DISSERTATION

EFFECTS OF IRRIGATION AND NITROGEN MANAGEMENT ON WATER AND NITROGEN USE EFFICIENCY OF IRRIGATED CORN

Submitted by
Ronald E. Godin
Department of Soil and Crop Sciences

In partial fulfillment of the requirements
for the degree of Doctor of Philosophy
Colorado State University
Fort Collins, Colorado
Spring 1999

UMI Number: 9941537

COLORADO STATE UNIVERSITY

December 21, 1998

WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY RONALD E. GODIN ENTITLED **EFFECTS OF IRRIGATION AND NITROGEN MANAGEMENT ON WATER AND NITROGEN USE EFFICIENCY OF IRRIGATED CORN** BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

Committee on Graduate Work

Advisor

Co-Advisor

Department Head

ABSTRACT OF DISSERTATION

EFFECTS OF IRRIGATION AND NITROGEN MANAGEMENT ON WATER AND NITROGEN USE EFFICIENCY OF IRRIGATED CORN

The South Platte river basin of northeastern Colorado is an area of high agricultural production. Approximately 30% of the irrigated land is in corn production. Corn requires high levels of nitrogen (N) for maximum production. Recent studies have shown that incidence and levels of nitrate (NO_3) in the ground water are increasing and also that many growers over-irrigate and over-apply N fertilizer as insurance against poor yields. Nitrate is mobile in the soil environment and moves with water throughout the soil profile. Over-irrigation and/or over-fertilization may be exacerbating the NO_3-ground water problem. Many soils in the area have a high clay content that are not thought to be conducive to NO_3 leaching. Are growers benefitting from irrigation and N fertilizer applications beyond those recommended by university researchers, or are the over-applications costly to the grower and/or the environment? This study was undertaken to answer these questions. What effects, if any, do over-irrigation and over-fertilization have on corn grain yield, N loss from the cropping system from denitrification and NO_3 leaching, and do the recommended irrigation and N fertilizer applications lead to N losses and/or NO_3 leaching on these clayey soils. To evaluate these scenarios, a two-part study was conducted. In

the first part, corn was grown under a factorial combination of three irrigation and four labeled N (^{15}N) regimes in microplots. The high cost of ^{15}N prohibits field scale research. Enrichment N fertilizer with ^{15}N, a stable isotope of N, is a widely used and valuable technique in agricultural research for tracing movement of N fertilizers through the cropping system. In the second part, a field scale study was done with the same levels of irrigation and N fertilizer (unlabeled) as the ^{15}N microplot study to evaluate the field scale irrigation and N fertilizer dynamics of the cropping system on these clayey soils. It was found that the recommended N fertilizer application produces maximum grain yields without contributing to NO_3 leaching; that no benefit is derived from over-irrigation or over-fertilization; and that over-irrigation significantly reduces the water use efficiency of the crop while over-fertilization significantly increases NO_3 leaching, even on these clayey soils.

Ronald E. Godin
Department of Soil & Crop Sciences
Colorado State University
Ft. Collins, CO 80523
Spring 1999

ACKNOWLEDGMENTS

Many people deserve special thanks for assisting me with my studies and with the research to be discussed. Of special note are: Erin Pease and Jamie Annest, for excellent field and lab work; Ed Buenger, for all the assistance with the analysis of the ^{15}N plant and soil samples; the staff at ARDEC, especially Chris Fryrear and Reg Koll, for help with field preparation, planting and cultivating; Cretia Sherrod, for her patience through the lab analysis; Dr. Mark Brick, there was no deviation in his willingness to help me with stats; Dr. Grant Cardon, for his encouragement and enthusiasm; Dr. Ron Follett, for letting me be his first grad student, and for all the help and patience in leading me through my first ^{15}N study, and all the long hours of editing; Dr. Harold Duke, and Dr. Dwayne Westfall, for being terrific mentors, and for their knowledge, patience, and expert guidance throughout all of this research and my time at CSU; and finally, to Dr. Don Post, for getting me started on the "dirt" road to a Ph.D. in Agronomy, Dr. Tom Thompson for getting me interested in soil fertility, and Dr. Tom Doerge for always being willing to help, if it weren't for their enthusiasm, dedication and caring about students, this may not have come to pass.

Ron Godin
Ft. Collins, CO
December 1998

DEDICATION

To my wife
Margaret Mary Godin
my mother
Fleurette Rose Godin
my father
Aram Gaston Godin
and my sons
Gabriel Aram Godin
and
Geoffrey Conor Godin

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Appendix A

Plant and soil ^{15}N and ^{15}N budget data for 1996 and 1997.

APPENDIX B

Field study - plant and soil N and N budget data, 1996 and 1997

Chapter 1

INTRODUCTION

The South Platte river basin of northeastern Colorado is an area of high agricultural production with approximately 300 000 ha of irrigated crops. Approximately 30% of the irrigated land is in corn production to meet the needs of the numerous cattle feeding operations in the area (Hudson and Fretwell, 1997). Corn requires high levels of nitrogen (N) for maximum production. However, many growers in the area apply excess irrigation (irrigation above crop evapotranspiration (ET)) and excess fertilizer N (fertilizer N above crop N requirements) as insurance against poor yields (Emond et al. 1993). Are growers benefitting from irrigation and N fertilizer applications beyond those recommended by university researchers, or are the over-applications costly to the grower and/or the environment?

Nitrate (NO_3) is mobile in the soil environment and moves with water through the soil profile. Recent studies of the South Platte river basin indicate increasing levels and incidence of NO_3 contamination of ground water (Dubois, 1994; USGS, 1995). Over-irrigation and/or over-fertilization may be exacerbating the NO_3-ground water problem. Also, there is a growing public concern over NO_3 contamination of ground water. Therefore, it is necessary to evaluate the impact of current irrigation and N fertilizer application practices on corn production and NO_3 leaching potential.

Many soils in the area have a high clay content that is not thought to be conducive to NO_3 leaching (Smith and Cassel, 1991). Nitrate leaching on coarse textured soils is well documented (e.g. Gerwing et al. 1979; Hergert, 1986; Ritter et al. 1993; Sexton et al. 1996). However, there are few studies that evaluate NO_3 dynamics on clayey type soils, and leaching is thought to be minimal, with NO_3 losses mainly due to denitrification (Smith and Cassel, 1991; Vinten et al. 1994; Booltink, 1995).

This study was undertaken to answer the following questions: What effects, if any, do over-irrigation and over-fertilization have on corn grain yield, and N loss from the cropping system from denitrification and NO_3 leaching? Also, do the recommended irrigation and N fertilizer applications lead to N losses, especially NO_3 leaching, on these clayey soils?

To evaluate these scenarios, a two-part study was conducted in 1996 and 1997. In the first part, labeled N fertilizer was used to trace the fate of increasing levels of N fertilizer in the corn cropping system under different irrigation regimes. Enrichment of N fertilizer with ^{15}N, a stable isotope of N, is a widely used and valuable technique in agricultural research for tracing movement of N fertilizers through cropping systems. However, the high cost of ^{15}N prohibits field-scale research. Therefore, the ^{15}N part of the experiment was conducted on small-scale microplots contained within larger field-scale plots with the same irrigation and N fertilizer treatments. The use of microplots for ^{15}N studies is an accepted and widely used technique that allows for the determination of the fate of N fertilizer in the crop/soil system without incurring the prohibitive costs of field-scale ^{15}N application. The ^{15}N was applied only in 1996 and "traced" for the two years of this experiment. This was done to determine the impact of one application of N fertilizer on the corn cropping system. However, although the behavior of the N fertilizer in the ^{15}N microplots is similar to the field-scale N fertilizer behavior, it was found that the behavior of the ^{15}N fertilizer in the microplots did not exactly mirror the behavior of the unlabeled N fertilizer in the field-scale study (data not presented). The difference in response between the microplots and field-scale plots is possibly due to random variation between and within the crop/soil system, experiment error, and/or the small sampling size of the ^{15}N study imposed by the cost of the ^{15}N and plot size restrictions of the microplots. The second part of the study was conducted on field-scale plots to get a more complete picture of irrigation/N fertilizer dynamics of the corn cropping system on these clayey soils. The field-scale study was done with the same levels of irrigation and N fertilizer (unlabeled) as the ^{15}N microplot study. In both years of the study, 1996 and 1997, the irrigation treatments imposed were as follows: three target irrigation treatments of 70, 100, and 130% of evapotranspiration (ET) that correspond to deficient, recommended, and excessive irrigation, respectively. The four N fertilizer rate treatments that were imposed on this study in 1996 consisted of 0, 70, 135, and 200 kg N ha^{-1} that correspond to a check treatment, a deficient N treatment (deficient by 65 kg N ha^{-1}), the recommended N fertilizer rate, and an excessive N treatment (excessive by 65 kg N ha^{-1}). These treatments were replicated four times in a split-plot design with the irrigation treatments as the main plot factor and N fertilizer rates as the subplot factor. In 1997, the four N fertilizer rate treatments were 0, 85, 150, and 210 kg ha^{-1}.

This study was conducted at ARDEC, the Colorado State University research farm near Fort Collins, Colorado. For the ^{15}N study, ^{15}N labeled N fertilizer was applied to the microplots in 1996 and "traced" for two cropping seasons. The microplot size was 1.8 m long by 2.3 m wide and contained three rows. Unlabeled N fertilizer was applied to the microplots in 1997. This was done to mimic two years' N fertilizer application while still being able to trace the movement of the initial ^{15}N application through the two cropping seasons. Plant samples were taken at physiological maturity each season, from the middle of the center row of the three rows contained within the microplot, to determine ^{15}N fertilizer uptake by the crop. Soil samples were taken to 1.8 m in 0.3 m increments following harvest each season from either side of the center row, to determine ^{15}N fertilizer content and movement through the soil profile. The crop and soil parameters that were measured were the percent fertilizer ^{15}N recovered (%FNR), and N derived from ^{15}N fertilizer (Ndff) on a weight basis. The %FNR and Ndff were calculated for the whole plant (grain plus stover), the soil to 1.8 m, and the total (whole plant plus soil) %FNR and Ndff for each cropping season individually and for the two years of the study. The movement of Ndff in the soil profile to 1.8 m was also examined in detail. A ^{15}N budget based on ^{15}N mass balance was calculated for each year individually and for the two years of the study as a whole. From the ^{15}N budget, the unaccounted-for ^{15}N was determined and the possible pathway(s) responsible for the unaccounted-for ^{15}N, from either denitrification and/or NO_3 leaching was evaluated. A ^{15}N budget was also calculated for the soil sampling depth in two increments, from 0 to 0.9 m and from 0.9 to 1.8 m. This was done to get a more precise estimate of where denitrification and NO_3 leaching may have occurred, as the extent of the crop root zone was less than 0.9 m. Chapter two details the methods and results of this part of the experiment.

The field-scale portion of this experiment imposed the same irrigation and N fertilizer treatments as the ^{15}N study, however, unlabeled N fertilizer was used. The field-scale plots were 13.7 m long by 15.2 m wide and contained 18 rows. Plant samples were taken at the V6, V9, V12, VT, and R6 growth stages (Ritchie et al. 1993) in both years to determine crop N uptake through both growing seasons. Soil samples were taken in the field-scale plots to 1.5 m, in 0.3 m increments, prior to the initiation of the experiment and following harvest each season. Soil samples were analyzed for residual soil NO_3-N and NH_4-N content. The residual soil NO_3-N values, along with soil OM content and yield goal, were used to calculate the recommended fertilizer N application rate using a Nebraska algorithm (Hergert et al. 1995). The recommended N fertilizer application rate was 135 kg ha^{-1} in 1996, and 150 kg ha^{-1} in 1997, and were applied in one pre-plant application. The crop parameters that were determined were whole plant N uptake, dry matter (DM) production, and grain yield. Grain water use efficiency (GWUE) was calculated from the grain yield and total water received (precipitation plus irrigation) by each treatment. Available N use efficiency was calculated using grain yield and available N in the soil profile to 0.9 m. Several N budgets were also calculated for this portion of the study based on N mass balance. The N budgets were calculated for the 0 to the 1.5 m soil sampling depth and for the 0 to 0.9 m and 0.9 to 1.5 m for each year of the study. From these N budgets unaccounted-for N was determined and the possible pathway(s) responsible for the unaccounted-for N were evaluated. Chapter 3 details the methods and results of the field-scale portion of this study.

The results of the ^{15}N portion of this study found that fertilizer N rate significantly influence all crop and soil parameters examined except the Ndff in the crop root zone in 1997 that was significantly affected by irrigation treatment. The results of the field-scale portion of this study found that fertilizer N rate significantly affected most crop and soil parameters examined except GWUE that was significantly affected by the irrigation treatments.

It can be concluded from the two portions of this study that the recommended N fertilizer rate produces as high or higher grain yields than the excess fertilizer N rate without substantially contributing to NO_3 leaching under the treatments imposed; that no benefit is derived from over-application of either irrigation water or N fertilizer; and that the unaccounted-for N is largely due to denitrification, however, over-fertilization significantly increases NO_3 leaching, even on these clayey soils.

Chapter 2

FATE OF ^{15}N FERTILIZER IN IRRIGATED CORN

ABSTRACT

A large acreage (125 000 ha) of irrigated corn is grown annually in the South Platte river basin of northeastern Colorado and has high nitrogen (N) needs for maximum production. Recent studies have shown increasing levels of nitrate (NO_3) in ground water in areas of irrigated agriculture. A recent study found that most farmers in the area apply excess irrigation and N fertilizer above recommended rate as an insurance against poor yields. These factors, coupled with a growing public concern over NO_3 contamination of ground water, necessitate the evaluation of irrigation and fertilizer N requirements for irrigated corn to determine if excess applications of irrigation and fertilizer N lead to leaching of nitrates in these irrigated corn cropping management systems. Clay type soils are not thought to be as conducive to leaching as coarse textured soils. A two year irrigation and fertilizer ^{15}N rate study was undertaken to determine the effects of these factors and/or their interactions on: a) dry matter production, grain yield, and whole plant N uptake, b) fertilizer N recovery by plants and from soil from first year applied ^{15}N labeled fertilizer and from residual ^{15}N in the following year, c) unaccounted-for fertilizer ^{15}N from the cropping system, and d) fertilizer ^{15}N movement in the soil profile where measured. This

experiment should help determine whether excess irrigation and fertilizer N contribute to NO_3 impacts on ground water and if grain yields are maintained under these experimental conditions on these clayey soils. A split-plot design was used with main plot treatments consisting of three target irrigations of 70, 100, and 130% of calculated evapotranspiration (ET), and subplot treatments consisting of ^{15}N labeled fertilizer at rates of 0, 70, 135, and 200 kg N ha^{-1}, with four replications. Irrigation and fertilizer N treatments were applied to the same plots in both years on a Fort Collins clay loam soil (fine, loamy, mixed, mesic, Ustolic Haplargid), with clay subsoil. Labeled fertilizer ^{15}N was applied in 1996 and unlabeled fertilizer N was applied in 1997. The 135 kg N ha^{-1} rate was the recommended application rate as calculated from soil test results of residual soil NO_3-N and soil organic matter (OM) content and a yield goal of 11 Mg ha^{-1}. The ^{15}N fertilized microplots (2.3 m x 1.8 m) were established in 1996 and fertilized with liquid UAN ($(NH_2)_2$ CO NH_4 $^{15}NO_3$). Only the NO_3 fraction of the UAN was labeled with ^{15}N. The ^{15}N labeled fertilizer was applied in 1996 and natural abundance fertilizer N (non-labeled) was applied in 1997 at the recommended rate ± 65 kg N ha^{-1}. No significant irrigation by year or N rate by year interactions occurred for whole plant (grain plus stover) dry matter (DM) production, grain yield, or grain N uptake. There was a significant N rate by year interaction for whole plant N uptake. Irrigation treatments had no significant effect on any crop or soil parameters examined except residual ^{15}N in the soil in the 0 to 0.9 m depth following the 1997 harvest. The fertilizer N application rate significantly influenced most crop and soil parameters examined. The percent fertilizer ^{15}N

recovered (%FNR) in the whole plant ranged from 36 to 69% in 1996 and from 7 to 11% in 1997. The %FNR in the grain ranged from 16 to 52% in 1996 and from 3 to 6% in 1997. The %FNR in the soil to a depth of 1.8 m following 1996 harvest ranged from 23 to 43% and from 16 to 27% in 1997. The %FNR over the two years of the study, from aboveground plant material (1996 plus 1997) and soil (1997), ranged from 74 to 91%. No N derived from ^{15}N fertilizer (Ndff) leached below 1.5 m in either the deficient (70 kg N ha^{-1}) or recommended (135 kg N ha^{-1}) fertilizer N application rates over the two years of the study, however, 6 kg ha^{-1} Ndff leaching below the crop root zone (0.9 m) in 1996. There was Ndff leached to the 1.5 to 1.8 m depth. Fourteen kg Ndff ha^{-1} leached below the crop root zone at the excess fertilizer N application rate (200 kg N ha^{-1}) in 1996. Unaccounted-for fertilizer ^{15}N ranged from 9 to 21% in 1996 and from 9 to 26% over both years of the study. The results show that irrigation management on these clayey soils is not as critical to reducing N losses as proper fertilizer N management. Although there was a trend toward more N movement and leaching as irrigation applications increased, the increases were not statistically significant. It was found that applying recommended fertilizer N rates can significantly increase yields and reduce N leaching below the crop root zone and unaccounted-for fertilizer N compared to applying excess fertilizer N. Grain yield was significantly higher at the recommended fertilizer N application rate and averaged 13.0 Mg ha^{-1} over both years of the study. These results show that significantly higher grain yields can be achieved at the recommended fertilizer N application rate compared to the excessive fertilizer N application rate.

INTRODUCTION

The South Platte river basin of Colorado is planted to approximately 125 000 ha of irrigated corn annually, with average yields of approximately 9.5 Mg ha^{-1} (Hudson and Fretwell, 1997). Growing public concern over nitrate (NO_3) contamination of ground water in irrigated areas, along with the high N needs of irrigated corn production, necessitates an evaluation of the interactions of irrigation and fertilizer N applications on corn production and NO_3 leaching potential. Recent studies of the South Platte river basin indicate increasing levels and incidence of NO_3 contamination of ground water (Dubois, 1994; USGS, 1995). Many farmers in the area apply excess irrigation (irrigation above crop evapotranspiration (ET)) and excess fertilizer N (fertilizer N above crop N requirements) as insurance against poor yields (Emond et al. 1993). These irrigation and fertilizer N management practices may lead to NO_3 leaching to the ground water, and therefore, careful management of these resources is needed to reduce NO_3 leaching potential.

Many of these soils have high clay content and are not thought to be prone to leaching. Nitrate leaching on coarse textured soils is well documented (e.g. Gerwing et al. 1979; Hergert, 1986; Ritter et al. 1993; Sexton et al. 1996). However, there are few studies of NO_3 leaching on clayey type soils and leaching is thought to be minimal, with NO_3 losses mainly due to denitrification (Smith and Cassel, 1991; Vinten et al. 1994; Booltink, 1995). Both lysimeter and field studies of NO_3 leaching on clayey type soils, over two and three years, have shown that small amounts (< 20 kg NO_3-N ha^{-1}) of nitrates can be leached on clayey type soils when excess irrigation is applied (Bergstrom and Johansson, 1991), or when excess fertilizer N is applied (Vinten et al. 1994; Booltink, 1995), or when both excess irrigation and excess fertilizer N are applied (Porter, 1995). Porter (1995) studied NO_3 leaching under irrigated corn with irrigation by N treatments on a silty clay loam soil and recovered small amounts (< 12 kg N ha^{-1}) of labeled N from vacuum extractors at a 1.2 m depth in the third year of cropping when excess fertilizer ^{15}N (376 kg N ha^{-1}) was applied each year of the study and irrigation was 150% of crop ET. In a study in northeastern Colorado, Mosier et al. (1986) found denitrification losses to be small, about 2.5% of the 200 kg N ha^{-1} application under irrigated corn on a clay loam soil. However, the denitrification study by Mosier et al. (1986) had limited irrigation (120 mm), and all the irrigation water was applied in three applications.

Several field studies have used ^{15}N labeled fertilizer in N rate studies to determine the fertilizer N recovery by corn. Reported results of fertilizer N recoveries by corn, in two and three year studies, range from 25-80%. Various studies report N recoveries greater than 50% in the whole plant and/or greater than 40% in the grain (Kitur et al. 1984; Jokela and Randall, 1989; Liang and MacKenzie, 1994; Reddy and Reddy 1993; Jokela and Randall, 1997). Other fertilizer ^{15}N rate studies have reported applied fertilizer N recoveries in the range of 25-45% for whole plant and 13-33% in the grain (Sanchez and Blackmer, 1988; Cerrato and Blackmer, 1990; Timmons and Baker, 1991). However, all the above studies were conducted under non-irrigated conditions. Bigeriego et al. (1979) examined fertilizer ^{15}N recovery under irrigated conditions on a silty clay loam soil, however, the study looked at N timing and not at a fertilizer N application rate variable. Olson (1980) studied fertilizer ^{15}N recovery under irrigated conditions on a silty clay loam soil, however, there was no irrigation variable. Russelle, et al. (1981) studied an irrigation frequency variable and N rate on a silty clay loam soil, however, the irrigation frequency variable had a set total irrigation amount (30 cm), applied over the growing season, which was not related to crop need or ET. A few studies have been reported that vary both irrigation and N application rate on corn using ^{15}N labeled fertilizer (Reichman and Trooien, 1993; Weinhold et al. 1995). However, these two studies were carried out in the northern Great Plains with a shorter growing season, different climatic conditions, and on loamy and sandy soils.

The objectives of the study reported here were to determine the effects of irrigation and fertilizer N and/or their interactions on: a) dry matter production, grain yield, and whole plant N uptake, b) fertilizer N recovery by plants and from soil from first year applied ^{15}N-labeled fertilizer and from residual ^{15}N in the following year, c) unaccounted-for fertilizer ^{15}N from the cropping system, and d) fertilizer ^{15}N movement in the soil profile where measured. The results of this experiment should help improve irrigation and fertilizer N management for irrigated corn and determine the potential impact of excess irrigation and fertilizer N applications on NO_3 leaching on clayey soils.

MATERIALS AND METHODS

Field Study

A field study was conducted near Ft. Collins, CO in 1996 and 1997. Sprinkler irrigated corn (Northrup King var. NK3030[1]; 95-day relative maturity) was grown on a Fort Collins clay loam soil (fine, loamy, mixed, mesic, Ustolic Haplargid), with a clay subsoil. The soil profile in the 0-0.3 m depth has a clay content of 36%, and clay content increases with depth to 46% at the 1.8 m depth. A split-plot design was used with factorial combinations of three irrigation treatments as main plots and four N rates as the subplot, with four replications.

The three target irrigation treatments were 70, 100, and 130% of calculated ET, to represent deficient to excessive irrigation. An on-site weather station and the Kimberly-Penman equation were used to calculate ET for the crop (Wright, 1982). The recommended fertilizer N application rate was calculated using the Nebraska algorithm which is dependent on average concentration of residual soil NO_3-N in the 0-60 cm depth, soil organic matter (OM) content and a yield goal (Hergert et al. 1995). Residual soil NO_3-N in the 0-60 cm depth prior to planting in 1996 averaged 8.5 ± 1.5 ppm (value ± SE), the average soil OM content was 22 ± 1 g kg^{-1} in the top 30 cm of the soil profile. Based on these levels of residual soil NO_3-N and soil OM, and a yield goal of 11 Mg ha^{-1}, the

---

[1] Trade and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product by the authors, Colorado State University, or USDA.

recommended N application rate was 135 kg N ha^{-1}. The four rates of fertilizer N application were 0, 70, 135, and 200 kg N ha^{-1} in 1996, to represent deficient to excessive fertilizer N application and were applied in one preplant application. Fertilizer N application was not split because a 5-year study on an adjacent field planted to continuous corn has shown no significant yield differences using split applications compared with one preplant application of fertilizer N (Iremonger, 1998). Irrigation water supplied an additional 3 to 5 kg N ha^{-1} in 1996 and 7 to10 kg N ha^{-1} in 1997 and was not considered when calculating the recommended fertilizer N applications. The rates of N application correspond to the recommended rate, the recommended rate ± 65 kg N ha^{-1}, and a check of zero kg of applied N. The average unlabeled N application rates for 1997 were 85, 150, and 215 kg N ha^{-1}. The 150 kg N ha^{-1} rate was the recommended rate.

Residual soil NO_3-N levels prior to planting in 1996 were in the range of 7.0 to 10 ppm NO_3-N and contribute between 60 and 80 kg N ha^{-1}. Soil OM mineralization contributes from 75 to 80 kg N ha^{-1}, using a soil OM content in the range of 21 to 23 g kg^{-1} with 3.5 kg N ha^{-1} yr^{-1} mineralized per 1g kg^{-1} soil OM (Mortvedt et al. 1996). The N available from residual soil NO_3-N plus soil OM mineralization ranged from 135 to 160 kg N ha^{-1} in all plots. The average residual soil NO_3-N in 1997 was 7.0 ± 2 ppm and the soil OM content was 20 ± 2 g kg^{-1} with the available soil NO_3-N plus soil OM mineralization ranging from 95 to 140 kg N ha^{-1} in all plots. Soil bulk density ranged from 1.50 g cm^{-3} in the 0 to 0.3 m depth to 1.40 g cm^{-3} in the 1.5 to 1.8 m depth (Zhang et al. 1999).

Borderless ^{15}N microplots (Follett et al. 1991) were located within larger plots with the same irrigation applications and unlabeled N treatments. Microplots were 1.8 by 2.3 m and contained three rows. Microplots were located in the larger plots that were 13.7 m long by 15.2 m wide. The ^{15}N was applied at a 2.8 atom percent ^{15}N enrichment as UAN 32 ($(NH_2)_2CO$ NH_4 $^{15}NO_3$) in a water solution prior to planting in 1996 (note that only the NO_3 fraction was labeled). The labeled UAN solution was uniformly applied prior to planting using a constant pressure hand sprayer. No precipitation occurred between ^{15}N application and the irrigation immediately following planting. Prior to planting in 1997, microplots were individually fertilized with unlabeled UAN 32 at the recommended rate (based on residual soil NO_3-N following 1996 harvest (Hergert et al. 1995)), the recommended rate ± 65 kg N ha^{-1}, plus a check of zero kg N applied. The same irrigation and N treatment was applied to the same plots in 1997 as in 1996. The recommended phosphorus application of 90 kg P ha^{-1} was broadcast and incorporated by disking prior to N fertilization and planting in both years.

Corn (Northrup King var. NK3030) was seeded into dry soil the first week of May in both years on 0.76 m row spacing with plant populations of 63 000 plants ha^{-1} in 1996, and 74 000 plants ha^{-1} in 1997. Plant populations were calculated by averaging the plant count in 10 random samples over the entire field in an eight row by 6.6 m block. Microplots were not cultivated between seasons to prevent mixing of residual ^{15}N near the soil surface with that of the lower tillage depths and to prevent dispersing the ^{15}N beyond the microplot area.

Because microplots were not tilled between seasons, the initial planting in 1997 did not germinate and had to be replanted on May 27, 1997. Plots were irrigated immediately following planting with 15 mm of irrigation water for germination and stand establishment.

The crop was irrigated weekly when needed using a computerized linear move sprinkler system with in-canopy sprayheads. Weekly irrigation amounts were determined using an on-site weather station and a the Kimberly-Penman equation to calculate water use by the 100% ET treatment since the previous irrigation (Wright, 1982). The target irrigation treatments were 70, 100, and 130% ET in both years. However, due to high in-season precipitation in 1996 (80 mm above long-term average), final irrigation applications were 100, 120, and 140% ET in 1996 and 90, 110, and 130% of ET in 1997 (in-season precipitation was 40 mm above the long-term average) (Table 2.1). The calculated 100% ET was 550 mm and 530 mm for 1996 and 1997, respectively. Total precipitation and irrigation in 1996 and 1997 was 663 mm and 570 mm, at the 100% ET target irrigation application (Table 2.1). The three irrigation treatments were obtained by fitting the sprinkler system with different size nozzles in the sprayheads where appropriate.

^{15}N Analysis

Plants were harvested when >85% of all plants over the entire experiment were at physiological maturity, which occurred on Sept. 24,1996, and Oct 3,1997. Harvesting was done when >85% of all plants reach physiological maturity to minimize the loss of plant N due to senescence in the early maturing treatments. Observations at the time of harvest each year showed that some of the plants in the highest fertilizer N rate were not completely mature, as noted by the absence of the abscission layer on some kernels. Two plants were harvested from the middle of the center row of the three rows within ^{15}N microplots for ^{15}N analysis in 1996 and 1997. Two additional plants were harvested from the microplots to estimate grain dry weights based on the four combined plant samples taken from each microplot. Grain yield was adjusted to 15.5% moisture. Following grain dry-down and harvest in 1996, all plants were cut at ground level and removed from the ^{15}N microplots so plant ^{15}N from 1996 would not contribute to residual soil ^{15}N during the 1997 cropping season. Plants were separated into leaves, stalks, and ears, dried at 60-65 C and ground to about 100 μm size. Plants were analyzed for ^{15}N and total N using a VG 903E isotope ratio mass spectrometer (VG Isogas Ltd, Cheshire, England).

Prior to planting in 1996 and immediately following harvest each year, six 2.5 cm diameter soil cores were taken from each microplot to a depth of 1.8 m and composited in 0.3 m increments for N analysis. Soils were air dried and subsamples were ground to about 100 μm size and analyzed for ^{15}N and total N using the VG 903E isotope ratio mass spectrometer. A second set of soil subsamples were ground to pass a 2 mm sieve, extracted with 2 *M* KCl (Keeney and Nelson, 1982) and analyzed for NO_3-N and NH_4-N using a Total Flow Solution auto analyzer (Alpkem Analytical, Wilsonville, OR) with cadmium reduction of NO_3 to nitrite (NO_2) and colorimetric determination of NO_2. The NO_3-N values obtained from the KCl extraction were used to calculate the recommended fertilizer N application rates, mentioned earlier.

The following equations were used for ^{15}N calculations:

$$\% \textbf{ Ndff} = \frac{\text{atom \% } ^{15}\text{N excess in sample*}}{\text{atom \% } ^{15}\text{N excess in fertilizer}} \times 100$$ (Rennie and Paul, 1971) [1]

*atom % ^{15}N abundance values from check plots were subtracted from atom % ^{15}N abundance values from fertilized plots to arrive at atom % ^{15}N excess in samples.

Ndff = % Ndff x total kg N in sample (adapted from Rennie and Paul, 1971) [2]

where: **Ndff** = N derived from fertilizer ^{15}N on a weight basis.

$$\% \textbf{ FNR} = \frac{\text{kg ha}^{-1}\ ^{15}\text{N fertilizer in sample}}{\text{kg ha}^{-1}\ ^{15}\text{N fertilizer applied}} \times 100$$ [3]

(adapted from Liang and MacKensie, 1994)

where: **%FNR** = percent fertilizer ^{15}N recovered.

A ^{15}N budget and unaccounted-for ^{15}N fertilizer was calculated for each year individually and for the combined two years of the experiment using the following equations:

Total Ndff (for individual years) = Ndff in whole plant + Ndff in soil to 1.8 m [4]

where: **Ndff** = N derived from fertilizer ^{15}N on a weight basis.

Total %FNR (for individual years) = %FNR in whole plant + %FNR in soil to 1.8 m [5]

where: **%FNR** = percent fertilizer ^{15}N recovered.

%FNR (year of application plus residual year) = %FNR in whole plant 1996 + %FNR in whole plant 1997 + %FNR in soil to 1.8 m 1997 [6]

Ndff (year of application plus residual year) = Ndff in whole plant 1996 + Ndff in whole plant 1997 + Ndff in soil to 1.8 m 1997 [7]

% Fertilizer ^{15}N Unaccounted-for (for individual year and year of application plus residual year) = 100 - Total %FNR [8]

Ndff Unaccounted-for (for individual year and year of application plus residual year) = kg ^{15}N ha^{-1} applied - Total Ndff. [9]

Water depletion data and observations of the crop rooting depth on an adjacent field planted to continuous corn for 5 yr showed rooting depths to be < 0.9 m in all instances (Iremonger, 1998). Because crop root depth does not exceed 0.9 m, a ^{15}N budget was also calculated for the soil profile for the 1997 cropping season in two depth intervals, Ndff in the 0 to 0.9 m depth and Ndff in the 0.9 to 1.8 m depth. This approach was used to determine plant uptake of Ndff and possible leaching and/or movement from the residual Ndff during the 1997 cropping season. The following equations were used to calculate Ndff unaccounted-for in the crop root zone (0-0.9 m) and below (0.9-1.8 m):

Ndff Unaccounted-for (0 to 0.9 m) = soil Ndff 1996 (0 to 0.9 m) - whole plant Ndff 1997 - soil Ndff 1997 (0 to 0.9 m) [10]

Ndff Unaccounted-for (0.9 to 1.8 m) = soil Ndff 1996 (0.9 to 1.8 m) - soil Ndff 1997 (0.9 to 1.8 m). [11]

A simple linear regression was performed using Statistical Analysis System (SAS Institute, 1985) to determine the relationship between actual soil Ndff following harvest each year to the 1.8 m soil sampling depth and calculated soil Ndff to 1.8 m using the following equation to determine the calculated soil Ndff:

Calculated Soil Ndff (1996) = kg ^{15}N ha^{-1} applied - whole plant Ndff 1996 [12]

Calculated Soil Ndff (1997) = soil Ndff 1996 - whole plant Ndff 1997 [13]

The above regression was performed to determine the accuracy of the difference method of calculating residual soil N.

Statistical Analysis

A standard analysis of variance for a 3 x 4 x 4 (irrigation treatments x fertilizer N rate treatments x replications) split-plot design was performed on all data using Statistical Analysis Systems (SAS Institute, 1985). The analysis of variance table for the split-plot design for this experiment is shown in Table 2.2. A split-plot design was used because of restrictions imposed on the number and placement of irrigation treatments by the sprinkler system, and also, large differences were anticipated between irrigation treatments. In a split-plot design, because of the relatively low number of degrees of freedom (DF) for main plot error (a), irrigation treatments, and a relatively large number of DF for subplot error (b), N treatments (Table 2.2), compared to a randomized complete block design (Steele and Torrie, 1980), the sensitivity to main plot treatment differences is reduced, and conversely, sensitivity to subplot treatment differences is increased. The split-plot design does not allow for the detection of small differences in main plot (irrigation) treatments but does allow for the detection of small differences in subplot (fertilizer N rate) treatments (Steele and Torrie, 1980). All parameters were evaluated at $P_{value} < 0.05$ and $P_{value} < 0.01$.

RESULTS and DISCUSSION

Introduction

The irrigation treatments did not have a significant effect on any crop or soil parameter examined, except unaccounted-for ^{15}N in the 0 to 0.9 m soil depth following the 1997 harvest, and were therefore averaged over N treatments where appropriate. The irrigation treatments probably did not produce significant responses for two reasons. First, clayey soils have a high water holding capacity (Hansen et al. 1980) and are therefore less likely to show an irrigation response than sandy soils. For example, excess irrigation on a coarse textured soil could result in NO_3 movement below the crop root zone due to comparatively high saturated hydraulic conductivity, and thereby reduce crop N uptake and yield. Deficit irrigation could produce water stress in the crop and reduce yield due to low water holding capacity. In both cases, a significant irrigation response is more likely on a coarse textured soil than on a clayey soil. Second, the split-plot experimental design is not sensitive to small differences in main plot (irrigation) treatment affects where higher sensitivity may have been needed to detect irrigation treatment differences. Most of the crop and soil parameters examined were significantly affected by fertilizer N application rate.

Dry Matter Production, Yield, and N Uptake

There were no significant irrigation x year or fertilizer N rate x year interactions for whole plant (grain plus stover) DM production, grain yield, or grain N uptake. Consequently, the data for these parameters were averaged over years (Table 2.3). However, there was a significant fertilizer N rate x year interaction for whole plant N uptake and this parameter will be addressed by individual year (Table 2.3).

The whole plant DM production was significantly influenced by fertilizer N rate and ranged from 19.0 Mg ha^{-1} at the zero N application rate to 22.0 Mg ha^{-1} at the 135 kg N ha^{-1} treatment (Table 2.3). The relatively high DM production at the zero N application rate is probably due to high residual NO_3 levels and soil OM mineralization. The DM production was significantly lower at the 200 kg N ha^{-1} treatment, compared to the 135 kg N ha^{-1} treatment, but the cause is not known and is contrary to those reported in other studies. Some N rate studies on corn have found that DM production does not decrease with excess fertilizer N application, but plateaus when N application rates exceed recommended rates (e.g. Russelle et al. 1981; Hatlitligil, 1984; Porter, 1995). The significantly lower DM production at the 200 kg N ha^{-1} treatment may be due to delayed maturity from excess fertilizer N application.

The whole plant N uptake showed a significant fertilizer N rate x year interaction, therefore, each year is presented separately. The significant N rate by year interaction is due to a change in the whole plant N uptake trend from 1996 to 1997, evidenced at the 200 kg N ha^{-1} application rate (Table 2.3). The whole plant N uptake at the 200 kg N ha^{-1} application rate in 1996 is not significantly different from the 135 kg N ha^{-1} application rate, however, in 1997, the whole plant N uptake at the 200 kg N ha^{-1} application rate is significantly less than at the 135 kg N ha^{-1} application rate, hence the fertilizer N rate by year interaction. The reason for significantly less whole plant N uptake in 1997 is not known. The whole plant N uptake in 1996 was significantly influenced by fertilizer N rate with the check plots and the 70 kg N ha^{-1} fertilizer N rates taking up significantly less N in the whole plant than the two higher N application rates (Table 2.3). The whole plant N uptake in the check plots (zero kg N ha^{-1} applied) in 1996 was 180 kg N ha^{-1} from residual soil NO_3-N and soil OM mineralization. These N uptake amounts are higher than N estimated to be available from residual soil NO_3-N and soil OM mineralization that ranged from 135 to 160 kg N ha^{-1}. This is possibly due to variations in the amount of N mineralized and available from the soil OM. The whole plant N uptake at the 135 and 200 kg N ha^{-1} application rate in 1996 were not significantly different. The whole plant N uptake in 1997 was significantly influenced by fertilizer N rate, however, only the 135 kg N ha^{-1} treatment had significantly higher N uptake than the other fertilizer N treatments (Table 2.3). The check plots averaged 155 kg N ha^{-1} in the whole plant in 1997.

Grain yield, adjusted to 15.5% moisture and averaged over both years, was significantly affected by fertilizer N rate and ranged from 11.0 to 13.0 Mg ha^{-1} (Table 2.3). The 135 kg N ha^{-1} treatment yielded significantly higher than all other treatments. The higher yield may be due to application of the recommended fertilizer N rate. The lack of yield response to excess fertilizer N application may be due to delayed crop maturity.

Fertilizer ^{15}N Recovered in the Crop

The %FNR and Ndff in the whole plants are presented separately by year because whole plant %FNR and Ndff are significantly higher in the year of labeled N application (1996) than in the residual year (1997). For each parameter examined, the % FNR will be addressed first followed by Ndff for that parameter. It is useful to consider both analyses to get a comprehensive picture of fertilizer N behavior in the crop.

The %FNR in the grain in 1996 was significantly affected by fertilizer N rate and ranged from 16 to 52% (Table 2.4), with %FNR increasing with decreasing N application rate. This reciprocal response is due to less plant-available N at the lower fertilizer N application rate, and therefore, a greater percentage of the fertilizer N (^{15}N) was taken up by the plant and then translocated into the grain. The Ndff in the grain in 1996 was not significantly affected by irrigation application or fertilizer N rate and averaged 35 kg ha^{-1} (Table 2.4).

The %FNR and Ndff in the grain in 1997 were significantly affected by fertilizer N rate and ranged from 3 to 6% and from 2 to 11 kg N ha^{-1}, respectively (Table 2.4). The low recovery of labeled fertilizer N by the crop in 1997 compared to the amounts of labeled fertilizer N in the soil following 1996 harvest results from fertilizer ^{15}N immobilization into soil OM, microbial and root biomass thus it was only slowly available for plant uptake in 1997. Experiments that have reported organic-inorganic ^{15}N fractionation in the soil following corn have found that most of the ^{15}N remaining in the soil following the first cropping season was in the organic form, making it only slowly available for crop uptake in a subsequent crop (e.g. Legg et al. 1971; Allen et al. 1973; Olson, 1980).

The %FNR in the whole plant (grain plus stover) in 1996, was significantly affected by fertilizer N rate, ranging from 36 to 69% with the highest %FNR at the 70 kg N ha^{-1} application rate (Figure 2.1a). These results show that as fertilizer N rate increases, the %FNR in the crop decreases. The decrease in %FNR as fertilizer N application rate increases is due to increasing amounts of applied fertilizer ^{15}N available for uptake by the crop, and therefore, less of a percentage of the N is required by the crop. The Ndff in the whole plant for 1996 ranged from 48 to 72 kg Ndff ha^{-1} with the highest Ndff at the 200 kg N ha^{-1} rate and was significantly affected by fertilizer N rate (Figure 2.1b). As N application rate increases, there is a corresponding increase in stover uptake of Ndff, showing that excess N application results in more vegetative uptake (luxury consumption) of Ndff, but does not increase grain yield above those of the recommended rate (Figure 2.1b and Table 2.3).

The %FNR in the whole plant in 1997, was significantly influenced by fertilizer ^{15}N application rate in 1996, with the two higher N rates having significantly higher %FNR than the lowest fertilizer N rate (Figure 2.2a). The low %FNR in the whole plant in 1997 was probably due to the large portion of residual Ndff in the soil during the 1997 cropping season residing in the organic N pool. The Ndff in the whole plant in 1997 was significantly influenced by the 1996 fertilizer ^{15}N application rate and ranged from 5 to 22 kg ha^{-1} with the Ndff in the whole plant significantly increasing with fertilizer N rate (Figure 2.2b). The

Ndff in the whole plant in 1997 corresponds to an approximate uptake of from 26 to 33% of the Ndff remaining in the soil following 1996 harvest.

Fertilizer ^{15}N Recovered in the Soil

The %FNR in the soil to a 1.8 m depth following harvest in 1996 was significantly influenced by fertilizer N rate and ranged from 23 to 43%, with increasing %FNR in the soil as the fertilizer N rate increased (Figure 2.3a). The %FNR in the whole plant in 1996 decreases as fertilizer N rate increased, and conversely, the %FNR in the soil increases as fertilizer N rate increased. As the fertilizer N rate increased it is likely that fertilizer N leaching below the crop root zone (0.9 m) increased and was not available for uptake up by the crop which led to the higher %FNR in the soil. However, the fertilizer N may still be within the 1.8 m soil sampling depth (evidence for this will be presented later). The Ndff in the soil to a 1.8 m depth following 1996 harvest was significantly affected by fertilizer N rate and was 16, 48, and 86 kg Ndff ha^{-1} at the 70, 135, and 200 kg N ha^{-1} rates, respectively (Figure 2.3b).

The %FNR and Ndff in the soil to 1.8 m following harvest in 1997 were both significantly affected by fertilizer N rate and ranged from 16 to 27% of fertilizer ^{15}N applied in 1996 (Figure 2.4a) and from 11 to 54 kg ha^{-1} (Figure 2.4b). The low Ndff in the whole plant in 1997, compared to the Ndff in the soil following harvest in 1996, suggests that much of the Ndff in the soil during the 1997 season was immobile and only slowly available for crop uptake, as detailed earlier. Another factor influencing the low recovery of the residual Ndff in 1997 is that the fertilizer N application in 1997 consisted of unlabeled fertilizer. It is possible that much of the crop N needs were supplied by unlabeled fertilizer N applied in 1997. Gass et al. (1971) found that the uptake of residual fertilizer N by a succeeding corn crop is significantly reduced by the addition of fertilizer N to the soil surface. However, the leaves of the corn grown under the 70 kg N ha^{-1} application treatment were chlorotic during the 1997 growing season indicating an N deficiency, this points to immobilization as the stronger influence for the low %FNR.

The Ndff in the soil by depth following 1996 harvest was significantly influenced by fertilizer N rate (Figure 2.5a and Table 2.5). As can be seen from the graph, Ndff in the soil behaved as expected with much of the Ndff in the upper portion of the soil profile following harvest in 1996 (Figure 2.5a, and Table 2.5). However, some Ndff did leach below the crop root zone (0.9 m) at all three fertilizer N rates. At the end of the growing season in 1996, at the 70, 135, and 200 kg N ha^{-1} rates, there was 1, 6, and 14 kg Ndff ha^{-1} below the crop root zone, respectively (Table 2.5). Nitrogen leached below the crop root zone at the 200 kg N ha^{-1} application rate was probably due to excess fertilizer N application. Although not statistically significant, there was a trend toward movement of larger amounts of fertilizer N deeper into the soil profile with each increasing irrigation treatment (data not presented). The residual Ndff in the soil by depth following 1997 harvest was also significantly affected by fertilizer N rate (Figure 2.5b and Table 2.5). The graph shows a decrease in the Ndff in 1997 from 1996 in the crop root zone (0-0.9 m) due to crop uptake and/or denitrification at all three N fertilizer rates. The graph also shows movement of Ndff deeper into the soil profile at the 200 kg N ha^{-1} treatment. This is evidenced by larger amounts of Ndff from 1996 to 1997 at the 1.2 to 1.5 m depth and at the 1.5 to 1.8 m depth. Following 1996 harvest, at the 0.9 to1.2 m depth, 9 kg Ndff ha^{-1} remained in the soil, while following 1997 harvest, only 4 kg Ndff ha^{-1} remained in the soil (Table 2.5). The Ndff decrease from 9 to 4 kg ha^{-1} at 0.9 to1.2 m depth while Ndff increases from 3 to 5 kg Ndff ha^{-1} in the 1.2 to 1.5 m depth. This is evidence that there was further NO_3 leaching in 1997 at the high N application rate. At the recommended N application rate there is no change in the amount of Ndff at the 1.2-1.5 m depth from 1966 to 1997 (Table 2.5), showing that in the two years of this study the recommended fertilizer N application rate did not exhibit N leaching below 1.5 m. Although N is considered leached once it moves below the crop root zone (0.9 m), no Ndff was found below 1.5 m in either year of the study for the recommended fertilizer N rate. This suggests that in addition to supplying adequate N for crop growth, using the recommended fertilizer N rate can also reduce NO_3 leaching from the cropping system when compared to the excess fertilizer N rate in these clayey soils.

^{15}N Budget

A ^{15}N budget was calculated for each year individually, and for the two years of the experiment combined. The ^{15}N budget will be address in three steps: 1) total ^{15}N recovered (whole plants plus soil), and unaccounted-for ^{15}N in 1996, 2) total ^{15}N recovered (whole plants plus soil), and unaccounted-for ^{15}N in 1997, 3) ^{15}N recovered (whole plants plus soil) and unaccounted-for ^{15}N for the two years of the experiment combined (year of ^{15}N application plus residual year).

The total %FNR (whole plants plus soil to 1.8 m) in 1996 was significantly affected by fertilizer N rate, and ranged from 79% at the 200 kg N ha^{-1} rate to 91% at the 70 kg N ha^{-1} rate (Figure 2.6a). The significant increase of the %FNR as fertilizer N rate decreases can be attributed to a greater crop N uptake efficiency with decreasing N application. As less N was applied a greater percentage of the applied N was taken up by the crop (Figure 2.6a). The reciprocal effect was evident in the %FNR in the soil following harvest in 1996 (Figure 2.3a). As fertilizer N application rate increases, %FNR in the soil increases due to reduced crop N uptake efficiency. The total Ndff recovered (whole plant plus soil), in 1996, also shows a significant response to fertilizer N rate, as would be expected, because as more N was applied more was recovered in the whole plant and soil combined (Figure 2.6b, Table 2.6).

The percent fertilizer ^{15}N unaccounted-for in 1996 shows a significant influence of fertilizer N application rate with the percent fertilizer ^{15}N unaccounted-for increasing from 9% at the 70 kg N ha^{-1} rate to 21% at the 200 kg N ha^{-1} rate (Figure 2.7a). As the fertilizer N application rate increases more N is available to be denitrified and/or leached. This coupled with decreased crop N uptake efficiency at the higher N application rates leads to significant increases in unaccounted-for N with increased fertilizer N applications. The Ndff unaccounted-for in 1996 shows a significant increase with each succeeding increase in fertilizer N application. The highest Ndff unaccounted-for in 1996 was 42 kg N ha^{-1} at the 200 kg N ha^{-1} rate (Figure 2.7b, and Table 2.6). At the 135 kg N ha^{-1} application rate no Ndff leached below the 1.5 m depth (Table 2.5), it can therefore be assumed that the Ndff unaccounted-for of 23 kg N ha^{-1}, or 17% of the applied ^{15}N, was lost due to denitrification, which is typical on these clayey soils. In their study on irrigated corn in a clay loam soil in northeastern Colorado with 200 kg N ha^{-1} applied, Mosier et al. (1986) found denitrification losses to be 5 kg N ha^{-1} over one cropping season, or 2.5% of N applied. However, irrigation water was applied on only three occasions and totaled 120 mm. In our study, ten irrigations were applied for an average irrigation application of 385 mm in 1996. The additional irrigations, along with the clayey soil, could account for the substantially higher denitrification losses in the first year of our study.

The total %FNR (whole plants plus soil) in 1997 (residual ^{15}N fertilizer year) was significantly affected by the 1996 fertilizer ^{15}N application rate and ranged from 23 to 38% of the ^{15}N applied in 1996 (Figure 2.8a). However, in 1997, the %FNR increased with increasing fertilizer N rate, whereas in 1996 %FNR decreased with increasing fertilizer N rate. The difference in %FNR between both years is due to less of a percentage of applied fertilizer ^{15}N remaining in the soil following the 1996 harvest as fertilizer N rate decreased, and therefore, a smaller percentage of fertilizer ^{15}N was available crop uptake in 1997. The total Ndff recovered in 1997 also shows a significant influence of fertilizer N rate and ranged from 16 to 76 kg Ndff ha^{-1} with a majority of Ndff present in the soil at all N treatments (Figure 2.8b, and Table 2.6).

The % fertilizer ^{15}N unaccounted-for in 1997 was significantly affected by fertilizer N application rate and ranged from < 1% at the 70 kg N ha^{-1} rate to 5% at the 200 kg N ha^{-1} rate (Figure 2.9a). The Ndff unaccounted-for in 1997 was significantly affected by fertilizer N application rate and ranged from < 1 kg N ha^{-1} at the 70 kg N ha^{-1} rate to 10 kg N ha^{-1} at the 200 kg N ha^{-1} rate (Figure 2.9b and Table 2.6). The soil data (Table 2.5) shows that in 1997 no Ndff leached below 0.9 m at the recommended fertilizer N application rate, and therefore, the 4 kg Ndff ha^{-1} unaccounted-for at the recommended rate can be attributed to denitrification. The 10 kg N ha^{-1} Ndff unaccounted-for at the 200 kg N ha^{-1} rate is likely due to denitrification and/or leaching, however, the amount of either cannot be definitely determined.

The %FNR for the two years of the study (year of ^{15}N application plus residual year) ranged from 74% at the 200 kg N ha^{-1} rate to 91% at the 70 kg N ha^{-1} rate and was significantly influenced by fertilizer N rate (Figure 2.10a). The majority of the %FNR for the two years of the study was recovered in the whole plant in 1996, as would be expected. Over the two years of the study the %FNR in the two crops accounted for 76, 59, and 47% at the 70, 135, and 200 kg N ha^{-1} rates, respectively, with significantly higher efficiency of N uptake at the recommended rate than at the excess fertilizer N application rate. The Ndff recovered over the two years of the study (year of ^{15}N application plus residual year) was significantly affected by fertilizer N rate, with 64, 106, and 147 kg Ndff ha^{-1} recovered at the 70, 135, and 200 kg N ha^{-1} rates, respectively (Figure 2.10b). These results are similar to those found by Jokela and Randall (1997) on a clay loam soil. Generally, recovery of Ndff increases as soil clay content increases, with sandy soils recovering less Ndff (Reddy and Reddy, 1993), than clayey soils (Jokela and Randall 1997) at similar fertilizer N application rates.

The % fertilizer ^{15}N unaccounted-for and Ndff unaccounted-for over the two years of the study were significantly affected by fertilizer N rate and increased significantly with increasing fertilizer N application (Figure 2.11a and 2.11b). The % fertilizer ^{15}N unaccounted-for and Ndff unaccounted-for over the two years of the study ranged from 9 to 26% and 6 to 52 kg Ndff ha^{-1} at the 70 and 200 kg N ha^{-1} rate, respectively. The Ndff unaccounted-for at the 70 and 135 kg N ha^{-1} rates can largely be attributed to denitrification, however, at the 200 kg N ha^{-1} rate the Ndff unaccounted-for is likely the result of both denitrification and leaching below the sampling depth, as discussed earlier. This illustrates that as fertilizer N application rate exceeds the recommended rate unaccounted-for Ndff increases significantly.

In order to better understand the N dynamics of the residual soil N in the crop root zone and deeper soil depths, a ^{15}N budget was calculated from Ndff in the soil following harvest in 1996 and Ndff in the soil following harvest in 1997, in two increments (Table 2.7). A ^{15}N budget was calculated for the 0 - 0.9 m depth (crop root zone), and the 0.9 - 1.8 m depth. The Ndff unaccounted-for in

1997 for the 0 to 0.9 m depth was significantly influence by irrigation treatment with 0, 4, and 7 kg Ndff ha^{-1} unaccounted for at the 90, 110, and 130% ET irrigation treatments, respectively (Table 2.7). It appears from the data that the Ndff unaccounted-for in the 0 to 0.9 m depth at the 70 and 135 kg N ha^{-1} application rates is due to denitrification because the Ndff lost in the upper portion of the soil profile (0 to 0.9 m) is not detected in the lower portion of the soil profile (0.9 to 18 m) (Table 2.5). The mechanism responsible for the Ndff unaccounted-for at the 200 kg N ha^{-1} application rate is Ndff leaching below the 1.8 m soil sampling depth, assuming that no capillary rise of Ndff occurred from below 0.9 m to above 0.9 m. The unaccounted-for Ndff in 1997 for the 0.9 to 1.8 m depth was not significantly influence by either irrigation treatment or fertilizer N application rate and averaged 2 kg ha^{-1} over all treatments (Table 2.7). These results indicate that leaching from residual Ndff in the crop root zone to below the crop root zone did not occur at the 70 and 135 kg N ha^{-1} application rate, however, at the 200 kg N ha^{-1} application rate, leaching did occur. These results are similar to those reported by Jokela and Randall (1997) for a clay loam soil.

A regression was calculated using the actual Ndff in the soil to a 1.8 m depth at the end of each year of the study versus the calculated Ndff (^{15}N applied - whole plant Ndff in 1996 - whole plant Ndff in 1997) in the soil to determine the relationship between the two factors. When regressing the actual Ndff in the soil with the Ndff calculated to be in the soil following each year the results are two first order linear functions (Figure 2.12a and 2.12b).

In 1996, the regression equation is:

$y = 0.7x + 2.5$, $R^2 = 0.97$ (Figure 2.12a).

The regression equation shows an overestimating of the calculated soil Ndff compared to the actual soil Ndff. This overestimating is due to denitrification and/or leaching below the 1.8 m soil sampling depth. The three groupings of data points correspond to the three fertilizer N application rates. The regression also reinforces the idea that unaccounted-for N increases as N application rates increase. Since it was determined that no leaching of Ndff occurred below the 1.5 m soil sampling depth at the 70 and 135 kg N ha^{-1} rates (Figure 2.5 and Table 2.5), it can be assumed that the overestimating of the calculated soil Ndff over the actual soil Ndff is due to denitrification at these two N application rates.

In 1997, the regression equation is:

$y = 0.8x + 2.6$, $R^2 = 0.89$ (Figure 2.12b).

Since it was determined that no Ndff leached below the 1.8 m soil sampling depth for the 70 and 135 kg N ha^{-1} application rates in 1997 (Figure 2.5 and Table 2.5), it can be assumed that the overestimating at these two N treatments in 1997 is also due to denitrification. The three fertilizer N application rates are less well defined for the 1997 data due to a second year of influence from rainfall and variability.

CONCLUSIONS

The results of this research have significance for both the agronomic and environmental factors of N fertilizer management. Agronomically, excess fertilizer N applications significantly reduced DM production and grain yield compared to the recommended fertilizer N rate. Environmentally, excess fertilizer N significantly increased denitrification and NO_3 leaching on these clayey soils, both of which could have long-term detrimental effects on the environment. Careful fertilizer N management is imperative if trends in ground water NO_3 content are to be reversed to improve ground water quality. The results show that the recommended fertilizer N rate (135 kg N ha^{-1}) adequately satisfies the crop N requirements resulting in high yields and higher percent recoveries of applied N fertilizer compared to the excess fertilizer N rate (200 kg N ha^{-1}).

Following the first cropping season after ^{15}N application, in 1996, 1 and 6 kg N ha^{-1}, of fertilizer ^{15}N were found to have leached below the crop root zone (0.9 m) at the 70 and 135 kg N ha^{-1} rates, respectively. However, the ^{15}N leached below the crop root zone in 1996 at these two fertilizer N application rates did not leach further in the subsequent cropping season (1997). At the excess fertilizer N rate (200 kg N ha^{-1}) there was leaching of 14 kg N ha^{-1} below the crop root zone in 1996 and evidence of further leaching in the subsequent cropping season but exact quantification was not possible. The mechanism responsible for the leaching through these clayey soil is not known, however, the

NO_3 leaching is probably due to NO_3 movement through root channels, and/or "bypass flow," the movement of soil solution containing NO_3 through large pores between soil ped faces that bypass the unsaturated soil matrix in clayey soils (Booltink, 1995). The implication is that, regardless of mechanism, over-application of fertilizer N contributes to substantial leaching of NO_3 below the crop root zone. Over time, the NO_3 leached below the crop root zone may contribute to increases in groundwater NO_3 content. Apply the recommended fertilizer N rate should reduce the NO_3 leaching potential.

These clayey soils are conducive to denitrification under irrigated conditions. The unaccounted-for fertilizer ^{15}N in the initial year of the study at the recommended N rate was 23 kg ha^{-1}, with the data indicating that all was denitrified. At the excess N rate the unaccounted-for fertilizer ^{15}N nearly doubled, most of which is likely due to denitrification. Growers who over-fertilize are losing approximately one third of their over-application in the first year alone. Over time, growers who continually over-fertilize are probably recovering little of their investment while significantly increasing the potential fro environmental degradation. Economic considerations aside, split applications of fertilizer N should be considered as a means of lowering denitrification and leaching. Reducing the amount of N available for denitrification and leaching at any one time by splitting N applications, provided the crop has sufficient N, should help reduce these losses even on these clayey soils.

In order to reduce N losses due to denitrification and leaching growers should soil test yearly for residual soil NO_3-N to more accurately fertilize their crop without over-fertilizing. Growers should also monitor crop ET reports to apply irrigation as closely as possible to actual crop ET thereby reducing the potential for N loss.

Table 2.1. Target irrigation applications, irrigation, precipitation and final irrigation applications,1996, and 1997.

1996

Target Irrigation Application	Irrigation	Precipitation	Total	Final Irrigation Application*
% ET		mm		% Calculated ET
70	270	280	550	100
100	385	280	665	120
130	500	280	780	140

* Calculated 100% ET 1996 = 550 mm

1997

Target Irrigation Application	Irrigation	Precipitation	Total	Final Irrigation Application*
% ET		mm		% Calculated ET
70	230	240	470	90
100	330	240	570	110
130	430	240	670	130

* Calculated 100% ET 1997 = 530 mm

Table 2.2. Analysis of variance table for split-plot design showing source of variance and degrees of freedom.

Source of Variance	Degrees of Freedom
Replications	3
Main Plot (A)	
Irrigation Treatments	2
Error (a)	6
Subplot (B)	
N Treatment	3
Irrigation x N	6
Error (b)	27
Total	47

Table 2.3. Whole plant (grain + stover) DM production and N uptake, grain yield and grain N uptake for 1996, and 1997.

N Treatment	Whole Plant DM Prod. 1996-97	Whole Plant N Uptake 1996	Whole Plant N Uptake 1997	Grain Yield 1996-97†	Grain N Uptake 1996-97
kg N ha^{-1}	Mg ha^{-1}	—— kg ha^{-1}	——	Mg ha^{-1}	kg ha^{-1}
0	19.0	180	155	11.5	120
70	20.0	175	180	11.5	120
135	22.0	200	215	13.0	145
200	20.0	205	180	11.0	130
Statistics					
Irrigation	NS	NS	NS	NS	NS
N Rate	**	**	**	**	**
Year	NS	NS	NS	NS	NS
Irrigation x Year	NS	NS	NS	NS	NS
N Rate x Year	NS	**	**	NS	NS
Irrigation x N rate	NS	NS	NS	NS	NS
Irrig. x N Rate x Year	NS	NS	NS	NS	NS
$LSD_{.05}$	1.5	15††	30††	1.0	15

† Grain yield adjusted to15.5% moisture.

†† $LSD_{.05}$ for N Rate; $LSD_{.05}$ for N Rate by Year interaction = 16.

*, **, NS, significant at 0.05, 0.01, not significant, respectively.

Table 2.4. Percent fertilizer ^{15}N recovered (%FNR) and nitrogen derived from fertilizer (Ndff) in grain in 1996 and 1997.

N Treatment	% FNR Grain 1996	Ndff Grain 1996	%FNR Grain 1997	Ndff Grain 1997
kg N ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}
70	52		3	2
135	28	35†	6	8
200	16		5	11
Statistics				
Irrigation	NS	NS	NS	NS
N rate	**	NS	*	**
Irrigation x N	NS	NS	NS	NS
$LSD_{.05}$	2		2	3

*, **, NS, significant at 0.05, 0.01, not significant, respectively.
† averaged over all treatments.

Table 2.5. Nitrogen derived from fertilizer (Ndff) in the soil by depth in 1996 and 1997.

	1996			1997		
	N Treatment kg N ha^{-1}					
	70	135	200	70	135	200
Depth (m)	kg N ha^{-1}					
0-0.3	9	22	29	6	15	18
0.3-0.6	4	13	26	3	7	15
0.6-0.9	2	7	17	1	4	9
0.9-1.2	1	5	9	1	1	4
1.2-1.5	0	1	3	0	1	5
1.5-1.8	0	0	2	0	0	3
Total	16	48	86	11	28	54

Table 2.6. The ^{15}N budget showing nitrogen derived from fertilizer in the whole plant, soil to 1.8 m, and unaccounted-for N, in 1996 and 1997.

N Treatment	Ndff Whole Plant 1996	Ndff Soil 0-1.8 m 1996	Ndff Unaccounted for 1996	Ndff Whole Plant 1997	Ndff Soil 0-1.8 m 1997	Ndff Unaccounted for 1997
kg N ha^{-1}	——— kg ha^{-1} ———					
70	48	16	6	5	11	0
135	64	48	23	16	28	4
200	72	86	42	22	54	10
<u>Statistics</u>						
Irrigation	NS	NS	NS	NS	NS	NS
N rate	**	**	*	**	**	*
Irrigation x N	NS	NS	NS	NS	NS	NS
$LSD_{.05}$	6	5	5	4	5	7

*, **, NS, significant at 0.05, 0.01, not significant, respectively.

Table 2.7. The ^{15}N budget in 1997 showing nitrogen derived from fertilizer (Ndff) in soil from 0 - 0.9 m and from 0.9 - 1.8 m depths, whole plant Ndff, and unaccounted-for Ndff.

N Treatment	Ndff Soil 1996 0 - 0.9 m	Ndff Soil 1996 0.9 - 1.8 m	Ndff Whole Plant 1997	Ndff Soil 1997 0 - 0.9 m	Ndff Soil 1997 0.9 - 1.8 m	Ndff Unaccounted for 1997 0 - 0.9 m	Ndff Unaccounted for 1997 0.9 - 1.8 m
kg N ha^{-1}	kg ha^{-1}						
70	15	1	5	10	1	(W1)† 0	
135	42	6	16	26	2	(W2) 4	2††
200	72	14	22	42	12	(W3) 7	
<u>Statistics</u>							
Irrigation	NS	NS	NS	NS	NS	**	NS
N rate	**	**	*	**	**	NS	NS
Irrigation x N	NS	NS	NS	NS	NS	NS	NS
$LSD_{.05}$	5	4	4	6	4	6	

*, **, NS, significant at 0.05, 0.01, not significant, respectively.
† irrigation applications W1, W2, and W3 = 90, 110, and 130% ET in 1997, respectively.
†† averaged over all treatments.

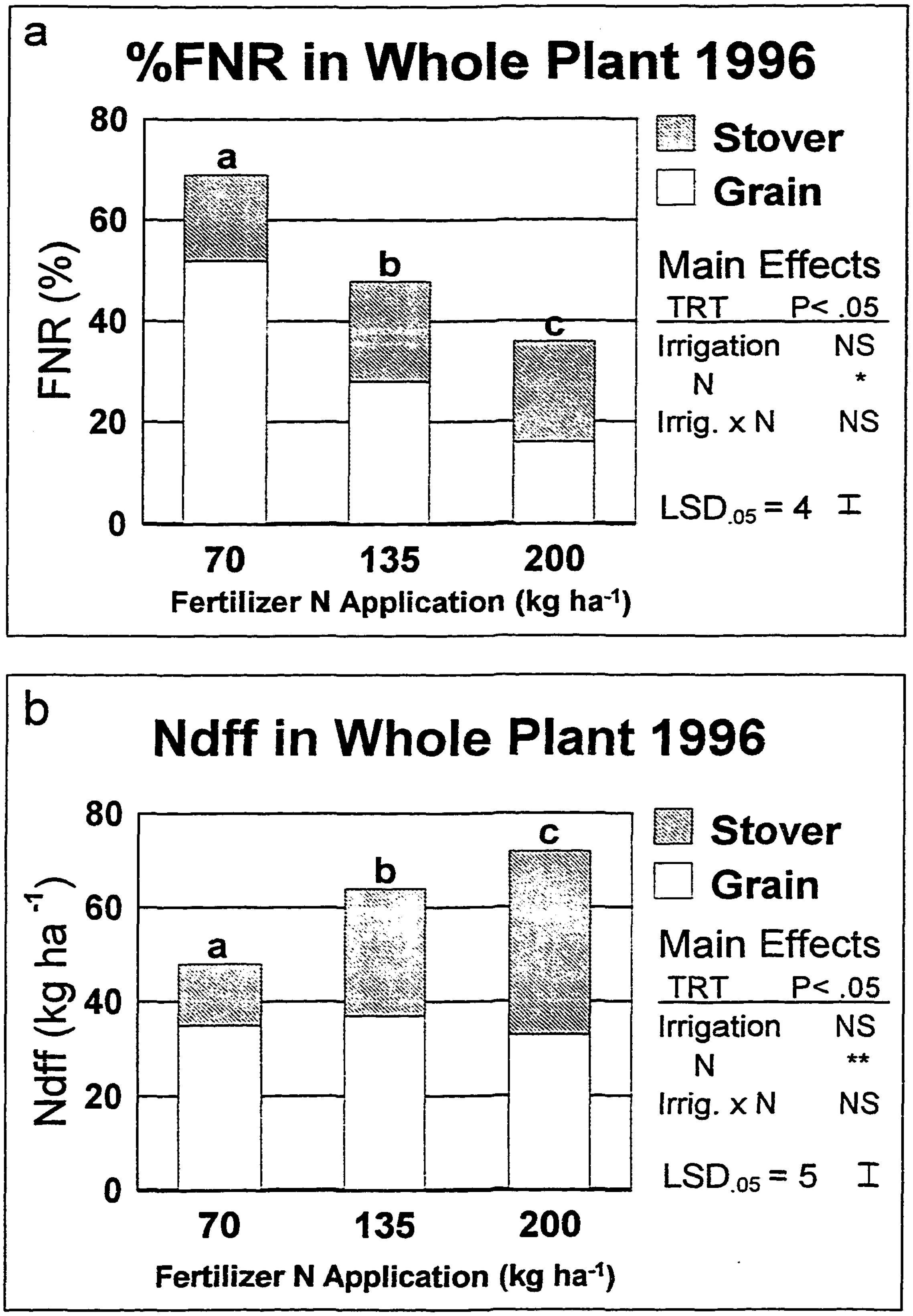


Figure 2.1. Percent fertilizer ^{15}N recovered (%FNR) and nitrogen derived from ^{15}N fertilizer (Ndff) in whole plant in 1996.

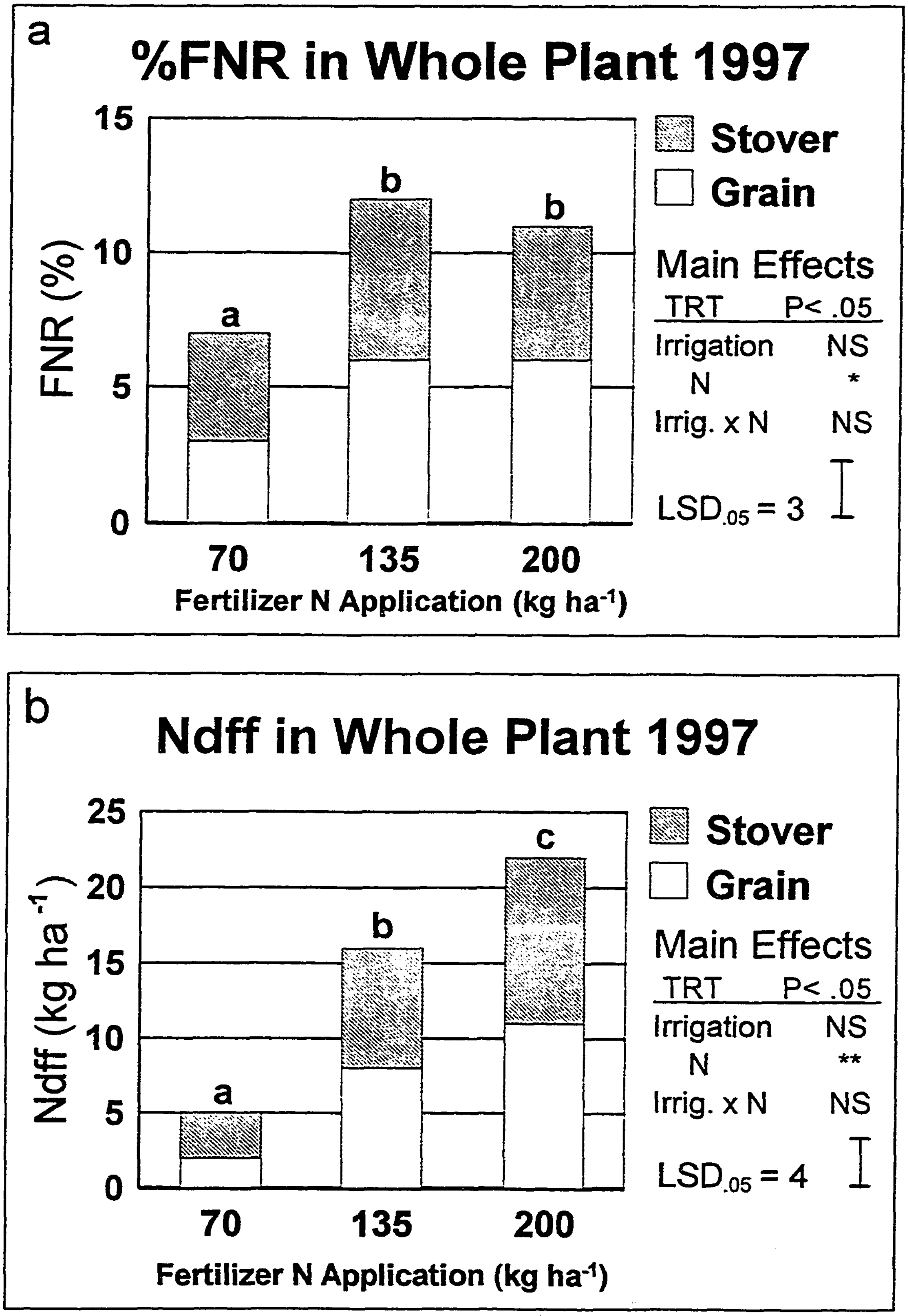


Figure 2.2. Percent fertilizer ^{15}N recovered (%FNR) and nitrogen derived from ^{15}N fertilizer (Ndff) in whole plant in 1997.

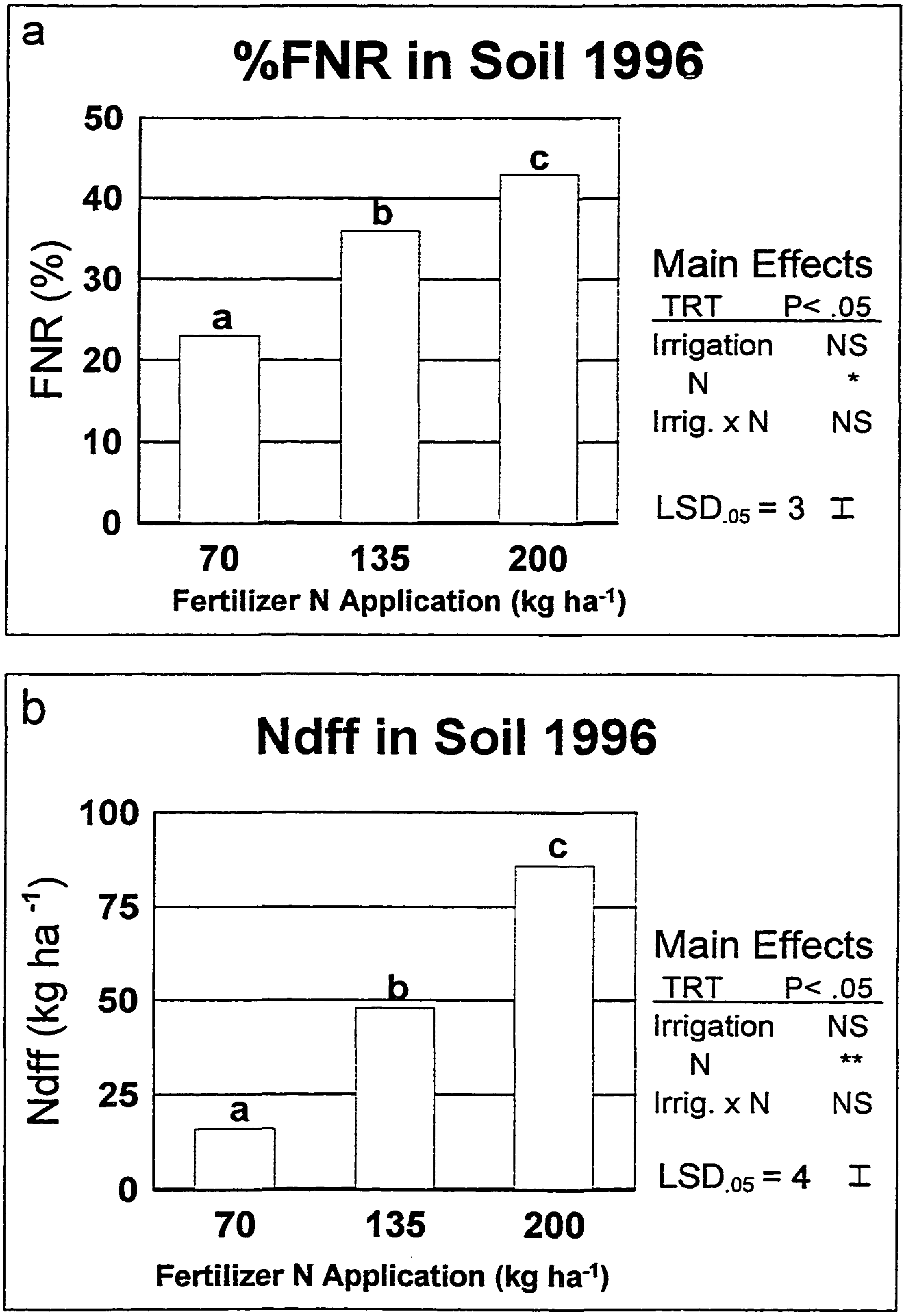
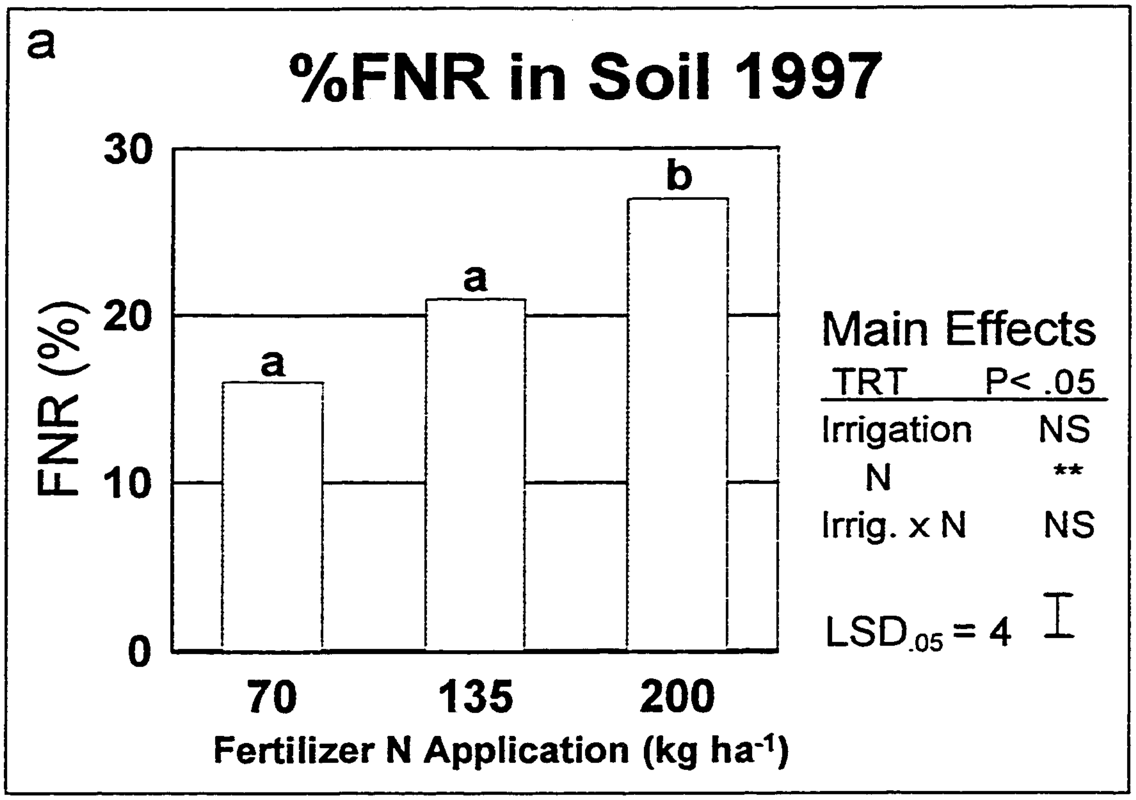


Figure 2.3. Percent fertilizer ^{15}N recovered (%FNR) and nitrogen derived from ^{15}N fertilizer (Ndff) in the soil to 1.8 m in 1996.



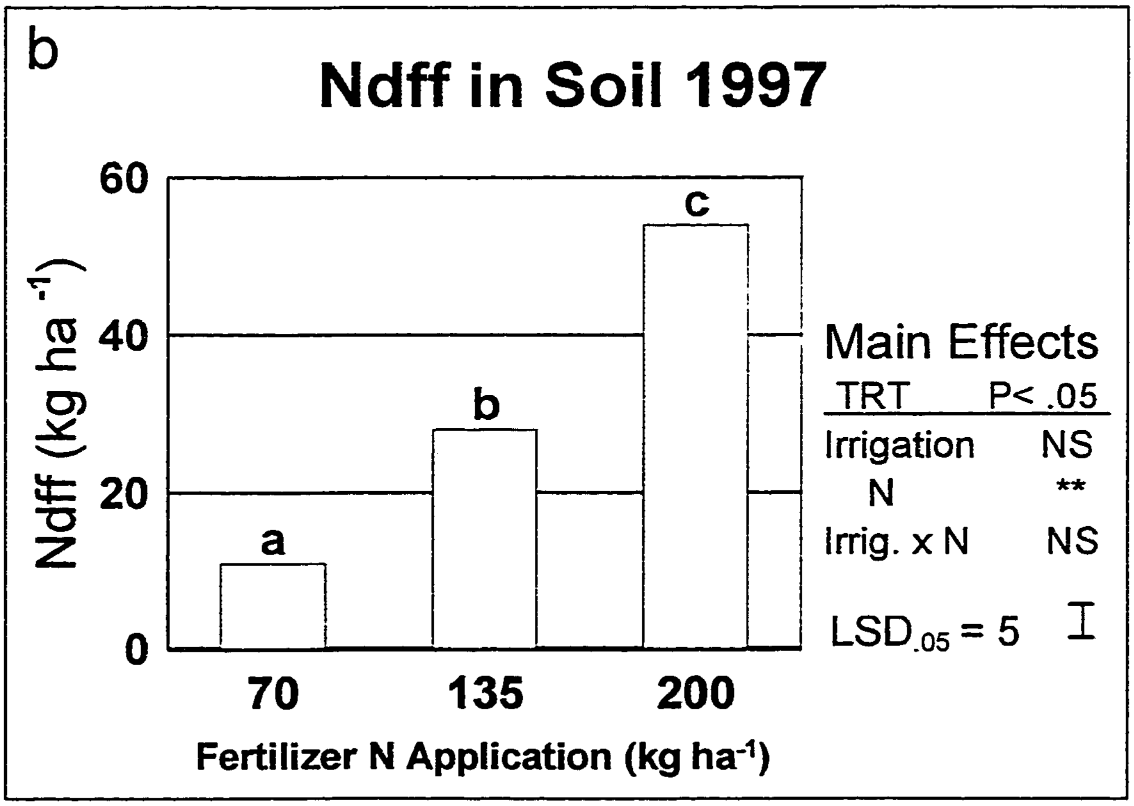


Figure 2.4. Percent fertilizer ^{15}N recovered (%FNR) and nitrogen derived from ^{15}N fertilizer (Ndff) in the soil to 1.8 m in 1997.

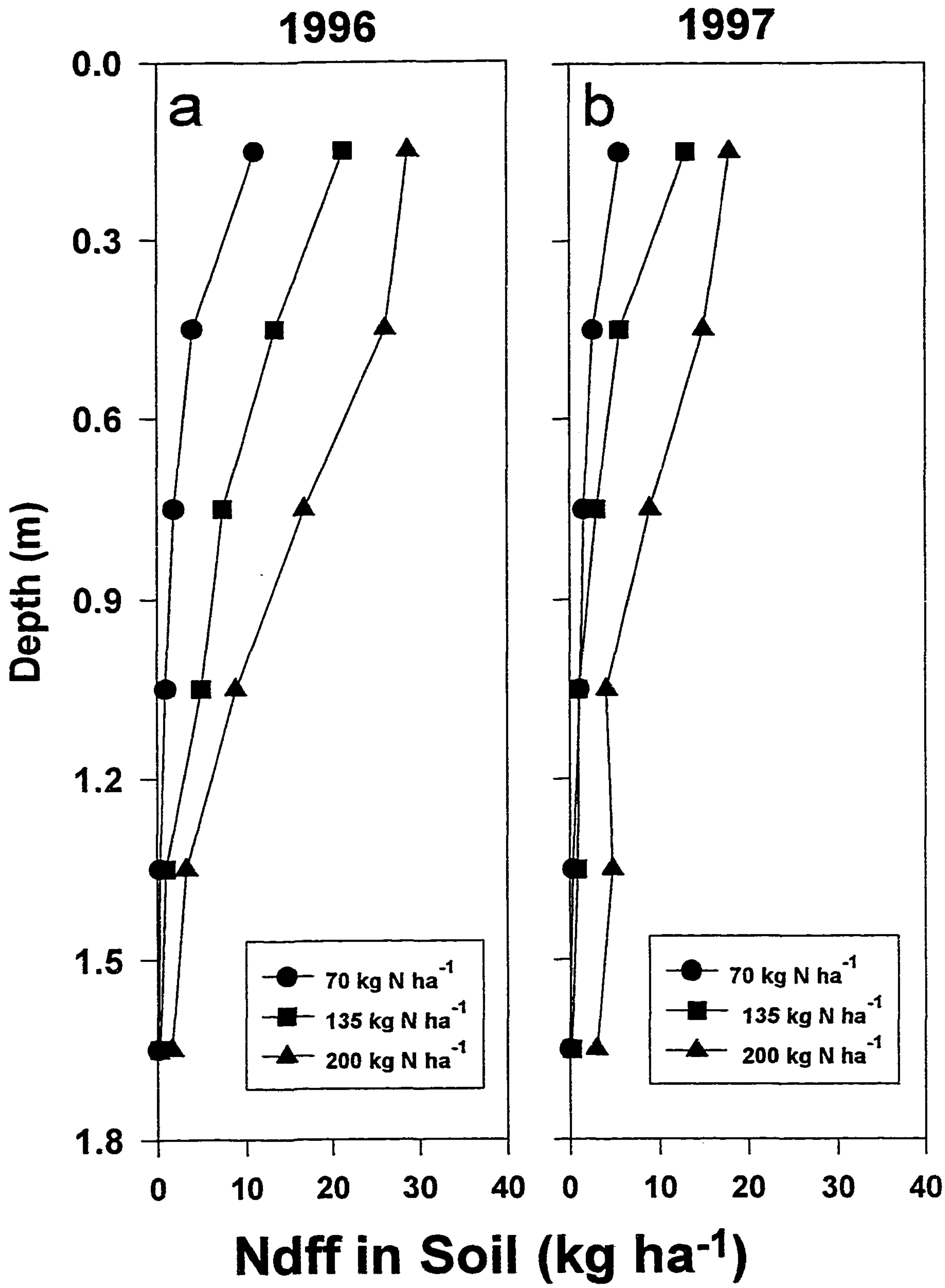


Figure 2.5. Nitrogen derived from ^{15}N fertilizer (Ndff) in soil to 1.8 m after harvest in 1996 and 1997.

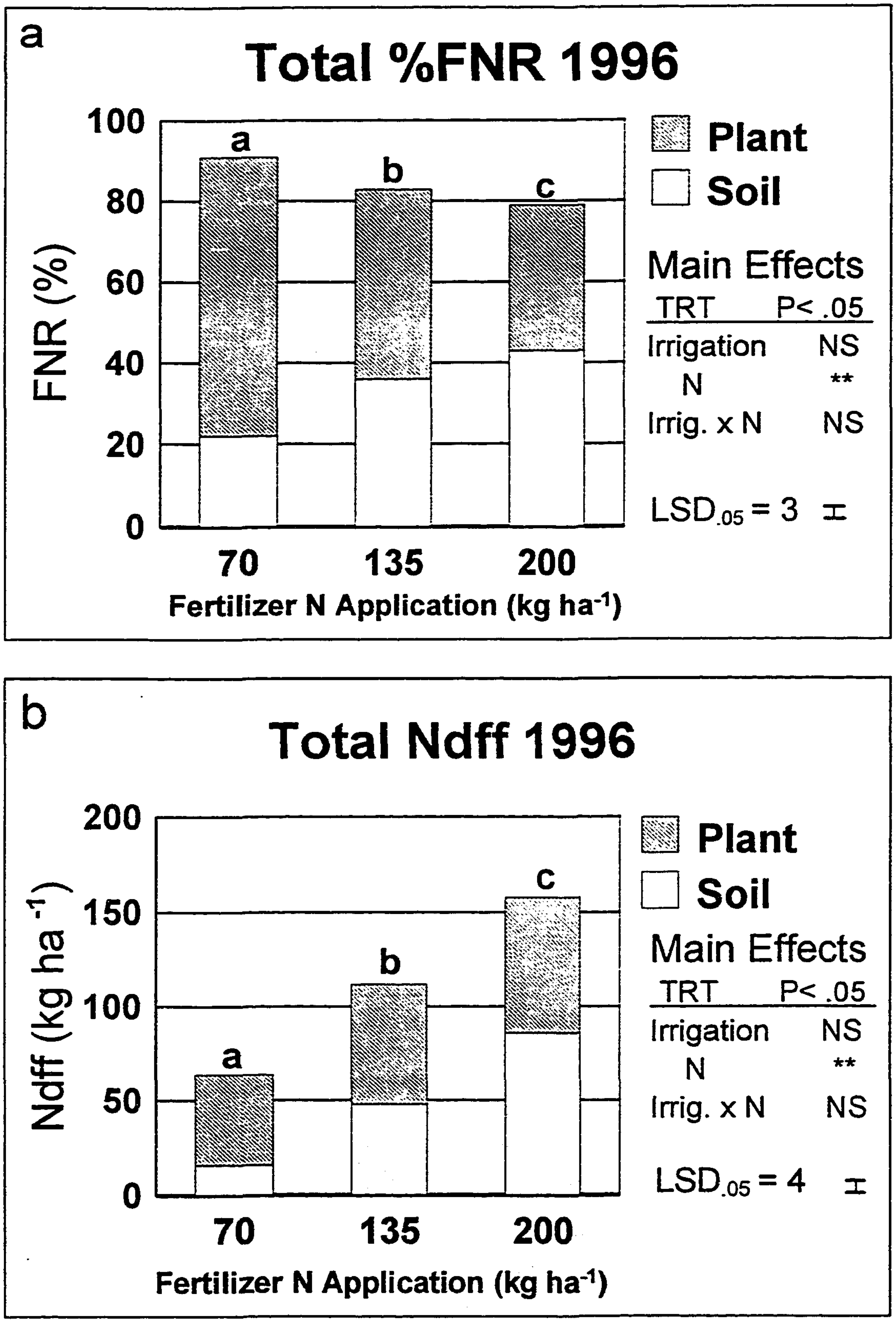


Figure 2.6. Total percent fertilizer ^{15}N recovered (%FNR) and total nitrogen derived from ^{15}N fertilizer (Ndff) in 1996.

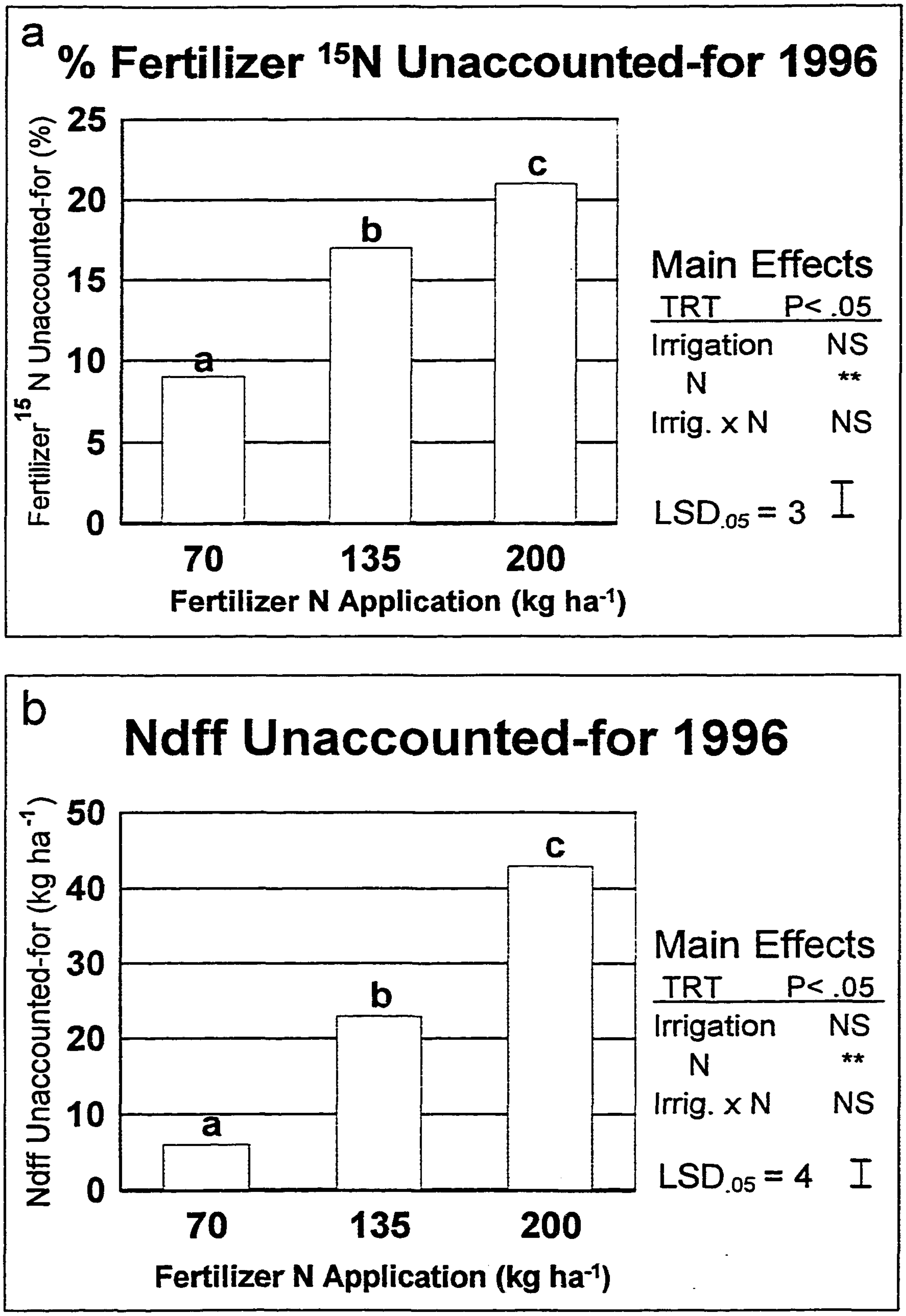


Figure 2.7. Percent fertilizer ^{15}N recovered (%FNR) and nitrogen derived from ^{15}N fertilizer (Ndff) unaccounted-for in 1996.

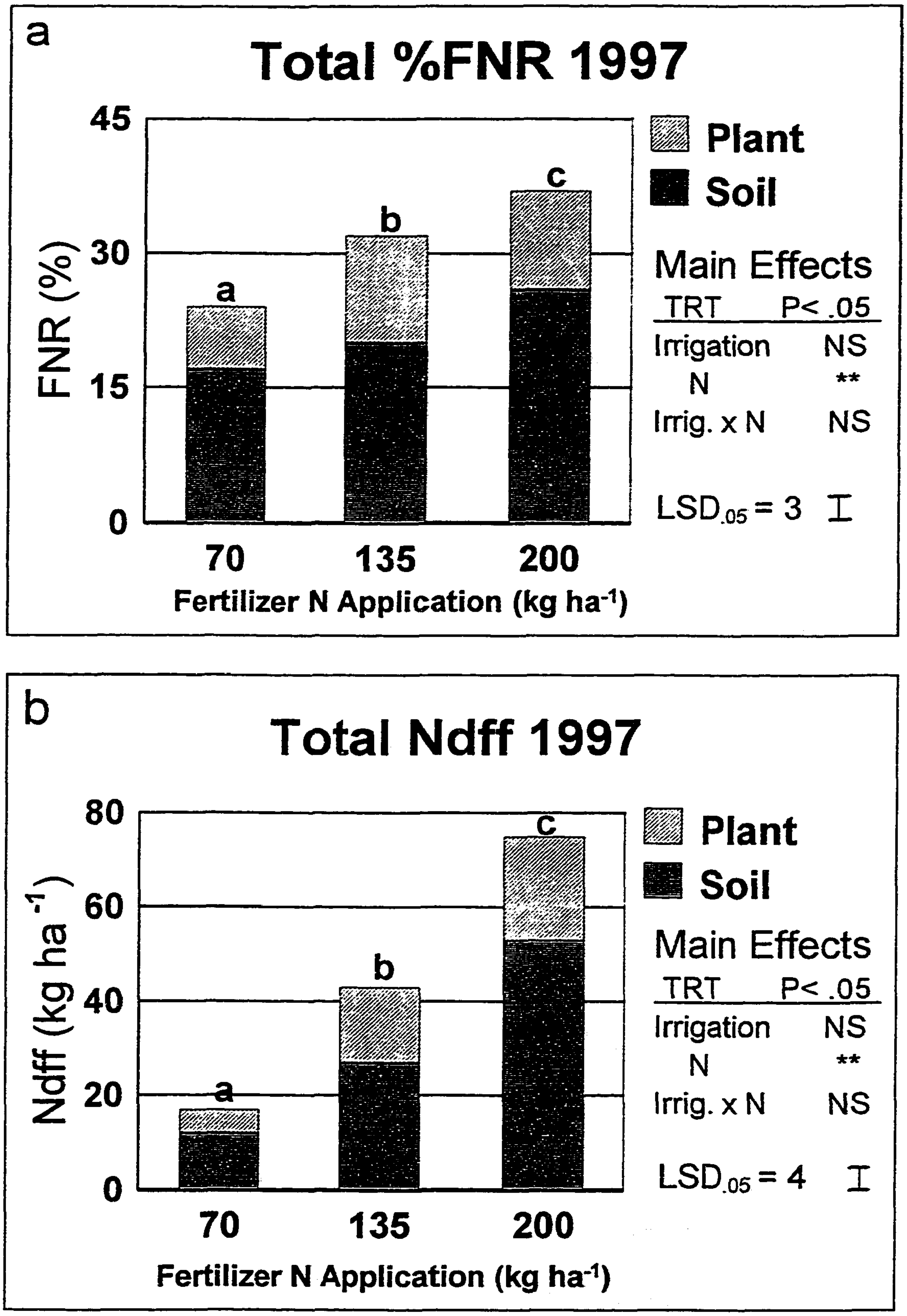
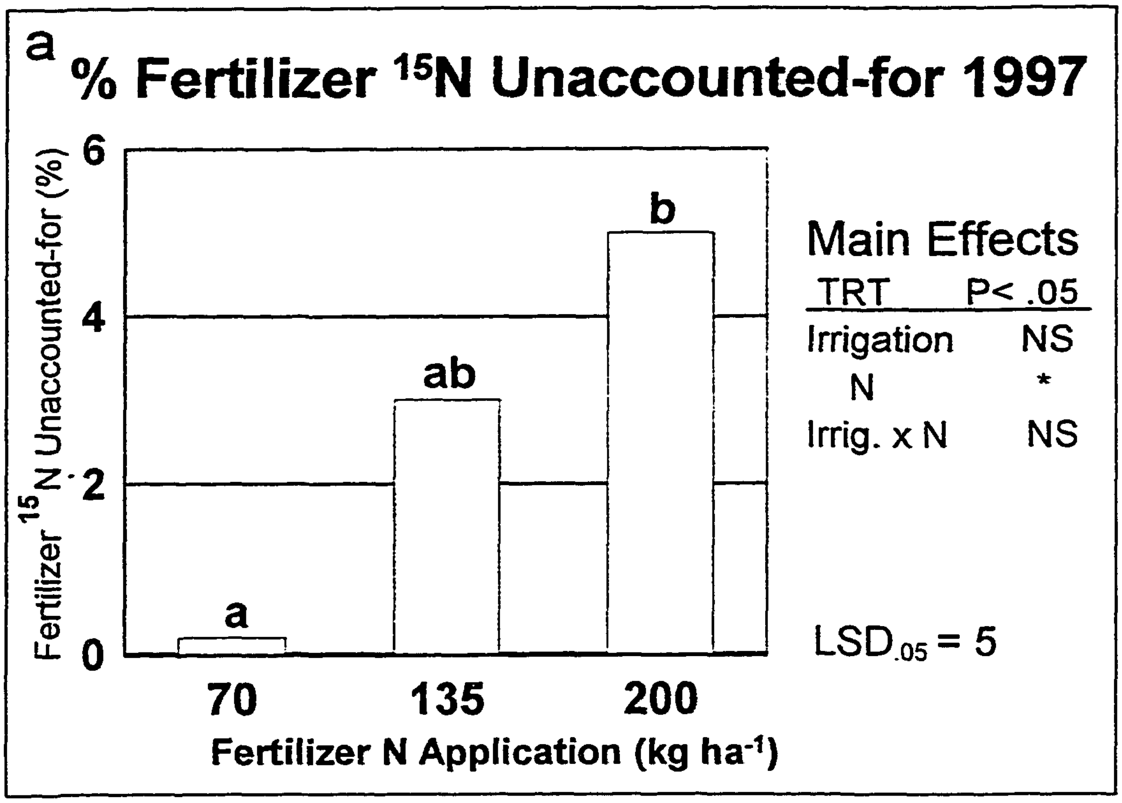


Figure 2.8. Total percent fertilizer ^{15}N recovered (%FNR) and total nitrogen derived from ^{15}N fertilizer (Ndff) in 1997.



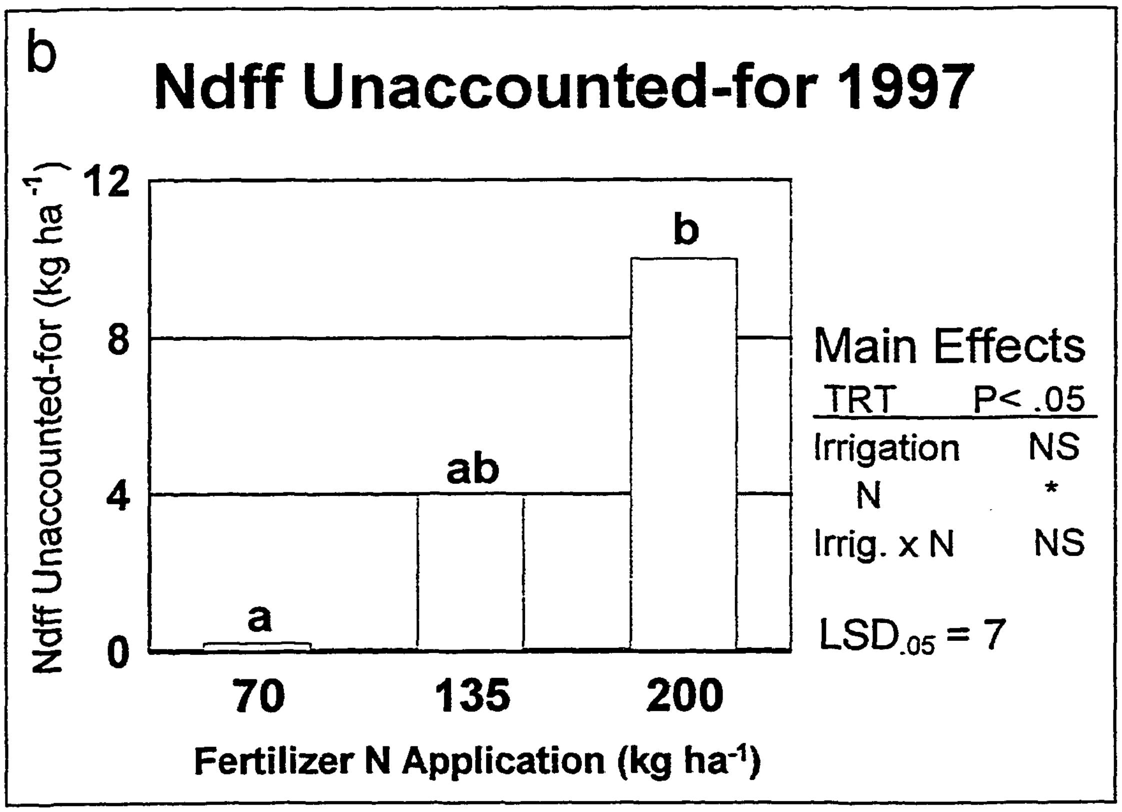
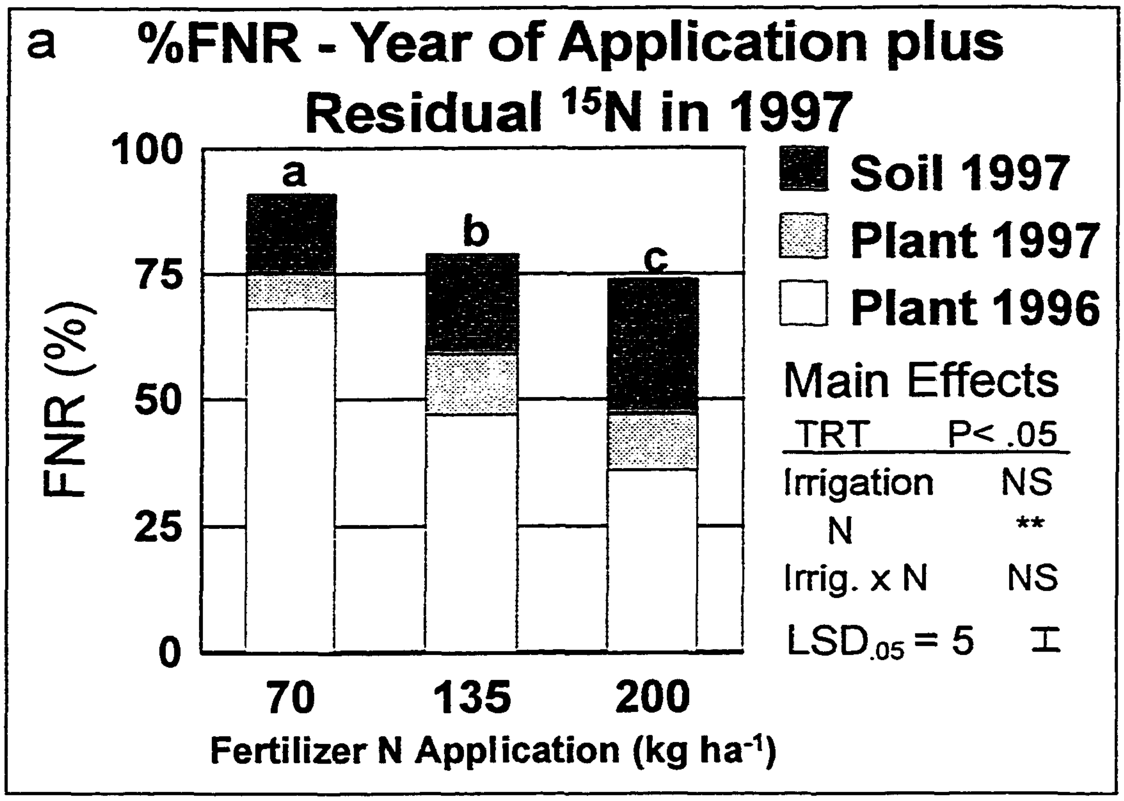


Figure 2.9. Percent fertilizer ^{15}N recovered (%FNR) and nitrogen derived from ^{15}N fertilizer (Ndff) unaccounted-for in 1997.



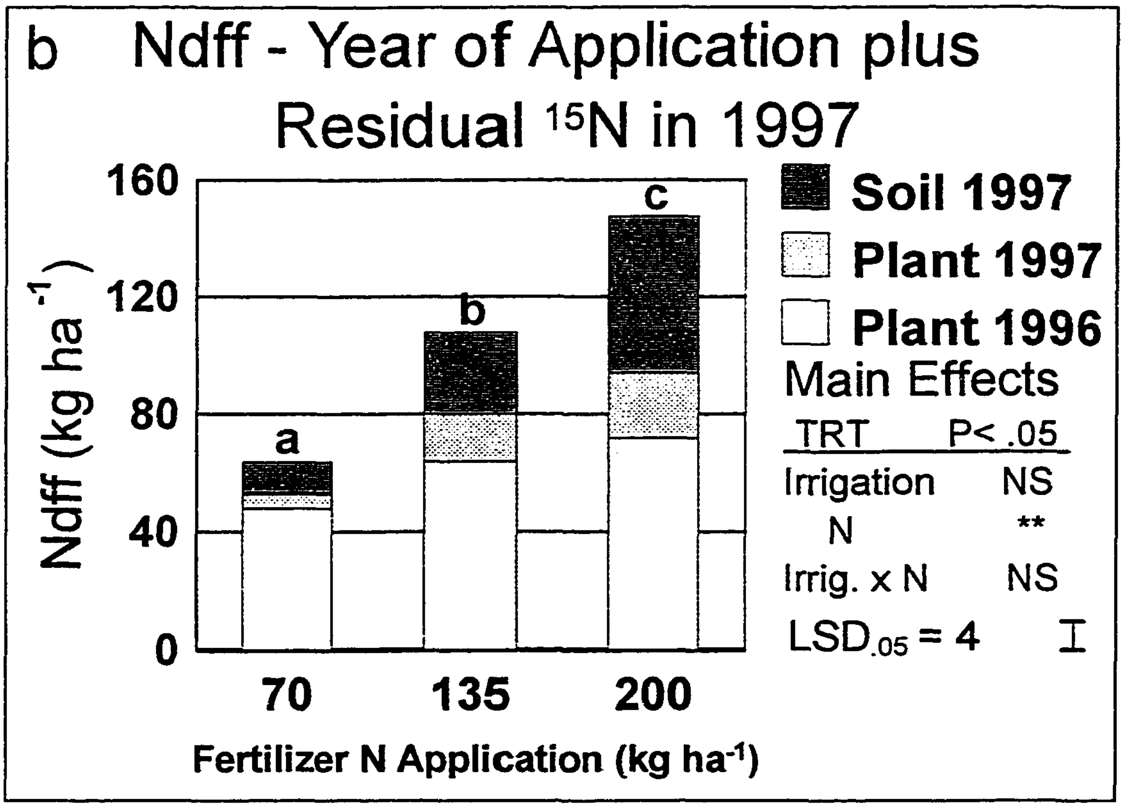
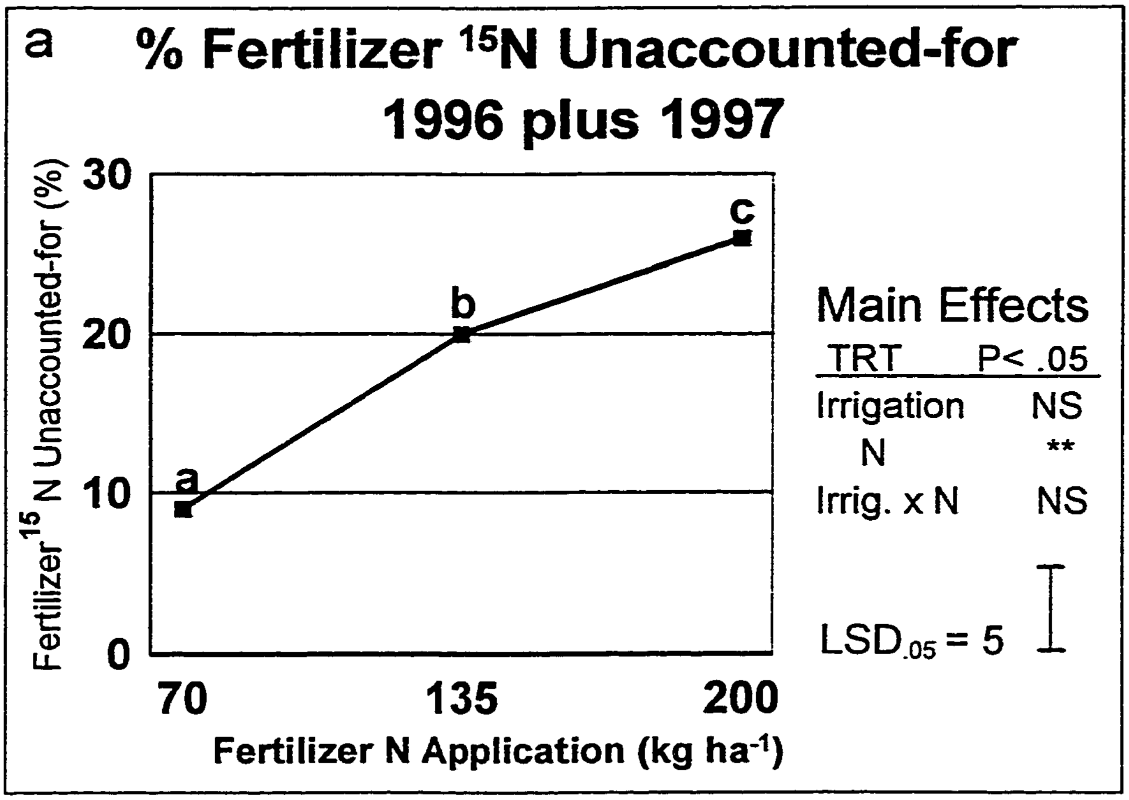


Figure 2.10. Percent fertilizer ^{15}N recovered (%FNR) and nitrogen derived from ^{15}N fertilizer (Ndff) for 2 yrs of this study (^{15}N applied in1996).



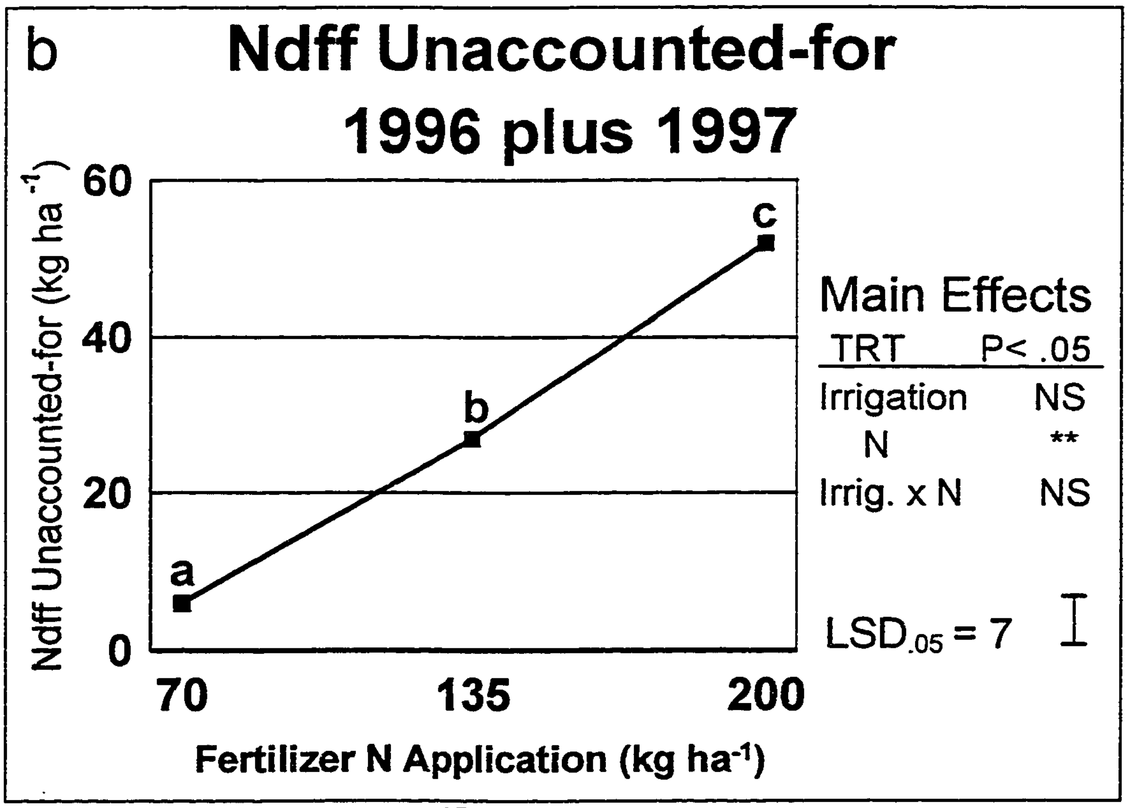


Figure 2.11. Percent fertilizer ^{15}N recovered (%FNR) and nitrogen derived from ^{15}N fertilizer (Ndff) unaccounted-for at the end of the second year of this study.

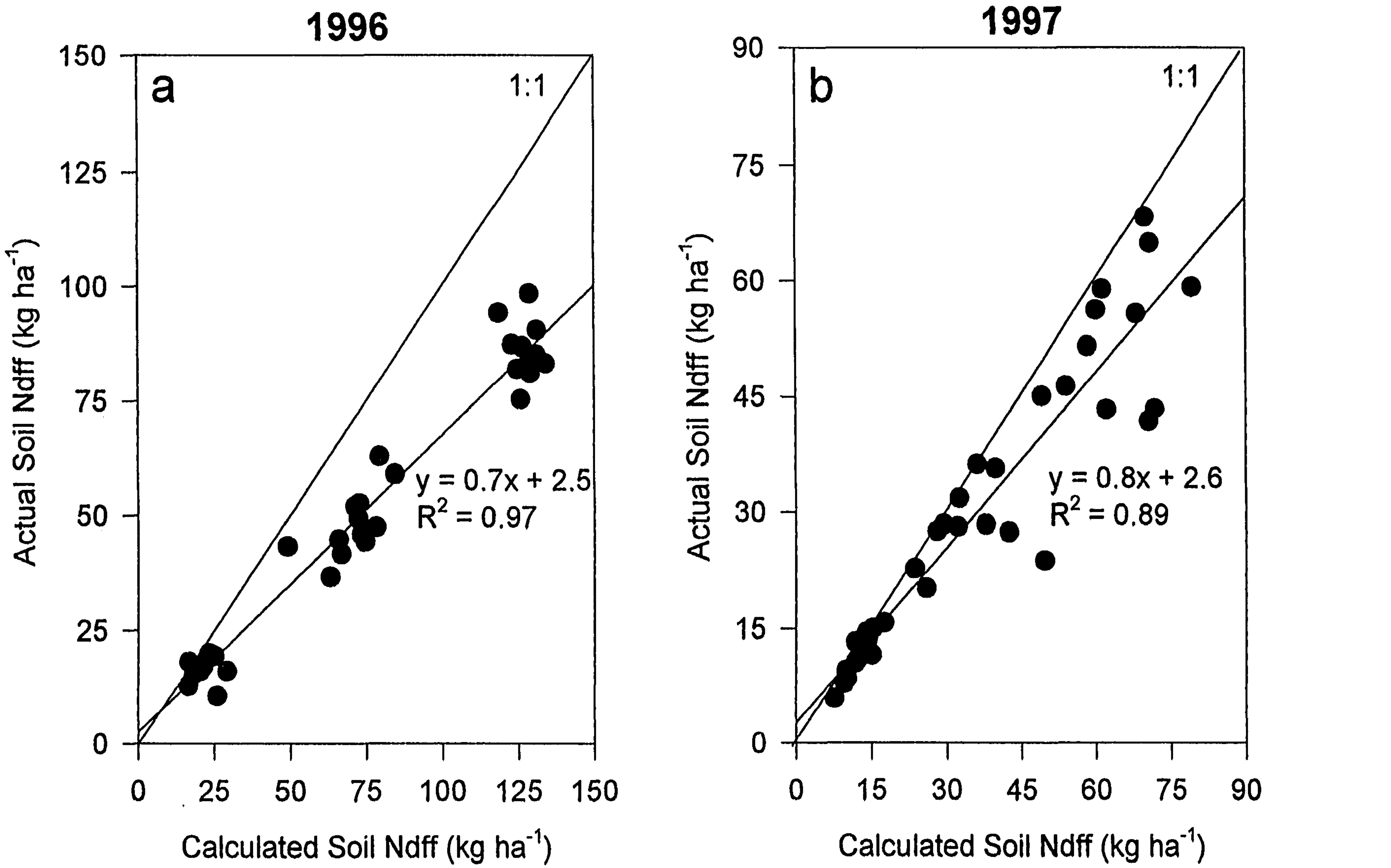


Figure 2.12. Soil nitrogen derived from ^{15}N fertilizer (Ndff) - Actual versus calculated after harvest in 1996 and 1997.

LITERATURE CITED

Allen, A.L., F.J. Stevenson, and L.T. Kurtz. 1973. Chemical distribution of residual fertilizer nitrogen in soils as revealed by nitrogen-15 studies. J. Environ. Qual. 21:120-124.

Bergstrom, L. and R. Johansson. 1991. Leaching of nitrate from monolith lysimeters of different types of agricultural soils. J. Environ. Qual. 20:801-807.

Bigeriego, M., R.D. Hauck, and R.A. Olson. 1979. Uptake, translocation and utilization of ^{15}N-depleted fertilizer in irrigated corn. Soil Sci. Soc. Am. J. 43:528-533.

Booltink, H.W.G. 1995. Field monitoring of nitrate leaching and water flow in a structured clay soil. Agric. Ecosystems & Environ. 52:251-261.

Cerrato, M.E., and A.M. Blackmer. 1990. Effects of nitrapyrin on corn yields and recovery of ammonium-N at 18 site years in Iowa. J. Prod. Agric. 3:513-521.

Dubois, D. 1994. Nutrient survey. North Front Range Water Quality Planning Association: Loveland CO.

Emond, H., J.C. Loftis, and T. Podmore. 1993. Impact of irrigation water use on water quality in the Central Colorado Water Conservancy District. Colorado Water Resource Research Institute. Ft. Collins, CO.

Follett, R.F., L.K. Porter, and A.D. Halvorson. 1991. Border effects on nitrogen-15 fertilized winter wheat microplots grown in the Great Plains. Agron. J. 83:608-612.

Gass, W.B., G.A. Peterson, R.D. Hauck, and R.A. Olson. 1971. Recovery of residual nitrogen by corn from various soil depths as measured by ^{15}N tracer techniques. Soil Sci. Soc. Am. Proc. 35:290-294.

Gerwing, J.R., A.C. Caldwell, and L.L. Goodroad. 1979. Fertilizer nitrogen distribution under irrigation between soil, plant, and aquifer. J. Environ. Qual. 8:281-284.

Hansen, V.E., O.A. Israelson, and G. Stingham. 1980. Irrigation principles and practice. John Wiley & Sons, Inc., New York. p.52.

Hatlitligil, M.B., R.A. Olson, and W.A. Compton. 1984. Yield, water use and nutrient uptake of corn hybrids under varied irrigation and nitrogen regimes. Fert. Res. 5:321-333.

Hergert, G.W. 1986. Nitrate leaching through sandy soil as affected by sprinkler irrigation management. J. Environ. Qual. 15:272-278.

Hergert, G.W., R.B. Ferguson, and C.A. Shapiro. 1995. Fertilizer suggestions for corn. NebGuide, Univ. of Nebraska, Lincoln.

Hudson, C.A. and L.A. Fretwell. 1997. Colorado agricultural statistics. Colorado Agric. Stat. Svc. Lakewood, CO.

Iremonger, C.J. 1998. Conjunctive management of irrigation water and nitrogen fertilizer on corn. Ph.D. diss. Colorado State Univ., Ft. Collins.

Jokela, W.E. and G.W. Randall. 1989. Corn yield and residual nitrate as affected by time an rate of nitrogen application. Agron. J. 81:720-726.

Jokela, W.E. and G.W. Randall. 1997. Fate of fertilizer nitrogen as affected by time and rate of application on corn. Soil Sci. Soc. Am. J. 61:1695-1703.

Keeney, D.R., and D.W. Nelson. 1982. Nitrogen - inorganic forms. *In* Page, A.L. (ed) Methods of soil analysis, part 2, chemical and microbiological properties. p. 648-649.

Kitur, B.K., M.S. Smith, R.L. Blevins, and W.W. Frye. 1984. Fate of ^{15}N-depleted ammonium nitrate applied to no-tillage and conventional tillage corn. Agron. J. 76:240-242.

Legg, J.O., F.W. Chichester, G. Stanford, and W.H. Demar. 1971. Incorporation of ^{15}N-tagged mineral nitrogen into stable forms of soil organic nitrogen. Soil Sci. Soc. Am. Proc. 35:273-276.

Liang, B.C., and A.F. MacKenzie. 1994. Corn yield, nitrogen uptake and nitrogen use efficiency as influenced by nitrogen fertilization. Can. J. Soil Sci. 74(2):235-240.

Mortvedt, J.J., D.G. Westfall and R.L. Croissant. 1996. Fertilizer suggestions for corn. Colorado State University Coop. Ext. no. 0.538, Ft. Collins, CO.

Mosier, A.R., W.D. Guenzi and E.E. Schweizer. 1986. Soil losses of dinitrogen and nitrous oxide form irrigated crops in northeastern Colorado. Soil Sci. Soc. Am. J. 50:344-348.

Olson, R.V. 1980. Fate of tagged nitrogen fertilizer applied to irrigated corn. Soil Sci. Soc. Am. J. 44:514-517.

Porter, L.K. 1995. Depleted ^{15}N carryover, leaching and uptake for three years of irrigated corn. J. Contaminant Hydro. 20:209-226.

Reddy, G.B., and K.R. Reddy. 1993. Fate of nitrogen-15 enriched ammonium nitrate applied to corn. Soil Sci Soc. Am. J. 57:111-115.

Rennie, D.A., and E.A. Paul. 1971. Isotope methodology and techniques in soil-plant nutrition and plant physiology. Sask. Inst. of Pedol. No. 76:117-121.

Reichman, G.A., and T.P. Trooien. 1993. Corn yield and salinity response to irrigation on slowly permeable subsoils. Soil Sci. Soc. Am. J. 57:1549-1554.

Ritchie, S.W., J.J. Hanway, and G.O. Benson. 1993. How a Corn Plant Develops: Special Report No. 48. Cooperative Ext. Svc. Iowa State Univ. Ames IA.

Ritter, W.F., R.W. Scarborough, and A.E. M. Chirnside. 1993. Nitrate leaching under irrigated corn. J. Irrigation and Drainage Eng. 119:544-553.

Russelle, M.P., E.J. Deibert, R.D. Hauck, M Stevanovic, and R.A. Olson. 1981. Effects of water and nitrogen management of on yield and ^{15}N-depleted fertilizer-use efficiency of irrigated corn. Soil Sci. Soc. Am. J. 45:553-558.

SAS Institute. 1985. SAS user's guide: Statistics. Version 5 ed. SAS Inst. Cary, NC.

Sanchez, C.A., and A.M. Blackmer. 1988. Recovery of anhydrous ammonia-derived nitrogen-15 during three years of corn production in Iowa. Agron. J. 80:102-108.

Sexton, B.T,, J.F. Moncrief, C.J. Rosen, S.C. Gupta, and H.H. Cheng. 1996. Optimizing nitrogen and irrigation inputs for corn based on nitrate leaching and yield on a coarse-textured soil. J. Environ. Qual. 25:982-992.

Smith, S.J., and D.K. Cassel. 1991. Estimating nitrate leaching in soil materials. *In* Follett, R. (ed.) Managing nitrogen for groundwater quality and farm profitability. Soil Sci. Soc. Am. Madison, WI.

Steele, R.G.D., and J.H. Torrie. 1980. Principles and procedures of statistics: A biometrical approach. 2d ed. McGraw-Hill, New York.

Timmons, D.R., and J.L. Baker. 1991. Recovery of point-injected labeled nitrogen by corn as affected by timing, rate, and tillage. Agron. J. 83:850-857.

United States Geological Survey (USGS). 1995. Nutrients in the South Platte River, 1993-95. National Water Quality Assessment Program. Colorado Fact Sheet; Denver, CO.

Vinten, A.J.A., B.J. Vivian, F. Wright, and R.S. Howard. 1994. A comparative study of nitrate leaching from soils of differing textures under similar climatic and cropping conditions. J. of Hydrology 159:197-213.

Weinhold, B.J., T.P. Trooien, and G.A. Reichman. 1995. Yield and nitrogen use efficiency of irrigated corn in the northern Great Plains. Agron. J. 87:842-846.

Wright, J.L. 1982. New evapotranspiration crop coefficients. J Irr. and Drainage Divn. ASCE 108 (IJ1):57-74.

Zhang, G.L., R.E. Smith, G.L. Butters, and G.E. Cardon. 1999. Analysis and testing of a concentric-disk tension infiltrometer. Soil Sci. Soc. Am., Madison, WI. (in-press).

Chapter 3

WATER AND NITROGEN MANAGEMENT OF IRRIGATED CORN ON CLAYEY SOILS

ABSTRACT

The irrigated regions in northeastern Colorado are highly productive with irrigated corn production accounting for greater than 30% of all irrigated crops. Irrigated corn has a high nitrogen (N) requirement for maximum production. Nitrate (NO_3) is mobile in soil and moves with irrigation water into the soil profile. If NO_3 moves below the crop root zone, it is lost to the crop and has the potential to impact ground water. Although the University extension service publishes irrigation and N fertilization guidelines for maximizing corn yield, relatively inexpensive irrigation water and N fertilizers induce growers to apply these inputs in excess of recommendations as "insurance" against poor yields. However, the combination of excess irrigation and excess N fertilizer application may be partially responsible for the increase in ground water NO_3 levels in the area. Therefore, it is necessary to evaluate the effects of both the recommended irrigation and N fertilizer applications and excess irrigation and N fertilizer applications on corn yield and potential NO_3 losses. This experiment was undertaken to determine if recommended and excess irrigation and fertilizer N contribute to NO_3 leaching below the crop root zone in clayey textured soils. A two-year irrigation and fertilizer N rate field experiment was undertaken to

determine the effects of these factors and/or their interactions on: a) N uptake, dry matter production, and grain yield of corn, b) amount and depth of N movement in the soil profile, and c) loss of N from the cropping system. The experiment was conducted on sprinkler irrigated corn (*Zea mays* L.) in 1996 and 1997 on a Fort Collins clay loam soil (fine, loamy, mixed, mesic, Ustolic Haplargid). The clay content in the 0 to 0.3 m depth is 36% and increases to 44% in the 1.2 to 1.5 m depth. A split-plot design was used with three target irrigation treatments as the main plot factor and four N fertilizer treatments as subplot factor, with four replications. The three target irrigation applications were 70, 100, and 130% of calculated evapotranspiration (ET) which correspond to the recommended irrigation and the recommended irrigation ± 30% ET. The four N fertilizer applications were zero kg N ha^{-1} (check), the recommended application rate, based on a Nebraska algorithm, and the recommended application rate ± 65 kg N ha^{-1}. The recommended N fertilizer application rates were 135 kg N ha^{-1} in 1996, and 150 kg N ha^{-1} in 1997. Results show that the amount of irrigation application significantly affects the grain water use efficiency (GWUE). The GWUE was reduced by approximately 15% with each incremental increase in irrigation water. Although irrigation applications did not have a significant effect on any other crop or soil parameters measured, there was a trend toward increased unaccounted-for N with increasing irrigation application. The unaccounted-for N in the cropping system could be due to denitrification and/or leaching. The fertilizer N application rate had a significant effect on all crop and soil parameters measured except GWUE. Whole plant N uptake and dry matter production were higher in 1996 than in 1997, however, grain yield was lower in 1996 than in 1997. This is probably due to high levels of residual soil NO_3-N prior to the initiation of the experiment which caused the 1996 crop to produce excess vegetative growth. Whole plant N uptake ranged from 180 to 200 kg ha^{-1} in 1996, and from 120 to 180 kg ha^{-1} in 1997. Dry matter production ranged from 20 to 21 Mg ha^{-1} in 1996, and from 14.5 to 20.5 Mg ha^{-1} in 1997. Grain yield ranged from 9 to 10 Mg ha^{-1} in 1996, and from 8 to 11 Mg ha^{-1} in 1997.

Nitrogen budgets were calculated for each season and unaccounted-for N ranged from 0 to 140 kg ha^{-1} in 1996, and from 25 to 110 kg ha^{-1} in 1997. The available N use efficiency (ANUE) ranged from 31 to 68 kg grain yield kg available N^{-1} in 1996, and from 38 to 56 kg grain yield kg available N^{-1} in 1997. These results show that applying the recommended irrigation and recommended fertilizer N rate increases input efficiencies, significantly reduces unaccounted-for-N, and adequately satisfies the crop N requirements for maintaining high yields.

INTRODUCTION

Northeast Colorado is planted to approximately 300 000 ha of irrigated crops annually, with approximately 125 000 ha planted to irrigated corn with an average yield of 9.5 Mg ha^{-1} (Hudson, 1997). Irrigated corn requires approximately 540 mm of water (precipitation plus irrigation) and 25 kg N Mg^{-1}

grain yield ha^{-1} for maximum yield (after Mortvedt et al. 1996). A Colorado study in the 1960's found elevated residual soil NO_3 levels under irrigated row crops compared to native vegetation (Stewart et al., 1967). Using the natural variation in N isotopes to determine sources of NO_3 in ground water, Gormly and Spalding (1979) reported that the main source of NO_3 in ground water was from N fertilizers. Colorado State University Cooperative Extension Service publishes irrigation and N fertilization recommendations for corn (Broner 1993; Mortvedt et al. 1996). The Extension Service also makes available to growers, up-to-date local weather information and local crop evapotranspiration (ET) estimates for proper irrigation management. Even with information readily available to growers, a study by Emond et al. (1993) found that most growers were over-applying both irrigation water and N fertilizer. Two recent studies of ground water NO_3 levels in northeastern Colorado found increasing levels and incidence of NO_3 contamination in ground water (Dubois, 1994; USGS 1995).

Some growers over-irrigate and over-applying N fertilizers as "insurance" against poor yields. These grower practices may be creating conditions that increase N fertilizer losses from the cropping system due to denitrification and leaching and thereby reducing income from the crop, and not "insuring" income as is thought. Conditions that are conducive to N losses from denitrification and leaching are high fertilizer N application rates, soil OM content > 2%, and irrigation practices that promote saturated and anaerobic soil conditions (Firestone, 1982).

Denitrification losses on clayey soils with high soil OM contents have been reported in the range of 25 to 55% (Meisinger and Randall, 1991). However, in a study using ^{15}N labeled fertilizer to study denitrification in northeastern Colorado, Mosier et al. (1986) found denitrification losses to be small, about 2.5% of the 200 kg N ha^{-1} application under irrigated corn on a clay loam soil during one cropping season. However, the denitrification study by Mosier et al., (1986) had only limited irrigation (120 mm), and all the irrigation water was applied in three applications. Over the two years of the study reported in this dissertation, irrigation applications averaged 360 mm applied in ten irrigations.

Nitrate leaching on coarse textured soils is well documented (e.g. Gerwing et al., 1979; Hergert, 1986; Ritter et al., 1993; Sexton et al., 1996). However, there are few field studies of NO_3 leaching on soils of high clay content. Nitrate leaching on clayey soils is thought to be minimal, with N losses mainly due to denitrification (Smith and Cassel, 1991; Vinten et al., 1994; Booltink, 1995). Both lysimeter and field experiments that have examined NO_3 leaching on clayey soils have shown that less than 20 kg ha^{-1} of NO_3-N were leached when excess irrigation water is applied (Bergstrom and Johansson, 1991), or when excess fertilizer N is applied (Vinten et al., 1994; Booltink, 1995), or when both excess irrigation and excess fertilizer N are applied (Porter, 1995). Porter (1995) studied NO_3 leaching under irrigated corn in northeastern Colorado with irrigation by N treatments on a silty clay loam soil. He recovered small amounts (< 20 kg N ha^{-1}) of ^{15}N labeled fertilizer from vacuum extractors at a 1.2 m depth in the third year of cropping when excess fertilizer N (376 kg N ha^{-1} yr^{-1}) and excess irrigation of 150% of crop ET were applied. The ^{15}N study by Porter (1995) also found that over three years, unaccounted-for ^{15}N, presumed to be denitrified since leaching was measured, was approximately 35% of the applied ^{15}N at the 100% ET irrigation treatment across all fertilizer N application treatments. Porter (1995) also found that unaccounted-for ^{15}N was approximately 45% of the applied ^{15}N at 150% ET irrigation treatment with excess fertilizer N application of 376 kg N ha^{-1} yr^{-1}. Porter (1995) applied irrigation weekly, a common practice among growers in the area. The results of the studies by Mosier et al. (1986) and Porter (1995) are somewhat contradictory. If unaccounted-for N is high and leaching is small (Porter, 1995), then denitrification must be the cause of the high unaccounted-for N, assuming NH_3 volatilization losses are minor when proper fertilizer N incorporation practices are followed, as was done in the experiments by both Mosier et al. (1986), and Porter (1995). It is possible that the fewer irrigations applied by Mosier et al. (1986) may account for the significantly smaller amounts of denitrification measured. As can be concluded from the research cited above, confusion exists regarding N management and N loss pathways on clayey soils. Therefore, this study was undertaken to better understand the impacts of irrigation and N fertilizer management practices on corn yield and unaccounted-for N on clayey soils under field conditions.

The objectives of the study reported here were to determine if irrigation, fertilizer N rate, and/or their interactions effect: a) N uptake, dry matter production, and grain yield of corn, b) amount and depth of fertilizer N movement in the soil profile, and c) loss of N from the cropping system. The results of this experiment should help improve irrigation and fertilizer N management for irrigated corn, determine the significance of NO_3 leaching from clayey soils, and aid in reducing fertilizer N losses from these irrigated corn cropping systems.

MATERIALS AND METHODS

A field study was conducted near Ft. Collins, CO in 1996 and 1997. Sprinkler irrigated corn (Northrup King var. NK3030[2]; 95-day relative maturity) was grown on a Fort Collins clay loam soil (fine, loamy, mixed, mesic, Ustolic Haplargid) with a clay subsoil. The clay content in the 0-0.3 m soil profile was 36% with clay content increasing to 44% at the 1.2 to1.5 m depth. A split-plot design was used with factorial combinations of three target irrigation treatments (deficient, recommended, excessive) as the main plots and four N rates (check (none), deficient, recommended, excessive) as the subplots, with four replications.

Field Study

Cropping

Corn was seeded into dry soil the first week of May in both years on 0.76 m row spacing. Plant populations of 63 000 plants ha^{-1} in 1996, and 74 000 plants

---

[2] Trade and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product by the authors, Colorado State University, or USDA.

ha^{-1} in 1997. Plant populations were calculated by averaging the plant count in 10 random samples over the entire field, at the V4 growth stage. Plots were 13.7 m long by 15.2 m wide and contained 18 rows. The area was irrigated immediately following planting with 15 mm of water for germination and stand establishment.

Irrigation Treatments

The crop was irrigated weekly when needed using a computerized linear move (LM) sprinkler system with in-canopy sprayheads. Weekly irrigation amounts were determined using an on-site weather station and a Kimberly-Penman equation (Wright, 1982). The three target irrigation treatments were 70, 100, and 130% ET in both years. However, due to high in-season precipitation in 1996 (80 mm above long-term average), final water applications that year were 100, 120, and 140% ET (Table 3.1). In 1997, the final water applications were 90, 110, and 130% of ET (in-season precipitation was 40 mm above the long-term average) (Table 3.1). The calculated 100% ET was 550 mm and 530 mm for 1996 and 1997, respectively. Total precipitation and irrigation in 1996 and 1997 were 665 mm and 570 mm, at the 100% ET target irrigation treatment (Table 3.1). The LM sprinkler system applied the three irrigation treatments using different size nozzles in the sprayheads.

Fertilizer N Treatments

The recommended N fertilizer application rate was calculated using an algorithm developed in Nebraska and adopted by Colorado (Hergert et al. 1995; Mortvedt et al. 1996).

$$\text{Fertilizer N Application Rate (kg ha}^{-1}) = 65 + [19 \times \text{YG (Mg ha}^{-1})]$$
$$- [9 \times \text{average ppm } NO_3\text{-N in the soil (0-0.6 m)}]$$
$$- [2.5 \times \text{YG (Mg ha}^{-1}) \times \%\text{OM}]$$
$$- \text{other N credits (kg ha}^{-1})$$

where: YG = yield goal

%OM = percent organic matter.

Residual soil NO_3-N in the 0-60 cm depth prior to planting in 1996 averaged 8.5 ± 1.5 ppm (value ± SE), the average soil OM content was 22 ± 1 g kg^{-1} in the top 0.3 m of the soil profile. Based on these levels of residual soil NO_3-N and soil OM, and a yield goal of 11 Mg ha^{-1}, the recommended N application rate was 135 kg N ha^{-1} in 1996. The four N application rates consisted of 0, 70, 135, and 200 kg N ha^{-1} in 1996 and were applied preplant. The N application rates correspond to the recommended rate, the recommended rate ± 65 kg N ha^{-1}, and a check of zero N applied. Fertilizer N application was not split because growers in the area generally apply all N fertilizer in one preplant application, and a 5-year study on an adjacent field planted to continuous corn showed no significant yield differences using split applications compared with one preplant application of fertilizer N (Iremonger, 1998). Plots were individually fertilized with liquid UAN 32 ($(NH_2)_2CO\ NH_4\ NO_3$) applied with a tractor mounted spray applicator. The recommended phosphorus application of 90 kg P ha^{-1} was broadcast and incorporated by disking prior to N fertilization and planting in both years.

Irrigation water supplied an average of 4 kg N ha^{-1} in 1996 and 8 kg N ha^{-1} in 1997 and was not considered when calculating the recommended fertilizer N applications. No precipitation occurred between N application and the irrigation immediately following planting.

In 1997, the average residual soil NO_3-N in the 0 to 0.6 m depth was 7.0 ± 2 ppm and the average soil OM content in the 0 to 0.3 m depth was 20 ± 2 g kg^{-1}. The N available from residual soil NO_3-N and soil OM mineralization in 1997, ranged from 90 to 140 kg N ha^{-1}. The average N rate treatments for 1997 were 85, 150, and 215 kg N ha^{-1}, the 150 kg N ha^{-1} being the recommended N application rate. The fertilizer N treatments in 1997 were applied to the same plots as in 1996 (e.g. deficient, recommended, and excess fertilizer N treatments in 1997 were applied to the same deficient, recommended and excess fertilizer N treatment plots that received those treatments in 1996).

Analysis

Plant Sampling and Analysis

Plant samples were taken at the V6, V9, V12, VT, and R6 growth stages (Ritchie et al., 1993) to determine N uptake in the above ground biomass through each growing season. Ten plants were collect at random from the center of the plot at each sampling date. Plants were cut at ground level and separated into leaves, stalks, and ears (R6, physiological maturity). At the R6 growth stage, plants were harvested when >85% of all plants over the whole experiment were at R6. This occurred on September 24, 1996, and on October 3, 1997. Harvesting when >85% of all plants reach physiological maturity was done to prevent the onset of senescence and loss of plant N in the early maturing treatments. Observations at the time of harvest each year showed that some of the plants in the highest fertilizer N rate treatments were not completely mature, noted by the absence of the abscission layer on some kernels. Plant samples were oven dried at 60-65 C, weighed, and ground to about 10 μm size. Plant samples were analyzed for total N using a CHN 1000 instrument (LECO Corp, St. Joseph, MI), that utilizes the Dumas (1831) dry oxidation method.

Soil Sampling and Analysis

Prior to planting in 1996, and following harvest each year, nine 2.5 cm soil cores were taken from each plot to a depth of 1.5 m. Soil samples were composited by 0.3 m increments for NO_3-N and NH_4-N analysis. Soils were air dried and subsamples were ground to pass a 2 mm sieve, then extracted with 2 *M* KCl (Keeney and Nelson, 1982). Soil KCl extracts were analyzed for NO_3-N and NH_4-N using a Total Flow Solution auto analyzer (Alpkem Analytical, Wilsonville, OR) with cadmium reduction of NO_3 to nitrite (NO_2) and colorimetric determination of NO_2. The residual soil NO_3-N, soil OM, and yield goal were used to calculate recommended fertilizer N application rates and N budgets.

Data Interpretation

Nitrogen Budget and Unaccounted-for N

A N budget was calculated for each growing season using an overall N mass balance to determine unaccounted-for N from the cropping system. Unaccounted-for N in the cropping system might occur due to NH_4 volatilization, denitrification, leaching or combinations of some or all of these N loss mechanisms. The NH_3 volatilization should be a minor component of unaccounted-for N since N fertilizer was incorporated soon after application. The following equation was used to calculate unaccounted-for N for the 0 to 1.5 m soil sampling depth:

$$\textbf{Unaccounted-for N} = (S_i + F_i + M_c + Ii) - (P_i + R_i) \qquad [1]$$

Where: S_i = soil inorganic N prior to each season to 1.5 m in plot *i*

F_i = N fertilizer applied in plot *i*

M_c = estimated soil OM and residue mineralization in check plots

Ii = irrigation water NO_3-N

P_i = whole plant N uptake in plot *i*

R_i = residual soil inorganic N after each season to 1.5 m in plot *i*

The estimated soil OM and residue mineralization in the check plots (M_c) was calculated using the following equation:

$$M_c = (P_c + R_c) - S_c \qquad [2]$$

Where: P_c= whole plant N uptake in check plots

R_c = residual soil inorganic N after each season to 1.5 m in check plots

S_c = soil inorganic N prior to each season to 1.5 m in check plots

Water depletion data and observations of the crop rooting depth on a adjacent field planted to continuous corn for 5 yr showed rooting depths to be < 0.9 m (Iremonger, 1998). Therefore, unaccounted-for N was also calculated for two separate soil depths to better understand the N dynamics and N loss mechanisms at these two different depths. Unaccounted-for N was calculated the 0 to 0.9 m depth (crop root zone) and for the 0 to 1.5 m depth (soil sampling depth).

Unaccounted-for N (0 to 0.9 m or 0.9 to 1.5 m) =

$$(S_i + F_i + M_c + Ii) - (P_i + R_i) \qquad [3]$$

Where: S_i = soil inorganic N prior to each season, 0 to 0.9 m or 0.9 to 1.5 m in plot *i*

F_i = N fertilizer applied in plot *i*

M_c = estimated soil OM and residue mineralization in check plots*

Ii = Irrigation water NO_3-N

P_i = whole plant N uptake in plot *i*

R_i = residual soil inorganic N after each season, 0 to 0.9 m or 0.9 to 1.5 m in plot *i*

The estimated soil OM and residue mineralization in check plots (M_c) was calculated using equation [2].

Grain Water Use Efficiency

Water use efficiency is defined as kg of dry matter (DM) produced per mm of water received (precipitation plus irrigation). However, DM production is not of practical use to growers, unless they are growing corn for silage, which is beyond the scope of this experiment. Therefore, grain water use efficiency (GWUE) was defined as kg grain yield per mm of water received, which is of more practical use to growers. The GWUE was calculated to determine if either irrigation application or N fertilizer application would have an effect how efficiently water was used by the crop. Water yield efficiency was calculated using the following equation:

$$\textbf{Grain Water Use Efficiency} = \frac{\text{kg grain yield}}{\text{mm of water received}} \qquad [4]$$

Where: mm of water received = precipitation + irrigation water applied

Available N Use Efficiency

The crop available N use efficiency (ANUE) was calculated to determine if either irrigation application or N fertilizer application affected available N. Since crop rooting depth did not exceed 0.9 m, ANUE was calculated using the available N (soil NO_3-N plus soil NH_4-N plus estimated soil OM and residue mineralization plus fertilizer N applied), in the 0 to 0.9 m soil depth. The ANUE was calculated using the following equation:

$$\textbf{Available N Use Efficiency (ANUE)} = \frac{\text{kg grain yield}}{\text{total soil inorganic N available}} \qquad [5]$$

Where: total inorganic N available = change in soil NO_3-N + NH_4-N (0 to 0.9 m) over the growing season + estimated soil OM and residue mineralization + fertilizer N applied

Statistical Analysis

A standard analysis of variance for a 3 x 4 x 4 (irrigation treatments x fertilizer N rate treatments x replications) split-plot design was performed on all data using Statistical Analysis Systems (SAS Institute, 1985). The analysis of variance (ANOVA) table for the split-plot design for this experiment is shown in Table 3.2. A split-plot design was used because of restrictions imposed on the possible number and placement of irrigation treatments by the LM sprinkler system, and also because large differences were anticipated between irrigation treatments. When comparing a randomized complete block design to a split-plot design, the split-plot design has a relatively low number of degrees of freedom (DF) for main plot *Error (a)*, irrigation treatments, and a relatively large number of DF for subplot *Error (b)*, N treatments. Therefore, the sensitivity to main plot treatment differences is reduced, and conversely, sensitivity to subplot treatment differences is increased, compared to a randomized complete block design (Steele and Torrie, 1980). All parameters were evaluated at $P_{value} < 0.05$ and $P_{value} < 0.01$.

RESULTS and DISCUSSION

Crop Growth

In 1996, crop growth was vigorous in all treatments and there were no visible symptoms of N deficiencies, such as chlorosis or stunting, even in the check plots. The only observed indication that the check plots had received no fertilizer N was that the plants in those treatments were somewhat shorter towards the end of the growing season compared to the treatments that had received fertilizer N applications. These observations are supported by whole plant N uptake values from plant samples taken throughout the growing season (Figure 3.1a and Table 3.3). There were no significant differences in N uptake between the N fertilized treatments at maturity (R6). However, from V12 to R6, the check plots had significantly less N uptake than the N-fertilized treatments.

In 1997, N deficiencies were evident throughout the growing season in the check plots. Yellowing was observed over the whole plant, especially on the lower leaves in the check plots shortly after the V6 growth stage which persisted through the remainder of the growing season. The plants in the check plots were also stunted. In the low N application treatment (85 kg N ha^{-1}) leaf yellowing in the lower leaves was not observed until the VT growth stage. At the recommended and excess fertilizer N application treatments, crop growth was vigorous throughout the growing season with no symptoms of N deficiencies. These observations are also supported by the N uptake data from samples taken throughout the 1997 growing season (Figure 3.1b and Table 3.4). From V6 through VT only the check plots had significantly less N uptake than the N fertilized plots. However, at physiological maturity (R6), there were significant differences in whole plant N uptake between most of the N treatments (to be discussed later). The reasons for the significant differences between the two seasons were the higher levels of residual soil NO_3-N in the crop root zone in 1996 than in 1997 and differences due to climatic influences between the two seasons.

The irrigation treatments had a significant effect on GWUE in 1996 and 1997, but not on any other crop or soil parameter examined. The irrigation treatments did not produce significant responses on the other crop and soil parameters examined for two possible reasons. First, clayey soils have a high water holding capacity (Hansen et al., 1980) and are therefore less likely to produce an irrigation response on either crops or soils. For example, excess irrigation on a coarse textured could produce NO_3 movement below the crop root zone, due to comparatively high saturated hydraulic conductivity, and thereby reduce crop N uptake and yield. Deficit irrigation could produce water stress in the crop and reduce yield, both cases might create a significant response due to irrigation treatment. Second, the split-plot experimental design is less sensitive to main plot (irrigation) treatment differences. These results show that irrigation management is not as critical to grain yield or NO_3 loss on high clay content soils as on coarse textured soils. However, careful irrigation management is important in maximizing the efficiency of irrigation water. All crop and soil parameters examined were significantly affected by fertilizer N application rate over the two years of the experiment, except GWUE in 1996.

Nitrogen Uptake, Dry Matter Production, and Grain Yield

The whole plant (grain plus stover) N uptake, DM production, and grain yield was significantly influenced by N rate, year, and N rate x year interaction, therefore, each will be addressed and plotted separately (Table 3.5). Nitrogen uptake and DM production were significantly higher in 1996 than in 1997 (Figure 3.2a and 3.3a), however, grain yield was significantly lower in 1996, than in 1997 (Figure 3.4).

Whole plant N uptake was 180 kg ha^{-1} in the check plots and 200 kg ha^{-1} at 70, 135 and 200 kg N ha^{-1} fertilizer treatments in 1996, and 120, 155, 165, and 180 kg ha^{-1} at the 0, 85, 150, and 215 kg N ha^{-1} fertilizer treatments in 1997

(Figure 3.2a). The N rate x year interaction is due to a different response to N fertilizer application between the two years due to higher residual soil NO_3-N in 1996 than in 1997. In 1996, whole plant N uptake ranged from 180 to 200 kg ha^{-1} (Figure 3.2b), while in 1997, whole plant N uptake ranged from 120 to 180 kg ha^{-1} (Figure 3.2c). In 1996, there was no response to applied fertilizer N, suggesting that even at the low N application rate of 70 kg N ha^{-1}, there was sufficient N available from the residual soil pool and N mineralized over the growing season to supply the N requirements of the crop (Figure 3.2b). Whole plant N uptake in 1996 was significantly affected by fertilizer N application rate, although the check treatment (zero N applied) was the only treatment with a significantly lower N uptake (Figure 3.2b). Whole plant N uptake in 1997 was significantly affected by fertilizer N application rate and ranged from 120 kg ha^{-1} in the check plots to 180 kg ha^{-1} at the 215 kg N ha^{-1} application rate (Figure 3.2c). The response to fertilizer treatments in 1997 is due to lower residual soil NO_3-N in the crop root zone compared to 1996.

Dry matter production was 20 Mg ha^{-1} in the check plots and 21 Mg ha^{-1} at the 70, 135 and 200 kg N ha^{-1} fertilizer treatments in 1996, and 14.5, 19.5, 20, and 20.5 Mg ha^{-1} at the 0, 85, 150, and 215 kg N ha^{-1} fertilizer treatments in 1997 (Figure 3.3a). The N rate x year interaction for DM production is due to a different response to the N fertilizer treatments between the two years. In 1996, DM production is relatively high with very little response to applied fertilizer N (Figure 3.3b). In 1996, the whole plant DM production was significantly influenced by fertilizer N application rate and ranged from 20 Mg ha^{-1} for the check treatment to 21 Mg ha^{-1} for all three fertilizer N application treatments. The lack of response to fertilizer N applications in 1996 is due to high levels of available N at all treatments. These results are similar to those found in the literature, that DM production plateaus when excess fertilizer N application rates are applied (e.g. Russelle et al., 1981; Hatlitligil et al., 1984; Porter, 1995). In 1997, whole plant DM production was significantly influenced by fertilizer N application rate and ranged from 14.5 Mg ha^{-1} for the check treatment to 20.5 Mg ha^{-1} at the 215 kg N ha^{-1} rate (Figure 3.3c). In 1997, there is a significant increase in the DM production with increasing N rate. This response to increasing fertilizer N applications in 1997, especially the increase from the check to the 85 kg N ha^{-1} application rate, is an indication that the 1996 crop N uptake lowered residual soil N sufficiently that a response to applied N occurred.

Grain yields were significantly higher for the N fertilized treatments in 1997 than in 1996 (Figure 3.4). Grain yields in 1996 were significantly affected by fertilizer N rate and ranged from 9 Mg ha^{-1} in the check plots to 10 Mg ha^{-1} at the three fertilizer N application rates (Figure 3.4). In 1997, grain yield was significantly affected by fertilizer N rate and ranged from 8 Mg ha^{-1} in the check treatment to 11 Mg ha^{-1} at the three fertilizer N application rates (Figure 3.4). Although yields were significantly higher in 1997 than in 1996, the three fertilizer N application rates showed no significant response to fertilizer N applications above the lowest rate in either year.

The significantly higher N uptake and DM production with significantly lower grain yields in 1996 suggests that high levels of available N (residual soil NO_3-N plus soil OM and residue mineralization) increased vegetative growth and luxury N consumption without increasing grain yield. Similar results are not found in the literature, however, excess vegetative growth in the presence of excess available N may be specific to the cultivar, otherwise, no cause can be attributed that would explain these contrary results.

Soil Nitrogen

The amount of residual soil NH_4-N remained relatively constant throughout the duration of the experiment. There were no significant differences in amount of NH_4-N in the soil from the soil sampling prior to planting, in 1996, through to the soil sampling following harvest in 1997 (data not presented). The amount of NH_4-N to a depth of 1.5 m averaged 60 kg ha^{-1} over all treatments.

Preplant levels of residual soil NO_3-N in 1996 were not significantly different at each 0.3 m increment, or total amount of residual soil NO_3-N to 1.5 m (Table 3.6 and 3.7). Preplant residual soil NO_3-N levels in 1996 varied with depth (Figure 3.5a), with a total of 180 kg N ha^{-1} to a depth of 1.5 m (Table 3.7).

Following harvest in 1996, the fertilizer N application rate had a significant influence on the residual soil NO_3-N found in the 0 to 0.3 m and 0.3 to 0.6 m depths, and the 1.5 m profile (Table 3.6 and 3.7, Figure 3.5b). The residual soil NO_3-N showed no significant differences in the 0.6 to 1.5 m profile. In the 0.6 to 0.9 m depth, the residual soil NO_3-N was significantly less following harvest in 1996 than preplant 1996. The residual soil NO_3-N at the 0.6 to 0.9 m depth decreased from 40 kg ha^{-1} at preplant in 1996 to 25 kg ha^{-1} after harvest in 1996 (Figure 3.5a and 3.5b). The reduction of 15 kg ha^{-1} in the 0.6 to 0.9 m depth is probably due to crop N uptake since there was no increase in residual soil NO_3-N in the 0.9 to 1.5 m depth. There was evidence of NO_3-N leaching deeper into the soil profile between preplant 1996 and after harvest in 1996. At preplant of 1996, there were 40 kg ha^{-1} of NO_3-N in the 0.9 to 1.2 m depth and after harvest in 1996 the amount was reduced to 35 kg ha^{-1}. However, there was a corresponding increase of 5 kg ha^{-1} at the 1.2 to 1.5 m depth (Figure 3.5a and 3.5b). Although there was NO_3-N leaching lower in the soil profile, it appears to have been uniform over all treatments as there was no significant influenced of either irrigation application or fertilizer N application rate (Table 3.6 and 3.7).

After harvest in 1997, the residual soil NO_3-N was significantly influenced by fertilizer N rate throughout the soil profile and the total residual soil NO_3-N to 1.5 m (Table 3.6 and 3.7, and Figure 3.5c). The difference in the effect of fertilizer N treatment between 1996 and 1997 is probably due to better overall crop vigor in 1996 from high levels of residual soil NO_3-N prior to planting in 1996 and less residual soil NO_3-N in 1997. In 1996, with adequate or near adequate N in all treatments, evidenced by the high N uptake and DM production, the crop probably developed an extensive root system along with the substantial above ground biomass which acted as a large sink for the residual soil NO_3-N. The high crop N uptake in 1996 may have removed a large enough portion of the NO_3-N from the residual soil N pool in the crop root zone to mitigate leaching below the root zone. It is reasonable to assume that in 1997 the crop root system was not as well developed in the check plots and 85 kg N ha^{-1} application rate as in 1996, due to less residual soil NO_3-N. A less developed root system and above ground crop would take up less water, which in turn might have increased NO_3-N leaching below the crop root zone in the check plots and 85 kg N ha^{-1} rate treatments. This may be the reason for the significant differences in the residual soil NO_3-N levels below the crop root zone found in 1997 that were not evidenced in 1996 in the zero and 85 kg N ha^{-1} treatments. In 1997, the check treatment showed a reduction in residual soil NO_3-N in the 0 to 0.9 m depth probably due to crop N uptake and denitrification. However, in the 0.9 to 1.5 m depth there is a significant loss of NO_3-N due to leaching (Table 3.7, and Figure 3.5b and c). In 1997, there were also significant differences due to fertilizer N application rate at all 0.3 m increments (Table 3.7 and Figure 3.5c) (detailed later).

The soil N data showed that fertilizer N rate had a significant effect on the residual soil NO_3-N in the 0 to 0.6 m depth, but not on the residual soil NO_3-N in the 0.6 to 1.5 m depth following the first cropping season in 1996. However, the fertilizer N rate had a significant effect on the residual soil NO_3-N in the 0 to 1.5 m depth at all 0.3 m increments following the second cropping season in 1997. The data also show that applying the recommended fertilizer N rate did not increase the residual soil NO_3-N in the crop root zone whereas residual soil NO_3-N did increase at the excess fertilizer rate.

Nitrogen Budget

Three N budgets were calculated for each year using the crop N uptake and residual soil NO_3-N to 1.5 m and the crop N uptake and residual soil NO_3-N in the 0 to 0.9 m and 0.9 to 1.5 m. This was done to get a more comprehensive picture of potential denitrification and NO_3-N leaching from these two soil profile zones. Therefore, the N budgets will be address in three steps: 1) the N budget for the crop and soil, and unaccounted-for N, from 0 to 1.5 m, in 1996 and 1997, 2) the N budget for the crop and soil, and unaccounted-for N, from 0 to 0.9 m, in 1996 and 1997, and 3) the N budget for the soil, and unaccounted-for N, from 0.9 to 1.5 m, in 1996 and 1997.

As mentioned earlier, preplant residual soil NO_3-N and NH_4-N in 1996, to 1.5 m, were not significantly different across the entire experimental area or across treatments. The preplant residual soil NO_3-N to 1.5 m averaged 180 kg ha^{-1}, and the preplant residual soil NH_4-N averaged 60 kg ha^{-1} (Table 3.8). Residual soil NH_4-N levels were not significantly different prior to the initiation of the experiment and remained constant throughout the two years of the experiment. In 1996, the preplant residual soil NO_3-N was 180 kg ha^{-1}, the check plot whole plant N uptake was 180 kg N ha^{-1}, while the residual soil NO_3-N to 1.5 m was 130 kg ha^{-1}. Since the N uptake and the preplant residual soil NO_3-N were equal in the check plots, the residual soil NO_3-N in the soil following harvest in 1996 had to be due to soil OM and residue mineralization, along with a small amount of NO_3-N (4 kg ha^{-1} averaged over irrigation treatments) from the irrigation water. If it is assumed that soil OM and residue mineralization plus irrigation water N inputs were the same in all treatments, this amount of available N is approximately 130 kg N ha^{-1} in 1996. The mineralization of barley residue from the previous crop could have contributed approximately 30 kg N ha^{-1}. The soil OM content prior to the 1996 growing season averaged 21 g kg^{-1} or 2.1%, and was estimated to produce approximately 100 kg N ha^{-1}. This mineralization rate of approximately 45 kg N ha^{-1} $\%OM^{-1}$ is 30% higher than soil OM mineralization credits suggested by Mortvedt et al. (1996). The higher than expected soil OM matter mineralization is probably due to high irrigation and precipitation received in 1996 (Table 3.1). The over-accounted-for N in the check plots of 130 kg N ha^{-1} precludes determining losses due to denitrification or leaching in the check plots. However, by assuming the same N mineralization over all plots we can get a general idea of unaccounted-for N in the treatments receiving fertilizer N applications.

The unaccounted-for N was significantly influenced by N rate, year, and N rate x year interactions over the two years of the experiment (Table 3.5). Unaccounted-for N in 1996 was significantly influenced by fertilizer N rate and ranged from 40 kg ha^{-1} at the 70 kg N ha^{-1} rate to 140 kg of unaccounted-for N ha^{-1} at the 200 kg N ha^{-1} rate (Table 3.8 and Figure 3.6). The unaccounted-for N in the check plots was artificially set at zero, as mentioned earlier, to determine unaccounted-for N in the N fertilized plots. The high amounts of unaccounted-for N in 1996, from denitrification and leaching, are probably due to high in-season precipitation (80 mm above long term average), and actual water applications higher than targeted applications which maintained high soil water content.

The N budget for 1997 shows a significant effect of fertilizer N treatment on whole plant N uptake, residual soil NO_3-N, and unaccounted-for N (Table 3.9). Whole plant N uptake was significantly lower in 1997 than in 1996, due to less N available from residual soil NO_3-N and mineralization. Residual soil NO_3-N in the fall of 1997 ranged from 80 kg ha^{-1} in the check plots to 190 kg ha^{-1} at 215 kg N ha^{-1} (Table 3.9). The 215 kg N ha^{-1} application increased the residual soil NO_3-N from 1996 to 1997, whereas, in the other three N treatments the residual soil NO_3-N levels decreased. This shows that the high rate of N fertilizer is in excess of crop N requirements. The over-accounted-for N in the check plots in 1997 was 70 kg N ha^{-1}. In 1997, the estimated soil OM and residue mineralization was estimated to be 95 kg N ha^{-1}, and was lower in 1997 than in 1996. The unaccounted-for N in 1997 ranged from 25 kg ha^{-1} in the check plot to 110 kg ha^{-1} at the 215 kg N ha^{-1} application rate (Table 3.9 and Figure 3.6). The reason for the 25 kg N ha^{-1} unaccounted-for from the 0.9 to 1.5 m depth in the check plots is that that amount was leached to below the soil sampling depth from 1996 to 1997 (Table 3.7, Figure 3.5b and 3.5c).

A second N budget was calculated for crop N uptake and residual soil N to a depth 0.9 m. The 0.9 m cut-off for residual soil N was chosen because crop rooting depth was less than 0.9 m and therefore all crop N uptake was assumed to come from 0 to 0.9 m. Using the 0.9 m cut-off for an N budget also aids in quantifying unaccounted-for N from the part of the soil profile influenced by the crop root zone.

After harvest in 1996, the amount of NO_3-N remaining in the soil to a depth of 0.9 m was significantly influenced by fertilizer N application rate and ranged from 60 kg ha^{-1} in the check plots to 100 kg ha^{-1} at 200 kg N ha^{-1} (Table 3.10). The unaccounted-for N to 0.9 m in 1996 was significantly influenced by fertilizer N application rate and ranged from zero in the check plots (detailed earlier), to 140 kg ha^{-1} at 200 kg N ha^{-1}. Since there was no increase in residual soil NO_3-N in the lower depths of the profile, the unaccounted-for N is probably due to denitrification, sampling error, and the assumption that N mineralization was the same in all treatments. High amounts of unaccounted-for N at similar N application rates, from 40 to 50% of N applied, were reported by Porter (1995), and presumed to be due to denitrification since leaching was measured. Although residual soil NO_3-N levels did not increase in the 0.9 to 1.5 m depth in 1996 (Table 3.7), it is possible, that some NO_3-N leached from the 0 to 0.9 m depth completely below the soil sampling depth. With the high in-season precipitation that occurred in 1996 and higher than targeted water applications, coupled with clayey soils that have the potential to remain saturated and anaerobic for extended periods, the conditions were conducive to leaching and high levels of denitrification.

The N budget to 0.9 m in 1997 shows that both residual soil NO_3-N and unaccounted for N were significantly influenced by fertilizer N rate (Table 3.11). The residual soil NO_3-N ranged from 35 kg ha^{-1} in the check plots to 112 kg ha^{-1} at 215 kg N ha^{-1} and were all lower in 1997 than in 1996, except for the highest fertilizer N application rate of 215 kg N ha^{-1} which was higher than in 1996. These results show that repeated over-application of N fertilizer leads to higher residual soil NO_3-N levels and higher leaching potential than will occur at the recommended N rate. The unaccounted-for N in the 0 to 0.9 m depth in 1997 was significantly influenced by fertilizer N rate and ranged from 39 to 118 kg ha^{-1} at 85 and 215 kg N ha^{-1}, respectively (Table 3.11). The unaccounted-for N in 1997 is similar to the unaccounted-for N values in 1996 except for the excess fertilizer N rate which had less unaccounted-for N in 1997. The reduction in unaccounted-for N at the excess fertilizer N application rate from 1996 to 1997 is probably due to two factors. First, there was less N available in 1997 than in 1996, and second, significantly less average total precipitation and irrigation at the 100% ET target reduced the potential for denitrification from 1996 levels.

The N budget calculated for the 0.9 to 1.5 m soil depth for 1996 shows no significant differences due to irrigation or fertilizer N rate for either residual soil NO_3-N or unaccounted-for N (Table 3.12). As mentioned earlier, there was movement of 5 kg N ha^{-1} from preplant 1996 to Fall 1996 from the 0.9 to 1.2 m depth to the 1.2 to 1.5 m depth (Table 3.7). Since there was no net change in the amount of residual soil NO_3-N for the 0.9 to 1.5 m depth over this time period, consequently, there was no unaccounted-for N.

The N budget calculated for the 0.9 to 1.5 m soil depth for 1997 shows a significant effect of fertilizer N rate on both residual soil NO_3-N and unaccounted-for N (Table 3.13). The residual soil NO_3-N ranged from 45 kg ha^{-1} in the check plots to 78 kg ha^{-1} at 215 kg N ha^{-1}. The unaccounted-for N ranged from -8 kg ha^{-1} (an increase in residual soil NO_3-N from shallower depths) at 215 kg N ha^{-1} to 25 kg ha^{-1} in the check plots. The unaccounted-for N in these depths is due to leaching below the soil sampling depth. The high levels of unaccounted-for N in the check treatment and at 85 kg N ha^{-1} is probably due to less crop and root system growth. With less N available to enhance crop and root system growth which could have taken up larger amounts of irrigation and precipitation, more water percolated through the soil profile and increased leaching. At the recommended fertilizer N rate of 150 kg N ha^{-1} in 1997, there was some leaching of residual soil NO_3-N to below the soil sampling depth. The leaching at the recommended fertilizer N application rate may be due to over-irrigation, with the average irrigation being 10% over the recommended 100% ET. At 215 kg N ha^{-1}, there is evidence that some (8 kg ha^{-1}) NO_3-N leached below the crop root zone to the 0.9 to 1.5 m depth. It is likely that NO_3-N leached below the soil sampling depth, however, the amount cannot be determined in this experiment.

The N budgets show that there was a 130 kg N ha^{-1} over-accounted-for in the check plots in 1996 due to soil OM and residue mineralization. Assuming all N treatments mineralized like amounts, the unaccounted-for N in 1996 ranged from 0 to 140 kg N ha^{-1}. The unaccounted-for N is due to denitrification and leaching, however, the amount of each cannot be determined although it appears that a significant portion was due to denitrification. In 1997, the over-accounted-for N in the check plots was 70 kg N ha^{-1} and unaccounted-for N ranged from 25 to 110 kg N ha^{-1}. Although much of the unaccounted-for N is likely due to denitrification, there was evidence of NO_3-N leaching in the check plots and at the 85 and 150 kg ha^{-1} rates. Nitrate leaching probably did occur from the 0 to 1.5 m soil sampling depth to below 1.5 m at the 215 kg ha^{-1} rate, however, NO_3-N leaching from above 0.9 m to the 0.9 to 1.5 m depth precludes this determination. Monitoring of crop ET reports and application of the recommended irrigation amounts should lessen denitrification and leaching losses on these clayey soils.

Grain Water Use Efficiency

The grain water yield efficiency (GWUE) analysis was carried out to determine whether irrigation water can be conserved while maintaining grain yield and whether irrigation applications or fertilizer N application influenced the GWUE. The benefits of conserving irrigation water are that reducing irrigation water input into the cropping system reduces the potential for both denitrification and leaching NO_3 below the crop root zone.

The GWUE over the two years of the experiment was significantly influenced by irrigation, N rate, year, and N rate x year interactions (Table 3.5). The GWUE was significantly higher in 1997 than in 1996. In general, the higher

GWUE in 1997 is due to the lower water (irrigation plus precipitation) input coupled with higher grain yield than in 1996. In 1996, GWUE was significantly affected by irrigation but not by N rate, and ranged from 12 kg mm^{-1} at the 140% ET irrigation to18 kg mm^{-1} at the 100% ET irrigation (Figure 3.7a). The decreasing GWUE with increasing water is a product of similar grain yields with increasingly more water. This shows that increasing irrigation applications above 100% ET is unnecessary since grain yields are not improved. In 1997, both irrigation and fertilizer N application rates had a significant effect on GWUE. The GWUE ranged from 13 kg mm^{-1} in the check plots at the 130% ET irrigation to 22 kg mm^{-1} at the three fertilizer N rates in the 90% ET irrigation (Figure 3.7b). Within each irrigation treatment, the N fertilized treatments were not significantly different, however, the 90% ET treatment had a significantly higher GWUE than the 110 or the 130% ET treatments (Figure 3.7). The recommended fertilizer N rate (150 kg N ha^{-1}) in 1997 was not significantly less than the excess fertilizer N rate within all three irrigations (Figure 3.7).

These results show that significantly higher GWUE can be attained at the lower irrigation applications and that monitoring ET to properly manage irrigation is critical to achieving the highest GWUE and maximum benefit from irrigation applications. Growers can also achieve equally high GWUE by applying the recommended fertilizer rate compared to the excess rate.

Available N Use Efficiency

Available N use efficiency (ANUE) (kg grain yield kg available N^{-1}) was significantly influenced by N rate, year, and N rate x year interaction (Table 3.5).

The significant N rate x year interaction is due to the different responses in the check plots from 1996 to 1997, which is a result of the higher grain yield in 1996 as a result of higher available N in the check plots in 1996 (Figure 3.8). The ANUE was significantly higher in the N fertilized treatments in 1997 than in 1996 due to higher yields with less available N in 1997 than in 1996.

The ANUE was significantly influenced by fertilizer N rate in 1996 and ranged from 31 at 200 kg N ha^{-1} to 68 in the check plots (Figure 3.8). In 1997, ANUE was significantly influenced by fertilizer N rate and ranged from 38 at 200 kg N ha^{-1} rate to 56 in the check plots (Figure 3.8). Excluding the check plots, the ANUE in 1996 ranged from 31 to 45 as fertilizer N rate decreased, and in 1997, ANUE ranged from 38 to 55 as fertilizer N rate decreased. The ANUE was significantly different at the recommended rate or the excess rate in either 1996 or 1997. Therefore, growers could maintain the ANUE and reduce N fertilizer inputs by use the recommended fertilizer N rate compared to the excess fertilizer N rate.

CONCLUSIONS

Whole plant N uptake and DM production were significantly higher in 1996 than in 1997, while grain yields were significantly lower in 1997 than in 1996. Whole plant N uptake ranged from 180 to 200 kg ha^{-1} in 1996, and from 120 to 180 kg ha^{-1} in 1997. Dry matter production ranged from 20 to 21 Mg ha^{-1} in 1996, and from 16 to 21 Mg ha^{-1} in 1997. Grain yields ranged from 9.3 to 10.0

Mg ha^{-1}, and from 8 to 11 Mg ha^{-1} in 1996 and 1997, respectively. The low grain yields in 1996 were probably a result of excess vegetative growth from high levels of available N. In general, in 1996, whole plant N uptake, DM production, and grain yields showed a lack of response to increasing applications of fertilizer N. There were pronounced responses of whole plant N uptake and DM production to increasing fertilizer N applications in 1997. However, grain yield did not respond to increasing applications of fertilizer N, probably due to sufficient levels of available N to meet crop N requirements.

Fertilizer N application rate had a significant effect on residual soil NO_3-N following both cropping seasons. However, in 1996, the fertilizer N application rate only influenced the residual soil NO_3-N to a depth of 0.6 m, indicating that crop uptake may have mitigated NO_3-N leaching below the crop root zone. Less available N throughout the growing season in 1997, especially in the check plots, reduced crop vigor and increased response to applied N.

Irrigation treatments had a significant effect on GWUE in both years of the study, with the best efficiencies found at the lower ET irrigation treatments. Grain water use efficiencies ranged from 12 to 18 kg mm^{-1} in 1996, and from 13 to 22 kg mm^{-1} in 1997. The significantly higher GWUE in 1997 is due to higher grain yield on lower water inputs (irrigation plus precipitation) due to lower precipitation in 1997. These results indicate that lower irrigation application led to higher GWUE while reducing the potential for denitrification and leaching of soil NO_3-N. Recoveries of residual soil NO_3-N from the soil following each harvest indicate that most of the unaccounted-for N is due to denitrification which has a high potential on these clayey soils and is probably exacerbated by weekly irrigations.

Available N use efficiency was significantly influenced by fertilizer N rate in both years. In general, higher ANUE was exhibited in the check plots and lowest fertilizer N rate plots with is probably due to high residual soil NO_3-N enhancing yields even at the low N rate. The values of ANUE ranged from 31 to 68 kg yield kg available N^{-1} in 1996, and from 38 to 56 kg yield kg available N^{-1} in 1997. At the two higher fertilizer N application rates, there was no significant difference in ANUE in either year, however, there was a trend towards lower ANUE with increased fertilizer N rate. Growers could maximize their fertilizer N efficiency and reduce their input costs by applying the recommended fertilizer N application rate.

The results of this study demonstrate that denitrification rates are high on these clayey soils. Growers should also adhere to the recommended N fertilizer rate because applying excess fertilizer N leads to significantly higher unaccounted-for N due to denitrification and NO_3-N leaching.

Growers should be advised to soil test for residual soil NO_3-N on a yearly basis to better project N availability from residual soil NO_3-N and prevent over-fertilization. The algorithm used to calculate recommended N fertilizer rate (Hergert et al. 1995; Mortvedt et al. 1996) may have to be modified to include soil OM mineralization credits for different soil types, however, more research should be done to further examine these relationships. However, it may not be possible to pinpoint exact N fertilization rates as year-to-year variations in climatic conditions may alter crop N uptake, soil OM mineralization, yields, and promote denitrification and NO_3 leaching on these clayey soils even at the recommended N rate.

Table 3.1. Target water applications, irrigation, precipitation, final water applications, in 1996 and 1997.

1996				
Target Water Application	Irrigation	Precipitation	Total	Final Water Application*
—— % ET ——		mm		% Calculated ET
70	270	280	550	100
100	385	280	665	120
130	500	280	780	140

* Calculated ET 1996 = 550 mm

1997				
Target Water Application	Irrigation	Precipitation	Total	Final Water Application*
—— % ET ——		mm		% Calculated ET
70	230	240	470	90
100	330	240	570	110
130	430	240	670	130

* Calculated ET 1997 = 530 mm

Table 3.2. Analysis of variance table for split-plot design showing source of variance and degrees of freedom.

Source of Variance	Degrees of Freedom
Replications	3
Main Plot (A)	
Irrigation Treatments	2
Error (a)	6
Subplot (B)	
N Treatment	3
Irrigation x N	6
Error (b)	27
Total	47

Table 3.3. Whole plant N uptake of corn by growth stage over the growing season in 1996.

N Treatment	Plant Growth Stage				
	V6	V9	V12	VT	R6
kg N ha^{-1}	kg N ha^{-1}				
0	9	65	95	105	180
70	10	65	100	115	200
135	11	65	105	120	200
200	11	70	105	125	200
Statistics					
Irrigation	NS	NS	NS	NS	NS
N rate	*	**	**	**	**
Irrigation x N	NS	NS	NS	NS	NS
$LSD_{.05}$	1	4	5	6	8

*, **, NS, significant at 0.05, 0.01, not significant, respectively.

Table 3.4. Whole plant N uptake of corn by growth stage over the growing season in 1997.

N Treatment	Plant Growth Stage				
	V6	V9	V12	VT	R6
kg N ha^{-1}	kg N ha^{-1}				
0	7	40	60	90	120
70	9	60	90	115	155
135	9	60	90	120	165
200	9	60	90	120	180
Statistics					
Irrigation	NS	NS	NS	NS	NS
N rate	**	**	**	**	**
Irrigation x N	NS	NS	NS	NS	NS
$LSD_{.05}$	1	4	8	10	17

*, **, NS, significant at 0.05, 0.01, not significant, respectively.

Table 3.5 Statistical analysis for comparison between 1996 and 1997 for whole plant N uptake, dry matter (DM) production, grain yield unaccounted-for N, grain water use efficiency (GWUE), and available N use efficiency (ANUE) for the two years of the experiment.

Main Effects	Whole Plant N Uptake	DM Production	Grain Yield	Unaccounted-for N	GWUE	ANUE
Irrigation	NS	NS	NS	NS	**	NS
N rate	**	**	**	**	**	**
Year	**	**	*	**	**	**
Irrigation x N rate	NS	NS	NS	NS	NS	NS
Irrigation x Year	NS	NS	NS	NS	NS	NS
N rate x Year	**	**	**	**	**	**
Irrigation x N rate x Year	NS	NS	NS	NS	NS	NS

*, **, NS, significant at 0.05, 0.01, not significant, respectively.

Table 3.6. Statistical analysis for soil NO_3-N by 0.3 m increments to 1.5 m depth for preplant 1996, after harvest 1996, and after harvest 1997.

		NO_3-N		
Sampling Time	Depth (m)	Irrigation	N Treatment	Irrigation x N TRT
Preplant	0-0.3	NS	NS	NS
1996	0.3-0.6	NS	NS	NS
	0.6-0.9	NS	NS	NS
	0.9-1.2	NS	NS	NS
	1.2-1.5	NS	NS	NS
	Total	NS	NS	NS
After	0-0.3	NS	*	NS
Harvest	0.3-0.6	NS	*	NS
1996	0.6-0.9	NS	NS	NS
	0.9-1.2	NS	NS	NS
	1.2-1.5	NS	NS	NS
	Total	NS	*	NS
After	0-0.3	NS	**	NS
Harvest	0.3-0.6	NS	**	NS
1997	0.6-0.9	NS	**	NS
	0.9-1.2	NS	**	NS
	1.2-1.5	NS	**	NS
	Total	NS	**	NS

*, **, NS = Significant at 0.05, 0.01, not significant, respectively.

Table 3.7. Soil NO_3-N by 0.3 m increments to 1.5 m depth for preplant 1996, after harvest 1996, and after harvest 1997.

Sampling Time	Depth (m)	N Treatment			
		N0*	N1	N2	N3
		kg NO_3-N ha^{-1}			
Preplant 1996	0-0.3	40**			
	0.3-0.6	30**			
	0.6-0.9	40**			
	0.9-1.2	40**			
	1.2-1.5	30**			
	Total	180			
After Harvest 1996	0-0.3	19	25	32	37
	0.3-0.6	16	20	33	38
	0.6-0.9	25**			
	0.9-1.2	35**			
	1.2-1.5	35**			
	Total	130	140	160	170
After Harvest 1997	0-0.3	16	21	27	34
	0.3-0.6	10	17	25	36
	0.6-0.9	9	18	25	42
	0.9-1.2	18	24	30	39
	1.2-1.5	27	30	33	39
	Total	80	110	140	190

* N0, N1, N2, N3 = 0, 70, 135, 200 kg N ha^{-1} in 1996, and 0, 85, 150, 215 kg N ha^{-1} in 1997, respectively.

** Soil NO_3-N averaged over all treatment when not significantly different at $P<0.05$.

Table 3.8. Nitrogen budget and unaccounted-for N from 0 to 1.5 m in 1996.

N Treatment	Soil NO_3-N Pre-Plant 1996 0-1.5 m	Soil NH_4-N Pre-Plant 1996 0-1.5 m	Whole Plant N Uptake 1996	Soil NO_3-N Fall 1996 0-1.5 m	Soil NH_4-N Fall 1996 0-1.5 m	Estimated Soil OM Min. 1996†	Unaccounted for N 1996 0-1.5 m
kg N ha^{-1}	kg N ha^{-1}						
0			180	130		130	0
70			200	140		130	40
135	180††	60††	200	160	60††	130	85
200			200	170		130	140
<u>Statistics</u>							
Irrigation	NS	NS	NS	NS	NS		NS
N rate	NS	NS	**	**	NS		**
Irrigation x	NS	NS	NS	NS	NS		NS
$LSD_{.05}$			5	30			40

*, **, NS, significant at 0.05, 0.01, not significant, respectively.
† Estimated OM mineralization based on over-accounted-for N in check plots.
†† averaged over all treatments.

Table 3.9. Nitrogen budget and unaccounted-for N from 0 to 1.5 m in 1997.

N Treatment	Soil NO_3-N Fall 1996 0-1.5 m	Soil NH_4-N Fall 1996 0-1.5 m	Whole Plant N Uptake 1997	Soil NO_3-N Fall 1997 0-1.5 m	Soil NH_4-N Fall 1997 0-1.5 m	Estimated Soil OM Min. 1997†	Unaccounted for N 1997 0-1.5 m
kg N ha^{-1}	kg N ha^{-1}						
0	130		120	80		95	25
85	140		155	110		95	55
150	160	60††	165	140	60††	95	100
215	170		180	190		95	110
Statistics							
Irrigation	NS	NS	NS	NS	NS		NS
N rate	**	NS	**	**	NS		**
Irrigation x	NS	NS	NS	NS	NS		NS
$LSD_{.05}$	30		6	35			15

*, **, NS, significant at 0.05, 0.01, not significant, respectively.
† Estimated OM mineralization based on over-accounted-for N in check plots.
†† averaged over all treatments.

Table 3.10. Nitrogen budget and unaccounted-for N from 0 to 0.9 m in 1996.

N Treatment	Soil NO_3-N Pre-Plant 1996 0-0.9 m	Soil NH_4-N Pre-Plant 1996 0-0.9 m	Whole Plant N Uptake 1996	Soil NO_3-N Fall 1996 0-0.9 m	Soil NH_4-N Fall 1996 0-0.9 m	Estimated Soil OM Min. 1996†	Unaccounted for N 1996 0-0.9 m
kg N ha^{-1}			kg N ha^{-1}				
0			180	60		130	0
70			200	70		130	40
135	110††	36††	200	90	36††	130	85
200			200	100		130	140
Statistics							
Irrigation	NS	NS	NS	NS	NS		NS
N rate	NS	NS	**	*	NS		**
Irrigation x N	NS	NS	NS	NS	NS		NS
$LSD_{.05}$			5	25			30

*, **, NS, significant at 0.05, 0.01, not significant, respectively.
†Estimated OM mineralization based on over-accounted-for N in check plots.
†† averaged over all treatments.

Table 3.11. Nitrogen budget and unaccounted-for N from 0 to 0.9 m in 1997

N Treatment	Soil NO_3-N Fall 1996 0-0.9 m	Soil NH_4-N Fall 1996 0-0.9 m	Whole Plant N Uptake 1997	Soil NO_3-N Fall 1997 0-0.9 m	Soil NH_4-N Fall 1997 0-0.9 m	Estimated Soil OM Min. 1997†	Unaccounted for N 1997 0-0.9 m
kg N ha^{-1}	————————	————————	————————	kg N ha^{-1}	————————	————————	————————
0	60		120	35		95	0
85	70		155	56		95	39
150	90	36††	165	77	36††	95	93
215	100		180	112		95	118
Statistics							
Irrigation	NS	NS	NS	NS	NS		NS
N rate	*	NS	**	**	NS		**
Irrigation x	NS	NS	NS	NS	NS		NS
$LSD_{.05}$	25		6	23			35

*, **, NS, significant at 0.05, 0.01, not significant, respectively.
†† Estimated OM mineralization based on over-accounted-for N in check plots.
† averaged over all treatments.

Table 3.12. Nitrogen budget and unaccounted-for N from 0.9 to 1.5 m in 1996

N Treatment	Soil NO_3-N Pre-Plant 1996 0.9 - 1.5 m	Soil NH_4-N Pre-Plant 1996 0.9 - 1.5 m	Soil NO_3-N Fall 1996 0.9 - 1.5 m	Soil NH_4-N Fall 1996 0.9 - 1.5 m	Unaccounted for N 1996 0.9 - 1.5 m
kg N ha^{-1}	kg N ha^{-1}				
0					0
70					0
135	70†	24†	70†	24†	0
200					0
Statistics					
Irrigation	NS	NS	NS	NS	NS
N rate	NS	NS	NS	NS	NS
Irrigation x N	NS	NS	NS	NS	NS
LSD$_{.05}$					

*, **, NS, significant at 0.05, 0.01, not significant, respectively.
† averaged over all treatments.

Table 3.13. Nitrogen budget and unaccounted-for N from 0.9 to 1.5 m in 1997.

N Treatment	Soil NO_3-N Fall 1996 0.9 - 1.5 m	Soil NH_4-N Fall 1996 0.9 - 1.5 m	Soil NO_3-N Fall 1997 0.9 - 1.5 m	Soil NH_4-N Fall 1997 0.9 - 1.5 m	Unaccounted for N 1997 0.9 - 1.5 m
kg N ha^{-1}	kg N ha^{-1}				
0			45		25
85			54		16
150	70†	24†	63	24†	7
215			78		-8
Statistics					
Irrigation	NS	NS	NS	NS	NS
N rate	NS	NS	**	NS	**
Irrigation x N	NS	NS	NS	NS	NS
LSD$_{.05}$			14		17

*, **, NS, significant at 0.05, 0.01, not significant, respectively.
† averaged over all treatments.

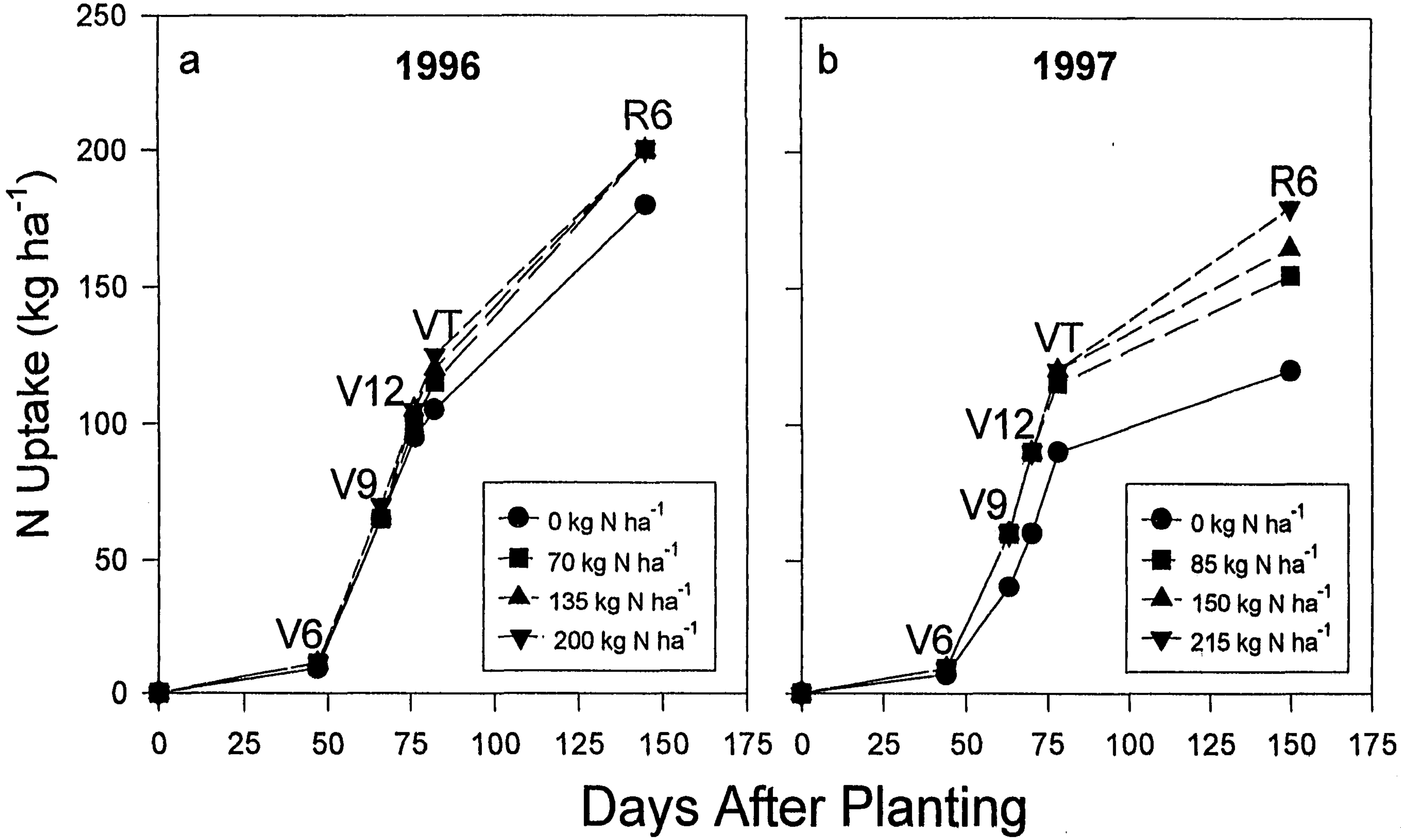


Figure 3.1. Whole plant N uptake over the growing season in 1996 and 1997.

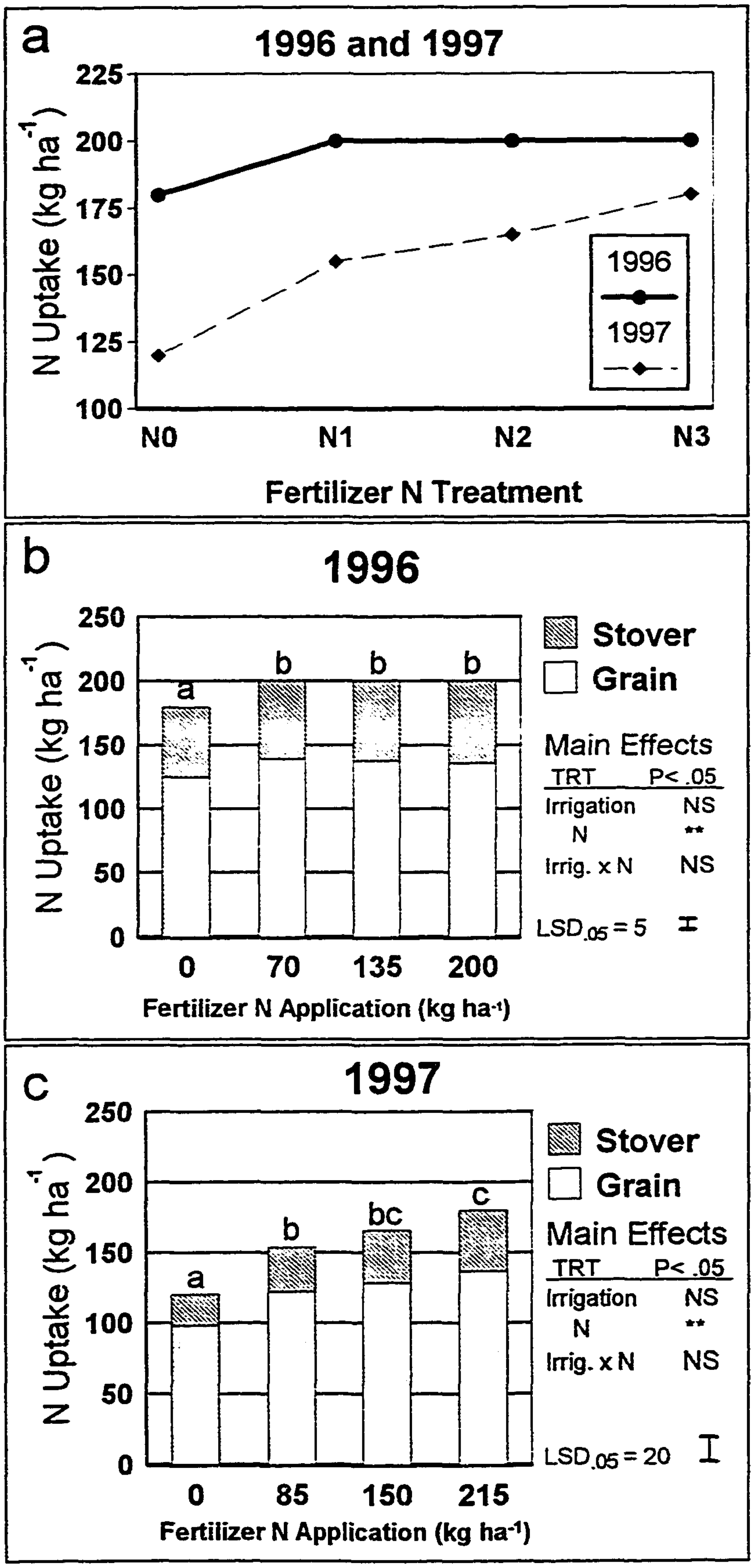


Figure 3.2. Whole plant N uptake as affected by N fertilizer rate in 1996 and 1997.

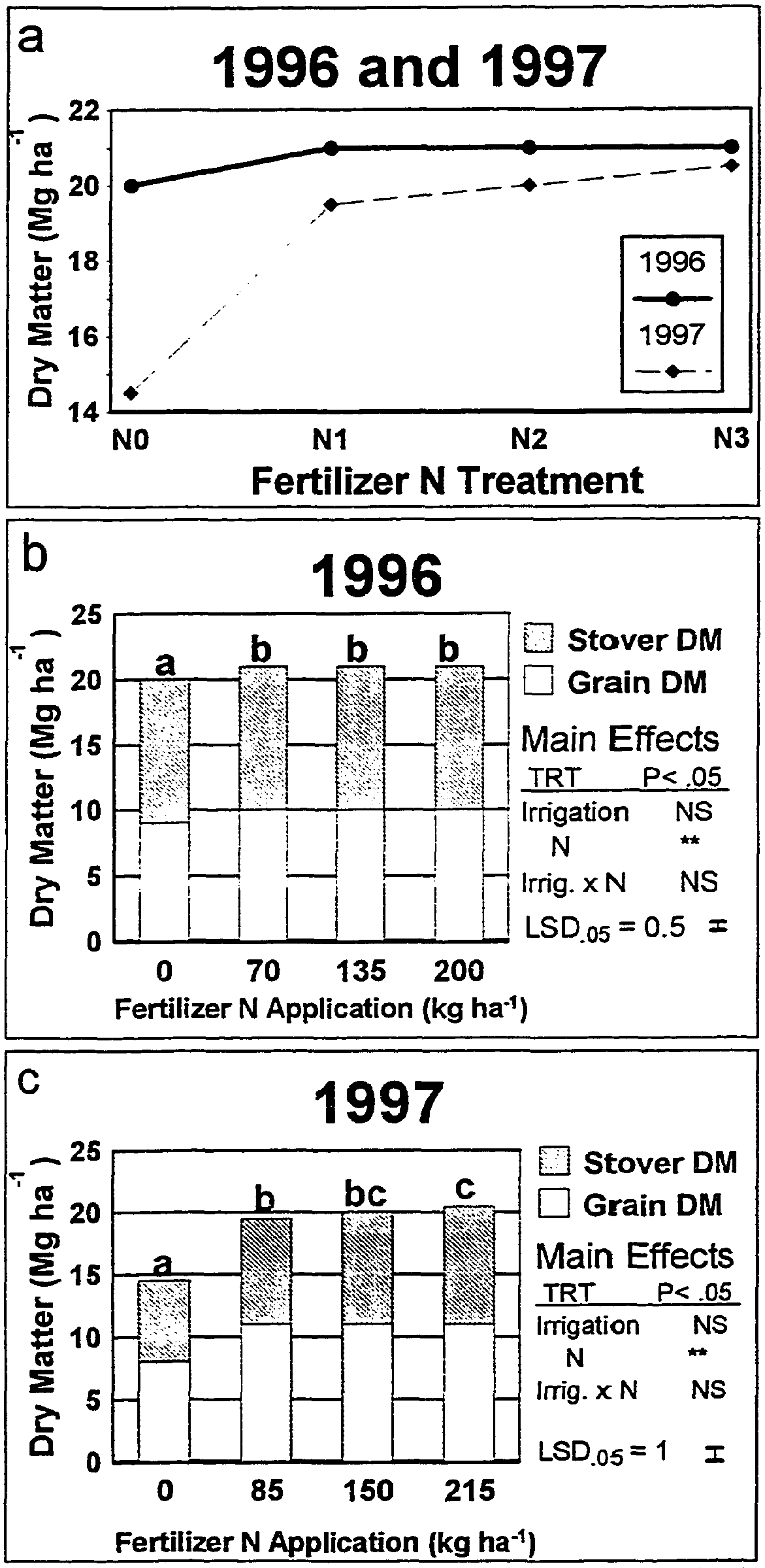


Figure 3.3. Dry matter (DM) production as affected by N fertilizer rate in 1996 and 1997.

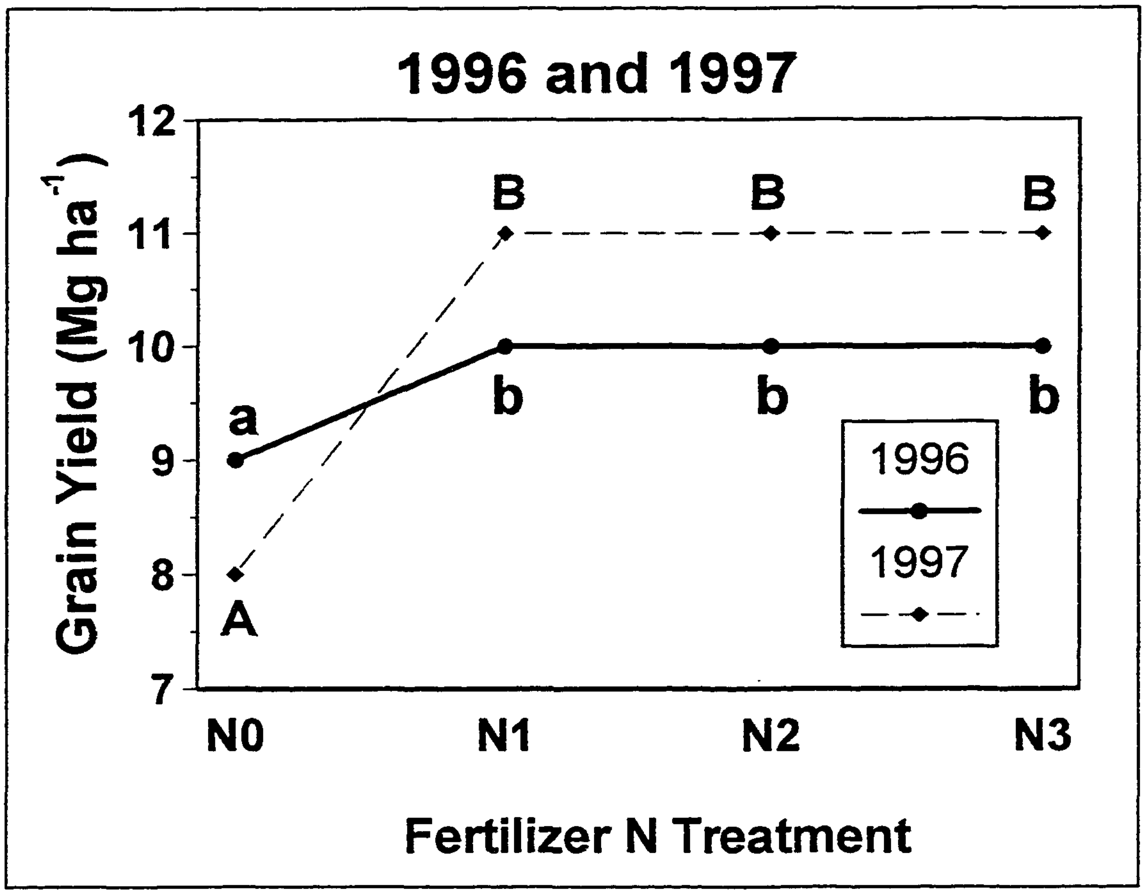


Figure 3.4. Grain yield as affected by N fertilizer rate in 1996 and 1997.

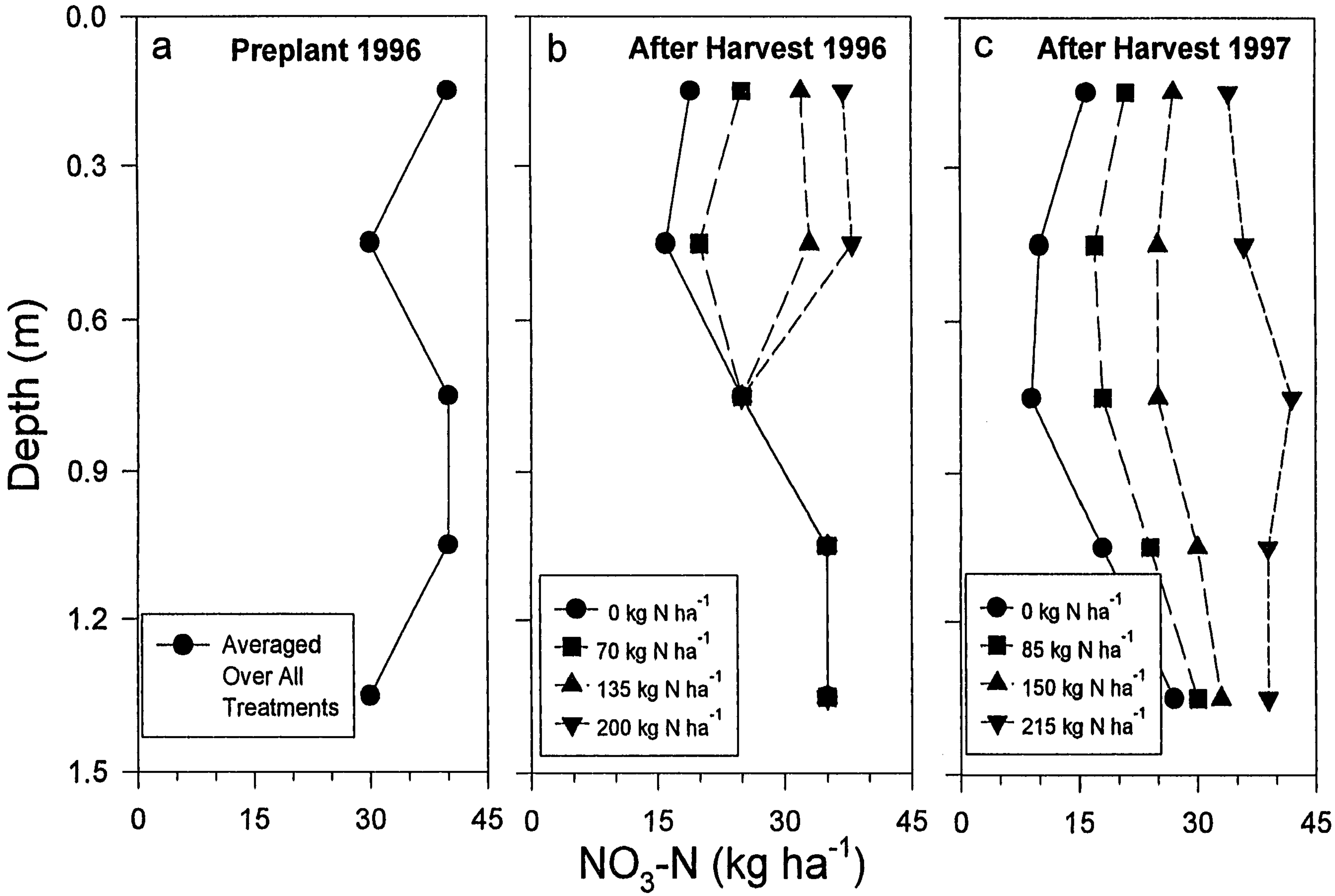


Figure 3.5. Soil profile NO_3-N distribution, preplant (prior to experiment initiation) 1996, after harvest in 1996 and 1997.

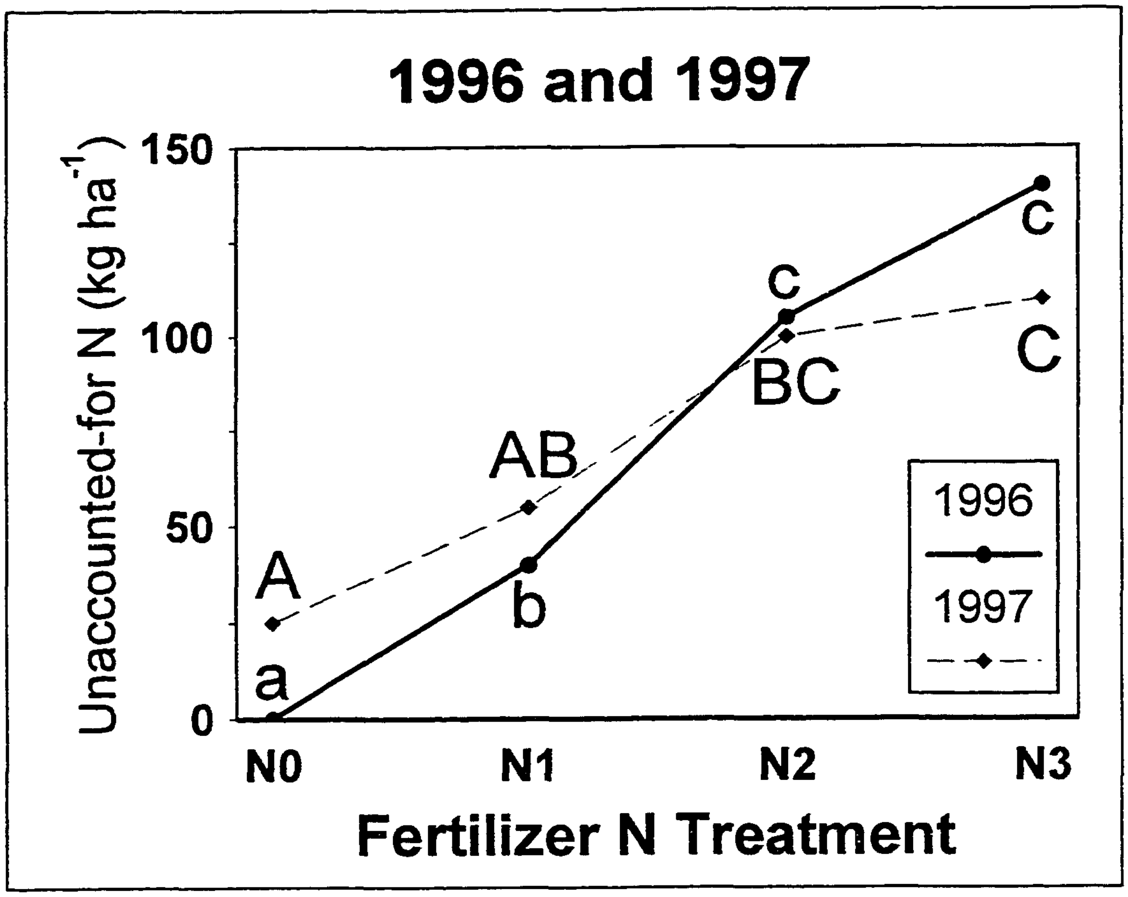


Figure 3.6. Unaccounted-for N as affected by N fertilizer rate in 1996 and 1997.

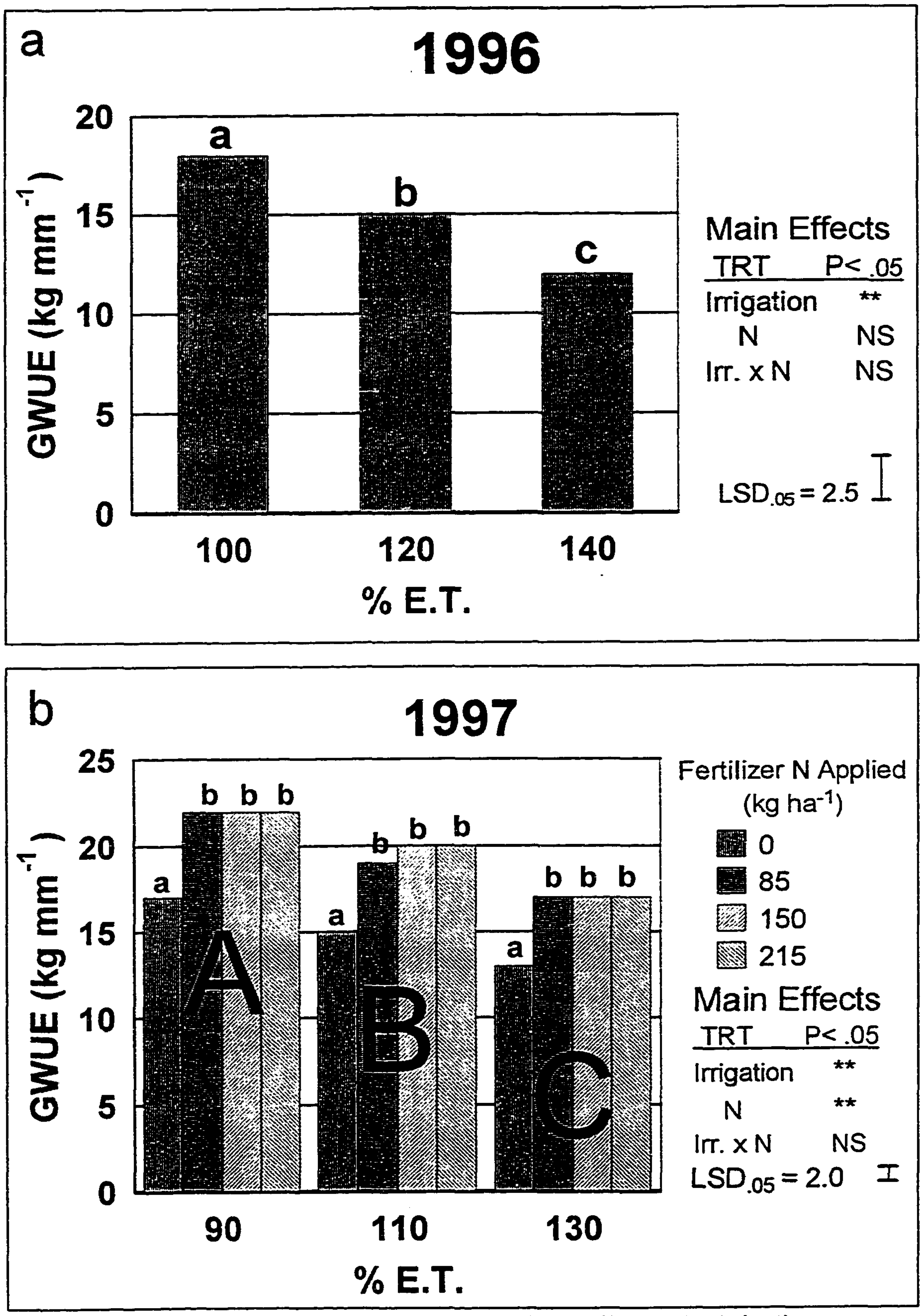


Figure 3.7. Grain water use efficiency (GWUE) as affected by irrigation treatment in 1996 and 1997.

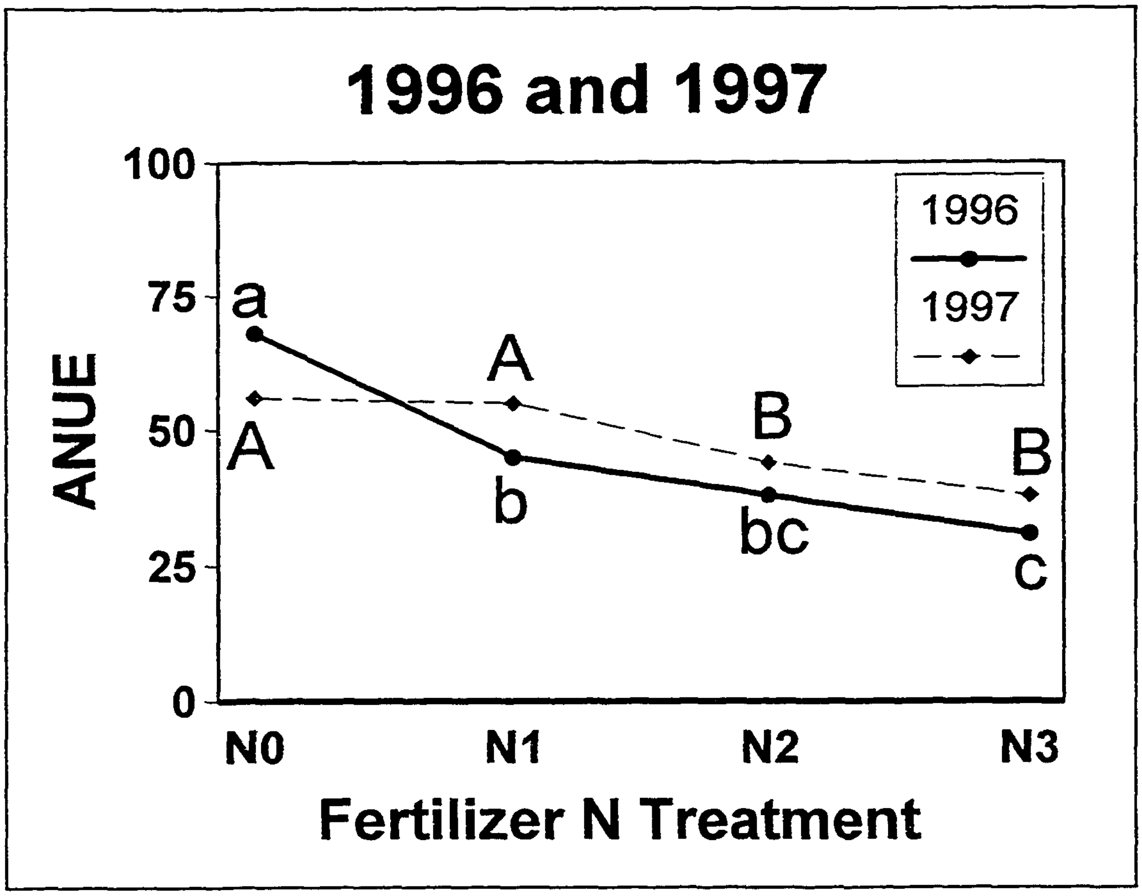


Figure 3.8. Available nitrogen use efficiency (ANUE) as affected by N fertilizer rate in 1996 and 1997.

LITERATURE CITED

Bergstrom, L. and R. Johansson. 1991. Leaching of nitrate from monolith lysimeters of different types of agricultural soils. J. Environ. Qual. 20:801-807.

Booltink, H.W.G. 1995. Field monitoring of nitrate leaching and water flow in a structured clay soil. Agric. Ecosystems & Environ. 52:251-261.

Broner, I. 1993. Irrigation scheduling: The water balance approach. Colorado State University Coop. Ext. Crop Series no. 4.707, Ft. Collins, CO.

Dubois, D. 1994. Nutrient survey. North Front Range Water Quality Planning Association: Loveland CO.

Dumas, J.B.A. 1831. Procédés de l'analyse. Ann. Chim. Phys. 2 47:198-213.

Emond, H., J.C. Loftis, and T. Podmore. 1993. Impact of irrigation water use on water quality in the Central Colorado Water Conservancy District. Colorado Water Resources Research Institute. Ft. Collins, CO.

Firestone, M.K. 1982. Biological denitrification. *In* F.J. Stevenson, J.M. Bremner, R.D. Hauck, and D.R. Keeney (eds.) Nitrogen in agricultural soils. ASA-CSSA-SSSA, Madison, WI. p. 289-326.

Gerwing, J.R., A.C. Caldwell, and L.L. Goodroad. 1979. Fertilizer nitrogen distribution under irrigation between soil, plant, and aquifer. J. Environ. Qual. 8:281-284.

Gormly, J.R. and R.F. Spalding. 1979. Sources and concentrations of nitrate-nitrogen in ground water of the Central Platte region, Nebraska. Ground Water 17:291-301.

Hansen, V.E., O.A. Israelson, and G. Stingham. 1980. Irrigation principles and practice. John Wiley & Sons, Inc., New York. p.52.

Hatlitligil, M.B., R.A. Olson, and W.A. Compton. 1984. Yield, water use and nutrient uptake of corn hybrids under varied irrigation and nitrogen regimes. Fert. Res. 5:321-333.

Hudson, C.A. and L.A. Fretwell. 1996. Colorado agricultural statistics. Colorado Agric. Stat. Svc. Lakewood, CO.

Hergert, G.W. 1986. Nitrate leaching through sandy soil as affected by sprinkler irrigation management. J. Environ. Qual. 15:272-278.

Hergert, G.W., R.B. Ferguson, and C.A. Shapiro. 1995. Fertilizer suggestions for corn. NebGuide, Univ. of Nebraska, Lincoln.

Jensen, M.E., R.D. Burman, and R.G. Allen (eds.). 1990. Evapotranspiration and irrigation water requirements. Am. Soc. Civil Eng. New York.

Keeney, D.R., and D.W. Nelson. 1982. Nitrogen - inorganic forms. *In* Page, A.L. (ed) Methods of soil analysis, Part 2, chemical and microbiological properties. p. 648-649.

Meisinger, J.J. and G.W. Randall. 1991. Estimating nitrogen budgets for soil-crop systems. *In* R.F. Follett, D.R. Keeney, and R.M. Cruse (eds.) Managing nitrogen for groundwater quality and farm profitability. SSSA. Madison, WI. p. 85-124.

Mortvedt, J.J., D.G. Westfall and R.L. Croissant. 1996. Fertilizer suggestions for corn. Colorado State University Coop. Ext. no. 0.538, Ft. Collins, CO.

Mosier, A.R., W.D. Guenzi and E.E. Schweizer. 1986. Soil losses of dinitrogen and nitrous oxide form irrigated crops in northeastern Colorado. Soil Sci. Soc. Am. J. 50:344-348.

Porter, L.K. 1995. Depleted ^{15}N carryover, leaching and uptake for three years of irrigated corn. J. Contaminant Hydro. 20:209-226.

Ritchie, S.W., J.J. Hanway, and G.O. Benson. 1993. How a corn plant develops: Special Report No. 48. Cooperative Ext. Svc., Iowa State Univ. Ames IA.

Ritter, W.F., R.W. Scarborough, and A.E. M. Chirnside. 1993. Nitrate leaching under irrigated corn. J. Irrigation and Drainage Eng. 119:544-553.

Russelle, M.P., E.J. Deibert, R.D. Hauck, M Stevanovic, and R.A. Olson. 1981. Effects of water and nitrogen management of on yield and ^{15}N-depleted fertilizer-use efficiency of irrigated corn. Soil Sci. Soc. Am. J. 45:553-558.

SAS Institute. 1985. SAS user's guide: Statistics. Version 5 ed. SAS Inst. Cary, NC.

Sexton, B.T,, J.F. Moncrief, C.J. Rosen, S.C. Gupta, and H.H. Cheng. 1996. Optimizing nitrogen and irrigation inputs for corn based on nitrate leaching and yield on a coarse-textured soil. J. Environ. Qual. 25:982-992.

Smith, S.J., and D.K. Cassel. 1991. Estimating nitrate leaching in soil materials. *In* Follett, R. (ed.) Managing nitrogen for groundwater quality and farm profitability. Soil Sci. Soc. Am. Madison, WI. p.165-188.

Steele, R.G.D., and J.H. Torrie. 1980. Principles and procedures of statistics: A biometrical approach. 2d ed. McGraw-Hill, New York. p.377-398.

Stewart, B.A., F.G. Viets, G.L. Hutchinson, W.D. Kemper, F.E. Clark, M.L. Fairbourn, and F. Strauch. 1967. Distribution of nitrates and other water pollutants under fields and corrals in the middle South Platte Valley of Colorado. No. 41-234. USDA-ARS, Ft. Collins, CO.

United States Geological Survey (USGS). 1995. Nutrients in the South Platte River, 1993-95. National Water Quality Assessment Program. Colorado Fact Sheet; Denver, CO.

Vinten, A.J.A., B.J. Vivian, F. Wright, and R.S. Howard. 1994. A comparative study of nitrate leaching from soils of differing textures under similar climatic and cropping conditions. J. of Hydrology 159:197-213.

Weinhold, B.J., T.P. Trooien, and G.A. Reichman. 1995. Yield and nitrogen use efficiency of irrigated corn in the northern Great Plains. Agron. J. 87:842-846.

Wright, J.L. 1982. New evapotranspiration crop coefficients. J. Irr. and Drainage Divn. ASCE, 108(IJ1):57-74.

APPENDIX A

Plant and soil ^{15}N and ^{15}N budget data for 1996 and 1997

A1. Plant ^{15}N data 1996: Plant weights for grain and leaves row 1 and row 2.

Plot #	W TRT	N TRT	REP	Grain Row 1 gram/2plts	Grain Row 2 gram/2plts	Leaves Row 1 gram/2plts	Leaves Row 2 gram/2plts
1	140	0	1	333.47	321.27	108.64	117.88
2	140	135	1	324.92	353.58	120.28	130.91
3	140	200	1	309.72	248.64	124.69	112.11
4	140	70	1	323.91	330.04	96.98	129.83
5	100	135	2	348.37	359.67	92.74	140.89
6	100	0	2	330.42	359.79	110.41	111.98
7	100	200	2	331.92	359.05	98.42	135.84
8	100	70	2	371.45	360.32	123.41	133.51
9	120	0	2	312.6	349.22	115.43	101.85
10	120	135	2	285.65	378.56	84.57	98.78
11	120	70	2	327.36	330.27	116.57	114.03
12	120	200	2	350.02	329.92	109.03	111.88
13	100	135	1	388.26	383.02	106.24	117.01
14	100	0	1	327.4	276.13	108.22	81.65
15	100	200	1	380.7	338.24	113.7	113.45
16	100	70	1	325.7	284.83	117.98	88.6
17	120	0	1	307.1	302.95	111.04	95.12
18	120	70	1	336.82	368.51	133	123.45
19	120	135	1	298.5	332.85	103.61	129.54
20	120	200	1	307.68	422.42	110.56	153.71
21	140	70	2	310.25	352.95	110.72	111.41
22	140	135	2	299.84	346.75	111.75	124.55
23	140	200	2	369.51	295.55	144.27	95.04
24	140	0	2	363.35	314.54	109.01	98.4
25	140	200	4	308.7	333.75	101.23	131.32
26	140	70	4	358.44	310.66	110.2	100.24
27	140	135	4	317.36	355.96	88.53	108.98
28	140	0	4	230.18	431.25	101.9	129.36
29	100	135	3	363.51	339.04	103.52	112.2
30	100	200	3	316.18	336.79	105.69	141.35
31	100	0	3	311.64	337.22	80.1	99.02
32	100	70	3	278.63	348.51	89.1	113.36
33	140	0	3	279.21	293.13	101.8	95.54
34	140	135	3	331.55	312.06	111.36	100.76
35	140	200	3	339.86	317.61	123.09	115.8
36	140	70	3	329.47	399.75	110.35	136.3
37	120	200	4	281.77	326.12	110.7	109.56
38	120	70	4	367.51	289.4	137.38	126.89
39	120	0	4	264.25	239.08	82.7	67.52
40	120	135	4	376.12	328.95	115.14	112.57
41	100	70	4	308.86	369.38	117.38	99.06
42	100	135	4	320.9	328.32	129.74	133.17
43	100	0	4	312.98	336.73	102.2	107.35
44	100	200	4	356.55	302.91	158.99	124.11
45	120	0	3	365.91	405.9	152.2	141.39
46	120	70	3	294.75	272.73	116.82	112.01
47	120	135	3	382.7	316.26	144.39	126.63
48	120	200	3	315.55	333.52	141.4	133.82

A2. Plant ^{15}N data 1996: Plant weights stalks and cobs row 1 and row 2 .

Plot #	Stalks Row 1 gram/2plts	Stalks Row 2 gram/2plts	Cobs Row 1 gram/2plts	Cobs Row 2 gram/2plts
1	145.28	153.06	62.36	57.49
2	181.88	160.39	64.04	65.11
3	208.69	135.84	67.49	53.39
4	157.15	199.85	62.72	67.79
5	176.09	161.55	66.39	63.76
6	185.41	146.66	67.84	69.38
7	184.01	97.11	62.82	78.61
8	193.44	206.77	72.82	75.84
9	180.77	191.31	63.73	61.92
10	161.58	185.89	57.3	64.97
11	237.71	222.05	88.33	65.49
12	200	191.21	60.36	65.59
13	203.1	176.39	71.1	70.46
14	212.89	134.49	64.27	55.41
15	187.47	182.24	70.05	69.64
16	207.39	151.97	69.32	53.05
17	155.44	169.17	60.31	60
18	175.71	141.35	66.29	68.07
19	166.87	166.69	58.24	61.42
20	155.13	170.67	64.07	73.65
21	164.06	135.74	58.1	58.79
22	164.58	171.75	66.59	61.42
23	178.03	139.8	71.63	51.99
24	194.32	155.75	62.72	60.65
25	167.12	192.6	63.96	69.63
26	199.02	150.16	70.21	54.65
27	143.1	225.67	59.65	70.02
28	160.66	198.73	59	82
29	202.53	171.21	71.23	65.84
30	196.55	254.37	71.53	71.36
31	125.69	172.37	54.11	59.91
32	125.41	161.68	48.58	64.86
33	144.85	148.31	56.16	56.25
34	84.84	178.13	67.73	54.99
35	185.07	188.09	69.29	64.62
36	145.72	206.79	67.3	83.86
37	142.86	143.42	64.6	62.43
38	186.77	168.92	75.79	63.89
39	102.68	107.05	45.35	47.27
40	177.27	106.37	71.01	63.8
41	129.45	160.6	61.12	67.88
42	161.56	143.08	65.81	67.68
43	91.87	127.2	57.61	63.09
44	166.58	127.48	70.33	56.18
45	186.38	132.51	74.81	71.06
46	147.78	106.71	62.25	48.45
47	144.1	146.38	70.11	60.32
48	159.22	154.07	62.07	67.55

A3. Plant ^{15}N data 1996: %N and atom % ^{15}N in grain and leaves .

Plot #	grain %N Row 1	grain %N Row 2	grain atom% ^{15}N Row 1	leaves %N Row 1	leaves %N Row 2	leaves atom% ^{15}N Row 1
1	1.250	1.432	0.37358	1.294	1.312	0.36974
2	1.439	1.441	1.13063	1.258	1.271	1.36257
3	1.439	1.419	1.45776	1.413	1.408	1.61776
4	1.200	1.333	0.75380	1.184	1.224	0.88899
5	1.378	1.305	1.11497	1.173	1.148	1.28520
6	1.507	1.381	0.37185	1.198	1.183	0.36981
7	1.363	1.396	1.35882	1.385	1.403	1.58291
8	1.356	1.384	0.68136	1.287	1.324	0.77798
9	1.385	1.434	0.37071	1.393	1.337	0.37175
10	1.278	1.230	1.16229	1.302	1.262	1.34681
11	1.284	1.378	0.80693	1.385	1.349	0.98129
12	1.358	1.393	1.56026	1.338	1.463	1.72202
13	1.287	1.281	1.35169	1.304	1.277	1.53959
14	1.373	1.255	0.36981	1.331	1.268	0.36911
15	1.360	1.330	1.38006	1.322	1.348	1.52530
16	1.398	1.200	0.79728	1.416	1.371	0.94443
17	1.271	1.378	0.36984	1.104	1.279	0.36937
18	1.320	1.131	0.90339	1.103	1.123	1.02582
19	1.332	1.279	1.00114	1.213	1.181	1.20254
20	1.337	1.279	1.61789	1.276	1.248	1.81362
21	1.229	1.314	0.87297	1.244	1.126	0.96685
22	1.376	1.326	1.22201	1.312	1.302	1.41154
23	1.355	1.175	1.53830	1.236	1.241	1.69308
24	1.343	1.339	0.36775	1.236	1.158	0.37053
25	1.461	1.398	1.38129	1.496	1.524	1.49381
26	1.206	1.132	0.77571	1.354	1.219	0.82882
27	1.277	1.457	1.22175	1.247	1.388	1.39779
28	1.496	1.260	0.36913	1.382	1.232	0.37142
29	1.446	1.352	1.25762	0.975	1.173	1.35848
30	1.512	1.538	1.51126	1.448	1.370	1.57332
31	1.279	1.299	0.36990	0.982	1.123	0.37851
32	1.199	1.220	0.82993	0.893	1.081	0.96406
33	1.306	1.209	0.36963	1.029	0.916	0.37527
34	1.306	1.503	1.06984	1.221	1.298	1.13442
35	1.350	1.368	1.57805	1.321	1.254	1.65748
36	1.181	1.204	0.85916	1.202	1.174	0.94993
37	1.374	1.264	1.61349	1.385	1.221	1.77038
38	1.323	1.302	0.83017	1.352	1.208	0.95093
39	1.048	1.068	0.37577	0.940	0.898	0.37813
40	1.311	1.293	1.29408	1.204	1.147	1.32217
41	1.076	1.147	0.76629	1.144	1.287	0.80464
42	1.417	1.307	1.21159	1.218	1.212	1.42821
43	1.315	1.074	0.37037	0.955	0.850	0.38042
44	1.448	1.272	1.58785	1.190	1.105	1.67616
45	1.383	1.202	0.36985	1.032	0.864	0.37516
46	1.252	1.266	0.85610	1.205	1.124	0.98186
47	1.229	1.366	1.31592	1.154	1.205	1.42803
48	1.352	1.251	1.47326	1.235	1.236	1.55097

A4. Plant ^{15}N data 1996: %N and atom % ^{15}N in stalk and cobs .

Plot #	stalk %N Row 1	stalk %N Row 2	stalk atom% ^{15}N Row 1	cobs %N Row 1	cobs %N Row 2	cobs atom % ^{15}N Row 1
1	0.305	0.310	0.37110	0.235	0.222	0.37007
2	0.295	0.346	1.24829	0.258	0.270	1.21021
3	0.411	0.484	1.53119	0.252	0.222	1.52829
4	0.342	0.290	0.82240	0.190	0.228	0.78902
5	0.399	0.482	1.18648	0.226	0.218	1.11509
6	0.336	0.326	0.37127	0.200	0.267	0.37129
7	0.405	0.441	1.45375	0.299	0.231	1.40635
8	0.422	0.353	0.73636	0.229	0.245	0.71773
9	0.305	0.339	0.37194	0.237	0.234	0.37064
10	0.342	0.425	1.25837	0.248	0.234	1.12061
11	0.383	0.348	0.89327	0.193	0.232	0.82852
12	0.419	0.418	1.62237	0.243	0.209	1.44624
13	0.448	0.391	1.43260	0.278	0.241	1.41568
14	0.341	0.293	0.37111	0.215	0.222	0.36899
15	0.476	0.377	1.47486	0.261	0.264	1.39652
16	0.449	0.301	0.85634	0.259	0.249	0.83715
17	0.270	0.307	0.37140	0.242	0.175	0.37029
18	0.305	0.292	0.95912	0.249	0.278	0.93006
19	0.281	0.310	1.09330	0.245	0.239	1.08872
20	0.296	0.439	1.70578	0.246	0.266	1.66167
21	0.315	0.495	0.91961	0.262	0.259	0.91022
22	0.309	0.314	1.29874	0.243	0.227	1.27771
23	0.344	0.366	1.60880	0.255	0.265	1.56552
24	0.301	0.265	0.37323	0.232	0.218	0.37111
25	0.538	0.405	1.43958	0.251	0.235	1.42595
26	0.406	0.291	0.79581	0.297	0.219	0.80037
27	0.372	0.360	1.29529	0.293	0.249	1.17152
28	0.456	0.427	0.37065	0.269	0.261	0.37141
29	0.482	0.392	1.27166	0.311	0.220	1.13856
30	0.533	0.587	1.55286	0.251	0.260	1.49187
31	0.353	0.293	0.37060	0.179	0.194	0.37065
32	0.334	0.422	0.89415	0.231	0.233	0.84195
33	0.248	0.228	0.37082	0.250	0.279	0.37021
34	0.290	0.332	1.04611	0.296	0.257	1.17407
35	0.371	0.357	1.62783	0.252	0.307	1.53623
36	0.248	0.266	0.90456	0.229	0.259	0.88014
37	0.380	0.411	1.69025	0.303	0.259	1.58721
38	0.296	0.424	0.88163	0.280	0.307	0.87710
39	0.253	0.215	0.37186	0.224	0.224	0.37131
40	0.313	0.302	1.31165	0.279	0.287	1.19856
41	0.243	0.306	0.79231	0.262	0.248	0.78645
42	0.294	0.282	1.30494	0.275	0.247	1.19178
43	0.256	0.231	0.37222	0.256	0.263	0.37163
44	0.440	0.331	1.63917	0.282	0.291	1.54959
45	0.230	0.237	0.37210	0.225	0.241	0.37215
46	0.265	0.380	0.92568	0.239	0.285	0.88070
47	0.373	0.334	1.35412	0.314	0.239	1.28843
48	0.453	0.368	1.53542	0.291	0.334	1.43405

A5. Plant ^{15}N data 1996: %Ndff in grain, stalk, leaves, and cobs *.

Plot #	W TRT	N TRT	REP	%Ndff grain	%Ndff stalk	%Ndff leaves	%Ndff cobs
2	140	135	1	36.07	36.43	41.17	34.85
3	140	202	1	28.45	48.17	51.77	48.05
4	140	67	1	29.62	18.75	21.51	17.36
5	100	135	2	34.34	33.86	37.96	30.90
7	100	202	2	30.89	44.96	50.32	42.99
8	100	67	2	31.72	15.18	16.90	14.40
10	120	135	2	32.03	36.85	40.52	31.13
11	120	67	2	36.73	21.69	25.34	19.00
12	120	202	2	31.85	51.96	56.10	44.65
13	100	135	1	35.79	44.08	48.52	43.38
15	100	202	1	32.00	45.84	47.93	42.58
16	100	67	1	31.58	20.16	23.81	19.36
18	120	67	1	42.98	24.42	27.19	23.22
19	120	135	1	25.24	29.99	34.53	29.80
20	120	202	1	30.51	55.42	59.90	53.59
21	140	67	2	39.54	22.78	24.75	22.39
22	140	135	2	36.13	38.52	43.21	37.65
23	140	202	2	32.22	51.40	54.90	49.60
25	140	202	4	30.44	44.37	46.62	43.81
26	140	67	4	29.58	17.64	19.01	17.83
27	140	135	4	38.05	38.38	42.64	33.24
29	100	135	3	42.35	37.40	41.00	31.87
30	100	202	3	34.80	49.07	49.92	46.54
32	100	67	3	32.52	21.73	24.63	19.56
34	140	135	3	30.70	28.04	31.70	33.35
35	140	202	3	35.38	52.19	53.42	48.38
36	140	67	3	39.64	22.16	24.04	21.15
37	120	202	4	32.68	54.78	58.11	50.50
38	120	67	4	36.97	21.21	24.08	21.02
40	120	135	4	41.19	39.06	39.50	34.37
41	100	67	4	26.19	17.50	18.01	17.26
42	100	135	4	38.34	38.78	43.90	34.08
44	100	202	4	33.63	52.66	54.19	48.94
46	120	67	3	32.37	23.04	25.37	21.17
47	120	135	3	36.88	40.82	43.89	38.10
48	120	202	3	30.54	48.35	49.00	44.14

*Plots with no ^{15}N applied have been omitted as values are zero.

A6. Plant ^{15}N data 1996: %FNR in grain, leaves, stalk, cobs, stover, and whole plant *.

Plot #	%FNR grain	%FNR leaves	%FNR stalk	%FNR cobs	%FNR stover	%FNR whole plt
2	36.07	15.30	4.68	1.39	21.37	57.44
3	28.45	13.66	5.87	1.09	20.62	49.07
4	29.62	13.21	4.76	1.07	19.04	48.66
5	34.34	12.05	5.89	1.05	18.99	53.33
7	30.89	12.98	4.22	1.27	18.48	49.38
8	31.72	9.77	3.84	1.07	14.68	46.40
10	32.03	12.36	5.75	1.07	19.18	51.22
11	36.73	16.41	5.88	1.40	23.69	60.42
12	31.85	13.71	6.72	1.00	21.43	53.28
13	35.79	16.36	7.79	1.87	26.01	61.80
15	32.00	11.48	5.71	1.23	18.43	50.43
16	31.58	14.67	5.09	1.35	21.11	52.69
18	42.98	17.46	5.21	1.85	24.51	67.50
19	25.24	11.28	3.46	1.01	15.75	40.99
20	30.51	13.99	5.25	1.49	20.73	51.24
21	39.54	14.65	6.22	1.54	22.40	61.94
22	36.13	15.61	4.72	1.33	21.66	57.79
23	32.22	12.85	4.87	1.26	18.98	51.20
25	30.44	12.93	5.95	1.12	20.00	50.44
26	29.58	11.58	4.82	1.29	17.69	47.27
27	38.05	12.98	6.07	1.37	20.42	58.47
29	42.35	11.12	6.19	1.36	18.67	61.02
30	34.80	12.62	6.53	1.34	20.49	55.29
32	32.52	11.07	5.30	1.16	17.53	50.05
34	30.70	9.91	3.50	1.32	14.73	45.44
35	35.38	12.98	5.60	1.43	20.01	55.39
36	39.64	15.84	4.52	1.64	21.99	61.63
37	32.68	13.17	4.90	1.42	19.50	52.18
38	36.97	15.55	6.10	1.87	23.52	60.49
40	41.19	12.37	4.83	1.53	18.73	59.92
41	26.19	10.66	3.13	1.28	15.07	41.26
42	38.34	13.92	3.99	1.39	19.30	57.64
44	33.63	13.91	4.71	1.40	20.02	53.65
46	32.37	15.20	4.25	1.38	20.83	53.20
47	36.88	16.42	4.91	1.61	22.94	59.82
48	30.54	12.20	4.91	1.41	18.52	49.07

*Plots with no ^{15}N applied have been omitted as values are zero.

A7. Plant ^{15}N data 1996: Ndff in grain, leaves, stalk, cobs, and whole plant*.

Plot #	grain Ndff kg/ha	leaf Ndff kg/ha	stalk Ndff kg/ha	cobs Ndff kg/ha	whole plt Ndff kg/ha
2	39.87	21.02	5.92	1.82	68.63
3	29.94	28.42	10.09	2.59	71.04
4	33.68	9.14	3.54	0.66	47.01
5	34.37	18.62	5.46	1.47	59.92
7	32.00	25.82	8.48	2.55	68.84
8	33.81	6.75	2.77	0.76	44.09
10	30.36	18.48	5.94	1.40	56.18
11	35.40	11.88	3.69	1.02	51.99
12	32.60	29.73	10.94	2.07	75.33
13	50.30	23.26	9.03	2.71	85.30
15	32.14	24.47	9.80	2.47	68.88
16	35.95	7.90	4.00	1.10	48.95
18	36.34	11.99	3.97	1.21	53.50
19	28.77	15.65	4.20	1.34	49.96
20	39.96	30.11	8.55	2.67	81.29
21	35.16	9.45	3.31	1.08	49.00
22	38.51	21.89	5.34	1.93	67.67
23	32.59	27.07	7.90	2.87	70.42
25	31.41	26.82	10.83	2.22	71.28
26	32.67	7.75	3.47	1.18	45.06
27	35.83	19.54	6.09	1.84	63.30
29	36.68	14.25	8.64	2.23	61.81
30	36.17	28.99	9.22	2.64	77.02
32	34.75	8.52	3.06	0.69	47.02
34	35.30	13.71	4.00	2.11	55.13
35	33.75	28.56	8.66	2.67	73.64
36	34.31	11.37	3.00	1.03	49.72
37	31.61	27.11	8.64	3.13	70.48
38	37.27	12.66	2.39	1.41	53.73
40	36.94	17.74	5.32	2.15	62.15
41	30.46	7.98	1.69	0.88	41.01
42	35.28	19.52	4.49	1.95	61.25
44	34.26	27.36	9.49	3.07	74.18
46	35.42	10.66	2.92	1.00	50.00
47	40.46	21.64	6.57	2.65	71.33
48	29.11	25.40	9.01	2.52	66.04

*Plots with no ^{15}N applied have been omitted as values are zero.

A8. Plant ^{15}N data 1996: N uptake in grain, leaves, stalk, cobs, stover, and whole plant.

Plot #	W TRT	N TRT	REP	N uptake grain kg/ha	N uptake leaves kg/ha	N uptake stalk kg/ha	N uptake cobs kg/ha	N uptake stover kg/ha	N uptake whole plt kg/ha
1	140	0	1	138.29	29.15	14.45	4.44	48.04	186.33
2	140	135	1	153.87	33.60	17.28	4.82	55.71	209.58
3	140	200	1	125.68	37.66	24.30	4.17	66.13	191.82
4	140	70	1	130.46	32.17	17.76	3.97	53.90	184.36
5	100	135	2	149.59	31.55	23.42	3.81	58.79	208.38
6	100	0	2	157.00	30.80	14.19	5.03	50.02	207.01
7	100	200	2	150.16	39.68	18.73	4.23	62.64	212.80
8	100	70	2	157.87	34.70	17.72	5.79	58.20	216.07
9	120	0	2	146.91	36.50	17.86	3.76	58.12	205.04
10	120	135	2	131.19	36.65	20.99	4.49	62.13	193.32
11	120	70	2	125.28	36.19	18.99	5.72	60.90	186.19
12	120	200	2	147.32	37.69	25.79	4.36	67.84	215.16
13	100	135	1	155.95	33.42	23.78	4.88	62.08	218.04
14	100	0	1	124.88	33.83	14.84	4.07	52.74	177.62
15	100	200	1	152.26	34.06	24.83	5.02	63.91	216.17
16	100	70	1	124.89	35.40	17.67	4.66	57.73	182.62
17	120	0	1	127.26	29.77	14.77	4.70	49.24	176.50
18	120	70	1	105.26	30.05	14.93	5.23	50.20	155.46
19	120	135	1	129.82	32.38	15.52	3.98	51.88	181.70
20	120	200	1	150.45	33.16	18.87	4.82	56.85	207.30
21	140	70	2	105.58	34.01	19.12	4.75	57.88	163.45
22	140	135	2	137.59	36.73	16.49	5.06	58.28	195.87
23	140	200	2	132.55	35.49	18.88	4.79	59.15	191.70
24	140	0	2	143.20	29.88	15.60	6.28	51.76	194.96
25	140	200	4	144.67	44.66	26.72	5.20	76.58	221.25
26	140	70	4	123.21	37.08	19.15	4.50	60.73	183.93
27	140	135	4	144.95	35.15	21.27	4.90	61.33	206.28
28	140	0	4	143.52	32.75	19.44	4.52	56.71	200.23
29	100	135	3	154.79	28.45	22.28	5.87	56.61	211.40
30	100	200	3	156.80	35.77	26.54	5.69	68.01	224.81
31	100	0	3	131.72	27.25	15.14	4.27	46.66	178.39
32	100	70	3	119.47	24.22	17.09	4.52	45.83	165.29
33	140	0	3	113.35	22.25	10.98	4.07	37.30	150.65
34	140	135	3	142.37	30.63	16.79	4.64	52.06	194.44
35	140	200	3	140.73	34.80	21.38	5.08	61.27	202.00
36	140	70	3	109.13	33.94	14.27	4.58	52.79	161.92
37	120	200	4	126.30	32.41	17.83	4.30	54.53	180.83
38	120	70	4	119.23	34.77	20.16	5.20	60.12	179.35
39	120	0	4	83.89	19.93	7.74	3.78	31.44	115.34
40	120	135	4	144.60	31.47	16.63	5.39	53.50	198.09
41	100	70	4	118.71	29.86	12.54	4.73	47.13	165.84
42	100	135	4	139.23	32.56	13.83	4.71	51.10	190.33
43	100	0	4	122.25	22.62	8.40	4.98	36.00	158.26
44	100	200	4	141.25	29.09	17.84	4.76	51.70	192.95
45	120	0	3	157.11	23.65	11.72	4.38	39.75	196.86
46	120	70	3	112.51	31.08	12.92	3.24	47.24	159.75
47	120	135	3	142.85	33.52	16.18	4.38	54.08	196.93
48	120	200	3	133.04	34.70	20.25	4.88	59.82	192.86

A9. Plant ^{15}N data 1996: Dry matter (DM) production in grain, leaves, stalk, cobs, stover, and whole plant .

Plot #	DM prod grain kg/ha	DM prod leaves kg/ha	DM prod stalk kg/ha	DM prod cobs kg/ha	DM prod stover kg/ha	DM prod whole plt kg/ha
1	10312	3095	4699	1888	9682	19994
2	10686	3956	5391	2034	11381	22067
3	8794	3730	5426	1904	11060	19854
4	10300	3572	5623	2056	11251	21550
5	11152	3680	5318	2050	11047	22199
6	10871	2873	4285	2004	9161	20032
7	10883	3690	4428	2228	10345	21228
8	11525	3101	4571	2184	9856	21382
9	10424	3265	5545	1664	10474	20898
10	10461	3203	5473	1926	10601	21062
11	9413	3317	5194	2423	10933	20346
12	10709	3479	6162	1984	11625	22334
13	12148	3516	5662	2230	11408	23555
14	9506	2833	4684	1885	9402	18907
15	11323	3578	5823	2200	11601	22924
16	9616	3096	4715	1927	9738	19354
17	9608	3247	5113	1895	10255	19863
18	8589	4039	4994	2116	11149	19738
19	9944	3672	5254	1885	10810	20754
20	11499	3690	5131	2169	10990	22489
21	8303	2869	4722	1841	9431	17735
22	10184	3722	5297	2016	11035	21219
23	10475	3769	5321	1947	11037	21512
24	10677	3267	5514	1943	10723	21400
25	10119	3663	5666	2104	11432	21551
26	10538	3314	5500	1967	10781	21319
27	10605	3111	5808	2042	10961	21566
28	10418	3327	4400	1906	9633	20051
29	11065	3398	5099	2159	10655	21721
30	10284	3576	4739	2251	10566	20850
31	10220	2821	4694	1796	9311	19531
32	9877	3189	4522	1787	9497	19375
33	9014	3108	4617	1770	9496	18510
34	10137	3341	5402	1933	10676	20812
35	10355	3763	5877	2109	11749	22104
36	9154	3885	5552	2223	11660	20814
37	9574	3469	4509	2001	9979	19553
38	9086	3532	5602	2121	11256	20342
39	7927	2366	3303	1459	7128	15055
40	11105	3586	5412	2123	11122	22227
41	10682	3409	4568	2032	10009	20691
42	10225	3511	4798	2102	10411	20637
43	10233	3300	3450	1901	8652	18885
44	10386	4459	4631	1993	11083	21469
45	12156	4152	5023	1982	11157	23313
46	8938	3604	4008	1744	9356	18294
47	11009	4269	4575	2054	10898	21907
48	10223	4020	4934	2042	10996	21218

A10. Plant ^{15}N data 1997: Plant weights of grain and leaves row 1 and row 2 .

Plot #	W TRT	N TRT	REP	Grain Row 1 gram/2plts	Grain Row 2 gram/2plts	Leaves Row 1 gram/2plts	Leaves Row 2 gram/2plts
1	130	0	1	484.15	507.92	171.70	177.83
2	130	135	1	281.46	307.20	122.62	125.00
3	130	200	1	245.68	278.37	131.94	109.75
4	130	70	1	259.35	329.75	129.59	123.11
5	90	135	2	357.91	304.55	157.00	134.51
6	90	0	2	416.34	198.74	172.22	94.48
7	90	200	2	194.01	242.30	94.01	112.25
8	90	70	2	259.06	170.98	117.70	74.68
9	110	0	2	170.16	262.98	90.65	127.95
10	110	135	2	382.22	276.92	165.22	127.96
11	110	70	2	359.31	267.09	147.08	113.08
12	110	200	2	175.56	326.02	86.69	156.99
13	90	135	1	322.94	353.01	146.05	167.48
14	90	0	1	253.48	321.30	107.27	113.16
15	90	200	1	225.11	255.67	91.39	113.87
16	90	70	1	355.33	319.14	197.31	130.62
17	110	0	1	275.31	358.53	99.91	134.55
18	110	70	1	251.72	356.73	106.71	156.42
19	110	135	1	349.05	326.38	128.93	120.17
20	110	200	1	214.13	256.36	112.22	112.02
21	130	70	2	240.83	326.29	104.97	122.89
22	130	135	2	178.19	347.59	92.04	151.60
23	130	200	2	261.56	152.11	126.00	76.92
24	130	0	2	332.77	175.28	153.17	65.08
25	130	200	4	207.90	321.60	116.02	148.21
26	130	70	4	386.38	279.55	160.27	110.09
27	130	135	4	280.32	115.77	117.29	83.18
28	130	0	4	162.46	349.17	78.11	125.67
29	90	135	3	278.76	272.42	123.46	113.02
30	90	200	3	230.87	220.99	120.00	118.28
31	90	0	3	202.42	345.68	104.01	103.59
32	90	70	3	224.41	283.01	112.04	120.51
33	130	0	3	257.12	100.24	106.52	65.41
34	130	135	3	254.07	450.95	108.69	141.60
35	130	200	3	176.98	527.74	79.94	176.34
36	130	70	3	287.26	233.98	111.35	97.64
37	110	200	4	194.10	159.23	92.03	69.15
38	110	70	4	230.32	177.44	97.28	69.74
39	110	0	4	249.64	175.73	142.15	69.86
40	110	135	4	368.42	351.10	157.75	137.26
41	90	70	4	227.89	85.89	141.33	80.78
42	90	135	4	130.26	288.22	73.69	123.03
43	90	0	4	290.75	185.47	76.03	84.52
44	90	200	4	273.49	239.65	102.53	114.80
45	110	0	3	438.27	182.45	160.75	118.46
46	110	70	3	189.93	267.09	95.43	113.08
47	110	135	3	309.21	318.13	138.30	128.46
48	110	200	3	218.94	228.31	92.71	80.32

A11. Plant ^{15}N data 1997: Plant weights stalks and cobs row 1 and row 2 .

Plot #	Stalks Row 1 gram/2plts	Stalks Row 2 gram/2plts	Cobs Row 1 gram/2plts	Cobs Row 2 gram/2plts
1	113.60	139.73	84.13	99.31
2	115.52	98.52	57.30	48.09
3	160.93	96.41	63.93	54.15
4	141.60	113.70	65.92	57.49
5	136.95	107.30	79.99	77.76
6	137.59	87.35	95.32	34.36
7	86.38	132.17	47.13	60.36
8	103.74	75.34	59.15	37.71
9	50.75	144.36	43.94	69.12
10	136.26	123.03	79.69	58.74
11	127.25	102.07	79.68	52.02
12	79.45	141.70	42.22	86.60
13	144.85	183.27	72.70	100.61
14	65.05	107.24	41.36	73.01
15	64.15	81.52	43.68	45.47
16	139.03	120.53	84.17	61.74
17	43.89	122.38	41.06	62.01
18	82.85	134.47	46.84	68.62
19	84.18	91.22	50.53	56.51
20	99.51	134.26	38.44	60.91
21	77.23	106.74	37.43	55.58
22	79.61	151.33	35.06	79.56
23	69.99	94.17	54.62	48.67
24	122.97	54.47	55.81	28.25
25	110.09	175.31	47.42	81.82
26	121.38	100.02	73.89	52.47
27	92.23	94.83	56.24	36.73
28	73.78	118.23	35.93	76.22
29	93.50	143.10	56.66	59.71
30	90.10	145.18	68.34	69.47
31	111.77	143.04	53.73	83.50
32	91.62	142.11	50.24	68.36
33	78.30	55.96	39.92	19.75
34	82.14	139.13	63.16	81.99
35	66.80	183.92	34.86	108.09
36	82.56	96.90	41.55	47.68
37	84.97	83.65	47.84	47.64
38	73.91	69.66	42.58	35.41
39	117.49	56.09	56.15	23.94
40	124.24	126.45	71.55	58.42
41	102.63	87.83	34.43	29.04
42	75.31	138.63	40.70	72.95
43	67.32	66.87	66.12	28.81
44	75.10	119.62	52.11	58.43
45	120.69	127.73	59.26	43.60
46	86.91	102.07	44.02	52.02
47	110.62	113.57	63.57	57.89
48	85.30	72.85	52.17	50.50

A12. Plant ^{15}N data 1997: %N and atom % ^{15}N in grain and leaves .

Plot #	grain %n Row 1	grain %n Row 2	grain atom% ^{15}N Row 1	leaves %n Row 1	leaves %n Row 2	leaves atom% ^{15}N Row 1
1	1.248	1.206	0.37622	0.899	0.934	0.37175
2	1.355	1.167	0.52057	1.167	1.020	0.50247
3	1.444	1.216	0.70846	1.192	1.321	0.64914
4	1.396	1.182	0.41377	0.872	0.832	0.41092
5	0.818	1.440	0.48907	1.057	1.091	0.47796
6	1.104	1.166	0.37288	0.675	0.703	0.37226
7	1.271	1.330	0.67061	1.170	1.281	0.67819
8	1.285	1.091	0.40862	1.060	0.732	0.40801
9	1.293	1.476	0.36835	0.853	1.042	0.37188
10	1.173	1.380	0.56342	0.986	1.218	0.52321
11	1.217	1.176	0.42788	1.006	0.807	0.42270
12	1.350	1.432	0.63214	1.169	1.251	0.62900
13	1.329	1.461	0.63739	1.096	1.206	0.63122
14	1.157	1.154	0.36902	0.799	0.851	0.37099
15	1.225	1.387	0.70456	1.026	0.982	0.70708
16	1.328	1.305	0.43565	0.936	1.005	0.43346
17	1.084	1.205	0.37089	0.562	0.685	0.37289
18	1.194	1.322	0.43988	0.664	0.917	0.43844
19	1.372	1.315	0.61086	0.793	0.876	0.58300
20	1.303	1.349	0.60490	0.639	1.147	0.40350
21	1.135	1.180	0.41477	0.703	0.678	0.41411
22	1.255	1.419	0.56446	1.012	1.125	0.54481
23	1.276	1.450	0.57541	1.107	1.220	0.54031
24	1.125	1.218	0.37263	0.605	0.879	0.37369
25	1.448	1.365	0.67401	1.057	1.111	0.64778
26	1.133	1.255	0.46995	0.986	0.872	0.44625
27	1.191	1.529	0.59548	1.017	1.034	0.62682
28	1.244	1.116	0.37365	0.975	0.907	0.37305
29	1.215	1.333	0.67773	0.995	1.086	0.70769
30	1.257	1.653	0.72048	0.992	1.280	0.69966
31	1.515	1.294	0.37134	0.975	0.755	0.37152
32	1.364	1.403	0.46161	1.055	1.108	0.45719
33	0.922	1.180	0.37384	0.495	0.470	0.37314
34	1.173	1.200	0.50406	0.876	0.760	0.49192
35	1.249	1.384	0.66424	0.970	1.139	0.61555
36	1.115	1.049	0.40612	0.653	0.678	0.40411
37	1.322	1.539	0.60052	1.079	1.036	0.58714
38	1.051	1.029	0.41587	0.620	0.697	0.41772
39	1.134	0.867	0.37230	0.639	0.492	0.37164
40	1.259	1.386	0.43339	0.972	1.085	0.43083
41	1.268	1.104	0.40400	0.814	0.834	0.39725
42	1.368	1.525	0.46579	1.085	0.982	0.47374
43	1.314	0.856	0.47032	0.577	0.506	0.37396
44	1.274	1.457	0.78626	0.781	1.181	0.71371
45	1.093	1.211	0.37271	0.561	0.603	0.37333
46	1.082	1.176	0.42472	0.651	0.807	0.42384
47	1.313	1.360	0.60778	0.977	1.060	0.57353
48	1.263	1.350	0.71066	1.200	0.819	0.58753

A13. Plant ^{15}N data 1997: %N and atom % ^{15}N in stalk and cobs.

Plot #	stalk %n Row 1	stalk %n Row 2	stalk atom% ^{15}N Row 1	cobs %n Row 1	cobs %n Row 2	cobs atom% ^{15}N Row 1
1	0.366	0.375	0.37474	0.475	0.261	0.41792
2	0.459	0.404	0.50488	0.389	0.285	0.51837
3	0.280	0.405	0.65150	0.411	0.295	0.70442
4	0.377	0.316	0.45889	0.386	0.346	0.41806
5	0.416	0.343	0.48810	0.384	0.368	0.48642
6	0.231	0.271	0.37645	0.322	0.230	0.42552
7	0.310	0.274	0.66755	0.258	0.251	0.67203
8	0.373	0.246	0.44009	0.453	0.299	0.41631
9	0.214	0.239	0.37673	0.326	0.382	0.40996
10	0.395	0.387	0.52731	0.529	0.297	0.55827
11	0.416	0.268	0.46023	0.423	0.299	0.43323
12	0.374	0.497	0.62802	0.422	0.493	0.63752
13	0.379	0.345	0.60555	0.503	0.319	0.62534
14	0.326	0.345	0.37458	0.292	0.296	0.40964
15	0.369	0.480	0.70129	0.421	0.589	0.71973
16	0.354	0.362	0.45348	0.432	0.269	0.43780
17	0.269	0.289	0.37538	0.328	0.273	0.39831
18	0.296	0.327	0.43605	0.301	0.329	0.45112
19	0.375	0.368	0.57332	0.543	0.273	0.60972
20	0.399	0.338	0.58894	0.360	0.305	0.62650
21	0.346	0.322	0.43109	0.342	0.435	0.42646
22	0.427	0.332	0.54229	0.522	0.343	0.56156
23	0.319	0.399	0.52934	0.410	0.368	0.57070
24	0.201	0.335	0.37907	0.283	0.249	0.40295
25	0.420	0.366	0.67420	0.428	0.424	0.69430
26	0.374	0.303	0.46051	0.296	0.432	0.47256
27	0.327	0.490	0.58247	0.437	0.535	0.64363
28	0.249	0.300	0.37810	0.283	0.317	0.39809
29	0.429	0.300	0.70719	0.460	0.245	0.71641
30	0.331	0.465	0.69855	0.367	0.376	0.72432
31	0.249	0.313	0.37714	0.312	0.271	0.38817
32	0.402	0.360	0.46072	0.287	0.515	0.46375
33	0.269	0.189	0.37447	0.272	0.279	0.39556
34	0.276	0.291	0.49379	0.429	0.432	0.52367
35	0.348	0.364	0.61585	0.303	0.307	0.65621
36	0.293	0.261	0.42642	0.412	0.284	0.41298
37	0.318	0.348	0.57486	0.413	0.268	0.59029
38	0.285	0.259	0.43386	0.444	0.269	0.42074
39	0.206	0.254	0.37733	0.239	0.302	0.39700
40	0.332	0.357	0.44458	0.463	0.305	0.44081
41	0.436	0.585	0.40848	0.817	0.863	0.39961
42	0.379	0.383	0.47974	0.474	0.539	0.48361
43	0.308	0.254	0.37576	0.681	0.273	0.37849
44	0.315	0.406	0.72682	0.422	0.405	0.78120
45	0.236	0.263	0.37796	0.260	0.249	0.39193
46	0.187	0.285	0.41406	0.267	0.299	0.44008
47	0.349	0.371	0.56512	0.378	0.292	0.60472
48	0.281	0.355	0.69342	0.303	0.363	0.70634

A14. Plant ^{15}N data 1997: %Ndff in grain, stalk, leaves, and cobs *.

Plot #	W TRT	N TRT	REP	grain %Ndff	leaves %Ndff	stalk %Ndff	cobs %Ndff
2	130	135	1	6.11	5.35	5.45	6.01
3	130	200	1	13.92	11.45	11.55	13.75
4	130	70	1	1.67	1.55	3.54	1.84
5	90	135	2	4.80	4.33	4.39	4.69
7	90	200	2	12.34	12.66	12.22	12.40
8	90	70	2	1.45	1.43	2.76	1.77
10	110	135	2	7.89	6.22	6.39	7.67
11	110	70	2	2.25	2.04	3.60	2.48
12	110	200	2	10.74	10.61	10.57	10.97
13	90	135	1	10.96	10.70	9.64	1.49
15	90	200	1	13.75	13.86	13.62	14.38
16	90	70	1	2.58	2.48	3.32	2.67
18	110	70	1	2.75	2.69	1.97	3.22
19	110	135	1	9.86	8.70	8.30	9.81
20	110	200	1	9.61	1.24	8.95	10.51
21	130	70	2	1.71	1.68	2.39	2.19
22	130	135	2	7.93	7.11	6.81	7.81
23	130	200	2	8.38	6.93	6.47	8.19
25	130	200	4	12.48	11.39	12.49	13.33
26	130	70	4	4.00	3.02	3.61	4.11
27	130	135	4	9.22	10.52	8.68	11.22
29	90	135	3	12.64	13.88	13.86	14.25
30	90	200	3	5.40	13.55	13.50	14.57
32	90	70	3	3.65	3.47	3.62	3.74
34	130	135	3	5.42	4.91	4.99	6.23
35	130	200	3	12.08	10.05	10.07	11.74
36	130	70	3	1.35	1.26	2.19	1.63
37	110	200	4	9.43	8.87	8.82	9.00
38	110	70	4	1.75	1.83	2.50	1.96
40	110	135	4	2.48	2.38	2.95	2.79
41	90	70	4	1.26	0.98	1.45	1.08
42	90	135	4	2.25	4.16	4.41	4.57
44	90	200	4	17.15	14.13	14.68	16.94
46	110	70	3	2.12	2.09	2.93	2.76
47	110	135	3	9.73	8.31	7.96	9.60
48	110	200	3	14.01	8.89	13.29	13.83

*Plots with no ^{15}N applied have been omitted as values are zero.

A15. Plant ^{15}N data 1997: Ndff in grain, leaves, stalk, cobs, and whole plant *.

Plot #	grain Ndff kg/ha	leaf Ndff kg/ha	stalk Ndff kg/ha	cob Ndff kg/ha	whole plt Ndff kg/ha
2	6.40	2.45	2.35	1.28	12.49
3	12.69	5.61	6.90	3.26	28.46
4	1.64	0.76	1.88	0.46	4.75
5	6.46	2.54	2.25	1.40	12.65
7	8.89	4.42	3.92	2.17	19.39
8	1.44	0.64	1.08	0.40	3.55
10	11.21	3.83	3.24	2.28	20.56
11	1.49	1.13	1.72	0.74	5.09
12	14.34	3.42	3.12	1.72	22.60
13	13.15	5.81	5.19	0.41	24.56
15	11.44	4.70	3.24	2.33	21.71
16	3.45	1.85	1.73	0.84	7.87
18	2.61	1.08	0.62	0.57	4.87
19	12.79	4.17	2.60	1.84	21.40
20	11.22	0.53	3.31	1.50	16.56
21	1.56	0.67	0.70	0.31	3.24
22	5.26	2.44	2.02	1.02	10.73
23	8.16	3.25	1.69	1.66	14.76
25	9.63	4.91	5.10	2.35	21.99
26	5.79	1.82	1.64	1.14	10.38
27	9.61	4.58	2.98	2.34	19.51
29	13.08	6.36	4.81	2.99	27.24
30	11.25	4.41	3.70	2.43	21.78
32	3.07	1.46	1.24	0.70	6.48
34	5.14	1.99	1.53	1.47	10.13
35	12.42	2.99	2.50	1.52	19.42
36	1.48	0.54	0.68	0.26	2.96
37	6.80	3.04	2.79	1.60	14.22
38	1.53	0.68	0.70	0.32	3.22
40	2.51	1.41	1.38	0.75	6.05
41	1.10	0.54	0.57	0.14	2.35
42	1.12	1.15	1.24	0.69	4.20
44	11.39	5.38	4.09	3.27	24.13
46	1.52	0.75	0.96	0.46	3.69
47	11.18	4.27	3.27	2.27	21.00
48	16.58	3.06	4.21	2.68	26.53

*Plots with no ^{15}N applied have been omitted as values are zero.

A16. Plant ^{15}N data 1997: %FNR in grain, leaves, stalk, cobs, stover, and whole plant *.

Plot #	% FNR grain	% FNR leaves	% FNR stalks	% FNR cobs	%FNR stover	%FNR whole plt
2	6.45	2.12	0.80	0.37	3.30	9.75
3	9.23	3.37	0.97	0.68	5.02	14.25
4	3.21	0.93	1.01	0.25	2.19	5.40
5	3.93	1.99	0.62	0.40	3.01	6.94
7	5.69	2.60	0.61	0.28	3.50	9.19
8	2.57	0.95	0.57	0.25	1.77	4.34
10	9.79	2.81	0.95	0.90	4.65	14.45
11	2.56	1.60	1.01	0.44	3.06	5.63
12	9.75	2.01	0.59	0.37	2.96	12.71
13	13.03	4.75	1.46	0.09	6.30	19.33
15	7.06	2.43	0.60	0.49	3.53	10.59
16	6.47	2.44	0.87	0.52	3.83	10.30
18	4.40	1.01	0.28	0.24	1.54	5.94
19	13.08	2.46	0.73	0.75	3.94	17.02
20	7.36	0.17	0.66	0.27	1.10	8.46
21	2.49	0.66	0.34	0.15	1.15	3.63
22	4.91	1.84	0.58	0.40	2.81	7.72
23	5.23	1.81	0.27	0.34	2.42	7.65
25	7.03	2.61	1.08	0.51	4.20	11.23
26	9.33	2.54	0.87	0.48	3.89	13.22
27	8.53	3.48	0.73	0.76	4.97	13.50
29	11.86	4.72	1.54	1.03	7.29	19.15
30	2.67	2.20	0.62	0.45	3.27	5.94
32	5.96	2.19	0.71	0.29	3.18	9.14
34	4.48	1.30	0.31	0.47	2.08	6.55
35	7.81	1.46	0.44	0.23	2.13	9.94
36	2.30	0.49	0.28	0.15	0.92	3.22
37	4.52	1.65	0.49	0.33	2.47	6.99
38	2.26	0.59	0.28	0.20	1.06	3.33
40	2.32	1.01	0.34	0.26	1.60	3.93
41	1.94	0.60	0.34	0.16	1.11	3.05
42	0.95	0.92	0.35	0.24	1.51	2.46
44	11.17	2.12	0.65	0.70	3.46	14.63
46	2.32	0.69	0.30	0.17	1.16	3.48
47	10.94	3.11	0.85	0.64	4.60	15.54
48	10.55	1.85	0.65	0.41	2.90	13.46

*Plots with no ^{15}N applied have been omitted as values are zero.

A17. Plant ^{15}N data 1997: Total N uptake in grain, leaves, stalk, cobs, stover, and whole plant .

Plot #	total N uptake grain kg/ha	total N uptake leaves kg/ha	total N uptake stalk kg/ha	total N uptake cobs kg/ha	total N uptake stover kg/ha	total N uptake whole plt kg/ha
1	138.29	29.15	14.45	4.44	48.04	186.33
2	153.87	33.60	17.28	4.82	55.71	209.58
3	125.68	37.66	24.30	4.17	66.13	191.82
4	130.46	32.17	17.76	3.97	53.90	184.36
5	149.59	31.55	23.42	3.81	58.79	208.38
6	157.00	30.80	14.19	5.03	50.02	207.01
7	150.16	39.68	18.73	4.23	62.64	212.80
8	157.87	34.70	17.72	5.79	58.20	216.07
9	146.91	36.50	17.86	3.76	58.12	205.04
10	131.19	36.65	20.99	4.49	62.13	193.32
11	125.28	36.19	18.99	5.72	60.90	186.19
12	147.32	37.69	25.79	4.36	67.84	215.16
13	155.95	33.42	23.78	4.88	62.08	218.04
14	124.88	33.83	14.84	4.07	52.74	177.62
15	152.26	34.06	24.83	5.02	63.91	216.17
16	124.89	35.40	17.67	4.66	57.73	182.62
17	127.26	29.77	14.77	4.70	49.24	176.50
18	105.26	30.05	14.93	5.23	50.20	155.46
19	129.82	32.38	15.52	3.98	51.88	181.70
20	150.45	33.16	18.87	4.82	56.85	207.30
21	105.58	34.01	19.12	4.75	57.88	163.45
22	137.59	36.73	16.49	5.06	58.28	195.87
23	132.55	35.49	18.88	4.79	59.15	191.70
24	143.20	29.88	15.60	6.28	51.76	194.96
25	144.67	44.66	26.72	5.20	76.58	221.25
26	123.21	37.08	19.15	4.50	60.73	183.93
27	144.95	35.15	21.27	4.90	61.33	206.28
28	143.52	32.75	19.44	4.52	56.71	200.23
29	154.79	28.45	22.28	5.87	56.61	211.40
30	156.80	35.77	26.54	5.69	68.01	224.81
31	131.72	27.25	15.14	4.27	46.66	178.39
32	119.47	24.22	17.09	4.52	45.83	165.29
33	113.35	22.25	10.98	4.07	37.30	150.65
34	142.37	30.63	16.79	4.64	52.06	194.44
35	140.73	34.80	21.38	5.08	61.27	202.00
36	109.13	33.94	14.27	4.58	52.79	161.92
37	126.30	32.41	17.83	4.30	54.53	180.83
38	119.23	34.77	20.16	5.20	60.12	179.35
39	83.89	19.93	7.74	3.78	31.44	115.34
40	144.60	31.47	16.63	5.39	53.50	198.09
41	118.71	29.86	12.54	4.73	47.13	165.84
42	139.23	32.56	13.83	4.71	51.10	190.33
43	122.25	22.62	8.40	4.98	36.00	158.26
44	141.25	29.09	17.84	4.76	51.70	192.95
45	157.11	23.65	11.72	4.38	39.75	196.86
46	112.51	31.08	12.92	3.24	47.24	159.75
47	142.85	33.52	16.18	4.38	54.08	196.93
48	133.04	34.70	20.25	4.88	59.82	192.86

A18. Plant ^{15}N data 1997: Dry matter (DM) production in grain, leaves, stalk, cobs, stover, and whole plant .

Plot #	DM prod grain kg/ha	DM prod leaves kg/ha	DM prod stalk kg/ha	DM prod cobs kg/ha	DM prod stover kg/ha	DM prod whole plt kg/ha
1	10953	4986	3947	1914	10847	21800
2	10890	4581	3960	1950	10490	21381
3	9695	4471	4761	2184	11417	21112
4	10898	4675	4723	2283	11681	22579
5	12256	5393	4519	2918	12830	25085
6	11379	4934	4161	2399	11494	22873
7	8072	3816	4043	1989	9848	17919
8	7956	3559	3313	1792	8664	16620
9	8013	4044	3610	2092	9745	17758
10	12194	5424	4797	2561	12782	24976
11	11588	4813	4242	2436	11492	23080
12	9279	4508	4091	2383	10983	20262
13	12505	5800	6070	3206	15077	27582
14	10633	4078	3187	2116	9381	20015
15	8894	3797	2695	1649	8141	17036
16	12478	6067	4802	2699	13568	26046
17	11726	4338	3076	1907	9320	21046
18	11256	4868	4020	2136	11024	22281
19	12495	4608	3245	1980	9833	22329
20	8704	4148	4325	1838	10311	19015
21	10492	4215	3403	1721	9340	19831
22	9727	4507	4272	2120	10900	20627
23	7653	3754	3037	1911	8702	16355
24	9399	4038	3283	1555	8875	18274
25	9796	4888	5280	2391	12559	22355
26	12320	5002	4096	2338	11435	23755
27	7328	3709	3461	1720	8889	16217
28	9465	3770	3552	2075	9397	18862
29	10197	4375	1730	2153	8257	18454
30	4088	4408	2686	1285	8379	12468
31	10140	3841	4714	2539	11093	21233
32	9387	4302	4324	2194	10820	20208
33	6611	3181	2484	1104	6768	13380
34	13043	4630	4093	2685	11409	24452
35	13037	4741	4638	2645	12024	25061
36	9643	3866	3320	1651	8837	18480
37	6537	2982	3119	1766	7868	14404
38	7544	3090	2656	1443	7189	14732
39	7869	3922	3211	1482	8615	16484
40	13311	5458	4638	2404	12500	25811
41	5805	4109	3524	1174	8807	14612
42	7742	3639	3958	2103	9700	17442
43	3431	2970	2483	533	5986	9417
44	9493	4021	3602	2045	9668	19161
45	11483	5165	4596	1903	11664	23147
46	8455	3857	3496	1777	9130	17585
47	11606	4935	4147	2247	11330	22935
48	8274	3201	2926	1899	8026	16300

A19. Soil ^{15}N data 1996 : Ndff in the soil by 0.3 m increments to 1.8 m, total Ndff from 0 to 1.8 m, and %FNR from 0 to 1.8 m *.

Plot #	W TRT	N TRT	REP	Ndff 0-0.3	Ndff 0.3-0.6	Ndff 0.6-0.9	Ndff 0.9-1.2	Ndff 1.2-1.5	Ndff 1.5-1.8	Ndff Total	%FNR
2	140	135	1	31.51	5.35	4.12	3.75	0.00	0.00	44.74	33.14
3	140	200	1	31.52	22.68	21.07	5.89	0.00	0.00	81.16	40.58
4	140	70	1	9.36	8.77	1.83	0.00	0.00	0.00	19.96	42.79
5	100	135	2	33.76	10.46	0.00	0.00	0.00	0.00	44.22	32.76
7	100	200	2	28.13	29.86	22.54	8.51	0.82	0.50	90.36	45.18
8	100	70	2	8.31	2.41	0.00	0.00	0.00	0.00	10.72	15.31
10	120	135	2	27.03	9.24	7.65	3.58	0.00	0.00	47.49	35.18
11	120	70	2	8.41	4.12	2.95	0.00	0.00	0.00	15.48	14.97
12	120	200	2	33.98	26.21	13.17	6.10	2.44	0.00	81.90	40.95
13	100	135	1	16.55	11.39	8.64	5.36	1.23	0.00	43.18	34.95
15	100	200	1	28.83	25.74	22.51	6.75	1.21	0.00	85.04	42.52
16	100	70	1	10.45	5.20	1.73	0.00	0.00	0.00	17.38	31.96
18	120	70	1	11.16	4.68	2.39	0.00	0.00	0.00	18.22	22.62
19	120	135	1	24.60	12.91	8.03	13.45	0.00	0.00	58.98	43.69
20	120	200	1	25.32	30.54	21.64	9.77	4.25	2.57	94.08	47.04
21	140	70	2	9.68	2.22	1.81	3.17	0.18	0.00	17.06	24.37
22	140	135	2	25.65	9.77	6.22	0.00	0.00	0.00	41.65	30.85
23	140	200	2	33.05	26.39	9.88	6.43	5.02	3.60	84.36	42.18
25	140	200	4	35.46	23.57	11.93	15.68	6.10	5.58	98.32	49.16
26	140	70	4	7.40	3.83	2.68	2.71	1.32	1.54	19.49	27.84
27	140	135	4	19.45	12.66	9.66	7.86	2.25	0.00	51.88	38.43
29	100	135	3	25.16	14.38	9.36	2.29	1.32	0.00	52.50	35.93
30	100	200	3	27.15	30.03	16.09	6.09	5.06	2.92	87.35	43.67
32	100	70	3	10.02	6.38	2.67	0.00	0.00	0.00	19.06	34.37
34	140	135	3	15.72	24.65	13.78	8.79	0.00	0.00	62.93	46.61
35	140	200	3	33.47	22.08	12.46	9.48	5.98	3.34	86.80	43.40
36	140	70	3	8.10	4.23	1.74	2.39	0.57	0.00	17.03	24.33
37	120	200	4	26.73	29.08	17.83	7.24	2.81	0.41	84.09	42.04
38	120	70	4	11.38	1.55	0.00	0.00	0.00	0.00	12.93	18.47
40	120	135	4	4.68	18.38	9.44	7.14	6.22	3.46	49.32	36.53
41	100	70	4	6.93	2.16	2.70	2.79	1.56	0.00	16.14	23.05
42	100	135	4	17.83	23.08	3.42	1.44	0.00	0.00	45.76	33.90
44	100	200	4	25.97	19.21	15.09	13.81	1.21	0.00	75.28	37.64
46	120	70	3	11.91	1.93	2.01	0.21	0.00	0.00	16.06	27.23
47	120	135	3	14.15	8.86	7.55	5.25	0.74	0.00	36.55	27.07
48	120	200	3	15.96	28.89	17.33	13.93	6.40	0.64	83.15	41.58

*Plots with no ^{15}N applied have been omitted as values are zero.

A20. Soil ^{15}N data 1997 : Ndff in the soil by 0.3 m increments to 1.8 m, total Ndff from 0 to 1.8 m, and %FNR from 0 to 1.8 m *.

Plot #	W TRT	N TRT	REP	0-0.3	0.3-0.6	0.6-0.9	0.9-1.2	1.2-1.5	1.5-1.8	Total	%FNR
2	130	135	1	13.30	5.97	3.97	3.64	1.27	0.00	28.15	20.85
3	130	200	1	13.16	5.37	9.69	4.68	9.37	4.08	46.35	23.18
4	130	70	1	8.66	1.77	3.00	2.00	0.00	0.00	15.43	22.05
5	90	135	2	19.20	9.65	5.98	0.00	0.00	0.00	34.83	25.80
7	90	200	2	19.72	18.63	8.61	0.00	4.19	4.54	55.70	27.85
8	90	70	2	2.94	0.00	1.04	1.87	0.00	0.00	5.85	8.36
10	110	135	2	11.72	5.93	4.00	3.00	4.00	0.00	28.65	21.22
11	110	70	2	1.79	0.71	2.13	1.58	1.67	0.00	7.88	11.26
12	110	200	2	19.85	14.56	19.04	0.00	1.12	1.61	56.18	28.09
13	90	135	1	13.03	5.91	4.78	0.00	0.00	0.00	23.71	17.56
15	90	200	1	19.32	20.83	15.68	0.00	3.03	0.00	58.87	29.43
16	90	70	1	4.87	3.58	0.00	0.00	0.00	0.00	8.45	12.07
18	110	70	1	6.33	4.53	0.00	0.00	0.00	0.00	10.87	15.52
19	110	135	1	15.06	9.46	3.83	0.00	0.00	0.00	28.35	21.00
20	110	200	1	15.37	16.28	7.37	8.61	6.66	4.92	59.20	29.60
21	130	70	2	6.91	1.50	2.85	1.12	0.00	0.00	12.38	17.69
22	130	135	2	13.32	5.48	1.43	0.00	0.00	0.00	20.23	14.98
23	130	200	2	13.86	6.41	5.08	4.68	6.82	6.53	43.37	21.69
25	130	200	4	14.16	13.19	6.01	4.47	2.31	1.63	41.78	20.89
26	130	70	4	5.74	2.27	1.75	1.24	0.76	0.00	11.76	16.80
27	130	135	4	14.78	4.21	7.36	3.72	3.51	2.65	36.22	26.83
29	90	135	3	15.52	6.27	5.76	0.00	0.00	0.00	27.55	20.40
30	90	200	3	23.06	23.83	7.58	6.76	5.99	1.10	68.32	34.16
32	90	70	3	7.02	5.38	3.00	0.00	0.00	0.00	15.39	21.99
34	130	135	3	14.27	6.59	2.85	0.00	0.00	0.00	23.71	17.56
35	130	200	3	16.00	16.09	8.55	4.74	2.83	3.28	51.48	25.74
36	130	70	3	3.70	3.54	1.80	3.20	2.20	0.00	14.44	20.62
37	110	200	4	20.66	20.16	8.05	6.03	5.92	4.09	64.91	32.46
38	110	70	4	7.51	1.03	0.93	0.00	0.00	0.00	9.47	13.53
40	110	135	4	17.41	5.99	3.98	0.00	0.00	0.00	27.39	20.29
41	90	70	4	4.05	5.43	2.27	1.86	0.00	0.00	13.60	19.43
42	90	135	4	22.50	10.64	2.56	0.00	0.00	0.00	35.71	26.45
44	90	200	4	19.50	16.13	7.29	6.83	6.36	2.05	58.16	29.08
46	110	70	3	8.43	2.48	1.01	1.27	0.00	0.00	13.20	18.86
47	110	135	3	6.35	3.88	2.22	2.16	2.96	2.36	19.92	14.76
48	110	200	3	18.32	12.00	3.34	3.50	3.43	2.75	43.33	21.67

*Plots with no ^{15}N applied have been omitted as values are zero.

A21. ^{15}N budget 1996 and 1997: Unaccounted-for %FNR and Ndff in 1996 and 1997, and %FNR and Ndff for two years of experiment *.

Plot #	W TRT	N TRT	REP	unacct %FNR 1996	unacct %FNR 1997	unacct Ndff 1996	unacct Ndff 1997	%FNR plt96+plt97 +soil97	Ndff plt96+plt97 +soil97
2	130	135	1	0.16	0.03	21.63	4.10	0.81	109.26
3	130	200	1	0.24	0.03	47.80	6.35	0.73	145.85
4	130	70	1	0.04	-0.00	3.03	-0.23	0.96	67.19
5	90	135	2	0.23	-0.02	30.86	-3.27	0.80	107.40
7	90	200	2	0.20	0.08	40.80	15.27	0.72	143.93
8	90	70	2	0.22	0.02	15.19	1.31	0.76	53.49
10	110	135	2	0.23	-0.01	31.33	-1.71	0.78	105.39
11	110	70	2	0.04	0.04	2.53	2.51	0.93	64.96
12	110	200	2	0.21	0.02	42.76	3.13	0.77	154.11
13	90	135	1	0.05	-0.04	6.52	-5.09	0.99	133.57
15	90	200	1	0.23	0.02	46.09	4.46	0.75	149.45
16	90	70	1	0.05	0.02	3.68	1.06	0.93	65.26
18	110	70	1	-0.02	0.04	-1.73	2.49	0.99	69.24
19	110	135	1	0.19	0.07	26.06	9.23	0.74	99.71
20	110	200	1	0.12	0.09	24.63	18.32	0.79	157.06
21	130	70	2	0.06	0.02	3.94	1.44	0.92	64.62
22	130	135	2	0.19	0.08	25.69	10.69	0.73	98.62
23	130	200	2	0.23	0.13	45.22	26.23	0.64	128.55
25	130	200	4	0.15	0.17	30.40	34.55	0.68	135.05
26	130	70	4	0.08	-0.04	5.45	-2.66	0.96	67.20
27	130	135	4	0.15	-0.03	19.82	-3.85	0.88	119.03
29	90	135	3	0.15	-0.02	20.69	-2.28	0.86	116.60
30	90	200	3	0.18	-0.01	35.63	-2.76	0.84	167.13
32	90	70	3	0.06	-0.04	3.92	-2.81	0.98	68.89
34	130	135	3	0.13	0.22	16.94	29.09	0.66	88.97
35	130	200	3	0.20	0.08	39.57	15.89	0.72	144.54
36	130	70	3	0.05	-0.01	3.25	-0.37	0.96	67.12
37	110	200	4	0.23	0.02	45.43	4.95	0.75	149.62
38	110	70	4	0.05	0.00	3.34	0.24	0.95	66.42
40	110	135	4	0.17	0.12	23.53	15.88	0.71	95.59
41	90	70	4	0.18	0.00	12.85	0.18	0.81	56.96
42	90	135	4	0.21	0.04	27.99	5.86	0.75	101.16
44	90	200	4	0.25	-0.04	50.53	-7.01	0.78	156.48
46	110	70	3	0.06	-0.01	3.94	-0.83	0.96	66.89
47	110	135	3	0.20	-0.03	27.12	-4.37	0.83	112.25
48	110	200	3	0.25	0.07	50.81	13.29	0.68	135.90

*Plots with no ^{15}N applied have been omitted as values are zero.

APPENDIX B

Plant and soil N and N budget data for 1996 and 1997

APPENDIX B: Plant and soil N and N budget data 1996 and 1997.

B1. Plant data 1996: Whole plant N uptake from V6 to R6 .

Plot #	W TRT	N TRT	REP	V6 Nup kg/ha	V9 Nup kg/ha	V12 Nup kg/ha	VT Nup kg/ha	R6 Nup kg/ha
1	130	0	1	10.25	67.59	86.93	101.34	197.03
2	130	150	1	11.81	73.32	95.85	126.51	226.31
3	130	215	1	10.56	72.31	102.83	119.39	232.10
4	130	85	1	10.42	59.94	96.87	125.23	219.37
5	90	150	2	11.01	70.74	114.35	107.33	203.72
6	90	0	2	8.94	67.35	100.77	108.65	198.95
7	90	215	2	9.33	73.63	110.82	116.78	215.65
8	90	85	2	10.29	65.90	114.03	119.26	196.08
9	110	0	2	9.44	56.81	84.95	103.41	206.28
10	110	150	2	10.07	71.78	113.75	132.31	211.73
11	110	85	2	8.52	68.63	104.26	135.48	213.48
12	110	215	2	11.58	75.76	109.59	134.94	233.03
13	90	150	1	11.08	72.18	100.92	110.90	220.56
14	90	0	1	7.28	64.08	103.57	111.38	202.14
15	90	215	1	11.19	64.73	115.31	122.17	200.26
16	90	85	1	11.62	66.15	112.30	114.02	210.17
17	110	0	1	10.33	64.41	106.05	106.15	236.13
18	110	85	1	10.58	66.72	103.74	118.67	239.94
19	110	150	1	10.55	73.06	98.64	130.81	214.54
20	110	215	1	9.45	73.92	100.51	127.74	211.58
21	130	85	2	11.71	72.67	105.76	120.92	217.66
22	130	150	2	8.61	65.69	113.58	132.63	228.46
23	130	215	2	10.01	66.25	103.09	134.75	210.70
24	130	0	2	9.16	55.43	98.93	105.48	174.85
25	130	215	4	12.66	74.46	101.18	116.33	219.28
26	130	85	4	9.99	74.43	102.68	110.69	225.18
27	130	150	4	10.05	63.34	111.14	115.69	200.69
28	130	0	4	9.97	66.52	108.92	120.94	209.49
29	90	150	3	12.85	62.18	108.90	137.52	200.76
30	90	215	3	12.13	75.35	108.77	129.30	195.14
31	90	0	3	7.92	68.97	87.77	117.58	199.12
32	90	85	3	9.04	72.84	101.58	129.29	217.12
33	130	0	3	8.22	59.64	80.92	100.86	189.78
34	130	150	3	8.80	52.90	100.46	125.02	216.31
35	130	215	3	8.55	62.73	84.65	127.63	202.03
36	130	85	3	12.16	52.99	92.72	109.02	205.60
37	110	215	4	8.04	61.53	111.30	113.69	205.16
38	110	85	4	8.09	53.82	89.10	108.57	202.24
39	110	0	4	9.17	61.92	78.64	95.48	180.57
40	110	150	4	11.43	60.04	98.27	105.45	204.18
41	90	85	4	9.61	64.31	101.90	108.06	206.48
42	90	150	4	11.46	55.21	96.51	128.26	206.65
43	90	0	4	9.29	63.77	87.37	105.83	193.93
44	90	215	4	13.21	62.21	108.26	115.52	215.27
45	110	0	3	8.44	56.52	90.83	95.45	186.65
46	110	85	3	8.96	57.52	91.09	102.58	213.56
47	110	150	3	12.45	57.78	98.67	117.48	203.15
48	110	215	3	11.34	71.14	105.05	114.68	218.10

B2. Plant data 1996: Plant dry weights at R6 plant sampling.

Plot #	grain g per plt	leaves g per plt	stalk g per plt	cobs g per plt
1	160.92	42.85	65.05	33.12
2	168.80	52.60	87.14	30.98
3	175.08	52.31	80.52	38.92
4	165.96	53.82	87.31	30.35
5	164.00	54.55	73.95	33.61
6	157.62	53.72	68.67	30.07
7	166.10	56.29	73.61	27.97
8	161.35	52.63	68.39	28.83
9	161.97	56.71	66.50	29.75
10	167.10	57.47	74.59	28.06
11	164.41	52.18	70.19	32.06
12	172.31	52.52	79.51	32.82
13	168.79	50.48	72.25	36.77
14	156.72	54.93	66.20	28.81
15	161.84	49.74	71.08	27.12
16	167.36	51.13	69.90	29.15
17	155.00	51.33	85.49	36.17
18	164.51	52.86	84.13	34.17
19	166.87	54.51	78.75	30.84
20	162.35	50.33	82.36	27.91
21	171.07	59.03	72.96	30.82
22	165.52	57.36	70.96	38.48
23	167.85	57.01	70.69	30.18
24	151.71	49.86	55.38	25.09
25	165.59	58.87	71.71	31.26
26	175.79	62.53	76.66	36.16
27	164.24	55.14	67.44	27.58
28	153.05	46.33	72.29	31.73
29	159.09	51.52	75.80	27.60
30	167.98	47.66	65.75	27.91
31	158.62	52.55	79.67	34.11
32	169.53	50.63	66.52	32.76
33	155.75	45.46	68.11	30.97
34	164.61	47.25	77.95	31.99
35	157.62	52.63	70.69	27.08
36	167.78	57.99	86.41	29.74
37	163.04	49.51	65.65	29.40
38	164.70	54.83	70.25	29.12
39	157.22	46.52	64.26	29.21
40	167.10	54.70	68.87	29.87
41	167.73	49.01	68.10	32.02
42	166.33	51.62	72.25	32.46
43	154.65	49.11	66.87	40.48
44	169.58	46.65	68.85	35.64
45	159.20	48.47	62.22	32.47
46	165.28	55.21	75.71	28.85
47	168.20	54.69	68.24	32.52
48	169.50	58.06	65.09	28.04

B3. Plant data 1996: Plant % total N at R6 plant sampling.

Plot #	Grain %N	Leaves %N	Stalk %N	Cob %N
1	1.300	1.306	0.364	0.235
2	1.384	1.310	0.391	0.237
3	1.389	1.412	0.382	0.219
4	1.341	1.305	0.373	0.193
5	1.332	1.070	0.328	0.186
6	1.303	0.982	0.332	0.251
7	1.355	1.282	0.395	0.190
8	1.317	1.164	0.346	0.265
9	1.296	1.073	0.320	0.226
10	1.341	1.230	0.360	0.233
11	1.328	1.196	0.380	0.236
12	1.380	1.325	0.400	0.220
13	1.334	1.117	0.465	0.219
14	1.352	1.113	0.335	0.216
15	1.412	1.257	0.381	0.228
16	1.308	1.274	0.351	0.242
17	1.389	1.301	0.377	0.248
18	1.391	1.321	0.361	0.247
19	1.345	1.196	0.406	0.211
20	1.295	1.290	0.383	0.222
21	1.291	1.075	0.343	0.258
22	1.313	1.261	0.341	0.251
23	1.249	1.221	0.350	0.246
24	1.197	1.136	0.283	0.323
25	1.335	1.252	0.379	0.247
26	1.311	1.045	0.313	0.229
27	1.261	1.254	0.330	0.240
28	1.317	1.219	0.401	0.237
29	1.282	1.027	0.334	0.272
30	1.312	1.245	0.359	0.253
31	1.349	0.995	0.307	0.238
32	1.331	1.012	0.388	0.253
33	1.212	1.216	0.322	0.230
34	1.327	1.306	0.349	0.240
35	1.251	1.230	0.368	0.241
36	1.293	1.120	0.338	0.206
37	1.261	1.306	0.342	0.215
38	1.276	1.176	0.288	0.245
39	1.126	1.267	0.265	0.259
40	1.212	1.268	0.364	0.254
41	1.272	1.110	0.320	0.233
42	1.283	1.086	0.319	0.224
43	1.190	1.022	0.313	0.262
44	1.287	1.281	0.329	0.239
45	1.320	1.075	0.316	0.221
46	1.381	1.205	0.343	0.186
47	1.318	1.266	0.370	0.213
48	1.363	1.254	0.390	0.239

B4. Plant data 1996: Plant % total N at R6 plant sampling.

Plot #	Grain %N	Leaves %N	Stalk %N	Cob %N
1	1.300	1.306	0.364	0.235
2	1.384	1.310	0.391	0.237
3	1.389	1.412	0.382	0.219
4	1.341	1.305	0.373	0.193
5	1.332	1.070	0.328	0.186
6	1.303	0.982	0.332	0.251
7	1.355	1.282	0.395	0.190
8	1.317	1.164	0.346	0.265
9	1.296	1.073	0.320	0.226
10	1.341	1.230	0.360	0.233
11	1.328	1.196	0.380	0.236
12	1.380	1.325	0.400	0.220
13	1.334	1.117	0.465	0.219
14	1.352	1.113	0.335	0.216
15	1.412	1.257	0.381	0.228
16	1.308	1.274	0.351	0.242
17	1.389	1.301	0.377	0.248
18	1.391	1.321	0.361	0.247
19	1.345	1.196	0.406	0.211
20	1.295	1.290	0.383	0.222
21	1.291	1.075	0.343	0.258
22	1.313	1.261	0.341	0.251
23	1.249	1.221	0.350	0.246
24	1.197	1.136	0.283	0.323
25	1.335	1.252	0.379	0.247
26	1.311	1.045	0.313	0.229
27	1.261	1.254	0.330	0.240
28	1.317	1.219	0.401	0.237
29	1.282	1.027	0.334	0.272
30	1.312	1.245	0.359	0.253
31	1.349	0.995	0.307	0.238
32	1.331	1.012	0.388	0.253
33	1.212	1.216	0.322	0.230
34	1.327	1.306	0.349	0.240
35	1.251	1.230	0.368	0.241
36	1.293	1.120	0.338	0.206
37	1.261	1.306	0.342	0.215
38	1.276	1.176	0.288	0.245
39	1.126	1.267	0.265	0.259
40	1.212	1.268	0.364	0.254
41	1.272	1.110	0.320	0.233
42	1.283	1.086	0.319	0.224
43	1.190	1.022	0.313	0.262
44	1.287	1.281	0.329	0.239
45	1.320	1.075	0.316	0.221
46	1.381	1.205	0.343	0.186
47	1.318	1.266	0.370	0.213
48	1.363	1.254	0.390	0.239

B5. Plant data 1997: N uptake by grain, leaves, stalk, cobs, stover, and whole plant.

Plot #	N uptake grain kg/ha	N uptake leaf kg/ha	N uptake stem kg/ha	N uptake cob kg/ha	N uptake stover kg/ha	N uptake whole plt kg/ha
1	122.51	25.92	6.27	3.39	35.59	158.10
2	148.34	33.09	8.25	3.20	44.55	192.88
3	145.36	33.81	6.68	3.68	44.17	189.54
4	113.45	20.80	7.04	1.78	29.63	143.07
5	130.76	25.88	4.95	3.86	34.69	165.45
6	120.70	10.29	7.42	5.05	22.76	143.45
7	145.68	29.73	8.22	2.96	40.92	186.60
8	143.55	20.93	6.60	3.17	30.70	174.25
9	91.13	9.86	5.86	3.24	18.96	110.09
10	120.49	25.74	5.90	3.00	34.64	155.13
11	139.13	32.97	7.48	2.87	43.31	182.44
12	131.45	20.15	5.43	3.59	29.18	160.63
13	105.59	28.84	8.87	3.20	40.91	146.50
14	124.41	10.18	3.38	2.42	15.97	140.38
15	140.53	27.00	9.26	2.77	39.03	179.56
16	134.55	17.49	7.52	2.59	27.60	162.16
17	115.53	14.42	3.88	3.44	21.74	137.27
18	126.16	19.88	7.66	3.48	31.03	157.19
19	122.53	20.54	5.97	2.87	29.38	151.91
20	135.21	32.03	11.00	3.09	46.12	181.33
21	124.10	18.59	8.23	3.14	29.97	154.07
22	137.54	27.47	10.13	3.53	41.14	178.68
23	135.20	29.57	10.27	3.40	43.25	178.45
24	91.46	15.10	5.97	2.29	23.37	114.82
25	141.45	34.58	8.41	4.38	47.37	188.83
26	125.32	27.20	5.31	3.80	36.31	161.64
27	105.91	26.32	6.90	2.87	36.10	142.00
28	124.08	16.38	8.76	3.21	28.34	152.42
29	126.11	22.54	4.46	3.62	30.63	156.74
30	130.88	30.93	7.01	2.91	40.84	171.72
31	78.80	12.46	5.08	2.58	20.13	98.93
32	128.20	21.10	4.94	2.52	28.56	156.76
33	56.54	10.30	3.49	2.27	16.06	72.60
34	130.48	29.58	11.51	3.81	44.90	175.38
35	121.88	33.24	8.78	5.05	47.07	168.95
36	110.05	23.64	7.56	3.32	34.52	144.57
37	151.94	33.09	7.17	3.58	43.84	195.78
38	86.88	16.56	6.99	2.89	26.45	113.33
39	67.99	14.22	4.54	2.23	20.99	88.97
40	116.55	25.60	7.60	2.76	35.96	152.50
41	136.41	27.60	7.00	3.19	37.80	174.20
42	137.49	32.84	6.90	3.68	43.41	180.90
43	62.78	9.39	3.26	2.79	15.44	78.23
44	117.84	35.77	5.95	3.27	44.99	162.83
45	109.09	4.64	3.77	2.12	10.53	119.62
46	114.36	22.29	6.23	3.02	31.54	145.90
47	133.00	32.29	7.15	2.45	41.89	174.89
48	147.92	36.38	6.28	3.74	46.40	194.33

B6. Plant data 1997: DM production of grain, leaves, stalk, cobs, stover, and whole plant.

Plot #	W TRT	N TRT	REP	DM prod grain kg/ha	DM prod leaves kg/ha	DM prod stalk kg/ha	DM prod cob kg/ha	DM prod stover kg/ha	DM prod whole plt kg/ha
1	130	0	1	10261	3850	3231	1704	8785	19046
2	130	150	1	12293	4482	3733	1712	9926	22220
3	130	215	1	11449	4674	3733	2066	10473	21922
4	130	85	1	11271	3661	3665	1590	8916	20187
5	90	150	2	11029	3849	2842	1748	8439	19468
6	90	0	2	10742	1839	2798	1844	6481	17223
7	90	215	2	11752	4600	3209	1786	9595	21346
8	90	85	2	11693	2914	3314	1821	8049	19742
9	110	0	2	9557	2138	2738	1618	6494	16051
10	110	150	2	9791	3444	2730	1586	7760	17551
11	110	85	2	11379	4219	3321	1613	9153	20532
12	110	215	2	10716	3590	2999	1727	8317	19033
13	90	150	1	10770	3554	3112	1606	8272	19042
14	90	0	1	10268	1612	1997	1350	4959	15227
15	90	215	1	11094	3957	2947	1379	8283	19377
16	90	85	1	11014	2441	2566	1123	6129	17143
17	110	0	1	10545	3622	2229	1727	7578	18123
18	110	85	1	10578	3764	3755	1732	9250	19828
19	110	150	1	10612	3760	2827	1543	8130	18742
20	110	215	1	11187	4088	3777	1739	9604	20791
21	130	85	2	10647	3051	3740	1517	8308	18955
22	130	150	2	11342	3991	3433	1627	9051	20394
23	130	215	2	11560	3653	3905	1744	9302	20862
24	130	0	2	9375	2954	3029	1414	7398	16773
25	130	215	4	12305	4512	3964	1992	10469	22773
26	130	85	4	11295	3689	3688	1711	9087	20382
27	130	150	4	10890	3674	3613	1596	8883	19773
28	130	0	4	10926	2827	3695	1724	8246	19172
29	90	150	3	10847	3712	2640	1533	7885	18732
30	90	215	3	11105	4200	3044	1721	8965	20069
31	90	0	3	7669	3091	2319	1067	6477	14146
32	90	85	3	10767	3765	2625	1659	8050	18817
33	130	0	3	7416	3166	1907	1226	6300	13716
34	130	150	3	11675	4322	3628	1765	9715	21390
35	130	215	3	10185	4264	3456	2395	10115	20300
36	130	85	3	10627	3496	3149	1509	8154	18781
37	110	215	4	12227	4311	3478	2001	9790	22017
38	110	85	4	7952	3654	2730	1445	7830	15781
39	110	0	4	7484	2815	2266	1149	6230	13713
40	110	150	4	10227	3912	3112	1654	8678	18905
41	90	85	4	11201	3551	3254	2047	8852	20052
42	90	150	4	11785	4139	2947	1641	8726	20512
43	90	0	4	6888	2184	2087	1091	5361	12249
44	90	215	4	10563	3811	2902	1826	8540	19103
45	110	0	3	12619	1111	2229	996	4336	16955
46	110	85	3	11663	3604	3261	1799	8664	20327
47	110	150	3	11816	4236	3538	1483	9257	21073
48	110	215	3	12476	4355	3269	1928	9552	22028

B7. Soil data 1996: Preplant residual soil NO_3-N by 0.3 m increments from 0 to 1.5 m.

Plot #	W TRT	N TRT	REP	NO3-N 0-0.3m kg/ha	NO3-N 0.3-0.6m kg/ha	NO3-N 0.6-0.9m kg/ha	NO3-N 0.9-1.2m kg/ha	NO3-N 1.2-1.5m kg/ha	NO3-N Total kg/ha
1	130	0	1	50.35	36.71	72.65	54.34	31.35	245.41
2	130	150	1	40.59	29.29	64.43	49.31	46.94	230.55
3	130	215	1	47.67	38.78	67.78	56.49	37.80	248.51
4	130	85	1	41.32	21.12	40.23	58.19	46.37	207.22
5	90	150	2	39.50	27.06	48.82	48.76	38.58	202.73
6	90	0	2	33.67	19.46	37.23	39.45	32.69	162.49
7	90	215	2	52.59	38.99	40.20	39.15	30.02	200.96
8	90	85	2	43.06	28.82	46.23	43.47	37.21	198.79
9	110	0	2	51.19	45.05	46.43	34.38	37.37	214.43
10	110	150	2	32.82	29.68	52.95	39.11	41.76	196.33
11	110	85	2	40.45	47.30	39.41	39.46	36.11	202.73
12	110	215	2	52.58	40.42	41.49	31.95	34.57	201.01
13	90	150	1	45.64	45.35	41.43	46.31	39.09	217.81
14	90	0	1	50.32	33.85	40.85	36.02	38.59	199.63
15	90	215	1	34.81	28.75	37.66	45.79	41.00	188.01
16	90	85	1	43.81	27.85	39.32	45.19	36.95	193.11
17	110	0	1	33.95	29.36	52.14	43.42	32.90	191.76
18	110	85	1	37.97	33.23	57.99	45.15	38.00	212.34
19	110	150	1	43.53	33.58	46.45	48.09	49.51	221.17
20	110	215	1	38.70	25.57	41.73	44.72	42.68	193.40
21	130	85	2	38.52	24.97	36.54	33.96	37.51	171.49
22	130	150	2	49.83	36.39	41.21	37.64	33.17	198.24
23	130	215	2	48.30	40.24	72.62	47.31	43.08	251.55
24	130	0	2	48.97	31.96	38.35	43.67	36.12	199.06
25	130	215	4	53.80	35.05	45.02	32.85	26.38	193.10
26	130	85	4	46.25	36.87	52.29	30.98	24.09	190.48
27	130	150	4	49.38	27.06	24.31	29.12	28.83	158.70
28	130	0	4	37.74	22.83	31.90	36.77	32.66	161.90
29	90	150	3	45.50	26.19	38.70	33.90	30.26	174.55
30	90	215	3	55.29	38.02	53.68	55.14	45.59	247.72
31	90	0	3	54.80	37.84	49.23	52.18	37.47	231.53
32	90	85	3	46.47	54.95	74.60	53.91	37.78	267.71
33	130	0	3	34.29	24.95	57.19	29.96	16.99	163.38
34	130	150	3	37.74	29.54	56.03	22.41	14.55	160.26
35	130	215	3	43.26	27.12	33.60	24.90	21.36	150.25
36	130	85	3	38.01	26.39	36.60	36.02	18.42	155.43
37	110	215	4	23.14	12.41	17.92	25.62	20.77	99.86
38	110	85	4	22.86	14.71	25.06	23.19	20.58	106.41
39	110	0	4	25.71	18.37	39.87	30.61	18.45	133.01
40	110	150	4	34.01	24.85	32.96	28.35	30.30	150.46
41	90	85	4	30.04	16.44	13.52	15.55	16.96	92.52
42	90	150	4	35.86	15.56	19.50	22.59	18.41	111.91
43	90	0	4	37.00	26.62	34.45	23.66	13.25	134.97
44	90	215	4	33.23	13.80	16.31	24.19	16.97	104.50
45	110	0	3	34.66	12.67	18.53	25.47	20.00	111.34
46	110	85	3	34.35	15.42	29.84	20.15	20.29	120.04
47	110	150	3	36.40	24.93	28.82	23.42	18.04	131.61
48	110	215	3	38.76	16.46	21.10	28.93	20.56	125.81

B8. Soil data 1996: Harvest residual soil NO_3-N by 0.3 m increments from 0 to 1.5 m.

Plot #	NO3-N 0-0.3m kg/ha	NO3-N 0.3-0.6m kg/ha	NO3-N 0.6-0.9m kg/ha	NO3-N 0.9-1.2m kg/ha	NO3-N 1.2-1.5m kg/ha	NO3-N Total kg/ha
1	19.71	23.87	63.00	44.79	26.92	178.29
2	41.66	69.42	70.11	42.33	36.70	260.22
3	41.44	42.26	63.62	46.53	42.63	236.49
4	21.86	13.00	17.40	25.43	27.75	105.44
5	37.87	26.78	37.51	45.60	36.20	183.95
6	25.59	17.96	26.46	39.13	35.28	144.41
7	53.48	58.68	60.19	49.78	34.89	257.03
8	28.25	30.56	42.73	47.67	38.77	187.99
9	23.89	18.17	18.49	27.72	35.61	123.89
10	29.79	33.37	33.52	38.27	36.62	171.58
11	32.64	22.14	25.39	32.74	40.08	153.00
12	41.21	37.78	36.47	34.67	47.40	197.53
13	27.19	29.90	30.63	41.15	40.14	169.00
14	24.79	19.17	33.57	47.21	38.52	163.26
15	49.28	51.81	45.58	44.12	40.98	231.77
16	34.26	33.96	43.77	43.34	36.52	191.85
17	29.32	16.53	16.50	31.76	37.09	131.19
18	25.12	22.94	27.91	37.98	42.10	156.04
19	42.22	54.33	42.52	38.66	44.84	222.57
20	37.07	45.19	34.34	40.50	47.66	204.76
21	28.15	30.36	22.88	28.22	30.87	140.48
22	30.33	29.42	22.71	18.09	26.07	126.63
23	31.35	24.11	21.40	27.06	28.16	132.07
24	24.11	13.16	15.12	20.77	21.62	94.78
25	20.67	26.45	34.29	49.64	47.33	178.38
26	15.02	11.25	14.50	28.45	34.89	104.12
27	32.01	38.02	22.63	29.94	28.98	151.58
28	22.37	30.96	30.33	34.58	30.20	148.43
29	25.67	28.60	29.28	33.70	30.57	147.81
30	20.32	17.00	15.56	21.63	25.39	99.90
31	19.96	18.63	13.39	18.32	27.44	97.73
32	18.75	28.18	40.01	40.22	40.74	167.89
33	39.44	33.17	19.91	23.15	29.71	145.38
34	20.06	11.55	12.07	18.58	22.01	84.27
35	18.11	12.75	15.95	22.77	24.17	93.75
36	20.82	23.78	19.11	26.24	26.74	116.69
37	19.51	13.67	13.20	17.30	32.72	96.40
38	36.15	32.65	30.93	37.19	30.57	167.49
39	30.85	28.15	33.62	50.65	47.93	191.20
40	22.03	10.13	9.77	22.15	25.50	89.58
41	24.59	15.04	12.78	17.87	22.38	92.66
42	32.39	31.57	27.79	33.75	27.31	152.81
43	19.85	12.52	16.76	26.71	28.99	104.84
44	44.68	43.33	31.11	29.65	25.85	174.62
45	17.10	9.83	7.99	12.82	18.37	66.10
46	15.77	17.88	16.03	21.12	28.92	99.72
47	32.97	30.72	21.48	30.29	28.58	144.03
48	27.47	47.94	29.45	30.68	29.15	164.70

B9. Soil data 1997: Harvest residual soil NO_3-N by 0.3 m increments from 0 to 1.5 m.

Plot #	NO3-N 0-0.3m kg/ha	NO3-N 0.3-0.6m kg/ha	NO3-N 0.6-0.9m kg/ha	NO3-N 0.9-1.2m kg/ha	NO3-N 1.2-1.5m kg/ha	NO3-N Total kg/ha
1	11.37	6.99	8.93	21.04	18.69	67.01
2	33.85	44.53	56.65	61.73	46.66	243.43
3	28.08	25.50	42.98	35.77	41.34	173.68
4	11.65	6.33	3.49	5.28	14.38	41.14
5	15.70	16.47	27.48	40.04	41.22	140.91
6	12.11	7.49	4.69	13.81	25.19	63.29
7	46.15	77.18	96.85	73.95	46.98	341.10
8	16.99	20.29	28.78	41.53	56.29	163.88
9	16.74	11.87	11.44	24.32	41.11	105.48
10	22.42	32.07	34.98	35.63	39.76	164.87
11	20.36	14.98	16.75	33.96	35.51	121.56
12	17.36	41.26	56.30	50.52	43.48	208.92
13	23.68	19.39	27.58	38.64	52.32	161.60
14	23.45	12.56	8.49	28.31	48.14	120.94
15	28.01	35.98	53.81	43.80	40.26	201.86
16	20.44	27.03	36.91	42.83	38.72	165.94
17	14.57	9.48	11.06	23.87	42.44	101.42
18	21.15	17.35	23.18	32.59	40.06	134.33
19	22.89	24.20	21.66	31.86	39.99	140.60
20	35.67	41.33	31.81	39.89	53.77	202.47
21	19.52	10.93	12.23	15.93	22.86	81.46
22	15.88	18.29	24.73	33.64	38.18	130.72
23	31.18	29.22	28.68	24.41	29.50	142.99
24	16.37	11.68	6.00	8.20	21.37	63.62
25	23.18	27.98	35.88	43.81	49.13	180.00
26	21.18	10.23	10.28	11.19	26.17	79.05
27	17.80	8.12	7.86	16.07	24.76	74.60
28	18.51	9.16	17.39	32.76	49.48	127.30
29	45.35	58.26	34.66	19.06	20.79	178.13
30	40.02	55.32	59.46	52.82	47.32	254.94
31	14.97	10.79	7.07	15.33	23.90	72.06
32	15.79	13.95	33.15	44.49	35.67	143.05
33	16.42	11.17	6.82	7.72	17.23	59.36
34	17.46	20.67	18.06	32.88	27.61	116.68
35	22.69	23.40	26.40	29.77	29.35	131.61
36	15.33	9.24	7.10	6.66	9.43	47.76
37	34.27	41.97	30.25	26.78	30.47	163.74
38	14.45	12.56	11.37	15.38	19.78	73.53
39	13.44	12.16	7.86	18.18	5.30	56.94
40	22.95	21.91	14.21	17.32	24.28	100.66
41	19.80	14.89	17.76	17.02	19.11	88.58
42	23.54	23.01	16.88	17.30	20.36	101.09
43	13.96	7.45	11.20	11.17	15.84	59.63
44	24.19	18.04	22.92	26.32	33.46	124.94
45	14.25	9.74	7.54	6.93	10.62	49.09
46	15.95	11.91	9.26	17.40	26.33	80.86
47	24.87	14.84	14.50	18.85	24.76	97.82
48	21.79	18.06	17.28	18.29	26.62	102.04

B10. N Budget for 1996 and 1997: Unaccounted-for N in 1996 and 1997.

Plot #	W TRT	N TRT	REP	Unacct N 1996 kg/ha	Unacct N 1997 kg/ha
1	130	0	1	-120.44	-37.50
2	130	150	1	-112.65	65.80
3	130	215	1	-13.29	75.01
4	130	85	1	-37.40	4.80
5	90	150	2	-38.98	24.82
6	90	0	2	-164.34	-61.96
7	90	215	2	-58.64	126.10
8	90	85	2	-111.85	-62.07
9	110	0	2	-98.38	-93.96
10	110	150	2	-48.25	-4.15
11	110	85	2	-79.19	-74.49
12	110	215	2	-15.55	43.74
13	90	150	1	-14.67	-14.95
14	90	0	1	-154.22	-92.42
15	90	215	1	-46.44	63.07
16	90	85	1	-128.08	-57.87
17	110	0	1	-143.85	-111.54
18	110	85	1	-86.84	-63.45
19	110	150	1	-68.32	73.15
20	110	215	1	-6.03	23.49
21	130	85	2	-99.36	-16.18
22	130	150	2	8.80	-41.88
23	130	215	2	129.78	27.03
24	130	0	2	-55.10	-84.28
25	130	215	4	13.71	16.93
26	130	85	4	-50.84	-54.89
27	130	150	4	-37.77	95.85
28	130	0	4	-172.78	-134.29
29	90	150	3	-18.68	-31.35
30	90	215	3	162.87	-80.78
31	90	0	3	-52.03	-68.38
32	90	85	3	-26.56	-45.97
33	130	0	3	-148.95	11.52
34	130	150	3	11.28	-68.04
35	130	215	3	73.64	-1.76
36	130	85	3	-84.51	6.53
37	110	215	4	17.50	-59.51
38	110	85	4	-173.04	59.53
39	110	0	4	-209.51	42.69
40	110	150	4	10.83	-21.36
41	90	85	4	-116.69	-83.58
42	90	150	4	-93.94	21.16
43	90	0	4	-135.94	-38.52
44	90	215	4	-64.78	102.46
45	110	0	3	-126.66	-106.13
46	110	85	3	-115.65	-47.67
47	110	150	3	-74.22	14.91
48	110	215	3	-44.41	78.27