Emerging Challenges in Land Management: An American Perspective on Efficiency

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ABSTRACT
Increasing concerns about nonpoint source pollution and the role of agricultural practices on the loss of nutrients has renewed interest in agronomic management. The balance between economic and production efficiency and environmental quality can be addressed from an understanding of the linkages between the soil resource and the agronomic system. The interrelationships among water, nitrogen, and radiation capture efficiency provide a framework for the evaluation of agronomic systems. Previous approaches have used one of these measures individually; however, crop production is an integration of these three components. There is a large variation among these components across a field and across regions. Studies in central Iowa have shown that it is possible to increase nitrogen, water, and radiation capture efficiency by 20-30% above current levels. Development of agronomic systems that are based on efficiency rather than production will increase the sustainability of production systems.

KEYWORDS
Nonpoint source pollution, water use efficiency, nitrogen use efficiency, radiation capture efficiency, soil variation, agronomic systems.

INTRODUCTION

In the past two decades there has been increased controversy about the role of agricultural production systems on environmental quality and production efficiency. The reoccurrence of the hypoxic zone within the Gulf of Mexico and the large increase in the size of this zone after the 1993 floods in the Midwest focussed attention on the role of agriculture in nonpoint source pollution. Burkart and James (1) evaluated the nitrogen balance for the Mississippi River Basin and concluded that mineralization of soil organic matter and application of commercial fertilizer were two primary contributors to nitrogen load. Jaynes et al. (10) after examination of a small watershed (5400 ha) in central Iowa found that nitrate-N losses averaged 20 kg ha^{-1} for this watershed and reached a level in excess of 40 kg ha^{-1} during 1993. Occurrence of the hypoxic zone has prompted an increased level of debate about the need to reduce nitrogen inputs into agricultural systems. Opponents of this conclusion argue that over the past 20 years the input of nitrogen fertilizer has not increased, soil organic matter levels haven't changed, and crop production levels have increased suggesting that the efficiency of the agronomic production system has increased and no change is needed.

An increasing population demands that agronomists continue to increase food supplies. This must be done with an ever-degrading soil resource base. It is currently estimated that around the world over 70% of the agricultural lands have reduced production capability because of erosion and decrease in soil organic matter content. It is assumed that degraded soils will not have the optimal level of performance under agronomic systems that only address inputs and not measures of efficiency. Continual degradation of the natural resource base will affect agronomic performance.

There are a number of challenges for agronomists to develop production systems that will increase the efficiency of the use of water, nutrients, and radiation. This is a departure from the traditional approach to agriculture where production levels have been the measure of performance. In this paper we will explore how efficiency measures can provide a different view of agricultural production.

RESULTS

Concepts of Efficiency

Water use efficiency has been expressed as the relationship between the grain or biomass production and the amount of water used during the growing season. There have been several variations on this to include either irrigation water supplies or only precipitation. A similar approach can be developed for nitrogen or radiation use efficiency that relates the amount of nutrient applied or radiation captured by the canopy relative to harvested yield or biomass produced. These relationships have generally shown to be linear across a range of soils, crops, and climates.

Water Use Efficiency

Water use efficiency is a linear response between water used and crop biomass or yield. Soil management affects water use efficiency and changing practices have the potential to significantly impact water use efficiency. Soil management practices that increase the availability of soil water in the soil profile have a positive impact on water use efficiency. These practices include reduced tillage, maintaining the crop residue on the soil surface, and changing the crop growth pattern to more effectively cover the soil surface and decrease the soil water evaporation rates.

One of the components in water use efficiency that has been overlooked is the depth of the soil profile. Degradation of the soil profile by erosion removes the topsoil and much of the soil water holding capacity. Tanaka (14) in a study in which he removed successive layers of topsoil, found a reduction in water use efficiency. Removal of the topsoil reduced the water use efficiency by over 50% because of the limitation of the soil water supply at critical plant growth stages (Tanaka, 14). Maintenance of the depth of the soil profile is important for proper plant development. An analogous parameter to change in depth of the soil profile is the effect of soil compaction on plant growth.

Water use efficiency has been primarily studied in semiarid agricultural regions. In these regions there has been an emphasis on using fallow portions of the crop rotation to increase the amount of soil water stored in the profile. There have been some changes in philosophy in the past 10 years to consider more intensive crop rotations. Farahani et al. (3) among others have shown that efficiency gains are due to reduced use of the fallow and using water for transpiration that otherwise is lost during fallow due to soil water evaporation, runoff, or deep percolation. In areas where fallow is practiced, the efficiency of precipitation storage is often low (between 10 and 15%), partly due to disturbance of the soil surface to control weeds. Changing the intensity of crop rotations may have a significant increase in overall water use efficiency. In more temperate climates, typical of the Midwestern United States, the concept of water use efficiency has not been used to evaluate crop response. Water use efficiency in temperate climates is often twice as large than in semiarid climates because of the reduced amount of water stress and increased amount of soil water.

Changing soil nutrient status influences water use efficiency. Soil nutrient status can influence plant growth and in turn the amount of biomass produced per unit of water consumed. It is assumed that proper nutrient balance of the crop leading to increased yields would lead to increased water use efficiency. Nitrogen has a positive impact on plant growth. Increasing nitrogen availability increases vegetative growth in nitrogen limiting soils if all other factors are non-limiting. There are changes in nitrogen dynamics and availability across the landscape due to a number of factors. Across a landscape above ground biomass and plant residue production increase downslope due to increased soil water availability. Halvorson et al. (5) showed that nitrogen additions in dryland cropping systems had a positive impact on the amount of residue returned to the soil and to the below ground residue carbon. Increasing nitrogen rates increased soil organic carbon and total nitrogen. Earlier they had found that the increased cropping intensity as suggested by Farahani et al. (3) would lead to changes in nitrogen management practices because of the low mineralization potential of dryland soils (Halvorson and Reule, 4). Nitrogen management is linked to water use rates in cropping systems. Changes in crop residue management used to increase water use efficiency may be linked to nitrogen dynamics in the soil.

Varvel (16) found that adding nitrogen fertilizer increased water use efficiency in grain sorghum, Smika et al. (12) found a similar response for native grasses, Campbell et al. (2) for wheat, and Varvel (15) for corn. For these studies, nitrogen additions increased water use efficiency through the effect on biomass production. Agronomic management can increase the efficiency of crop production through more efficient use of water and reduced water stress.

Water use varies across fields due to changes in soil water holding capacity. Hatfield and Prueger (6) found that water use by corn varied from 350 to 700 mm from the eroded Clarion soils to the poorly drained Okoboji soils in a year with less than normal rainfall during the growing season. These patterns are shown in Fig. 1. In years with above normal rainfall during the growing season there was only a minor difference among soils within the field. There was an interaction with nitrogen application rates on the soil water use patterns in this study indicating that soil nutrient impacts on water use need to be considered in agronomic studies. Jaynes and Colvin (9) found that variation of crop yields within a field were related to seasonal precipitation indicating that soil water dynamics need to be considered as part of the agronomic response.

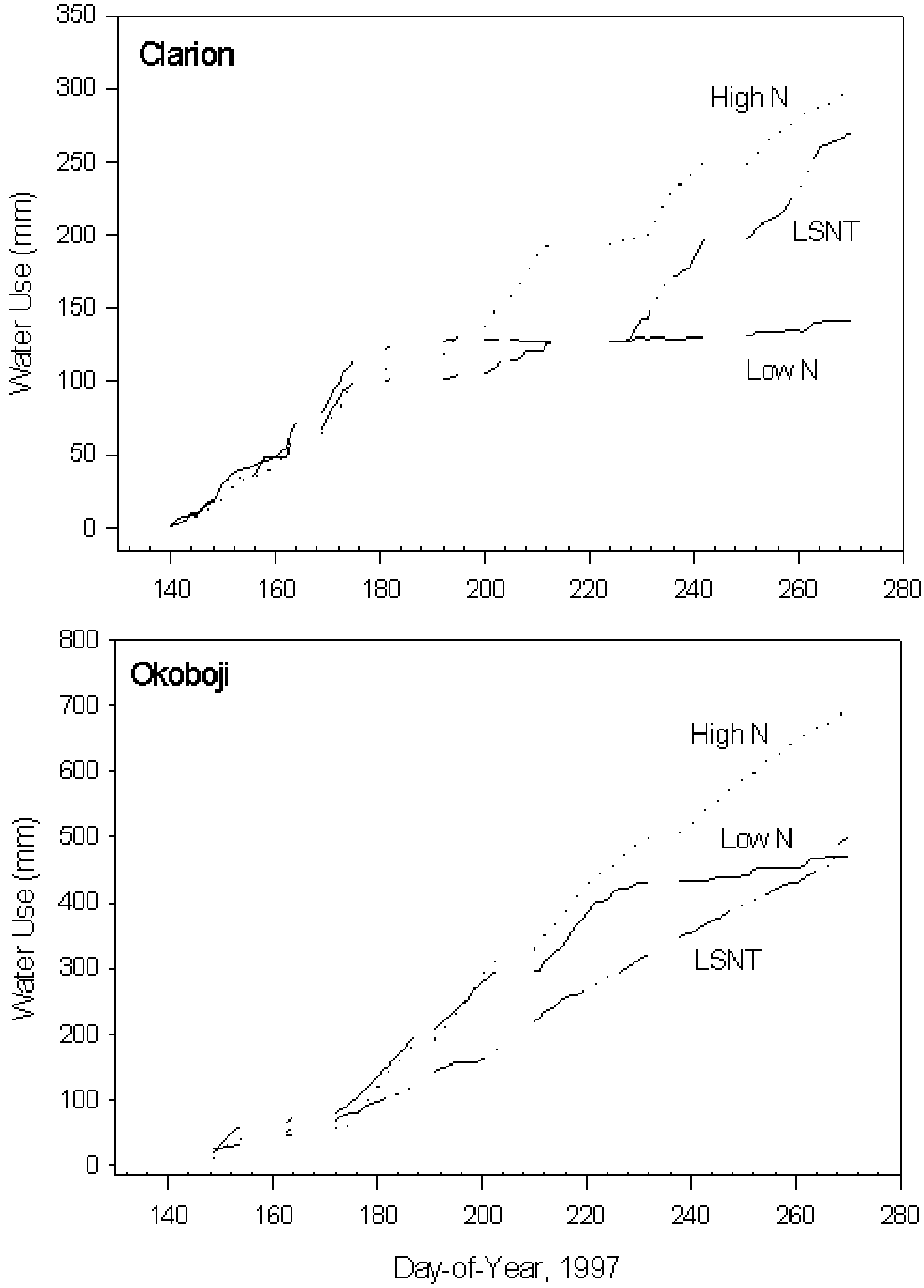

Figure 1. Seasonal patterns of crop water use for three nitrogen management schemes (Low N, starter only; LSNT, Late Spring Nitrate Test includes starter plus sidedress application; High N, starter plus 150 kg ha^{-1} as sidedress) for a Clarion and Okoboji soil in central Iowa during 1997.

Nitrogen Use Efficiency

Nitrogen use efficiency can be expressed as the yield or biomass production relative to the amount of nitrogen applied. Traditional nitrogen studies have related nitrogen application rates to yield and most observe that yield response begins to decline with nitrogen applications above the optimum rate.

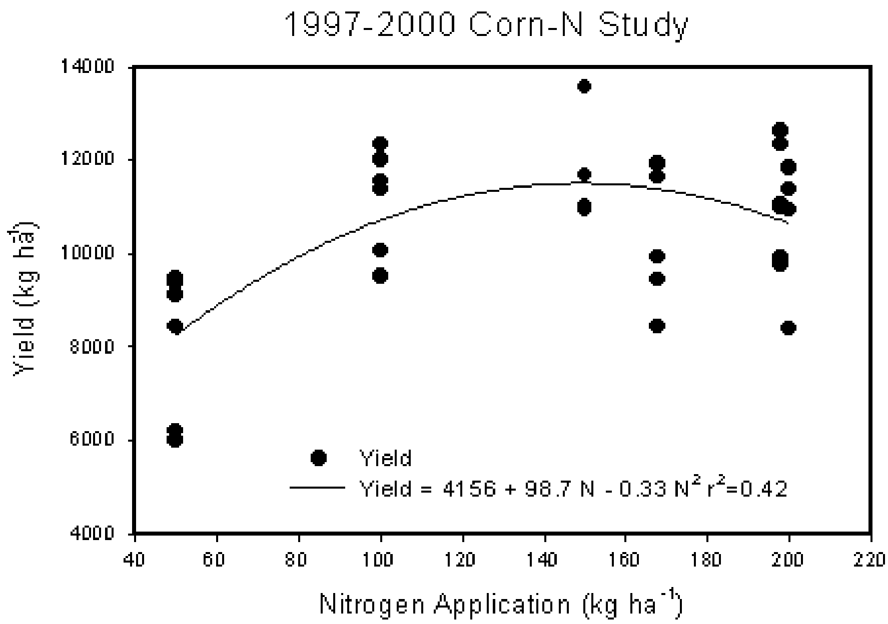

Figure 2. Yield response of corn in central Iowa for a range of nitrogen application rates and four soils.

However, throughout the Midwest there is a tendency to overapply nitrogen to ensure an adequate N supply for the crop during better-than-average weather conditions. When the weather conditions do not permit above normal yields the excess nitrogen remains in the soil profile. Nitrogen which remains in the soil profile after harvest may contribute to leaching losses in the following seasons. Both of these observations have prompted many discussions about methods to improve nitrogen management. We have been trying to link nitrogen management to soil variation within fields to better understand the interactions among nitrogen, water, and soil types. Nitrogen management strategies have been evaluated for a series of studies conducted in central Iowa across a range of four years and four different soil types. In these studies, increases in yield with nitrogen application rates above the optimal rate were observed in Fig. 2. An optimal rate of 140 kg ha^{-1} of nitrogen was applied in this study. When Nitrogen Use Efficiency (NUE) was calculated based on the nitrogen application rate, there were differences among years and soils. Nitrogen use efficiency decreased with nitrogen application rates (Fig. 3). These data show that the low rate of nitrogen fertilizer application has the highest efficiency in this environment because the mineralization of soil organic matter provides additional nitrogen supplies for the crop. Nitrogen use efficiency as a concept has to be developed to account for the soil mineralization potential and water stress effects on crop yield.

Radiation Use Efficiency

Radiation use efficiency was proposed as a concept by Monteith (11). He proposed that yield would be a linear function of the amount of light intercepted by a crop during the growing season. This is a simplification of the processes involved in the accumulation of dry matter by a crop. There have been continuing attempts to relate the radiation capture efficiency to yield. However, these approaches have not been used extensively in the Midwest because of a lack of concern about the role that light capture plays in the management of agronomic crops. In studies, we have conducted within the same fields as the nitrogen management and water use comparisons we have been measuring the light intercepted by the corn canopy for each of the soil type-nitrogen management combinations. To estimate the intercepted light, we have been using the approach developed by Hatfield et al. (7) that utilizes the Normalized Difference Vegetation Index (NDVI) derived from reflected radiation in the red and near-infrared wavebands as a surrogate for the interception efficiency. These data are coupled with the solar radiation observations from nearby weather stations to estimate the amount of radiation absorbed by the canopy each day. The relationship developed for the nitrogen-population studies in 1998 are shown in Fig. 4.

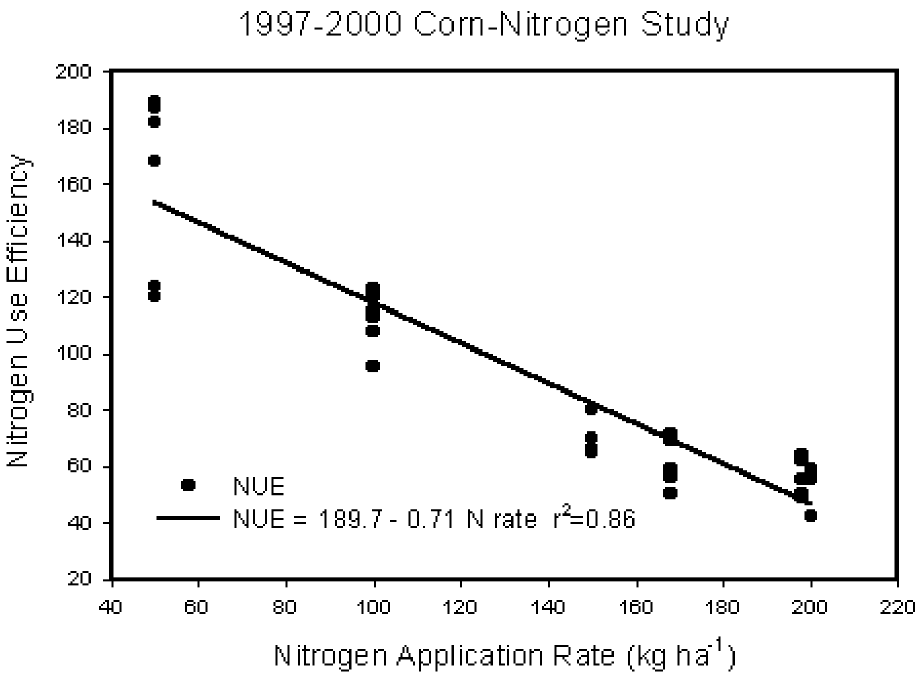

Figure 3. Nitrogen use efficiency for corn in central Iowa for four soil types.

There is a linear relationship between cumulative radiation intercepted and the harvested yield for these corn crops. We have seen this relationship be true for other years in our studies; however, we have observed that early season management and rainfall patterns play a large role in the changing the slope of this relationship. In 1999, late season water stress caused the slope of the line to change from positive to negative for a range of high plant population-high nitrogen application rates on corn. The lack of soil water in the Clarion soils caused the plant to abort several fertilized kernels and to undergo rapid senescence. In these four years we have found that the faster the rate of decline of green leaf area during grain fill, the lower the harvested yield. On the lower water holding capacity soils, as shown in Fig. 1, for the Clarion soils, early season water use that depletes the soil profile places the crop at risk in years when the precipitation during the grain-filling is below normal. Water use patterns and nitrogen management strategies will have to be linked in the central United States in order to increase efficiency in crop production.

Improving Production Efficiency

Water, nitrogen, and radiation use efficiency are all concepts that have been used to evaluate the relationship of crop yield or biomass production to individual components. These have not been integrated together to examine where the components in the system could be modified to achieve the optimal farming system. Soil water availability is one of the major crop growth and yield limiting factors in the central United States. Annual precipitation exceeds 800 mm over most of the Corn Belt; however, short-term periods of limited water supplies create water stress and limit yields. Producers have begun to notice this effect as yield data are being collected with monitors on the combines. Across the landscape the soil water holding capacity varies from 50 mm in the upper 0.25 m of the soil profile in the Clarion soils, 95 mm in the Okoboji soils, and 117 mm in the Canisteo soils. Throughout the soil profile to a depth of 1 m the soil water availability ranges from 275 mm in the Canisteo to 310 mm in the Okoboji profiles. The upper portion of the soil profile is a critical water supply for early season plant growth.

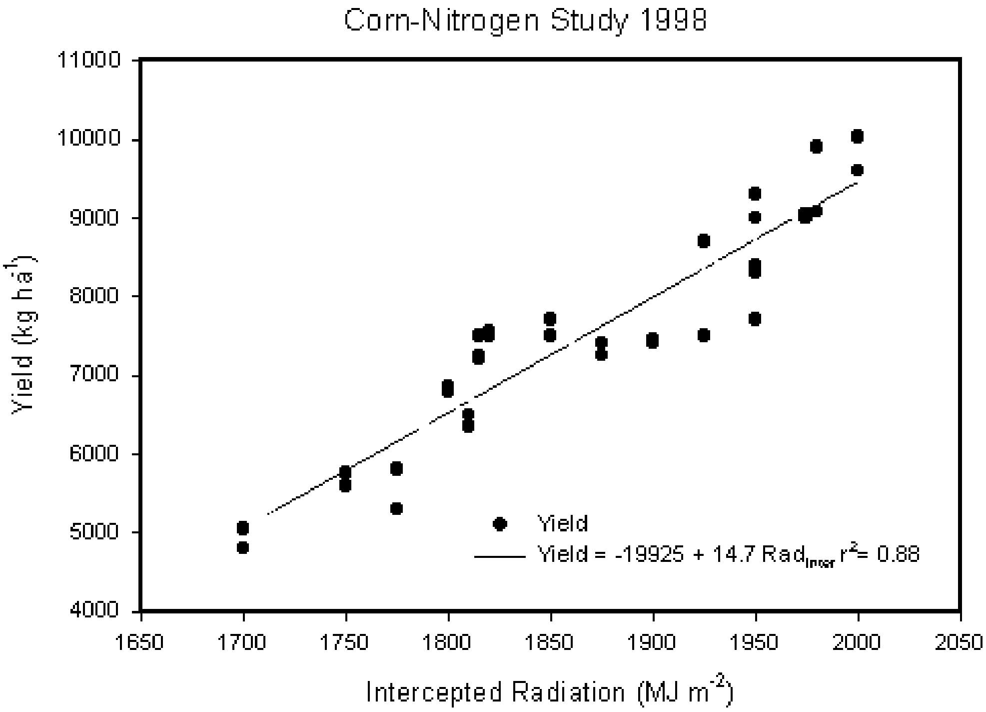

Figure 4. Intercepted solar radiation for corn canopies with different nitrogen management application rates in central Iowa in 1998.

Observations we have made across different soils and residue management practices have shown that tillage in the spring evaporates on the average 10-15 mm per tillage operation. Typical tillage operations before planting in the Corn Belt use two primary tillage operations which would remove as much as 30 mm of available soil water. In soils with limited water holding capacity, this creates a condition in which the plant is at greater risk due to water stress. This has been observed under field conditions in which early season water use by both corn and soybean crops showed a response to different tillage practices. Fields managed with the normal cultural operations, two tillage prior to planting, began to exhibit reduced evapotranspiration and reduced growth within four weeks after emergence while those fields that were planting directly into crop residue without tillage did not exhibit any reduction in evapotranspiration rates or growth until eight weeks after emergence. The increase in soil water availability increased the growth rate of the crop and created a larger yield potential. In this year; however, the yield potential difference between the two tillage systems was not realized because of excessive rainfall later in the season. Evidence gathered from Midwestern producers has shown that corn and soybean yields were not increased by adoption of no-till systems. However, over the course of 10 years, the variation of the yields decreased by 50% suggesting that although the increased amount of soil water did not affect yield, it created a condition that reduced the extremes in crop response. These results do provide evidence that we need to consider landscape position and soil type in conducting field scale experiments.

Increasing soil water holding capacity has been related to soil organic matter. Hudson (8) showed a linear relationship between soil organic matter content and soil water holding capacity across a range of soils in the United States. Soil organic matter can be increased through changes in crop residue management and adoption of conservation tillage systems has a positive impact on soil water availability. Water use efficiency is enhanced by changes in soil water availability in the early growing season. Soil organic matter can be increased through the use of manure. Sommerfeldt and Chang (13) showed that manure increased soil organic matter in the upper soil profile by 1% per ton of manure applied. They also showed bulk density decreased and water infiltration increased as a result of manure applications to soil. All of these changes are positive effects on soil water holding capacity. Across the landscapes of the Corn Belt increasing the water holding capacity of the soil on eroded areas of the field could have a large impact on water use efficiency of the crop. We estimate based on the experiments conducted in Iowa that increases of 10-20% would not be reasonable.

Nitrogen management changes coupled with an improved understanding of the soil water dynamics can improve efficiency. Observations collected from these field experiments revealed that use of a nitrogen application at planting increased the nitrogen use efficiency because of the positive impact on early season plant growth. This additional amount of nitrogen increased the water use efficiency because water use rates were not increased in proportion to growth rate or potential yield. This was observed in the 1998 growing season when there was excessive rainfall after application of nitrogen and the soils were saturated. Water use rates were reduced by poor root function and although nitrogen was available in the soil profile, the available nitrogen was not in the upper soil profile where water was being extracted by the roots. This season produced the lowest yields of the last four years even though the seasonal rainfall would indicate the potential for producing a crop without significant water deficits. Excess soil water during critical periods of growth and the interaction with nitrogen has an impact on growth and yield and presents an opportunity to improve both water and nitrogen use efficiency. Nitrogen use efficiency as shown in Fig.3 suggests that the linkages between nitrogen and water need to be more clearly defined to better quantify farming system responses to management.

CONCLUSIONS

Emerging Challenges

There are a number of emerging challenges that we need to address as agronomists. Repeated observations across fields with varying soils have shown that we lack the ability to quantify many of the interactions among the soil-plant-atmosphere components that relate to the variation in crop growth or yield. The focus on yield rather than efficiency of production has created a situation in which we regard the soil within the farming system as a medium in which we place seed, fertilizer, and chemicals. We have rarely examined the differences across a field to determine how the input factors interact with the weather and soil throughout the year to explain the physiological path that the plant used to produce yield at the end of the growing season. There are a number of challenges that I feel need to be addressed to increase the efficiency of agricultural production. These are presented in bullet form to promote discussion and dialog among agronomists.

- Adopt a system of comparing farming systems that are based on the natural resource and weather conditions rather than yield comparisons.
- Develop an understanding of the interactions between water, nitrogen, and radiation use efficiency to permit the quantitative comparisons of farming systems.
- Conduct experiments across fields to directly compare soil and landscape effects on crop response to water and nitrogen management.
- Quantify the interactions across years and landscape positions to determine the potential impact of soil modification, e.g., crop residue, tillage, or organic matter changes on water, nitrogen, and radiation use efficiency.
- Develop statistical methods to permit direct comparisons across soils or landscape positions within fields.
- Quantify the spatial and temporal dynamics of farming systems to allow for the comparison across a range of conditions.
- Adopt a research approach that considers the yearly variation as part of the experimental protocol.

These challenges offer us an opportunity to begin to address the needs of society that include more efficient food, feed, and fiber production and to develop farming systems for crop production that are more sustainable. We have an obligation to use our scientific talents to develop solutions that producers can use readily adopt into their current enterprises.

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