Nitrogen Over-use, Under-use, and Efficiency

J.L. Hatfield[1] and J.H. Prueger[1]

[1]USDA-ARS National Soil Tilth Laboratory, 2150 Pammel Drive, Ames, Iowa 50011 USA Email: hatfield@nstl.gov

Abstract
Nitrogen is a critical element for plant growth and plant response to added nitrogen (N) has proven to be a valuable agronomic practice. However, N is subject to losses from a number of pathways of which leaching of nitrate is one of the most important because it is extremely mobile leading to increases in nitrate concentrations in surface and ground water. These detections are often attributed to application rates to crops that exceed agronomic needs. Nitrate in water is a world-wide problem and agriculture is being asked to develop farming systems that will reduce the leaching of nitrate from fields and decreases both the concentration and load of nitrate in water. Nitrogen fertilizer use in the world continues to increase in many countries and has remained relatively constant for the past 15 years in Western Europe and the United States. Nitrogen Use Efficiency (NUE), expressed as grain production per unit of N applied, has shown a decrease for all countries. Grain production within each country shows a linear increase with N applied. Management of N in farming systems is difficult because of the interactions between soil mineralization potential, soil water availability, and the type of crop grown. An example of the interaction between N use and water on yield is shown in a detailed study on maize (*Zea mays* L.) in Iowa. Yield response to N showed a decrease with N rates above 116 kg ha^{-1} due to water deficits during grain-filling that reduced yield and water use efficiency. Increasing N rates decreased the yield variation within fields without increasing the yield. Management of N within fields can be improved through an analysis of the soil organic matter content and the soil water holding capacity. Integrating soil water with N management will increase the efficiency of N use and decrease the environmental impact of agriculture.

Media Summary
Nitrogen (N) is necessary for plant growth and the increasing world population increases the demand for more food production. Nitrogen, as nitrate in water is an environmental problem and agriculture has a responsibility to develop practices that increase the efficiency of nitrogen use by crops. Adoption of new management techniques that are based on water and nitrogen use efficiency (NUE) will enhance our ability to efficiently produce food and fiber around the world.

Keywords
Nitrogen use efficiency, water use patterns, water use efficiency, cropping systems, spatial variability, nitrogen management

Introduction
Nitrogen is one of the critical elements essential for life. However, it is also one of the most complex elements when one considers all of the potential forms and processes involved in the N cycle. Keeney and Hatfield (2001) summarized the historical perspective on the N cycle and world patterns for N use to show that N use continues to increase. Data from the Food Agricultural Organization (FAO) on N use shows the largest increases are in developing countries while developed countries have fairly consistent levels of N use for the past two decades (FAO, 2000). Nitrogen fertilizer consumption by agriculture is shown in Fig. 1 for six regions throughout the world. China has shown a linear increase in N fertilizer use since 1976 with a nearly level use since 1996 while Western Europe and the United states have had no significant change in annual N use since 1978 (Fig. 1). Increased human population will require increased food production and Bouwman and Booji (1998) suggest that global cereal production will increase to meet the increasing demand with the result being N transport among regions. To meet increased protein requirements will require either more N inputs to produce grains and forage or increased efficiency of N use. Smil (1999) reached a similar conclusion on global N cycles and stated N use will increase to meet the demands for food supply. van Egmand et al. (2002) evaluated the N budget for Europe and concluded that the NO_3-N levels were increasing and that N losses were due to denitrification, emission of NH_3 and NO_y, and exported products. In a similar study for Asia, Zheng et al. (2002) found that environmental N enrichment are due to the increasing demand for food supply and one method to reduce this excess was to reduce the application rate of inorganic N fertilizers. Richter and Roelcke (2000) examined central

Europe and China farming systems and N use and found N surpluses in Germany of 110-130 kg N ha^{-1} yr^{-1} and in the loess plateau of China of 125 to 230 kg N ha^{-1} yr^{-1}. These surpluses were related to water quality problems in both surface and ground water. Increasing concern about the environmental impacts of nitrate leaching into ground water or movement into surface water raises questions about the need to re-examine the amount of N used in crop production and whether increases in efficiency can reduce environmental problems.

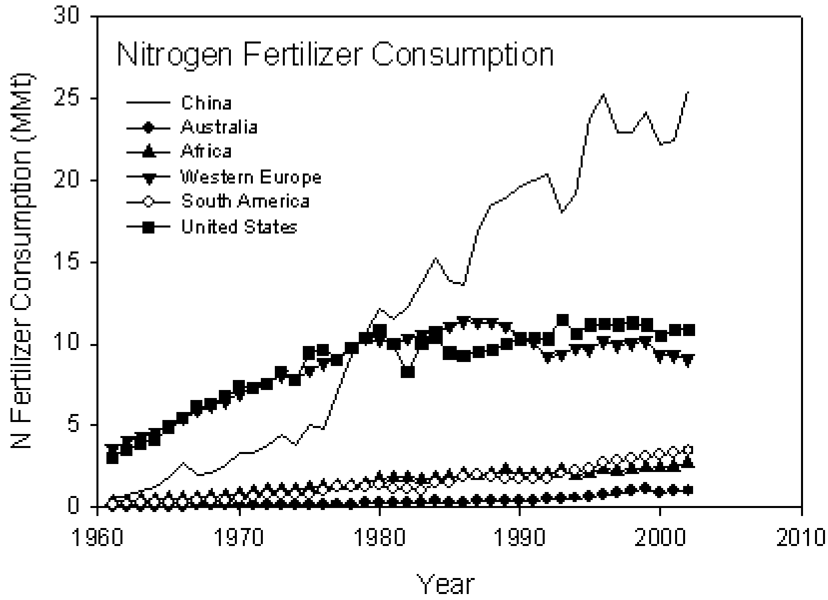

Figure 1. Nitrogen fertilizer consumption for five regions throughout the world for the 1961 to 2002 period. (Data source is http://faostat.fao.org/faostat).

The role of agricultural practices on environmental quality has been examined in the past two decades because of the links between decreased environmental quality and increasing agricultural production. Granstedt (2000) evaluated the N loads into the Baltic Sea and found that Sweden human activities accounted for 54% of the annual N input. He found that inputs in inorganic fertilizer were related outputs of agricultural products and concluded that the losses were due to local and regional specialization of agricultural production. To reduce the nutrient losses requires a reduction of inputs to the agricultural system and increased recycling within the agricultural system (Granstedt, 2000). In China, Zhang et al. (1996) observed nitrate concentrations in shallow groundwater wells in excess of 300 mg l^{-1} and these high concentrations were associated with N application rates in excess of 500 kg N ha^{-1}. They concluded that NO_3-N problems in the environment would increase in China because of the increasing demand for food supply. Grimvall and Stalnacke (2001) observed that increases in NO_3–N in the Baltic Sea drainage basin have been observed since the late 1940's. The large increase in the size of the hypoxic zone in the Gulf of Mexico after the 1993 floods in the Midwest focused attention on the role of agriculture in nonpoint source pollution. Burkart and James (1999) evaluated the N balance for the Mississippi River Basin and concluded that two primary contributors to N load were mineralization of soil organic matter and commercial fertilizer. Schilling and Libra (2000) showed that NO_3-N losses from watersheds in Iowa were directly related to the intensity of row crop production. However, a similar analysis of Midwestern watersheds by Hatfield et al. (2001) showed that the relationship between total N load applied and NO_3-N concentrations in Iowa and Illinois watersheds was not well-defined and there was not a simple relationship between water quality and agronomic management. Nitrate-N losses from watersheds are not isolated to the Mississippi River Basin. Throughout the world, there is increasing evidence that water quality is being degraded by the movement of nutrients from agricultural lands into water bodies. Environmental quality impacts from excess nutrients were the cause of the development of the Mineral Accounting System (MINAS) in the Netherlands. This system provides an accounting for all nutrients entering and leaving a farm to ensure a balance of nutrients on farms (Ondersteijn et al., 2002). The MINAS approach is having a positive impact as shown by De Koeijer et al. (2003) and has increased farmer awareness of the impacts that farming practices have on environmental quality and the natural resources.

Nutrient management begins at the field scale where decisions are made about the amount and timing of nutrient application. Management of N at the field scale to increase efficiency of N use in maize has proven to be complex because of the spatial and temporal variation in yields. Doerge (2002) proposed that variable N rates across a field has the potential to reduce NO_3-N loads in surface and ground water and to increase profits by linking N fertilizer rates to N requirements within a field. The evidence for a straightforward approach to N management in maize has not been forthcoming because of the variability in the results from different studies. For example, Schmidt et al. (2002) reported that N requirement for maize production was not related to soil organic matter and Sogbedji et al. (2000) found the N requirement was not related to the soil drainage class within a field. In a recent study, Katsvario et al. (2003) compared two maize hybrids at two N rates, 110 vs. 165 kg ha^{-1}, across three sites and found spatial variability in yield for dry years but not in the wet year. They concluded that variable N rate management requires more information than soil NO_3-N concentrations and yield maps. This was based on the observation that spatial yield differences in response to N rate existed on only 2 of 13 site-year comparisons. Sogbedji et al. (2001) found that maize yields showed greater temporal variability than spatial variability. This response has been observed across a number of soils and climates (Jaynes and Colvin, 1997; Lamb et al., 1997; and Porter et al., 1998). Jaynes et al. (2003) found that cluster analysis may be useful in quantifying factors contributing to spatial variation in yield. They found cluster membership was primarily due to yield differences in growing seasons with precipitation differences greater than the 40-year mean. This method may provide an approach to quantifying management zones within fields. Management of N in maize has proven to be a complex topic in which there have been no simple answers and spatial and temporal patterns within fields are difficult to quantify.

Managing farming systems to reduce nitrate losses has been the focus of several studies throughout the world. Oenema and Pietrzak (2002) concluded that management is the most important factor in determining the economic and environmental performance of agroecosystems. They found that management accounts for more than 50% of the variance in nutrient budgets and nutrient input-output ratios among farms. They also found that the management practices needed to be defined at the proper spatial and temporal scale. Powers et al. (2001) summarized the efforts of several research projects in the Midwestern United States on management practices to reduce nitrate losses. They observed several common factors from a number of research projects: 1) continuous maize was not an environmentally acceptable practice in tile-drained soils because of the large losses of nitrate into the drainage flow; 2) reduced tillage or no-till systems provided a better synchronization of soil N mineralization with N uptake requirement; 3) improving water management practices in irrigated systems improved environmental quality; 4) maize-soybean rotations may not produce improved environmental quality if proper accounting for the soil N contributions from the soybean crop; 5) a good soil testing program is needed to implement the best fertilizer N rate for crops; 6) new technologies to assess N requirements of the crop and to address the problem of weather and soil variability; and 7) present practices in the Midwest may produce little environmental impact through nitrate loss; however, these systems may fail under conditions of abnormal weather variability. One of the emerging technologies is the observation of the plant for N status in combination with soil testing. The premise is that the plant may be a better indicator of actual N status than inference from soil test. Blackmer and Schepers (1994) showed that leaf chlorophyll measurements provided a useful method for measuring N status of the leaves and the results compared favorably with the leaf N concentrations. They found that reflectance near 0.55 µm detected N deficiencies in maize. Blackmer et al. (1996) detected N deficiencies in maize canopies under irrigated conditions using reflectance of visible and near-infrared wavebands. This approach was refined by Bausch and Duke (1996) with the development of a nitrogen reflectance index for a field that was based on comparing the reflectance across the field with an area in which N was assumed to be non-limiting. Diker and Bausch (2003) further refined to show that this index can be used to assess within-field variation of maize yield. Osborne et al. (2002) found that N status in maize was best predicted with reflectance in the green and red portions of the spectrum while grain yield was related to reflectance in the near-infrared. These methods have been extended to wheat (*Triticum aestivum* L.) that use remote sensing to estimate tiller density and from estimates of tiller number determine the amount of N to be supplied for maximum yield (Flowers et al., 2003). Scharf et al. (2002) have shown that remote sensing can provide information about the N requirements of maize but also feedback across a field about the effect of the N management decision. The current research on reflectance to assess and predict N requirements for maize and wheat may provide management practices that improve environmental quality.

Improvements in water quality are considered as potential outcomes from improvements in the efficiency of nitrogen use by crops. Nitrogen use efficiency for grain crops are generally computed based on the grain yield relative to the amount of N fertilizer applied. Cassman et al. (2002) evaluated crop yield and N application results and concluded that N fertilizer recovery efficiency (RE_n) could be achieved through increased yields, improved management of other production factors, and improved N-fertilizer management. Interest in NUE has occurred because of the linkage between N leaching and fertilizer application, although the direct evidence between N rate and leaching has not been found. Nissen and Wander (2003) studied NUE in relation to particulate organic matter and aggregate dry mean weight diameter in a greenhouse study on maize and found NUE declined with increasing N application rates. They concluded that soil management practices that increase particulate organic matter would be a substitute for fertilizer N additions with the added benefit of improving long-term soil productivity. Strategies to improve NUE in wheat have been studied by Blankenau et al. (2002). They found NUE could be improved if N availability to the crop could be increased at critical growth stages. In wheat, this could be accomplished by modifying N application systems to lower N application at tillering with higher N rates during later growth stages. Singh and Arora (2001) compared NUE for 20 wheat varieties and found NUE was higher in tall varieties for dry matter production while dwarf varieties had higher NUE for grain production. These studies demonstrate that NUE can be changed by N management but is further complicated by genetic differences. Assessment of NUE has generally been completed in laboratory or small plot studies with little attempt to evaluate the change in NUE across fields in which spatial or temporal variability in yield has been observed.

Assessment of N across fields provides a measure of feedback about the efficiency of N management decisions. Eghball et al. (2003) completed a study on variable rate additions of N to maize in Nebraska and observed that a variable rate of 7% of the recommended rate decreased the amount of residual soil NO_3-N but didn't decrease maize yields. They found that spatial variability in maize yield was less than the spatial variability in soil NO_3-N and concluded that using soil NO_3-N measurements may be ineffective for N management decisions. Balkcom et al. (2003) evaluated soil test NO_3-N and late season maize stalk NO_3-N across fields within a watershed. Their observations showed it may be possible to reduce NO_3-N levels in surface waters by delaying N applications to more closely match plant N needs and the combined approach of soil and plant tests could help improve efficiency of N use by producers.

Development of management systems that demonstrate increased NUE and decreased environmental impact are needed in the areas in which there is significant NO_3-N loss to surface waters. Observations of spatial variation of maize yield across fields are not directly related to N management decisions and many studies on NUE and N rates have been confined to a single soil type. The response of a crop to N availability within the soil profile has shown to affect NUE in wheat (Blankenau et al., 2002). The observation of greater spatial variation in maize yields among fields in dry compared to wet years suggest that soil water availability and timing of precipitation events may be an underlying factor affecting NUE in maize. There are challenges in studying N response of crops and environmental quality at the field scale; however, these relationships must be understood if science is to increase production and protect the environment simultaneously. We have been conducting studies across central Iowa fields to evaluate the interactions among crop water use, N management, and crop yield in order to develop an understanding of NUE and water use efficiency (WUE) in Midwestern cropping systems. The objective of this paper is to present the results of these studies and to propose how this framework can be used to increase our understanding of improving crop production efficiency and environmental quality.

Case Studies

Worldwide Nitrogen Use and Crop Yields

Nitrogen fertilizer data throughout the world shows that annual use rate is increasing. The worldwide database compiled by FAO (http://faostat.fao.org/faostat) provides a long-term data base for these evaluations. Nitrogen fertilizer use data and the crop production data in the FAO database shows that NUE decreases exponentially in all countries except Western Europe and the United States with increasing amount of N fertilizer applied (Fig. 2). Grain production was computed as the sum of all cereal crops and maize production. During this time period, grain production has increased linearly in the

United States and Western Europe (Fig. 3). These changes in grain production have caused a slight increase in NUE in the last decade.

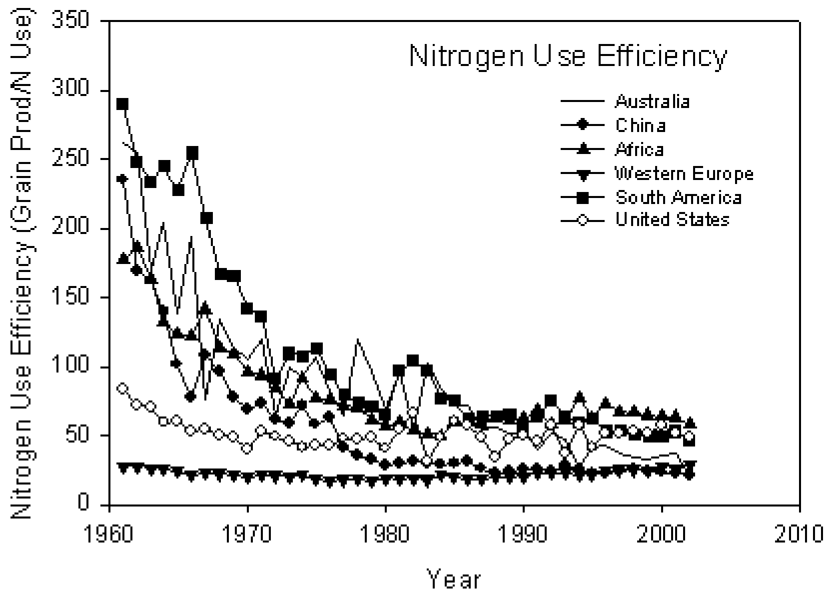

Figure 2. Nitrogen use efficiency for grain production relative to N fertilizer use for 1961-2002 for selected regions in the world. (Data source is http://faostat.fao.org/faostat).

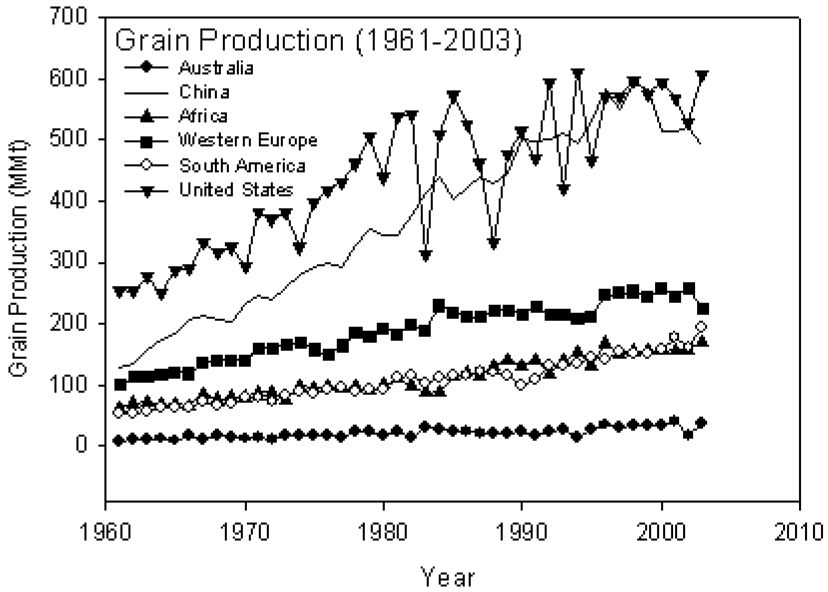

Figure 3. Grain production (cereal and maize) for selected regions of the world for the 1961-2003 period. (Data source is http://faostat.fao.org/faostat).

There is a linear increase in grain yield with increasing N fertilizer use (Fig. 4). There are; however, differences among the regions in response to N application with the higher N rates. The linear relationship for China and South America shows little deviation from the line while Australia shows years when there is extremely low production compared to the N applied. This is due to widespread drought across the continent and water becomes a limited factor in production. The expanses of the growing regions in China and South America for grain production provide a buffer against drought on a large scale. Observations for the United States and Western Europe (data not shown) show increasing variation in grain yield at the higher N application amounts. These variations would be attributed to other factors, e.g., weather or management, which would be expressed in addition to N application. It is important to note that the N application amounts are vastly different among these regions (Fig. 4). There is not a simple strategy for increasing NUE and Zhu and Chen (2002) suggest for China that emphasis be placed on optimization of N application rates, deep placement of N, matching N application with crop demands, balanced fertilizer application, and use of controlled release N fertilizer of nitrification inhibitors.

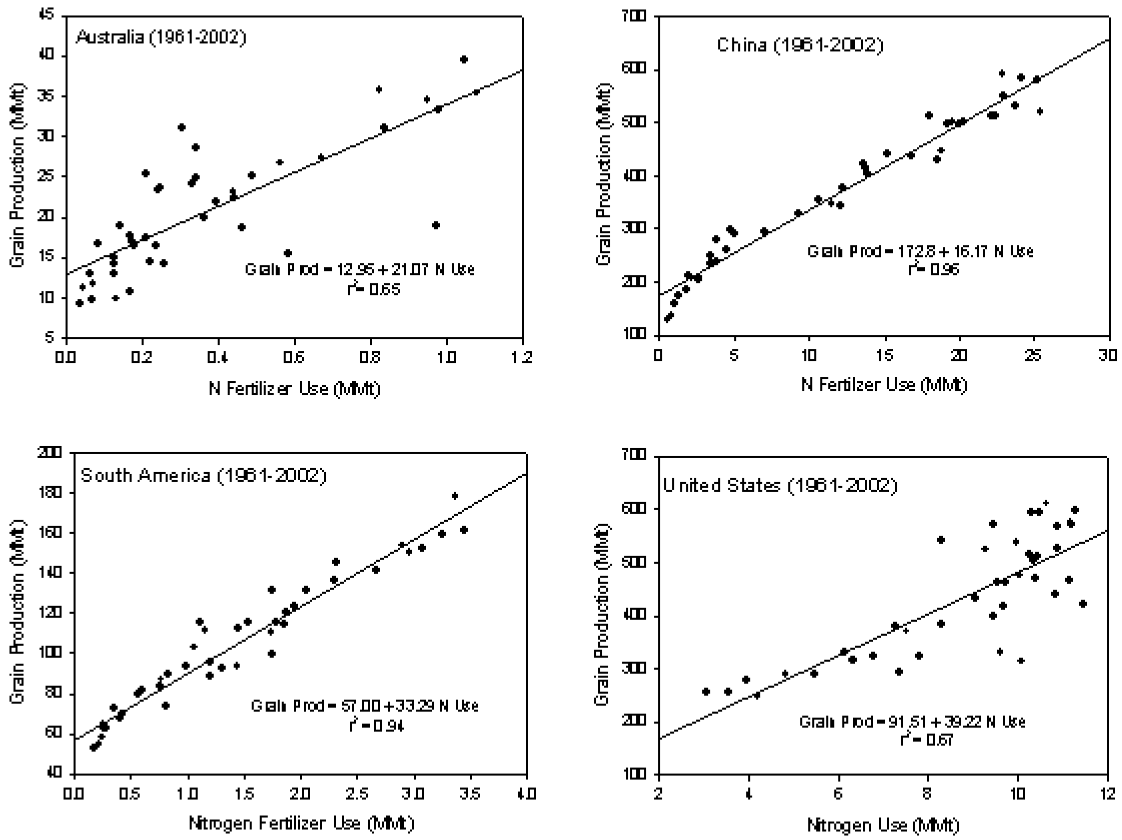

Figure 4. Grain production in Australia, China, South America, and United States relative to N fertilizer use for the 1961-2002 period. (Data source is http://faostat.fao.org/faostat).

Field-scale Case Study

Nitrogen management strategies to improve NUE have been limited and observations from several production areas throughout the world demonstrate the importance of soil water availability on grain production. An illustration of the field-scale N response is provided in this case study from the Midwestern United States based on observations from production fields. Details of this experiment are provided in Hatfield and Prueger (2001).

Crop Water Use and Water Use Efficiency

Crop water use patterns showed large differences between soil types within N treatments. An example for 1999 is shown in Fig. 5 for the 168 kg N ha^{-1} treatment. These data are typical of what we observed through the five years of the study. Differences were greater among soil types than among N rates for a given year. Differences among N rates were less than 30 mm of evapotranspiration (ET) while differences among soils were as large as 300 mm. Differences among years can be attributed to the early precipitation patterns and the frequency of soil wetting that contributed to soil water evaporation when the crops did not cover the soil. This leads to a large portion of the water use by evaporation rather than transpiration (Ritchie and Burnett, 1971). Early in the season there was no difference among soils and the greatest separation occurred later in the season when the precipitation amounts began to decrease and ET increased because of the greater plant size (Fig.5). Water use patterns across fields separate more than expected throughout the season but is reasonable given the differences in soil water holding capacity across the landscape. These differences between soils would explain why there is increased spatial variability in yields in dry years compared to wet years as observed by Katsvario et al. (2003). Precipitation patterns over the five years of this study have ranged from above normal in 1998 to below normal amounts in the growing season during 1999, 2000, and 2001. Studies that examine the spatial variability of yield need to consider the temporal dynamic of precipitation during the growing season as part of the discussion rather than characterize the years as either wet or dry.

Seasonal water use patterns were adjusted for soil water evaporation to compute the transpiration rate in order to compute WUE for each soil-N rate combination. Although there have not been any direct measurements of WUE in the Midwest and particularly under different N management systems, the expectation was for a common relationship to encompass all of the observations. Actual observations showed a large variation in WUE across the observations (Fig. 6). A linear relationship fit to the 168 kg N ha^{-1} data showed many of the observations were below the line (Fig. 6). The observations below the regression line indicate that there was a yield reduction for the amount of transpiration. Many of these observations were yields from the 56 and 232 kg ha^{-1} rate showed there was a low yield for the amount of water transpired. These relationships were not expected because the assumption is that the harvest index (grain yield/total biomass) would be nearly constant. The transpiration rate for many of the treatments was greater than the yield produced because of the water stress during the grain-filling period. The seasonal water use curve shown in Fig. 5 reveals that in the low organic matter soils, e.g., Clarion and Canisteo, water stress was prevalent during the grain filling period and these low yields would be expected. The observations with low WUE were also found in the higher water holding soils with both the low and high N rates. The causes for this yield response will be discussed in the next section. These data suggest that the N rates may not be optimum for WUE. Evaluating WUE in different N rates may

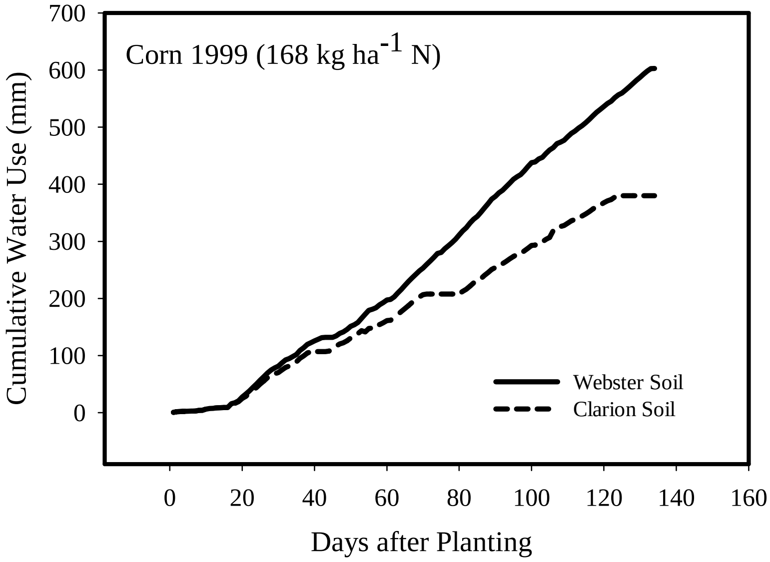

Figure 5. Cumulative crop water use for maize grown on Clarion and Webster soils at 168 kg N ha^{-1} in central Iowa during 1999.

provide insight into improvements for NUE. Norwood (2001) observed that WUE of maize in western Kansas was related to hybrid maturity and planting date; however, in this study we have maintained the same hybrid over the four years. In Argentina, Calvino et al. (2003) observed that maize yield was related to water availability during the flowering period and shallow soils produced lower yields than deeper soils for the same amount of rainfall. Soil water availability is critical to efficient crop production and improvements in WUE may enhance efficiency of N use by the crop.

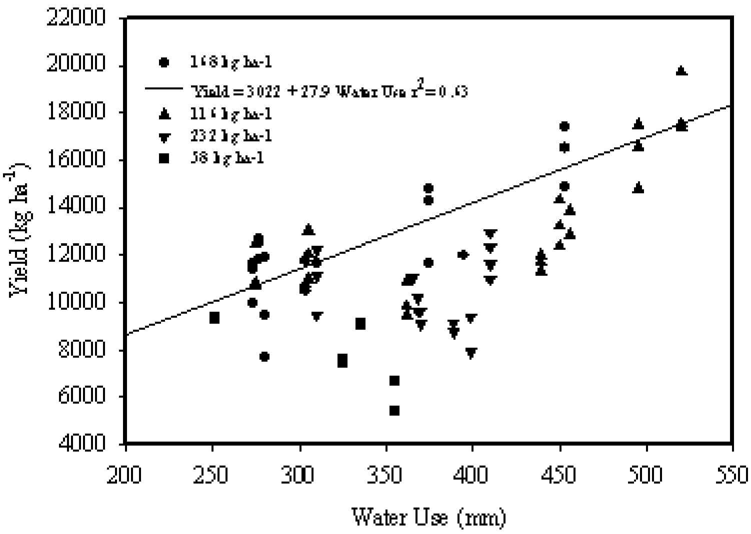

Figure 6. Water use efficiency for maize grown in central Iowa under different nitrogen rates.

Nitrogen Use Patterns and Nitrogen Use Efficiency

Maize yields across N rates and soils showed an interesting pattern. Not surprising was the large increase in yield with the addition of N above 56 kg ha^{-1}; however, what was surprising was the decrease in mean yields at N rates above 116 kg ha^{-1} (Fig.7). The mean yield for the 56 kg ha^{-1} rate was 7,530 kg ha^{-1}, 112 kg ha^{-1} was 12,278 kg ha^{-1}, 168 kg ha^{-1} was 11,400 kg ha^{-1}, and 232 kg ha^{-1} was 10,604 kg ha^{-1}. The means yields were significantly different from each other. In field scale studies conducted across central Iowa we have not observed a dramatic yield decrease with increasing N rates; however, we have observed that the optimum N rate is between 100 to 135 kg ha^{-1}. In many fields there is no effect of the N application in areas of the field with soils that have limited water holding capacity. This observation would confirm the reports of increased spatial variation in dry years by Katsvario et al. (2003).

Observations at each N rate showed a large variation in yield. The largest variation was at the 116 kg ha^{-1} rate (Fig. 7). When the data were segregated by soil type, soils began to separate within each N rate with the higher organic matter soils (Nicollet, Okoboji, and Webster) having the higher yields within a N rate with the lower organic matter soils (Canisteo and Clarion) having the lower yields (Fig. 7). The Webster soils were able to maintain a consistent yield at 112 and 168 kg ha^{-1} but still declined at 232 kg ha^{-1}, while the other soils showed a decrease at both the 168 and 232 kg ha^{-1} rates. The available soil water holding capacity for a 1.5 m rooting profile in the Webster soil is 325 mm compared to 268 mm in the Clarion soils. This difference in available soil water is sufficient to supply adequate water during the grain-filling period during periods of no or limited precipitation. During this study limited rainfall created a situation in which the high organic matter soils exhibited some degree of water stress. These results show that the N response curve is dependent upon soil type due to the availability of soil water and crop water use patterns. A similar response has been observed in canola (*Brassica rapa*) in which the yield response to additional N increased the most in areas of the field where soil water availability was the highest (Pennock et al, 2001). Evaluation of yield variation across fields is providing evidence of the complex interactions among soil type, N management, and soil water availability.

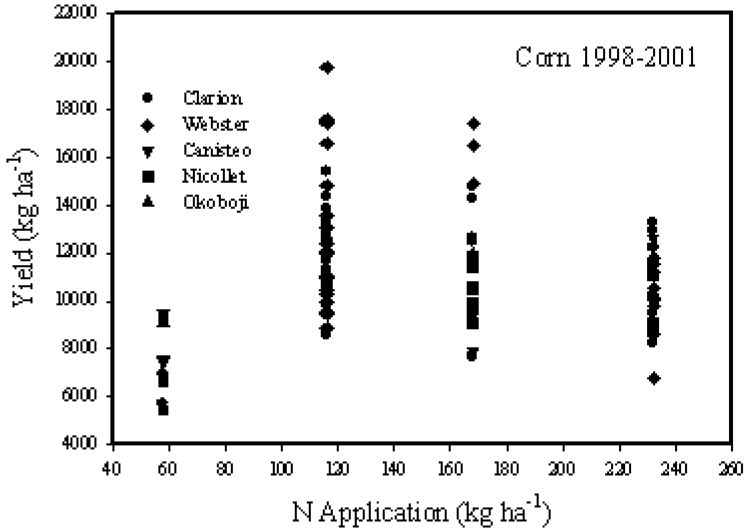

Figure 7. Maize grain yield collected from a production field with different N rates from 1998 – 2001.

The patterns of variability within fields may provide insights into crop response to management practices. Increased variability at the lower N rates was observed in field scale studies. Yield variability within the field showed a similar pattern to the observations shown in Fig. 7. The frequency distribution of yield across this field showed a decrease in the variability with increasing N application rates (Fig. 8). Mean yields across these strips were 10,494, 12,730, and 12,362 kg ha^{-1} in the 67, 134, and 202 kg ha^{-1} N rates, respectively. There was a decrease in the variability within each strip across the field with the addition of N. Although, there was no significant increase in yield with the addition of N field variability decreased. Understanding the variability patterns as suggested by Eghball et al. (2003) may provide further insights into why these patterns are present in field scaled-scale studies.

Nitrogen use efficiency calculated based on the crop yield and N applied showed a decrease with the amount of N applied (Fig. 9). The decline of NUE with increasing N rates is typical in what other studies show; however, what may be unique in these observations is the linear decline in NUE. Average NUE at 116 kg ha^{-1} was 118 showing that soil organic matter contributed to the N requirements. The converse of this is the 232 kg ha^{-1} rate had a NUE of 55, which leaves N remaining in the soil. Residual N is then available in soil profile for potential leaching. A comparison of six different maize hybrids for their NUE showed NUE ranged from 86 to 111 at a rate of 116 kg ha^{-1}. Yield variation for these hybrids was from 10,065 to 12,985 kg ha^{-1}. This range of grain yield for the same environment and soil management conditions is quite large. The variation among hybrids was as large as the variation induced by soil water differences. The efficiency of N use by a crop depends upon the response of water and N availability during the growing season and suggests that evaluations of these interactions would produce useful guidelines for producers. An interesting observation reported by Hasegawa (2003) on rice (*Oryza sativa* L.) in Japan showed that rice cultivars with high-yield potential showed the highest NUE coupled with greater dry matter accumulation, harvest index, and yield. He suggested that there are significant advantages to using high-yielding rice cultivars even under reduced N rates because of the improved efficiency in production. This analysis for rice would suggest that N management for maize consider the yield potential of the hybrid; however, a complication for rainfed maize production is the identification of hybrids that are drought tolerant.

Nitrogen Uptake Rates

The observations of variability in water use and maize yield within fields pose a question about the nitrogen dynamics of the plant. In this study we collected the N concentration in the leaves, stalks, and grain in the growing season. These data were coupled with the biomass accumulation to create the N content in the plant and then used to estimate the N uptake on a per day basis for the growing season.

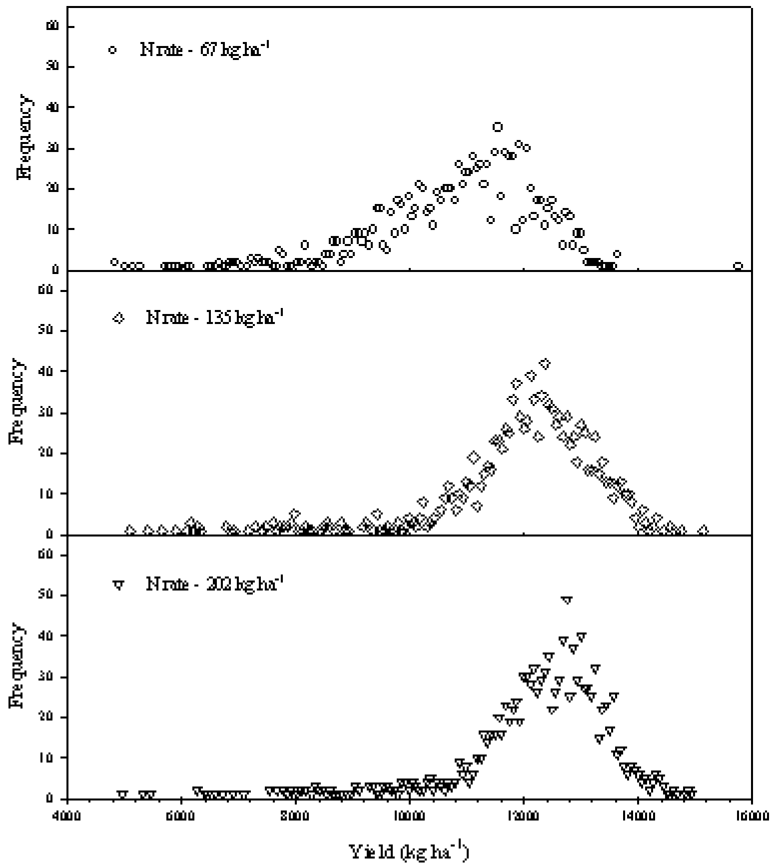

Figure 8. Frequency distribution of maize yield across a production field at three N rates during the 2002 growing season in central Iowa.

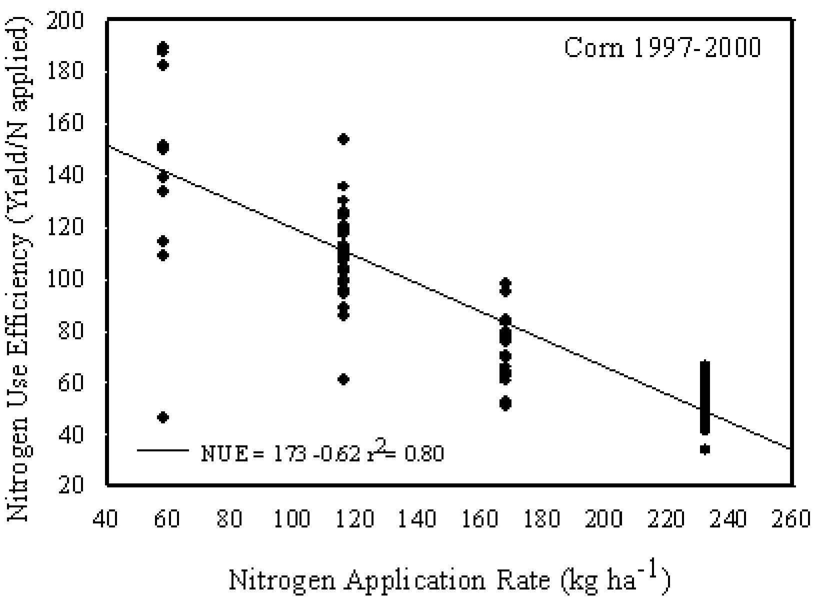

Figure 9. Nitrogen use efficiency of maize grown in central Iowa from 1997-2000.

When combined over the growing season into a seasonal average of N uptake per day, the Clarion and Webster soils create two separate populations (Fig. 9). The slope of the line on N uptake relative to yield shows the Webster soil to have a rate nearly four times more efficient than the Clarion soils (Fig.9). Part of this difference can be explained by water stress in the Clarion soil during the grain fill period and the reduced yield. Plants on the Webster soil are extracting more N from the soil for growth and using more of the available N in the soil mineralization pool. Soil organic contents within this field were 1.5% for the Clarion soil and 5.7% for the upper meter of the Webster soil. The combination of increased water availability during the grain-filling period and greater access to available N in the soil profile create a condition in which there is increased N uptake. Plants in the Clarion soil are water limited more than N limited. Although the rainfall patterns during the 1997 to 2001 growing seasons has shown a tendency toward more limited rainfall during grain-fill, there is evidence that unless rainfall is above normal there will be a decreased yield in the lower organic matter soils.

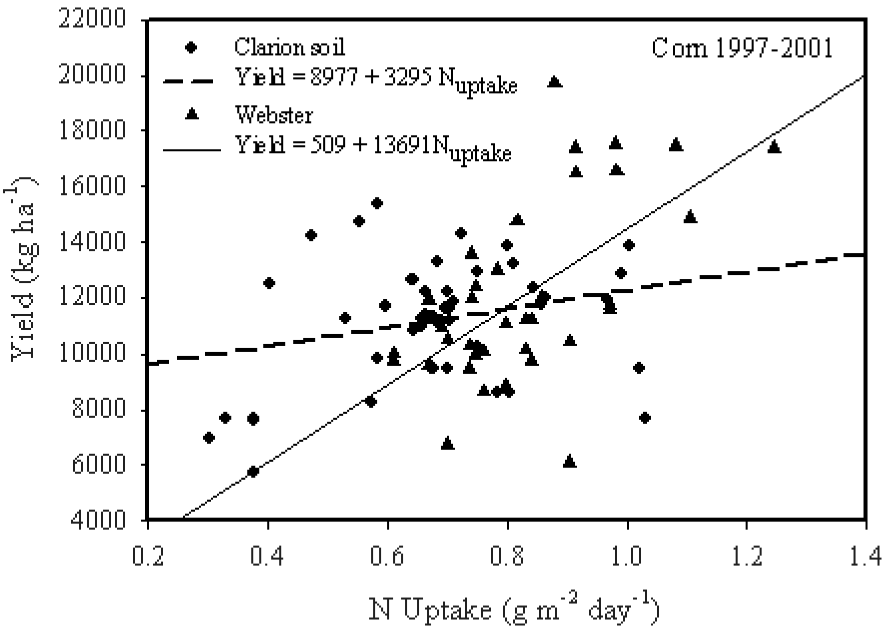

Figure 10. Nitrogen uptake per day relative to yield of maize grown in a range of N management practices in central Iowa from 1997 – 2001.

Implications and Challenges

Improving NUE will require an integration of the spatial and temporal interactions of soil water, agronomic management, and N management practices. Spatial and temporal variability in maize yields across fields have prompted a number of research studies to address the problem by changing N management. Studies by Eghball et al. (2003) raise questions about the cause of spatial variation in maize fields since changes in N application are not detectable in yield. The observations by Katsvairo et al. (2003) show the spatial variation is greater in dry years than wet years and suggest that soil water and N management may be more linked than has been considered in many studies. Improvement of NUE may not come from more studies on the N rates and spatial yield patterns within production fields, but rather studies that integrate seasonal crop growth to refine our understanding of the interactions of water and N across different soils. Increasing the efficiency of crop production while decreasing the environmental impact is an achievable goal but we need to address the problem from integrated studies across landscapes and multiple years. Soil water status is a primary factor affecting yield and improved ability in estimating the seasonal patterns of soil water based on improved meteorological forecasts which may return large dividends in enhancing NUE. Nitrogen management practices associated with application timing, e.g., sidedressing or split applications, would be improved with better soil water estimates. These studies cannot be undertaken without consideration of the micronutrient status in the plant or pest impacts on yield. These types of studies are difficult but are necessary if we are to achieve the goal of increased food supply with a reduced environmental impact. There are a series of complex policy issues surrounding N use and management that addresses potential regulations of N rates, cropping system management, and commodity programs that are beyond the scope of this paper.

Improved environmental quality, through a reduction in NO_3-N leaching from the soil profile, presents a challenge to crop scientists. The goal is to reduce the NO_3-N loss from the soil profile while increasing crop production. Oenema and Pietrzak (2002) and Cassman et al. (2002) have detailed potential approaches that could be applied to improving N management and decreasing the environmental impact.

The original premise was that additional amounts of N would lead to increases in crop yield; however, crop yields have continued to increase with nearly stable amounts of N being applied in the Corn Belt of the United States. Overall, the NUE has increased due to improved genetics and agronomic management, e.g., plant population, uniformity of stand, and pest management. These increases in efficiency have not resulted in improved water quality. Nitrate concentrations and loads in rivers and streams have not improved and intensity of row crop production may be related to the maintenance of these levels (Schilling and Libra, 2000; Zhu and Chen, 2002). The challenge remains to link crop production efficiency with environmental quality. In irrigated agricultural systems, these achievements have been possible because of the ability to link N and water management (Spalding et al., 2001). This linkage is more difficult in rainfed agriculture because of the variability of precipitation patterns but improvements could be achieved through improved residue management and conservation tillage. A challenge is to begin to more critically examine water management options throughout the year in rainfed environments. Management of nutrients may be relatively easy compared to managing water with variable weather patterns. These management practices need to be linked with studies that involve genetic variation and crop rotations in order to maximize the efficiency of use of the natural resource base.

The primary challenge to crop scientists will be to develop practices based on measures of efficiency. The concepts of water, nitrogen, and radiation use efficiency are often examined from an ecological concept; however, to solve the problem of balancing production and environmental quality endpoints, a re-examination of these concepts in agricultural systems may yield large benefits. The rewards of this type of research will be management practices that producers at all sizes and in all environments can see how these principles apply to their production system. The product will be a food and fiber production system that exhibits decreased variability due to weather and a diminished environmental impact. If we address these concerns as a community of scientists in cooperation with producers to ensure that the information is integrated into their production systems, then all humankind will benefit.

Improvements in NUE will begin at the field scale because the national data reveals that production continues to increase with increasing N applications. However, implementation of improved N management will begin at the field with the development of practices that maximize NUE while increasing the stability of crop production and decreasing risk. National scale policies can address the desire to achieve environmental and economic goals and promote improved management. Decisions will continue to be made at the field scale where producers need to be able to address their own production problems and the variability in their soils, climates, and cropping patterns. Richter and Roelcke (2000) present a challenge based on an analysis of central Europe and China that proposes that science address the N surplus problem by considering the development of more stable and sustainable agricultural systems. They advocate an analysis of the energy flows in the agricultural system to determine how efficiency could be enhanced. This is similar to the approach advocated by Addiscott (1995) who proposed that an examination of the entropy of agricultural systems be used to determine how best to optimize agricultural sustainability. Producers will continue to be concerned about production on their farm and increasing yield, while a stable food supply within a given country provides the impetus for increased N use, and environmental quality issues will be viewed as a downstream problem away from the field boundary where production decisions are made. The challenge stated by Wagner et al. (2002) suggests that solutions to environmental quality problems will come from a comparative analysis of watersheds around the world that can be used to identify new concepts for sustainable management. To correct this problem will require a combined effort that begins to examine agricultural production systems from a systems perspective with the emphasis on efficiency and sustainability. The advantages of alternative cropping systems with more complex rotations, cover crops, or N management practices have been shown to increase NUE; however, the adoption is extremely limited because of the increased demand for more production. To achieve a solution to the agronomic production and environmental quality problem will require innovative approaches to field-scale research that demonstrates to producers the production, economic, and environmental advantages of improved N management. These challenges may appear daunting but are not impossible and the rewards of developing solutions to these complex problems will yield benefits for humankind in the security of food supply and enhanced environmental quality.

Acknowledgements
The diligent support of Wolfgang Oesterreich, Tim Hart, Forrest Goodman, Brooks Engelhardt, Bert Swalla, DeeAnn Hehr, and Shannon Kulisky to collect the plant and yield samples and water use data are gratefully appreciated. Without their efforts, experiments of this complexity and scope would not be possible.

References
Addiscott TM (1995) Entropy and sustainability. European Journal of Soil Science 46,161-168.

Balkcom KS, Blackmer AM, Hansen DJ, Morris TF, and Mallarino AP (2003). Testing soils and cornstalks to evaluate nitrogen management on the watershed scale. Journal of Environmental Quality 32, 1015-1024.

Bausch WC and Duke HR (1996). Remote sensing of plant nitrogen status in corn. Transactions of the ASAE 39, 1869-1875.

Blackmer TM and Schepers JS (1994). Techniques for monitoring crop nitrogen status in corn. Communications in Soil Science and Plant Analysis 25, 1791 – 1800.

Blackmer TM, Schepers JS, Varvel GE, and Walter-Shea EA (1996). Nitrogen deficiency detection using reflected shortwave radiation from irrigated corn canopies. Agronomy Journal 88, 1-5.

Blankenau K, Olfs HW, and Kuhlmann H (2002). Strategies to improve the use efficiency of mineral fertilizer nitrogen applied to winter wheat. Journal of Agronomy and Crop Science 188, 146-154.

Bouwman AF and H Booji (1998) Global use and trade of feedstuffs and consequences for the nitrogen cycle. Nutrient Cycling in Agroecosystems 52, 261-267.

Burkart MR and James DE (1999). Agricultural nitrogen contributions to hypoxia in the Gulf of Mexico. Journal of Environmental Quality 28, 850-859.

Calvino PA, Andrade FH, and Sadras VO (2003). Maize yield as affected by water availability, soil depth, and crop management. Agronomy Journal 95, 275-281.

Cassman KG, Dobermann A, and Walters DT (2002) Agroecosystems, nitrogen-use efficiency, and nitrogen management Ambio 31, 132-140.

De Koeijer TJ, Wossink GAA, Smit AB, Janssens SRM, Renkema JA, and Struik PC (2003). Assessment of the quality of farmers' environmental management and its effect on resource use efficiency: A Dutch case study. Agricultural Systems 78, 85-103.

Diker K and Bausch WC (2003). Potential use of nitrogen reflectance index to estimate plant parameters and yield of maize. Biosystems Engineering 85, 437-447.

Doerge, TA (2002). Variable-rate nitrogen management creates opportunities and challenges for corn producers [Online] http://www.plantmanagementnetwork.org/cm/ Crop Management doi 10.1094/cm-2002-0905-01-RS.

Eghball B, Schepers JS, Negahban M, and Schlemmer MR (2003). Spatial and temporal variaibility of soil nitrate and corn yield: Multifractal analysis. Agronomy Journal 95, 339-346.

Flowers M, Weisz R, Heiniger R, Tarleton B, and Meijer A (2003). Field validation of a remotes sensing technique for early nitrogen application decisions in wheat. Agronomy Journal 95, 167-176.

Granstedt A (2000) Increasing efficiency of plant nutrient recycling within the agricultural systems as a way of reducing the load to the environment- experience from Sweden and Finland. Agriculture, Ecosystems and Environment 80, 169-185.

Grimvall A and Stalnacke P (2001) Riverine inputs of nutrients to the Baltic Sea. In Wulff FV, Rahm LA and Larsson p (eds.) A systems analysis of the Baltic Sea. Ecological Studies 148, 113-131.

Hasegawa H (2003). High-yielding cultivars perform best even at reduced nitrogen fertilizer rate. Crop Science 43, 921-926.

Hatfield JL and Prueger JH (2001). Increasing nitrogen use efficiency of corn in Midwestern cropping systems. Proceedings of the 2nd International Nitrogen Conference on Science and Policy. TheScientificWorld, 1(S2), 682-690.

Hatfield JL, McCaslin SL, and Prueger JH (2001). Crop production BMP effectiveness and prediction of water quality improvements. TMDL Science Issues Conference. Water Environment Federation, Washington, DC. pp. 205-224.

Jaynes DB and Colvin TS (1997). Spatiotemporal variability of corn and soybean yield. Agronomy Journal 89, 30-37.

Jaynes DB, Kaspar TC, Colvin TS, and James DE (2003). Cluster analysis of spatiotemporal corn yield patterns in an Iowa field. Agronomy Journal 95, 574-586.

Katsvario TW, Cox WJ, Van Es HM, and Glos M (2003). Spatial yield response of two corn hybrids at two nitrogen levels. Agronomy Journal 95, 1012-1022.

Keeney DR and Hatfield JL (2001). The Nitrogen Cycle, Historical Perspective, and Current and Potential Future Concerns. In Follett RF and Hatfield JL (eds.) Nitrogen in the Environment: Sources, Problems, and Management. Elsevier, New York. Pp. 3-16.

Lamb JA, Dowdy RH, Anderson JL, and Rehm GW (1997). Spatial and temporal stability of corn grain yields. Journal Production Agriculture 10, 410-414.

Nissen TM and Wander MM (2003). Management and soil-quality effects on fertilizer-use efficiency and leaching. Soil Science Society America Journal 67, 1524-1532.

Norwood CA (2001). Planting date, hybrid maturity, and plant population effects on soil water depletion, water use, and yield of dryland corn. Agronomy Journal 93, 1034-1042.

Oenema O and Pietrzak S (2002) Nutrient management in food production: Achieving agronomic and environmental targets Ambio 31, 159-168.

Ondersteijn CJM, Beldman ACG, Daatselaar CHG, Giesen GWJ, and Huirne RBM (2002). The Dutch mineral accounting systems and the European nitrate directive: Implications for N and P management and farm performance. Agricultural Ecosystems and Environment 92, 283-296.

Osborne SL, Schepers JS, Francis DD, and Schlemmer MR (2002) Detection of phosphorus and nitrogen deficiencies in corn using spectral reflectance measurements. Agronomy Journal 94, 1215-1221.

Pennock D, Walley F, Solohub M, Si B, and Hnatowich G (2001). Topographically controlled yield response of canola to nitrogen fertilizer. Soil Science Society of America Journal 65, 1838 – 1845.

Porter PM, Lauer JG, Huggins DR, Oplinger ES, and Crookston RK (1998). Assessing spatial and temporal variability of corn and soybean yields. Journal Production Agriculture 11, 359-363.

Power JF, Weise R, and Flowerday D (2001). Managing farming systems for nitrate control: A research review from management systems evaluation areas. Journal of Environmental Quality 30, 1866 – 18803.

Richter J and Roelcke M (2000) The N-cycle as determined by intensive agriculture- examples from central Europe and China. Nutrient Cycling in Agroecosystems 57, 33-46.

Ritchie JT and Burnett E (1971). Dryland evaporative flux in a subhumid climate: II. Plant influences. Agronomy Journal 63, 56-62.

Scharf PC, Schmidt AP, Kitchen NR, Sudduth KA, Hong SY, Lory JA, and Davis JG (2002). Remote sensing for nitrogen management. Journal of Soil and Water Conservation 57, 518 – 5524.

Schilling KE and Libra RD (2000). The relationships of nitrate concentrations in streams to row crop land use in Iowa. Journal of Environmental Quality 29, 1846-1851.

Schmidt, JP, Dejoia AJ, Ferguson RB, Taylor RK, Young RK, and Harlin JL (2002). Corn yield response to nitrogen at multiple in-field locations. Agronomy Journal 94, 798-806.

Singh VP and Arora A (2001). Intraspecific variation in nitrogen uptake and nitrogen utilization efficiency in wheat (*Triticum aestivum* L.). Journal of Agronomy and Crop Science 186, 239-244.

Smil V (1999) Nitrogen in crop production. An account of global flows. Global Biogeochemical Cycles 13, 647-662.

Sogbedji JM, van Es HM, Yang CL, Goehring LD, and Magdoff FR (2000). Nitrate leaching and N budget as affected by maize N fertilizer rate and soil type. Journal of Environmental Quality 29, 764-773.

Sogbedji JM, van Es HM, Klausner SD, Bouldin DR, and Cox WJ (2001). Spatial and temporal processes affecting nitrogen availability at the landscape scale. Soil Tillage Research 58, 233-234.

Spalding RF, Watts DE, Schepers JS, Burbach ME, Exner ME, Poreda RJ, and Martin GE (2001). Controlling nitrate leaching in irrigated agriculture. Journal of Environmental Quality 30, 1184-1194.

United Nations Food Agricultural Organization (FAO) (2000). http://appa.fao.org/page/form?collection=Fertilizer&Domain

Wagner W, Gawel J, Furumai H, De Souza AM, Teixeira D, Rios L, Ohgaki S, Zehnder AJB, and Helmond HF (2002) Sustainable watershed management: An international mulit-watershed case study. Ambio 31, 2-13.

Zhu ZL and Chen DL (2002) Nitrogen fertilizer use in China- Contributions to food production, impacts on the environment and best management strategies. Nutrient Cycling in Agroecosystems 63, 117-127.