CHANGES IN CROP PRODUCTION EFFICIENCY WITH HIGH YIELD PRODUCTION

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Abstract

Increases in crop yields are due to changes in the genetic efficiency in the use of inputs. However, there are constraints on efficient use of resources, e.g., water, nitrogen, solar radiation, that limit consistent high yield response. The interactions of water, nitrogen, and light form a basis for understanding how crop production efficiency can be improved. Carbon dioxide is an input to crop production that has been overlooked and understanding this environmental component will help identify barriers to high yield production. Increasing crop production efficiency is a key to increasing crop yields.

Introduction

High yields are considered an anomaly. Over the past decades corn (*Zea mays* L.) yields have steadily increased each year to genetic improvements. Producers continually search for agronomic practices that will increase yields; however, they are often frustrated by the yield variation they observe or the lack of yield response to changing management practices. Yield variation across production fields has begun to enlighten the research community and producers about the complexity of the interactions that exist within a crop production system that limit yields. Recent observations on cotton (*Gossypium hirsutum* L.) and corn in Texas have demonstrated that yield variation across a field is a complex interaction of topography (Li et al., 2002; Machado et al., 2002). Li et al. (2002) used irrigated cotton grown under two nitrogen rates to demonstrate that field heterogeneity interacted with irrigation and N fertilization in affecting lint yield. Machado et al. (2002) clustered corn grain yields into four groups and found that in dry years the clusters were influenced by elevation and soil texture and in wet years the elevation and texture combinations influencing yield changed. They were able to identify areas of poor plant performance that could potentially be used to determine the benefit of in-season management decisions. Jaynes and Colvin (1997) have shown that yield variation among years in a field in central Iowa is due to soil and seasonal precipitation. Understanding the variation in yield across fields has begun to demonstrate how the natural resources and agronomic practices interact to affect yield. Within these interactions lies the key to understanding how we can increase the efficiency of crop production and crop yields.

This paper assembles some of the current information on crop production efficiency parameters and offers suggestions on how we could increase crop yields through understanding crop production efficiency. These results are the result of various experiments that we have conducted in central Iowa on corn.

Approach

Studies have been conducted on a production scale field (150 acres) in central Iowa under a range of different management scenarios. These studies have been described by Hatfield and Prueger (2001a and 2001b) and a brief synopsis will be presented in this paper. The objectives of these studies have been to evaluate the interactions of soil water and nitrogen on crop yield response across a production field. The field is in a corn-soybean (*Glycine max* L. Merr.) rotation and the observations have been made in areas of the field that have been located with a GPS unit to identify the same experimental area each year. We have divided the production field into different nitrogen treatments that cover a range of application times (fall vs. spring and single vs. multiple applications). In this study we have located the intensive observation areas in the major soil types of the field with the focus on the Canisteo, Clarion, and Webster soils since these represent a range of organic matter contents and soil water holding capacities.

A series of measurements have been made in each experimental area. We have measured crop growth parameters, e.g., leaf area, crop height, phenology, crop biomass, leaf tissue N content, yield, and grain quality. The crop growth parameters have been measured as frequently as once per week during the growing season. These measurements are made on 10 plants collected from three replicates in each treatment. Observations of the crop water use rates have been made with energy balance equipment that measures the evaporation rate of water from the crop. These measurements are made continuously from shortly after planting until maturity. In 2000 we added the measurement of CO_2 to the suite of measurements in order to quantify the exchange of carbon and water vapor. We also added a measurement system that collects CO_2 and H_2O vapor concentrations at eight heights within a canopy. These measurements are used to estimate the water use efficiency at the canopy level in response to various management practices.

Across the different treatments we have collected reflectance data with a broad-band radiometer that measures the reflectance from the canopy in the same wavebands that are used on the Landsat satellites. This radiometer is mounted on a highboy tractor with a boom that positions the radiometer at 2 m above the canopy. These data are used to approximate the light interception and leaf area index of the canopy at various locations within the field. Leaf chlorophyll measurements are made with a leaf chlorophyll meter with 30 measurements made in each plot. These measurements are made on the upper leaf until tasseling and then the ear leaf is measured. Measurements commence when the corn plant is at the 6-leaf stage and continues until physiological maturity. The combination of the canopy reflectance data and the leaf chlorophyll data are used to provide a spatial estimate of the variation in crop growth response to nitrogen management.

All of these data have been assembled over these fields since 1997 to provide a measure of the interactions that occur among soil, crop water use, nitrogen management, and yield. If we are to understand the factors that limit yield or conversely contribute to high yields then we need to define these interactions.

Results

Water Use Efficiency

Water use efficiency (WUE) has been a standard parameter in semi-arid or irrigated agriculture to determine the return on the investment of water. The approach has shown that there is a linear relationship between crop water use (transpiration) and crop yield. The more water the plant transpired the greater the crop yield. The assumption has been that WUE is affected by soil water availability with a smaller effect caused by soil management parameters. Hatfield et al. (2001) showed that nutrient management could have a major impact on WUE. The yield observations we have assembled for corn in central Iowa with a range of N management scenarios has shown that WUE response is more complex than we thought. This is illustrated by the results shown in Fig. 1.

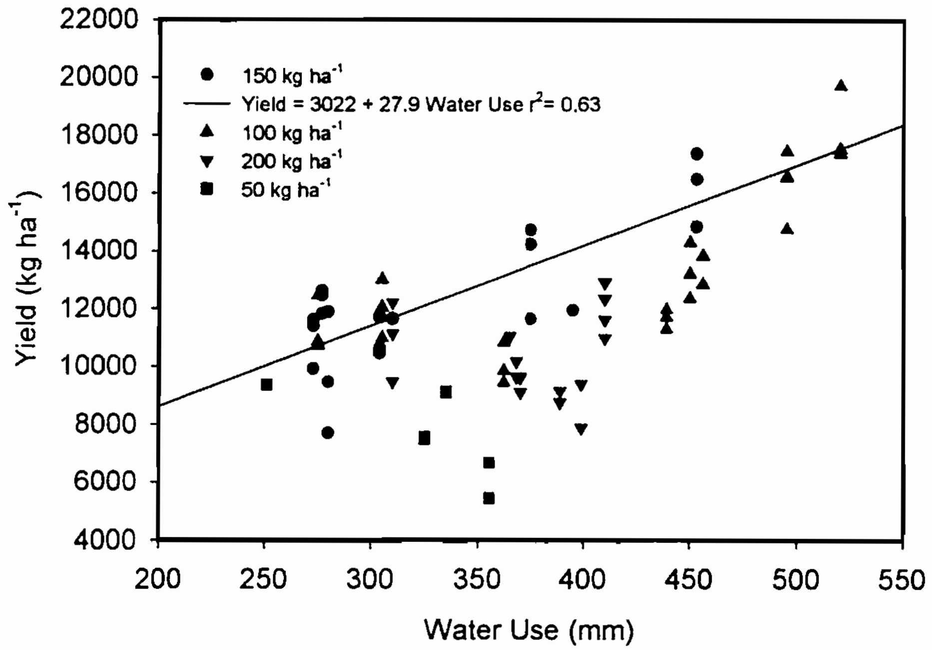

Figure 1. Water use efficiency derived from corn grain yield and crop water use for corn grown under a range of N application rates across a range of soils.

These data were developed by collecting the water use amounts from the energy balance systems across the field and then estimating the soil water evaporation rate to subtract from the total water use. When this was completed we found that crop water use rates were similar until tasseling and then during grain filling differences in crop water use began to emerge. Reduced crop water use after tasseling was evident in the Clarion and Canisteo soils because the soil reservoir was insufficient to maintain the demand of the crop. This created a situation where the plant was not able to utilize the applied N in the field. Examination of Fig. 1 reveals the 50 and 200 kg ha^{-1} N rates were below the line fit through the 150 kg ha^{-1} N rate. There is potential to increase WUE and yield by matching soil water holding capacity to N rates and several of the 100 kg ha^{-1} points are above the line in Fig. 1. We could also increase WUE efficiency by increasing the soil water holding capacity of the soil. Any management practice that increases infiltration and water availability will have a positive impact on WUE. We need to explore more options in soil management relative to this goal. The observations of several research groups that cluster soil texture and elevation are finding these factors as surrogates for crop water use.

Crop Nitrogen Response

Across the soils within the field we observed a large range in crop yield relative to N application rate (Fig. 2). One of the striking observations was the large variation within each N rate in yield response. Upon further examination we found that the data points clustered at the lower yields within a N rate were from the soils with the lower soil organic matter and soil water holding capacity. The inconsistency in yield response to N is not always reported and these data show that above 100 kg ha^{-1} N applied there was no response to N and actually a decrease in yield of 4.5 kg ha^{-1} per kg ha^{-1} N applied. These interactions of reduced yield result in the low WUE shown in Fig. 1. Management of N to the crop to increase yield may not lead to increased yield unless there is sufficient soil water to supply crop needs. In this field we observed that the nitrogen use efficiency (NUE) calculated based on the N application rate showed a linear decrease with increasing N application (Fig. 3). Understanding N responses across fields may lead to increased yield and yield stability across soils and years. If we examine the variation in NUE at each of the application rates the variation is the largest at the low rates and decreases (Fig. 3). The NUE decreases with application rate because the return to yield does not offset the additional amount of N applied. This relationship would apply to only soils with higher soil organic matter contents.

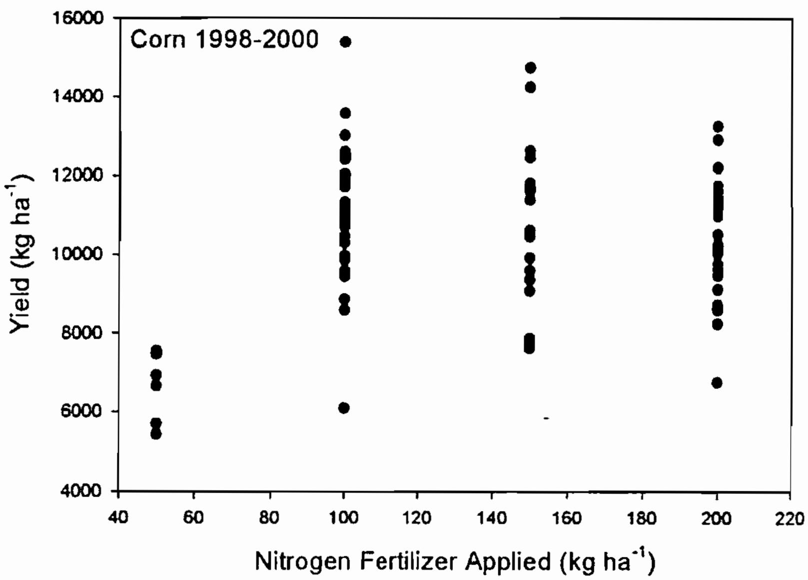

Figure 2. Corn yield response to N applied across a production field in central Iowa.

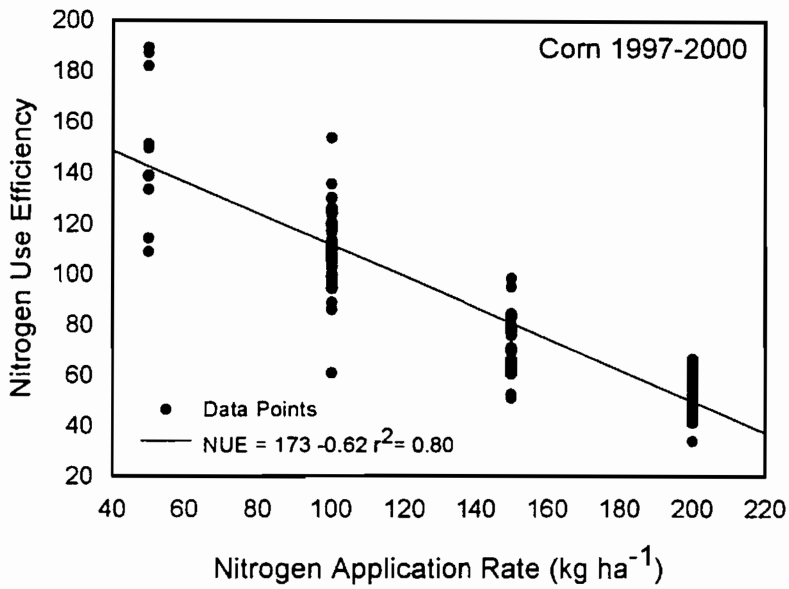

Figure 3. Nitrogen use efficiency for corn grown in central Iowa under a range of N application rates and across soil types from 1997 to 2000.

Light Use Efficiency

One of the critical components in crop production is solar radiation. The conversion of sunlight to carbohydrates through the photosynthetic process represents the ability of plant to capture and utilize sunlight as an energy source. The accumulation of biomass and grain yield represents the accumulation of sunlight. These basic properties are often overlooked in the assessment of production efficiency. In these fields where we have collected grain yield and water use data we have been able to estimate the interception of solar radiation by the corn canopy. There is a linear relationship between the amount of solar radiation intercepted by the canopy and the crop yield (Fig. 4). The slope of the light is the light capture efficiency term. This term has often been overlooked in evaluating agronomic systems because of the difficulty in measuring light interception.

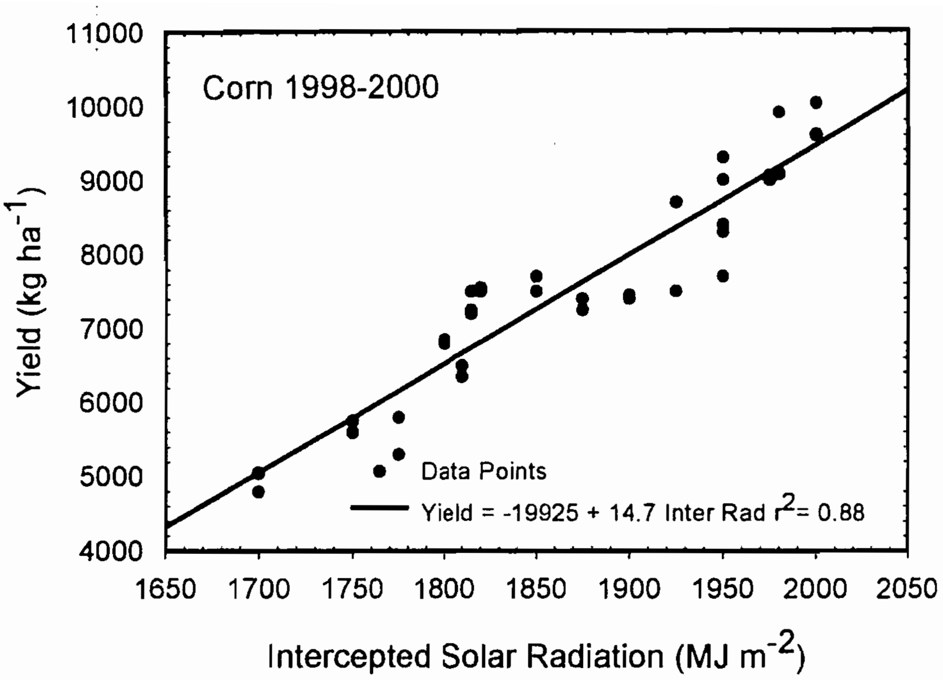

Figure 4. Corn yield as a function of intercepted solar radiation estimated from corn growth and reflectance observations during the growing season.

The linear increase in yield with intercepted solar radiation offers some potential to explain differences among different locations in a field. We have also observed that differences in this relationship (Fig. 4) occur because of the effects of stress during grain-filling. We have found that the rate of senescence from the onset of grain fill to maturity forms a linear relationship to grain yield. In order to obtain the highest grain yield we will have to optimize the capture of solar radiation by the canopy and then convert this intercepted radiation into photosynthetic material. In this field we observed that the field was most uniform at the tasseling stage and that variability began to appear during the grain-filling period. This variability was due to the differing rates of senescence across the field. We also observed that potential yield was consistent across the field at the onset of the reproductive period. These observations have led us to conclude that crop yield for fields in central Iowa is determined by how well the soil can supply water to meet crop needs during the grain-filling period. Reductions in WUE, NUE, and light capture efficiency all demonstrate the need for management systems that optimize these factors.

Carbon Dioxide Dynamics

Carbon dioxide is one of the key components in crop production. Light capture by the canopy converts CO_2 into carbohydrates. Observations of CO_2 uptake patterns for fields with the same intensity of data collection as crop water use are lacking. Fortunately, we have been able to assemble equipment that allows for the measurement of both CO_2 and H_2O vapor above and within canopies. These data are beginning to confirm what we have observed in other parts of the study. Stress caused by low soil water reduces the uptake of CO_2 by the canopy. We observed that the dynamics of both CO_2 and H_2O vapor within corn canopies that a reduction in transpiration rate reduces CO_2 uptake and the slope of the relationship is a dynamic measure of crop WUE. The comparison of CO_2 and H_2O vapor dynamics within canopies will help explain variations we observe in crop response to N management.

We observed other relationships within the canopy. Carbon dioxide profiles within the canopy show a large diurnal range. The largest concentrations occur at night with low or no windspeeds and there is an increase near the soil surface. A portion of the increase is due to respiration at night; however, the profiles within the canopy suggest that respiration from the soil contributes to the canopy CO_2 pool. When the sun rises in the morning and light begins to penetrate the canopy this pool rapidly disappears and by 8:00-9:00 in the morning, the C are near ambient levels and decrease until early afternoon. On many days the CO_2 concentrations are below 280 ppm which is sufficient to limit effective photosynthesis. At the same time the H_2O vapor concentrations continued to increase in the canopy showing that the canopy WUE was decreasing. One of the key attributes to achieving high yields is to ensure that the photosynthetic rate is operating at maximum efficiency and our observations suggest that this may not occur in many situations in field environments.

Other Stresses

There are other stresses, e.g., insects, diseases, weeds, that limit crop performance. Observations of smut in corn by Machado et al. (2002) in the water-stressed parts of the field coincide with our observations during the 2002 growing season in which we found that presence of smut increased in spring tillage plots (Hatfield and Sauer, unpublished data). In the spring tillage plots there was a reduction in the amount of soil water available in the early growing season and this created an insect stress during ear development that allowed the fungus to be present in the kernels. There are other insect and diseases stresses that may be present in crops that we don't associate with management practices that affect water or nutrient availability. These interactions need to be quantified if we are to completely understand the dynamics of crop production efficiency.

High Yield Responses

Achieving high yields from crops will require that we begin to approach the problem of increasing yield from the perspective of crop production efficiency. In agronomy we have examined yield from a response to input set of relationships, i.e., we discuss yield relative to N or other nutrient inputs or plant populations. We have not tried to dissect yield to determine how it relates to production efficiency parameters. There may be barriers to WUE and NUE changes within a field due to the soil properties that limit water supply at critical growth stages. In the Corn Belt where we rely on precipitation for crop production we need to begin to develop a more complete understanding of these interactions across fields. The observations we have collected to date across a production field are beginning to reveal how we can integrate these pieces into management systems that will further increase yields. In 2001 we were able to produce 20,000 kg ha^{-1} of corn grain on 100 kg ha^{-1} which was the highest of any WUE or NUE efficiency values we have observed in our studies. This was possible because we have begun to understand how these factors interact across the different soils and climates.

As we begin to develop a more comprehensive understanding of crop production it is possible to further increase crop yield by creating a more efficient system. This provides a new opportunity for us to begin to explore how natural resource factors, e.g., solar radiation, temperature, precipitation, interact with the soils and topography and agronomic factors, e.g., nutrients, genetics, and plant populations to create the most efficient production system. Through this approach we will be able to increase crop yields through better and more efficient use of these resources.

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