Optimizing Soil and Fertilizer Nitrogen Use by Intensively Managed Soft Red Winter Wheat

by

Walter E. Baethgen

Dissertation submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in

Agronomy

APPROVED:

M. M. Alley, Chairman

D. C. Martens

L. W. Zelazny

D. E. Brann

M. Lentner

May, 1987

Blacksburg, Virginia

Optimizing Soil and Fertilizer Nitrogen Use by Intensively Managed Soft Red Winter Wheat

by

Walter E. Baethgen

M. M. Alley, Chairman

Agronomy

(ABSTRACT)

Field experiments were conducted in the Coastal Plain and Ridge and Valley regions of Virginia during the 1981-82 through 1985-86 winter wheat growing seasons. The treatments in all experiments consisted of varying amounts of N fertilizer rates applied at Zadoks' growth stages 25 (GS 25) and 30 (GS 30). The research was divided into three studies. The first study was conducted to assess the effect of N fertilizer rates and climatic conditions on the amounts and patterns of the crop N uptake. Dry matter production and total N concentration were measured in total above ground plant material at different growth stages, as well as in leaves, stems, and spikes. Plant N uptake was affected by the climatic conditions in the different growing seasons. Temperature and precipitation variations in early spring determined the differences in amounts and patterns of the N uptake by whole plants and by the various plant portions. Maximum N uptake daily rates were obtained in the period immediately after GS 30 suggesting that this is the wheat growth stage in which the highest efficiency of N fertilizer use could be expected. Crop N uptake at GS 30 also appeared to be a potentially good indicator of the plant N requirements.

The second study was designed to develop models for determining critical N levels and optimum N fertilizer rates for winter wheat. Two nonlinear models were successfully

developed to determine critical N levels at GS 30 utilizing plant N concentration at GS 30 (N%30) and crop N uptake at GS 30 (NUP30). The R^2 values for the models utilizing N%30 and NUP30 as independent variables were 0.87, and 0.82, respectively. Simple regression models were successfully developed to predict N rates required at GS 30 to obtain either maximum or economically optimum grain yields. The models utilized NUP30 as the independent variable and had high correlation coefficients and good predicting ability.

The objective of the third study was to determine the recommended amount of N fertilizer to be applied at GS 25 that would optimize the use of the simple linear regression models developed in the second study. Quadratic programming models were developed with the objective of maximizing marginal profit with N fertilizer application. The models were then solved to determine the amounts of N at GS 25 and at GS 30 that would produce the maximum attainable profit. Four recommended nitrogen fertilizer rates at GS 25 (N25) were evaluated: 0, 30, 60, and 100 kg N ha^{-1}. The difference (D) between the yields with maximum attainable profit (Y) and the yields when N25 was forced to be 0, 30, 60, and 100 kg N ha^{-1} (Y^R) was then calculated ($D = Y - Y^R$). The best N25 recommendation was the one that minimized the mean value, standard deviation, and coefficient of variation of D. This methodology was used for 3 nitrogen fertilizer : wheat price ratios (2.0, 4.0, and 8.0). The results indicated that the best recommendations for N25 were 50 - 60 kg N ha^{-1} for N fertilizer : wheat price ratios of 2.0 - 4.0, and 40 - 50 kg N ha^{-1} for a price ratio of 8.0. Sensitivity analysis was then performed to study the effect of variations in the N fertilizer : wheat price ratio on the the recommended N rates. The results indicated that the recommended N rates were essentially insensitive to the variations in the price ratio of N fertilizer : wheat.

DEDICATION

To

Acknowledgements

I wish to express my sincere appreciation to Dr. Marcus M. Alley for his guidance, assistance, and especially for his friendship and support during my graduate program. Gratitude is also extended to the other members of the committee Drs. David C. Martens, Lucian W. Zelazny, Daniel E. Brann, and Marvin Lentner.

I am very grateful to for his extensive help with the field experiments, and to secretaries for their friendship and aid throughout my course of study.

I am especially grateful to

whose friendship and support have been invaluable. Gratitude is also extended to

and to the other faculty, staff, and graduate students in the Agronomy Department whose friendship is very much appreciated.

Table of Contents

List of Illustrations

List of Tables

Introduction

World Nitrogen fertilizer consumption has increased markedly since the 1950's. Since 1970, a large part of this rise has been in undeveloped and developing countries (Keeney, 1982). The United Nations Industrial Development Organization (UNIDO) estimates a total demand of 165 million metric tons N by the year 2000 (Fig. 1).

Plants consume only about 50% of the added N, and there is a strong need to increase this utilization level. From the economical standpoint an increase in the N utilization by plants would result in a more efficient use of this resource. From a social approach, cereal grain is still the principal source of protein for a major portion of the human population. An increase in the utilization of N by cereals would improve the quality of human nutrition without increasing production costs. Finally, the N that is not utilized by the plant will directly or indirectly constitute a potential environmental hazard mainly through surface and groundwater contamination (Gillelan and Macknis, 1983).

Several techniques have been proposed to improve N management in crop production. One of the most obvious techniques is to develop accurate soil and/or tissue testing

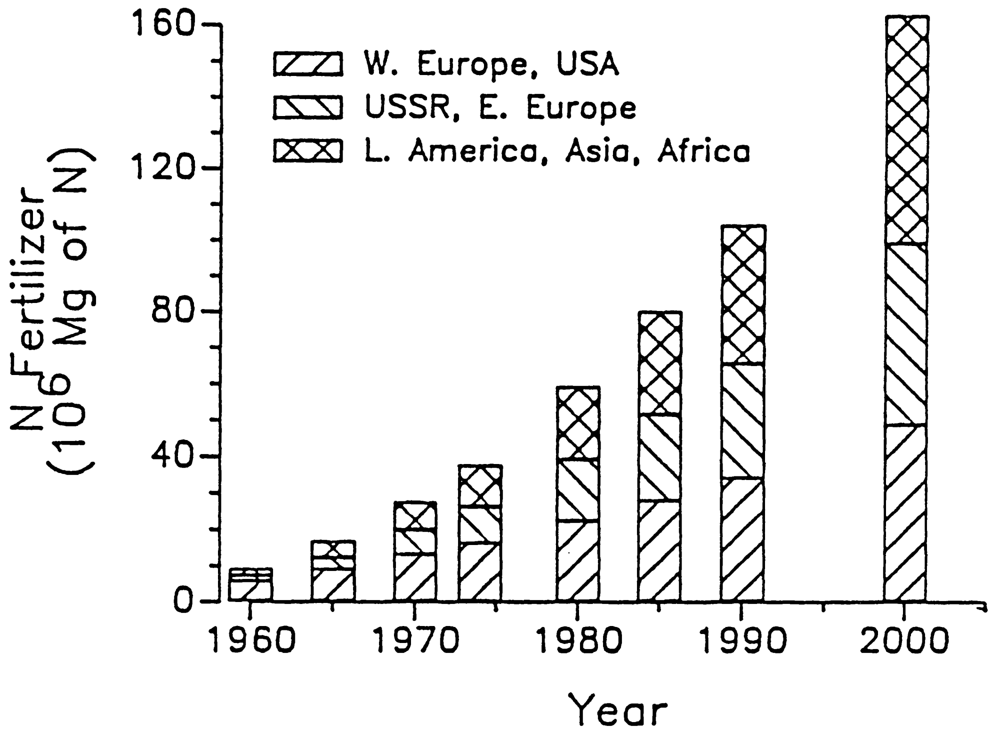

Figure 1. World consumption and future demand of N fertilizer.

procedures to determine N requirement for optimum crop yields. The large variation of plant available soil N throughout the growing season and the lack of a mechanism for long-term storage of plant available fertilizer N in soils make the development of suitable soil testing procedures a difficult task (Stanford, 1982; Olson and Kurtz, 1982; Burns, 1982; Dahnke and Vasey, 1973; Becker and Aufhammer, 1982; Needham, 1982). Also, tissue N tests in annual crops can be difficult to interpret (Jones and Eck, 1973), and in many situations the tissue analysis is performed too late in the growing season to correct a possible defficiency (Pierre et al., 1977).

An additional logical approach to increase N fertilizer efficiency and hence to reduce environmental impacts of N is to supply the N as it is needed, i.e., to match applications as closely as possible to the plant N uptake throughout the growing season (Scarbrook, 1965). This attempt can be accomplished by supplying the N fertilizer in a number of applications. However, with the exception of sprinkler or drip-irrigated crops, additional applications of N fertilizer may result in excessive increases in operating costs.

The determination of a few growth stages when high efficiency of N utilization can be expected, may be the most reasonable approach to establish optimum timing of fertilizer applications. Higher efficiency of N use could also be accomplished with the utilization of slow-release fertilizers and with effective urease and nitrification inhibitors. However, these materials require further research before their use becomes practical.

The area of wheat grown in the U.S.A. has varied between 25 and 40 million ha (Reitz, 1967). Kansas and North Dakota have been the traditional leading states and together they account for 25-30% of the total area in most years. The area devoted to winter wheat in Virginia has varied between 150000 and 200000 ha. The majority of the crop is grown in the Atlantic Coastal Plain region.

In 1981 Dr. M. M. Alley started a set of experiments with the objective of improving crop management practices for winter wheat production. Some of the aspects studied in these experiments included row spacing and seeding rate (Joseph et al., 1985), P fertilization (Alley and Brann, 1987), N fertilizer timing (Gravelle, 1983), and effects of plant growth regulators.

The present study includes the results obtained in N fertilizer experiments conducted in 1981-82 through 1985-86 winter wheat growing seasons. The objectives of the research presented in each chapter were as follows:

1. Chapter 2: (1) to measure the pattern of winter wheat N uptake through the growing season for different rates and timings of N application, (2) to study the effect of climatic conditions on the amounts and patterns of N uptake, and (3) to evaluate the distribution of N to different plant parts during the spring growth period.

2. Chapter 3: (1) to determine N fertilizer critical levels for winter wheat utilizing plant tissue analysis early in the spring, and (2) to establish the basis of a system for predicting economically optimum rates of N fertilization (EORN) for winter wheat to be used within the same growth season.

3. Chapter 4: (1) to use a quadratic programming approach to determine the recommended N fertilizer rate to be applied at Zadoks' growth stage 25, that would optimize the use of the model developed in Chapter 3 to predict EORN for winter wheat, and (2) to perform sensitivity analyses on the data to study the variation in the recommended EORN values for different N fertilizer : wheat price ratios ($ / kg N : $ / kg wheat).

References

Alley, M. M. and D. E. Brann. 1987. Phosphorous fertilization of intensively managed soft red winter wheat. J. Fert. Issues 4:53-59.

Batey, T. 1977. Prediction by leaf analysis of nitrogen fertiliser required for winter wheat.

J. Sci. Food Agric. 28:275-278.

Becker, F. A., and W. Aufhammer. 1982. Nitrogen fertilisation and methods of predicting the N requirements of winter wheat in the Federal Republic of Germany. p. 33-66. In Symposium on fertilisers and intensive wheat production in the EEC. The Fertiliser Society. Proc. 211., London, UK.

Burns, I. G. 1982. Estimation of annual variations in leaching of residual nitrate under deep-rooted crops during winter. p. 95-101. In The nitrogen requirements of cereals. Ministry of Agriculture, Fisheries and Food. Reference book 385. London, UK.

Dahnke, W. C., and E. H. Vasey. 1973. Testing soils for nitrogen. p. 97-114. In L. M. Walsh and J. D. Beaton (ed.) Soil testing and plant analysis. Soil Science Society of America, Madison, WI.

Gillelan, M. E., and J. Macknis. 1983. Nutrients. p.39-88. In D. A. Barker, M. Manganello, D. Parvlowicz, and S. Katsanos (ed.) Chesapeake Bay: a framework for action. E.P.A. Philadelphia, PA.

Gravelle, W. D. 1983. Influence of timing of nitrogen application on yield and nutrient uptake of winter wheat (Triticum aestivum L.). M.S. Thesis. Virginia Polytechnic Institute and State University, Blacksburg.

Jones Jr., J. B. and H. V. Eck. 1973. Plant analysis as an aid in fertilizing corn and grain sorghum. p. 349-364. In L. M. Walsh and J. D. Beaton (ed.) Soil testing and plant analysis. Soil Science Society of America, Madison, WI.

Joseph, K. D. S. M., M. M. Alley, D. E. Brann, and W. D. Gravelle. 1985. Row spacing and seeding rate effects on yield and yield components of soft red winter wheat. Agron. J. 77:211-214.

Keeney, D. R. 1982. Nitrogen management for maximum eficiency and minimum pollution. In F. J. Stevenson (ed.) Nitrogen in agricultural soils. Agronomy 22:605-650.

Needham, P. 1982. The role of nitrogen in wheat production: response, interaction and prediction of nitrogen requirements in the UK. p. 125-147. In Symposium on fertilisers and intensive wheat production in the EEC. The Fertiliser Society. Proc. 211. London, UK.

Olson, R. A., and L. T. Kurtz. 1982. Crop nitrogen requirements, utilization, and fertilization In F. J. Stevenson (ed.) Nitrogen in agricultural soils. Agronomy 22:567-604.

Pierre, W. H., L. Dumenil, and J. Henao. 1977. Relationship between corn yield, expressed as a percentage of maximum, and the N percentage in grain. II. Diagnostic use. Agron. J. 69:221-226.

Reitz, L. P. 1965. World distribution and importance of wheat. In K. S. Quisenberry (ed.) Wheat and wheat improvement. Agronomy 13:1-18.

Scarbrook, C. E. 1965. Nitrogen availability. In W. V. Bartholomew and F. E. Clark (ed.) Soil Nitrogen. Agronomy 10:481-502.

Stanford, G. 1982. Assesment of soil nitrogen availability. In F. J. Stevenson (ed.) Nitrogen in agricultural soils. Agronomy 22:651-688.

Crop Nitrogen Uptake

Abstract

There is a lack of information in the southeastern U.S.A. on the N uptake evolution of intensively managed winter wheat through the growing season. Such information would provide an important decision making tool for N fertilizer management, increase the precision of simulation models used in research, and delineate crop growth stages for use as indicators of plant N needs. Field experiments were conducted in the Atlantic Coastal Plain region during the 1981-82 through 1984-85 winter wheat growing seasons. The treatments in these experiments consisted of varying N fertilizer rates applied at Zadok's growth stages 25 (GS 25) and 30 (GS 30). Dry matter production and total N concentration was measured in total above ground plant material as well as in leaves, stems, and heads, at different growth stages to assess the effects of the different N fertilizer rates and climatic conditions on the amounts and patterns of the crop N uptake. Maximum daily N uptake rates were obtained in the period immediately after GS 30 suggesting that this is the wheat growth stage in which the highest efficiency of N fertilizer use could

be expected. Crop N uptake at GS 30 also appeared as a potentially good indicator of the plant N requirement.

The total N found in leaves and stems decreased with time during the spring, while spike N increased from the early stages of head development until harvest. Plant N uptake was clearly affected by the climatic conditions in the different growing season. Precipitation values during soil tillage and in early spring probably affected the amounts of residual N in the soil. The amount of residual N jointly with variations of the temperatures in early spring determined the differences in amounts and patterns of the N uptake by whole plants and by the various plant fractions.

Introduction

Knowledge of the crop N uptake pattern is important for N fertilizer management, especially as a decision-making tool for timing N fertilizer application. It is also important for increasing the precision of simulation models, particularly for varying climatic conditions. Several experiments to measure dry matter accumulation and N distribution in winter wheat over the growing season have been conducted in the midwestern U.S.A. (Karlen and Whitney, 1980; McNeal et al., 1968; Flowerday, 1979). However, there is a lack of such information on N uptake patterns and on the effects of different climatic conditions on amounts and patterns of winter wheat N uptake for the mid-Atlantic U.S.A.

The determination of optimum N fertilizer rates for winter wheat is a major unsolved problem in most humid regions of the world (Stanford, 1982). Measurement of soil NO_3^--N as a basis for predicting optimum N fertilizer applications is being done routinely in the Great Plains and arid regions (Keeney, 1982; Dahnke and Vasey, 1973). Soil mineral N content is generally considered to vary too widely in humid regions to be viewed as a good indicator of N availability to crops (Fox and Piekeleck, 1983). Plant analysis appears to offer a viable approach to the problem of predicting optimum N fertilizer rates in humid regions. Studying N uptake through the growing season would provide valuable information with respect to growth stages in which plant N content can possibly be utilized as an indicator of winter wheat N needs and, therefore, to predict N fertilizer requirements.

The objectives of this research were (1) to study the pattern of winter wheat N uptake through the growing season for different rates and timings of N application, (2) to study the effect of climatic conditions on the amounts and patterns of N uptake,; and (3) to evaluate the distribution of N to different plant parts during the spring growth period.

Materials and Methods

Field experiments were established in the Atlantic Coastal Plain region of Virginia during the 1981-82 through 1984-85 winter wheat growing seasons. Soil types and classifications are shown in Table 1. Primary tillage was moldboard plowing at all locations followed by disking and final seedbed preparation with a culti-mulcher or a roterra. Preplant fertilization to supply adequate soil nutrients other than N included 62 kg P, 232 kg K, 28 kg Mg, 28 kg S, 28 kg Mn, 11 kg Zn, and 7 kg Cu ha^{-1} in all experiments. Preplant incorporated N applications were 17 kg ha^{-1} in all years except 1982 when 34 kg N ha^{-1} was applied. Plot sizes were 5.2 x 6.1 m in all years except 1984-85 when plot sizes were 5.2 x 4.9 m. All plots consisted of three 1.73 m-wide drill swaths planted with a custom-built grain drill. Plant tissue samples were collected from the side swaths of each plot and the center swath was the harvest area for grain yield. Row width was 10 cm and all plots were planted at the rate of 420 seeds m^{-2}. The soft red winter wheat cv. 'Tyler' was planted in the 1981-82 and 1982-83 experiments while the 'Coker 916' cultivar was used in the 1983-84 and 1984-85 experiments. The spring N treatments consisted of different rates of N fertilizer applied at Zadok's (1974) growth stage (GS) 25 in the 1981-82 and 1982-83 experiments and at GS 25 and GS 30 in the 1983-84 and 1984-85 experiments. In all experiments the N fertilizer rates ranged from 0 to 135 kg N ha^{-1}. The treatments were arranged in incomplete factorials using a randomized complete block design with four replications in all experiments.

Wheat tissue samples were taken shortly after dormancy, at GS 30, 45, and 58 and at harvest. Each sample consisted of the entire above ground plants removed from four 0.9-m sections of a row. These bulk samples were used to determine dry matter production. In the 1981-82 and 1982-83 experiments, a subsample of 20 tillers was randomly selected from the bulk sample and separated into the different plant parts. Samples taken at GS 30 and thereafter were portioned into leaves and stems, while samples taken at GS 45 and thereafter were divided into leaves, stems, and heads.

All plant tissue samples were dried at 65°C and ground with a Wiley mill to pass a 1-mm screen prior to digestion. The ground plant tissue was analyzed for total N using microKjeldahl digestion with concentrated H_2SO_4. Ammonium in solution was deter-

Table 1. Soil type and classification for the experimental sites.

Site	Year	Soil Type	Soil Classification
I	1981-82	State sl	Typic Hapludult, siliceous thermic, fine loamy
II	1982-83	State sl	Typic Hapludult, mixed thermic, fine loamy
III	1983-84	Suffolk sl	Typic Hapludult, siliceous, thermic, fine loamy
IV	1984-85	Kempsville sl	Typic Hapludult, siliceous, thermic, fine loamy

mined colorimetrically with Na salicylate, Na nitropusside and Na hypochlorite (EPA, 1979). Plant N uptake (kg N ha^{-1}) was calculated by multiplying the N concentration in the tissue by the dry matter production (kg ha^{-1}).

Grain yields were harvested from the center swath of each plot. Moisture content of the grain from each plot was determined with an electronic moisture meter. All yields were adjusted to 13.5% moisture content.

Results and Discussion

N Uptake by Whole Plants

The effects of N fertilizer rates and climatic conditions on the N uptake by whole plants was evaluated for the 1983-84 and 1984-85 experiments in which N fertilizer was applied at GS 25 and GS 30. The climatic characteristics of these years differed considerably, and as a result the amount and pattern of the crop N uptake also varied. The 1983-84 growing season had high levels of precipitation during the spring months. The average rainfall values for March, April, and May of 1984 were 17.9, 2.9, and 7.8 cm above the 30-year average values for this experimental site, respectively (Table 2). The excessive rainfall induced soil moisture conditions near saturation for long periods of time, and probably promoted the loss of soil mineral N through leaching and/or denitrification. Also, the average temperature values for March and April of 1984 were approximately 4°C lower than in 1985. As a result, early spring wheat growth rate was slow, and the crop N uptake and the daily N uptake values were low relative to the 1984-85 experiments (Fig. 2a, 2b, 3a, and 3b). However, crop growth increased dramatically immediately after the spring N fertilizer applications. This rapid growth resulted in rates of N uptake by wheat of >4.0 kg N $ha^{-1}day^{-1}$ for both the 90 and 135 kg N ha^{-1} treatments applied at GS 30 (Fig. 3a, and 3b).

The 1984-85 spring growing season was characterized by very low rainfall. Precipitation for March, April, and May was 6.4, 6.8, and 1.0 cm below the 30-year average values, respectively (Table 2). The rainfall values for the previous autumn (August, September, October, and December) and throughout the winter were also considerably below the average values. This resulted in conditions that probably increased the soil mineral N content in the fall and the spring. The high grain yields obtained in the treatments with no spring N applications (Table 3) demonstrate the existence of relatively high amounts of available N to the crop throughout the growing season. As a result of the high N availability to the crop early in the spring, the wheat growth started immediately after temperatures increased in late February.

Consequently, the effect of the 1984-85 spring N fertilizer applications on the wheat N uptake values (Fig. 2c and 2d) and on the N uptake daily rates (Fig. 3c, and 3d) was considerably less than in the 1983-84 growing season. However, the maximum values of daily N uptake for the 1983-84 and 1984-85 growing seasons were attained at or shortly after GS 30 for all N applications (Fig. 4). These results indicate that the period immediately before jointing, GS 30, is the wheat growth stage indicative of the highest efficiency of N fertilizer use. The high yields obtained in the treatments with N fertilizer applications only at GS 30 confirm this observation (Table 3). The high expected efficiency of N use shortly after GS 30, and the large grain yield response to N fertilizer

Table 2. Monthly variations from 30-year average values for temperatures and precipitation (1981-82 through 1984-85 growing seasons)

Temperature departures

Month	1981-82	1982-83	1983-84	1984-85
	°C			
August	-0.1	-1.7	+1.2	-0.2
September	-0.9	-1.2	+0.3	-1.3
October	-1.3	-0.2	+0.8	+3.7
November	+0.1	+1.6	+0.7	-1.1
December	-1.4	+3.5	-1.5	+4.3
January	-3.1	+0.7	-2.2	-2.1
February	+0.6	-0.2	+3.6	+0.6
March	+0.1	+1.6	-2.0	+2.2
April	-1.6	-1.7	-1.6	+2.3
May	+1.2	-0.4	-0.4	+1.4
June	-0.7	-0.1	+1.1	-0.2

Precipitation departures

Month	1981-82	1982-83	1983-84	1984-85
	cm			
August	+1.0	+5.6	-5.4	-3.7
September	+2.4	-3.5	+2.0	-8.4
October	-3.2	-3.1	+4.0	-1.5
November	-5.9	+2.7	+3.6	+1.2
December	+0.1	-1.3	+5.5	-4.8
January	+0.5	-4.4	+2.3	-1.5
February	+2.1	-1.3	-1.0	1.3
March	-1.8	+6.3	+17.9	-6.4
April	-0.2	+10.8	+2.9	-6.8
May	-6.5	+3.0	+7.8	-1.0
June	+1.2	-0.8	-4.6	-3.5

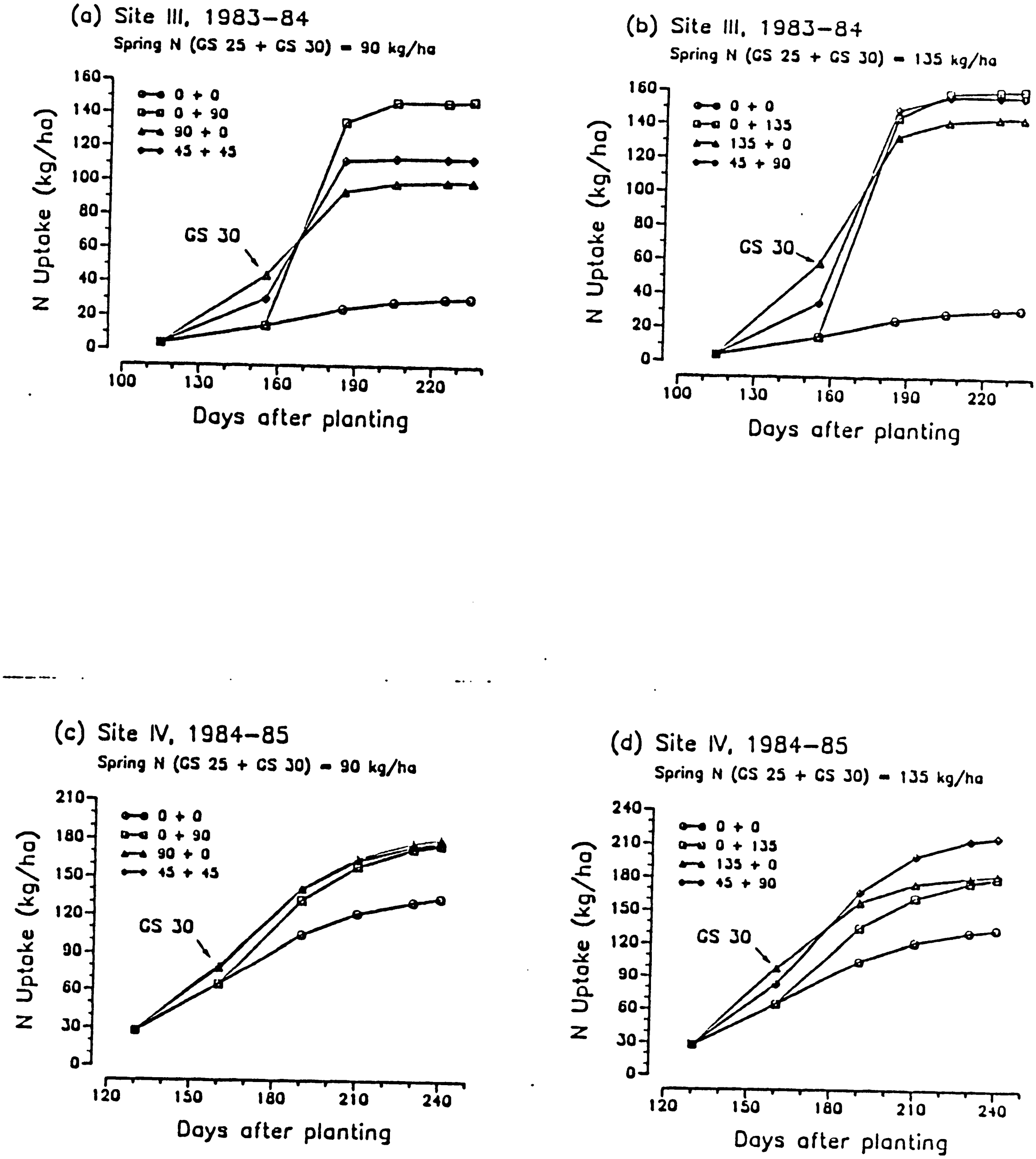

Figure 2. Wheat N uptake at two experimental sites for the spring (GS 25 + GS 30) N application rates of 90 and 135 kg N/ha.

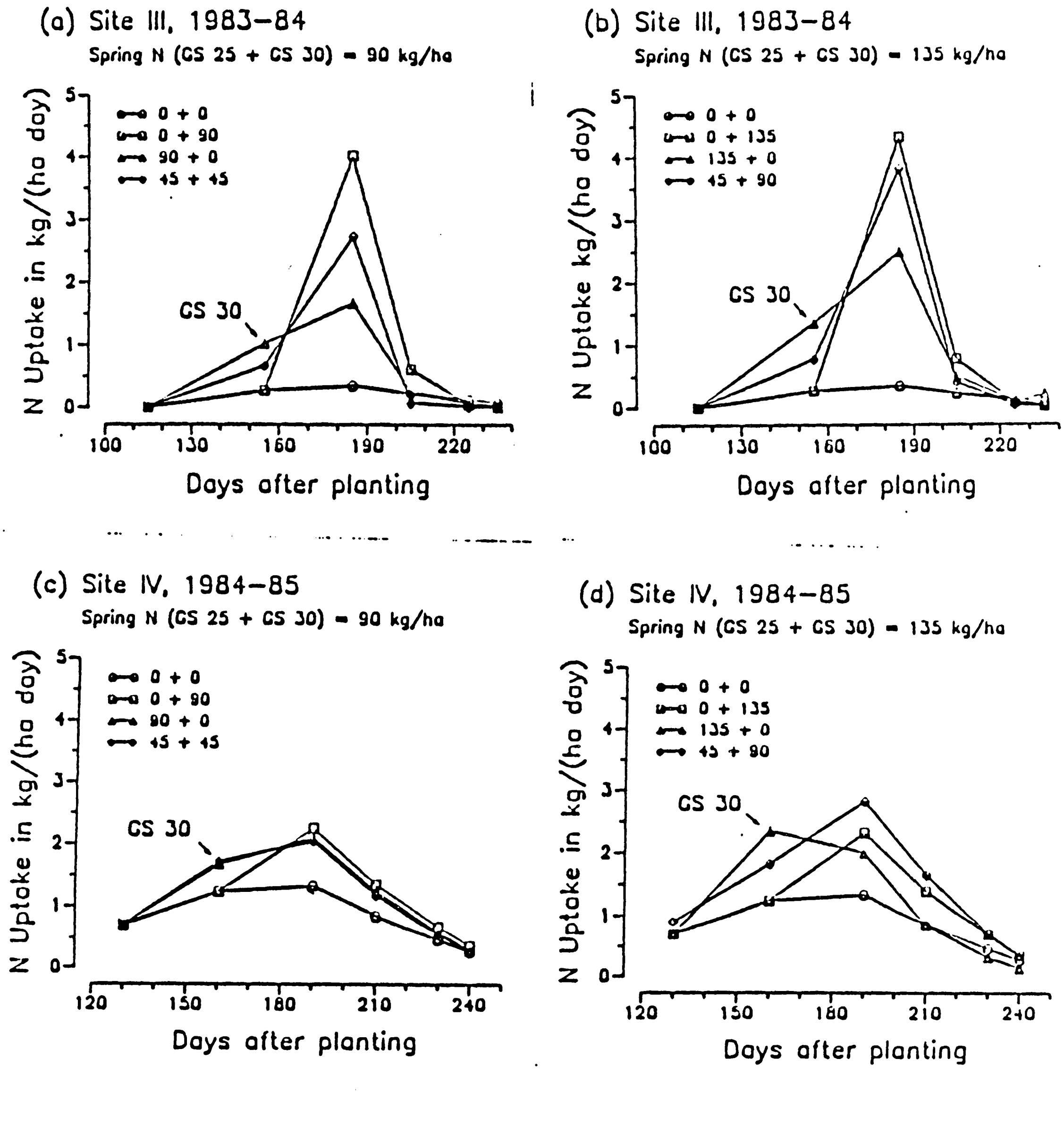

Figure 3. Daily N uptake rates by wheat at two sites for the spring (GS 25 + GS 30) N fertilizer rates of 90 and 135 kg/ha.

applications at GS 30 also indicate that N uptake at GS 30 would be a useful indicator of crop N needs and a good predictor of N fertilizer required to obtain optimum yields.

N Uptake by Leaves, Stems, and Spikes

Samples of leaves, stems and spikes were taken in the experiments conducted in 1981-82 and 1982-83 to study the N uptake patterns in these plant fractions. The principal reason for studying these patterns is that they indicate the importance of N translocation from leaves and stems to the spikes early in the spring. Large quantities of translocated N would emphasize the importance of ensuring adequate N availability levels to the crop early in the spring growth period.

The general trends of N distribution from leaves and stems to spikes found in both seasons for the different N fertilizer treatments agree with results reported from previous experiments conducted in the Midwest U.S.A. (Karlen and Whitney, 1980) and other regions of the world (Lal et al., 1978). Thus, N uptake by leaves and stems decreased with time during the spring, while spike N uptake increased from the early stages of head development until harvest (Fig. 4).

The 1981-82 growing season climatic conditions were different from those of the 1982-83 growing season. Consequently, the magnitude and slopes of the changes in the N uptake by the various plant fractions were also different for the two growing seasons. For example, 1981-82 rainfall from September to January (tillage, early growth and dormancy periods) was 6.6 cm below the 30-year average values (Table 2). The low precipitation probably allowed the accumulation of mineralized N that was available when the dormancy period ended. Temperatures and rainfall in February, March, and April were

Table 3. **Grain yields obtained for the various N fertilizer rate and timing treatments.**

Site	Year	N fertilizer applied at GS 25	GS 30	Grain yield
		------- kg N ha^{-1}	-------	Mg ha^{-1}
I	1981-82	0	0	5.40
I	1981-82	90	0	6.06
I	1981-82	135	0	5.87
II	1982-83	0	0	4.06
II	1982-83	90	0	7.45
II	1982-83	135	0	7.54
III	1983-84	0	0	2.04
III	1983-84	0	90	5.31
III	1983-84	90	0	5.33
III	1983-84	45	45	5.57
III	1983-84	0	135	6.24
III	1983-84	135	0	6.24
III	1983-84	45	90	6.23
IV	1984-85	0	0	5.98
IV	1984-85	0	90	6.78
IV	1984-85	90	0	6.08
IV	1984-85	45	45	6.66
IV	1984-85	0	135	6.04
IV	1984-85	135	0	5.64
IV	1984-85	45	90	6.38
IV	1984-85	90	45	5.59

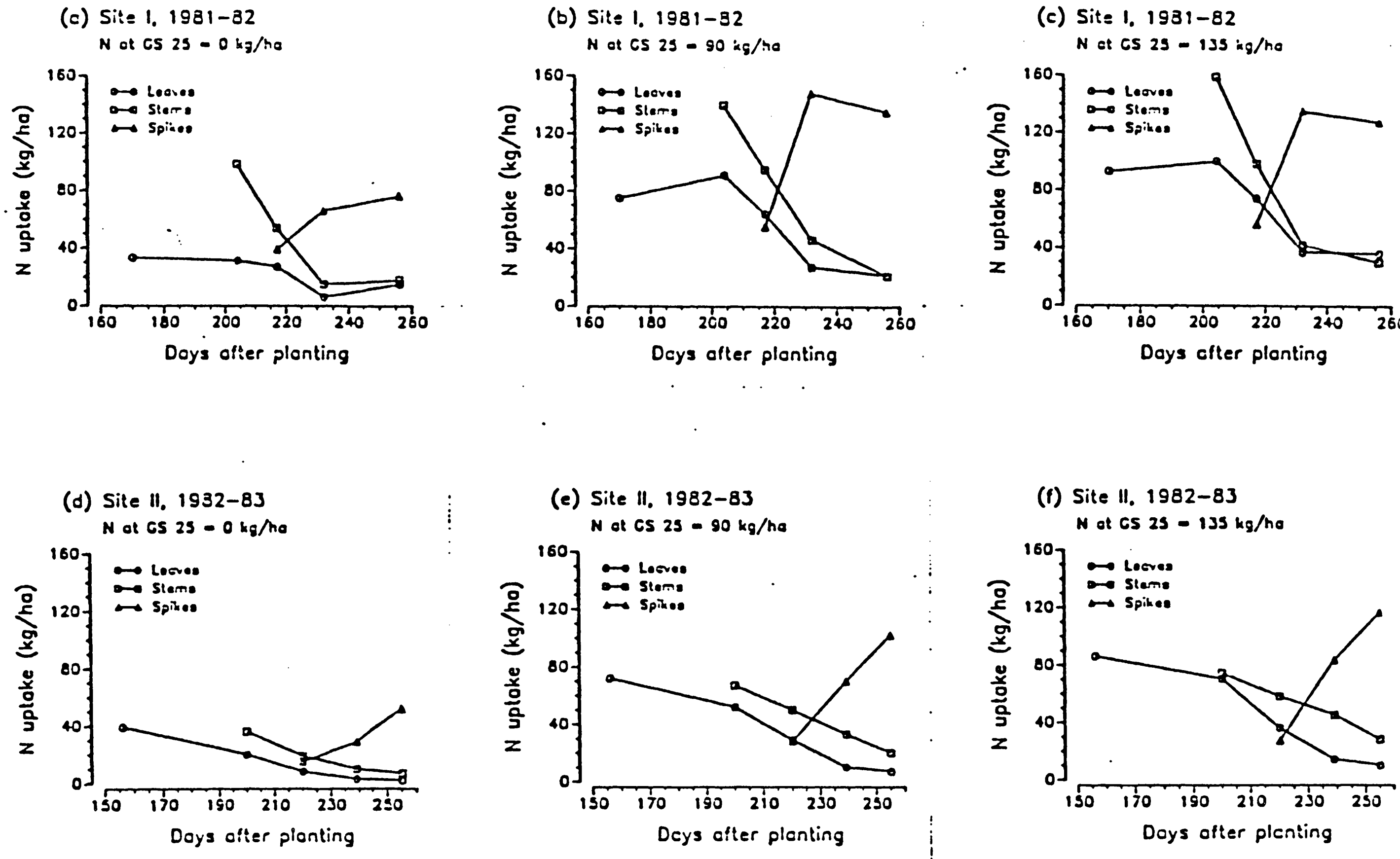

Figure 4. Nitrogen uptake by wheat leaves, stems, and spikes at two sites for three N fertilizer rates applied at GS 25.

nearly normal which jointly with the high residual N availability resulted in large amounts of N uptake early in the spring, even in the treatments where no N fertilizer was added at GS 25 (Fig. 4). The amounts of available N in the soil in the plots that did not receive spring N applications probably allowed the wheat to start the stem elongation stage without the need to translocate N from the leaves (Fig. 4a). The wheat leaf N uptake values were similar for the first two sampling dates where N was not applied in the spring (Fig 4a). The same trend was observed for the treatments where 90 and 135 kg N ha^{-1} was applied at GS 25 (Fig. 4b and 4c). In all the treatments, the N uptake values for leaves and stems started to decrease with initiation of the head development (Fig. 4a, 4b, and 4c). Grain N uptake increased through late spring and reached a plateau 2-3 weeks before harvest. These data indicate that N availability was not a limiting factor for the 1981-82 growing season.

The precipitation during the months of tillage, early growth and dormancy for the 1982-83 growing season were also less than the 30-year average values. This resulted in wheat N uptake values at GS 30 that were very similar to the ones observed in 1981-82. However, the rainfall for March and April was 17.1 cm higher than the 30-year average values for the region. This excess rainfall probably resulted in lower amounts of available soil N to the crop later in the spring and consequently, when stem elongation started, N needed to be translocated from the leaves (Fig. 4d, 4e, and 4f). The total wheat N uptake values after GS 30 for 1981-82 were twice as large as the corresponding values for the 1982-83 growing season for the treatments that received 0, 90 or 135 kg N ha^{-1} at GS 25.

In contrast with the 1981-82 growing season, the grain N uptake in 1982-83 did not reach a plateau but continued increasing at an almost constant rate until crop maturity

(Fig. 4d, 4e, and 4f). Consequently, the amount of spike N uptake at harvest was similar for both growing seasons. This was especially true for the treatment that received 135 kg N ha^{-1} at GS 25 (Fig. 4c and 4f), indicating that the amount of N translocated from stems and leaves from this treatment was sufficient to ensure adequate levels of spike N uptake.

The results presented in Fig. 5 confirm the differences observed in the N uptake pattern by the plant portions during 1981-82 and 1982-83. Thus, the spike N uptake for 1981-82 represented 70, 76, and 66 percent of the total crop N uptake for the treatments with 0, 90, and 135 kg N ha^{-1} applied at GS 25, respectively. The corresponding values for 1982-83 were 85, 79, and 75 percent, which indicates a much more intense N translocation from stems and leaves to spikes for the latter growing season. These results point-out that N translocation from leaves and stems to spikes should be considered in N fertilizer management decisions. This translocation will probably be most necessary when the amounts of plant available soil N are low in late spring.

The experiments conducted in 1981-82 and 1982-83 did not include treatments with N fertilizer application at GS 30. However, the results of the experiments conducted in 1983-84 and 1984-85 reported in the previous section of this paper, reasonably lead to an expectation that smaller differences in the final spike N uptake values for 1981-82 and 1982-83 would have occurred if N fertilizer had been applied at GS 30.

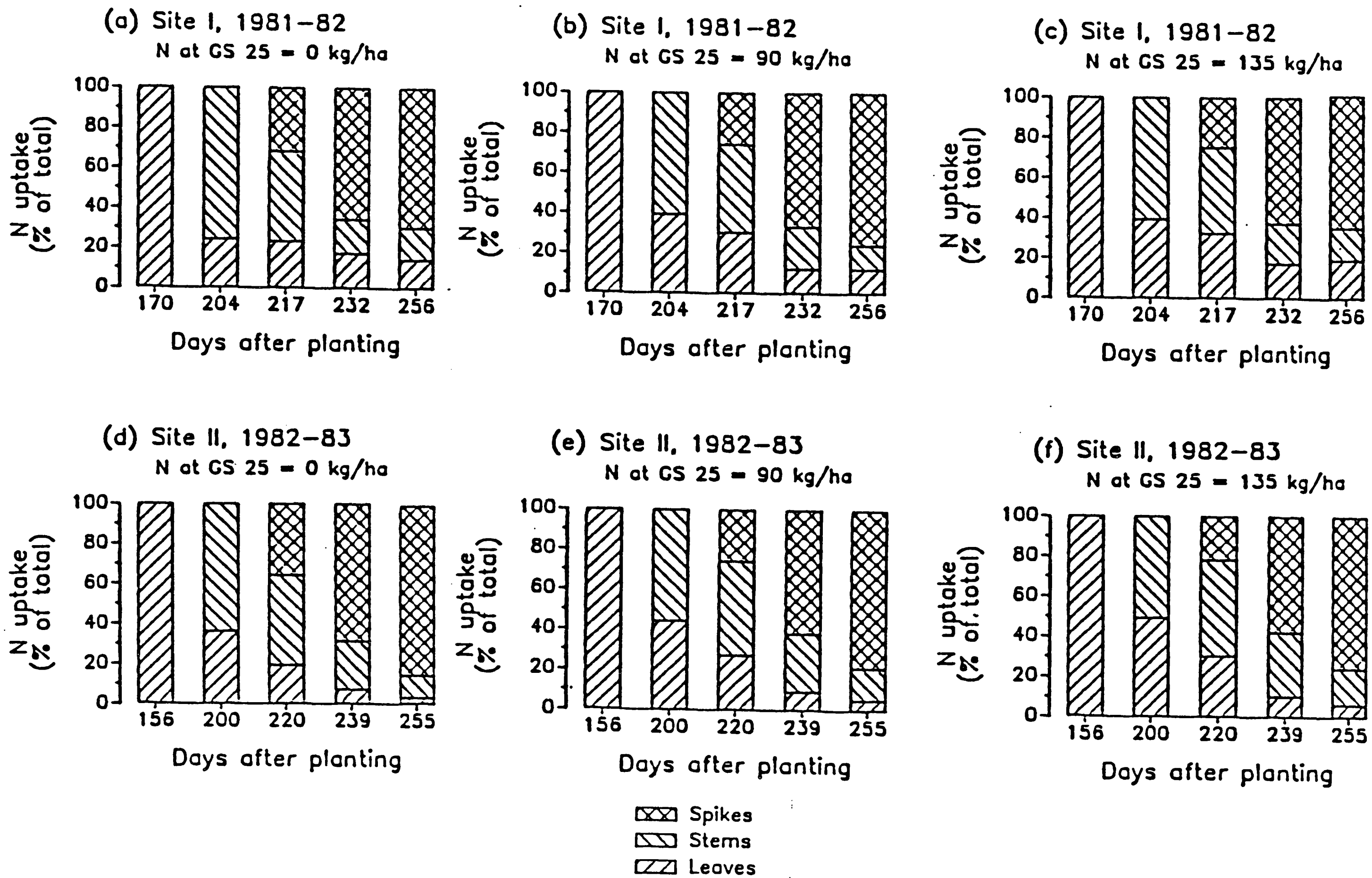

Figure 5. Nitrogen uptake (% of total) by wheat leaves, stems, and spikes at two sites for three N fertilizer rates at at GS 25.

Conclusions

Winter wheat N uptake was affected by the N fertilizer treatments as well as by the climatic characteristics of the different years. The effect of spring N fertilizer applications was especially noticeable in the 1983-84 growing season where the precipitation level during dormancy and early in the spring was high. The maximum values of daily N uptake for the evaluated growing seasons were attained at or shortly after GS 30. These findings indicate that N uptake at this growth stage could possibly be used as an indicator of the crop N needs. Large amounts of N were translocated from leaves and stems to spikes, especially in 1982-83 where the amounts of plant available soil N in late spring were probably low.

References

Dahnke, W. C., and E. H. Vasey. 1973. Testing soils for nitrogen. p. 97-114. In L. M. Walsh, and J. D. Beaton (ed.) Soil testing and plant analysis. Soil Science Society of America, Madison, WI.

Fox, R. H., and W. P. Piekielek. 1984. Relationship among anaerobically mineralized nitrogen, chemical indexes and nitrogen availability to corn. Soil Sci. Soc. Am. J. 48:1087-1090.

Karlen, D. L., and D. A. Whitney. 1980. Dry matter accumulation, mineral concentrations, and nutrient distribution in winter wheat. Agronomy J. 72:281-288.

Keeney, D. R. 1982. Nitrogen availability indices. In A. L. Page et al. (ed.) Methods of soil analysis, Part 2. 2nd ed. Agronomy 9:711-733.

McNeal, F. H., G. O. Boatwright, M. A. Berg, and C. A. Watson. 1968. Nitrogen in plant parts of seven spring wheat varieties at successive stages of development. Crop Sci. 8:535-537.

Stanford, G. 1982. Assessment of soil nitrogen availability. In F. J. Stevenson (ed.) Nitrogen in Agricultural soils. Agronomy 22:651-688.

U.S. Environmental Protection Agency. 1979. Methods for chemical analyses of water and wastes. EPA report no. 600/4-79-020, Cincinnati, OH.

Waldren, W. P., and A. D. Flowerday. 1979. Growth stages and distribution of dry matter, N, P, and K in winter wheat. Agron. J. 71:391-397.

Zadoks, J. C., T. T. Chang, and C. F. Zonzak. 1974. A decimal code for the growth stages of cereals. Weed. Res. 14:415-421.

Critical levels and Optimum Rates of N Fertilizer

Abstract

The assessment of optimum N fertilizer rates for winter wheat production is a major unsolved problem, particularly in humid climates. Field experiments were conducted in the Coastal Plain and Ridge and Valley regions of Virginia during the 1981-82, 1982-83, 1983-84, 1984-85, and 1985-86 winter wheat growing seasons to determine critical N levels and optimum rates of N fertilization. The treatments in these experiments consisted of various N fertilizer rates applied at Zadok's growth stages 25 (GS 25) and 30 (GS 30). Plant N concentration (N%30) and crop N uptake at GS 30 (NUP30) were measured immediately prior to the N fertilizer application. Nitrogen critical levels were defined as the N%30 or NUP30 values that produced 90% of maximum grain yields with no further N fertilizer application. Two nonlinear models were developed to determine critical levels at GS 30 utilizing N%30 and NUP30 as the independent variable. The R^2 values of the models utilizing N%30 and NUP30 were 0.87 and 0.82, respectively. A family of response curves of grain yield to N fertilizer applied at GS 30 was fitted at

each experimental site. The amount of N fertilizer required at GS 30 to obtain maximum grain yield (NMAX30) was calculated for each response curve. Regression analysis was utilized to develop models for estimating the amount of N fertilizer required at GS 30 to produce maximum grain yields, for any given value of N%30 or NUP30. Best models were selected considering fit, significance of the regression coefficients, and predictive ability. The best models in both cases were simple linear regressions. The model using NUP30 as the independent variable had a larger correlation coefficient (r = -0.87) and a better predicting ability than the model using N%30. Regression analysis was also used to develop models to estimate the amount of N fertilizer required at GS 30 to produce economically optimum yields using NUP30 as the independent variable. Three N fertilizer : wheat price ratios were evaluated (2.0, 4.0, and 6.0), and the three simple linear regression models presented large correlation coefficients (-0.88, -0.89, and -0.88, respectively).

Introduction

Proper N fertilization of winter wheat is crucial: sub-optimum N rates have been shown to result in lower number of tillers, and consequently in lower grain yields (Ayoub, 1974; Hucklesby, 1971; Power and Allessi, 1978; Robinson et al., 1979). Excessive N fertilization increases lodging with subsequent yield reductions of up to 25-50% (Prutskova and Ukanova, 1972), delays harvesting, and increases the potential of environmental contamination (Gillelan and Macknis, 1983). Nevertheless, the assessment of optimum N fertilizer rates is still a major unsolved problem in winter wheat production, particularly in humid climates. The most common approaches to determine optimum N rates in the U.S.A. and other countries have considered expected crop yields, soil N tests, and plant tissue analyses. In the former approach, average expected wheat yields are assigned to different soil types, and the corresponding N fertilizer recommendations are determined by estimating the crop requirements to attain these yields. A major disadvantage of this approach consists of the inaccuracy with which the expected yields are estimated due to the large variation found in the crop yields for a given soil type at different sites and in different years.

Several efforts have been made to develop a suitable soil testing procedure for determining optimum N fertilizer rates. The consideration of residual mineral N and/or mineralizable organic N indices have been successfully used in areas where the removal of NO_3^--N from the rooting zone by leaching is minimal (Dahnke and Vassey, 1973; Soper et al., 1971; Olson and Swallow, 1984). Consequently, Keeney (1982) reported that 13 states in the U.S.A. are currently measuring NO_3^--N content in their soil testing laboratories and utilizing these values in making N fertilizer recommendations. However, in humid climatic areas, the N content of the soil during spring and winter varies too greatly to be considered as a good indicator of the crop N requirements (Fox and Pieckielek, 1978).

Previous research conducted in Virginia (Baethgen and Alley, 1987) suggested that a potentially more successful approach than soil testing in humid climates could involve plant tissue testing during early stages of spring growth, and determination of optimum N rates for subsequent fertilization. Plant tissue analysis in small grain production has been successfully used in the United Kingdom (O'Neil et al., 1983a, 1983b; Batey, 1977; Needham, 1982), Germany (Becker and Aufhammer, 1982), Australia (Papastylianou, 1984), and U.S.A. (Donohue and Brann, 1984; Hargrove, 1983). These researchers have used plant tissue analysis to assess soil N status, to predict final crop N uptake, and to establish critical levels, i.e., plant N content values above which response to further N fertilization is not expected. However, there are no reports in the literature of the utilization of this information to determine the N fertilizer rates required to optimize grain yields within the same growth season.

The objectives of this research are: (1) to determine N fertilizer critical levels for winter wheat utilizing plant tissue analysis early in the spring, and (2) to establish the basis of a system for predicting optimum rates of N fertilization for winter wheat to be used within the same growth season.

Materials and Methods

Description of the Experiments

Field experiments were established in the Coastal Plain region of Virginia during the 1981-82, 1982-83, 1983-84, 1984-85, and 1985-86 winter wheat growing seasons. Soil types and classifications are shown in Table 4. Primary tillage was moldboard plowing at all locations followed by disking and final seedbed preparation with either culti-mulcher or roterra. Preplant fertilization to eliminate soil fertility other than N as being yield limiting factors included 62 kg P, 232 kg K, 28 kg Mg, 28 kg S, 28 kg Mn, 11 kg Zn, and 7 kg Cu ha^{-1} in all experiments. Preplant incorporated N applications were 17 kg ha^{-1} in all years except 1982 when 34 kg N ha^{-1} was applied. Plot sizes were 5.2 x 6.1 m in all years except in 1984-85 and 1985-86 when plot sizes were 5.2 x 4.9 m, and consisted of three 1.73 m-wide drill swaths planted with a custom-built grain drill. Plant tissue samples were collected from the side swaths of each plot and the center swath was the harvest area for grain yield. Row width was 10 cm and all plots were planted at the rate of 420 seeds m^{-2}. The soft red winter wheat cv. 'Tyler' was planted in the 1981-82 and 1982-83 experiments while the 'Coker 916' cultivar was used in the 1983-84, 1984-85, and 1985-86 experiments.

Table 4. Soil type and classification for the experimental sites.

Site	Year	Soil Type	Soil Classification
I	1981-82	State sl	Typic Hapludult, siliceous thermic, fine loamy
II	1982-83	State sl	Typic Hapludult, mixed thermic, fine loamy
III	1983-84	Suffolk sl	Typic Hapludult, siliceous, thermic, fine loamy
IV	1983-84	Ross sl	Cumulic Hapludoll, mixed mesic, fine loamy
V	1984-85	Kempsville sl	Typic Hapludult, siliceous, thermic, fine loamy
VI	1984-85	Ross sl	Cumulic Hapludoll, mixed mesic, fine loamy
VII	1985-86	State sl	Typic Hapludult, siliceous thermic, fine loamy
VIII	1985-86	Ross sl	Cumulic Hapludoll, mixed mesic, fine loamy

Treatments and Experimental Design

The spring N treatments consisted of different rates of N fertilizer applied at Zadok's (1974) growth stage (GS) 25 in the 1981-82 and 1982-83 experiments, and at GS 25 and GS 30 in the 1983-84, 1984-85, and 1985-86 experiments. The N fertilizer rates at GS 25 in the experiments conducted in 1981-82 through 1984-85 ranged from 0 to 135 kg N ha^{-1}. The treatments were arranged in incomplete factorials using a randomized block design with four replications. In the 1985-86 experiments, the treatments also consisted of different N fertilizer applications at GS 25 (0, 28, 56, 112, and 168 kg N ha^{-1}) and at GS 30 (0, 56, 112, and 168 kg N ha^{-1}), and formed a complete 5 x 4 factorial arranged in a randomized complete block design with 4 replications.

Plant Tissue Sampling and Grain Yield Determination

Wheat tissue samples consisting of the entire above ground plants removed from four 0.9-m sections of a row were taken immediately before the N fertilizer application at GS 30, and used to determine dry matter production. The samples were dried at 65°C and ground with a Wiley mill to pass a 1-mm screen prior to digestion. The ground plant tissue was analyzed for total N using microKjedahl digestion with concentrated H_2SO_4. Ammonium in solution was determined colorimetrically with Na salicylate, Na nitropusside and Na hypochlorite (EPA, 1979). Plant N uptake (kg N ha^{-1}) was calculated by multiplying the N concentration (%N) in the tissue by the dry matter production (kg ha^{-1}).

Table 5. Maximum, minimum, and mean grain yields obtained at the different experimental sites.

Site	Year	Grain yield Minimum	Maximum	Mean
		------Mg ha^{-1}------		
I	1981-82	5.40	6.70	6.25
II	1982-83	4.06	8.11	7.21
III	1983-84	2.04	6.41	5.24
IV	1983-84	5.39	8.96	7.48
V	1984-85	5.98	6.79	6.20
VI	1984-85	2.94	6.02	5.58
VII	1985-86	3.62	8.66	7.17
VIII	1985-86	3.07	6.17	5.04

Grain yields were harvested from the center swath of each plot using a small plot combine. Moisture content was determined with an electronic moisture meter on the grain from each plot and all yields were adjusted to 13.5% moisture content. The maximum, minimum, and mean grain yields obtained at the different experimental sites are presented in Table 5.

Data Analysis

The different rates of N fertilizer applied at GS 25 provided a wide range of variation in the plant N uptake at GS 30. The relationships of plant N concentration at GS 30 (N%) and N uptake by wheat at GS 30 with grain yields was studied utilizing nonlinear regression analysis procedures, in the treatments with no N fertilizer applications after GS 30. The critical level at GS 30 was calculated as the plant tissue N concentration (N%) or the crop N uptake value at GS 30 that produced 90% of the maximum grain yield with no further N fertilizer application.

A family of response curves of wheat grain yield as a function of N applied at GS 30 for each level of N fertilizer applied at GS 25 was fitted for the different experimental sites using regression analysis (Montgomery and Peck, 1982). The rate of N fertilizer applied at GS 30 needed to obtain maximum (NMAX30) and optimum (NOPT30) grain yields was determined for each of these response curves. The NMAX30 value for any given response curve is the N fertilizer rate value that makes the first derivative of the response curve function equal to zero. The NOPT30 value for any given response curve is the N fertilizer rate value that makes the first derivative of the response function equal to the price ratio of N fertilizer : wheat ($ / kg N : $ / kg wheat) (Heady et al., 1955). Three price ratios were used in this research to determine NOPT30 values: 2.0, 4.0, and 6.0. Various regression models were developed using NMAX30 as the dependent variable, and either N%30 or NUP30 as the independent variable. The selection of the best model was performed considering measurements of fit (R^2 value, standard error of the predicted values), significance of the estimated regression coefficients, and predictive ability of the models. Predictive ability was determined by calculating the PRESS statistic (Montgomery and Peck, 1982) for the different models evaluated.

Results and Discussion

Determination of Critical Levels

Critical or sufficiency levels were defined as the plant tissue N concentration (%) or the crop N uptake (kg ha^{-1}) values at GS 30 that produced 90% of the maximum yield at each site with no further N fertilizer application. For this purpose, grain yields in the treatments with no N fertilizer application after GS 25 were expressed as a percentage of the maximum yield obtained at each experimental site. The relationship between these relative yields from 5 years of experiments and the plant tissue N concentration (N%) or N uptake (kg ha^{-1}) was studied utilizing nonlinear regression analysis (Montgomery and Peck, 1982).

Numerous nonlinear models were developed with the relative yields as the independent variable and N%30 as the independent variable. The model with the largest R^2 value and the smallest standard error of the estimated regression coefficients was selected as the best model (Fig. 6). The best model for N% at GS 30 was:

$$RY = \beta_1 \times \exp(-\beta_2 \times \exp(-\beta_3 \times N\%30)$$

where

RY = relative yield

N%30 = N% in the plant tissue at GS 30,

β_1, β_2, and β_3 are the estimated regression coefficients.

The values of β_1, β_2, and β_3 were 93.2, 19.90, and 1.67, respectively, and the R^2 value for the model was 0.88.

The calculated critical level was 3.8% N in the plant tissue at GS 30.

The same methodology was used to determine critical levels utilizing crop N uptake at GS 30. Again, numerous nonlinear models were evaluated with relative yields as the dependent variable and N uptake at GS 30 as the independent variable. The model with largest R^2 and smallest standard error of the regression coefficients was of the form:

$$RY = \beta_1 \times \exp(-\beta_2 \times \exp(-\beta_3 \times NUP30)$$

where

RY = relative yield

NUP30 = crop N uptake at GS 30,

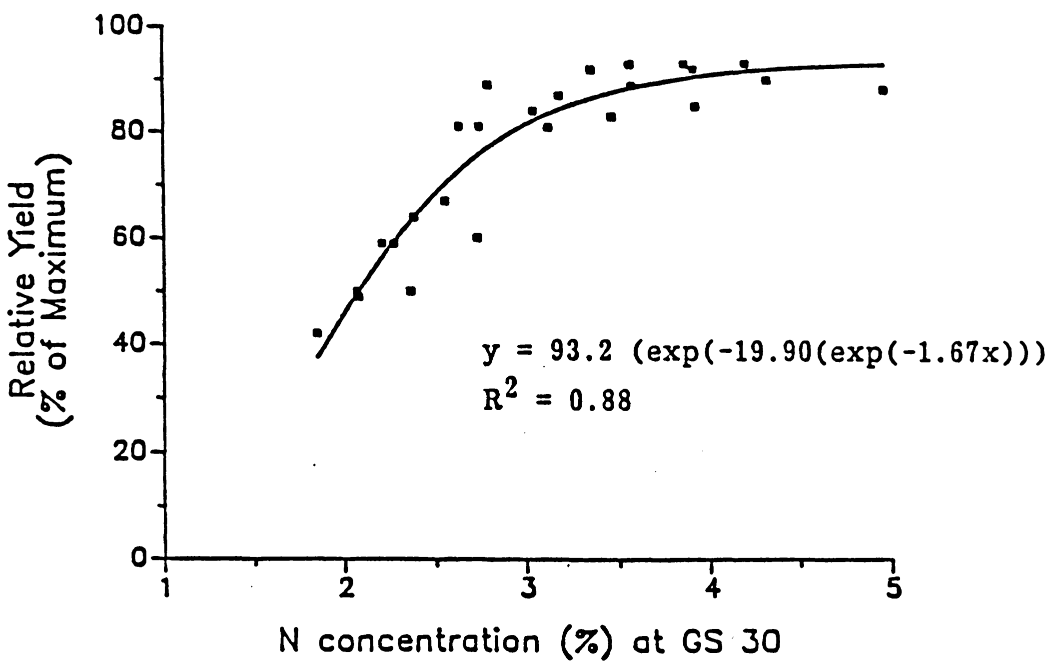

Figure 6. Nonlinear model used to calculate N fertilizer critical level with plant N concentration at GS 30.

β_1, β_2, and β_3 are the estimated regression coefficients.

The values of β_1, β_2, and β_3 were 107.0, 1.99, and 0.03, respectively. The R^2 for the model was 0.83 and the calculated critical level was 95 kg N ha^{-1} of N uptake at GS 30 (Fig. 7).

Determination of N Fertilizer Rates for Maximum and Optimum Grain Yields

The response of wheat grain yield to N fertilizer applied at GS 30 for each experimental site was studied utilizing analysis of variance by partitioning the treatment sums of squares into orthogonal contrasts to detect linear and/or quadratic response trends (Snedecor and Cochran, 1967). The response to N fertilizer was considered significant when the linear and/or quadratic component was significant at the 5% level of probability.

A family of response curves of wheat grain yield to N fertilizer applied at GS 30 for each level of N fertilizer applied at GS 25 was fitted using regression analysis at each experimental site. An example of the family of response curves obtained for one experimental site is shown in Fig. 8. In each of these response curves the amount of N fertilizer required at GS 30 to produce maximum grain yields (NMAX30) was calculated. In two situations the yield response to N fertilizer was linear, and in one situation the calculated NMAX30 value exceeded the largest N fertilizer rate used in the corresponding experiment. In these cases the NMAX30 values were defined as the largest rate of N fertilizer

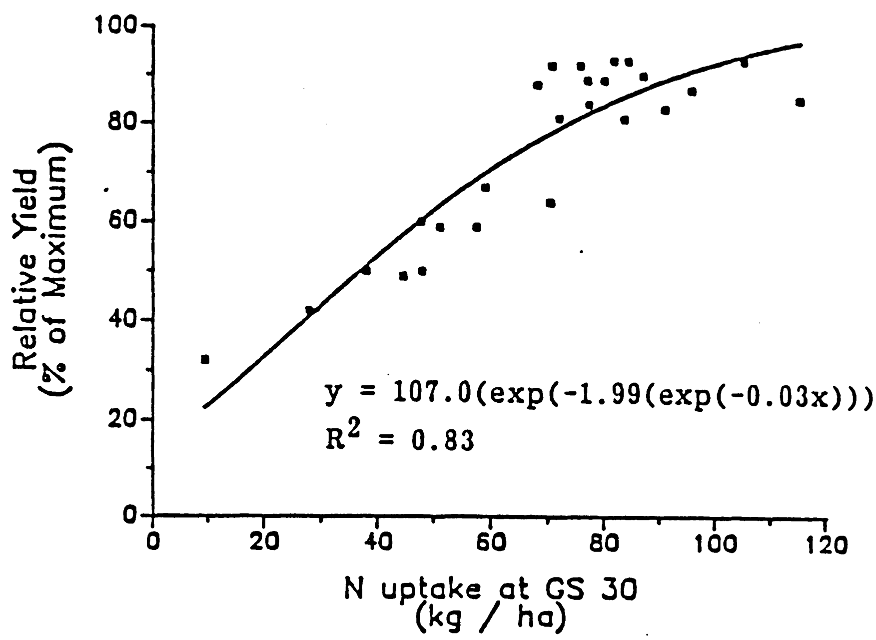

Figure 7. Nonlinear model used to calculate N fertilizer critical level with crop N uptake at GS 30.

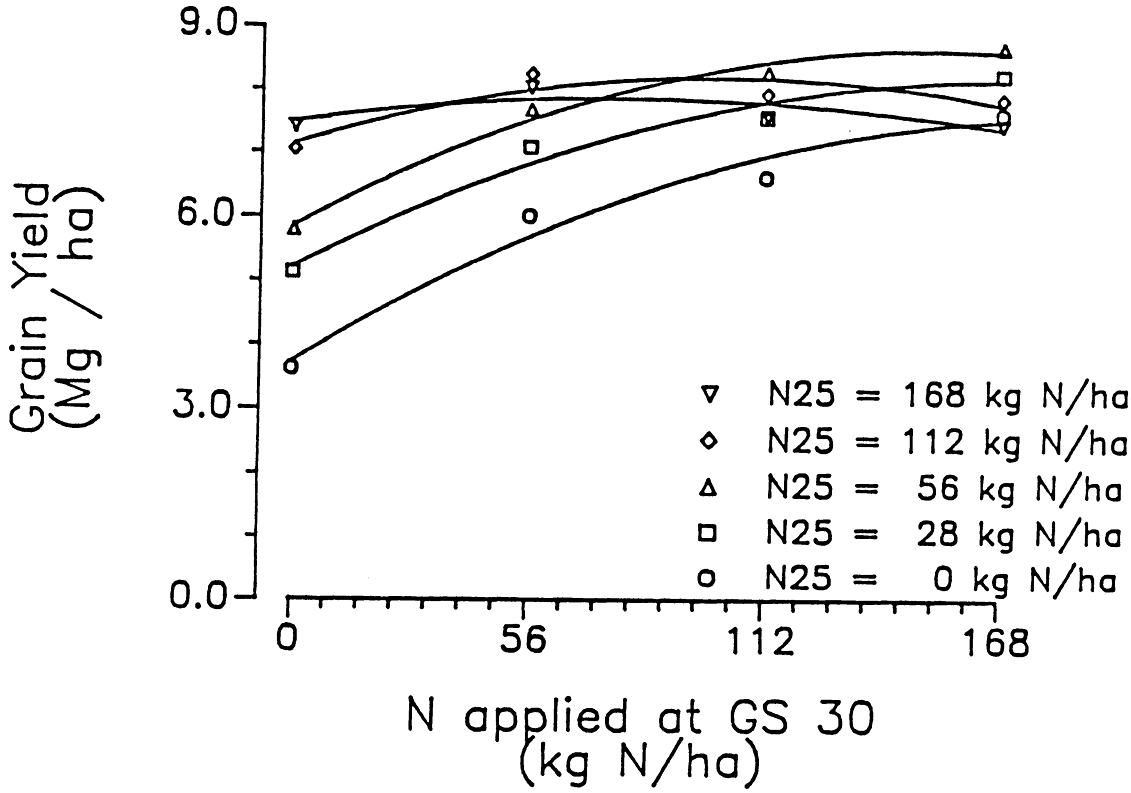

Figure 8. Family of response curves of grain yield to N applied at GS 30 for different rates of N applied at GS 25 (site VIII).

used in the corresponding experiment. Finally, in the situations where the response to N fertilizer was non-significant, the value of NMAX30 was set equal to zero.

Plant tissue N concentration at GS 30 (N%30) and crop N uptake at GS 30 (NUP30) were measured immediately before the N fertilizer application at GS 30. Thus, two pairs of values were obtained for each response curve at each experimental site: (a) N%30 and the amount of N fertilizer required at GS 30 to obtain maximum grain yield (NMAX30), and (b) NUP30 and NMAX30.

The relationship between N%30 and NMAX30 was studied utilizing regression analysis with the objective of developing a model capable of estimating the amount of N fertilizer needed at GS 30 to obtain maximum grain yield, for a given value of plant tissue N concentration (N%) at GS 30. A simple regression with NMAX30 as the dependent variable and N%30 as the independent variable was the model with best fit ($r = -0.69$, $P < .01$), smallest standard error of the regression coefficients, and best predictive ability (Fig. 9). A simple regression model was also the one that presented the best fit ($r = -0.87$, $P < .01$), the smallest standard error of the regression coefficients, and the best predictive ability for N fertilizer required at GS 30 to obtain maximum grain yields, considering the crop N uptake at GS 30 (Fig. 10).

The high correlation found in the model using NUP30 (Fig. 10) and the low value of the PRESS statistic (data not shown) indicates that NUP30 can be a good predictor of the amount of N fertilizer required at GS 30 to obtain maximum grain yield. The inclusion of a component for the wheat dry matter production at GS 30 in the calculation of NUP30 is probably the most important factor determining the better predictive ability of NUP30 compared to N%30. The relationship between wheat dry matter production at GS 30 and the total number of tillers at GS 30 was studied at Site VII, in the 1985-86

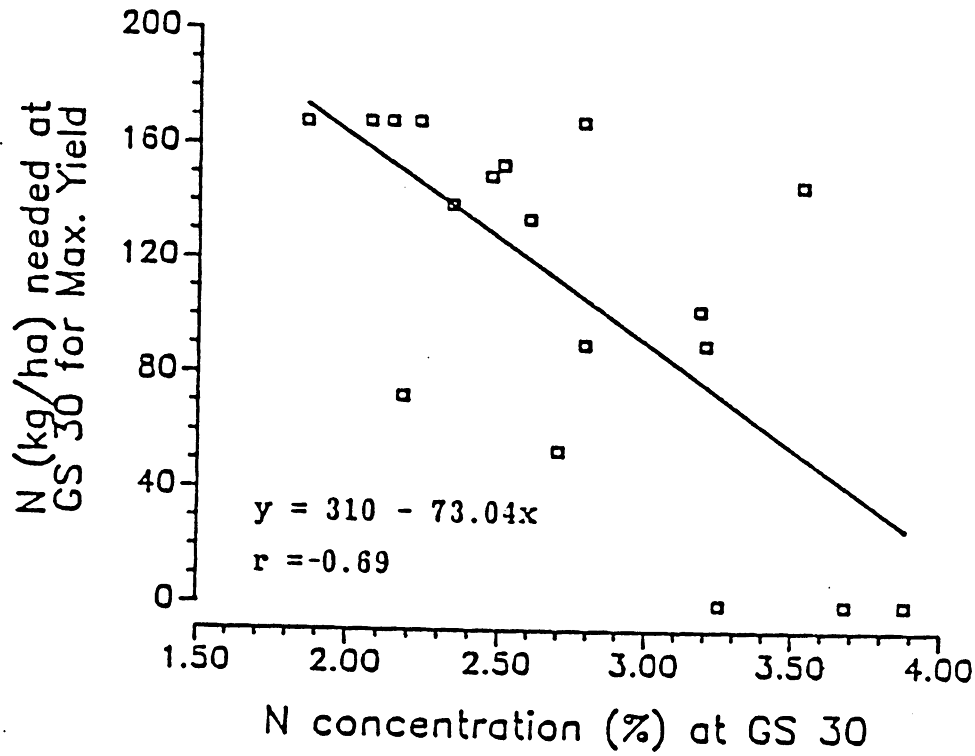

Figure 9. Model to predict the amount of N required at GS 30 to obtain maximum grain yields, with the plant N concentration at GS 30.

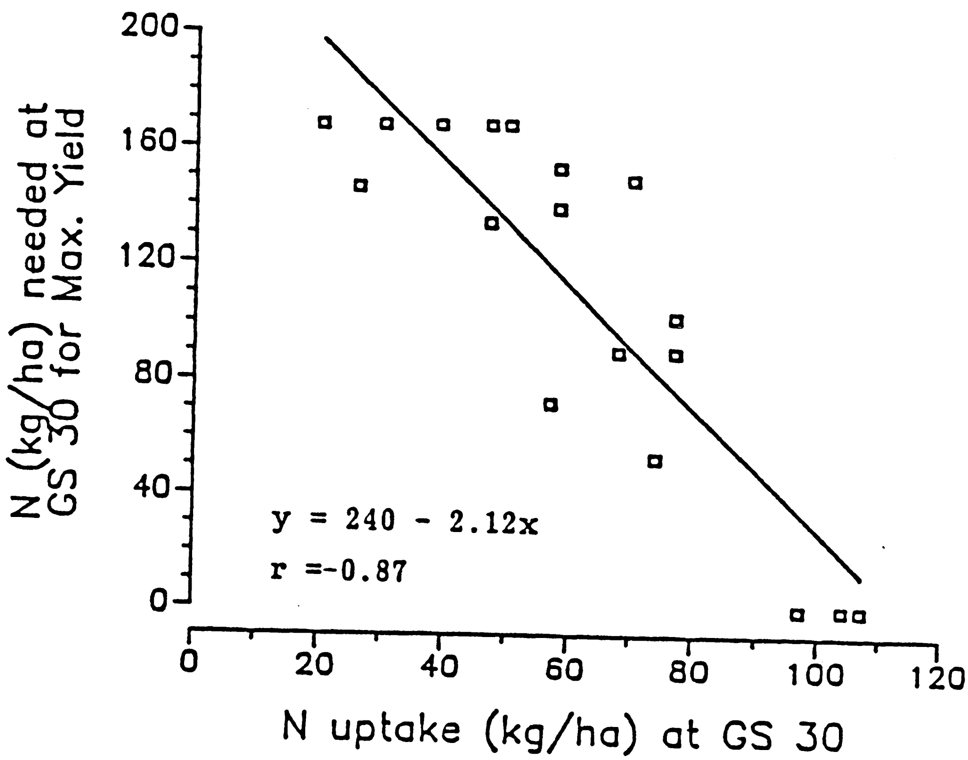

Figure 10. Model to predict the amount of N required at GS 30 to obtain maximum grain yields, with the crop N uptake at GS 30.

growing season (Fig. 11). The high correlation found between theses two variables indicates that the NUP30 values are indirectly including a component of the number of tillers at GS 30.

For each one of the response curves of grain yield to N fertilizer applied at GS 30 mentioned earlier in this section, the amount of N fertilizer required at GS 30 to obtain optimum grain yield (NOPT30) was also calculated. The NOPT30 value for any given response curve is the N fertilizer rate value that makes the first derivative of the response curve function equal to the N fertilizer : wheat price ratio ($ / kg N : $ / kg wheat) (Heady et al., 1955). Three price ratios were used in this research to determine NOPT30 values: 4.0 (a historically average price ratio for Virginia), 2.0, and 6.0. The relationship between the calculated NOPT30 values for each price ratio and the crop N uptake at GS 30 was studied utilizing regression analysis. In all three cases the best model was a simple linear regression. The linear correlation values for the models with price ratios of 2.0, 4.0, and 6.0, were -0.88, -0.89, and -0.88, respectively, all significant at the 1% level (Fig. 12). The regression functions obtained for the three price ratios were very similar, i.e., for any given value of NUP30, the amount of N fertilizer required to obtain optimum grain yields predicted by the three models was similar. These results indicate the importance of N fertilization in obtaining optimum wheat grain yields, even in situations where the price ratio of N fertilizer : wheat is high.

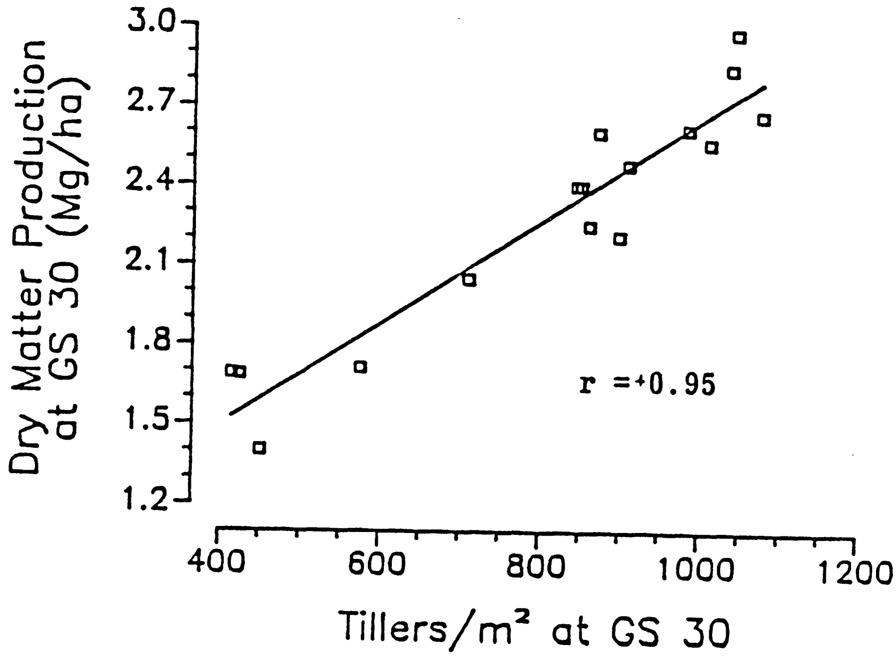

Figure 11. Relationship between winter wheat dry matter production at GS 30 and total number of tillers at GS 30.

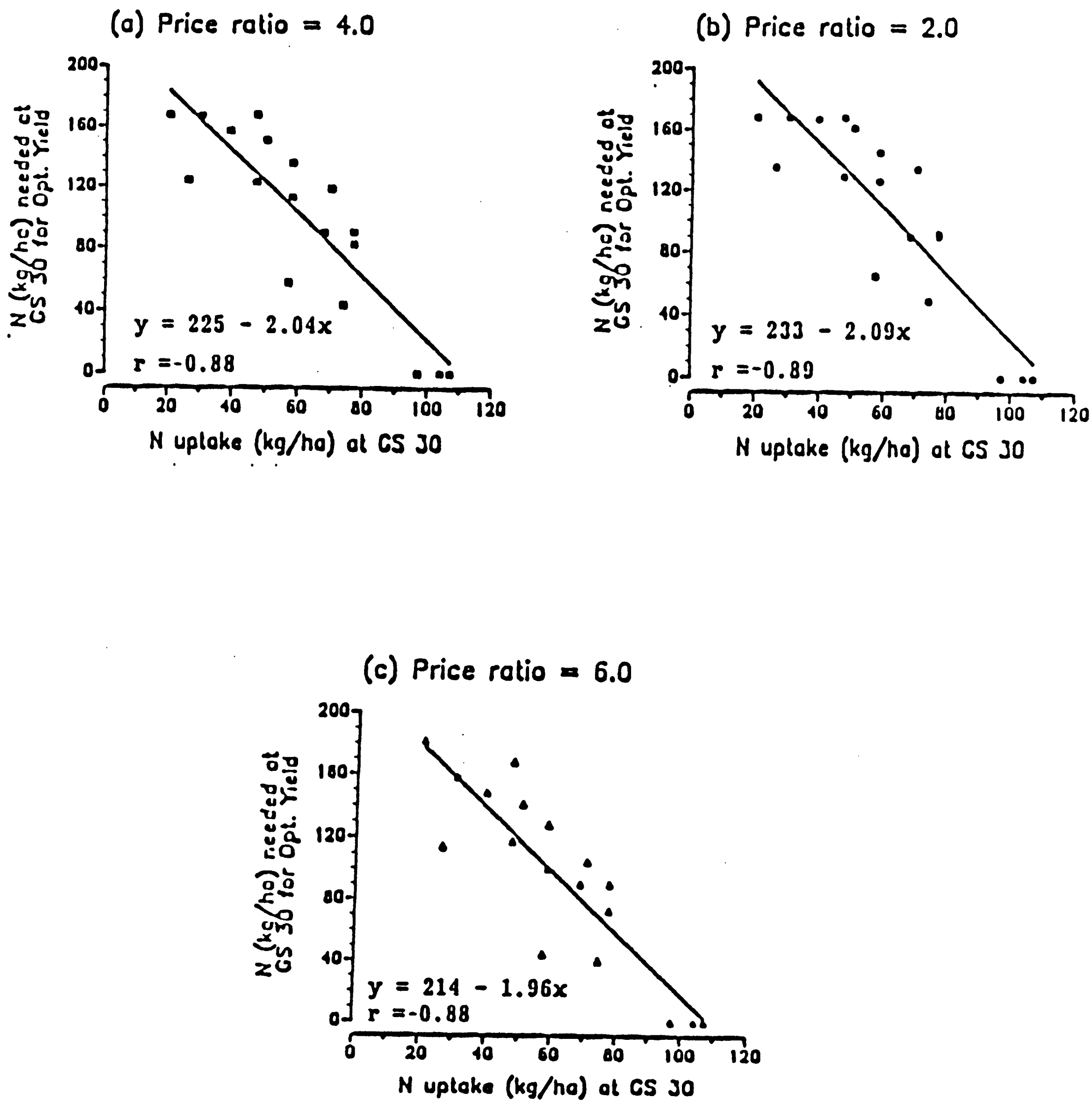

Figure 12. Models to predict the amount of N required at GS 30 to obtain optimum grain yields, for three N : wheat price ratios.

Conclusions

Plant N concentration (N%) and crop N uptake at GS 30 were good indicators of N fertilizer sufficiency levels for winter wheat. Nonlinear models indicated that the N fertilizer critical level for the crop was 3.8% N in the plant tissue at GS 30 or 95 kg N ha^{-1} of N uptake at the same growth stage. A model with good fit and predictive ability was developed to estimate the amount of N fertilizer required at GS 30 to obtain maximum grain yields, using the crop N uptake at GS 30 as the independent variable. Wheat N uptake at GS 30 was also a good indicator of the amount of N fertilizer required at GS 30 to produce economically optimum grain yields.

References

Ayoub, A. T. 1974. Effect of N source and time of application on wheat N uptake and grain yield. J. Agric. Sci. 82: 567-569.

Baethgen, W.E. and M.M. Alley. 1987. Optimizing soil and fertilizer nitrogen use by intensively managed winter wheat in Virginia. I. Nitrogen uptake. Agron. J. (In review).

Batey, T. 1977. Prediction by leaf analysis of nitrogen fertiliser required for winter wheat. J. Sci. Food Agric. 28: 275-278.

Becker, F. A., and W. Aufhammer. 1982. Nitrogen fertilisation and methods of predicting the N requirements of winter wheat in the Federal Republic of Germany. In Symposium on fertilisers and intensive wheat production in the EEC. The Fertiliser Society. Proc. 211. pp. 33-66.

Dahnke, W. C., and E. H. Vasey. 1973. Testing soils for nitrogen. p. 97-114. In L. M. Walsh and J. D. Beaton (ed.) Soil testing and plant analysis. Soil Science Society of America, Madison, WI.

Donohue, S. J., and D. E. Brann. 1984. Optimum N concentration in winter wheat grown in the Coastal Plain region of Virginia. Commun. Soil Sci. Plant Anal. 15: 651-661.

Fox, R. H., and W. P. Pieckielek. 1978. Field testing of several nitrogen availability indices. Soil Sci. Soc. Am. J. 42:747-750.

Gillelan, M. E., and J. Macknis. 1983. Nutrients. p.39-88. In D. A. Barker, M. Manganello, D. Parvlowicz, and S. Katsanos (ed.) Chesapeake Bay: a framework for action. E.P.A. Philadelphia, PA.

Heady, E. O., J. T. Pesek, and W. G. Brown. 1955. Crop response surfaces and economic optima in fertilizer use. Iowa State Coll. Res. Bull. 424.

Hucklesby, D. P. 1971. Late spring applications of N for efficient utilization and enhanced production of grain and grain protein of wheat. Agron. J. 63: 274-276.

Keeney, D. R., and D. W. Nelson. 1982. Nitrogen inorganic forms. In A.L. Page et al. (ed.) Methods of soil analysis, Part 2, 2nd edition. Agronomy 9:643-698.

Montgomery, D. C., and E. A. Peck. 1982. Introduction to linear regression analysis. John Wiley and Sons, Inc., New York, NY.

Needham, P. 1982. The role of nitrogen in wheat production: response, interaction and prediction of nitrogen requirements in the UK. p. 125-147. In Symposium on fertilisers and intensive wheat production in the EEC. The Fertiliser Society. Proc.. London.

Olson, R. V., and C. W. Swallow. 1984. Fate of labeled nitrogen fertilizer applied to winter wheat for five years. Soil Sci. Soc. Am. J. 48: 583-586.

O'Neil, E. J., T. Batey, and M. S. Cresser. 1983. Assessment of nitrogen status of soils for cereal crops: use of plant and soil analysis to diagnose nitrogen status of spring barley. J. Sci. Food Agric. 34: 549-558.

Power, J. F., and J. Alessi. 1978. Tiller development and yield of standard and semidwarf spring wheat varieties as affected by nitrogen fertilizer. J. Agric. Sci. 90: 97-108.

Prutskova, M. G., and O. I. Ukanova. 1972. New varieties of winter wheat. In P. O. Luk'yaneko (ed.) Amerinal Publishing Co. Pvt. Ltd., New Delhi.

Robinson, F. E., D. W. Cudney, and W. L. Lehman. 1979. Nitrogen fertilizer timing, irrigation, protein, and yellow berry in durum wheat. Agron. J. 71: 304-308.

Snedecor, G. W., and W. G. Cochran. 1967. Statistical methods, 6th. ed. The Iowa State University Press, Ames, Iowa.

Soper, R. J., G. J. Racz, and P. I. Fehr. 1971. Nitrate N in soil as a means of predicting the fertilizer requirements of barley. Can. J. Soil Sci. 51: 45-49.

Zadoks, J.C., T.T. Chang, and C.F. Zonzak. 1974. A decimal code for the growth stages of cereals. Weed Res. 14:415:421.

Determination of Optimum Nitrogen Fertilizer Rates at Tillering

Abstract

The objective of this study was to determine the recommended amount of nitrogen (N) fertilizer to be applied to winter wheat at Zadoks growth stage 25 (GS 25) that would optimize the use of a previously developed model to predict N required at GS 30. Quadratic programming models were developed for six experimental sites with the objective of maximizing marginal profit with N fertilizer application. The models were then solved to determine the amounts of N at GS 25 and at GS 30 that would produce the maximum attainable profit. Four recommended nitrogen fertilizer rates at GS 25 (N25) were evaluated: 0, 30, 60, and 100 kg N ha^{-1}. For this purpose the N25 value was forced to be each of these four pre-determined amounts and profit was again maximized. The difference (D) between the yields with maximum attainable profit (Y) and the yields when N25 was forced to be 0, 30, 60, and 100 kg N ha^{-1} (Y^R) was then calculated (D

= Y - Y^R). The best N25 recommendation was the one that minimized the mean value, standard deviation, and coefficient of variation of D. This methodology was used for 3 nitrogen fertilizer : wheat price ratios (2.0, 4.0, and 8.0). The results indicated that the best recommendations for N25 were 50 - 60 kg N ha^{-1} for N fertilizer : wheat price ratios of 2.0 and 4.0, and 40 - 50 kg N ha^{-1} for a price ratio of 8.0. Sensitivity analysis was then performed to study the effect of variations in the N fertilizer : wheat price ratio on the the recommended N rates. The results indicated that the recommended N rates were essentially insensitive to the variations in the price ratio of N fertilizer : wheat.

Introduction

Proper nitrogen (N) fertilization is crucial for economical wheat production. Suboptimal N fertilizer applications produce low numbers of tillers m^{-2}, heads m^{-2}, and smaller heads, thus resulting in low grain yields (Ayoub, 1974; Hucklesby, 1971; Power and Alessi, 1978; Robinson et al., 1979). Excessive plant-available N early in the growing season produces plants that are susceptible to lodging and diseases, with consequent decreased yields and increased costs (Prutskova and Ukanova, 1972). Excessive N fertilization also constitutes a potential environmental problem through nitrate contamination of surface and ground waters (Gillelan and Macknis, 1983).

The prediction of optimal N fertilizer rates for winter wheat is still a major unsolved problem in most humid areas of the world. The traditional recommendation of N fertilization for winter wheat in Virginia included a low rate at planting, and rates ranging from 80 to 120 kg N ha^{-1} at tillering or Zadoks' growth stage (GS) 25 (Zadoks et al., 1974). Results by Baethgen and Alley (1985) and Alley et al. (1986) revealed an advantage of splitting the spring N fertilization into two application times: one at Zadoks' GS 25 and another at Zadoks' GS 30, which is immediately before stem elongation.

More recently Baethgen and Alley (1987) developed a model to predict economically optimum rates of N fertilization (EORN) for winter wheat in Virginia. The model is based on the crop N uptake (N % in the plant tissue × dry matter production in kg ha^{-1}) at GS 30. However, crop N uptake at GS 30 greatly depends on the N fertilizer application at tillering (GS 25). For this reason the authors studied the wheat response to N fertilization at GS 30, for different rates of N fertilizer applied at tillering. These experiments indicated that low rates of N fertilizer at GS 25 resulted in a low number of tillers m^{-2}, thus limiting the crop response to N applied at GS 30. Large N rates at GS 25 resulted in an excessive number of tillers m^{-2} , which in turn increased lodging and disease problems. However, Baethgen and Alley (1987) did not determine a precise recommendation of N fertilizer application at GS 25.

The principal objective of the research presented in this report was to use a Quadratic programming approach to determine the recommended N fertilizer rate to be applied at GS 25, that would optimize the use of the model by Baethgen and Alley (1987) to predict EORN for winter wheat. A second objective was to perform sensitivity analyses on the data to study the variation in the recommended EORN values for different N fertilizer : wheat price ratios (\$ / kg N : \$ / kg wheat).

Methods

Multiple linear regression functions were developed for each of six experimental sites (Baethgen and Alley, 1987). The dependent variable in these functions was wheat grain yield in kg ha^{-1} (Y), and the independent variables were N fertilizer rates in kg ha^{-1} applied at GS 25 (N25) and at GS 30 (N30). The functions also included quadratic terms for N25 and N30, and a term for the interaction N25 x N30 (INT). The resulting models for each experimental site were of the form:

$$Y = \beta_0 + \beta_1 N25 + \beta_2 N30 + \beta_3 N25^2 + \beta_4 N30^2 + \beta_5 INT.$$

The estimated regression coefficients (β_i) for each of these terms, and the response surfaces obtained for each function are presented in Table 6 and Figure 14, respectively.

Multiplying both sides of each of these equations by the price of wheat in \$ / kg (P_w) results in N fertilizer gross income ($P_w Y$, in \$ ha^{-1}) functions.

Multiplying the amounts of N fertilizer applied at GS 25 and GS 30 by the price of N fertilizer in \$ / kg N (P_N) gives the cost of N fertilizer ($P_N N25$, $P_N N30$). Finally, subtracting the total cost of N fertilizer ($P_N N25 + P_N N30$) from the gross income ($P_w Y$) results in N fertilizer marginal profit (π, in \$ ha^{-1}) functions.

$$\pi = P_w Y - (P_N N25 + P_N N30)$$

Table 6. Regression coefficients obtained in each site, for wheat grain yield response to N applied at GS 25 (N25)d at GS 30 (N30).

	---Regression coefficients---					
Site	Intercept	N25	N30	N252	N302	INT(†)
III	2018	49.74	48.23	-0.1338	-0.1274	-0.2433
IV	5420	49.75	51.10	-0.1974	-0.1895	-0.3887
V	5910	14.50	21.13	-0.1298	-0.1428	-0.2257
VI	2943	35.74	37.96	-0.1322	-0.1145	-0.2464
VII	3882	45.03	38.94	-0.1443	-0.0988	-0.1435
VIII	3115	22.35	17.30	-0.0430	-0.0399	-0.0553

†INT = N25 x N30 Interaction.

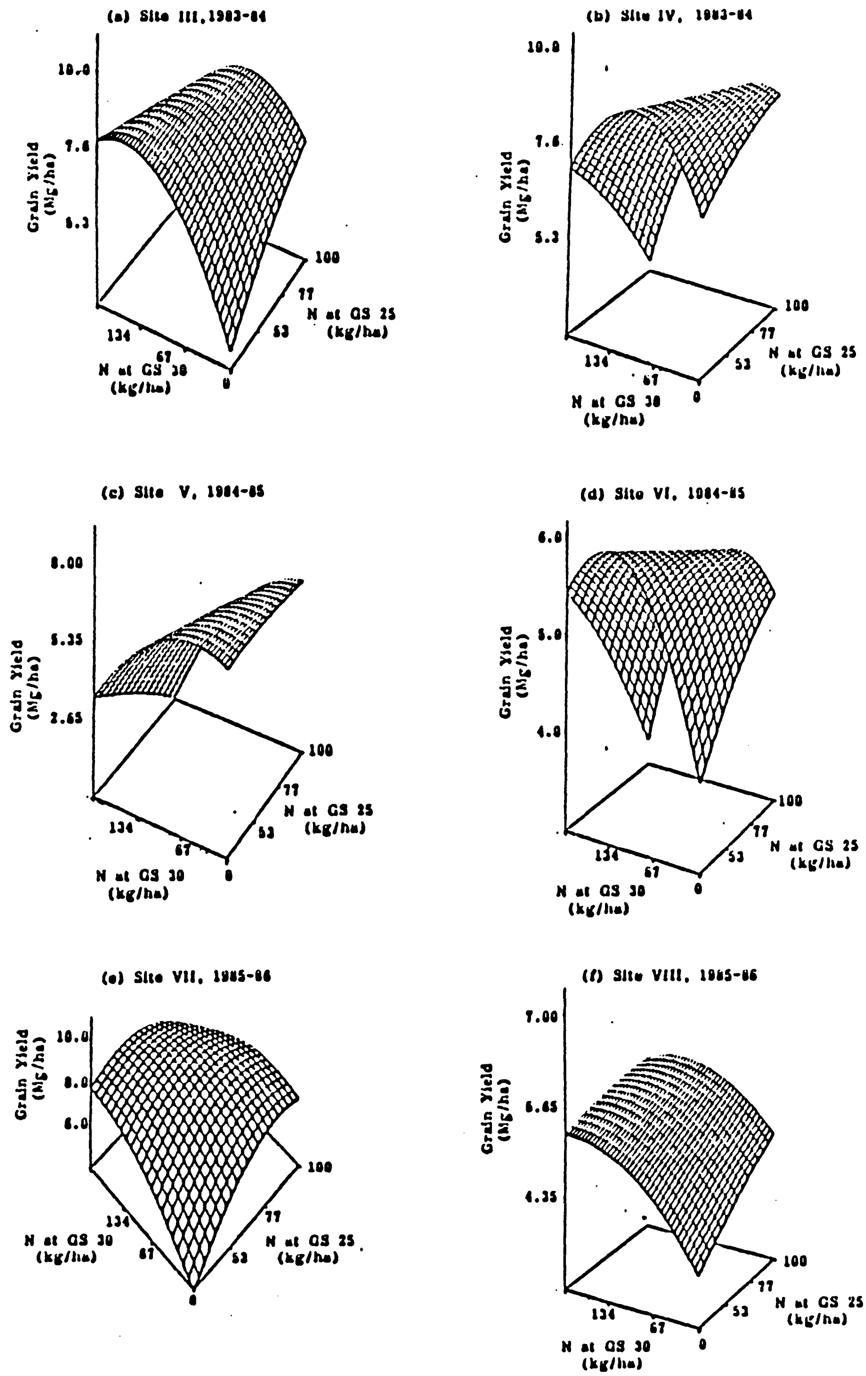

Figure 13. Response surfaces of wheat grain yield response to N fertilizer applied at GS 25 (N at GS 25) and at GS 30 (N at GS 30).

Quadratic programming models were then solved for each one of the six functions obtained at each experimental site, to determine the amounts of N applied at GS 25 and at GS 30 that would maximize π. The expanded objective function and the constraints for each experimental site were of the form:

$$\max \pi = P_w\beta_0 + P_w\beta_1 N25 + P_w\beta_2 N30 + P_w\beta_3 N25^2 + P_w\beta_4 N30^2 + P_w\beta_5 INT +$$

$$- P_N N25 - P_N N30$$

Subject to the following constraints:

[1] $N25 \leq 150$

[2] $N25 + N30 \leq 250$

[3] $N25, N30 \geq 0$

The values used in the right hand side of constraints [1] and [2] were selected considering the results of the field experiments. Nitrogen fertilizer rates larger than 150 kg N ha^{-1} at GS 25 were shown to increase lodging problems. Also, total N fertilizer applications larger than 250 kg N ha^{-1} resulted in very low N fertilizer use efficiency values, which would increase the potential for environmental contamination (Alley et al., 1986).

It should be noted that this structure does not include the intercept of the original multiple regression models (β_0). Consequently, π actually represents the increase in profit attributed to N fertilization since the intercept term represents yields with zero N fertilization. The values of π , N25, and N30 were determined at each experimental site, using three N fertilizer : wheat price ratios: 4.0 (a historically average price ratio for

Virginia), 2.0, and 8.0, by setting the price of N fertilizer at 0.40 \$ kg N^{-1}, and the price of wheat at 0.10, 0.2, and 0.05 \$ kg^{-1}, respectively. The quadratic programming functions were solved using the QCP subroutine of the LINDO program (Schrage, 1984).

Four recommended N fertilizer rates at GS 25 ($N25^R$) were then evaluated: 0, 30, 60, and 100 kg N ha^{-1}. For this purpose a new constraint was added to the original quadratic programming models to force the N25 value to be each of these pre-determined amounts, and profit (π^R) was again maximized at each experimental site. The difference (D) between the yields obtained at maximum profit without forcing N25 to any pre-determined value (Y), and the yields when N25 was forced to be 0, 30, 60 or 100 kg N ha^{-1}(Y^R) was then calculated as:

$$D = Y - Y^R$$

The average D value for the six experimental sites ($\overline{D}$), the standard deviation (S.D.) and the coefficient of variation (C.V.) of $\overline{D}$ were then determined. The best recommendation of N fertilizer rate to be applied at GS 25 was defined as the one which minimized the value of $\overline{D}$, S.D., and C.V. This methodology was applied for the three N fertilizer : wheat price ratios included in this research to study the variation of recommendations with different wheat prices.

Results

The calculated values of the yield (Y) when maximizing profit (π) for a N fertilizer : wheat price ratio of 4.0, and the N fertilizer rates required at GS 25 and GS 30 to maximize π at each experimental site appear in Table 7. This table also presents the results of the yields (Y^R) for the maximum profit (π^R) obtained at each site, when the N fertilizer rate applied at GS 25 was forced to be 0, 30, 60, and 100 kg N ha^{-1} ($N25^R$), as well as the corresponding N fertilizer rates required at GS 30 selected by the model. The difference (D) between the yields obtained at maximum attainable profit yield (Y) and the yield obtained for the different N25 recommendations (Y^R) is also presented in Table 7. The best recommendation for the N fertilizer rate to be applied at GS 25 would be the one which minimizes the mean value of D for the six experimental sites ($\overline{D}$). The relationship between $\overline{D}$ and the recommended N rate at GS 25 was curvilinear. Thus the value of $\overline{D}$ decreased when the recommended N rate at GS 25 increased from 0 to 60 kg N ha^{-1}, and then increased for $N25^R$ = 100 kg N ha^{-1}.

Consistency in the adequacy of the recommendation for different years and locations was also pursued. Consequently the standard deviation (S.D.) and the coefficient of variation (C.V.) of $\overline{D}$ for each value of $N25^R$ was determined (Table 7). The most consistent recommendation for N fertilizer application at GS 25 will be the one which minimizes the values of S.D. and C.V. The effect of the magnitude of $N25^R$ on S.D. and C.V. was similar to the effect of $N25^R$ on the value of $\overline{D}$.

Three regression models were then fitted to study the relationship between $N25^R$ (used as the independent variable) and $\overline{D}$, S.D., and C.V. (dependent variables). The three models included a quadratic term for $N25^R$ given the curvilinear relationship mentioned above. The values of $N25^R$ that minimized $\overline{D}$, S.D., and C.V. were determined by setting the partial derivative of the regression functions with respect to $N25^R$ equal to zero, and solving for $N25^R$. The values of $N25^R$ that minimized $\overline{D}$, S.D., and C.V. were 51, 55, and 58 kg N ha^{-1}, respectively (Table 8).

----Maximum Profit-----				---N25^R=0 kg N ha^{-1}---				--N25^R=30 kg N ha^{-1}---				--N25^R=60 kg N ha^{-1}---				--N25^R=100 kg N ha^{-1}---			
Site	Y†	N25	N30	Y^R	D	N25^R	N30	Y^R	D	N25^R	N30	Y^R	D	N25^R	N30	Y^R	D	N25^R	N30
III	4014	99	79	3840	174	0	174	3929	85	30	145	3987	27	60	116	4014	0	100	78
IV	2926	0	124	2926	0	0	124	2851	75	30	93	2780	146	60	63	2690	236	100	22
V	514	0	60	514	0	0	60	386	128	30	36	185	329	60	13	-248	762	100	0
VI	2518	0	148	2518	0	0	248	2374	144	30	116	2227	291	60	84	2040	478	100	40
VII	3754	85	115	3089	665	0	177	3475	279	30	155	3696	58	60	133	3733	21	100	104
VIII	1944	150	63	1108	836	0	167	1361	583	30	145	1571	373	60	125	1784	160	100	97
				$\bar{D}$‡= 279.2 kg				$\bar{D}$ = 215.7 kg				$\bar{D}$ = 2.04.0 kg				$\bar{D}$ = 276.1 kg			
				S. D. = 375.2 kg				S. D. = 194.2 kg				S. D. = 146.8 kg				S. D. = 294.4 kg			
				C. V. = 134%				C. V. = 90%				C. V. = 72%				C. V. = 107%			

†Y, Y^R in kg wheat ha^{-1}, N25, N30, and N25^R in kg N ha^{-1}.
‡$\bar{D}$, S. D., and C. V. are the mean, standard deviation, and coefficient of variation of D.

Table 7. Results of Y, YR, D, N25R, and N30 utilizing a N fertilizer : wheat price ratio of 4.0.

Table 8. Models used to determine the values of N25R that minimize $\bar{D}$, S.D., and C.V. (N fertilizer : wheat price ratio = 4.0).

a) Dependent variable: $\bar{D}$

Parameter	Estimate	Pr (t)	R^2
Intercept	279.5	< 0.01	
$N25^R$	-3.0616	< 0.01	0.99
$N25^{R2}$	0.0303	< 0.01	

Minimum $\bar{D}$ for N25 = 51 kg N ha^{-1}

b) Dependent variable: S.D.

Parameter	Estimate	Pr (t)	R^2
Intercept	375.3	< 0.01	
$N25^R$	-8.2941	< 0.01	0.99
$N25^{R2}$	0.0748	< 0.01	

Mininum S.D. for $N25^R$ = 55 kg N ha^{-1}

c) Dependent variable: C.V.

Parameter	Estimate	Pr (t)	R^2
Intercept	134.8	0.02	
$N25^R$	-2.1127	0.06	0.99
$N25^{R2}$	0.0183	0.07	

Minimum C.V. for $N25^R$ = 58 kg N ha^{-1}

A second objective of this study was to investigate the effect of variations in the N fertilizer : wheat price ratios on the recommendation for N fertilization at GS 25. The same methodology described above was used to determine the values of $N25^R$ that minimized $\overline{D}$, S.D., and C.V. when the N fertilizer : wheat price ratio was 2.0 (Table 9) and 8.0 (Table 10). The $N25^R$ that minimized $\overline{D}$, S.D., and C.V. were 56, 60, and 61 kg N ha^{-1}, respectively, for a price ratio of 2.0 (Table 11), and 39, 45, and 50 kg N ha^{-1}, for a price ratio of 8.0 (Table 12).

These results indicate that the most appropriate implementation of the system to predict EORN for winter wheat proposed by Baethgen and Alley (1987) would be as follows: The crop should be fertilized with 50-60 kg N ha^{-1} at tillering, when the N fertilizer : wheat price ratio is normal to low (4.0 or lower), and with 40-50 kg N ha^{-1} in situations where the N fertilizer:wheat price ratio is high (4.0 - 8.0). Plant tissue samples should be taken at GS 30 and plant N uptake would be determined to estimate the EORN using the model by Baethgen and Alley (1987).

A final objective of this research was to study the sensitivity of the model, i.e., the variation in the values of N25 and N30 for different N fertilizer : wheat price ratios. The different experimental sites were grouped into three categories (high, medium, and low) considering the crop response to N fertilization. The N25 and N30 mean values were determined for each one of these categories for three N fertilizer : wheat price ratios (2.0, 4.0, and 8.0) (Table 13). The difference among the recommended N25 and N30 values for the two extreme price ratios ranged from 8 to 25 kg N ha^{-1} indicating that the recommended N fertilizer rates were essentially insensitive for the three price ratios evaluated. These results emphasize the importance of N fertilization in obtaining optimum wheat grain yields, even in situations where the price ratio of N fertilizer : wheat is high.

----Maximum Profit-----				---N25^R=0 kg N ha^{-1}---				--N25^R=30 kg N ha^{-1}---				--N25^R=60 kg N ha^{-1}---				--N25^R=100 kg N ha^{-1}---			
Site	Y†	N25	N30	Y^R	D	N25^R	N30	Y^R	D	N25^R	N30	Y^R	D	N25^R	N30	Y^R	D	N25^R	N30
III	3326	94	68	3176	150	0	158	3260	66	30	129	3312	14	60	101	3326	0	100	62
IV	2450	0	114	2450	0	0	114	2378	72	30	83	2310	140	60	52	2224	226	100	11
V	302	0	46	302	0	0	46	149	153	30	22	-75	380	60	0	-648	950	100	0
VI	1960	0	131	1960	0	0	131	1825	135	30	99	1691	269	60	66	1514	446	100	23
VII	2997	79	99	2420	577	0	157	2776	221	30	175	2964	33	60	113	2956	41	100	84
VIII	1193	150	15	638	555	0	137	822	371	30	113	970	223	60	88	1110	83	100	56
				$\bar{D}$ = 214 kg				$\bar{D}$ = 170 kg				$\bar{D}$ = 177 kg				$\bar{D}$ = 291 kg			
				S. D. = 279 kg				S. D. = 114 kg				S. D. = 142 kg				S. D. = 361 kg			
				C. V. = 131%				C. V. = 67%				C. V. = 80%				C. V. = 124%			

†Y, Y^R in kg wheat ha^{-1}, N25, N30, and N25^R in kg N ha^{-1}.
†$\bar{D}$, S. D., and C. V. are the mean, standard deviation, and coefficient of variation of D.

Table 9. Results of Y, YR, D, N25R, and N30 utilizing a N fertilizer : wheat price ratio of 2.0.

----Maximum Profit-----				---N25^R=0 kg N ha^{-1}---				--N25^R=30 kg N ha^{-1}---				--N25^R=60 kg N ha^{-1}---				--N25^R=100 kg N ha^{-1}---			
Site	Y†	N25	N30	Y^R	D	N25^R	N30	Y^R	D	N25^R	N30	Y^R	D	N25^R	N30	Y^R	D	N25^R	N30
III	4378	102	84	4195	183	0	181	4287	91	30	153	4347	31	60	124	4378	0	100	86
IV	3180	0	130	3180	0	0	130	3104	76	30	99	3031	149	60	68	2939	241	100	27
V	640	0	67	640	0	0	67	526	114	30	43	337	303	60	20	-48	688	100	0
VI	2824	0	157	2824	0	0	157	2675	149	30	125	2528	296	60	92	2332	492	100	49
VII	4165	88	123	3453	712	0	187	3856	309	30	165	4094	71	60	143	4152	13	100	114
VIII	2394	150	88	1467	927	0	192	1738	656	30	171	1966	428	60	150	2204	190	100	122
				$\bar{D}$† = 304 kg				$\bar{D}$ = 233 kg				$\bar{D}$ = 213 kg				$\bar{D}$ = 271 kg			
				S. D. = 411 kg				S. D. = 224 kg				S. D. = 154 kg				S. D. = 272 kg			
				C. V. = 135%				C. V. = 96%				C. V. = 74%				C. V. = 101%			

† Y, Y^R in kg wheat ha^{-1}, N25, N30, and N25^R in kg N ha^{-1}.
† $\bar{D}$, S. D., and C. V. are the mean, standard deviation, and coefficient of variation of D.

Table 10. Results of Y, YR, $\bar{D}$, N25R, and N30 utilizing a N fertilizer : wheat price ratio of 8.0.

Table 11. Models used to determine the values of N25R that minimize $\bar{D}$, S.D., and C.V. (N fertilizer : wheat price ratio = 2.0).

a) Dependent variable: $\bar{D}$

Parameter	Estimate	Pr (t)	R^2
Intercept	304.2	<0.01	
$N25^R$	-3.2778	<0.01	0.99
$N25^{R2}$	0.0294	<0.01	

Minimum $\bar{D}$ for N25 = 56 kg N ha^{-1}

b) Dependent variable: S.D.

Parameter	Estimate	Pr (t)	R^2
Intercept	412.2	<0.01	
$N25^R$	-8.5195	0.02	0.99
$N25^{R2}$	0.0711	0.02	

Mininum S.D. for $N25^R$ = 60 kg N ha^{-1}

c) Dependent variable: C.V.

Parameter	Estimate	Pr (t)	R^2
Intercept	136.5	0.03	
$N25^R$	-1.9816	0.09	0.98
$N25^{R2}$	0.0162	0.10	

Minimum C.V. for $N25^R$ = 61 kg N ha^{-1}

Table 12. Models used to determine the values of N25R that minimize $\bar{D}$, S.D., and C.V. (N fertilizer : wheat price ratio = 8.0).

a) Dependent variable: $\bar{D}$

Parameter	Estimate	Pr (t)	R^2
Intercept	215.0	0.01	
$N25^R$	-2.6070	0.05	0.99
$N25^{R2}$	0.0336	0.03	

Minimum $\bar{D}$ for N25 = 39 kg N ha^{-1}

b) Dependent variable: S.D.

Parameter	Estimate	Pr (t)	R^2
Intercept	274.2	0.04	
$N25^R$	-7.3580	0.08	0.99
$N25^{R2}$	0.0826	0.07	

Mininum S.D. for $N25^R$ = 45 kg N ha^{-1}

c) Dependent variable: C.V.

Parameter	Estimate	Pr (t)	R^2
Intercept	127.2	0.07	
$N25^R$	-2.3496	0.10	0.93
$N25^{R2}$	0.0234	0.09	

Minimum C.V. for $N25^R$ = 50 kg N ha^{-1}

Table 13. Variation in the values of maximum attainable profit, N25, and N30 for three N fertilizer : wheat price ratios.

Category	------PR = 2.0------			------PR = 4.0------			------PR = 8.0------		
	Y(†)	N25	N30	Y	N25	N30	Y	N25	N30
High	4271	95	104	3884	92	97	3162	87	84
Medium	2823	68	112	2477	64	102	1868	50	84
Low	640	0	67	514	0	60	302	0	46

†Y values in kg wheat ha^{-1}. N25 and N30 values in kg N ha^{-1}.

Conclusions

Quadratic programming models indicated that the optimum amount of N fertilizer to be applied at GS 25 was 50-60 kg N ha^{-1} for N fertilizer : wheat price ratios of 2.0-4.0, and 40-50 kg N ha^{-1} for price ratios larger than 4.0. Sensitivity analysis indicated that the recommended N fertilizer rates were essentially insensitive to variations in the price ratio of N fertilizer : wheat in the range of 2.0 to 8.0.

References

Alley , M. M., W. E. Baethgen, and D. E. Brann. 1986. Determining nitrogen needs for maximum economic wheat yields in humid region. Proceedings of the Maximum Wheat Yield Systems Workshop, March 5-7, Denver, CO, Potash and Phosphate Institute, Atlanta, GA.

Ayoub, A. T. 1974. Effect of N source and time of application on wheat N uptake and grain yield. J. Agric. Sci. 82: 567-569.

Baethgen, W.E., and M.M. Alley. 1987. Optimizing soil and fertilizer nitrogen use by intensively managed winter wheat. II. Determination of critical levels and optimum rates of nitrogen fertilizer. Agron. J. (In review).

Baethgen, W.E., and M.M. Alley. 1985. Rates and timing of N fertilization for winter wheat. Agron. Abstr. American Society of Agronomy, Madison, WI. p.165.

Gillelan, M. E., and J. Macknis. 1983. Nutrients. p.39-88. In D. A. Barker, M. Manganello, D. Parvlowicz, and S. Katsanos (ed.) Chesapeake Bay: a framework for action. E.P.A. Philadelphia, PA.

Heady, E. O.; J. T. Pesek, and W. G. Brown. 1955. Crop response surfaces and economic optima in fertilizer use. Iowa State Coll. Res. Bull. 424.

Hucklesby, D. P. 1971. Late spring applications of N for efficient utilization and enhanced production of grain and grain protein of wheat. Agron. J. 63: 274-276.

Power, J. F., and J. Alessi. 1978. Tiller developement and yield of standard and semidwarf spring wheat varieties as affected by nitrogen fertilizer. J. Agric. Sci. 90: 97-108.

Prutskova, M. G., and O. I. Ukanova. 1972. New varieties of winter wheat. P. O. Luk'yaneko (ed.) Amerinal Publishing Co. Pvt. Ltd., New Delhi.

Robinson, F. E., D. W. Cudney, and W. L. Lehman. 1979. Nitrogen fertilizer timing, irrigation, protein, and yellow berry in durum wheat. Agron. J. 71: 304-308.

Shrage, L. 1984. Linear, integer, and quadratic programming with LINDO. The Scientific Press. Palo Alto, CA.

Zadoks, J.C., T.T. Chang, and C.F. Zonzak. 1974. A decimal code for the growth stages of cereals. Weed Res. 14:415:421.

Summary and Conclusions

Field experiments were conducted in the Coastal Plain and Ridge and Valley regions of Virginia during the 1981-82 through 1985-86 winter wheat growing seasons. The treatments in all experiments consisted of varying amounts of N fertilizer rates applied at Zadoks' growth stages 25 (GS 25) and 30 (GS 30). The research was divided into three studies. The first study was conducted to assess the effect of N fertilizer rates on the amounts and patterns of the crop N uptake. Dry matter production and total N concentration were measured in total above ground plant material at different growth stages, as well as in leaves, stems, and spikes in selected experiments. Maximum N uptake daily rates were obtained in the period immediately after GS 30 which suggests that this is the wheat growth stage in which the highest efficiency of N fertilizer use could be expected. Crop N uptake at GS 30 also appeared as a potentially good indicator of the plant N requirements.

The second study was designed to develop models for determining critical N levels and optimum N fertilizer rates for winter wheat. Two nonlinear models were successfully developed to determine critical N levels at GS 30 utilizing plant N concentration at GS

30 (N%30) and crop N uptake at GS 30 (NUP30). Both nonlinear model were of the form:

$$RY = \beta_1 \times \exp(-\beta_2 \times \exp(-\beta_3 \times N30)$$

where

RY = relative yield

N30 = N% in the plant tissue, or N uptake at GS 30,

β_1, β_2, and β_3 are the estimated regression coefficients.

The values of β_1, β_2, and β_3 were 93.2, 19.90, and 1.67, respectively, for the model utilizing N%30, and the R^2 value for the model was 0.88. The values of β_1, β_2, and β_3 were 107.0, 1.99, and 0.03, respectively, for the model utilizing NUP30, and the R^2 value for the model was 0.83.

The best model to predict N rates required at GS 30 to obtain maximum grain yields was a simple regression model utilizing NUP30 as independent variable. The model had a high correlation coefficient ($r = -0.87$, $P < 0.01$), and a good predicting ability (low PRESS statistic value). Simple regression models were also the best models to predict N rates required at GS 30 to obtain optimum grain yields. Three N fertilizer : wheat price ratios were studied (2.0, 4.0, and 8.0), and the three resulting models had high correlation coefficients ($r < -.88$), and low PRESS statistic values.

The objective of the third study was to use a quadratic programming approach for determininig the recommended amount of N fertilizer to be applied at GS 25 that would optimize the use of the simple linear regression models developed in the second study. The results indicated that the best recommendations for N25 were 50 - 60 kg N ha^{-1} for N fertilizer : wheat price ratios of 2.0 and 4.0, and 40 - 50 kg N ha^{-1} for a price ratio of 8.0.

A second objective of this research was to study the sensitivity of the model, i.e., the variation in the values of N25 and N30 for different N fertilizer : wheat price ratios. The difference among the recommended N25 and N30 values for the two extreme price ratios ranged from 8 to 25 kg N ha^{-1} indicating that the recommended N fertilizer rates were essentially insensitive for the three price ratios evaluated. These results emphasize the importance of N fertilization in obtaining optimum wheat grain yields, even in situations where the price ratio of N fertilizer : wheat is high.

Appendix A. Description of the treatments

Year	Treatment	Nitrogen applied at GS 25	GS 30	GS 45	GS 58
		------------------ Kg N ha^{-1}			------------------
1981-82	1	0	0	0	0
1981-82	2	90	0	0	0
1981-82	3	135	0	0	0
1981-82	4	67	0	23	0
1981-82	5	45	0	23	23
1981-82	6	45	0	0	45
1981-82	7	67	0	67	0
1981-82	8	67	0	34	34
1981-82	9	67	0	0	67
1982-83	1	0	0	0	0
1982-83	2	90	0	0	0
1982-83	3	135	0	0	0
1982-83	4	67	0	23	0
1982-83	5	45	0	23	23
1982-83	6	45	0	0	45
1982-83	7	67	0	67	0
1982-83	8	67	0	34	34
1982-83	9	67	0	0	67

Year	Treatment	Nitrogen applied at GS 25	GS 30	GS 45
		Kg N ha^{-1}		
1983-84	1	0	0	0
1983-84	2	90	0	0
1983-84	3	45	45	0
1983-84	4	0	90	0
1983-84	5	45	0	45
1983-84	6	0	45	45
1983-84	7	135	0	0
1983-84	8	45	90	0
1983-84	9	0	135	0
1983-84	10	45	67	23
1983-84	11	0	90	45
1983-84	12	0	45	0
1984-85	1	0	0	0
1984-85	2	0	45	0
1984-85	3	0	90	0
1984-85	4	0	135	0
1984-85	5	90	0	0
1984-85	6	135	0	0
1984-85	7	45	45	0
1984-85	8	45	0	45
1984-85	9	0	45	45
1984-85	10	45	90	0
1984-85	11	0	90	45
1984-85	12	90	45	0

Year	Treatment	Nitrogen applied at GS 25	GS 30
		---------------- Kg N ha^{-1}	----------------
1985-86	1	0	0
1985-86	2	25	0
1985-86	3	50	0
1985-86	4	100	0
1985-86	5	150	0
1985-86	6	0	50
1985-86	7	0	100
1985-86	8	0	150
1985-86	9	25	50
1985-86	10	25	100
1985-86	11	25	150
1985-86	12	50	50
1985-86	13	50	100
1985-86	14	50	150
1985-86	15	100	50
1985-86	16	100	100
1985-86	17	100	150
1985-86	18	150	50
1985-86	19	150	100
1985-86	20	150	150

Appendix B. Data from the 1981-82 Experiment

Variable	Mean	Std. Error
---------------- Treatment: 1 --------------------------		
Lodging intensity	1.00	0.00
Lodging index	1.00	0.00
Lodging area	1.00	0.00
1000 kernel weight	37.8	3.51
Kernels /head	22.8	1.72
Tillers / m^2	640	32
Kernels / m^2	14752	1721
Grain yield (Mg/ha)	5.40	0.30
harvest index	0.32	0.00
---------------- Treatment: 2 --------------------------		
Lodging intensity	4.67	2.05
Lodging index	2.33	0.60
Lodging area	1.83	0.33
1000 kernel weight	30.6	1.43
Kernels /head	24.6	0.74
Tillers / m^2	806	5
Kernels / m^2	19885	730
Grain yield (Mg/ha)	6.06	0.08
harvest index	0.31	0.01
---------------- Treatment: 3 --------------------------		
Lodging intensity	19.00	4.80
Lodging index	3.63	0.37
Lodging area	5.13	1.01
1000 kernel weight	28.3	0.82
Kernels /head	26.6	1.91
Tillers / m^2	790	58
Kernels / m^2	20763	177
Grain yield (Mg/ha)	5.87	0.13
harvest index	0.31	0.01

Variable	Mean	Std. Error
---------------- Treatment: 4 --------------------------		
Lodging intensity	1.00	0.00
Lodging index	1.00	0.00
Lodging area	1.00	0.00
1000 kernel weight	31.7	0.87
Kernels /head	26.9	0.61
Tillers / m^2	740	28
Kernels / m^2	19892	680
Grain yield (Mg/ha)	6.29	0.18
harvest index	0.34	0.00
---------------- Treatment: 5 --------------------------		
Lodging intensity	1.00	0.00
Lodging index	1.00	0.00
Lodging area	1.00	0.00
1000 kernel weight	34.4	1.27
Kernels /head	27.1	0.16
Tillers / m^2	700	47
Kernels / m^2	19044	1374
Grain yield (Mg/ha)	6.50	0.26
harvest index	0.35	0.00
---------------- Treatment: 6 --------------------------		
Lodging intensity	1.00	0.00
Lodging index	1.00	0.00
Lodging area	1.00	0.00
1000 kernel weight	35.5	1.00
Kernels /head	26.6	1.20
Tillers / m^2	677	27
Kernels / m^2	18065	1009
Grain yield (Mg/ha)	6.38	0.19
harvest index	0.35	0.02

Variable	Mean	Std. Error
---------------- Treatment: 7 -------------------------		
Lodging intensity	1.88	0.87
Lodging index	1.50	0.50
Lodging area	1.13	0.12
1000 kernel weight	34.6	2.96
Kernels /head	26.2	2.73
Tillers / m^2	732	27
Kernels / m^2	19273	2182
Grain yield (Mg/ha)	6.48	0.30
harvest index	0.36	0.01
---------------- Treatment: 8 -------------------------		
Lodging intensity	3.25	2.25
Lodging index	1.75	0.75
Lodging area	1.38	0.37
1000 kernel weight	36.43	2.40
Kernels /head	24.14	2.67
Tillers / m^2	765	37
Kernels / m^2	18259	1563
Grain yield (Mg/ha)	6.53	0.22
harvest index	0.34	0.01
---------------- Treatment: 9 -------------------------		
Lodging intensity	1.50	0.50
Lodging index	1.25	0.25
Lodging area	1.13	0.12
1000 kernel weight	32.2	0.98
Kernels /head	28.1	0.27
Tillers / m^2	743	35
Kernels / m^2	20927	1011
Grain yield (Mg/ha)	6.71	0.25
harvest index	0.36	0.00

Appendix C. Data from the 1982-83 Experiment

Variable	Mean	Std. Error
------------ Treatment: 1------------------		
Leaf DM (Mg/ha)	0.36	0.11
Stem DM (Mg/ha)	4.11	1.12
Grain DM (Mg/ha)	3.51	0.61
Total DM (Mg/ha)	7.98	1.82
Leaf N uptake (kg/ha)	1.72	0.54
Stem N uptake (kg/ha)	6.90	1.69
Grain N uptake (kg/ha)	51.46	8.60
Nitrogen uptake (kg/ha)	60.09	10.64
N% in leaves	0.47	0.01
N% in grain	1.48	0.07
N% in stems	0.17	0.01
------------ Treatment: 2 ------------------		
Leaf DM (Mg/ha)	1.03	0.11
Stem DM (Mg/ha)	8.74	0.63
Grain DM (Mg/ha)	6.46	0.23
Total DM (Mg/ha)	16.23	0.93
Leaf N uptake (kg/ha)	6.63	1.12
Stem N uptake (kg/ha)	19.48	2.85
Grain N uptake (kg/ha)	102.13	6.24
Nitrogen uptake (kg/ha)	128.24	9.52
N% in leaves	0.63	0.05
N% in grain	1.58	0.05
N% in stems	0.22	0.02
------------ Treatment: 3 ------------------		
Leaf DM (Mg/ha)	1.26	0.09
Stem DM (Mg/ha)	9.79	0.48
Grain DM (Mg/ha)	6.53	0.17
Total DM (Mg/ha)	17.57	0.46
Leaf N uptake (kg/ha)	9.98	0.97
Stem N uptake (kg/ha)	28.13	1.93
Grain N uptake (kg/ha)	116.62	4.04
Nitrogen uptake (kg/ha)	154.73	6.25
N% in leaves	0.79	0.05
N% in grain	1.79	0.04
N% in stems	0.29	0.01

Variable	Mean	Std. Error
------------ Treatment: 4 ------------------		
Leaf DM (Mg/ha)	0.96	0.12
Stem DM (Mg/ha)	9.67	1.14
Grain DM (Mg/ha)	6.48	0.17
Total DM (Mg/ha)	17.11	1.37
Leaf N uptake (kg/ha)	6.34	0.77
Stem N uptake (kg/ha)	21.37	3.22
Grain N uptake (kg/ha)	108.06	5.03
Nitrogen uptake (kg/ha)	135.76	7.82
N% in leaves	0.66	0.03
N% in grain	1.66	0.04
N% in stems	0.22	0.02
------------ Treatment: 5 ------------------		
Leaf DM (Mg/ha)	0.69	0.06
Stem DM (Mg/ha)	7.75	0.35
Grain DM (Mg/ha)	6.24	0.38
Total DM (Mg/ha)	14.68	0.76
Leaf N uptake (kg/ha)	4.39	0.72
Stem N uptake (kg/ha)	15.34	1.20
Grain N uptake (kg/ha)	110.09	7.46
Nitrogen uptake (kg/ha)	129.83	9.37
N% in leaves	0.62	0.05
N% in grain	1.76	0.02
N% in stems	0.20	0.01
------------ Treatment: 6 ------------------		
Leaf DM (Mg/ha)	0.66	0.06
Stem DM (Mg/ha)	7.30	0.59
Grain DM (Mg/ha)	6.22	0.34
Total DM (Mg/ha)	14.17	0.97
Leaf N uptake (kg/ha)	3.87	0.37
Stem N uptake (kg/ha)	14.81	1.53
Grain N uptake (kg/ha)	112.63	5.15
Nitrogen uptake (kg/ha)	131.31	6.88
N% in leaves	0.59	0.01
N% in grain	1.81	0.03
N% in stems	0.20	0.01

Variable	Mean	Std. Error
------------ Treatment: 7 ------------------		
Leaf DM (Mg/ha)	0.81	0.07
Stem DM (Mg/ha)	8.21	0.57
Grain DM (Mg/ha)	6.96	0.09
Total DM (Mg/ha)	15.99	0.71
Leaf N uptake (kg/ha)	6.33	0.62
Stem N uptake (kg/ha)	23.37	2.87
Grain N uptake (kg/ha)	141.41	2.56
Nitrogen uptake (kg/ha)	171.11	4.31
N% in leaves	0.78	0.04
N% in grain	2.03	0.05
N% in stems	0.28	0.03
------------ Treatment: 8 ------------------		
Leaf DM (Mg/ha)	0.92	0.09
Stem DM (Mg/ha)	8.70	0.73
Grain DM (Mg/ha)	6.70	0.24
Total DM (Mg/ha)	16.32	1.01
Leaf N uptake (kg/ha)	6.03	0.51
Stem N uptake (kg/ha)	20.00	1.74
Grain N uptake (kg/ha)	128.26	4.16
Nitrogen uptake (kg/ha)	154.28	5.90
N% in leaves	0.66	0.02
N% in grain	1.92	0.04
N% in stems	0.23	0.01
------------ Treatment: 9 ------------------		
Leaf DM (Mg/ha)	0.84	0.12
Stem DM (Mg/ha)	8.14	0.73
Grain DM (Mg/ha)	6.98	0.15
Total DM (Mg/ha)	15.96	0.92
Leaf N uptake (kg/ha)	5.50	1.00
Stem N uptake (kg/ha)	18.99	2.38
Grain N uptake (kg/ha)	137.61	4.27
Nitrogen uptake (kg/ha)	162.09	6.60
N% in leaves	0.64	0.04
N% in grain	1.97	0.03
N% in stems	0.23	0.01

Appendix D. Data from the 1983-84 Experiments

Variable	Mean	Std. Error
--------- Site: III, Treatment: 1 -----------		
N% at GS 30	2.74	0.06
DM at GS 30 (kg/ha)	335	115
N uptake at GS 30	9.28	3.29
N% at GS 58	1.07	0.03
N uptake at harvest (kg/ha)	35.80	5.51
DM at harvest (kg/ha)	3010	478
Grain N uptake (kg/ha)	32.24	5.45
Stem N uptake (kg/ha)	3.56	0.89
Grain yield (Mg/ha)	2.04	0.45
Tillers /m^2	501	17
1000 kernel weight	38.14	1.01
Test weight (Lb/Bu)	57.55	0.46
--------- Site: III, Treatment: 2 -----------		
N% at GS 30	4.39	0.11
DM at GS 30 (kg/ha)	913	93
N uptake at GS 30	40	4.24
N% at GS 58	1.09	0.02
N uptake at harvest (kg/ha)	84	7.14
DM at harvest (kg/ha)	8339	766
Grain N uptake (kg/ha)	77.54	4.53
Stem N uptake (kg/ha)	6.75	0.86
Grain yield (Mg/ha)	5.33	0.27
Tillers /m^2	710	37
1000 kernel weight	36.6	0.20
Test weight (Lb/Bu)	55.2	0.21
--------- Site: III, Treatment: 3 -----------		
N% at GS 30	3.50	0.13
DM at GS 30 (kg/ha)	758	142
N uptake at GS 30	26.0	4.34
N% at GS 58	1.29	0.04
N uptake at harvest (kg/ha)	93	7.34
DM at harvest (kg/ha)	9313	739
Grain N uptake (kg/ha)	83	6.09
Stem N uptake (kg/ha)	9.9	1.57
Grain yield (Mg/ha)	5.5	0.41
Tillers /m^2	745	45
1000 kernel weight	36.3	0.89
Test weight (Lb/Bu)	55.8	0.20

Variable	Mean	Std. Error
--------- Site: III, Treatment: 4 -----------		
N% at GS 30	2.83	0.06
DM at GS 30 (kg/ha)	329	62
N uptake at GS 30	9.35	1.88
N% at GS 58	1.80	0.07
N uptake at harvest (kg/ha)	93	2.28
DM at harvest (kg/ha)	8178	896
Grain N uptake (kg/ha)	86	2.96
Stem N uptake (kg/ha)	7.45	1.49
Grain yield (Mg/ha)	5.31	0.30
Tillers /m^2	751	38
1000 kernel weight	36.3	0.67
Test weight (Lb/Bu)	56.1	0.27
--------- Site: III, Treatment: 5 -----------		
N% at GS 30	3.59	0.14
DM at GS 30 (kg/ha)	725	47
N uptake at GS 30	26.1	2.38
N% at GS 58	0.97	0.03
N uptake at harvest (kg/ha)	103	9.59
DM at harvest (kg/ha)	7613	342
Grain N uptake (kg/ha)	86	8.21
Stem N uptake (kg/ha)	11.1	1.25
Grain yield (Mg/ha)	4.53	0.43
Tillers /m^2	590	26
1000 kernel weight	43.3	0.36
Test weight (Lb/Bu)	58.2	0.15
--------- Site: III, Treatment: 6 -----------		
N% at GS 30	2.73	0.06
DM at GS 30 (kg/ha)	329	92
N uptake at GS 30	9.03	2.56
N% at GS 58	1.32	0.06
N uptake at harvest (kg/ha)	97	6.51
DM at harvest (kg/ha)	6199	355
Grain N uptake (kg/ha)	91	7.26
Stem N uptake (kg/ha)	5.42	1.57
Grain yield (Mg/ha)	4.75	0.38
Tillers /m^2	569	15
1000 kernel weight	43.6	0.16
Test weight (Lb/Bu)	58.5	0.03

Variable	Mean	Std. Error
--------- Site: III, Treatment: 7 -----------		
N% at GS 30	4.82	0.07
DM at GS 30 (kg/ha)	1034	148
N uptake at GS 30	49	6.98
N% at GS 58	1.37	0.11
N uptake at harvest (kg/ha)	118	8.31
DM at harvest (kg/ha)	10571	385
Grain N uptake (kg/ha)	104	7.21
Stem N uptake (kg/ha)	13.83	1.63
Grain yield (Mg/ha)	6.32	0.29
Tillers /m^2	821	51
1000 kernel weight	33.6	0.38
Test weight (Lb/Bu)	56.1	0.78
--------- Site: III, Treatment: 8 -----------		
N% at GS 30	3.49	0.12
DM at GS 30 (kg/ha)	752	112
N uptake at GS 30	26.4	4.09
N% at GS 58	1.74	0.10
N uptake at harvest (kg/ha)	120	6.60
DM at harvest (kg/ha)	10129	1274
Grain N uptake (kg/ha)	106	5.61
Stem N uptake (kg/ha)	13.93	4.00
Grain yield (Mg/ha)	6.23	0.41
Tillers /m^2	828	48
1000 kernel weight	34.3	0.93
Test weight (Lb/Bu)	55.7	0.37
--------- Site: III, Treatment: 9 -----------		
N% at GS 30	2.78	0.04
DM at GS 30 (kg/ha)	396	80
N uptake at GS 30	11.07	2.28
N% at GS 58	2.34	0.10
N uptake at harvest (kg/ha)	126	12.95
DM at harvest (kg/ha)	9900	676
Grain N uptake (kg/ha)	111	12.32
Stem N uptake (kg/ha)	15.55	2.28
Grain yield (Mg/ha)	6.24	0.39
Tillers /m^2	894	77.94
1000 kernel weight	35.4	0.99
Test weight (Lb/Bu)	56.8	0.22

Variable	Mean	Std. Error
--------- Site: III, Treatment: 10 ----------		
N% at GS 30	3.49	0.05
DM at GS 30 (kg/ha)	752	64
N uptake at GS 30	26.22	2.13
N% at GS 58	1.66	0.11
N uptake at harvest (kg/ha)	113	7.90
DM at harvest (kg/ha)	10246	868
Grain N uptake (kg/ha)	100	6.69
Stem N uptake (kg/ha)	13.85	2.00
Grain yield (Mg/ha)	6.39	0.28
Tillers /m^2	782	50
1000 kernel weight	36.2	0.68
Test weight (Lb/Bu)	56.6	0.05
--------- Site: III, Treatment: 11 ----------		
N% at GS 30	2.96	0.07
DM at GS 30 (kg/ha)	329	73
N uptake at GS 30	9.8	2.29
N% at GS 58	1.82	0.22
N uptake at harvest (kg/ha)	144	9.98
DM at harvest (kg/ha)	10058	773
Grain N uptake (kg/ha)	129	7.59
Stem N uptake (kg/ha)	15.87	3.08
Grain yield (Mg/ha)	6.41	0.50
Tillers /m^2	865	47
1000 kernel weight	38.8	0.82
Test weight (Lb/Bu)	57.3	0.22
--------- Site: III, Treatment: 12 ----------		
N% at GS 30	2.78	0.07
DM at GS 30 (kg/ha)	322	84
N uptake at GS 30	8.88	2.21
N% at GS 58	1.32	0.06
N uptake at harvest (kg/ha)	63	7.93
DM at harvest (kg/ha)	6102	469
Grain N uptake (kg/ha)	53	6.43
Stem N uptake (kg/ha)	6.68	2.07
Grain yield (Mg/ha)	3.87	0.25
Tillers /m^2	639	24
1000 kernel weight	37.8	0.63
Test weight (Lb/Bu)	55.7	0.11

Variable	Mean	Std. Error
--------- Site: IV, Treatment: 1 --------------		
N% at GS 30	2.72	0.23
DM at GS 30 (kg/ha)	1746	29
N uptake at GS 30	47	4.57
N% at GS 58	1.15	0.06
N uptake at harvest (kg/ha)	85	4.19
DM at harvest (kg/ha)	11352	572
Grain N uptake (kg/ha)	72	4.99
Stem N uptake (kg/ha)	13.21	1.28
Grain yield (Mg/ha)	5.39	0.28
Tillers /m^2	453	27.9
1000 kernel weight	39.2	0.29
Test weight (Lb/Bu)	57.6	0.13
--------- Site: IV, Treatment: 2 --------------		
N% at GS 30	3.55	0.45
DM at GS 30 (kg/ha)	2317	58
N uptake at GS 30	81	9.43
N% at GS 58	1.56	0.09
N uptake at harvest (kg/ha)	151	4.53
DM at harvest (kg/ha)	13728	537
Grain N uptake (kg/ha)	133	2.34
Stem N uptake (kg/ha)	17.9	2.09
Grain yield (Mg/ha)	8.31	0.12
Tillers /m^2	590	16
1000 kernel weight	36.9	0.49
Test weight (Lb/Bu)	58.3	0.06
--------- Site: IV, Treatment: 3 --------------		
N% at GS 30	3.21	0.11
DM at GS 30 (kg/ha)	1974	100
N uptake at GS 30	63	3.84
N% at GS 58	1.78	0.15
N uptake at harvest (kg/ha)	166	3.93
DM at harvest (kg/ha)	16248	308
Grain N uptake (kg/ha)	141	3.95
Stem N uptake (kg/ha)	24.31	2.34
Grain yield (Mg/ha)	8.37	0.18
Tillers /m^2	584	21
1000 kernel weight	36.8	0.10
Test weight (Lb/Bu)	58.4	0.14

Variable	Mean	Std. Error
--------- Site: IV, Treatment: 4 --------------		
N% at GS 30	2.75	0.27
DM at GS 30 (kg/ha)	1779	61
N uptake at GS 30	48	4.89
N% at GS 58	1.94	0.08
N uptake at harvest (kg/ha)	166	3.64
DM at harvest (kg/ha)	16008	767
Grain N uptake (kg/ha)	142	3.27
Stem N uptake (kg/ha)	24.5	4.02
Grain yield (Mg/ha)	8.39	0.15
Tillers /m^2	576	8
1000 kernel weight	36.4	0.19
Test weight (Lb/Bu)	58.3	0.09
--------- Site: IV, Treatment: 5 --------------		
N% at GS 30	3.34	0.11
DM at GS 30 (kg/ha)	2263	79
N uptake at GS 30	75	3.47
N% at GS 58	1.22	0.05
N uptake at harvest (kg/ha)	166	3.07
DM at harvest (kg/ha)	15771	1119
Grain N uptake (kg/ha)	140	2.31
Stem N uptake (kg/ha)	25.6	3.49
Grain yield (Mg/ha)	8.2	0.06
Tillers /m^2	593	32
1000 kernel weight	41.7	0.41
Test weight (Lb/Bu)	59.7	0.09
--------- Site: IV, Treatment: 6 --------------		
N% at GS 30	2.45	0.06
DM at GS 30 (kg/ha)	1766	129
N uptake at GS 30	43	3.41
N% at GS 58	1.58	0.09
N uptake at harvest (kg/ha)	172	7.18
DM at harvest (kg/ha)	14240	1102
Grain N uptake (kg/ha)	152	4.57
Stem N uptake (kg/ha)	19.7	4.05
Grain yield (Mg/ha)	8.25	0.25
Tillers /m^2	528	19
1000 kernel weight	41.2	0.27
Test weight (Lb/Bu)	59.8	0.07

Variable	Mean	Std. Error
--------- Site: IV, Treatment: 7 -------------		
N% at GS 30	4.31	0.14
DM at GS 30 (kg/ha)	2209	59
N uptake at GS 30	95	4.03
N% at GS 58	1.85	0.13
N uptake at harvest (kg/ha)	204	4.11
DM at harvest (kg/ha)	18411	731
Grain N uptake (kg/ha)	163	2.26
Stem N uptake (kg/ha)	40.6	3.40
Grain yield (Mg/ha)	8.54	0.04
Tillers /m^2	718	24
1000 kernel weight	36.0	0.55
Test weight (Lb/Bu)	58.5	0.20
--------- Site: IV, Treatment: 8 -------------		
N% at GS 30	3.03	0.19
DM at GS 30 (kg/ha)	2155	146
N uptake at GS 30	65	6.86
N% at GS 58	2.08	0.12
N uptake at harvest (kg/ha)	196	3.48
DM at harvest (kg/ha)	17852	715
Grain N uptake (kg/ha)	165	4.60
Stem N uptake (kg/ha)	30.2	2.18
Grain yield (Mg/ha)	8.76	0.04
Tillers /m^2	627	11
1000 kernel weight	35.5	0.42
Test weight (Lb/Bu)	58.7	0.20
--------- Site: IV, Treatment: 9 -------------		
N% at GS 30	2.53	0.04
DM at GS 30 (kg/ha)	1887	158
N uptake at GS 30	47	4.00
N% at GS 58	1.98	0.07
N uptake at harvest (kg/ha)	205	5.03
DM at harvest (kg/ha)	14546	504
Grain N uptake (kg/ha)	180	4.38
Stem N uptake (kg/ha)	25.06	2.23
Grain yield (Mg/ha)	8.89	0.08
Tillers /m^2	648	33
1000 kernel weight	35.1	0.19
Test weight (Lb/Bu)	58.4	0.10

Variable	Mean	Std. Error
--------- Site: IV, Treatment: 10 --------------		
N% at GS 30	3.05	0.13
DM at GS 30 (kg/ha)	1867	172
N uptake at GS 30	56	5.70
N% at GS 58	1.99	0.10
N uptake at harvest (kg/ha)	201	5.83
DM at harvest (kg/ha)	16905	1118
Grain N uptake (kg/ha)	169	6.90
Stem N uptake (kg/ha)	31.8	3.04
Grain yield (Mg/ha)	8.64	0.25
Tillers /m^2	605	26
1000 kernel weight	37.1	0.39
Test weight (Lb/Bu)	58.9	0.23
--------- Site: IV, Treatment: 11 --------------		
N% at GS 30	2.50	0.05
DM at GS 30 (kg/ha)	1806	106
N uptake at GS 30	45	3.20
N% at GS 58	1.83	0.13
N uptake at harvest (kg/ha)	224	7.78
DM at harvest (kg/ha)	18253	830
Grain N uptake (kg/ha)	191	6.20
Stem N uptake (kg/ha)	33.4	2.63
Grain yield (Mg/ha)	8.9	0.16
Tillers /m^2	597	32
1000 kernel weight	38.6	0.73
Test weight (Lb/Bu)	59.5	0.17
--------- Site: IV, Treatment: 12 --------------		
N% at GS 30	2.40	0.10
DM at GS 30 (kg/ha)	1739	68
N uptake at GS 30	41	2.80
N% at GS 58	1.49	0.05
N uptake at harvest (kg/ha)	128	5.55
DM at harvest (kg/ha)	13735	1014
Grain N uptake (kg/ha)	111	2.68
Stem N uptake (kg/ha)	16.6	3.97
Grain yield (Mg/ha)	7.4	0.18
Tillers /m^2	480	38
1000 kernel weight	38.03	0.11
Test weight (Lb/Bu)	57.82	0.21

Appendix E. Data from the 1984-85 Experiments

Variable	Mean	Std. Error
----------- Site: V, Treatment: 1 --------------------		
DM at GS 30 (kg/ha)	2434	154
N% at GS 30	2.22	0.05
N uptake at GS 30	54	3.62
N% at GS 58	1.07	0.11
DM at GS 58 (kg/ha)	11584	629
N uptake at GS 58	123	12.36
Tillers /m^2	547	38.50
DM at harvest (kg/ha)	9001	887
Grain yield (Mg/ha)	5.98	0.29
Test weight (Lb/Bu)	57.4	0.26
1000 Kernel weight	39.9	0.50
----------- Site: V, Treatment: 2 --------------------		
DM at GS 30 (kg/ha)	2865	246
N% at GS 30	2.15	0.09
N uptake at GS 30	62	7.33
N% at GS 58	0.97	0.09
DM at GS 58 (kg/ha)	12512	627
N uptake at GS 58	119	6.35
Tillers /m^2	570	20.65
DM at harvest (kg/ha)	9512	612
Grain yield (Mg/ha)	6.37	0.48
Test weight (Lb/Bu)	57.2	0.02
1000 Kernel weight	34.4	0.38
----------- Site: V, Treatment: 3 --------------------		
DM at GS 30 (kg/ha)	2650	174
N% at GS 30	2.16	0.05
N uptake at GS 30	57	5.08
N% at GS 58	1.20	0.13
DM at GS 58 (kg/ha)	13454	666
N uptake at GS 58	163	21.75
Tillers /m^2	536	64.29
DM at harvest (kg/ha)	11181	847
Grain yield (Mg/ha)	6.78	0.45
Test weight (Lb/Bu)	57.3	0.39
1000 Kernel weight	34.4	1.48

Variable	Mean	Std. Error
------------ Site: V, Treatment: 4 --------------------		
DM at GS 30 (kg/ha)	2529	322
N% at GS 30	2.16	0.07
N uptake at GS 30	54	7.11
N% at GS 58	1.34	0.08
DM at GS 58 (kg/ha)	12217	432
N uptake at GS 58	163	8.11
Tillers /m^2	542	18.56
DM at harvest (kg/ha)	10051	470
Grain yield (Mg/ha)	6.04	0.16
Test weight (Lb/Bu)	56.0	0.25
1000 Kernel weight	30.6	0.41
------------ Site: V, Treatment: 5 --------------------		
DM at GS 30 (kg/ha)	2946	330
N% at GS 30	2.92	0.10
N uptake at GS 30	87	12.53
N% at GS 58	1.26	0.14
DM at GS 58 (kg/ha)	13401	1066
N uptake at GS 58	166	15.25
Tillers /m^2	630	39.43
DM at harvest (kg/ha)	9956	645
Grain yield (Mg/ha)	6.08	0.48
Test weight (Lb/Bu)	57.8	0.22
1000 Kernel weight	34.5	1.16
------------ Site: V, Treatment: 6 --------------------		
DM at GS 30 (kg/ha)	2932	306
N% at GS 30	3.46	0.14
N uptake at GS 30	101	12.59
N% at GS 58	1.41	0.06
DM at GS 58 (kg/ha)	12163	639
N uptake at GS 58	171	7.84
Tillers /m^2	598	36.17
DM at harvest (kg/ha)	8678	1374
Grain yield (Mg/ha)	5.64	0.28
Test weight (Lb/Bu)	56.8	0.68
1000 Kernel weight	31.2	1.51

Variable	Mean	Std. Error
------------ Site: V, Treatment: 7 --------------------		
DM at GS 30 (kg/ha)	3201	213
N% at GS 30	2.63	0.10
N uptake at GS 30	84	6.55
N% at GS 58	1.24	0.06
DM at GS 58 (kg/ha)	13279	810
N uptake at GS 58	164	8.23
Tillers /m^2	617	43.30
DM at harvest (kg/ha)	9768	532
Grain yield (Mg/ha)	6.66	0.52
Test weight (Lb/Bu)	57.6	0.37
1000 Kernel weight	34.2	1.56
------------ Site: V, Treatment: 8 --------------------		
DM at GS 30 (kg/ha)	2784	439
N% at GS 30	2.79	0.09
N uptake at GS 30	76	11.27
N% at GS 58	1.23	0.08
DM at GS 58 (kg/ha)	14033	865
N uptake at GS 58	174	20.30
Tillers /m^2	590	27.70
DM at harvest (kg/ha)	10266	654
Grain yield (Mg/ha)	6.04	0.10
Test weight (Lb/Bu)	59.1	0.22
1000 Kernel weight	37.6	0.71
------------ Site: V, Treatment: 9 --------------------		
DM at GS 30 (kg/ha)	2717	250
N% at GS 30	2.29	0.10
N uptake at GS 30	62	7.88
N% at GS 58	1.27	0.02
DM at GS 58 (kg/ha)	13064	1212
N uptake at GS 58	165	13.79
Tillers /m^2	520	19.50
DM at harvest (kg/ha)	10656	122
Grain yield (Mg/ha)	6.48	0.10
Test weight (Lb/Bu)	58.5	0.22
1000 Kernel weight	37.2	1.33

Variable	Mean	Std. Error
---------- Site: V, Treatment: 10 ----------		
DM at GS 30 (kg/ha)	2313	216
N% at GS 30	2.69	0.08
N uptake at GS 30	61	3.67
N% at GS 58	1.43	0.12
DM at GS 58 (kg/ha)	14060	1304
N uptake at GS 58	198	18.84
Tillers /m^2	602	40.76
DM at harvest (kg/ha)	11060	1058
Grain yield (Mg/ha)	6.38	0.33
Test weight (Lb/Bu)	56.8	0.59
1000 Kernel weight	32.2	1.45
---------- Site: V, Treatment: 11 ----------		
DM at GS 30 (kg/ha)	2502	307
N% at GS 30	2.14	0.08
N uptake at GS 30	53	7.60
N% at GS 58	1.36	0.08
DM at GS 58 (kg/ha)	11665	1575
N uptake at GS 58	159	24.84
Tillers /m^2	556	28.49
DM at harvest (kg/ha)	10265	288
Grain yield (Mg/ha)	6.34	0.47
Test weight (Lb/Bu)	57.4	0.12
1000 Kernel weight	34.2	0.23
---------- Site: V, Treatment: 12 ----------		
DM at GS 30 (kg/ha)	2071	473
N% at GS 30	2.92	0.10
N uptake at GS 30	59.8	12.38
N% at GS 58	1.37	0.02
DM at GS 58 (kg/ha)	14087	1095
N uptake at GS 58	192	14.07
Tillers /m^2	616	31.47
DM at harvest (kg/ha)	8853	1019
Grain yield (Mg/ha)	5.59	0.40
Test weight (Lb/Bu)	56.0	0.24
1000 Kernel weight	30.2	0.62

Variable	Mean	Std. Error
------------ Site: VI, Treatment: 1 ---------------------		
DM at GS 30 (kg/ha)	2152	179
N% at GS 30	2.07	0.07
N uptake at GS 30	44	3.28
N% at GS 58	0.85	0.07
DM at GS 58 (kg/ha)	6901	528
N uptake at GS 58	59	8.03
Grain yield (Mg/ha)	2.94	0.21
Test weight (Lb/Bu)	58	0.22
1000 Kernel weight	32.6	0.09
------------ Site: VI, Treatment: 2 ---------------------		
DM at GS 30 (kg/ha)	1735	194
N% at GS 30	2.23	0.11
N uptake at GS 30	38	4.14
N% at GS 58	0.88	0.11
DM at GS 58 (kg/ha)	8651	236
N uptake at GS 58	76	10.51
Grain yield (Mg/ha)	4.43	0.10
Test weight (Lb/Bu)	59.3	0.31
1000 Kernel weight	32.9	0.61
------------ Site: VI, Treatment: 3 ---------------------		
DM at GS 30 (kg/ha)	1628	106
N% at GS 30	2.18	0.06
N uptake at GS 30	35	3.25
N% at GS 58	1.11	0.05
DM at GS 58 (kg/ha)	10037	329
N uptake at GS 58	111	1.53
Grain yield (Mg/ha)	5.37	0.07
Test weight (Lb/Bu)	59.2	0.05
1000 Kernel weight	32.2	0.47

Variable	Mean	Std. Error
------------ Site: VI, Treatment: 4 ----------------------		
DM at GS 30 (kg/ha)	1816	158
N% at GS 30	2.06	0.05
N uptake at GS 30	37	3.97
N% at GS 58	1.31	0.14
DM at GS 58 (kg/ha)	9956	375
N uptake at GS 58	131	17.5
Grain yield (Mg/ha)	6.02	0.15
Test weight (Lb/Bu)	59.0	0.41
1000 Kernel weight	31.6	0.39
------------ Site: VI, Treatment: 5 ----------------------		
DM at GS 30 (kg/ha)	2529	335
N% at GS 30	3.04	0.05
N uptake at GS 30	77	10.88
N% at GS 58	1.09	0.06
DM at GS 58 (kg/ha)	10252	1150
N uptake at GS 58	111	12.67
Grain yield (Mg/ha)	5.04	0.08
Test weight (Lb/Bu)	57.6	0.13
1000 Kernel weight	30.7	0.37
------------ Site: VI, Treatment: 6 ----------------------		
DM at GS 30 (kg/ha)	2220	251
N% at GS 30	3.57	0.17
N uptake at GS 30	79	11.24
N% at GS 58	1.24	0.03
DM at GS 58 (kg/ha)	12337	298
N uptake at GS 58	153	6.71
Grain yield (Mg/ha)	5.37	0.08
Test weight (Lb/Bu)	56.3	0.37
1000 Kernel weight	30.1	0.40

Variable	Mean	Std. Error
------------ Site: VI, Treatment: 7 ----------------------		
DM at GS 30 (kg/ha)	2704	164
N% at GS 30	2.82	0.04
N uptake at GS 30	76	4.83
N% at GS 58	1.02	0.03
DM at GS 58 (kg/ha)	9754	442
N uptake at GS 58	99	2.99
Grain yield (Mg/ha)	5.36	0.08
Test weight (Lb/Bu)	58.4	0.14
1000 Kernel weight	30.8	0.52
------------ Site: VI, Treatment: 8 ----------------------		
DM at GS 30 (kg/ha)	2623	77
N% at GS 30	2.74	0.18
N uptake at GS 30	72	6.91
N% at GS 58	1.21	0.03
DM at GS 58 (kg/ha)	10696	355
N uptake at GS 58	128	3.88
Grain yield (Mg/ha)	4.90	0.06
Test weight (Lb/Bu)	59.3	0.18
1000 Kernel weight	35.0	0.54
------------ Site: VI, Treatment: 9 ----------------------		
DM at GS 30 (kg/ha)	2045	87
N% at GS 30	1.89	0.22
N uptake at GS 30	38	3.99
N% at GS 58	1.25	0.09
DM at GS 58 (kg/ha)	8947	310
N uptake at GS 58	111	9.35
Grain yield (Mg/ha)	4.76	0.05
Test weight (Lb/Bu)	60.5	0.45
1000 Kernel weight	35.9	0.33

Variable	Mean	Std. Error
------------ Site: VI, Treatment: 10 --------------------		
DM at GS 30 (kg/ha)	2906	200
N% at GS 30	2.80	0.07
N uptake at GS 30	81	6.89
N% at GS 58	1.26	0.11
DM at GS 58 (kg/ha)	11503	614
N uptake at GS 58	143	7.30
Grain yield (Mg/ha)	5.71	0.07
Test weight (Lb/Bu)	58.0	0.45
1000 Kernel weight	31.7	0.34
------------ Site: VI, Treatment: 11 --------------------		
DM at GS 30 (kg/ha)	1803	189
N% at GS 30	2.10	0.08
N uptake at GS 30	37	4.04
N% at GS 58	1.14	0.08
DM at GS 58 (kg/ha)	10144	612
N uptake at GS 58	115	9.57
Grain yield (Mg/ha)	5.60	0.14
Test weight (Lb/Bu)	59.3	0.42
1000 Kernel weight	33.5	0.68
------------ Site: VI, Treatment: 12 --------------------		
DM at GS 30 (kg/ha)	2085	358
N% at GS 30	3.12	0.19
N uptake at GS 30	64	9.48
N% at GS 58	1.21	0.05
DM at GS 58 (kg/ha)	11517	237
N uptake at GS 58	139	6.69
Grain yield (Mg/ha)	5.59	0.08
Test weight (Lb/Bu)	57.9	0.13
1000 Kernel weight	30.9	0.51

Appendix F. Data from the 1985-86 Experiments

Variable	Mean	Std. Error
-------------- Site: VII, Treatment: 1--------------		
N% at GS 30	1.85	0.06
DM at GS 30 (kg/ha)	1.51	0.07
N uptake at GS 30 (kg/ha)	27	1.39
Lodging index at 5/23	0.20	0.00
Lodging index at 5/27	0.20	0.00
Lodging index at 6/ 5	0.20	0.00
1000 kernel weight	40.3	0.37
Test weight (lb/Bu)	59.4	0.09
Tillers/m^2	371	31.1
Grain yield (Mg/ha)	3.62	0.26
-------------- Site: VII, Treatment: 2--------------		
N% at GS 30	2.21	0.04
DM at GS 30 (kg/ha)	2.31	0.11
N uptake at GS 30 (kg/ha)	51	1.86
Lodging index at 5/23	0.20	0.00
Lodging index at 5/27	0.20	0.00
Lodging index at 6/ 5	0.20	0.00
1000 kernel weight	40.5	0.47
Test weight (lb/Bu)	59.5	0.17
Tillers/m^2	506	43
Grain yield (Mg/ha)	5.12	0.25
-------------- Site: VII, Treatment: 3--------------		
N% at GS 30	2.55	0.10
DM at GS 30 (kg/ha)	2.34	0.37
N uptake at GS 30 (kg/ha)	59	8.12
Lodging index at 5/23	0.20	0.00
Lodging index at 5/27	0.20	0.00
Lodging index at 6/ 5	0.20	0.00
1000 kernel weight	39.9	0.22
Test weight (lb/Bu)	59.9	0.10
Tillers/m^2	499	31
Grain yield (Mg/ha)	5.78	0.19

Variable	Mean	Std. Error
-------------- Site: VII, Treatment: 4---------------		
N% at GS 30	3.12	0.05
DM at GS 30 (kg/ha)	2.68	0.12
N uptake at GS 30 (kg/ha)	83	3.99
Lodging index at 5/23	0.20	0.00
Lodging index at 5/27	0.20	0.00
Lodging index at 6/ 5	0.20	0.00
1000 kernel weight	38.3	0.75
Test weight (lb/Bu)	60.0	0.25
Tillers/m^2	637	29
Grain yield (Mg/ha)	7.03	0.45
-------------- Site: VII, Treatment: 5---------------		
N% at GS 30	3.92	0.04
DM at GS 30 (kg/ha)	2.93	0.20
N uptake at GS 30 (kg/ha)	115	8.80
Lodging index at 5/23	3.95	0.96
Lodging index at 5/27	4.34	1.13
Lodging index at 6/ 5	5.54	0.28
1000 kernel weight	36.0	1.13
Test weight (lb/Bu)	60.1	0.39
Tillers/m^2	713	50
Grain yield (Mg/ha)	7.40	0.14
-------------- Site: VII, Treatment: 6---------------		
N% at GS 30	1.90	0.06
DM at GS 30 (kg/ha)	1.71	0.21
N uptake at GS 30 (kg/ha)	32	3.16
Lodging index at 5/23	0.20	0.00
Lodging index at 5/27	0.20	0.00
Lodging index at 6/ 5	0.20	0.00
1000 kernel weight	39.3	0.49
Test weight (lb/Bu)	60.5	0.31
Tillers/m^2	.	.
Grain yield (Mg/ha)	6.00	0.25

Variable	Mean	Std. Error
	-------------- Site: VII, Treatment: 7---------------	
N% at GS 30	1.82	0.06
DM at GS 30 (kg/ha)	1.57	0.19
N uptake at GS 30 (kg/ha)	28	4.01
Lodging index at 5/23	0.20	0.00
Lodging index at 5/27	0.20	0.00
Lodging index at 6/ 5	0.20	0.00
1000 kernel weight	39.3	0.63
Test weight (lb/Bu)	61.0	0.62
Tillers/m^2	477	15
Grain yield (Mg/ha)	6.61	0.39
	-------------- Site: VII, Treatment: 8---------------	
N% at GS 30	1.85	0.05
DM at GS 30 (kg/ha)	1.63	0.16
N uptake at GS 30 (kg/ha)	30	3.13
Lodging index at 5/23	0.20	0.00
Lodging index at 5/27	0.20	0.00
Lodging index at 6/ 5	1.05	0.30
1000 kernel weight	41.2	0.80
Test weight (lb/Bu)	62.3	0.30
Tillers/m^2	495	36
Grain yield (Mg/ha)	7.61	0.29
	-------------- Site: VII, Treatment: 9---------------	
N% at GS 30	2.30	0.12
DM at GS 30 (kg/ha)	2.19	0.24
N uptake at GS 30 (kg/ha)	51	7.60
Lodging index at 5/23	0.20	0.00
Lodging index at 5/27	0.20	0.00
Lodging index at 6/ 5	0.20	0.00
1000 kernel weight	39.3	0.68
Test weight (lb/Bu)	60.5	0.30
Tillers/m^2	.	.
Grain yield (Mg/ha)	7.07	0.34

Variable	Mean	Std. Error
	------------- Site: VII, Treatment: 10---------------	
N% at GS 30	2.26	0.10
DM at GS 30 (kg/ha)	1.97	0.19
N uptake at GS 30 (kg/ha)	45	6.59
Lodging index at 5/23	0.20	0.00
Lodging index at 5/27	0.20	0.00
Lodging index at 6/ 5	0.20	0.00
1000 kernel weight	38.5	1.06
Test weight (lb/Bu)	61.0	0.55
Tillers/m^2	.	.
Grain yield (Mg/ha)	7.53	0.34
	------------- Site: VII, Treatment: 11---------------	
N% at GS 30	2.15	0.06
DM at GS 30 (kg/ha)	2.42	0.16
N uptake at GS 30 (kg/ha)	52	3.03
Lodging index at 5/23	0.20	0.00
Lodging index at 5/27	0.20	0.00
Lodging index at 6/ 5	0.85	0.28
1000 kernel weight	38.4	0.93
Test weight (lb/Bu)	61.5	0.23
Tillers/m^2	.	.
Grain yield (Mg/ha)	8.23	0.18
	------------- Site: VII, Treatment: 12---------------	
N% at GS 30	2.40	0.11
DM at GS 30 (kg/ha)	2.29	0.10
N uptake at GS 30 (kg/ha)	55	4.69
Lodging index at 5/23	0.20	0.00
Lodging index at 5/27	0.20	0.00
Lodging index at 6/ 5	0.20	0.00
1000 kernel weight	38.8	0.89
Test weight (lb/Bu)	60.2	0.30
Tillers/m^2	543	34
Grain yield (Mg/ha)	7.67	0.34

Variable	Mean	Std. Error
-------------- Site: VII, Treatment: 13---------------		
N% at GS 30	2.49	0.06
DM at GS 30 (kg/ha)	2.40	0.21
N uptake at GS 30 (kg/ha)	59	5.66
Lodging index at 5/23	0.45	0.25
Lodging index at 5/27	0.37	0.17
Lodging index at 6/ 5	1.30	0.80
1000 kernel weight	37.8	0.97
Test weight (lb/Bu)	60.9	0.38
Tillers/m^2	579	35
Grain yield (Mg/ha)	8.27	0.16
-------------- Site: VII, Treatment: 14---------------		
N% at GS 30	2.59	0.04
DM at GS 30 (kg/ha)	2.29	0.17
N uptake at GS 30 (kg/ha)	59	4.69
Lodging index at 5/23	0.35	0.15
Lodging index at 5/27	0.25	0.05
Lodging index at 6/ 5	1.60	0.28
1000 kernel weight	38.5	0.30
Test weight (lb/Bu)	61.7	0.24
Tillers/m^2	581	45
Grain yield (Mg/ha)	8.66	0.27
-------------- Site: VII, Treatment: 15---------------		
N% at GS 30	3.12	0.13
DM at GS 30 (kg/ha)	2.32	0.21
N uptake at GS 30 (kg/ha)	72	8.19
Lodging index at 5/23	0.50	0.17
Lodging index at 5/27	0.40	0.12
Lodging index at 6/ 5	1.10	0.48
1000 kernel weight	37.5	0.29
Test weight (lb/Bu)	60.8	0.11
Tillers/m^2	.	.
Grain yield (Mg/ha)	8.24	0.17

Variable	Mean	Std. Error
-------------- Site: VII, Treatment: 16---------------		
N% at GS 30	3.21	0.14
DM at GS 30 (kg/ha)	2.38	0.24
N uptake at GS 30 (kg/ha)	76	9.45
Lodging index at 5/23	3.42	0.87
Lodging index at 5/27	4.46	0.63
Lodging index at 6/ 5	4.84	0.41
1000 kernel weight	36.1	0.72
Test weight (lb/Bu)	60.1	0.33
Tillers/m^2	.	.
Grain yield (Mg/ha)	7.92	0.24
-------------- Site: VII, Treatment: 17---------------		
N% at GS 30	3.24	0.09
DM at GS 30 (kg/ha)	2.29	0.18
N uptake at GS 30 (kg/ha)	74	7.95
Lodging index at 5/23	5.62	0.55
Lodging index at 5/27	5.77	0.73
Lodging index at 6/ 5	6.30	0.41
1000 kernel weight	35.9	0.51
Test weight (lb/Bu)	60.3	0.36
Tillers/m^2	.	.
Grain yield (Mg/ha)	7.84	0.10
-------------- Site: VII, Treatment: 18---------------		
N% at GS 30	3.81	0.08
DM at GS 30 (kg/ha)	2.91	0.15
N uptake at GS 30 (kg/ha)	110	4.88
Lodging index at 5/23	6.00	0.23
Lodging index at 5/27	6.39	0.37
Lodging index at 6/ 5	6.39	0.37
1000 kernel weight	32.7	0.78
Test weight (lb/Bu)	59.2	0.30
Tillers/m^2	.	.
Grain yield (Mg/ha)	8.03	0.49

Variable	Mean	Std. Error
-------------- Site: VII, Treatment: 19---------------		
N% at GS 30	3.86	0.11
DM at GS 30 (kg/ha)	2.60	0.11
N uptake at GS 30 (kg/ha)	100	3.36
Lodging index at 5/23	6.40	0.33
Lodging index at 5/27	6.60	0.35
Lodging index at 6/ 5	6.60	0.35
1000 kernel weight	33.0	0.38
Test weight (lb/Bu)	58.9	0.49
Tillers/m^2	.	.
Grain yield (Mg/ha)	7.57	0.31
-------------- Site: VII, Treatment: 20---------------		
N% at GS 30	3.91	0.08
DM at GS 30 (kg/ha)	2.60	0.16
N uptake at GS 30 (kg/ha)	101	7.86
Lodging index at 5/23	7.00	0.20
Lodging index at 5/27	7.32	0.27
Lodging index at 6/ 5	7.32	0.27
1000 kernel weight	32.6	0.50
Test weight (lb/Bu)	58.6	0.23
Tillers/m^2	.	.
Grain yield (Mg/ha)	7.43	0.20

Variable	Mean	Std. Error
--------------- Site: VIII, Treatment: 1 ----------------		
N% at GS 30	2.07	0.03
DM at GS 30 (Mg/ha)	2.31	0.05
N uptake at GS 30 (kg/ha)	47	1.61
Grain yield (Mg/ha)	3.07	0.31
1000 kernel weight	34.6	0.50
Test weight (lb/Bu)	60.4	0.10
--------------- Site: VIII, Treatment: 2 ----------------		
N% at GS 30	2.27	0.05
DM at GS 30 (Mg/ha)	2.53	0.26
N uptake at GS 30 (kg/ha)	57	6.47
Grain yield (Mg/ha)	3.66	0.44
1000 kernel weight	35.6	1.58
Test weight (lb/Bu)	59.7	0.13
--------------- Site: VIII, Treatment: 3 ----------------		
N% at GS 30	2.38	0.09
DM at GS 30 (Mg/ha)	2.94	0.18
N uptake at GS 30 (kg/ha)	70	6.38
Grain yield (Mg/ha)	3.93	0.25
1000 kernel weight	35.3	0.51
Test weight (lb/Bu)	60.1	0.06
--------------- Site: VIII, Treatment: 4 ----------------		
N% at GS 30	3.17	0.11
DM at GS 30 (Mg/ha)	3.00	0.22
N uptake at GS 30 (kg/ha)	95	9.33
Grain yield (Mg/ha)	5.38	0.26
1000 kernel weight	36.3	0.76
Test weight (lb/Bu)	60.1	0.04

Variable	Mean	Std. Error
--------------- Site: VIII, Treatment: 5 ---------------		
N% at GS 30	3.86	0.04
DM at GS 30 (Mg/ha)	2.72	0.11
N uptake at GS 30 (kg/ha)	105	5.36
Grain yield (Mg/ha)	5.73	0.43
1000 kernel weight	34.9	1.10
Test weight (lb/Bu)	60.5	0.04
--------------- Site: VIII, Treatment: 6 ---------------		
N% at GS 30	2.21	0.10
DM at GS 30 (Mg/ha)	2.38	0.15
N uptake at GS 30 (kg/ha)	52	2.78
Grain yield (Mg/ha)	3.94	0.33
1000 kernel weight	35.4	0.72
Test weight (lb/Bu)	61.1	0.09
--------------- Site: VIII, Treatment: 7 ---------------		
N% at GS 30	1.99	0.01
DM at GS 30 (Mg/ha)	1.95	0.06
N uptake at GS 30 (kg/ha)	38	1.17
Grain yield (Mg/ha)	4.57	0.37
1000 kernel weight	35.0	1.25
Test weight (lb/Bu)	61.0	0.07
--------------- Site: VIII, Treatment: 8 ---------------		
N% at GS 30	1.98	0.12
DM at GS 30 (Mg/ha)	2.50	0.13
N uptake at GS 30 (kg/ha)	49	3.80
Grain yield (Mg/ha)	4.91	0.40
1000 kernel weight	33.8	1.23
Test weight (lb/Bu)	60.3	0.10

Variable	Mean	Std. Error
-------------- Site: VIII, Treatment: 9 ---------------		
N% at GS 30	2.33	0.03
DM at GS 30 (Mg/ha)	2.37	0.18
N uptake at GS 30 (kg/ha)	55	4.04
Grain yield (Mg/ha)	4.71	0.07
1000 kernel weight	35.9	0.88
Test weight (lb/Bu)	60.0	0.09
-------------- Site: VIII, Treatment: 10 ---------------		
N% at GS 30	2.30	0.13
DM at GS 30 (Mg/ha)	2.38	0.12
N uptake at GS 30 (kg/ha)	54	2.67
Grain yield (Mg/ha)	5.06	0.12
1000 kernel weight	35.6	0.52
Test weight (lb/Bu)	60.2	0.09
-------------- Site: VIII, Treatment: 11 ---------------		
N% at GS 30	2.46	0.12
DM at GS 30 (Mg/ha)	2.62	0.27
N uptake at GS 30 (kg/ha)	64	5.80
Grain yield (Mg/ha)	5.14	0.21
1000 kernel weight	35.4	0.87
Test weight (lb/Bu)	59.8	0.05
-------------- Site: VIII, Treatment: 12 ---------------		
N% at GS 30	2.44	0.14
DM at GS 30 (Mg/ha)	2.67	0.11
N uptake at GS 30 (kg/ha)	65	6.15
Grain yield (Mg/ha)	5.03	0.45
1000 kernel weight	35.3	0.75
Test weight (lb/Bu)	60.4	0.11

Variable	Mean	Std. Error
--------------- Site: VIII, Treatment: 13 ---------------		
N% at GS 30	2.48	0.07
DM at GS 30 (Mg/ha)	2.72	0.13
N uptake at GS 30 (kg/ha)	67	4.51
Grain yield (Mg/ha)	5.25	0.19
1000 kernel weight	34.8	0.61
Test weight (lb/Bu)	60.4	0.06
--------------- Site: VIII, Treatment: 14 ---------------		
N% at GS 30	2.58	0.07
DM at GS 30 (Mg/ha)	2.93	0.10
N uptake at GS 30 (kg/ha)	75	4.20
Grain yield (Mg/ha)	5.49	0.25
1000 kernel weight	34.9	0.69
Test weight (lb/Bu)	60.6	0.04
--------------- Site: VIII, Treatment: 15 ---------------		
N% at GS 30	3.16	0.10
DM at GS 30 (Mg/ha)	2.80	0.26
N uptake at GS 30 (kg/ha)	88	6.38
Grain yield (Mg/ha)	5.58	0.25
1000 kernel weight	34.8	0.30
Test weight (lb/Bu)	60.5	0.08
--------------- Site: VIII, Treatment: 16 ---------------		
N% at GS 30	3.26	0.21
DM at GS 30 (Mg/ha)	3.08	0.17
N uptake at GS 30 (kg/ha)	100	5.54
Grain yield (Mg/ha)	5.83	0.17
1000 kernel weight	35.4	0.93
Test weight (lb/Bu)	60.3	0.09

Variable	Mean	Std. Error
--------------- Site: VIII, Treatment: 17 ---------------		
N% at GS 30	3.39	0.05
DM at GS 30 (Mg/ha)	3.03	0.15
N uptake at GS 30 (kg/ha)	102	4.12
Grain yield (Mg/ha)	5.65	0.33
1000 kernel weight	34.3	0.39
Test weight (lb/Bu)	60.3	0.13
--------------- Site: VIII, Treatment: 18 ---------------		
N% at GS 30	3.79	0.12
DM at GS 30 (Mg/ha)	3.00	0.24
N uptake at GS 30 (kg/ha)	113	8.28
Grain yield (Mg/ha)	5.75	0.35
1000 kernel weight	34.5	0.54
Test weight (lb/Bu)	60.3	0.11
--------------- Site: VIII, Treatment: 19 ---------------		
N% at GS 30	3.26	0.33
DM at GS 30 (Mg/ha)	2.85	0.16
N uptake at GS 30 (kg/ha)	92	11.39
Grain yield (Mg/ha)	5.90	0.04
1000 kernel weight	34.1	0.23
Test weight (lb/Bu)	60.5	0.06
--------------- Site: VIII, Treatment: 20 ---------------		
N% at GS 30	3.79	0.07
DM at GS 30 (Mg/ha)	2.79	0.20
N uptake at GS 30 (kg/ha)	105	8.94
Grain yield (Mg/ha)	6.17	0.17
1000 kernel weight	34.2	0.39
Test weight (lb/Bu)	60.1	0.23

The vita has been removed from the scanned document