, priority should be given to planting cover crops at these sites. Drought impacted sites can be identified during the mid-reproductive growth stages of corn using NDVI measured remotely from either aerial or satellite imagery. This information could be used to target sites in a region for planting cover crops and for targeting incentives to farmers who have sites with the greatest N loss risk.

This study indicates a lower CSNT level than the widely accepted upper bound of the CSNT sufficiency range (2.0 g NO_3-N kg^{-1}) may identify N sufficiency for corn in Maryland. Assessment of appropriate CSNT recommendations for Maryland, which consider post-harvest soil residual NO_3-N accumulation, in addition to corn yield, is needed, especially in light of the current emphasis on reducing N losses to the Chesapeake Bay.

Application of the EONR in corn production will maximize profits and reduce N loading, accumulation, and loss. However, without irrigation, corn yields in Maryland are prone to large annual fluctuation. This is problematic, as fertilizer N is typically applied in the early vegetative growth stages with no knowledge of growing season moisture availability. This problem needs to be addressed, perhaps by delaying application of a portion of the total fertilizer N rate until the late-vegetative or early-reproductive growth stages; a time when more is known about moisture availability for the crop. However, machine capability to traverse the crop later in the season without causing damage is currently a practical constraint on this approach.

Where the EONR or the University of Maryland Extension recommendation of 18 kg N Mg^{-1} grain is exceeded, elevated post-harvest residual soil NO_3-N is most likely to occur. At these sites, soil testing to determine NO_3-N availability should be conducted before applying fall starter N to a following commodity small grain. If small grains are not planted, these sites should be prioritized for early establishment of cover crops to reduce N loss.

Fall starter N is unnecessary where soil NO_3-N levels exceed 15 mg kg^{-1} to 15 cm depth. At sites where NO_3-N levels are ≤15 mg kg^{-1}, application of 17 to 34 kg N ha^{-1} fall starter N is warranted. However, in the majority of cases, forgoing the starter N application and participating in the Maryland commodity cover crop program (which pays \$62 ha^{-1} in 2010) provides the greatest net return.

Large over winter reductions in soil NO_3-N occur under winter wheat where levels are high in fall. Starter N application does not significantly increase winter soil NO_3-N carryover. Consequently, fall starter N should not be applied at sites which have fall soil NO_3-N levels exceeding the N requirements of the wheat crop as they are likely to compound N losses.

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