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Nitrogen Variability: A Need for Precision Agriculture

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Abstract: Nitrogen (N) variability can have a negative impact on many production practices as well as having a negative influence on the environment. Nitrogen can be highly variable, both spatially and temporally. This is due to the N cycle being such a dynamic system. Producers have to change management practices to account for this variability. One way to manage N variability is the implementation of precision management practices. Scale of N variability is important, when implementing precision management. In some sites, the resolution of N variability is too fine to implement traditional precision agriculture management, such as management zone soil sampling, therefore remote sensing needs to be implemented. Many ground-based remote sensors are able to detect fine resolution differences however, delays between sensing and implementing management practices makes them flawed. Therefore, on-the-go sensors that indirectly measure nutrient status by plant tissue can be utilized to minimize this downtime. Many of these sensors are available, such as the Greenseeker™ and the Crop Circle™. Implementing these practices has been shown to increase the N use efficiency in crops therefore increasing potential yield and decreasing environmental hazards.

Key words: Nitrogen, spatial variability, temporal variability, precision agriculture, remote sensing, precision farming, site-specific management, nitrogen use efficiency, Greenseeker™, Crop Circle™

INTRODUCTION

Nitrogen is often a limiting growth factor in soil systems (Ketterings *et al*., 2003). After water, N is generally the most limiting factor in crop production systems. Nitrogen is an essential component of proteins therefore, it is considered an essential macronutrient. Plants demonstrate a N deficiency with chlorosis of the lower leaves, stunted growth and eventually necrosis. Not all N in the soil is plant available. For agriculturalists, variability of soil N is not solely dependent on the variability of total soil N, but also plant available N. Plants can only uptake inorganic forms of N such as, nitrate (NO_3^-) and ammonium (NH_4^+) (Havlin *et al*., 2005).

Once N is applied to the soil it can be lost through many different routes including volatilization, leaching, denitrification and immobilization (Havlin *et al*., 2005). These different losses, which can occur throughout the soil system can create pockets of low plant available N. Nitrogen that is applied to the soil as fertilizer and is not taken up by the plant is an economic loss for the producer (Doerge, 2002). Excess N can be a threat to the environment (Doerge, 2002). This economic loss and environmental concern can vary in severity depending on both spatial and temporal variability of plant available N. However, N is not solely added to the soil by the application of fertilizers. Johnson and Raun (2003) found that non-fertilized control plots showed a high amount of variation in the amount of soil-supplied N. Nitrogen can also be added through mineralization and atmospheric deposition, which can vary spatially and temporally (Havlin *et al*., 2005).

The use of site-specific management, including precision agriculture, can help to alleviate the problems of spatial and temporal variability, which are either the over application or the under application of N to the soil. Precision management applies fertilizer only in N deficient areas of the field.

Variability of nitrogen: Soil N can have high spatial variability. Soil N has been shown to vary over the landscape in both natural and tilled soils (Bennett and Adams, 1998; Gallardo and Parama, 2007; Harris, 1998; Moulin *et al*., 2002). Gallardo and Parama (2007) reported that soil N showed spatial variability in well developed natural grassland soils and less developed shrubland soils, unlike other essential plant nutrients. Tsegaye and Hill (1998) reported that soil N was moderately variable in intensively tilled soils. Tsegaye and Hill (1998) also noted that plant biomass variability was correlated to soil NO_3-N. Moulin *et al*. (2002) reported that soil NO_3-N was highly variable over the landscape within distinct yield zones, zones where yield was not significantly variable.

In addition to varying spatially, soil N can show high variability within seasons and between years. Cahn *et al*. (1994) reported that soil N can show temporal variability.

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They suggested that the use of NO_3-N was not a good estimate of plant available N, in site-specific management, due to spatial patterns not highly correlated over long time intervals. This illustrates the high amount of variability that soil N can show within a single growing season. This high amount of temporal variability is one of the main reasons that trying to predict fertilizer requirement by soil testing can be difficult. Harris (1998) found that soil N varied between agricultural producers, within fields and between years within the same field. Harris (1998) reported that in one particular landscape, soil N was highly variable over time and space. Moulin *et al.* (2002) also found that NO_3-N could be highly variable between years within yield zones, however not significant. Temporal variability must be accounted for, when developing a nutrient management plan. Continually applying the same rate of N over the landscape yearly could be highly detrimental to both producer profit and the surrounding environment.

The scale of N variability is also important for determining management zones, which can be treated similarly. Robertson *et al.* (1988) found that N availability was highly variable and tried to determine the scale of variability using a semi-variogram. Semi-variogram range and nugget variances are a tool that can be used to determine spatial variability (Webster and Oliver, 1992). Robertson *et al.* (1988) found nugget variances of 27-37%; indicating scale variation >1 m. They also reported that N variability did not occur in a uniform distribution throughout the soil but instead showed swales, areas of high soil N. These different patterns of high N throughout the soil may indicate that soil physicochemical properties are also highly variable to include texture, Soil Organic Matter (SOM) and slope. Wang *et al.* (2007) found, based on nugget values that the scale for variability was <5 m. Solie *et al.* (1999) reported that determining the amount of some soil variables, such as N, at intervals of >50 m would miss important short distance changes. Solie *et al.* (1999) noted that soil N can show variability down to the meter or sub-meter level. Small scale variability indicates that measuring soil N at intervals of >1 m will not account for some variability in soil N. This fine of a scale for measuring N variability might not be economical for agricultural producers to achieve but variability needs to be considered, when attempting to create management zones.

Nitrogen variability can also be found outside of the immediate rooting zone (top 15 cm). Ganawa *et al.* (2003) found that total soil N showed high variability in the topsoil (0-20 cm) and subsoil (20-30 cm). They found that the scale of N variability changed with depth of the sample and reported that soils collected from 0-20 cm were similar along a 0.46 km transect, whereas soils collected from 20-30 cm were similar along a 4.55 km transect. This indicates that the soil and chemical process within the upper 20 cm are heavily influencing soil N variability. The stability of N also increases with increasing depth to 30 cm, in this study. This zone of highly variable soil may change with both landscape and variable land use.

Soil microbiology plays a large role in the variability of soil N and its many forms. Through many natural processes plant growth may be stimulated (by providing usable forms of soil nutrients), or inhibited (by immobilizing available soil N) (Hoskinson *et al*., 1999). Robertson *et al.* (1993) found that the mineralization (conversion of Organic N to plant available forms) rate differed depending on whether the site was cultivated or uncultivated. They found that in virgin sites, N mineralization tended to be patchier than cultivated sites. Hirobe *et al.* (1998) agreed, reporting that N transformation processes did not show a clear gradient throughout the soil. Areas of high transformation and low transformation were present in the soil with the transition zone in between showing areas of patchiness between both high and low rates of N transformations. Wang *et al.* (2007) found that N transformations in the soil, especially nitrification and mineralization, were correlated to topography in a subtropical forest in southwest China. They found that mineralization and nitrification rates were higher at lower elevations. Verchot *et al.* (2002) also found that lower regions showed higher rates of mineralization and nitrification. Higher available N might be due to deeper and moister soils present in lower regions.

Precision agriculture: With many factors influencing N variability, it can be difficult to adjust management practices. Also, the scale at which it has been shown that N can be highly variable can provide an economic obstacle for producers, when trying to implement nutrient strategies to manage in-field variability. One land management tool for considering variability is Site Specific Management (SSM). Site-specific management has been shown to improve N Use Efficiency (NUE) and profitability (Sawyer, 1994; Wollenhaupt and Buchholz, 1993). Johnson and Raun (2003) documented that in long term corn and wheat trials, plots that did not receive any fertilizer N showed a high amount of variation in N being supplied by the soil. They documented a need for quantifying N mineralization and deposition throughout the year, when determining mid-season N rates. Traditional means of determining in season N requirements are usually based on soil samples or tissue sampling (Magdoff, 1991; Tyner and Webb, 1946). These means of determining optimum mid-season N can be very costly, labor intensive and intrusive. Also, these means of N determination cause a time lag between sampling and determining optimal N. A more streamlined determination method of mid-season N is necessary for precision agriculture and SSM. Remote sensors have been used to help accurately determine in-season N-rates, weed detection, water stress and biotic stresses (Raun *et al.*, 2002; Raun *et al.*, 2005; Wang *et al.*, 2007; Hunt and Rock, 1989). Site-specific management can use sensors to determine the amount of mid-season soil N that is present at a given site. Adamchuk *et al.* (2004) gave an overview of soil sensors that are available for determining the amount of soil NO_3-N and total soil N. They reported that electrical, electromagnetic, optical, radiometric and electrochemical sensors are used for sensing residual soil NO_3-N.

Lund *et al.* (1999) and Colburn (1999) reported that the use of Electrical Conductivity (EC), from electrical and electromagnetic sensors, could be used to determine soil N levels. However, other soil physical characteristics can also potentially affect the readings. Lund *et al.* (2001) reported that the use of EC readings, in a field in Louisiana, could help to devise a N recommendation without soil sampling however, previous knowledge of the field would be necessary.

Ehsani *et al.* (1999) constructed both laboratory and field experiments to determine if the use of optical sensors in the Near Infrared (NIR) wavelengths could determine soil NO_3-N levels. They successfully determined soil nitrate content using NIR spectroscopy and found the most successful wavelengths were between 1800 and 2300 nm. However, due to the influence of other soil factors, field calibration is necessary to map soil NO_3-N level variation over large areas. Ehsani *et al.* (2000) found that the NO_3-N ion signature was not present in the NIR region but mid-infrared wavelengths were effective for determining soil nitrate levels. They reported that a wavelength of approximately 7194 nm produced a prominent NO_3-N peak.

Both electric or electromagnetic and optical sensors have been a relatively indirect means of determining soil N levels. The use of electrochemical sensors and more specifically the use of Ion-Selective Field Effect Transistors (ISFET) have been evaluated as a possible technique for direct real-time measurement of soil ions (Adsett *et al.*, 1999; Birrell and Hummel, 2000; Loreto and Morgan, 1996; Yildirim *et al.*, 2003). Laboratory tests indicate that these sensors can give accurate, real-time soil NO_3-N levels but field tests have been unsuccessful.

In recent years, vegetative spectral reflectance has been used to successfully quantify N variability (Raun and Johnson, 1999; Graeff and Claupein, 2003; Osborne *et al.*, 2002; Moges *et al.*, 2004). Instead of identifying a direct measurement of total or available N, the use of vegetative remote sensors obtain an indirect measure of the nutrient status of growing plants by obtaining reflectance measurements at various wavelengths. Shafri *et al.* (2006) used red edge technology to analyze different age and vegetative types. Red edge technology senses at the break between visible wavelengths and NIR wavelengths (680-740 nm). Datt (1998) reported that the green wavelength (550 nm) was sensitive for determining the pigment content of Eucalyptus leaves. While such approaches show promise, limited wavelength data is currently available for proving their utility among multiple crops. The use of a vegetative index based algorithm equation is a useful means of summarizing reflectance data. One of the most commonly used vegetation indices is the Normalized Difference Vegetative Index (NDVI). Normalized difference vegetative index is the ratio between visible red reflectance and NIR reflectance (Eq. 1) (Weier and Herring, 2009).

$$\text{NDVI} = \frac{(\text{NIR-RED})}{(\text{NIR+RED})} \qquad (1)$$

Raun *et al.* (2002) used NDVI to make predictions that could determine an estimate of yield with no additional N, the response of a crop to additional N application and estimate yield with additional N application. Raun *et al.* (2002) conducted a study to determine if using these predictions to set mid-season N fertilization rates helped to increase efficiency compared to using a flat N-rate over four separate wheat fields. They found that when using an in-season estimate of yield and Response Index (RI) to develop N-rates, NUE increased by up to 15%. Plant *et al.* (2000) used NDVI from aerial photography to detect N stress in cotton, even N stress that did not significantly decrease cotton lint yields.

Although, detecting variable N uptake by plants via satellites has been successful, there are drawbacks. One potential alternative to using spectral reflectance to determine mid-season N rates is the use of ground-based proximal sensors. Ground based sensors are advantageous as they limit the effects of cloud cover, eliminate delay between sensing and obtaining the data and provide ultimate control of the sensing area (Rataj *et al.*, 2007).

Two ground-based sensors that have been tested regularly are the GreenSeeker™ (N-Tech, Ukiah, CA, USA) and the Crop Circle (Holland Scientific, Lincoln, NE, USA). Even though both of these sensors are a good means to determine mid-season NDVI readings, research has shown that there is possible difference in their readings (Sudduth *et al*., 2005). Discrepancies exist between the GreenSeeker and the Crop Circle for readings taken at dusk (1800 h). However, when data points are normalized within each field, the sensors respond similarly.

Once the spatial variability of the mid-season N has been obtained, Variable Rate Technology (VRT) can be implemented. Varible rate technology only supplies soils with the amount of N they need, which helps decrease costs and possible environmental contamination. Raun *et al*. (2005) found that using a sensor-based variable rate N application (instead of a flat N-rate application) increase NUE by 15%. Welsh *et al*. (2003) found that N application based on shoot densities (increasing N application to areas with high shoot densities and decreasing N applications to areas with low shoot densities) resulted in an increase of 0.36 t ha^{-1} compared to traditional barley production practices. Babcock and Pautsch (1998) reported that when supplying a uniform rate of N over 240 sampled fields, 66% of the fields received an oversupply of N and 4% were undersupplied with N. Therefore, only 30% (72) of the fields received optimal N supplies. Babcock and Pautsch (1998) found that implementing VRT would increase net returns by $1.19-6.83 by decreasing production costs and increasing yields, at the county level. Wang *et al*. (2003) found that the use of VRT could increase yields and decrease the impact on water sources. However, VRT does not always show the highest economic benefit compared to uniform N-rates. If soils are not highly variable, the increased cost of the technology may decrease net return. Wang *et al*. (2003) also found that within some fields a uniform rate of N either did not significantly decrease or increase corn grain yields.

Need for further research: Future research on this topic should focus on the use of remote sensing to further determine nutrient stress. This research should evaluate ground-based sensors and test the use of different wavelengths to determine N stress or chlorophyll content in living tissue. Further investigation of known N-related wavelengths and others, such as green and blue visible wavelengths might provide new utility of remotely sensed data. In addition to trying to develop other wavelengths for usage, more crops need to be evaluated to determine their feasibility for using remote sensing to determine their mid-season N level. As N prices increase, new crop varieties are developed and environmental variables change, a continuous economic analysis needs to be conducted to help producers determine if it is economical to implement remote sensing precision agriculture techniques.

CONCLUSION

Overall, further research in this field of N variability will be needed. With world-wide NUE values of approximately 33%, increasing this value by 20% would be worth about 26 billion dollars (Raun and Johnson, 1999). With the population continuing to rise and the amount of arable land decreasing, increased technology and increased efficiency will be needed to continue to feed the people of the world.

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