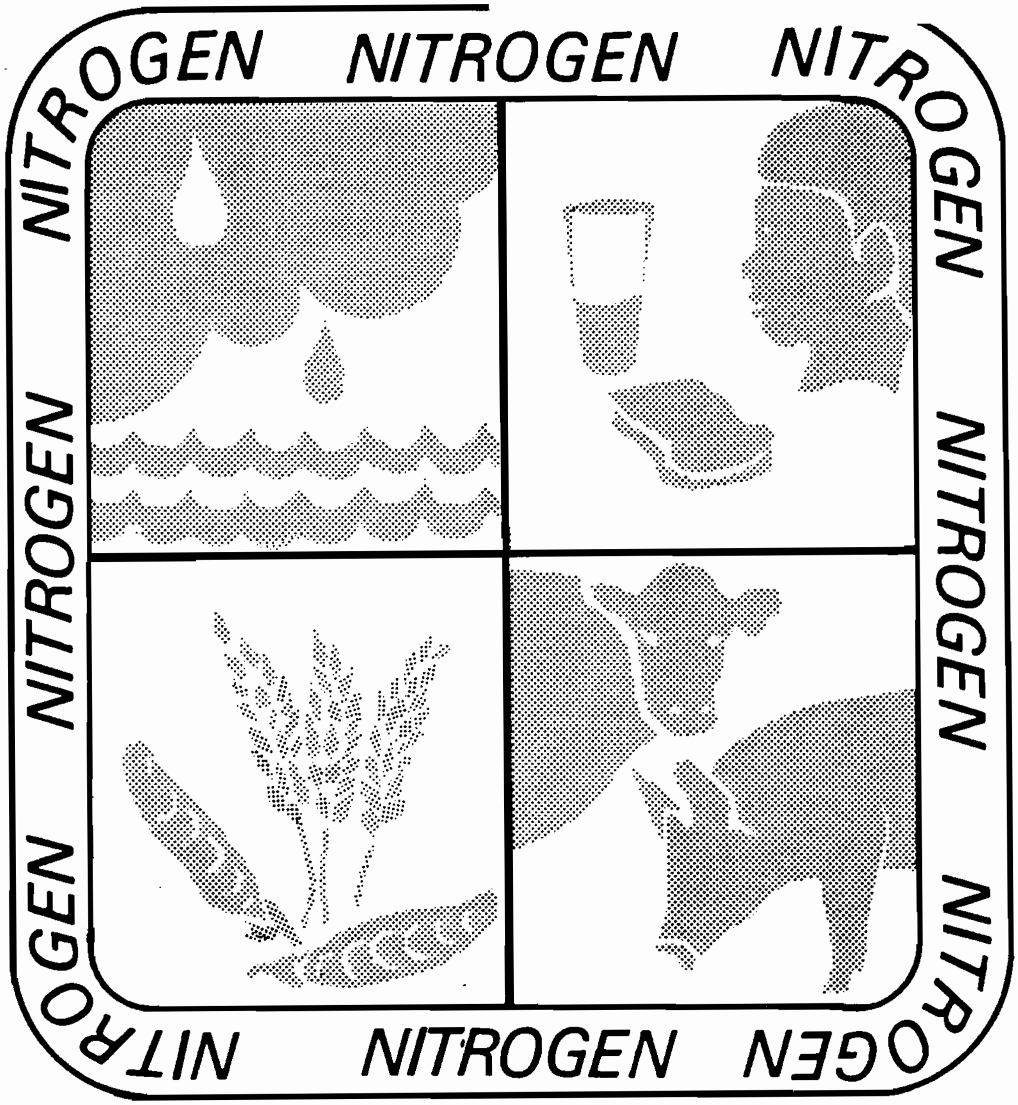

NITROGEN RESEARCH-1989

Current Advances And Future Priorities

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NITROGEN RESEARCH 1989

Current Advances and

Future Priorities

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ADVANCES IN N USE EFFICIENCY

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ABSTRACT

Factors affecting N use efficiency (NUE) by crops, current technology, and future research needs to improve NUE are discussed herein. Long-term trends in corn and wheat yields for the U.S. indicate that yields and rate of N application have increased with time. For wheat, genetic advancements have been credited with 43 to 74% and N fertilization with about 22% of this total increase in yield. Nitrogen use efficiency (g N applied/kg grain) has changed very little since the early 1970's. Thus one may ask the question if any advancement in NUE has really occurred over the last 15 years.

Changes in energy costs and availability, increasing N prices, changes in tillage practices, and environmental concerns have caused a change in attitude of researchers and educators, but apparently not farmers toward NUE in the last 10 years. Urea has become a dominant fertilizer N source in world markets, a phenomenon with implications for NUE. Factors affecting NUE that are currently being emphasized include: N source, timing of N application, placement of N to enhance plant uptake and reduce NH_3 losses, crop rotation, climatic and soil factors, water supply and crop yield potential, variety/hybrid selection, plant population, disease, weeds, insects, nitrification inhibitors to reduce NO_3-N losses, NH_4 vs NO_3 requirements of plants for optimum yield, urease inhibitors

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to reduce NH_3 losses, irrigation management, and improvements in N recommendations which are based on soil testing for easily mineralizable and residual soil N, credits for legumes, manures, and other wastes applied, and consideration of yield potential based on crop production factors. Factors that affect N uptake by the crop and its yield potential can affect NUE.

Future research needs include development of methods to improve N utilization by crops and reduce N losses to the environment. Development of cropping and crop management systems for efficient water and N use is critical for all crops and climatic conditions. Future research should also address environmental concerns of N in agriculture while maintaining an economically sustainable agriculture in the future. Increasing NUE may have an economic price tag attached for the farmer and society. Our goal should be to integrate all the management, physical, and chemical factors that affect yield into site specific N best management practices that will raise yields with the same amount of N input or maintain current yields with lower N input.

INTRODUCTION

Most U. S. soils are deficient in N for commercial production of cereals. Nitrogen inputs are therefore needed to sustain commercially viable cereal crop systems. The N inputs for modern crop production can come from manures, fertilizer, or legume residues. Prior to 1950 agriculture relied on manure and legume N inputs from small rotation-livestock systems in order to sustain cereal crop production. Since 1950, use of fertilizer N has increased greatly while wide spread use of manure and legume N has decreased due to the advent of large single species animal enterprises and the costs associated with moving manure. The concentration of animals into large units has increased the manure loading rates on most livestock farms. Prior to 1975, the primary goal of N management was to improve agronomic effectiveness and economic return. Since 1975, considerable agronomic research has dealt with improving N use efficiency and quantifying N losses from agricultural systems (Hauck, 1984a; Hergert, 1986; The Fertilizer Institute, 1985). Today, improving crop N (manure N, fertilizer N, legume N) utilization in modern agricultural systems is still a major concern (Keeney, 1982, 1985, 1986; Nelson, 1985). Optimizing economic returns and making efficient use of N requires that crop N supplies be adjusted to changes in other crop production factors (Halvorson and Murphy, 1987). Factors that must be considered in optimizing N utilization include: 1) climate and soils; 2) plant-available water and yield potential; 3) tillage method and water conservation practices; 4) timing of N application; 5) N source and placement; 6) soil testing and residual soil NO_3 levels; 7) variety/hybrid selection; 8) plant population and row spacing; 9) seeding date; 10) crop rotation; 11) pests (weeds, insects, disease); 12) efficient irrigation management (minimum NO_3 leaching potential); 13) leaching; and 14) denitrification. Any crop production factor that limits or reduces crop yield with given inputs will generally lower N use efficiency (NUE). Bock (1984) indicated that NUE can be characterized by several relationships: a) the relationship between yield and N rate is yield efficiency (g N applied/kg grain); b) N recovered and N rate is N recovery efficiency (g N uptake/g N applied); and c) N recovered and yield is physiological efficiency (g N uptake/kg grain). Each of these is a distinctly different quantity, so we need to define exactly what is meant by NUE when reporting or utilizing this term. In this paper, we will define NUE as yield efficiency, g N applied/kg grain.

A concern in today's agriculture is the environmental effects of fertilizer use as well as its impact on food production (Aldrich, 1984). Nitrogen is leaking from agricultural ecosystems into groundwater and surface water (Madison and Brunett, 1985; Chen and Druliner, 1988; Eckhardt and Oaksford, 1988; Keeney, 1985; Keeney, 1986). A balance between food production, profit, and environmental quality must be achieved and maintained by modern agriculture.

An analysis of wheat yield increases relative to advances in technology from 1954 to 1979 shows that wheat yields increased 30 kg/ha per year in the Great Plains states and 43 kg/ha per year in the Cornbelt states (Feyerherm et al., 1988). In the Great Plains, 43, 22, and 35% of the total increase was attributed to genetic improvement, applied N, and other sources, respectively, compared to 74, 22, and 2% for the Cornbelt. Genetics and applied N accounted for almost all of the yield gain in the Cornbelt, but other factors (irrigation, pesticides, improved tillage, water conservation, etc.) contributed about one-third of the gain in the Great Plains. Corn and wheat grain yields and N applied to each crop increased from 1954 through 1988 as shown in Figures 1 and 2 (Adams et al., 1958; Hargett et al., 1987; ERS, 1985; NASS 1988). The ratio of fertilizer N applied to grain yield shows that

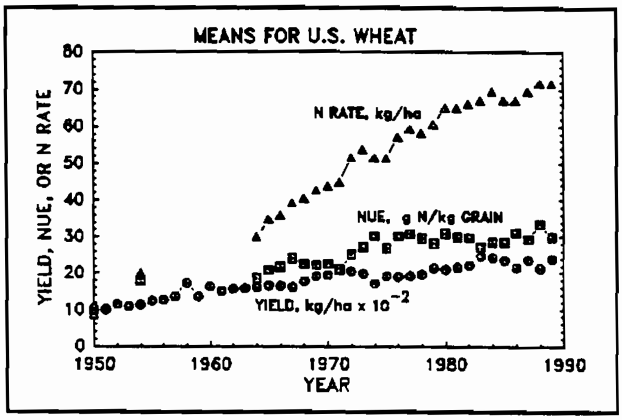

Figure 1. Changes in wheat yields and nitrogen use with time.

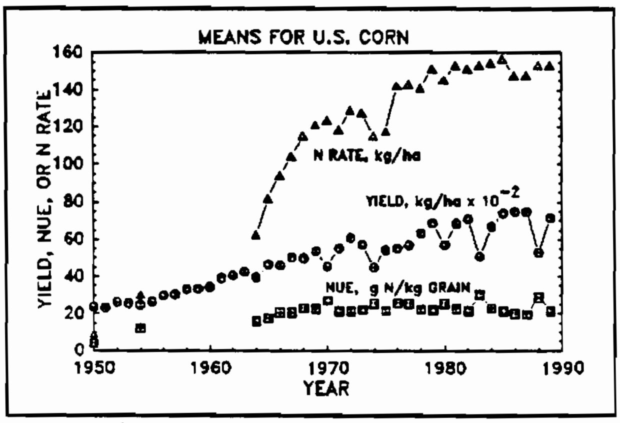

Figure 2. Changes in corn yields and nitrogen use with time.

about 30 g N/kg wheat and about 22 g N/kg corn has been maintained for the past 15 years. This translates into an efficiency of about 55% (kg N in grain/kg N applied) if we assume wheat contains about 2% N, corn about 1.5% N and both grains contain about 15% moisture. This may indicate that on a national basis, little progress has been made in changing NUE by these two crops over the past 15 years. Obviously, NUE can greatly affect N losses from agricultural ecosystems; because N not recovered by the crop potentially may be lost to the environment.

Hauck (1984a) summarized the fate of isotopically labelled N applied to soils. Generally, 50 to 60% of the N applied is taken up by crop plants during the season of application, with a range of 25 to 80%. About 25% of the N applied remains in the soil in inorganic or organic forms after cropping with a range of 15 to 45%. About 25% is lost from the soil-plant system through leaching, denitrification, and/or ammonia volatilization. These numbers represent the partitioning of applied N among plants, soil, waters, and atmosphere during and immediately after the growing season.

Nitrogen application practices, mainly N rate, timing, and placement can have significant effects on NUE. Technological approaches for increasing the efficiency of fertilizer N use by crop plants have included the use of (a) slow-release N fertilizers; (b) chemicals that inhibit biological N transformations in soils; (c) amendments to N fertilizers that alter their physical and/or chemical properties; and (d) improved crop and soil management practices (Hauck, 1984b). These N application practices and technological approaches are directed mainly toward reducing N losses or maintaining an adequate supply of plant-available N in the plant root zone. Major avenues of N loss from the soil-crop systems are leaching, biological denitrification, and ammonia volatilization from soil.

The topic of N use efficiency is broad and covers many crops and management systems; therefore, our comments will deal mainly with wheat and corn. Recent review articles provide detailed discussions of many of the factors discussed in this paper.

FACTORS AFFECTING N USE EFFICIENCY

Nitrogen use efficiency is affected by many factors. Some are not subject to management (weather, soil type, etc.), but many are readily managed (crop variety, N rate, N timing, tillage, irrigation, etc.). Some of the major factors affecting NUE will be discussed.

Climate and Soils

Temperature (air and soil), precipitation (amount and distribution), and length of growing season (frost free days) determine crop adaptation and greatly influence yield potential, particularly of dryland crops. Soil physical and chemical characteristics also influence yield potential. Soil texture affects the quantity of soil water that can be held for crop use. Soil compaction can reduce plant growth, root growth and penetration, and water and air movement in soil which can contribute to reduced yields and inefficient use of plant available N. Soil acidity and salinity can decrease crop yield potentials and response to applied N. Soil organic matter content and parent material influence native soil fertility level and plant nutrient supplying power.

Yield Potential and Crop N Requirement

The crop N requirement is determined by the type of crop and its yield potential. Predicting yield potential or setting a realistic yield goal is critical for efficient N utilization (Bock and Hergert, 1989). The higher the yield potential, the greater the total N requirement needed to achieve this yield and maintain crop quality (Black and Bauer, 1986). Wheat generally requires about 40 g N/kg grain to optimize yields (Halvorson et al., 1987), corn about 20-23 g N/kg grain (Fixen, 1985; Meisinger et al., 1985). To optimize profits (least cost per unit of produce), a farmer should neither under nor over estimate a yield goal. Yield limiting factors that can not be controlled by a producer should be considered when establishing yield potentials and determining plant N requirements to insure optimum NUE. For example, yield potential is directly a function of water available for plant growth in semi-arid and arid regions, particularly for dryland crops. In these regions, plant-available water (stored soil water plus growing season precipitation) can be used to predict yield potential (Halvorson and Kresge, 1982; Isfan, 1979).

Nitrogen uptake patterns vary for different crops (Olson and Kurtz, 1982; Bauer et al., 1987). Crops differ in time of year they need N and in total N requirements; however, crops generally need a large amount of N over a relatively short time. Wheat uses about 1.4 kg N/ha (3 lb/a) per day during its "grand (rapid) period of growth" and the corresponding value for corn is about 1.1 kg N/ha (2.5 lb/a) per day. Therefore, in order to insure an adequate N supply in N deficient soils, a rapid N release source or a large pool of NO_3 from mineralization is needed just before this "grand period of growth".

Much progress has been made in the area of establishing realistic yield goals in the last 10 years (Bock and Hergert, 1989); however, more correlation work is needed in the future to establish yield-N need relationships for crops other than wheat and corn.

Soil Testing and Predicting Plant N Requirements

Twenty years ago, soil testing for NO_3-N was considered of limited value in crop production. However, research has shown that NO_3-N tests can be used very effectively for improving N fertilizer recommendations. Crop N requirements have been more clearly defined for many crops as agricultural research has studied crop N uptake associated with various yield levels. Soil NO_3-N tests can increase fertilizer NUE by enabling adjustment of fertilizer N rates to reflect soil NO_3-N content and predicted crop needs. Soil N tests estimating residual NO_3-N within the root-zone (0.6-1.8 m depth) works very well in drier areas of the western U.S. (west of Missouri River). Many western states have active NO_3-N test programs in operation (Hergert, 1987).

Soil NO_3-N testing also is proving to be useful in humid climates, particularly after drought years when residual NO_3-N is likely to be high and after dry winter seasons (Bock and Kelley, 1989; Bundy and Malone, 1988; Mapels et al., 1977). The participants of a soil testing workshop held in February 1989 at TVA emphasized the need for soil and/or plant N tests that can refine N rate recommendations and identify N non-responsive sites as a means of reducing adverse environmental effects of agricultural N anu improve economic returns in humid areas of the U.S. (Bock and Kelley, 1989). A pre-sidedress soil NO_3-N test (nitrate measured in the top foot of soil just before sidedressing time) has been highly correlated with corn response to N fertilizer in Vermont (Magdoff et al., 1984), Pennsylvania (Fox and Piekielek, 1984; Fox et al., 1989), and Iowa (Blackmer et al., 1989), areas where soil NO_3-N has been considered impractical in the past. Root-zone sampling for residual NO_3-N provides an excellent opportunity for improving N use efficiency.

Fertilizer recommendations have been adjusted to give credits for other N sources such as manure and legume crops. Determining N rate requirements based on yield potential and N budgets (i.e.- residual soil NO_3 and NH_4; organic matter; mineralization capacities, etc.) can greatly enhance NUE. A major goal for the next 10 years is to convince all commercial concerns to adopt soil NO_3-N testing as a standard part of making N rate recommendations. Obtaining near maximum yields, maximum N use efficiency, and minimal residual soil NO_3-N carryover at the end of the growing season should be the goal of a proper N fertilization program.

Timing of N Application

Timing of N application has received much attention, especially with regard to preventing or reducing the leaching potential of NO_3-N in agricultural systems (Follett et al., 1989). Application of N just before the time of most rapid N uptake generally assures the best crop use of N under irrigation and in humid areas (Welch, 1971; Meisinger, 1984). In semi-arid areas, lack of rainfall can result in N that is positionally unavailable (in dry surface layers) to the crop at critical growth stages, if the N is not applied early enough. Much of the leaching potential exists between cropping seasons or before crops start growing rapidly. In these situations, post-plant application of N is effective because N is supplied in close proximity with crop N uptake. Data from Malzer and Graff (1984, 1985) shows that less N was required to optimize corn grain yields when sidedressed than when N was applied preplant. In irrigated areas, applying N with irrigation water just preceding maximum N uptake periods is another good method for improving N use efficiency. Careful irrigation management must be practiced in order to avoid over-irrigation, resulting in movement of NO_3 out of the root-zone. Another problem is untimely rainfalls which occur just after "fertigation". Fertigation is the application of N via an irrigation system by injecting the N into the water flowing through the system. Irrigation scheduling is being adapted to improve water use efficiency which should improve NUE by reducing leaching losses. Gardner and Roth (1984) present a thorough discussion of irrigation method as related to N application.

Split N applications for corn/wheat are known to be the most efficient way to supply N to corn even in drier climates, provided the N is placed into the root-zone and that adequate N is supplied in early part of growing season (Olson et al., 1964; Boswell et al., 1985). With no-tillage or conservation tillage, split N applications have been shown to be especially beneficial due to greater denitrification potential in no-till (wetter soil, more organic matter, denser soil), rapid immobilization of surface applied N in previous crop residues, and greater infiltration of water (with consequent, greater potential leaching) in no-till (Fox and Bandel, 1986; Thomas and Frye, 1984; Wells, 1984). Split applications of N are being evaluated and promoted for use on corn, particularly with irrigation. Split applications of N for dryland wheat are being evaluated as a means of increasing wheat production levels and enhancing grain protein (Alley et al., 1988; personal communications with Armand Bauer, USDA-ARS).

N Source and Placement

Consumption of solid fertilizer N sources has changed considerably from 1962 until now (Harre and Bridges, 1988). In 1962, ammonium nitrate, ammonium sulfate, and urea occupied 27, 18, and 5% of the world share of N consumption, respectively. In 1986, the world consumption of these respective products were 15, 5, and 37%. Thus urea is now the dominant N source in world markets. Other N sources, primarily anhydrous ammonia and liquid N sources occupied 29% of the world N market in 1986. In the United States, anhydrous ammonia, N solutions, and urea represent about 40, 20, and 15% of the N fertilizer use. Urea use has increased at the expense of ammonium nitrate.

In summarizing N-source comparison research with respect to N use efficiency and yield response, Hargrove (1988) indicated that when N fertilizers are not incorporated, urea is inferior to ammonium salts as an N source on noncalcareous soils, but for calcareous soils urea can be equal to or only slightly inferior to ammonium nitrate and superior to ammonium sulfate. Fertilizer physical form also affects NH_3 loss. When broadcast, urea-containing N solutions tend to lose more NH_3 than dry sources. Thus, with increasing use of urea and urea-containing N solutions, agronomic management practices in the future need to be developed and adapted that will insure high levels of NUE from these N sources. Method of application will greatly influence NH_3 loss, with maximum losses occurring with broadcast surface applications that receive no incorporation.

Fertigation is one way to reduce N volatilization losses (water carries N into soil), however, some loss may still occur. Fertigation has been practiced with sprinkler, furrow, and drip irrigation (Hargrove, 1988; Randall, 1984). Fertigation also allows timing of N application to coincide with plant N demand periods. Banding N sources on the soil surface or below the soil surface will generally reduce NH_3 losses, but may or may not increase yields compared to surface broadcast applications, depending on the N loss processes at the specific site.

Bock (1987) reviewed the agronomic differences between supplying plants with NO_3 and NH_4. The relative level of each of these N species in soil can affect crop nutrition, N availability to the roots, and N losses from the root zone. He indicated that inconsistent responses to enhanced ammonium nutrition have been reported from field studies. For corn, the trend is for enhanced ammonium nutrition to increase grain yields of the highest yielding hybrids and within high yield crop production systems. A potential exists for achieving greater yield responses by selecting genotypes specifically for their ability to respond to enhanced ammonium nutrition. The concept of enhanced ammonium nutrition needs considerable development before it is ready for general use by farmers.

The release characteristics of the N source being utilized should also be considered in relation to the N uptake pattern of the crop being grown. Highest efficiency will be realized if the N release occurs just before (about 2 weeks) the rapid N uptake pattern of the crop. Slow-release commercial N fertilizers are of four types: (1) water soluble N sources with coatings; (2) materials of limited water solubility containing plant-available forms of N; (3) materials of limited water solubility, which, during decomposition release plant-available forms of N; and (4) water-soluble materials that gradually release plant-available N (Allen, 1984; Hauck, 1985). These types of fertilizers represent a wide range in patterns of N release. Nitrogen release patterns differ for various manures. For example, poultry manure has very rapid N release and needs to be used almost like fertilizer N (Bitzer and Sims, 1988; Sims, 1986) while cattle manure has a slow to rapid N release pattern depending on type of manure, bedding, storage conditions and application conditions (surface vs. incorporation). One of the best ways to use manure efficiently is to test it for NH_4-N or total N content, then base application rates on actual analysis and application methods (Klausner and Bouldin, 1983; USDA, 1979). Sludges or composted sludges are also good N sources but the N release patterns can be greatly reduced by composting (O'Keefe et al. 1986; Epstein et al. 1978; Sommers and Giordano, 1984). Loading rates and N use efficiency should therefore be adjusted for N release characteristics of the sludge or manure (Sabey et al.

1975; USDA, 1979). Conventional N fertilizers give virtually immediate (within 2 weeks) N availability since most of these materials contain or convert quickly to NH_4 or NO_3.

For high N use efficiency, ideally the N source should be placed where the N release occurs within the active water uptake portion of the crop's root-zone. Nitrate moves to roots by mass flow with water. In sub-humid and arid parts of the country (west of Missouri River), N sources need to be placed in the root-zone to give best N uptake efficiency and avoid having the NO_3 accumulate on the dry soil surface where water uptake is low.

Placing N below the soil surface will reduce N volatilization losses, reduce the amount of organic matter tie-up of N, and generally make the N source more readily available to the crop. Advances in fertilizer application equipment will enhance NUE (Murphy and Beaton, 1988; Randall et al., 1985). Combining fertilizer application equipment with computer technology will allow commercial application of prescribed amounts of N for each soil type as the applicator proceeds across a field. Fertilization by soil type should reduce N leaching losses, reduce over and under fertilization problems, and result in improved NUE.

N placement for no-tillage (or conservation tillage) is especially important for urea containing fertilizers. (Fox and Bandel, 1986; Thomas and Frye, 1984; Murphy and Beaton, 1988). Urea fertilizers quickly hydrolyze on the urease rich surface residues of no-till and can lose significant amounts of N through ammonia volatilization (often 5-25% of the urea N). To control these losses, an effort needs to be made to incorporate urea sources by injection behind a coulter, knifed in with common anhydrous equipment or to use N sources not containing urea (Fox and Bandel 1986; Thomas and Frye 1984; Wells, 1984). These same problems also apply to manure N (which contains urea) in no-till systems. Non-urea N sources generally can be spread on the soil surface with good results. An exception is ammonium sulfate which has a relatively high potential for ammonia volatilization from calcareous soils.

N Fertilizer Amendments

Nitrogen use efficiency may also be increased by the use of additives or amendments to N sources. Seven chemicals are produced commercially worldwide for use as nitrification inhibitors with N fertilizers. In 1984, only two chemicals, nitrapyrin and Terrazol, were licensed for use as nitrification inhibitors in the U.S.. Dicyandiamide (DCD) was being test marketed (Hauck, 1984b). The search for urease inhibitors to control rapid urea hydrolysis and the consequent liberation of ammonia is becoming more important as farmers use increasing amounts of urea and UAN solutions, especially with non-incorporated surface applications (Radel et al., 1988; Voss, 1984).

Nitrification inhibitors should be viewed as a N management tool. The benefit to be derived depends on the soil type, time and rate of N application, and weather conditions between N application and crop uptake. The greatest potential for benefits are with soils that frequently remain saturated with water during the early part of the growing season, primarily the poorly drained soils. Coarse-textured soils are likely to benefit more than the finer-textured soils (except those that are poorly drained), since the use of nitrification inhibitors will reduce the high potential for leaching that exists with such soils (Hoeft, 1984).

Cropping Systems

Rotation of crops within a cropping system often shows beneficial effects on crop yield (Pierce and Rice, 1988; Power and Doran, 1988). Higher yields resulting from rotating crops at the same N level will improve NUE. Hook and

Guscho (1988) point out that with multiple cropping systems, N that is not utilized by the first crop can often be utilized by the second crop (providing allowances are made for residual soil N), thus giving more efficient use of N. Jones et al.(1980) found that NUE was higher for annual cropping systems than with a wheat-fallow rotation. Utilization of flexible, more intensive cropping systems to make more efficient use of water will also make more efficient use of N inputs. Cropping systems designed to utilize water efficiently can reduce the loss of N through leaching (Halvorson and Kresge, 1982; Halvorson, 1988). Using cropping systems with legumes (soybeans, forages, etc.) is also an excellent way to improve recovery of residual N since legumes generally utilize available soil N before they begin to fix N (Meisinger and Randall, 1989). Cropping system design needs to consider crop water use patterns, rooting depths, and N needs.

Variety/Hybrid Selection

Variety or hybrid selection for specific site conditions can greatly influence yield potential, response to N, and profitability. A variety/ hybrid's response to the environment affects both yield and crop quality. Selecting the best adapted varieties or hybrids with the best yield potential for a given area will enhance NUE efficiency for a given N rate. When N rate is adjusted in accordance with yield potential, varieties/hybrids with the highest yield potential may or may not give the highest NUE. Varieties should be chosen for resistance to lodging, diseases, and insects under high N fertility, high yield environments and/or sensitivity to low soil pH conditions. Timian and McMullen (1986) found the spring wheat variety "Olso" had a 33% reduction in grain yield when infected with the wheat streak mosaic virus versus a 98% reduction for "Olaf". Unruh and Whitney (1986) reported that the winter wheat varieties

"Newton" and "Tam 105" were extremely sensitive to low soil pH, high Al concentrations, whereas "Hawk" and "Bounty 203" hybrid showed more tolerance, with yields 3 to 4 times greater. Grain yields are also influenced by plant population and row spacings (Alley et al., 1988).

Economics

From an individual field cost-price economic stand point, generally it is better to error on the high side than on the low side of N recommendations with current N:crop price ratios (Bock and Hergert, 1989) because under dryland, N not taken up or lost in dry years tend to remain as residual N for the next crop, depending on winter leaching. This is particularly true if N limits yields in wet years; therefore, to error on high side of N recommendations is more economical, but not as environmentally sound. Thus, the immediate short-term economics of the farmer are potentially out of harmony with the long-term environmental goal of minimizing NO_3 losses.

In recent years, there has been considerable interest in the concept of Maximum Economic Yield (MEY) (Wagner, 1988). The MEY concept can enhance or improve NUE by encouraging farmers to use best management practices (BMP) to achieve optimum yields with the most profit. The objective of MEY is to obtain the most economical yield return (not maximum yield); therefore, application of excessive N from an economical perspective is not encouraged. Soil testing, planting date, plant population, herbicide, fungicides, harvest, varieties, etc, are all factors that will improve yield and profit potential (Alley et al., 1988). However, economic and environmental goals relating to NUE may not always be totally compatible (Bock, 1984). The resolution of this situation will likely involve the farmer improving NUE by soil testing, realistic yield goals, etc. and society realizing that it must accept some NO_3 loss to the environment in order to produce sufficient food and fiber.

FUTURE NEEDS

Economic Viability

As yield potentials increase with advancing technology and crop N needs also increase, we need to consider whether or not we are actually increasing NUE. Can we reduce N losses from agricultural systems and yet maintain crop productivity and economic viability of the farmer? If farmers are going to convert to no-till cropping systems which will save more water, increase yield potential, and reduce soil erosion, should they consider more intensive cropping systems to make more efficient use of water and N (Halvorson, 1988; Schepers, 1988)? Additional research on development of cropping systems for more efficient water and N use and an economically sustainable agriculture is needed.

Improved Management Of N Sources

Managing N sources (manure, fertilizer or legume residues) in the future for high efficiency, especially in no-till or conventional systems, will require a site-specific prescription which should consider: a) crop N requirements reflecting the management skills of the farmer; b) the soils ability to supply N from organic and inorganic sources; c) N release characteristics of the N source(s); d) time of N source application in relation to its release characteristics, climatic conditions (i.e. - rainfall distribution), and crop uptake demand pattern; e) N placement for efficient crop utilization, with consideration for time and energy costs to the farmer; f) use of additives or amendments to the N source that may affect N efficiency; g) and finally the rate of N applied which should consider all the above factors but primarily items a), b), d) and e) above. Future work is also needed to improve the utilization of manure and other waste N sources by: a) testing manure or wastes for total N and NH_4-N; b) developing methods to utilize manure N content data to forecast N mineralization rates and release patterns; and c) developing better application equipment to improve uniformity and rate of manure and waste applications.

Environmental Concerns

Legislation in Nebraska, Iowa, and other states will require changes in N management on sandy soils, shallow water table areas, and areas where NO_3 is leaching into groundwater (Hauck, 1988). This emphasis on groundwater quality was not a major concern 15 years ago when many of our N management practices were being developed. From an environmental stand point, we need research to evaluate and develop field methods to measure leachate/water quality on a small-plot scale. Effects of our "Known BMP's" on groundwater quality (or leachate quality) need to be evaluated, such as: 1) How large is the effect of reducing N rates on groundwater quality?; Is the economic optimum environmentally acceptable?; 2) What are the effects of N sources (slow release sources, manures, inhibitors etc.) on groundwater quality?; 3) How large is the effect of improved N timing (sidedress vs fall N) on groundwater quality?; 4) How large is the effect of improved N placement (injection vs surface vs fertigation) on ground water quality?; and 5) How large is the effect of cropping sequence (monoculture vs rotation etc.) on ground water quality?

Improved Cropping Systems

Cropping systems for more efficient N use need to be designed that consider crop rooting depth, water extraction patterns, N requirements, and their effects on NUE. Cropping systems are needed to handle problem sites such as high N mineralization rates resulting from grasslands being converted to crop production, high mineralization rates from past additions of manure or sludges, high soil NO_3-N due to drought, or high soil NO_3 due to geologic sources of NO_3. We also need to design inter-cropping or sequential cropping systems for more climates to achieve better water and N use efficiency. Use of cover crops or N scavenging crops to recover excess N should be studied. Efforts should also be made through crop breeding to improve N recovery, to produce larger root systems, to increase the N harvest index, and to tolerate sub-optimal conditions (subsoil acidity, salts, etc.).

Improved Prediction and Management Models

Systems research is needed in the future to provide information for development of management strategies and models. Methods to make more site-specific N recommendations need to be researched and developed. These methods include use of: a) computer models; b) soil resource data (soil maps etc.); c) weather data (past weather and projected weather); d) irrigation scheduling; and e) detailed soil NO_3-N data with depth. Research needs to continue on improving N soil tests as well as developing better methods for plant tissue testing by utilizing computer models. Methods for predicting N release patterns and N availability from legumes and/or soil organic matter in crop rotations are needed if N fertilization rates are to be adjusted accordingly.

Systems need to be improved for fertilizing areas within a field differently. Field equipment is now available to apply variable rates of N across a field according to soil type and soil test level. Environmental, economic, and nutrient use efficiency benefits from this technology need to be evaluated. Integration of all crop management factors and the resulting N management system will be specific for a given site because soils, crops, water management, tillage, N sources, etc, will all change from farm to farm, from field to field, and even among areas within a field. Thus recent work on fertilization by soil type rather than on a field basis (Murphy and Beaton, 1988) will help make more efficient use of N and protect the environment.

Technology Transfer

More effective ways to transfer known technologies to the farmer need to be developed. Probably the two most effective approaches to increasing the efficiency by which crop plants use agricultural N are: (a) to apply the knowledge already available to an increasing number of farms; and (b) to strive for an economically acceptable yield, not the maximum possible yield that may leave excessive amounts of inorganic N in the soil after harvest. Even in our relatively efficient systems of agriculture, improving fertilizers and the ways that they are used is an achievable goal (Hauck, 1984a). Achieving high NUE in agriculture requires integration of all the above factors into a comprehensive site-specific N management system (Alley et al., 1988; Keeney, 1985; Meisinger, 1984). Each of the above factors (crop management, soil, climate, N rate, timing, placement, additives, etc.) interact with each other to give the final NUE of the N management system. The final N management system for a given site should be based on education and training of the farmer through appropriate extension service programs based on current research information.

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