Nitrogen fertilizer strategies and empirical models for rainfed spring wheat
by Shaukat Mahmood

A thesis submitted in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY in Crop and Soil Science
Montana State University

Abstract:
Nitrogen plays a significant role in crop production and available N can have a significant effect on crop growth, yield, and quality. Consequently, use of N fertilizer offers substantial opportunity for increasing food production in many parts of the world. The supply of available N can be a decisive factor in dryland wheat production systems. Because of the nature of N and the processes N is involved in in the soil-plant system, N management can play a key role in crop production. Two studies were conducted to evaluate N fertilizer management and its effect on dryland spring wheat yield and quality and N use efficiency.. The studies were conducted at two locations in 1992 and 1993.

The effect of different N' fertilizer management strategies on plant emergence, plant growth, dry matter production, tillering, test weight, grain protein percent, harvestable protein, and grain yield were studied. The data and information obtained from these studies were used to generate nitrogen fertilizer management models, predicting grain protein percent, harvestable protein, and grain yield. Regression models were developed on the basis of time of application of N fertilizer. Treatments where fertilizer was applied on or before tillering were designated as group 1 and the treatment where fertilizer was split applied between planting and heading was designated as group 2. Separate regression models were developed for each variable for group 1 and group 2. .

Neither source of N fertilizer nor method of application of N fertilizer had a significant effect on the measured parameters. Differences in N fertilizer rate resulted in significant differences in all the measured parameters; the significant differences were more pronounced on sites initially testing low in soil NO3-N. Time of application of N had a significant effect on grain protein percent, harvestable protein, and grain yield. Split application of nitrogen between planting and heading resulted in a significant increase in grain protein percent. However, harvestable protein and grain yield were significantly reduced by delaying application, especially on sites initially testing low in soil NO3-N.

NITROGEN FERTILIZER STRATEGIES AND EMPIRICAL MODELS

FOR RAINFED SPRING WHEAT

by

Shaukat Mahmood

A thesis submitted in partial fulfillment
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APPROVAL

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Shaukat Mahmood

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Dedicated to HOLY PROPHET MUHAMMAD
(Peace be upon him)
The Great Social Reformer

VITA

Shaukat Mahmood born at Sher Garh, Gujrat, Pakistan, April 25, 1952; son of Chaudhary Hakim Ali and Mrs Nazir Begum; married Sakina Sultana; have son Adnan-ur-Rehman Shaukat, born December 15, 1984. Attended high school Daulat Nagar, Gujrat; graduated in 1967; received a Bachelor of Science (Hons) degree in Agronomy in 1972 and a Master of Science (Hons) degree in Agronomy in 1974, from University of Agriculture, Faisalabad, Pakistan; worked 2 years as Junior Agronomist in Water and Power Development Authority in Pakistan, 8 years as Agronomist and Project Manager in Mada-Dep River Basin Development Authority, Nigeria; Assistant Professor of Agronomy at Barani Agricultural College, Rawalpindi, Pakistan; completed requirements for the Doctor of Philosophy majoring in Soil and Water Management at Montana State University, Bozeman, Montana in 1994.

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ABSTRACT

Nitrogen plays a significant role in crop production and available N can have a significant effect on crop growth, yield, and quality. Consequently, use of N fertilizer offers substantial opportunity for increasing food production in many parts of the world. The supply of available N can be a decisive factor in dryland wheat production systems. Because of the nature of N and the processes N is involved in in the soil-plant system, N management can play a key role in crop production. Two studies were conducted to evaluate N fertilizer management and its effect on dryland spring wheat yield and quality and N use efficiency. The studies were conducted at two locations in 1992 and 1993.

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Neither source of N fertilizer nor method of application of N fertilizer had a significant effect on the measured parameters. Differences in N fertilizer rate resulted in significant differences in all the measured parameters; the significant differences were more pronounced on sites initially testing low in soil NO_3-N. Time of application of N had a significant effect on grain protein percent, harvestable protein, and grain yield. Split application of nitrogen between planting and heading resulted in a significant increase in grain protein percent. However, harvestable protein and grain yield were significantly reduced by delaying application, especially on sites initially testing low in soil NO_3-N.

CHAPTER 1

INTRODUCTION

Meeting demands for food is likely to be a problem of paramount importance to developing countries in the next decade. Few "third" world countries presently have the capacity, resources, or capability to produce sufficient food supplies to satisfy their domestic demands. Correspondingly, nearly all developing third-world countries regularly experience food shortages.

It is estimated that two-thirds of the 5 billion people in the world exist on an inadequate diet (FAO, 1992). This condition, coupled with the prediction that the world population will reach 6-7 billion by the year 2000 (Jamison et al., 1987; Tisdale et al., 1993), suggests that the amount of food available per person globally will drastically decrease. Undoubtedly, this decrease will be accompanied by a concomitant increase in global tension economically, politically, and socially.

The current and impending demand for food has increased the significance of food production in arid and semiarid regions of the world. These regions constitute nearly one-third of the area of the globe (James et al., 1982) and are homelands of a majority of the world population. With the world's population expanding exponentially, there is increasing need to bring this land under production.

The potential problem of disparity between food supply and demand exists because arable land is scarce in supply. The limited supply of arable land places serious restraints on agricultural production, particularly food output. This presents an imposing challenge to the world's producers of food and fibre. Agricultural scientists and food producers are, of necessity, continuously trying to refine and transfer to developing countries agricultural production practices and technologies which will help achieve maximum food production with the available resources.

Technological improvements of agriculture can, within limits, reduce the effect of land shortage. Technologies which can serve as substitutes for arable land include management skills, improved varieties, certified seeds, pesticides, use of fertilizer, and other technological forms of capital and improved cultural practices.

Probably the single most important advancement in agricultural management for crop production, with the exception of genetic advances, has been refinement of the use of fertilizers. Use of fertilizer, especially N fertilizer, offers substantial opportunity for increasing food production (Black and Ford, 1976; Tisdale et al., 1993). Furthermore, proper management of fertilizer, including the source of N, time of application, and method of application, can have a significant effect on crop growth, yield, and quality.

The N supply is a decisive factor in crop production, especially in dryland cropping systems. In many agricultural systems, it is customary to increase the input of N through fertilization. However growing attention to human health and environmental issues has resulted in questions being raised concerning N use and its impact on the environment and groundwater contamination.

Nitrogen can enter and leave the soil-plant system by more routes than any other nutrient. It is involved with complex processes (Figure 1) in the soil such as:

N fixation - reduction of atmospheric N to NH_3 (Stevenson, 1982),

immobilization - conversion of inorganic N by plants and soil microorganisms to organic forms of N (Jansson and Persson, 1982),

mineralization - decomposition of organic N to NH_4 (Jansson and Persson, 1982),

denitrification - reduction of NO_2 or NO_3 to N gas (Firestone, 1982),

nitrification - oxidation of NH_4 or NH_3 to NO_3 (Schmidt, 1982),

volatilization - losses of N as a gas to the atmosphere (Nelson, 1982),

utilization - release or uptake of atmospheric NH_4 by crops or soils,

substitution - reversible exchange of ions between soil water and clay particles.

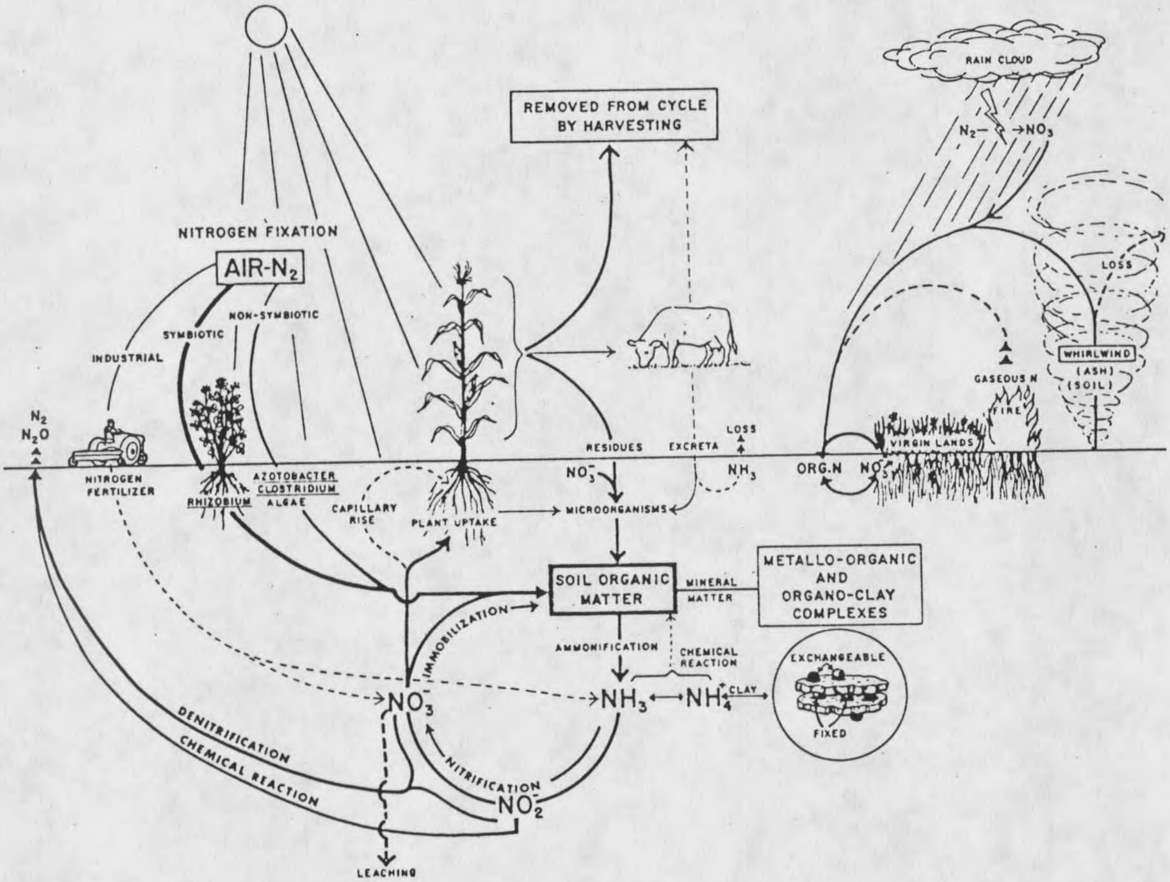

Figure 1. The Nitrogen cycle (Stevenson, 1982).

Residual N fertilizer is susceptible to denitrification and NO^-_3 leaching, with possible contamination of adjoining natural water systems. Nitrogen losses following fertilizer application have been reported as high as 50% (Allison, 1966; DeDatta et el., 1988; Olson, 1982). Consequently, there is need to improve N use efficiency of crop production, both by increasing the efficiency with which N is utilized by crops and by limiting N losses to the environment.

Objectives

In order to gain more information about the role and importance of N fertilizer in rainfed wheat (Triticum aestivum L.) production, two studies were conducted to determine the effect of source, rate, timing of application, and methods of application of N fertilizer on spring wheat yield and quality and N use efficiency. By determining the relationship between these N fertilizer management variables and crop production and the significance of the interactions of these variables, it should be possible to develop reliable, empirical prediction equations, which can be used to enhance efficient N fertilization programs. Utilization of defined management models to implement fertilizer strategies should result in maximum economic returns while having minimal impact on the environment.

Integrated goals of this Ph.D research program were to gain additional training and expertise relative to:

1) data integration, assimilation, and development of management practices using empirical techniques;

2) design, implementation, assessment, and interpretation of practical field research;

3) practical and theoretical training in wheat production under rainfed conditions;

4) technology transfer of currently accepted dryland wheat production practices in USA to Pakistan.

CHAPTER 2

LITERATURE REVIEW

An agricultural management system intended to maximize crop uptake of N must, directly or indirectly, incorporate a system management approach, i.e., the impact of the total system on crop yields must be considered. Crop production is dependent on many factors, including crop variety, moisture availability and timing, temperature conditions, light intensity, plant population, and nutrient availability (Keeney, 1982). Interaction of these factors influences plant growth. Management practices directly or indirectly influence some of the environmental factors that affect crop production. For instance, nutrient availability can easily be influenced by fertilizer management practices. Thus, it is important to predict accurately the N rate-crop response relationships for a given crop on a given farm based on the factors involved in the on-farm response of crops to N fertilizer.

Two principal soil phenomena which can significantly influence N nutrition are denitrification and leaching (Firestone, 1982; Legg and Meisinger, 1982; Nelson, 1982). Loss of fertilizer N from the soil via leaching or denitrification before crop uptake can result in environmental pollution and reduced yields. Timing N fertilizer applications to coincide with the rapid uptake period of the crop can result in more efficient fertilizer use. Similarly, fertilizer placement to encourage deeper and more dense root growth can lead to increased uptake of N before it is leached from the root zone. In addition, the type of N fertilizer used, amount of available N, and application practices can affect the crop yield response curve.

Nitrogen Rate

Three factors which establish the upper limit of yield of crops are: (1) the amount of moisture available during the growing season; (2) length of the growing season; and (3) soil fertility. A considerable amount of research has demonstrated that soil fertility influences crop growth (Brady, 1984; Fowler et al., 1989; Olson and Kurtz, 1982; Singer and Munns, 1987; Viets, 1965).

Sixteen elements are required by most plants for growth and yield (Brady, 1984; Singer and Munns, 1987; Tisdale et al., 1993). Those needed in large quantities are called macronutrients or major elements and those required in smaller amounts are called micronutrients or trace elements. Tisdale et al. (1993) have indicated that yields often do not reach the genetic limit of the crop because of nutrient deficiencies.

Nitrogen is required in large quantities for plant growth. Plants normally contain between 1 and 5% N by dry weight (Tisdale et al., 1993). About 2-3 kg of N are required to produce 100 kg of wheat (Black and Ford, 1976; Laloux et al., 1980; Schafer et al., 1985). Nitrogen is used by plants to synthesize amino acids and proteins. Nitrogen is also a component of chlorophyll and enzymes. Knowledgeable management of N is important to cereal crop production, since deficiencies and excesses of N influence plant growth, grain yield, and grain quality. Plants deficient in nitrogen exhibit stunted growth, poor tillering, loss of chlorophyll, short heads, low yields, and low protein content (Jacobsen and Jasper, 1991; Olson and Kurtz, 1982; Tisdale et al., 1993; Viets, 1965).

The effects of excess N on plant performance are less obvious than those of N deficiency, but they include excessive plant height, lodging in cereals, susceptibility to insect attack, severe damage from drought, delayed flowering, delayed maturity, and reduced yield (Black and Siddoway, 1977; Boquet and Johnson, 1987; Campbell et al., 1977; Frederick and Marshall, 1985; Roth et al., 1984; Viets, 1965).

Several researchers have proposed using high rates of N to insure that N deficiency does not occur. However, a wheat crop may respond to additions of N fertilizer with a decrease, an increase, or no change in yield. Nitrogen fertilization may increase vegetative growth, water use, and/or yield (Bacon and Wells, 1991; Boquet and Johnson, 1987; Brown, 1971; Luebs and Laag, 1969; Roth and Marshall, 1987; Spiertz and Ellen, 1978; Stanford and Hunter, 1973). Nitrogen in excess of plant needs may increase water stress and significantly decrease grain yield (Luebs and Laag, 1969; Ramig et al., 1975; Rasmussen and Rohde, 1991). The practice of using high rates of N fertilizer on lodging-resistant cultivars has increased but this does not necessarily guarantee maximum yields (Campbell et al., 1977).

At some point along the N rate-yield response curve, the N efficiency (the relative relationship between N applied and N utilized by the crop to synthesize yield or protein) begins decreasing (Stanford and Hunter, 1973). Grain yield may be negatively affected by N application at rates above this point (Bacon and wells, 1991). The variety, soil N supply in relation to plant needs, and the effect of proceeding increments of N affect response to an increment of N (Viets, 1965). An idealized response of non-legumes to N fertilizer is shown in Figure 2.

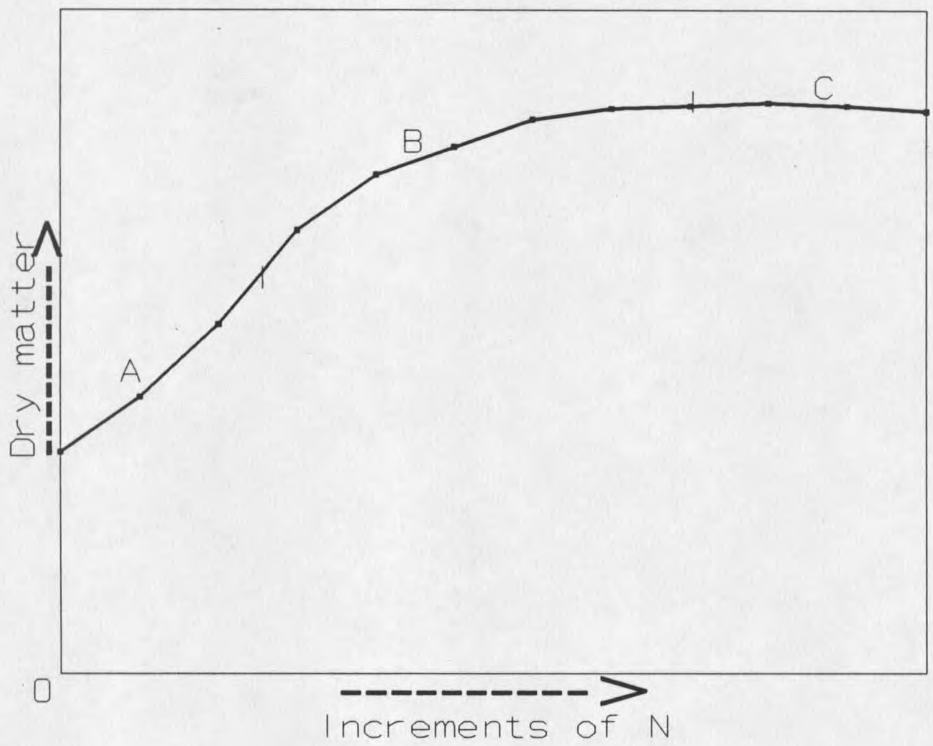

Figure 2. Idealized response in dry matter production of a non-legume to increments of N fertilizer (Viets, 1965).

The response curve can be divided into three segments. Successive increments of N fertilizer produce successively larger increments in yield increase in segment A. In segment B, the increase in yield in response to each successive N addition is large but not as large as the increases experienced in segment A, while in segment C the increases in yield are small and N recovery efficiency is reduced below that in the other segments.

In general, adverse effects of N on the crop occur when N inputs from mineralization and fertilization greatly exceed the amounts of N which can be efficiently used by the crop. Long term N fertilization at rates greater than a crop can utilize can result in accumulation of soil N and increased NO_3^--N movement through the soil into ground or surface waters (Bauder et al., 1993; Cooper et al., 1984; Jacobsen and Johnson, 1991; Rutter and Chirnside, 1984) and loss of large amounts of NH_3 or N_2O to the atmosphere (Keeney, 1982).

Numerous studies have considered wheat responses to soil N and N fertilizer rates (Bacon and Wells, 1991; Boquet and Johnson, 1987; Fowler and Brydon, 1991; Fowler et al., 1989; Fredrick and Marshall, 1985; Jacobsen et al., 1993; Roth and Marshall, 1987; Roth et al., 1984). Results of these studies indicate that availability of N can have a significant effect on the crop from germination through maturity. Consequently, with some crops the rate of development, overall growth, and grain yield are dependent on soil N status throughout the growing season. If fertilizer applications are always at efficient response levels, losses of N will be minimal and N uptake will be maximum, resulting in optimum yield and maximum N recovery.

Nitrogen Source and Crop Growth

Plants absorb N as either NH_4 or NO_3. Preference of plants for either NH_4 or NO_3 is determined by the age and type of plant, the environment, and other factors. The question of which form of N to supply to the crop at specific growth stages has perplexed scientists and producers for many years. Each form of N has characteristic advantages and disadvantages. A theoretical advantage of the NH_4 form is that energy does not need to be expended to reduce N to the -3 valance state, which is the most preferred form for assimilation in the developing plant. From a practical perspective, another advantage associated with use of NH_4 forms is that NH_4 is less subject than NO_3 to losses by leaching and denitrification. Blair et al. (1970) postulated that NH_4 is likely to enhance uptake of P in young plants. Plants supplied with NH_4 may have increased carbohydrate and protein levels, compared to plants supplied with NO_3. Disadvantages of applying NH_4 forms of N fertilizer include a relatively high susceptibility of NH_4 to immobilization by soil microorganisms (Jansson and Persson, 1982), susceptibility of NH_4 to volatilization loss in high-pH soils, potential of NH_4 addition to acidify the soil, and the potential for chemical or clay mineral fixation of NH_4 in certain soils. Absorption of NH_4 by roots reduces Ca^{2+}, Mg^{2+}, and K^+ uptake (Tisdale et al., 1993). The limit of crop tolerance to NH_4 concentrations is relatively low, with excessive levels of NH_4 producing a toxic reaction by the crop. High concentrations of NH_4 can retard crop growth, restrict uptake of K^+, and produce symptoms of K^+ deficiency.

In contrast, plants will tolerate large excesses of NO_3 and accumulate NO_3 to comparatively high levels in their tissues. Nitrate is more mobile than most other N forms and can be readily taken up by plants. The rate of NO_3 uptake is high compared to the rate of uptake of N in other forms at the same concentration. When plants accumulate high concentrations of NO_3, organic anion synthesis within the plant increases and is coupled with a corresponding increase in the accumulation of Ca^{2+}, Mg^{2+}, and K^+ (Tisdale et al., 1993).

Three major processes involved in nutrient uptake by plants are: (1) diffusion, (2) mass flow, and (3) root interception. Most N taken up by plants must move to root surfaces before being absorbed because roots usually occupy only 1 to 2% of soil volume in the root zone (Barber, 1976). Nitrate is free to move to roots by mass flow and diffusion. In moist, well-drained soils, NH_4 is usually nitrified rapidly to NO_3. Under wet conditions NO_3 is subject to loss due to leaching and denitrification. Francis et al. (1993) reported that NO_3 can be leached out of the emerging plant's root zone before it can be fully utilized, while NH_4-N sources may improve plant N uptake.

Nitrogen uptake and losses can be significantly affected by nitrification and denitrification. Nitrate concentration affects the rate of denitrification. The rate of denitrification is directly correlated with NO_3 concentration in the soil (Firestone, 1982).

Urea is a commonly used form of N fertilizer. Urea accounts for about 25% of USA and 80% of Asian N fertilizer use (Harre and Bridges, 1988; Hauck, 1984; Voss, 1984). Urea is the predominant N fertilizer used in Pakistan because large quantities of urea are produced within the country, making urea less expensive than other N forms. However, little information is available concerning the N recovery efficiency from urea forms of N or the ultimate fate of urea-N in the soil.

Nitrogen recovery from urea has been reported lower than N recovery from NH_4NO_3 or $(NH_4)_2SO_4$ (Laughlin, 1963). Low crop recovery of urea-N has often been attributed to NH_3 volatilization losses (Nelson, 1982). Knight and Sparrow (1993) reported that a barley crop recovered about 60% of the N from urea and 73% of the N from $Ca(NO_3)_2$. They further reported that total plant N uptake was greater when N was applied as $Ca(NO_3)_2$, compared to when the N source was urea. Touchton and Hargrove (1982), comparing three N sources and their effects on corn yield and N recovered in grain, reported the order of efficiency of N uptake from various N sources was urea < urea-ammonium nitrate $\leq$ ammonium nitrate. Fox and Hoffman (1981) also reported lower yields and less N uptake when N was applied as urea compared to when non-urea N sources were applied.

Bauder and Montgomery (1980) reported more NO_3-N leaching associated with NO_3- based fertilizers than with NH_3- based fertilizers. They reported the contribution of N source to NO_3-N leaching as $CO(NH_2)_2 \leq$ check < $(NH_4)_2SO_4$ < $Ca(NO_3)_2$. Accordingly, they proposed that NO_3 leaching from N fertilizers under irrigation could be minimized by use of NH_3- based fertilizers.

Time of Application

The quantity of N available to plants is a function of the amounts applied as fertilizer and mineralized from organic soil N. The amount of N released from organic sources, and to some extent, the amount of fertilizer-derived N existing in the soil after the addition of NH_4 or NO_3 depends on the factors affecting N mineralization, immobilization, and losses from the soil. Nitrogen fertilizers applied in any form are quickly converted to NO_3 through nitrification. Nitrate is soluble in water, is not adsorbed by soil colloids, and is highly mobile. Consequently, NO_3 is subject to loss through leaching and denitrification (Huber et al., 1977; Legg and Meisinger, 1982; Macdonald et al., 1989; Mosier et al., 1986; Olson and Swallow, 1984; Olson, 1982).

Some of the factors that can influence the magnitude of NO_3 leaching are: (1) use of nitrification inhibitors; (2) crop uptake of N; (3) soil characteristics; (4) pattern and time of irrigation and/or precipitation; and (5) rate, time, sources, and method of N fertilization.

One approach to increasing N fertilizer efficiency and simultaneously lessening the potential impact of N on the environment is to supply the N when it is needed by the crop, i.e., match fertilizer applications to N uptake by the crop throughout the growing season (Scarsbrook, 1965). Fertilizer application timing depends on the soil, climate, nutrient type, and crop. The N loss mechanisms must be considered in selecting the time of fertilizer application. Theoretically, it would be desirable to apply N as close as possible to the time of peak N demand of the crop.

An important factor in fertilizer dose-response relationship is the rate at which the crop takes up N. Wheat, for example, takes up N in large quantities beginning about 1 month after emergence or from start of tillering onward (Laloux et al., 1980). Single applications of N often result in lower fertilizer-use efficiency (Bauder and Schneider, 1979; Christensen and Meints, 1982; Grant et al., 1985) and reduced grain yields (Roth et al., 1984) because of losses via leaching, denitrification, and volatilization.

Under some conditions, split or delayed N applications can reduce N losses due to leaching, denitrification, and volatilization and improve the yield response to fertilizer. Top-dressing N (applying fertilizer to the soil surface after the crop has emerged) is reported to increase fertilizer efficiency (Black and Siddoway, 1977; Christensen and Meints,1982). Bauder and Schneider (1979) reported reduced NO_3-N leaching losses in irrigated wheat when the total N fertilizer requirement was split into two applications. Gravelle et al. (1988) reported an increase in N fertilizer efficiency and increased grain yield for wheat by splitting N fertilizer applications between Feekes scale growth stages 4, 9, and 10.5 (Large, 1954) or between any two of these growth stages relative to a single N application at any one growth stage. Split application of N fertilizer results in greater N uptake, greater grain yield, and less lodging than with a single application of all N fertilizer (Alcoz et al., 1993). Compared to early applications, delaying some N may reduce excessive tillering and subsequent lodging (Cook, 1982). Splitting the application of N facilitates the use of tissue tests to determine the need for additional N (Becker and Aufhammer, 1982; Cook, 1982; Tinker and Widdowson, 1982) and may also improve the opportunity to match the total fertilizer needed to the available soil moisture during the middle of the growing season.

In several European countries, N is applied at different growth stages (Becker and Aufhammer, 1982; Dilz et al., 1982; Remy and Viaux, 1982). Currently, splitting of N fertilizer between fall and spring applications is being practiced for winter wheat in certain parts of the United States (Roth and Marshall, 1987; Tisdale et al., 1993). In contrast, in the rainfed areas of Pakistan N is usually applied as a single application, before planting or at the time money and fertilizer are available.

Fertilizer Placement

Proper fertilizer placement can contribute to efficient use of nutrients by the crop from emergence to maturity, prevent salt injury to seedlings, and enhance deeper rooting to compensate for dry conditions at the soil surface.

Fertilizer N frequently is applied to the soil surface before wheat is planted. Because most plant uptake of N does not take place until plants start vigorous growth, some surface-applied N may be lost through leaching or by volatilization. Ammonia volatilization is a function of the buffer capacity of the soil (Avinimelech and Laher, 1977) and the NH_3-NH_4 equilibrium in the soil, which is dependent on soil pH (du Plessis and Kroontjie, 1964). Nitrogen losses due to hydrolysis of urea are greater in alkaline soils than in acidic soils (Fan and Mackenzie, 1993; Fenn et al., 1981). Other factors which play a significant role in volatilization include N source and rate, temperature, soil water content, and in the case of urea-containing fertilizers, urease activity in the soil.

Surface-applied urea may be lost through NO_3 leaching or NH_4 volatilization (Fenn and Hossner, 1985; Freney et al., 1983; Jones et al., 1977; Macdonald et al., 1989; Nelson, 1982; Sanchez and Blackmer, 1988). Urea applied on the soil surface has seldom been as effective as NH_4NO_3 or $(NH_4)_2SO_4$ (Laughlin, 1963). However, urea can be as effective as NH_4NO_3 or $(NH_4)SO_4$ when incorporated into the soil (Laughlin, 1971).

Generally, fertilizer efficiency can be increased by incorporating the fertilizer into the soil (Maddux et al., 1991; Meyer et al., 1961; Volk, 1966). Several researchers have reported that banding urea fertilizer usually results in greater N efficiencies than broadcast or broadcast-incorporated applications of urea (Jacobsen et al., 1993; Maddux et al., 1984; Maddux et al., 1991). Banding urea fertilizer increased N uptake by barley 38% beyond that with broadcast-incorporated urea (Malhi and Nyborg, 1985). Similarly, Tomar and Soper (1981) reported that banding urea increased N uptake and yield, compared with broadcasting urea, in barley. The authors concluded that these increases in efficiency were a result of reduction of immobilization and denitrification.

Urea is rapidly becoming a major N source in fertilizers because of advantages in production and handling. However, urea has an inherent disadvantage of susceptibility to NH_3 volatilization when surface-applied (Christianson, 1989; Fenn and Miyamoto, 1981). Volatilization losses can occur from acid or alkaline soils due to high pH and NH_4 concentration at the microsites where urea granules dissolve and hydrolyze (Fenn and Richards, 1986). The reaction can be summarized as follows.

$$CO(NH_2)_2 + 3H_2O \text{ --------> } 2NH_4 + OH^- + HCO_3$$

$$NH_4 + OH^- <====> NH_3 + H_2O$$

The amount of urea lost through NH_3 volatilization from surface-placed urea may range from 1 to 60% of the applied N in agricultural soils (Christianson, 1989; Matocha, 1976).

Reduction of NH_3 losses can be achieved by: (1) coating the urea granule with materials that slow the rate of dissolution of urea (Matocha, 1976); (2) reducing hydrolysis with urease inhibitors (Bremner and Douglas, 1971); (3) adding neutral salts containing Ca^+ or K^+ (Fenn and Miyamoto, 1981); or (4) reducing microsite pH with acidic materials (Stumpe et al., 1984).

Excessive concentration of soluble salts in contact with roots or germinating seeds can have injurious effects on the seeds or seedlings through plasmolysis, restriction of moisture availability, or actual toxicity. The term fertilizer burn is commonly used when fertilizer contact causes the plant to desiccate and exhibit symptoms similar to those of drought. Black et al. (1980), Deibert et al. (1985), Devine and Holmes (1963), Fowler and Brydon (1991), Hunter and Rosenau (1966), Olson and Dreier (1956), and Toews and Soper (1978) have reported severe damage to crops when N exceeding 20 kg ha^{-1} was placed in contact with seed. This is especially true for ammonium-based fertilizers or fertilizers which result in NH_3 volatilization. Seedling damage is caused by NH_3 volatilization, according to Bremner and Douglas (1971). Urea, di-ammonium phosphate (DAP), $(NH_4)_2$ CO_3, and NH_4OH may cause more damage than mono-ammonium phosphate (MAP), $(NH_4)_2SO_4$, and NH_4NO_3.

Modeling Crop Responses

Growth is defined as progressive development of an organism. There are several ways in which this development can be expressed in plants, i.e., increase in size, volume, or yield. Plant growth is a function of many growth factors; conceptually, growth may be expressed as

$$G = f(x_1, x_2, x_3, \ldots, x_n)$$

where

$$G = \text{some measure of plant growth}$$

and

$$x_1, x_2, x_3, \ldots, x_n = \text{the various growth factors.}$$

Growth of annual plants follows a well-defined pattern. Plant responses to environmental conditions, including the supply of plant nutrients, also follow a set pattern. When growth is plotted as a function of increasing amounts of applied nutrients