EFFICIENCY OF WATER AND NITROGEN USE
BY WHEAT AND LEGUMES IN ZAMBIA

A THESIS

Submitted to the Faculty of Graduate Studies

In Partial Fulfillment of the Requirements

for the Degree of

Doctor of Philosophy

in the

Department of Renewable Resources

Macdonald College of

McGill University

by

© Kalaluka Munyinda

Ste. Anne de Bellevue, Quebec

July 1987

ABSTRACT

Ph.D. K. Munyinda Renewable Resources

EFFICIENCY OF WATER AND NITROGEN USE BY WHEAT AND LEGUMES IN ZAMBIA

Maximum wheat (Triticum aestivum L.) yields in Zambia were obtained with weekly irrigation at 85% of class A pan evaporation during the whole irrigation interval and split application of urea N of which the initial portion of the fertilizer was either broadcast and incorporated or broadcast after the crop had established itself. This corresponded with maximum utilization of fertilizer N. The proportion of N derived from fertilizer was independent of fertilizer placement at various water regimes and N utilization was primarily a function of water availability.

Two nonnodulating soybean (Glycine max L.) cultivars, Clark RJ1 and N77, or in their absence Pearl millet (Panicum glaucum L.) were judged to be appropriate reference crops for estimating N_2 fixation by soybeans using ^{15}N isotope dilution techniques. A local soybean cultivar, Magoye, was rated highest among three cultivars tested for its ability to support N_2 fixation by Bradyrhizobium japonicum and contributed biologically fixed N_2 to a subsequent wheat crop.

RESUME

Ph.D. K. Munyinda Ressources Renouvelables

EFFICACITÉ D' UTILIZATION D' EAU ET D' AZOTE PAR LE BLÉ ET LES LÉGUMINEUSES EN ZAMBIE

Des rendements maximaux de blé (Triticum aestivum L.) ont été réalisés avec une irrigation par semaine à 85% du taux d'évaporation d'un bac de classe A et avec une application fractionnée d'urée dont la fraction initiale était semée soit à la volée et incorporée par la suite, soit uniquement à la volée après établissement. Ceci correspond à une utilisation maximale d'engrais azoté et la proportion d'azote provenant de celui-ci était indépendante de son épandage sous différents régimes d'irrigation. L'utilisation de l'azote était principalement une fonction de la disponibilité de l'eau.

On a jugé deux cultivars de soya (Glycine max L.) sans nodules, Clark RJ1 et N77, ou, en leur absence, le millet perlé (Panicum glaucum L.) comme les meilleures plantes de référence dans l'évaluation de la quantité d'azote fixée par le soya utilisant la technique de dilution de l'isotope ^{15}N. Un cultivar local de soya, Magoye, a été le plus habile de trois cultivars testés à supporter la fixation d'azote par Bradyrhizobium japonicum et a fourni à une culture subséquente de blé de l'azote fixé biologiquement.

Suggested Short title -

WATER AND N USE BY WHEAT AND LEGUMES IN ZAMBIA

Acknowledgements

The author wishes to express his gratitudes to Professors A.F. MacKenzie and I.P. O'Halloran and especially to Dr. R.E. Karamanos for his assistance in planning the project; for his unrelenting assistance and encouragement during the research; his guidance in writing the thesis and his patience in reviewing it. The author also wishes to express his thanks to Dr. Y. Barrada and J.O. Legg for their assistance in planning part of the project. The helpful discussions with Dr. H.H. Janzen and R.M.N. Kucey are gratefully acknowledged.

To the Government of the Republic of Zambia for granting me study leave and support of the research.

To the International Atomic Energy Agency for granting the scholarship and support of the research. The financial assistance of the Natural Sciences and Engineering Research Council of Canada in the last phase of the research is gratefully acknowledged. Finally the author wishes to thank Mrs. Mrak for her assistance in typing the manuscript.

TABLE OF CONTENTS

		Page
	FORWARD	1
1.	INTRODUCTION	2
2.	LITERATURE REVIEW	9
2.1	Water Use	9
2.1.1	Determining soil moisture	10
2.1.2	Estimating evapotranspiration	14
2.1.2.1	Penman method	14
2.1.2.2	Combination method	15
2.1.2.3	Class A-pan	16
2.1.3	Plant water uptake	18
2.1.4	Required amount of irrigation water	20
2.1.4.1	Supply requirements	22
2.1.4.2	Irrigation application interval	23
2.1.4.3	Irrigation supply schedules	24
2.1.5	Effects of soil moisture on growth of wheat	25
2.1.5.1	Critical stages	26
2.1.5.2	Water use efficiency	27
2.1.6	Yield-protein relationships in wheat grain as affected by nitrogen and water	33
2.2	Efficiency of Fertilizer N	33
2.2.1	Losses of N	34
2.2.1.1	Loss of N through volatilization	34
2.2.1.1.1	Effect of NH_4^+ concentration	36
2.2.1.1.2	Effect of organic residues	37
2.2.1.2	Reducing losses	38
2.2.1.3	Loss of N through denitrification	38
2.2.1.3.1	Effect of organic matter	40
2.2.1.3.2	Effect of pH	40
2.2.1.3.3	Effect of temperature	41
2.2.1.4	Gaseous nitrogen losses from soils through nitrite reaction	41

Page

2.2.1.5 Loss of N through chemodentrification . 43
2.2.1.6 Fixation of N by organic matter 44
2.2.1.7 Importance of nitrite reactions in nitrogen losses from soils 44
2.2.1.8 Loss of N through plant canopy 45
2.2.1.9 Leaching losses 45

2.2.2 N uptake 47

2.2.3 Methods of improving N efficiency 49

2.2.4 Methods of ^{15}N assay 50

2.2.4.1 ^{15}N terminology 52

2.2.4.2 Use of isotope derived criteria 55

2.3 Utilization of Residual Nitrogen 56

2.4 Nitrogen Derived from Nitrogen Fixation 57

2.4.1 Amount of nitrogen fixed 58

2.4.2 Use of ^{15}N in biological dinitrogen fixation . . . 58

2.4.3 Estimation of biological dinitrogen fixation (BNF) 59

3. INFLUENCE OF IRRIGATION SCHEDULES AND NITROGEN PLACEMENT ON WHEAT 63

3.1 Introduction 63

3.2 Materials and methods 64

3.2.1 First year study (1982) 64

3.2.2 Second year study (1983) 66

3.2.3 Third year study (1984) 68

3.3 Results and Discussion 69

3.3.1 Effect of Irrigation 69

3.3.2 Effect of N rate and method of placement 71

3.3.3 Interaction of irrigation, N rate and method of N placement 71

3.4 Conclusions 80

		Page
4.	EFFECT OF IRRIGATION SCHEDULES AND REGIMES ON WHEAT YIELD	85
	4.1 Introduction	85
	4.2 Materials and Methods	86
	4.3 Results and Discussion	87
5.	UTILIZATION OF ^{15}N-UREA FERTILIZER BY IRRIGATED WHEAT IN ZAMBIA	100
	5.1 Introduction	100
	5.2 Materials and Methods	102
	5.3 Results and Discussion	106
	5.4 Conclusions	115
6.	NITROGEN FIXATION BY SOYBEANS (<u>Glycine max</u>) IN ZAMBIA	118
	6.1 Introduction	118
	6.2 Materials and Methods	119
	6.3 Results and Discussion	125
	6.4. Conclusions	140
7.	WHEAT YIELDS IN MAIZE-WHEAT AND SOYBEAN-WHEAT ROTATIONS	143
	7.1 Introduction	143
	7.2 Materials and Methods	144
	7.3 Results and Discussion	147
8.	SUMMARY AND CONCLUSIONS	163
	REFERENCES	169

LIST OF TABLES

Table		Page
3.1	Nitrogen fertilizer program for the 1982 experiment	65
3.2	Nitrogen fertilization program for the 1983 experiment .	67
3.3	F values associated with the effects of irrigation schedule, method of nitrogen application and/or placement, nitrogen rates and their interaction on the grain yield of wheat grown at Naga, Zambia	72
3.4	Benefit of split application of nitrogen fertilizer placement methods on the basis of irrigation schedule and nitrogen rate in 1983	78
3.5	Effect of nitrogen rate and placement on the grain yield of wheat under various irrigation regimes in 1983	79
3.6	Benefit of split application on the basis of nitrogen fertilizer placement methods and nitrogen rate in 1984 . .	83
4.1	Dates of sowing, irrigation and harvesting	88
4.2	Relationship between applied irrigation and depth of irrigation in 1982	93
4.3	Yield of irrigated wheat Mg ha^{-1} (Aeppli, 1977)	97
4.4	Apparent water use of wheat in different irrigation treatments	98
5.1	Nitrogen fertilizer program for the 1982 experiment . . .	104
5.2	Nitrogen fertilizer program for the 1983 experiment . . .	105
5.3	Effect of irrigation schedule and method of urea application on DM yield of wheat grain and straw in the 1982 experiment	107
5.4	Effect of irrigation schedule and method of urea application and placement on DM yield of wheat grain and straw in the 1983 experiment	108
5.5	Effect of irrigation schedule and method of urea application on total uptake into the grain and straw and % Ndff in the grain of wheat in the 1982 experiment .	110

		Page
5.6	Effect of irrigation schedule and method of urea application and placement on total uptake into the grain and straw and %-Ndff in the grain of wheat in the 1983 experiment	111
5.7	Effect of irrigation schedule and method of urea application on fertilizer uptake and % utilization by wheat grain and straw in the 1982 experiment	113
5.8	Effect of irrigation schedule and method of urea application and placement on fertilizer uptake and % utilization by wheat grain and straw in the 1983 experiment	114
6.1	Components of the experiment for selection of non-nodulating soybean cultivars as reference crops by ^{15}N isotope dilution and of fixing cultivars selected for their ability to support N_2 fixation by B. japonicum	121
6.2	Growth stages of soybean (Glycine max) at which harvests were taken	123
6.3	Dry matter yield of soybeans and nonnodulating control plants at the four harvest times	126
6.4	Nitrogen yields of soybeans and nonnodulating control plants at four harvest times	127
6.5	Atom % ^{15}N excess in soybeans and nonnodulating control plants at the four harvest times	128
6.6	Comparison of possible non-legume crops as reference for estimating N_2 fixation by ^{15}N isotope dilution	129
6.7	Percent Ndfa in soybeans estimated from various control plants at the four harvest times	132
6.8	Dry matter and nitrogen yield and N isotope characteristics of nonnodulating soybean cultivars at 46 days after planting	133
6.9	Dry matter and nitrogen yield of nonnodulating soybean cultivars 84 days after planting	134
6.10	Nitrogen isotope characteristics of nonnodulating soybean cultivars 84 days after planting	135
6.11	Comparison of soybean cultivars at 46 days after planting for their ability to support symbiotic N_2 fixation at Nanga, Zambia	137

Page

6.12 'A' values for nodulating cultivars of soybean calculated on the basis of nonnodulating cultivars at 46 days after planting 138

6.13 Dry matter and nitrogen yield of nodulating soybean cultivars 84 days after planting 139

6.14 Comparison of soybean cultivars for their ability to support symbiotic N_2 fixation 84 days after planting 141

6.15 'A' values for nodulating cultivars of soybean calculated on the basis of nonnodulating cultivars at 84 days after planting 142

7.1 Fertilizer P and N treatments of two season rotations in Zambia 146

7.2 Comparison of soybean cultivars for their ability to support symbiotic N_2 fixation by B. japonicum at 42 days after planting 148

7.3 Dry matter and nitrogen yield of soybean cultivars 72 days after planting 149

7.4 Comparison of soybean cultivars for their ability to support symbiotic N_2 fixation by B. japonicum 72 days after planting 150

7.5 'A' values for nonnodulating and nodulating soybean cultivars 151

7.6 Grain DM yields of soybean cultivars 153

7.7 Dry matter yields of Maize in first season of the rotation . 154

7.8 Wheat grain DM yields in the second season of the rotation . 155

7.9 Phosphorus levels and isotopic characteristics of wheat in the second season of the rotation 157

7.10 Significance of contrasts among P levels, %Pdff, fertilizer uptake and 'A' values of wheat in the second season of the rotation 158

7.11 Nitrogen derived from atmosphere, fertilizer and soil by crops in the first season of the rotation 161

7.12 Total N uptake of wheat in the second season of the rotation 162

LIST OF FIGURES

Figure		Page
1.1	Major agroecological zones in Zambia	3
1.2	Mean length of the rainy season in Zambia	4
3.1	Average effect of irrigation schedule on grain yield of wheat	70
3.2	Average effect of nitrogen rate on yield of wheat	73
3.3	Average effect of method of nitrogen application on grain yield of wheat	74
3.4	Effect of method of placement and application of nitrogen fertilizer on grain yield of wheat in 1983	75
3.5	Grain yields of wheat grown in the 1982 experiment as affected by irrigation schedule and method of nitrogen fertilizer placement	76
3.6	Grain yields obtained by the weekly irrigation schedule in 1983 as affected by the method of nitrogen application (S = single, T = two split) and placement (average yields of all treatments for the every two and three week irrigation schedules are presented for visual comparison only)	81
3.7	Grain yields obtained in 1984 as affected by the method of nitrogen application and placement	82
4.1	Average effect of irrigation schedule on grain yield of wheat	89
4.2	Cummulative pan evaporation on a weekly basis and relative humidity during the growing season	91
4.3	Relationship between grain yield of wheat and cummulative depth of irrigaiton in mm	95
5.1	Effect of irrigation rate and %Ndff on the grain dry matter (DM) yield of wheat	116
6.1	Changes in Nitrogen uptake by _Glycine_ _max_ cv. Magoye (●) and D680099 (o) and non-fixing reference crops (* _Eleuisine_ _corocana_ L., □ _Panicum_ _glaucum_ L., x _Chloris_ _gayana_ L.) between sampling intervals during the growing season	131

CONTRIBUTIONS TO KNOWLEDGE

The main contributions to knowledge included the following:

1. Highest wheat grain yields were obtained with cultivar EMU'S when irrigation was applied weekly at a rate of 85% of total pan evaporation. Grain yields were increased when irrigation was applied either every two or three weeks, indicating water stress was the main yield limiting factor. Although the apparent water use efficiency increased with the longer irrigation intervals, the loss in yield was too large to warrant their implementation.

2. Split application of N produced significantly higher grain yields. The highest grain yield obtained when the initial portion of N was either broadcast and incorporated prior to seeding or broadcast two weeks after seeding. The increase in grain yields with split application was due to a higher uptake and efficient utilization of fertilizer N.

3. The percent NDFF for any placement method was independent of water regime, indicating the same positional availability of the applied N to the wheat.

4. Grain DM yields of wheat was primarily a function of available water and was affected by %NDFF at lower water regimes. Increasing % NDFF at low water regimes resulted in increased DM yields but the increase did not compensate for yield loss due to restricted moisture.

4. Grain DM yields of wheat was primarily a function of available water and was affected by %NDFF at lower water regimes. Increasing % NDFF at low water regimes resulted in increased DM yields but the increase did not compensate for yield loss due to restricted moisture.

5. Low recoveries of N by wheat found in this study, suggest a significant loss of applied fertilizer N. The magnitude and mechanism of nitrogen loss should be further evaluated in order to develop techniques and use of improved N sources for improved N efficiency.

6. Non-nodulating soybeans (Glycine max L.) cultivar Clark Rji and N77 were found to be appropriate reference plants for estimating biological N_2-fixation by the isotope dilution method in Zambia. In their absence Pearl millet (Panicum glaucum L.) was suitable.

7. A local soybean (Glycine max L.) cultivar Magoye rated highest among other soybean cultivars (Bossier, Santa Rosa) in supporting symbiotic N_2-fixation.

8. When Magoye was inoculated with a local rhizobium (B. japonicum) isolate (MM48) up to 70% of the total N was derived from N_2-fixation, N_2-fixed amounted to 225 kg N ha^{-1}.

9. Total soybean DM yields were lower with high inorganic N application rates (100 kg N ha^{-1}). However, when soil N was in organic form, no yield decrease was observed with the same high N application rate. Therefore, inhibition of N_2-fixation by high rates of fertilizer N was not only dependent on the absolute amounts of N applied but also on the source of N.

10. When wheat was grown in rotation with maize and soybeans as first crops, high wheat grain yields were obtained when the preceeding crop had the least soil N requirement.

FOREWORD

This thesis has been submitted in paper format. There are eight Sections consisting of Introduction to the thesis, Literature review, five papers in a form suitable for publication, and overall summary and conclusions.

The third Section "Influence of irrigation schedules and nitrogen placement on wheat" and the forth Section "Effect of irrigation schedules and regimes on wheat yield" have been published in the Comm. Soil Sci. Plant Anal. with the co-authorship of A. Bunyolo and R.E. Karamanos. The fifth Section "Utilization of ^{15}N-urea fertilizer by irrigated wheat in Zambia" was submitted for publication to the Plant and Soil on 10 July, 1987 with the co-authorship of R.E. Karamanos and A.F. MacKenzie. The sixth Section "Nitrogen fixation by soybeans (Glycine max L.)" was submitted for publication to the Plant and Soil on 23 July, 1987 with the co-authorship of R.E. Karamanos, J.O. Legg and A. Sanogho. The seventh Section "Wheat yields in maize-wheat and soybean-wheat rotations" was submitted for publication to the Can. J. Soil Sci. on 17 September 1987 under the co-authorship of R.E. Karamanos and I.P. O'Halloran.

1. INTRODUCTION

Zambia is located in central southern Africa. It shares common borders with Tanzania, Malawi, Mozambique, Zimbabwe, Botswana, Namibia, Angola and Zaire. The country is completely landlocked. The national territory covers about 750,000 km^2. The altitude varies from 1000 m over most of the country to peaks of about 2500 m.

The country can be divided into roughly four major agroecological zones (Fig. 1.1):

A.- The Northern high rainfall zone comprises the major part of the Northern, Luapula, Copperbelt and North Western Provinces. It is characterized by higher rainfall than the rest of the country (1,000 to 1,500 mm on average all falling between November and April) and generally very poor, leached sandveld soils. The mean length of the rainy season (145 to 190 days) favors annual crops with a long growing season (Fig. 1.2). However, high rainfall, low sunshine hours, and cloud cover reduce temperatures to an average of 20^o C, which makes the zone somewhat less favourable for optimum growth of maize and limits the possibility of growing cotton (*Gossypium Livsutum* L.), virginia or barley tobacco (*Nicotiana tobacum* L.). Various forms of shifting cultivation (Chitemene) have evolved in this region. This is the zone being considered for rainfed wheat.

B. The Western Semi-Arid Plains Zone includes most of the Western Province and the Zambezi District of the North Western Province. It is the driest region in Zambia. The average rainfall varies from 600 to 1,000 mm, decreasing towards the south. The major climatic limitations to plant

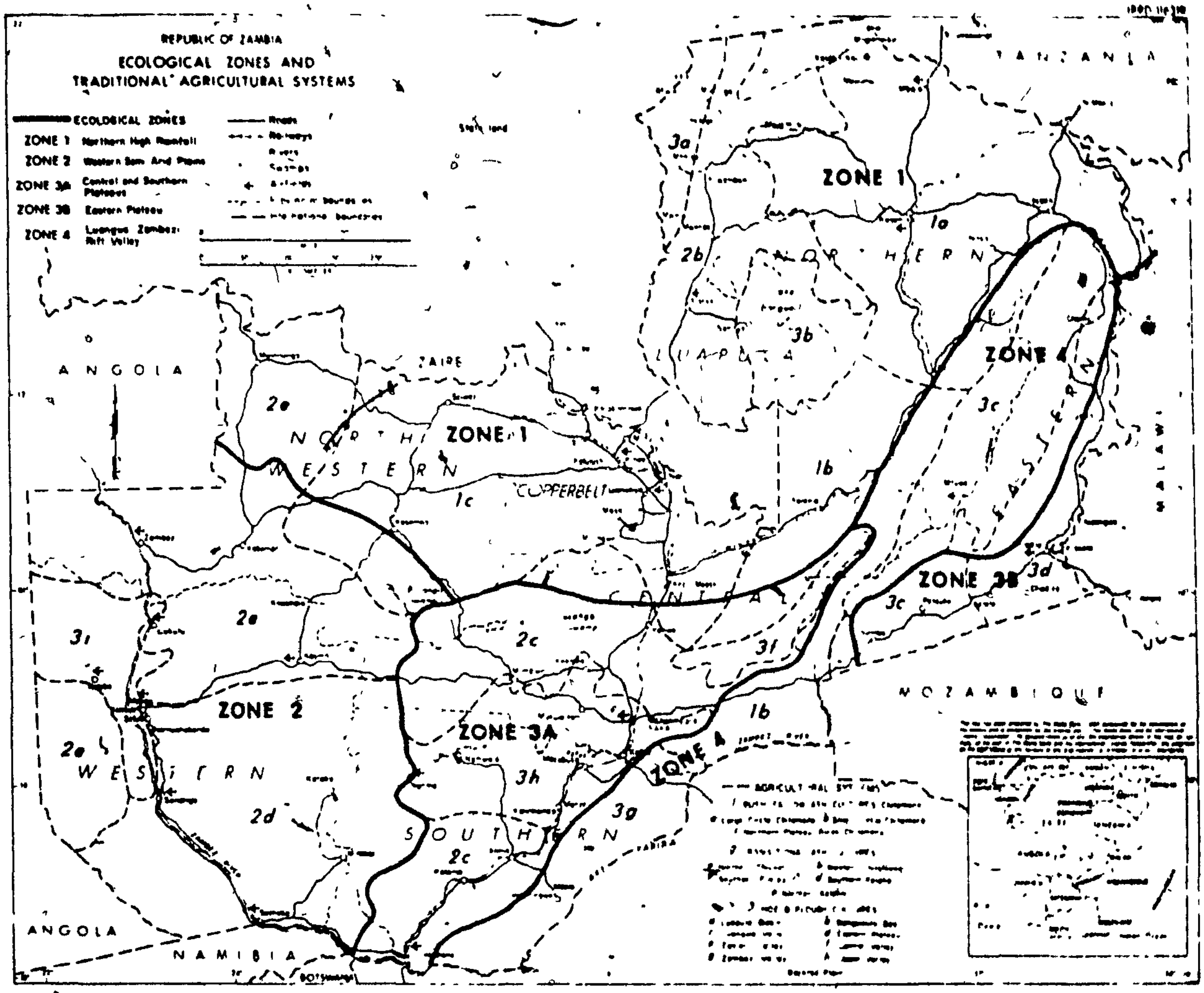

Figure 1.1 Major agroecological zones of Zambia

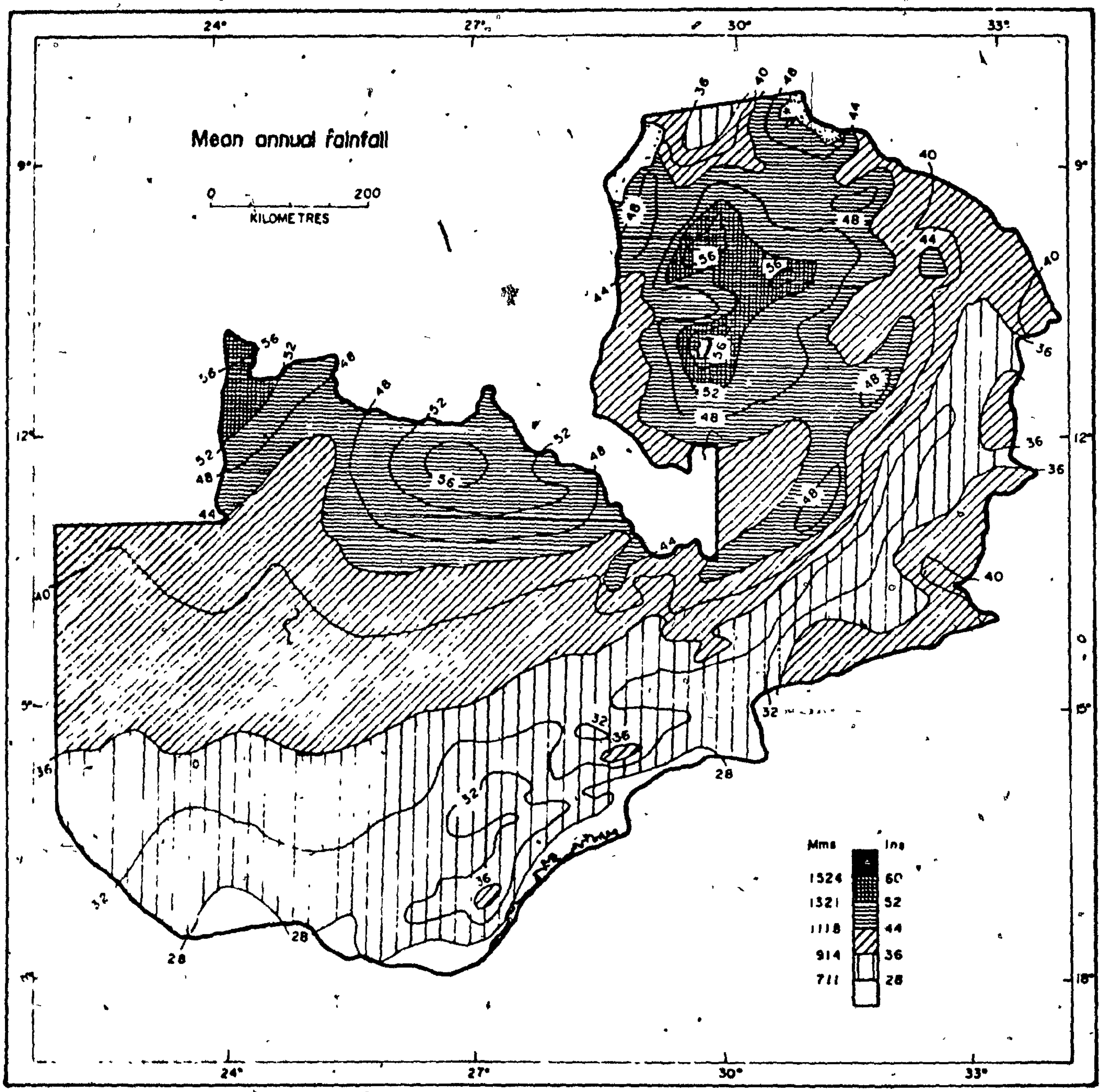

Figure 1.2 Mean length of the rainy season in Zambia

growth are the extremes of heat, frost, and aridity in the Southern and Western margins of the area.

C. The Central, Southern and Eastern plateaus. The plateau areas of Central, Southern and Eastern Provinces generally contain the most fertile soils in Zambia. The upper valley soils which border the Kafue flats in the Mazabuka and Lusaka District of Southern and Central Province, the Petauke and, to a lesser extent, Katete and Chipata Districts of Eastern Provinces support a variety of crops including maize (*Zea mays* L.), groundnuts (*Arachis hypogea* L.), sunflower (*Helianthus annus* L.), cotton, irrigated wheat (*Triticum aestivum* L.) etc. The soils of the Southern and Eastern plateau are less leached and have a higher percentage of more fertile red earths or loams and can support a variety of crops similar to the upper valley soils. The sandveld soils of Mkushi, Kabwe, Choma, Kalomo, Katete and Chipata are best suited to tobacco and maize. The red loams of Eastern Provinces in Petauke and Katete, like the upper valley soils of Mumbwa, Mazabuka and Lusaka, are more suited to cotton, maize, sunflower, soybeans, irrigated wheat cotton and groundnuts. Some of the most advanced agricultural systems have evolved in this region, i.e., oxen or mechanized production.

D. The Luangwa-Zambezi rift valley. The altitude is down to 600 m with a rainfall less than 750 mm per year to 1,200 mm in the north of the Luangwa valley. The zone has a humid hot climate for most of the year. The region is not suitable for agriculture except for isolated pockets of good soils. Development is confined to the lower valley soils which occur in small areas along the Luangwa valley and Gwembe valley bordering the Zambezi river and Lake Kariba. Sorghums (*Sorghum vulgarae* L.) and millets (*Panicum glaucum* L.) are grown in the area.

Although agriculture supports over 50% of Zambia's population, it accounts for only about 15% of Growth Domestic Product (GDP). The mining sector, mainly for copper mining, has traditionally dominated the economy and accounts for an overwhelming proportion of GDP and foreign exchange earnings. The mining sector currently faces significant medium and long term problems. Since 1976, the economy has been in depression, due to mainly a 40% decline in the price of copper but also to military and political events in neighboring countries.

Without a successful diversification policy and considerably long-term structural adjustments, Zambia faces a relatively bleak economic future. Any significant economic growth will have to come from the agricultural sector and this will be the country's serious challenge for the rest of this century and probably well into the next.

Historically the development of agricultural exports has been limited. Apart from small quantities of maize exported to neighboring countries until 1978, the only regular exports have been tobacco and confectionary groundnuts, although they account for less than 1% of total export earnings. Imports of agricultural commodities, on the other hand, showed an increased trend during the 1970's reaching about 8% of total exports. The major imported agricultural goods have been cereals (mainly wheat and rice), vegetable oil and oilseed cakes, which accounted for 50%, 11% and 17% of total agricultural imports in 1979. Increasing quantities of wheat are being imported and this is a significant drain on the scarce foreign exchange.

In an effort to diversify the economy and avoid the heavy reliance on the mining sector, the country has embarked on a major food program aimed at self-sufficiency in food and fiber production. The country possesses a tremendous potential in implementing multicropping systems which promise increased agricultural production. To utilize part of this potential, yields of the main field crops, maize, sunflower, soybeans, groundnuts, cotton can be increased through plant breeding, efficient utilization of fertilizer and better management practices. The yields of wheat especially grown in the dry season (May to August) can be increased through more rational use of water and fertilizer, especially nitrogen.

The maintenance of N fertility of soils cropped to cereals depends upon the addition of nitrogenous fertilizers or upon biological N_2-fixation, often following the introduction of legumes grown in rotations. Legumes provide a source of fixed nitrogen in crop rotations. This is of extreme importance to developing countries since fertilizer N costs are increasing and consequently the fertilizer supply to farmers is being reduced. Thus, biological N_2-fixation may be a viable alternative for countries such as Zambia where escalating energy costs render the cost of synthetic nitrogen products prohibitive.

The hypotheses for this thesis were:

1. Rational application of water through appropriate irrigation scheduling and rate, timing and placement of N fertilizer

application will contribute to increased water and N use efficiency and lead to higher grain yields.

2. N_2 fixation by soybeans will contribute to efficient use of N resources in Zambia.

The objectives of the project were to:

1. Determine the effect of different irrigation regimes on the grain yield of wheat.
2. Evaluate irrigation water use efficiency.
3. Determine the effect of different irrigation regimes, time, rate and placement of N fertilizer application on the grain yield of wheat.
4. Compare and select the most appropriate non-fixing control for estimating N_2 fixation and assess yields and N_2 fixation by soybeans.
5. Determine amounts of N_2 fixed by two soybean crops at two levels of P and evaluate the residual effect of N and P on wheat growth when the preceding crops were either cereal or legume.

2. LITERATURE REVIEW

Fertilizer recommendations on wheat in Zambia have been based on fertility and irrigation trials of wheat in neighboring countries, such as Zimbabwe. However, because of different climatic conditions, information is required on the correct use of fertilizers and irrigation water in conjunction with such agronomic variables as date of planting, plant populations and spacing for improving the yield of promising varieties. This literature review will deal with the main factors affecting water and nitrogen use.

2.1 Water Use

Earlier work at the National Irrigation Research Station at Nanga, Zambia (Aeppli, 1977) could not lead to final recommendations on crop water use because of a number of obstacles encountered, especially with proper determination of soil moisture. Crop water requirements were determined on the basis of potential evapotranspiration from climatic data. The concept of potential evapotranspiration is an attempt to characterize the macrometeorological environment of a field in terms of an evaporative power or demand which the atmosphere is capable of extracting from a field of given surface properties. Evapotranspiration is the conversion of water to vapor and the transport of the vapor away from the watershed surface (surface of leaves, soil and water surfaces) into the atmosphere.

Application of water can result in N and irrigation interaction. The added water may leach N into the profile reducing its availability. On the other hand added water can result in increased soil and fertilizer N and higher crop yields.

2.1.1 Determining soil moisture

To obtain valid field data on evapotranspiration requires a large number of soil moisture measurements at various soil depths. There are several methods of determining soil moisture. The most common is the gravimetric method of weighing a soil sample before and after oven drying. Other methods measure soil moisture indirectly. A soil characteristic other than moisture, such as electrical and thermal conductivity, thermal diffusivity, dielectric constant, or moisture tension is measured (Gardner and Kirkham, 1952).

The neutron moisture method is used for measuring soil water contents in studies on water conservation and management (Carneiro and de Jong, 1985). This method depends on the fact that hydrogen slows fast neutrons to thermal energies (0.025 eV) more efficiently than any other common element. The cross section for hydrogen increases greatly from 2.55 to 47.5 barns as the neutrons slow down. The cross section expresses the probability that a neutron will interact with an atom of given element and is measured in barns. A barn is equivalent to $10^{-24} cm^2$. The cross section depends primarily upon the energy of the neutron and for the lightest elements and at low neutron velocities, the chemical binding of the atom. The large cross section of hydrogen results in a greater probability for the neutron to interact with hydrogen compared with any other element. For most of the elements in the soil, the cross section is small (less than 1 barn) and remains the same. Also, elements may be present in insignificant quantities (Gardner and Kirkham, 1952; Barrada, 1965).

The presence of significant amounts of Cl, Cd, Li, or B would cause the count-rate corresponding to a certain moisture content to decrease owing to neutron capture. In most soils, only the Cl content could play an important role as its effective cross section for the capture of thermal neutrons amounts to 33 barns. As for B, the measured moisture content would be 1-2 volume percent too low if the B content of the soil was 30 mg kg^{-1} larger than implied in the calibration curve (Haahr and Olgarrd, 1965).

The most important source of hydrogen in soil, other than that of soil water itself, is the hydrogen in soil organic matter. The hydrogen content of humus is about 5% of its weight. As the amount of hydrogen in water is about 11% of its weight, the amount of hydrogen in organic matter may be an appreciable part of the total hydrogen (Gardner and Kirkham, 1952). A small amount of hydrogen is found in the mineral fraction, and this amount, being in chemical combination, should be relatively constant.

Agreement is obtained between the neutron probe and the gravimetric method of moisture determination. The relationship is true, however, only if the moisture content is expressed on a volume basis. Otherwise, there is scatter in the data (Gardner and Kirkham, 1952). In agricultural work, moisture on a volume basis is generally more desirable than on a weight basis. The count rate is a direct function of the apparent density of the soil. Any variation in apparent density would cause a change in the intercept of the calibration curve, while the slope remains constant (Barrada, 1965). Soil density constitutes the most critical of the factors influencing moisture determinations. A difference in density of 100 kg m^{-3} resulted in an error of water content about 1 volume percent (Haahr and Olgaard, 1965). If the actual density was higher than the calibration curve density the water content derived would be too large.

At low moisture values (less than 10%), experimental values fall below theoretical values (Stewart and Taylor, 1957; Haahr and Olgaard, 1965; Carneiro and de Jong, 1985). When the neutron moisture method is used, the surface soil and possibly other depths should be calibrated separately, depending on the desired accuracy and precision (Stewart and Taylor, 1957).

The calibration curve of most neutron probes (Carneiro and de Jong, 1985) can be approximated by the equation:

$$\theta = a + b * CR \qquad [2.1]$$

where,

θ = volumetric water content (cm^3/cm^3)

CR = count ratio (actual count/reference count)

a and b are constants.

The amount of water (in cm) to depth z is given by

$$\int_0^z dz = az + b \int_0^z CR\, dz \qquad [2.2]$$

The value of b can be determined by successive additions of known amounts of water to a soil, each followed by scanning of the soil profile with a neutron probe (Caneiro and de Jong, 1985). The value of b can be determined from the expression

$$I_{i+1} - I_i = b \int_0^z (CR_{i+1} - CR_i)\, dz \qquad [2.3]$$

where,

I_i = total depth of water in cm, after the ith addition of water.

The intercept of the calibration curve can be obtained by determining the volumetric water content of the cores extracted during installation of the access tubes and solving for the above equation by using the initial count ratios and the value of b determined.

The use of the standard or reference source of counts increases the accuracy in calibrating the neutron meter. Field calibration without taking standard readings results in poor correlation between neutron meter reading and moisture content of the soil (Stewart and Taylor, 1957; Barrada, 1965). The neutron moisture meter is reliable in all types of inorganic soils of medium texture regardless of salt content and soil type (Stewart and Taylor, 1957).

Barrada (1965) cited several advantages of the neutron moisture meter:

1. Simple operation that enables one or two operators with little technical training to use the equipment.
2. Saving in time as usually 2 to 5 min are enough for a single measurement.
3. A large volume of soil is analyzed in a single measurement as the probes normally measure an almost spherical volume with an average diameter of 0.35 m increased to 0.75 m in soils of very low moisture content.
4. Measurements are nondestructive, allowing for long-term studies on the same soil volume.

2.1.2 Estimating evapotranspiration

The measurement of soil moisture content by itself does not indicate the presence of plant available water. The difference between moisture content at a given time and that corresponding to a certain point of reference, such as field capacity (Barrada, 1965) indicates plant available water. Changes in soil moisture content are needed to calculate the crop water consumption and the amount evaporated, or to study the water movement in the soil. The soil moisture and the evaporative demand determine what proportion of the actual to potential transpiration a plant will achieve (Hann et al., 1982).

Many methods of estimating potential evapotranspiration whether for hydrologic models or irrigation scheduling are based on potential evapotranspiration as a physiologically based process, i.e. the plant participates as it were in determining its potential evapotranspiration even when it is well endowed with water (Hillel, 1982). The procedure is to first estimate or measure a potential for evapotranspiration based on meteorological factors and then compute the amount of that potential utilized by the actual evapotranspiration process.

2.1.2.1 Penman method

Various empirical models have been proposed for estimating the potential evapotranspiration. The method proposed by Penman (1948) is based on the measurement of net radiation, temperature, vapor pressure and wind velocity taken at one level above the field and is given by:

$$LE = \frac{(\Delta/\gamma)\ Jn + LEa}{\Delta/\gamma + 1} \qquad [2.4]$$

where,

$LEa = 0.35(ea-e)\ (0.5+U2)/100\ (mm/day^{-1})$,

ea = saturated vapor pressure at mean temperature (mm Hg)

e = mean vapor pressure in air,

γ = psychometric constant ~ 0.66 mbar $^{o}C^{-1}$

U2 = mean wind speed in miles per day at two meters above ground

LE = rate of energy utilization in evapotranspiration.

The potential evapotranspiration as determined by the Penman equation does not take into account the possible fluctuation of the soil heat flux. The formulation does not take into account, surface roughness or air instability (buoyancy effects).

2.1 2.2 Combination method

There are several modifications of the Penman equation (Penman, 1948; 1956). The combination method based on the modified Penman equation now represents one of the more reliable techniques for predicting potential evapotranspiration from climatic data. The refinements were made by Businger (1956), Tanner and Pelton (1960), and van Bavel (1966). Monteith (1965) added a term to account for vapor movement resistance from an evaporating surface and similarly Tanner and Fuchs (1968) incorporated a surface temperature value. The derivation of the combination equation is

$$LE \quad \frac{(\Delta/\gamma)R_n+(KLd_aU_a)/[\ln(z_a-d)/z_o)]^2}{1+(\Delta/\gamma)} \qquad [2.6]$$

$$K = \frac{\rho k^2_{\epsilon}}{P}$$

where,

LE = latent heat flux.

L_o = latent head of vaporization (cal g^{-1}).

E = potential evapotranspiration rate (cm day^{-1}).

Δ = slope of the psychrometric saturation line (mbars $^oC^{-1}$).

γ = psychrometric constant (mbars $^oC^{-1}$).

R_n = net radiation flux (cal cm^{-2} day^{-1}).

d_a = saturation vapor pressure deficit of air [(e_o-e_1)mbars].

Ua = windspeed at elevation z_a (m day^{-1}).

z_a = anemometer height above soil (cm).

d = wind profile displacement height (cm).

ρ = air density (g cm^{-3}).

k = van Karman coefficient (0.41).

ϵ = water/air molecular ratio (0.622).

P = ambient air pressure (mbars).

zo = wind profile roughness height (cm).

All terms of k and the value of L are treated as constants in most applications. The (Δ/γ) term is a function of temperature and tabled values are available (van Bavel, 1966).

2.1 2.3 Class A-pan

The potential evapotranspiration can also be estimated from pan evaporation. Good results are obtained by class A-pan, however, the values the usually higher than the potential evapotranspiration from a well vegetated surface because of the pan's excessive exposure and lower reflection of solar radiation. The A-pan values are also influenced by the pan's surrounding fetch, relative humidity and windspeed. Heat transfer through the sides of the pan may occur which may be severe for sunken pans. Storage of heat within the pan can be appreciable and may cause almost equal evaporation during night and day (Doorenbos and Pruitt, 1977). The A-pan values have therefore to be adjusted with coefficients which take into account the effects of plant growth characteristics (date of planting, rate of crop development, length of growing season and climatic conditions) and average water availability. Crop coefficients show a large variation between major groups of crops. The difference is largely due to resistance to transpiration of different plants, such as waxy leaves of plants, crop height, crop roughness, reflection and ground cover.

$$EtO = CE_t \; Ep \qquad [2.7]$$

where,

EtO = potential evapotranspiration.

Ep = class A-pan.

CE_t = coefficients.

The coefficients range from 0.5 to 0.8, but other than extreme conditions, the coefficients stabilize to about 0.77 over several days. Specific coefficient values for application to specific locations have to be found. However, representative values from other studies provide guidance. Several researchers have obtained best results by applying seasonally varied coefficients and average water availability.

There is a correlation between the predicted potential evapotranspiration using the combination model and class A-pan evaporation. The improved correlation is largely due to the added consideration of the aerodynamic terms in the combination equation. The other methods for estimating potential evapotranspiration are based on:

1. Vertical energy budget of a vegetated surface.
2. Air temperature such as the Blaney-Criddle (1966) method, which has been extensively used in irrigation designs in the Western U.S.

A commonly used method of estimating actual evapotranspiration is by lysimeter. This is normally done by the measurement of soil container mass changes. With lysimeters such as that developed by Dugas et al. (1985), it is possible to evaluate (throughout the profile) the interrelationships between rooting depth and density, soil water content, plant water uptake and evaporative demand.

2.1.3 Plant water uptake

Brun et al. (1985) investigated simple empirical equations that would adequately describe actual evapotranspiration as a function of soil moisture content or pan evaporation or both. By including the pan evaporation factor, the coefficient of estimation (R^2) was markedly increased from 0.69 to 0.89. Thus soil moisture and pan evaporation were found to be both necessary to produce acceptable models for predicting crop evapotranspiration, with soil being the more important factor. Tanner and Jury (1976) developed and tested an actual evapotranspiration model based on the potential evapotranspiration formula of Priestly and Taylor (1972). Calculated evaporation (E) and transpiration (T) estimates were consistent with measured values by the lysimeter. At low leaf area index (LAI), E comprises a large fraction of the potential evapotranspiration and cannot be estimated unless E and T are considered separately, since E and T usually do not vary proportionately. Tanner and Jury (1976) estimated E when it was less than potential (the falling rate phase), by two approaches based on E falling as $t^{1/2}$. The model, however, assumes T at the potential rate.

The general flow equation for a one dimensional flow describes the water flow in the unsaturated zone (Alaerts et al., 1985). A modification of the flow equation to include the plant root extraction term (the so called sink term), along the lines of Whistler et al. (1968) and Molz and Remson (1970), describes the model of water balance of a cropped soil. The objective of a sink term is to distribute an atmospheric demand over the root zone and to reduce eventually the water loss from the crop according to the water uptake status of the root zone (Alaerts et al., 1985), the water uptake status in the root zone being equal to the evapotranspiration.

$$\frac{d\theta}{dt} = \frac{d}{dz} K(\theta) \frac{dH}{dz} + A(z,t) \qquad [2.8]$$

where,

A(z,t) = root extraction term (sink term).

θ = volumetric water content

t = time

z = depth

K = hydraulic conductivity

H = hydraulic head (sum of pressure head h, and gravity head)

The simple least-energy model performs similarly to the complex Nimah-Hanks model for unsaturated, lower boundary conditions, but fails to simulate a realistic extraction pattern when a water table is present. Other models such as the Hooglands extraction term cannot simulate the daily potential transpiration (Alaerts et al., 1985).

2.1.4 Required amount of irrigation water

The required amount of irrigation water is calculated on the basis of meeting the evapotranspiration rate of a disease-free crop growing in large fields under optimal growing conditions (Doorenboos and Pruitt, 1977). The $Et_{(crop)}$ (crop evapotranspiration) is determined by balancing the inputs (precipitation or irrigation, upward flow from water tables and soil water storage) to evaporation losses, drainage and runoff.

$$In = Et_{(crop)} - (Pe + Ge + Wb \pm D - Q) \qquad [2.9]$$

where,

In = net irrigation,

Pe = precipitation,

Ge = groundwater contribution,

Wb = stored water at the beginning of each period,

D = root zone drainage ("+" upward flow to root zone or "-" downward flow from the root zone),

Q = the field runoff.

$Et_{(crop)}$ = crop evapotranspiration

Abstracting of Et from each rooting layer can also be done through consideration of the various sink terms (Alaerts et al., 1985), through plotting of isograms of constant soil moisture with depth as ordinate and moisture as abscissa over the growing season from a lysimeter as described by Brun et al., (1985). It can also be done through measuring root length, density and water content throughout the soil profile in specially designed lysimeters using mini-rhizotrons (Dugas et al., 1985). Drainage is estimated by redistribution and percolation by a Darcy-type unsaturated flow computation. The actual $Et_{(crop)}$ is computed through sequential consideration of plant phenology to describe the transpirability of the existing canopy, root redistribution and water stress relationships.

The $Et_{(crop)}$ varies with the dynamic development and decay of a plant canopy. The degree of canopy development proportions the radiant energy between the plant and the soil. Before complete canopy development, energy from a dry soil and air not used for evaporation is reradiated for transpiration to increase the $Et_{(crop)}$. To a good approximation Eta rate is proportional to leaf area index (LAI) up to 2.5 - 3.0, above which evaporation occurs at a potential rate. $Et_{(crop)}$ is modified by the plants phenological development, which may occur independent of crop canopy present. The phenology relates to stomatal control of water through the plant depending on atmospheric conditions. The root distribution reflects where in the soil profile the plant is attempting to obtain water, and a water-stress relationship, which is applied to each layer and is a function of the plant available water of that soil layer and the atmospheric demand of that plant.

Other than meeting the net irrigation requirements, water is needed for leaching accumulated salts from the root zone and other cultural practices (Doorenbos and Pruitt, 1977). To account for losses of water incurred during conveyance and application to the field, field canal and application efficiencies are taken into account. Field canal efficiency is defined as the ratio between water received at the field inlet and that received at the inlet of the block of fields. Field application efficiency is the ratio between the water directly available to the plant and that received at the field inlet. For sprinkler irrigation field application efficiency is 0.7 for moderate climates, while the canal efficiency is 0.8. In sprinkler irrigation, losses due to wind drift and spray evaporation can be significant.

2.1.4.1 Supply requirements

The supply requirements at the field level are determined by the depth and interval of irrigation and are primarily determined by (i) the total available soil water, (ii) the fraction of available soil water permitting unrestricted evapotranspiration and/or optimal growth, and (iii) the rooting depth.

The depth of irrigation application (d) is equal to the readily available soil water over the root zone and an application efficiency factor to account for uneven application over the field.

$$d = \frac{(pSa)\ D}{Ea} \quad (mm) \qquad [2.10]$$

where,

d = depth of irrigation application,

p = fraction of available soil water permitting unrestricted evapotranspiration and/or optimal crop growth,

Sa = total available soil water, mm soil depth,

Ea = application efficiency, fraction

The value of p depends mainly only on the type of crop and evaporation demand. Some crops such as cotton and wheat will tolerate higher soil water depletion levels. The tolerable depletion level varies greatly with crop development stage. The depth of soil water readily available to the crop will also vary with level of evaporative demand.

2.1.4.2. Irrigation application interval

There is need to determine the number of irrigations as well as quantity of water per irrigation in order to relate the water use to the N fertilizer needs. Correct timing of irrigation application is of major importance. Delayed irrigation particularly when the crop is sensitive to water stress, could affect yields and cannot be compensated for by subsequent overwatering. Timing of irrigation should conform to soil water depletion requirements, which vary with evaporative demand, rooting depth, soil type and stages of crop growth.

$$i = \frac{(pSa)D}{Et_{(crop)}} \qquad [2.11]$$

where

i = irrigation interval,

p = fraction of available soil water permitting unrestricted evapotranspiration,

Sa = total available soil water, mm soil depth,

D = rooting depth, m,

$Et_{(crop)}$ = crop evapotranspiration.

2.1.4.3 Irrigation supply schedules

Field irrigation supply is determined primarily by the depth and interval of irrigation and the method of irrigation.

$$qt = \frac{10\ (pSa)\ DA(m^3)}{Ea} \qquad [2.12]$$

where,

q = stream size $Lsec^{-1}$,

t = supply duration,

Sa = total available soil, mm soil depth,

p = fraction of available soil water permitting unrestricted evapotranspiration,

D = rooting depth,

Ea = application efficiency,

A = area, ha.

In sprinkler irrigation the stream size is determined by the application rate which in turn is governed by the soil infiltration rate and by the number of sprinklers operating simultaneously. For a given system, the depth and interval of irrigation can be changed by varying the application duration and number of days between irrigations.

Prihar et al. (1974) used the ratio between the depth of irrigation water applied and cumulative pan evaporation (IW/PAN-E) between the irrigation interval as a guide for scheduling irrigation. He found that for optimum yield, wheat should be irrigated on the basis of IW/PAN-E of 0.57 to 1.00. This approach offers two ways of saving irrigation water (i) a narrow IW/PAN-E ratio, and (ii) terminating irrigation at later growth stages when wheat suffers minimum loss in yield.

2.1.5 Effects of soil moisture on growth of wheat

The movement of water from the soil through the plant to the atmosphere follows a gradient of potential energy (Gardner, 1965; Slatyer, 1967). The rate of flow is determined by the magnitude of the potential gradient and resistances to liquid and vapor movement through the soil and the plant. Soil water resistance is inversely proportional to capillary conductivity and root density. As the soil dries out, the soil water potential declines and the capillary conductivity decreases rapidly. As a consequence, the resistance to water movement in the soil limits the rate of water uptake by roots (Gardner and Ehlig, 1962). Water absorption by the roots within any soil layer is largely influenced by the radial resistance to water movement from the soil to the root surface and through root tissues to the xylem and the axial resistance of the xylem. When there is a shortage of water, the major resistance to water flow is located in the leaf-air boundary (Phillip, 1957). As the rate of water supplied from the soil lags behind transpiration rate, the turgor pressure decreases, the stomata start to close and transpiration decreases (Yang and de Jong, 1972). This leads to decreased photosynthate production because at extremely low leaf water potentials, which occur when the stomatal resistance is great, CO_2 uptake is limited by enzymatic reactions associated with photosynthesis (Dennis et al., 1985).

Soil moisture stress at any stage of growth decreases yield for both grain and stover (Datsur and Desai, 1933). Soil moisture stress reduces photosynthetic activity, since it is related to water content per unit of leaf area (Dastur, 1924).

Lack of moisture reduces root growth and prevents normal plant growth and activity (Gingrich and Russel, 1957; Mirreh and Ketcheson, 1973). Reduced moisture conditions led to a decrease in root elongation, as it is in part a hydration process (Peters, 1957). The increased shear strength of soil at low soil moisture will further reduce root elongation by increasing mechanical impedance (Barley, 1963). This reduction becomes more pronounced as the soil bulk density increases (Mirreh and Ketcheson, 1973).

Soil moisture affects the parameters involved in the mechanism in nutrient uptake by the plant roots. These are root growth rate, nutrient movement to the root by diffusion and mass flow, and nutrient absorption according to the concentration in the soil solution and the root surface (Barber and MacKay, 1985). Lower moisture reduces P diffusion, the principal mechanism for P movement through the soil to the root surface (Barber et al., 1963; Mahhab et al., 1971; Hira and Singh, 1977). The increase of the effective diffusion coefficient with increase in the soil moisture content is due to a decrease in tortuosity and an increase in the cross section of the pathway for diffusion. The detrimental effect of low soil moisture on P and K uptake on a plant (corn) can be offset in part by increasing the initial P concentration in the soil solution (Cl_i). Under very dry conditions, however, Aina (1980) found that added fertilizer K was of little benefit.

2.1.5.1 Critical stages

Stressing wheat for water at jointing resulted in fewer days from planting to flowering, shorter plants, more lodging, lower grain volume-weight, fewer heads per unit area, and fewer seeds per head. Similar results were reported by Johnson (1953) for winter wheat. A number of researchers (Móliboga, 1928; Kezer and Sackett, 1931; Robertson et al., 1934, Azzi, 1952) working with irrigated wheat concluded that the most critical period for water was during heading stage.

2.1.5.2 Water use efficiency

Water use efficiency is defined as the mass ratio of crop yield to water use (Viets, 1962; Yates and Taylor, 1986). Dennis et al. (1985) defined water use efficiency as the CO_2-water flux ratio. Water use efficiency defined in this manner is referred to as transpirational water efficiency (Zur and Jones, 1984). Shih (1983), on the other hand, defined water use efficiency as the ratio of water-to-fresh biomass or water-to-marketable yield. The yield can be characterized by the end product of a plant (grain, seed, lint, etc), by the vegetative component (leaves, stover, etc), or by the combination of both, representing the total biological yield. The yield can also be characterized by CO_2 flux (photosynthate yield). The amount of water used can be characterized by the water stored in the plant and transpiration, i.e. evapotranspiration. The total water balance is generally determined by the soil water balance (Howell and Hiler, 1975). The expression of water use efficiency by Howell et al. (1975) is:

$$WUE = \frac{Y}{Et} \qquad [2.13]$$

where,

WUE = water use efficiency, kg ha^{-1} mm^{-1},

Y = grain yield, kg ha^{-1},

Et = the seasonal water use, mm.

$$Et = Sw_1 - Sw_2 + R + Irr + D - Q \quad [2.14]$$

Sw_1 = the initial soil water content, mm,

Sw_2 = the final water content, mm,

Irr = the total irrigation, mm,

D = the root zone drainage ("+" upward flow to root zone or "-" downward flow from root zone),

Q = the field runoff, mm,

R = rainfall, mm.

Theoretical justification for a constant crop-dependent WUE is based on the fact that solar radiation is the dominant factor influencing both transpiration and photosynthesis (de Wit, 1958) and that both processes take place through the stomata. However, despite the work of de Wit (1958), Arkley (1963) and Bierhuizen and Slatyer (1965) to correct for the effects of climate by daily free water evaporation, average air relative humidity value and a representative seasonal average of vapor pressure deficit, the WUE efficient is neither unique for given crop nor independent of climatic conditions (de Wit, 1958; Arkley, 1963; Bierhuizen and Slatyer, 1965; Hanks, 1983).

It is generally accepted that both dry matter yield and cumulative transpiration are time integrals of photosynthesis and transpiration (Zur and Jones, 1984). Bierhuizen and Slatyer (1965) were among the first to propose an expression for the instantaneous water use efficiency (WUE_i) of single leaves.

$$WUEi = \frac{CER}{TR} = \frac{k}{\frac{(e^*-e)(r'_a + r'_c + r_m)}{(r_a + r_c)}} \qquad [2.16]$$

where,

CER = net CO_2 exchange rate,

TR = transpiration rate,

(e* - e) = vapor pressure deficit of the air,

k = crop dependent constant,

r_a = boundary layer resistance to water vapor diffusion,

r_c = stomatal diffusive resistance to transpiration,

r'a = laminar air resistance to CO_2 diffusion,

r'c = stomatal resistance to CO_2 diffusion,

r_m = internal or mesophyll resistance to CO_2.

The r_m is assumed to be constant and small except under severe water deficit. The ratio of the resistances to water and CO_2 diffusion is expected to be constant under normal conditions and WUE_i is reduced to:

$$CER/TR = k' / (e^* - e) \qquad [2.17]$$

$$k' = k(r_a + r_c) / (r'_a + r'_c) \qquad [2.18]$$

$$CE = k' \; TR / (e^* - e) \qquad [2.19]$$

Tanner and Sinclair (1983) extended the Bierhuizen and Slatyer (1965) equation to a canopy basis and proposed a theoretical expression for calculating the crop dependent constant, k'. They also extended the validity of eq. (2.16) for instantaneous WUE_i to daily and seasonal WUE_i and found good agreement between computed and measured values of k'. Both CER and TR are sensitive to a variety of environmental conditions. Conditions which cause a different change in CER than in TR would result in a change in the WUE_i as would changes in (e* - e).

WUE_i is constant under a range of standard conditions where CER and TR change similarly in response to environmental changes,

$$\frac{(CER)}{dx} = \frac{a\ d(TR)}{dx} \qquad [2.20]$$

where, x is an environmental parameter and a is a constant. This applies to conditions of clear skies during noon hours and for fully open stomata. WUE_i will tend to increase,

$$\frac{d(CER)}{dx} > \frac{a\ d(TR)}{dx} \qquad [2.21]$$

when CER increases more than TR, such as under conditions of improved light penetration into the canopy, elevated CO_2 content, high frequency irrigation, and high nitrogen levels applied to the crop, under controlled conditions of high light intensity and low vapor pressure deficit, and for crops with a low internal resistance to CO_2 diffusion. WUE_i would tend to decrease,

$$\frac{d(CER)}{dx} < \frac{a\ d(TR)}{dx} \qquad [2.22]$$

when the crop is exposed to water or nitrogen stress, during advective conditions, with a high vapor pressure deficit conditions (Sinclair et al., 1975; Baldocchi et al., 1981; Zur and Jones, 1984). Negative water use efficiencies indicate a net loss of CO_2 from the crop canopy while transpiration was still occurring.

Water use efficiency can also be increased by (i) increasing yield and maintaining equal water use or (ii) maintaining equal yield and decreasing water use. Yield can be increased by better methods of pest and disease control and plant breeding. Some of these practices will invariably cause some change in the water use pattern, which will also directly affect water use efficiency. Increasing water use efficiency by increasing crop yields through decreasing the crop evapotranspiration is valid for well-watered crop regimes, as plants growing in the field are subject to an externally imposed evaporative demand, This approach, however, does not fully explore the possible implications of limited irrigation in regions of short and/or costly water supplies (Howell and Hiler, 1975).

Maximizing WUE may not be desirable since crops grown under dryland conditions frequently use water more efficiently than "well watered" crops, but at much lower levels of production. Maximum yields are seldom desirable from an economic viewpoint, since either resources, fertilizer and disease control, labor, etc, are not utilized efficiently. However, an "optimum" WUE - maximum yield subject to local constraints of water is the desirable goal.

WUE_i exhibits a diurnal pattern both for the wet and dry cycle conditions. Diurnal changes in a water-stressed crop are characterized by progressively lower WUE_i (Sinclair et al., 1975; Zur and Jones, 1984). Lower WUE_i values are due to a decrease in CER in response to the decrease in radiation flux which is larger than the corresponding decrease in TR. In addition the decrease in WUE_i is due to an increase in leaf temperature associated with stomatal closure, resulting in an increased leaf to air vapor pressure gradient which tends to counteract the effect of a decrease in TR as a result of increased stomatal resistance to CO_2 diffusion. The higher values are probably due to a faster increase in the radiation flux than air temperature and vapor pressure deficit, resulting in CER increasing faster than the corresponding TR values. The WUE_1 decreases with increasing stomatal resistance under strong irradiance or water stress (Zur and Jones, 1984; Dennis et al., 1985). A strong correlation was observed between the CO_2 flux and the water vapor pressure deficit (Zur and Jones, 1984), although this effect appeared to be an artifact of stomatal closure (Dennis et al., 1985). After correction for the water pressure deficit, Zur and Jones (1984) found a quadratic relationship ($R^2 = 0.86$) between CER and TR / VPD especially for midday values. All linear and quadratic terms had a negative intercept suggesting the following relationships

$$CER = k' (TR / VPD) - C \qquad [2.23]$$

where,

VPD = vapor pressure deficit

The negative y intercept suggests that below a certain value of TR, CER becomes zero and even negative, while TR is still positive. Under conditions of severe water stress, there is a significant increase in the internal resistance to CO_2 exchange above that of stomatal resistance. Shih (1983) found the WUE to be inversely related to the water table depth. The study of Singh et al. (1979) showed the apparent water use (tonnes ha^{-1} of grain produced cm^{-1} of water) by wheat increased with an increase in number of irrigations. The water use efficiency (increase in yield cm^{-1} of water) decreased with increase in number of irrigations.

2.1.6 Yield-protein relationships in wheat grain as affected by nitrogen and water.

Increases in yield caused by nutrients other than N, high seeding rates, water or other factors have usually caused decreases in protein content of the grain. This results from the dilution of a given amount of N in the crop by the higher yields (Terman et al., 1968). Terman et al. (1968) showed a highly significant inverse relationship between N content of wheat grain and applied water. The chief effect of applied N with adequate water was to increase yields while that of severe water deficits was to increase protein content. Only when N is absorbed in excess of vegetative needs does an increase in protein content of forage and grain occur.

2.2 Efficiency of Fertilizer N

Nitrogen fertilizers are the most widely used fertilizer materials and are applied in large amounts. They are also susceptible to losses by leaching and by gaseous losses in the field through denitrification, volatilization and loss from plant canopies.

Efficient fertilizer practices aim at maximizing the utilization of applied fertilizer by the crop in the most economic way for optimum crop production. This requires evaluation of the actual uptake by a crop as a function of different management practices such as:

a. Time of application,

b. Rate and method of placement,

c. Nature of fertilizer,

d. Irrigation scheduling and frequency,

e. Soil and climatic conditions.

2.2.1 Losses of N

Many laboratory and greenhouse studies have shown that losses of N from soils may occur under a variety of conditions, the amount lost depending mostly upon the form of N added, pH, moisture content of the soil and degree of aeration (Carter et al., 1967).

2.2.1.1 Loss of N through volatilization

Nitrogen loss through ammonia volatilization is implicated in some studies. Volatilization of NH_3 can be regarded as a chain of events the overall rate of which can be controlled by any one link in the chain of events represented (Vlek et al., 1981) by

$$NH_{4(aq)} \text{-------}> NH_{3(aq)} + H^{+} \text{-------}> NH_{3(g)} \text{--------}> NH_{3(atm)}$$

Where $NH_{4(aq)}$ depends on the soil cation-exchange reactions (Fenn and Kissel, 1976; Fenn and Escarzaga, 1977) and net mineralization.

Ammonium containing or forming fertilizer salts will react with calcareous soils to form $(NH_4)_2CO_3$ and calcium precipitates (Fenn and Kissel, 1975). The $(NH_4)_2CO_3$ formed is unstable and decomposes as follows:

$$(NH_4)_2CO_3 + H_2O \longrightarrow 2NH_3 \uparrow + H_2O + CO_2 \uparrow \qquad [2.4]$$

$$\downarrow$$

$$2NH_4OH$$

Ammonia loss is greatest from ammonium fertilizer salts, which react with calcium carbonate to form precipitates of low solubility (Fenn and Kissel, 1973). CO_2 is lost from solution at a faster rate than NH_3, thereby producing additional OH^- and more NH_4^+ becomes electrically balanced by OH^- which would favor NH_3 loss as follows (Fenn and Kissel, 1973; Woodmansee, 1978; Stillwell and Woodmansee, 1981):

$$NH_4^+ + OH^- \longrightarrow NH_4OH \rightleftharpoons NH_3 + H_2O \qquad [2.25]$$

The ammonium volatilization capacity depends on the buffering capacity of the system. The volatilization process will continue if the system is alkaline and contains the buffering substances to perpetuate the volatilization process (Vlek and Stumpe, 1978). Urea is lost from all soils irrespective of pH because, upon hydrolysis, it serves as an effective alkaline buffer (Vlek and Stumpe, 1978). Loss of NH_3 is accompanied by an equivalent loss of alkalinity, and depletion of alkalinity will terminate the ammonia volatilization process (Vlek and Stumpe, 1978).

Many studies have shown that, the higher the pH, the greater is the NH_3 loss (Chao and Kroontje, 1964; du Plessis and Kroontje, 1966; Stillwell and Woodmansee, 1981). du Plessis and Kroontje (1966) found a large increase in NH_3 loss with pH increase from 4.5 to 7.1. Chao and Kroontje (1964) showed a 40% increase in NH_3 evolution with a pH from 7.4 to 7.8. This effect was greater for alkaline soils with a high clay content.

Significant amounts of NH_3, however, may be lost at soil pH values as low as 5.5 if large amounts of urea or NH_4^+ salts are surface applied or if high incubation temperatures are used (Ernest and Massey, 1960; du Plessis and Kroontje, 1966; Blasco and Cornfield, 1966).

2.2.1.1.1 Effect of NH_4^+ concentration

The amount of NH_3 evolved increases with increasing rate of NH_4^+-N added but the proportion of added N volatilizing as NH_3 is constant (Martin and Chapman, 1951; Chao and Kroontje, 1964; Hargrove et al., 1977; Vlek and Stumpe, 1978). Other investigators have reported that the proportion of added NH_4^+ or urea N evolved as NH_3 increases with fertilizer addition rate (Wahhab et al., 1957; Overrein and More, 1967: Baligar and Patil, 1968). The same authors concluded that the addition of NH_4^+ salts which form soluble precipitates by reaction with $CaCO_3$ is of critical importance in determining both the total NH_3 losses and the proportion of added NH_3 losses and the proportion of added NH_4^+-N evolved as NH_3. The concentration of $NH_{3(aq)}$ increases about ten-fold per unit increase in pH up to pH 9 (Vlek and Stumpe, 1978) and approximately linearly with temperature (Craswell and Vlek, 1980).

Chao and Kroontje (1964) observed that the water loss rate was constant with time, whereas NH_3 volatilization decreased with time. Substantial NH_3 loss occurred without drying but greater NH_3 volatilization took place when slow drying of soil occurred. The process of drying increased the $NH_{3(aq)}$ concentration in the soil solution and prevented nitrification of NH_4^+. Very rapid drying of soil resulted in low losses of applied urea N because of the moisture requirement for dissolution of the fertilizer and hydrolysis of urea. Essentially no NH_3 losses are observed when dry fertilizer is added to soils of low moisture content or when fertilizer solutions are applied to very dry soils.

The rate of NH_3 loss from a solution is proportional to the partial pressure gradient of $NH_{3(aq)}$ and NH_3 in the atmosphere above the solution (Inoue et al., 1975; Vlek et al., 1981). Conditions of light precipitation, which provide moisture adequate for urea hydrolysis but insufficient to leach urea, result in the greatest loss of NH_3 (Bouwmeester et al., 1985). This results in the development of high concentrations of ammoniacal N at the soil surface providing a condition which is the main driving force for ammonia volatilization (Boumeester et al., 1985). Placement or leaching of urea below the depth of possible capillary movement to the surface will greatly reduce NH_3 loss through volatilization (Fenn and Miyamoto, 1981).

The rate of NH_3 loss depends on the CEC. The higher the CEC the greater is the proportion of added NH_4^+, which would be present on the exchangeable complex, and less NH_3 would be present in soil solution (Wahhab et al., 1957; Verma et al, 1974; Fenn and Kissel, 1976; Gandhi and Paliwal, 1976). The nature of the exchange complex affect NH_3 volatilization from soil. Martin and Chapman (1951) reported higher losses of NH_3 from K^+ and Na^+ saturated than from Ca^{2+} and Mg^{2+} saturated soils apparently as a result of the higher pH of K^+ and Na^+ soils.

2.2.1.1.2 Effect of organic residues

The effect of organic residues on volatilization is inconsistent and largely depends on the nature and rate of organic residue added (Volk, 1959; Mayer et al., 1961; Moe, 1967; Volk, 1970; Khan and Rashid, 1971;

Watkins et al., 1972; Verma et al, 1974; Rashid, 1977).

2.2.1.2 Reducing losses

Mixing neutral NH_4^+ salts or acidifying reagents, such as H_3PO_4 or $NH_4H_2POH_4$, with urea prior to their addition to the soil surface markedly reduces NH_3 volatilization (Terman et al., 1968; Bremner and Douglas, 1971; Watkins et al., 1972) Inclusion of $NH_4H_2PO_4$ at a rate of 30% of N in a fertilizer mixture markedly reduced NH_3 losses when $(NH_4)_2SO_4$ or NH_4F mixtures were added to calcareous soils (Fenn, 1975). Mixing NH_4NO_3 with urea reduced NH_3 volatilization relative to the application of urea alone (Kresge and Satchell, 1960).

2.2.1.3 **Loss of N through denitrification**

Extensive losses of ^{15}N in the field experiments are often attributed to denitrification despite the lack of evidence of such a loss (Broadbent and Clark, 1965; Allison, 1966). Denitrification is the reduction of NO_3^- to NO_2^- and to gaseous forms of N, N_2O, NO and N_2 The most probable pathway leading to these losses (Payne, 1973) is as follows:

$$HNO_3 \xrightarrow[-H_2O]{+4H} 2HNO_2 \xrightarrow[-H_2O]{+2H} 2NO \xrightarrow[-H_2O]{+2H} N_2O \xrightarrow[-H_2O]{+2H} N_2 \qquad [2.26]$$

Dissimilatory nitrate reduction as defined by Verhoeven (1956), Fewson and Nicholas (1961) and Campbell and Lees (1967) embodies not only the conversion of NO_3^- to N_2 and N_2O but also the reduction of NO_3^- to NH_4^+ under anaerobic conditions. The conversion may involve the following sequence of reductions (Campbell and Lees, 1967):

$$
2NO_3^- \longrightarrow 2NO_2^- \longrightarrow 2[HNO] \begin{cases} H_2N_2O_2 \longrightarrow N_2O \longrightarrow N_2 \quad \ldots\ldots a \\ 2NH_2OH \longrightarrow 2NH_4^+ \quad \ldots\ldots b \end{cases} \qquad [2.27]
$$

Assimilation of hydroxylamine (NH_2OH) and NH_4^+ by microbial cells may be considered an extension of pathway (b) in eg. [2.27].

NO_3^- reduction to NH_4^+ may be a significant process in some soils but not in others as also suggested by findings of MacRae et al. (1968). Ammonium accumulation accompanying nitrate dessimilation in soils is a nitrogen-conserving process and should not be ignored in nitrogen balance investigations.

Denitrification occurs when dissolved oxygen is limiting in soil solution at high respiration rates or at moderate to low respiration rates when soil water films are thick enough to reduce oxygen supply by diffusion. Pilot and Patrick (1972) found that the critical air-filled porosities below which denitrification became significant ranged from 11-14% in several soils. The finer the soil texture, the higher the critical air-filled porosity.

Although soil water content may be useful for predicting the potential for denitrification, Craswell and Martin (1974) found no significant denitrification in a well-structured clay even with moisture contents of about 90% (by weight). Only at moisture contents greater than 100% did they record significant denitrification. Volz et al. (1976) found that during the early stages of an irrigation event, root uptake of NO_3^- was favored by aerobic conditions so that plant uptake was 50% of the total NO_3^-. After several hours of ponding, the decreased O_2 availability in the root zone inhibited root uptake and enhanced microbial NO_3^- utilization, so that microbial biomass accounted for 90% of the NO_3^- disappearance.

2.2.1.3.1 Effect of organic matter

Denitrification is strongly dependent on the availability of organic compounds (Bremner and Shaw, 1958; Burford and Bremner, 1975; Stanford et al., 1975; Brar et al., 1978). The presence of ample organic compounds can also cause rapid oxygen consumption and possible depletion in soil microenvironments, thus indirectly enhancing the potential for denitrification. Such microsites have been postulated by many workers as pockets of intensive respiratory activity rather than passive anaerobiosis (Craswell and Martin, 1975). Even in arid regions poor oxygen supply to soil aggregates could result in localized anaerobiosis and denitrification (Allison et al., 1952; Burford and Millington, 1968. Dowdell and Smith, 1974).

The rate of denitrification is affected by the NO_3^- level when C is not limiting and NO_3^- levels are lower than 40 mg kg^{-1} (Stanford et al., 1975), while no effect of NO_3^- is found in a C-limited systems or NO_3^- concentrations above 40 mg kg^{-1} (Starr and Parlenge, 1975).

Ryden and Lund (1980) reported that peak denitrification rates occurred between suctions of 50-100 mbars and that above 250 mbars the rates were quite low. The various redox potentials at which denitrification has been reported to be significant range between 300-650mV (Ryden and Lund, 1980; Bailey and Beauchamp, 1973).

2.2.1.3.2 Effect of pH

There is little effect of pH on denitrification in the relatively neutral pH (6-8) of soils (Khan and Moore, 1968; Wijler and Delwiche, 1954; Burford and Bremner, 1975). Denitrification is generally lower at pH less than 5. Significant loss of N, however, can occur at pH less than 5 (Ekpete and Cornfield, 1965; van Cleemput and Patric, 1974; Gilliam and Gamrell, 1978). The low rates of denitrification at extremely low pH (3.5-4.0) are possibly due to:

a) microbial species with low pH tolerances,

b) a general population with neutral growth optima that functions poorly at low pH,

c) direct effect of soil solution or from pH inducing deficiencies or toxicites.

2.2.1.3.3 Effect of temperature.

Denitrification occurs slowly at 2 °C but increases strongly with temperature, the optimum being 25 °C and above. The transformation is still rapid at temperatures of 60-65 °C but not at all at 70 °C. This indicates that an active thermophilic denitrification flora exists.

Denitrification was higher in a planted than unplanted soils in the presence of sufficient NO_3^-, but when NO_3^- availability was low, the presence of plants decreased denitrifying activity (Stefanson, 1976; Smith and Tiedje, 1979). Owens (1960) reported loss of N through denitrification of uncropped soils to range from none to 80%. Denitrification rates are probably drastically reduced by plant competition for NO_3^- as well as reduction of anaerobic volume resulting from depletion of soil moisture by the growing plants to levels below field capacity.

2.2.1.4 Gaseous nitrogen losses from soils through nitrite reactions.

There is evidence that N can be released to the atmosphere by non-enzymatic decomposition of NO_2^-. Some of the loss mechanisms may include the following:

1. The van Slyke reaction, defined as the reaction between nitrous acid and -amino acids,
2. Formation and decomposition of NH_4NO_2,
3. Self decomposition of HNO_2 at pH values below 5.0 with resultant formation of NO plus N_2O,
4. Dissimilation of NO_2^- by reducing organic compounds,
5. Fixation of NO_2^- by reducing organic matter and partial conversion of some NO_2^- to N_2 and N_2O,
6. Catalytic reaction of NO_2^- with reduced transitional metals such as Cu, Fe and Mn.

The van Slyke reaction loss mechanism is rarely if ever important in soils (Allison and Doetsch, 1951; Allison et al., 1952). Self decomposition of nitrous acid is only occasionally important and only in acid soils of low exchange capacity (Gerretsen and de Hoop, 1957; Allison, 1973).

Formation and decomposition of HNO_2 may be the major channel of loss apart from ammonia volatilization and biological denitrification. Nitrite does not usually accumulate in soil. When, however, fertilizer materials such as urea, anhydrous ammonia, aqua ammonia or diammonium phosphate are applied at high rates or when they are applied in bands, they create localized microsites with basic pH and high NH_4^+ concentrations irrespective of the original bulk pH. Accumulation of nitrite is attributed to the suppressive effect of high concentrations of NH_4^+ salts at the alkaline soil pH values on the <u>Nitrobacter</u> group of organisms (Tisdale et al., 1985).

Loss of N as N-O compounds and as N_2 can also occur by the chemical reaction between HNO_2 formed during nitrification and the NH_4^+ present in soil solution when the buffer capacity of the soils and the pH of the soil drops below 5.5 during nitrification. The largest losses of N are likely where there are high concentrations of NO_2^- and NH_4^+ through initial addition or desiccation or where both nitrification and ammonification proceed vigorously (Wahhab and Uddin, 1954; Gerretsen and de Hoop, 1957). Allison and Dietsch (1950) underestimated the loss of N due to this reaction especially if the process lasts several weeks instead of hours.

In some acid soils (pH 4.0-4.5), however, considerable loss of N has been observed without the soil passing through a decreasing series of pH (Gerretsen and de Hoop, 1957). Loss of up to 74% of the $(NH_4)_2SO_4$ added was observed in pot experiments with acid sandy soils from different parts of the Netherlands (Gerretsen and de Hoop, 1957).

2.2.1.5 Loss of N through chemodenitrification

Loss of N from NO_2^- by chemodenitrification has been shown to increase with organic matter content (Smith and Clark, 1960; Reus and Smith, 1965). The reduction of HNO_2 to N_2 and N_2O supposedly takes place under mildly acidic and acidic conditions at phenolic sites of organic matter with nitrosophenols as intermediates. The nitrosophenols are believed to tautomerize to quinone oximes, which subsequently reduce some of the HNO_2 to N_2O or N_2. N can also be lost through the decomposition of the diazo group in the diazonium compounds (Morel and Sisley, 1927; Philpot and Small, 1938; Bremner, 1957).

2.2.1.6 **Fixation of N by organic matter**

The amount of added NO_2^--N which is fixed increases with a decrease of soil pH, an increase in organic matter and an increase of NO_2^- concentration (Smith and Chalk, 1980b). The lignin-derived fraction of soil organic matter is responsible for NO_2^- fixation and the mechanism for fixation involves formation of nitroso groups on phenolic rings (Bremner and Fuhr, 1966). Nelson and Bremner (1969) demonstrated that a wide variety of soils having pH values as high as 7.8 are capable of fixing NO_2^-, that air drying soil promotes NO_2^- fixation and that addition of $CaCO_3$ markedly reduces NO_2^- fixation.

2.2.1.7 **Importance of nitrite reactions in nitrogen losses from soils**

There seems to be little loss of N from NO_2^- reactions from neutral and alkaline soils that accumulate NO_2^- during nitrification, because NO_2^- is relatively unreactive at high pH and little N_2 or $(NO + NO_2)$-N is evolved. Smith and Chalk (1980a), however, found significant loss of N_2, $NO + NO_2$ and N_2O during nitrification of NH_4OH in alkaline soils.

Loss of N through NO_2^- reactions is much more likely during nitrification in acidic soils. NO_2^- accumulates in the periphery of NH_3, NH_4OH, urea bands and prills (Smith and Chalk, 1980a). When NO_2^- diffuses from the alkaline zone surrounding the band or prill into the surrounding acid soil, HNO_2 is formed immediately and reacts with soil organic matter to liberate N_2 and to be fixed or undergo soil decomposition with the evolution of $(NO + NO_2)$-N.

2.2.1.8 **Loss of N through plant canopy**

The amount of gaseous loss of N by wheat through the plant canopy was estimated to be about 15% (Carter et al., 1967). This source may account for some part of the widespread losses of N found in many N balance studies. Other workers (Boatwright and Haas, 1961; Storrier, 1962; Barley and Naidu, 1964) without the use of ^{15}N showed that maturing crops can lose extensive quantities of N.

2.2.1.9 **Leaching losses**

Leaching is often the most important channel of N loss from field soils other than accounted for in plant uptake (Allison, 1973). Losses occur mainly as NO_3^-, the movement of which is closely related to water movement, as rainfall or irrigation.

NO_3^- losses occur when (i) soil NO_3^- content is high and (ii) water movement is large. As high as 85% ^{15}N was lost through leaching in a high water control treatment while the lower water treatment retained about 85% of the ^{15}N in mineral forms (Rolston et al., 1978; 1979). A treatment receiving high water and manure lost more ^{15}N (13%), with no leaching losses in a treatment receiving manure with a lesser amount of water (Rolston et al., 1978; 1979).

Tillage leads to loss of NO_3^- because it stimulates ammonification of soil organic N and subsequent nitrification, leaves the soil bare for a period of time and sets the stage for possible NO_3^- loss through leaching. Such losses of N on virgin grassland soils were estimated to range from 30 to 40% of the total N in the upper 30 cm of soil under low erosion conditions and up to 75% or more where serious erosion had occurred (Legg and Meisinger, 1982). Losses of N are less under grasses or legumes because less NO_3^- accumulates than under continuous cereals (Hensler and Attoe, 1970). In studies of leaching losses from lysimeters in relation to soil texture and drainage (Kolenbrander, 1972), losses from soil organic matter ranged from 45 kg N ha^{-1} $year^{-1}$ on sandy soils to 5 kg N ha^{-1} $year^{-1}$ on heavy clay soils. The difference was attributed to loss by denitrification.

Leaching losses are strongly influenced by seasonal factors, such as water and temperature. In humid temperate zones, increased mineralization after winter and subsequent nitrification will result in significant leaching losses of NO_3^- below the root zone, if heavy rains occur before spring planted crops are growing vigorously. In humid areas, NO_3^- can be removed from the soil profile by leaching, denitrification, or both, or it may accumulate in the soil profile and move downward into the groundwater depending on the soil, climate, fertilization and management practices. Leaching losses also occur under subhumid conditions where summerfallow is practiced. Summerfallow practices allowed deeper penetration of precipitation than was possible before cultivation, resulting in mineralized soil N moving into the lower horizons. NO_3^- leaching is least likely to take place during the summer (Allison, 1973; Chichester, 1977), when evapotranspiration usually exceeds precipitation, and plant uptake rates are high. Also, a critical factor which determines the amount of N leached is the amount of N remaining in the profile after crop harvest.

Leaching of NO_3^- in irrigated agriculture depends on the method of irrigation. Flood and sprinkler irrigation cause a more uniform downward movement of NO_3^-. Movement of NO_3^- under furrow irrigation depends on the method of N placement (Viets et al., 1967). In studies of McNeal and Pratt (1978), leaching losses from some typical Southern California croplands ranged from 13 to 102% and commonly averaged 25 - 50% of the applied N in most cropping situations. In the study of Pratt et al. (1976a, b), irrigation had little effect on crop N removals, but increased leaching losses. Use of liquid manure resulted in greater mineralization and crop uptake, greater leaching, greater gaseous losses, and less soil organic N accumulation.

Owens (1960) found that the amount of total N lost through leaching was directly proportional to the amount of spring moisture passing through the profile and nitrogen leaching losses were reflected in a reduction in the subsequent N uptake by the crop.

2.2.2 N uptake

Tracer and non tracer experiments reviewed by Allison (1966) indicate average recoveries of fertilizer N under field conditions in a single harvest to range between 50-70%. Estimates of fertilizer nitrogen recovered by arable crops are not more than 20 to 50% (Cooke, 1967; Carter et al., 1967). A review by Kundler (1970) of work utilizing ^{15}N labelled fertilizer reports first-year recoveries in the crop of 30-70%, with 10-40% unaccounted for and presumed lost. The data of Hauck (1971) show total recoveries of applied N in the crop and soil as low as 60% and as high as 110%. The near total recoveries of Craswell and Martin (1975) of ^{15}N

balance experiments are similar to other studies. Carter et al. (1967), Henzell (1971), Vallis et al. (1973), and Shields et al. (1973) reported recoveries greater than 95%. In the first three of these studies high ^{15}N recoveries were found amidst extensive losses in other phases of the work. In the work of Carter et al. (1967), the recovery of ^{15}N from field plots varied from 96.3 to 101.8% and averaged 99.0% of that of added N. This was the result of treatments, such as cropping, time of application of N of the two sources of N tested, the plot size, and exposure to natural rainfall. Portion of the remaining N was recovered by subsequent crops. Another portion was probably lost through leaching beyond the root zone, or may have been incorporated in soil organic matter, and a portion presumably escaped as gases.

A number of ^{15}N balance studies have shown extensive quantities of added ^{15}N to be unaccounted for after soil and plant analysis. Greenhouse studies by Zamyatina et al. (1968) showed 30 to 70% of the applied N was taken up by the plants, 7 to 45% was incorporated into soil organic matter and 11 to 35% was unaccounted for and presumably lost as gaseous nitrogen. Myers and Paul (1971) reported 64.4 to 83.8% of the added N as NH_4NO_3 was recovered by wheat indicating losses of 16 to 36% N possibly due to volatilization and/or denitrification. When ^{15}N labelled $(NH_4)_2SO_4$ was applied to maize at 100 kg N ha^{-1} 41% of the applied N was unaccounted for after 12 weeks.

Losses of ^{15}N have tended to be low in the humid and subhumid areas of Africa, averaging 20% and 24%, respectively and were significantly less than the average of 40% found over all treatments and sources in Niger at a semiarid site (Vlek, 1985). The low losses in the humid and subhumid zones may be in part attributed to high crop densities which can be supported in the more moist zones and results in a high uptake of applied N by the plant. Plant uptake accounted for 45% of the applied fertilizer N in the humid zones compared to only 28% in the semiarid zone. The living plant material acts as a sink for fertilizer N, trapping it and reducing its loss via volatilization or leaching.

2.2.3 Methods of improving N efficiency

Response of wheat to a given application of N depends upon the availability of soil N and water. The merits of split application of N for increasing yields seem to be largely dependent on growth season and soil conditions. Irrigated wheat grain yields have been increased by splitting N applications between seeding and tillering or stem elongation (Wahhab and Hussain, 1957; Jain et al., 1971; Hamid and Sarwar, 1976). Khalifa (1973) found no apparent benefit from split N application at seeding and tillering with different wheat varieties.

Data from the four year isotope studies on wheat fertilization (IAEA, 1974) in several countries, Arab Republic of Egypt, Turkey, Pakistan, Lebanon, Peru, Uruguay and Romania under different climatic conditions have generally shown split application of N to be superior in supplying N to wheat. In Italy, where single application of N was superior, precipitation in the later growth stages was insignificant to move N into the root zone. In general, the two-split application was at least as good as the three-split application for the carriers used. The two-split application incorporates the two most efficient times of application. The superiority of the split application was mainly due to the higher uptake efficiency from the nitrogen applied at tillering stage.

In the humid and subhumid zones of Africa the best combination of N source and management over all sites was urea split broadcast treatment which gave both highest N uptake in the grain and lowest losses. Split application of calcium ammonium nitrate (CAN) also resulted in high grain N contents and broadcasting was the best method of application to assure good N uptake in the grain. Over all zones, the point-placed urea (as urea supergranules) tended to do poorly and performed significantly more poorly than other sources in the semiarid zone as represented by the Niger site. Concentrated placement of urea in points or in bands may lead to increased leaching of fertilizer N due to limited access to the sorption sites of the soil. The problem is accentuated in light textured soils (Vlek et al., 1980; Mughogho and Bationo, 1985).

Late applications of nitrogen has aroused interest because of the possibility of increasing protein content and grain yields. A significant increase in both yields and grain protein was obtained in winter wheat when N was applied in late spring (Johnson et al., 1973). Hammid and Sarwar (1976) reported that N applied at boot stage or later increased wheat grain protein but not yield. Early applications of N to wheat are effective in increasing grain yields, while later applications are reflected in increased N content of grain and less effect on yield.

2.2.4 Methods of ^{15}N assay

Isotopes provide the only direct way of measuring the uptake of a nutrient from applied fertilizers as affected by timing, placement, fertilizer source, and environmental interactions (Fried et al., 1975). These authors extended the technique to measure efficiencies without interactions as to form of N and, further, to permit the direct quantitative measurement of interactions. The direct measurement of the nutrient uptake from a fertilizer has enabled the quantitative separation of the two major sources of nutrient supply, i.e. the soil and the fertilizer. Labelling with ^{15}N permits more accurate evaluation of the contribution of fertilizers under test than either yields or total nitrogen contents of the crop (Craswell and Martin, 1975).

Conventional field experiments based on crop yield data, may or may not give reliable information (IAEA, 1974). The amount of fertilizer nitrogen utilized by a crop, for example would be greatly underestimated in an experiment based on yield data under conditions where there is no yield response to added nitrogen, and exaggerated under conditions of severe nitrogen deficiency.

In split application of fertilizers the efficiency of nutrient utilization of each application relative to the others can be determined. At each time of application, fertilizer tagged with ^{15}N is added in a separate sub-plot. In the case of a three-way split, three separate sub-plots are required. When ^{15}N tagged fertilizer is not added for any given application time, untagged fertilizer is used. Although three separate sub-plots are employed, in reality they have the same treatment, the only difference is in the position of the label. Thus it is possible to study the effect of the time of N application on N utilization without the confounding effect of N supply on plant growth and utilization of plant nutrients.

2.2.4.1 ^{15}N terminology

The common working value in ^{15}N tracer studies is the "atom percent excess ^{15}N". This value is the percent abundance ^{15}N in the sample (A) minus the percent abundance ^{15}N in the standard gas or in a control sample with the appropriate correction of the atom-percent ^{15}N for the reagent blank (Rice, 1966).

$$A = \frac{\text{no. of } ^{15}N \text{ atoms}}{\text{no. of } ^{14}N \text{ atoms} + \text{no. of } ^{15}N \text{ atoms}}$$

$$= \frac{[^{14}N^{15}N] + 2[^{15}N^{15}N]}{2[^{14}N^{14}N] + 2[^{14}N^{15}N] + 2[^{15}N^{15}N]} \qquad [2.28]$$

where,

A = atom percent ^{15}N.

The ion current corresponding to mass 30 ($^{15}N^{15}N$) in the mass spectrometer is not measured, as N_2 is in equilibrium in accordance with the equation

$$^{14}N^{14}N + ^{15}N^{15}N \rightleftharpoons ^{14}N^{15}N + ^{14}N^{15}N \qquad [2.29]$$

The equilibrium constant of this reaction at room temperature is 4:

$$\frac{[^{14}N^{15}N]^2}{[^{14}N^{14}N]\,[^{15}N^{15}N]} = 4 \qquad [2.30]$$

Hence,

$$A = \frac{100}{2R + 1} \qquad [2.31]$$

where

$$R = \frac{\text{mass } 28}{\text{mass } 29} \qquad [2.32]$$

In the analysis of atom percent ^{15}N by emission spectrometry, nitrogen gas at a low pressure in a glass discharge tube is excited by radio frequency energy. The wavelength of light emitted is related to the isotopic form of nitrogen (Jones and Adam, 1975). Thus in the 2 - 0 band the nitrogen molecules $^{14}N^{14}N$ emit light at wavelength 297.9 nm, $^{14}N^{15}N$ at 298.3 nm and $^{15}N^{15}N$ at 298.9 nm. In the Statron spectrometer model NOI-5 utilized in part of this study, a rock salt prism monochrometer is fitted with an automatic scanning device that traverses these wavelengths repeatedly at 1 minute intervals. The monochrometer output is detected by a photomultiplier and after appropriate amplification the signal is fed to a chart recorder. The ^{15}N enrichment is calculated from measurements of the relative intensities of the $^{14}N^{14}N$ and $^{14}N^{15}N$ peaks (eq. [2.32]) because equilibrium is established by the high-frequency source used to excite the nitrogen gas. Atom %^{15}N is then calculated from eq. [2.31].

The limited resolution of the instrument renders calibration with known standards essential. Correction for background emission is a major problem at low ^{15}N abundances. One of the major advantages of the instrument is lower cost and the small sample size, typically of the order of 10 ug of N. Nitrogen gas is generated by the Dumas combustion or by the lithium hyprobromite oxidation procedure.

Application of the final atom percent excess ^{15}N value in the sample leads to:

$$N_t = \frac{(A_t)\ (N_f)}{A_o} \qquad [2.33]$$

where,

N_t = the quantity of labelled N present in any given fraction after some form of translocation. In a fertilizer uptake experiment N_t is the quantity of labelled nitrogen present in any specific fraction of the plant or soil where the labelled fertilizer N is translocated. In a nitrogen fixation experiment, N_t is the quantity of labelled N in the organic matter which has been translocated from the labelled atmosphere or labelled fertilizer and labelled organic nitrogen source via microbial fixation.

A_t = atom percent excess ^{15}N in the specific fraction which receives the translocated nitrogen. Atom percent excess ^{15}N is the % ^{15}N enrichment, which gives the % ^{15}N above the natural abundance 0.366 (%^{15}N excess = %^{15}N abundance - 0.366).

N_f = the quantity of the N in the specific fraction which received the translocated N.

A_o = the atom percent excess ^{15}N in the labelled nitrogen source, ie, fertilizer, fertilizer-soil mineral nitrogen pool, atmosphere etc.

Where several plant parts are analyzed for atom percent ^{15}N, such as stover, pods or seed, the weighted atom percent ^{15}N for the sample is

$$A_w = \frac{\text{Atom\% } ^{15}N \text{ ex (A)} * \text{N yield (A)} + \text{Atom\% } ^{15}N \text{ ex (B)} * \text{N yield (B)}}{\text{N yield of (A) + (B)}} \qquad [2.34]$$

where,

A_w = weighted Atom% ^{15}N excess of sample

A = plant part such as stover

B = plant part such as pods or seed

2.2.4.2 Use of isotope derived criteria

Isotope derived criteria commonly used to express results obtained from soil-plant nutrition experiments involving labelled fertilizers fall into two groups:

a) Yield dependent, and

b) Yield independent factors

The yield independent factors such as percent nitrogen derived from fertilizer (%Ndff) are calculated directly from estimates of isotopic dilution.

$$\%Ndff = \frac{\text{atom \% } ^{15}N \text{ excess in plant sample}}{\text{atom \% } ^{15}N \text{ excess in fertilizer}} * 100 \qquad [2.35]$$

An assessment of plant yield is not required. The %Ndff provides a sensitive criterion to assess specific fertilizer management practices. Of importance is the observation that identical conclusions can be drawn from %Ndff values as kg N ha^{-1} taken by the crop for any one particular experiment (Rennie and Fried, 1971). This is a significant observation in that in formal plot layouts, the labor inputs and costs involved in obtaining a yield dependent function such as Kg N ha^{-1} uptake are several orders of magnitude greater than that required to obtain %Ndff.

However, when comparing results obtained from experiments carried over several locations, the yield dependent criteria should be used. The %Ndff values not only reflect the extent of isotope dilution of the applied ^{15}N label as a function of a single variable, such as different fertilizer placement or form etc, but also the influence of a number of other factors which may vary from one location to another, such as available soil nitrogen, variable climatic conditions and different degrees of fertilizer nitrogen-soil nitrogen interactions. The yield dependent criteria, such as "percent utilization of the applied fertilizer N" require in addition to a measure of isotopic dilution, an estimate of total yield, and % N in the plant. The percent utilization of the applied fertilizer nutrient provides a criterion by which the performance of one or more fertilizer sources or placements etc. can be evaluated.

$$FUE = \frac{\text{amount of N in plant derived from fertilizer}}{\text{fertilizer N applied}} \times 100 \quad [2.36]$$

where,

FUE = percent utilization of the applied N fertilizer

2.3 Utilization of Residual Nitrogen

Legumes are known to increase soil N levels (National Academy of Sciences, 1979) and consequently the productivity of succeeding cereal crops (Singh and Awasthi 1978). Senescent leaves add a substantial amount of N to the soil. Reddy et al. (1986) indicated 50 kg N ha^{-1} to have been added by senesced leaves of tropical legumes and to some extent roots and nodules. Ladd et al. (1981) found after 32 weeks decomposition, 60-65% of the added ^{15}N labelled medic remained in the soils (0-20 cm) as ^{15}N labelled residues. After another 4 years the values declined to 45-50%. ^{14}C and ^{15}N biomass was 8-12% of the total residual organic residues. After another 4 years the values declined to 6 and 9% of ^{14}C and ^{15}N labelled biomass respectively (Ladd et al., 1981).

Wheat plants took up only 10.9 to 27.3% of the ^{15}N from previously added legume material. Grain ^{15}N accounted for 51 to 70% of the total ^{15}N recovered in the wheat; root ^{15}N contained 3.5 to 7.2% only, despite root N being generally of higher enrichment than those of grain N and straw N (Ladd et al., 1981). The amount of N of the soil profiles derived from mineralization of soil organic matter varied from 1.21 to 1.85% for Australian soils investigated (Ladd et al., 1981). The medic legume material thus contributed only small proportions of the available N pools after 15 months of decomposition at the three test sites. The main value of the legumes in terms of supplying N to succeeding crops would appear to be long term, i.e., their capacity to maintain or improve concentrations of soil organic N to be decomposed at relatively slow rates in the following years (Ladd et al., 1981).

2.4 Nitrogen Derived from Nitrogen Fixation

Lysimeter values of %Ndfa have varied from 38-70% depending on soil and plant growth stage and harvest. A high value of 67% was found in the field. Other studies using ^{15}N isotope dilution have reported %Ndfa for Chappewa soybeans of 61% in Austria (Rennie, 1982), 50% in Sri Lanka, 38%

in the USA and 38% in Hungary (Rennie et al., 1978). Ford soybeans had a %Ndfa of up to 60% in the USA (Deibert et al., 1979) and Clay soybeans an average of 37% (Ham and Caldwell, 1978). An average estimate of %Ndfa for soybeans would be about 50% (Rennie, 1982).

2.4.1 Amount of nitrogen fixed

Recorded values based on ^{15}N isotope dilution indicate amounts of N_2 fixed are 92 kg ha^{-1} in Sri Lanka and 108 kg ha^{-1} for Ford soybeans in the USA (Rennie et al., 1978). Deibert et al. (1979) reported N_2 fixed by Clay soybeans of up to 149 kg ha^{-1} in the USA. Ham and Caldwell (1978) estimated that the amount of N_2 fixed by Clay soybeans was 114 kg ha^{-1} in the USA. The amount of N_2 fixed by soybeans on average is approximately 100 kg ha^{-1}.

The reasons for the difference in percent N_2 derived from fixation and the amount of N_2-fixed are due to: (i) difference in potential for N_2-fixation by different legumes, (ii) suitability of the reference crop and time of harvest in N_2-fixing systems, based on when enough N_2 above experimental error has been fixed, (iii) temperature during the growth period of the reference and fixing crop, (iv) choice of sampling material, (v) efficiency of N_2-fixation by <u>Rhizobium</u> strains, and (vi) status of soil N (Fried et al., 1983; Witty, 1983).

2.4.2 Use of ^{15}N in biological dinitrogen fixation.

In the use of ^{15}N for biological nitrogen fixation studies, Danso (1986) has enumerated the advantages of the isotope dilution method:

a) The isotope dilution method gives a truly integrated value for N_2- fixation in the field.

b) It is the only method which permits quantitative separation of the contributions to plant-N of the soil, fertilizer and atmospheric nitrogen.

c) The proportion of atmospheric nitrogen fixed by a crop can be determined, even if the yield cannot be measured because of damage due to disease, animals, soil, etc.

d) Unlike the nitrogen balance method it is not necessary to grow the control crop with zero or an unnatural low level of fertilizer.

e) In plant breeding trials when the objective is to breed for higher nitrogen fixation either by breeding for superior legume cultivars or selection of superior rhizobium strains, the N_2 fixation method can be used simply by comparing the atom ^{15}N excess within treatments or among genotypes, without any need for a reference crop.

2.4.3 Estimation of biological dinitrogen fixation (BNF)

The most suitable methods of estimating N_2 fixation are methods which integrate N_2 fixation over the growing season, i.e. nitrogen balance (NB) and the ^{15}N isotope dilution method (ID). The NB method is based on the assumption that both fixing and nonfixing crops assimilate identical amounts of soil and fertilizer N. The difference in N yield is attributed to fixation.

Thus N_2 fixed = N yield (fs) - N yield (nfs)

$$\%Ndfa = \frac{[(N\ yield\ (fs) - N\ yield\ (nfs)] * 100}{N\ yield\ (fs)} \qquad [2.37]$$

where,

fs = fixing system (crop)

nfs = non fixing system (crop)

%Ndfa = percent plant N derived from the atmosphere (fixation)

The ID technique of estimating biological dinitrogen fixation (BNF) depends upon differences in isotopic composition of the sources available for plant growth, i.e., soil N, fertilizer N and atmospheric N_2 (Bergersen and Turner, 1983). The differences may arise from small natural enrichment of ^{15}N in soil N, or from the addition of ^{15}N enriched or ^{15}N depleted materials to the soil. ^{15}N enriched fertilizer N taken up from the soil by the legume is diluted by fixed atmospheric N_2 of low natural abundance (0.3663 atom % ^{15}N).

Quantifying N_2 fixation requires reference to a nonfixing control plant. The estimation of N_2 fixed generally involves labelling the soil with ^{15}N (organically or inorganically) growing the legume along with a nonfixing control and calculating N_2 fixed as follows:

$$N_2 \text{ fixed} = 1 - \frac{\text{atom \% } ^{15}\text{N excess (fs)}}{\text{atom \% } ^{15}\text{N excess (nfs)}} * \text{N yield (fs)} \qquad [2.38]$$

and,

$$\% \text{ Ndfa} = 1 - \frac{\text{atom \% } ^{15}\text{N excess (fs)}}{\text{atom \% } ^{15}\text{N excess (nfs)}} \times 100 \qquad [2.39]$$

where,

%Ndfa = percent plant N derived from the atmosphere

atom % ^{15}N excess = atom percent ^{15}N excess

The basic assumption of the ID procedure is that the fixing and the reference plants should absorb the soil N and fertilizer N in the same ratio (Fried et al., 1983; Broadbent et al., 1983). When there are differences in N uptake profiles practices which result in a less drastic decline of $^{15}N/^{14}N$ ratio in the soil, such as direct incorporation of ^{15}N-labelled organic matter (Hauck 1973), the addition of fertilizer together with an available carbon source (Legg and Slogger, 1975) or the use of slow release ^{15}N fertilizer formulations, which lead to a more stable enrichment, should be adopted (Witty, 1983). A suitable reference plant can be a nodulating line in nonfixing mode, either as uninoculated or inoculated with an ineffective Rhizobium (Rennie, 1981), nonfixing isoline (Fried and Broeshart, 1975; Legg and Slogger, 1975; Ham and Caldwell, 1978, Deibert et al., 1979, Demenach et al., 1979; Rushel et al., 1979) and a nonlegume such as barley. Barley has been used as a reference plant for soybeans (Fried and Broeshart, 1975; Rennie et al., 1976) and for *Phaseolus vulgaris* (Rennie and Kemp, 1983; 1984).

N_2 fixation as estimated by the isotope dilution method is not necessarily the amount of N_2 fuxed byt rather an estimate of the amount of fixed N_2 contained in the harvested portion of the crop (Witty, 1983). The difference between the two values depends on the proportion of N lost from the crop such as leaf, nodule senescence and gaseous loss from plants (Witty, 1983). Calculations made by Bergesen and Turner (1983) indicated that when %Ndfa was more than 50%, foliar analysis provided adequate data for estimation of %Ndfa and considerable effort of root collection could be avoided.

Identical estimates of N_2 fixed by the NB and ID methods has been obtained only when the fertilizer use efficiency (FUE) or in unfertilized experiment, the soil N uptake of the fs was identical to the nfs (Deibert et al., 1979; Rennie and Kemp, 1983; Witty, 1983; Rennie, 1984; Rennie and Dubetz, 1984). Field estimates of fixation based on the NB method of a legume and control combination having the same percentage fertilizer uptake could not be reliably obtained because the relative fertilizer uptake of the two crops varied from season to season (Witty, 1983).

3. INFLUENCE OF IRRIGATION SCHEDULES AND NITROGEN PLACEMENT ON WHEAT YIELD

3.1 Introduction

Research involving irrigated wheat in Zambia is limited. Although the plant nutrient needs for wheat are known, irrigation rates and methods of N fertilizer placement have not been fully determined with Zambian conditions and soils. Fertilizer recommendations are usually based on fertility and irrigation trials with wheat in the neighboring country of Zimbabwe.

Much research work has shown that while wheat is sensitive to moisture stress at earlier growth stages, irrigation water can be saved by omitting irrigation late in the growing season (Kezer and Robertson, 1927; Day and Intalap, 1970; Sing et al., 1979). Response of wheat to a given application of N depends upon the availability of soil N and water. Further, irrigated wheat grain yields have been increased by splitting N applications between seeding and tillering or stem elongation (Wahhab and Hussain, 1957; Jain et al., 1971; Hammid and Sarwar, 1976). Hammid and Sarwar (1976) reported that N applied at boot stage or later increased wheat grain protein but not yield. Further, there was better utilization of fertilizer N when it was split equally between seeding and tillering than for a single application at seeding. In contrast, Khalifa (1973) found no apparent benefit from split N application at seeding and tillering with different wheat varieties.

The study reported here was carried out to investigate the effect of different irrigation regimes, rates and methods of N placement on the yield of wheat grown on a sandy clay loam soil belonging to the Typic Haplustalfs.

3.2 Materials and methods

A three year study was conducted under sprinkler irrigation on a nearly level sandy clay loam at the National Irrigation Research Station at Nanga, Zambia. The soil belongs to the Mazabuka series, which includes chromic luvisols or Dystric Nitosols (FAO-UNESCO) or Typic Haplustalfs (USDA) occurring on elevated sites under miombo Savannah of moderate rainfall. They are deep well-drained soils with characteristic red argillic B horizon developed over calcium-silicate schists. The soil had a pH of 5.5, CEC of approximately 7 cmoles kg^{-1} and total N content in the order of 0.8 g kg^{-1}.

3.2.1 First year study (1982)

Wheat (*Triticum aestivum* L.-EMU's) was grown under three methods of fertilizer application and three irrigation regimes. A total of 150 kg N ha^{-1} in the form of urea was broadcast prior to seeding either in one portion, two portions (75 kg N ha^{-1} each), or three portions (50 kg N ha^{-1} each). The fertilization schedule is summarized in Table 3.I.

The irrigation schedules included: (i) every week irrigation at a rate of 70% of the total class A pan evaporation during the whole irrigation interval; (ii) every two weeks irrigation at 60% of the total class A pan evaporation during the whole irrigation interval; and (ii) every three weeks irrigation at 50% of the total class A pan evaporation during the whole irrigation interval. These schedules were implemented at tillering.

Table 3.1 Nitrogen fertilizer program for the 1982 experiment

Method of application	Time of application and amount of fertilizer		
	At seeding	At 4 weeks after seeding	At 7 weeks after seeding
	kg ha^{-1}		
One portion	150	-	-
Two portions	75	75	-
Three portions	50	50	50

The experiment had a partly randomized split plot design with irrigation as main plots and methods of fertilizer application as subplots with six replications. Main plots were 12m x 12m and subplots were 3m x 4m. Subplots contained 16 rows of wheat that were 0.25 m apart.

Pre-irrigation was applied to the whole experimental site seven days prior to seeding to establish a homogeneous moisture profile to a 1.2 m. depth. Planting took place on 28 May 1982 and the differential irrigation was started on 21 July 1982.

Samples for grain yield determination were harvested from a 1.5 m^2 area (4 rows 1.5 m long). The samples were oven dried at 60 °C and hand threshed.

Analyses of variance were calculated assuming a randomized block with a split plot for the methods of N application.

3.2.2 Second year study (1983)

In the 1983 experiment wheat (<u>Triticum</u> <u>aestivum</u> L. EMU'S') was grown at an adjacent site to the 1982 experiment under four N placement methods and two methods of application each, two nitrogen rates and three irrigation regimes. Fertilizer placement methods were broadcast or broadcast and incorporation before seeding, side-banding (at a narrow band 2.5 cm to the side of the seed) at seeding and broadcast two weeks after seeding. Fertilizer rates applied in 1983 were 75 and 150 kg ha^{-1} N in urea form. The fertilization schedule for the 1983 program is summarized in Table 3.2.

The irrigation and pre-irrigation schedules were identical to those in the 1982 experiment.

The experiment had a randomized split-split plot design with

Table 3.2 Nitrogen fertilization program for the 1983 experiment

Placement method		N rate	Time of application and amount of fertilizer: At seeding	At 2 weeks	At tillering
			kg ha^{-1}		
Broadcast	BA_1	75	75	-	-
		150	150	-	-
	BA_2	75	50	-	25
		150	50	-	100
Broadcast and incorporation	IA_1	75	75	-	-
		150	150	-	-
	IA_2	75	50	-	25
		150	50	-	100
Side-banding	SA_1	75	75	-	-
		150	150	-	-
	SA_2	75	50	-	25
		150	50	-	100
Late broadcasting	LA_1	75	-	75	-
		150	-	150	-
	LA_2	75	-	50	25
		150	-	50	100

irrigation treatments as main plots, N rates as subplots and methods of N placement as sub-subplots with four replications.

Main plots were 8 m x 8 m, sub-plots 4 m x 8 m. Sub-subplots contained 5 rows of wheat that were 0.20 m apart. Planting took place on 9 June 1983 and differential irrigation on 10 August 1983.

Samples for grain yield determination were harvested from a 1 m^2 area in each plot. The samples were treated as in the 1982 experiment.

Analyses of variance were calculated for the randomized block with a split plot for N rates and a split-split plot for methods of placement.

3.2.3 Third year study (1984)

Preliminary analysis of irrigation data from the first two years of this study suggested that a more intensive irrigation program be implemented in order to obtain maximum yields (Section 4). Thus in the 1984 experiment wheat (Triticum aestivum L. EMU'S') was grown under four N placement methods and two methods of application each, two nitrogen rates and one irrigation regime only. Fertilizer placement and application methods were identical to the 1983 experiments (Section 3.2.2). Pre-irrigation was identical to the two previous experiments but irrigation was applied every week at a rate of 85% of the total class A pan evaporation during the whole irrigation interval.

The experiment had a randomized split-split plot design with N rates as main plots, methods of N application (single and split) as sub-plots and methods of N placement (broadcast, broadcast and incorporation, side-band and late application) as sub-subplots with four replications.

Plot sizes were identical to those of the 1983 experiment (Section 3.2.2). Planting took place on 2 June 1984 and differential irrigation commenced on 27 June, 1984.

Harvesting of the plots and statistical analysis of harvest dates were the same as for the 1983 experiment (Section 3.2.2).

3.3 Results and Discussion

3.3.1 Effect of Irrigation

Because the same irrigation schedules were followed during the first two years of the study, the irrigation applied was expressed on the basis of the maximum irrigation, which was assumed to have been applied with the weekly irrigation schedule. Thus, although the actual amounts of water applied in each year of the experiment differed, the amount of water applied by the every three week and every two week schedules in both years was 24% and 43% respectively, of the maximum applied by the weekly irrigation.

The average effect of irrigation schedule for the first two years is illustrated in Fig. 3.1. The average yields obtained in 1983 were lower than those obtained in 1982, which may be associated partly with the delayed seeding and partly with a brief interruption of the irrigation schedules during the growing season. In both years, the weekly irrigation schedule produced significantly higher yields. Plants under the every two and three week irrigation schedules exhibited signs of water stress during both growing seasons. Data from individual years showed that equivalent stress periods affected yields considerably more in 1983 (average yield reduction for both irrigation schedules of 36%) than in 1982 (corresponding average yield decrease of 20%). Climatic conditions during stress periods undoubtedly affected the severity of the stress effects.

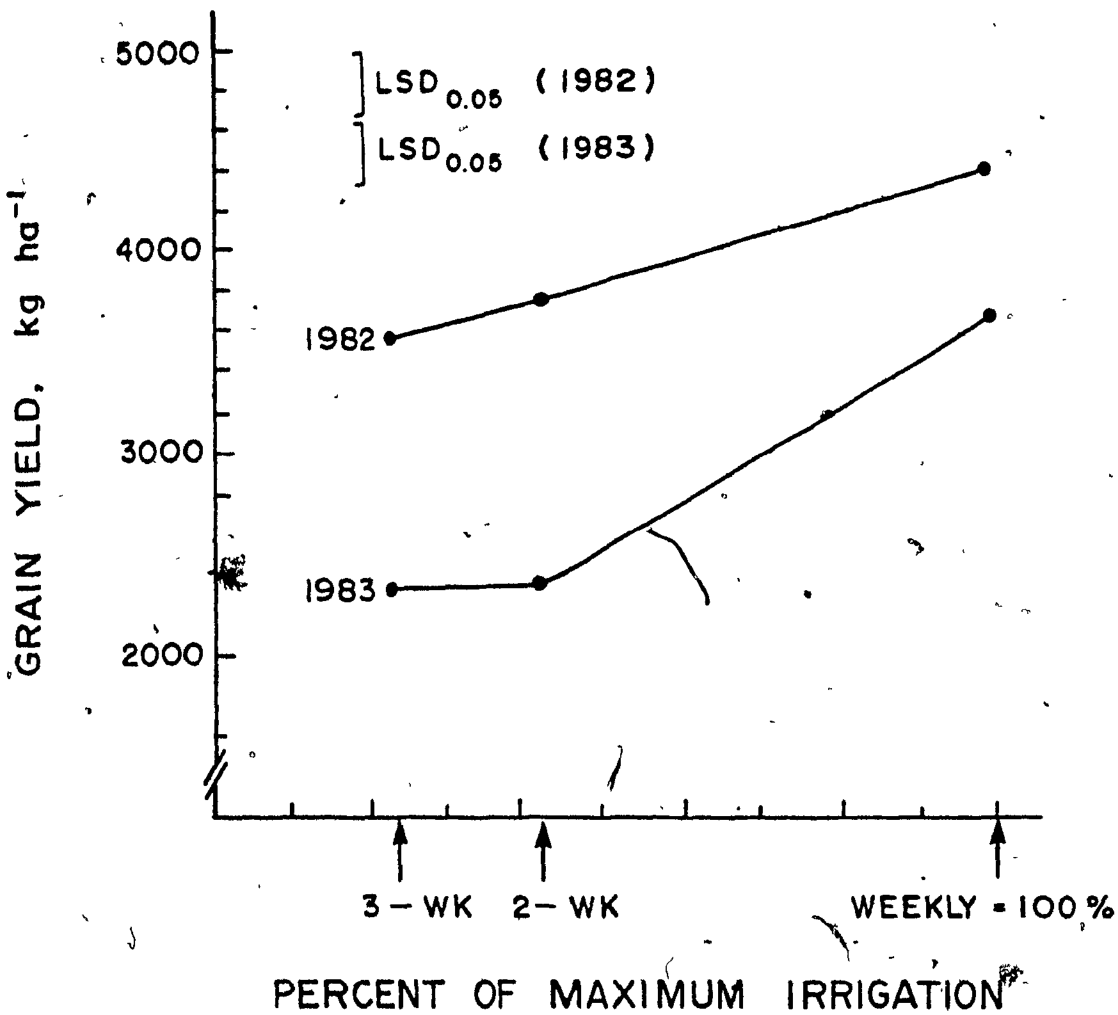

Fig. 3.1 Average effect of irrigation schedule on grain yield of wheat

There were no statistical differences in the grain yield between the every two week and every three week irrigation schedules.

There was an interaction between irrigation schedules and method of N application or placement during both years of the study (Table 3.3). However, there was no overall interaction between the fertilizer rates and amount of irrigation in 1983 (Table 3.3). Examination of the data on an individual irrigation schedule basis revealed that side-banding of higher N rates produced slightly ($P < 0.1$) lower yields under reduced irrigation, whereas under weekly irrigation broadcasting of higher N rates caused a significant ($P < 0.05$) increase. These interactions are discussed in detail below.

3.3.2 Effect of N rate and method of placement

Differential N fertilization was applied in 1983 and 1984 (75 and 150 kg N ha^{-1}, respectively). No overall differences in the grain yield produced by the application of two different levels of N were observed (Table 3.3 and Fig. 3.2). On the average, topdressing of N fertilizer produced statistically higher yields in all three years (Fig. 3.3). However, in 1983 the effect of topdressing was dependent on the method of fertilizer placement. Thus, statistically significant differences between single and two-split N applications were obtained only when the N fertilizer was broadcast and incorporated or the initial portion of the fertilizer was broadcast two weeks after seeding (Fig. 3.4).

3.3.3 Interaction of irrigation, N rate and method of N placement

The yield curves in Fig. 3.5 show that in the 1982 experiment, there was an interaction between irrigation schedule and method of N application.

Table 3.3 F values associated with the effects of irrigation schedule, method of nitrogen application and/or placement, nitrogen rates and their interaction on the grain yield of wheat grown at Nanga, Zambia.

Year	F Values						
	IR[1]	P	N	IRXP	IRXN	NXP	IRXNXP
1982	2.77***	2.98**	-	1.23	-	-	-
1983	283.37***	48.00***	0.27	45.9***	2.42	14.8***	2.26***
	N	A	P	NXA	NXP	AXP	NXAXP
1984	.099	14.64**	30.26***	1.57	2.27	2.09	0.45

1. IR = irrigation schedule; P = method of application and/or placement;
N = nitrogen rate; A = method of application

*** and ** significant at P < 0.0001 and < 0.01, respectively

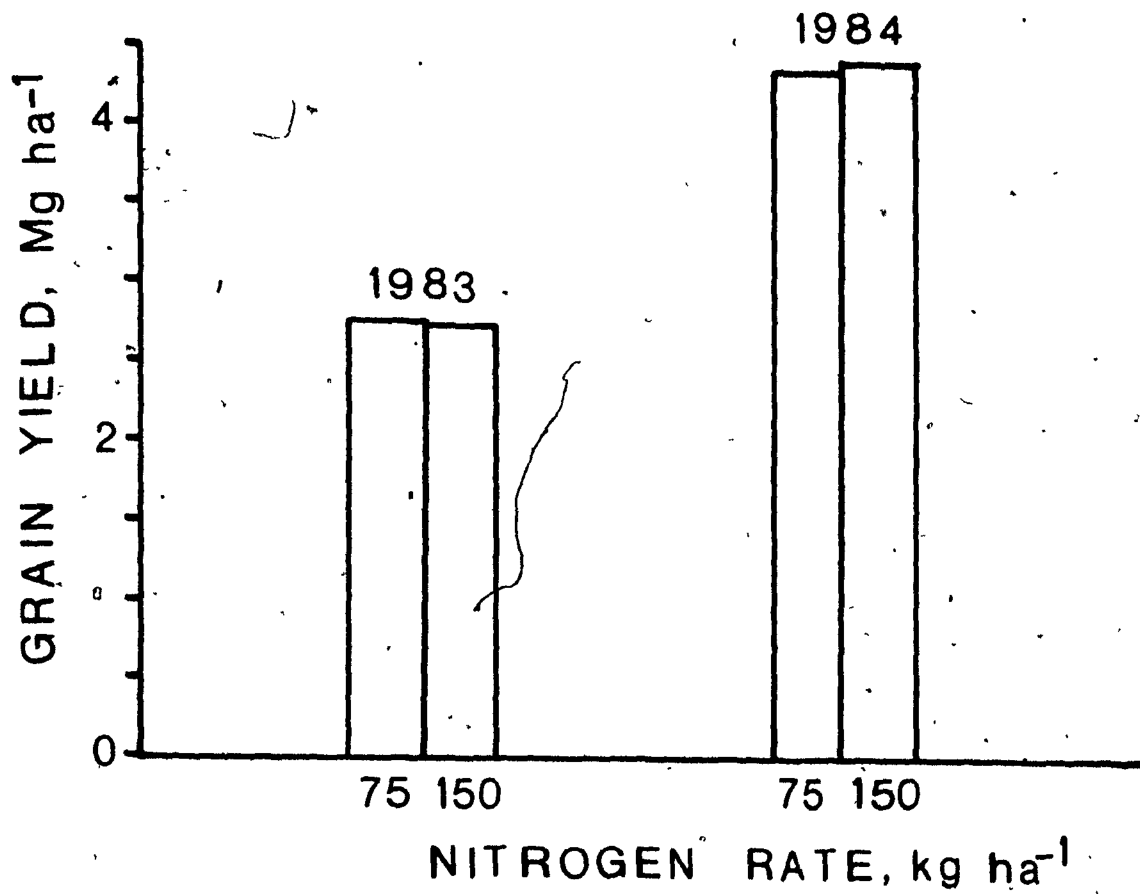

Fig. 3.2 Average effect of nitrogen rate on yield of wheat

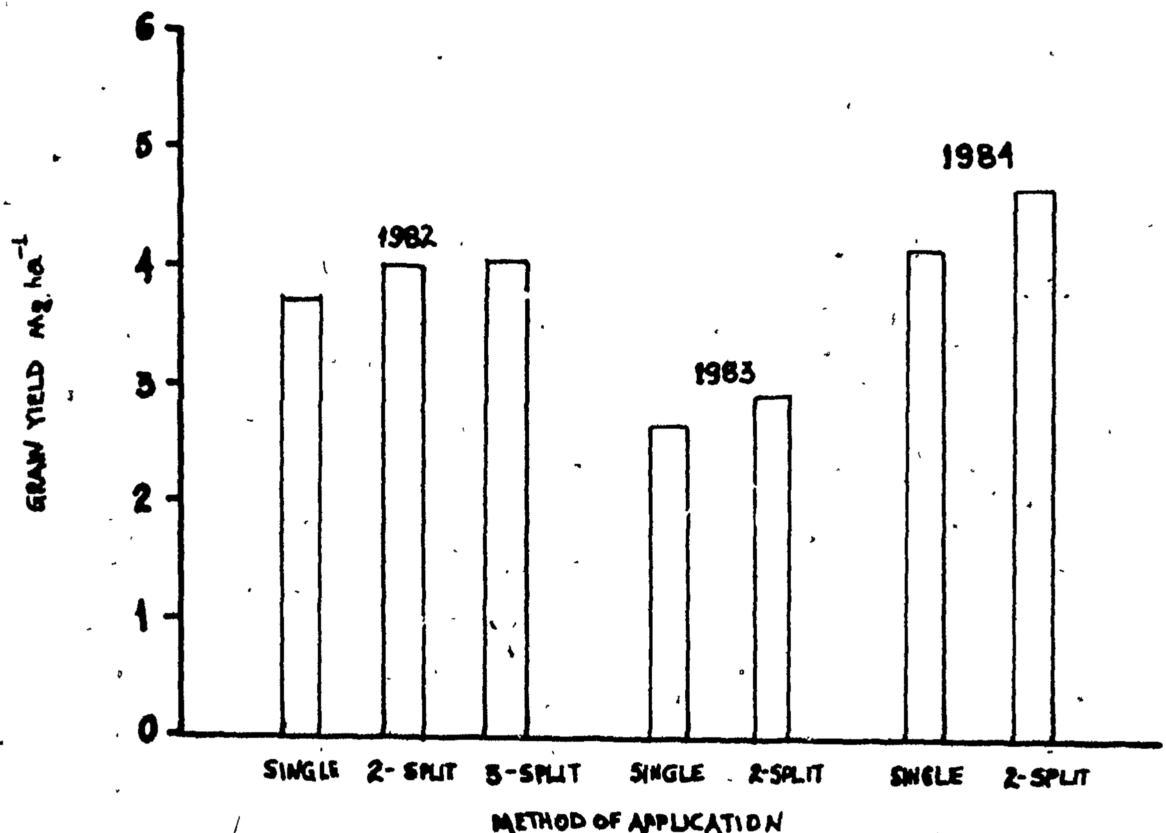

Fig. 3.3 Average effect of method of nitrogen application on grain yield of wheat

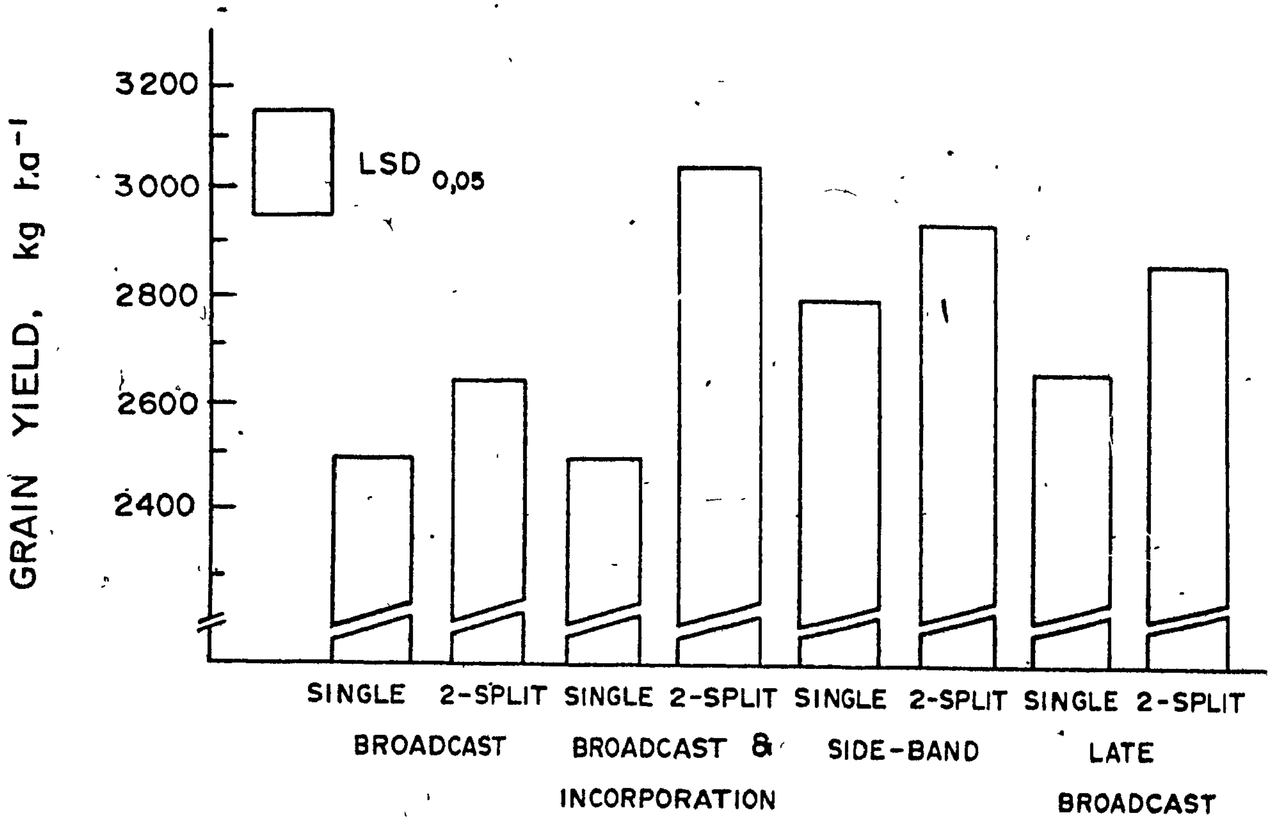

Fig. 3.4 Effect of method of placement and application of nitrogen fertilizer on grain yield of wheat in 1983

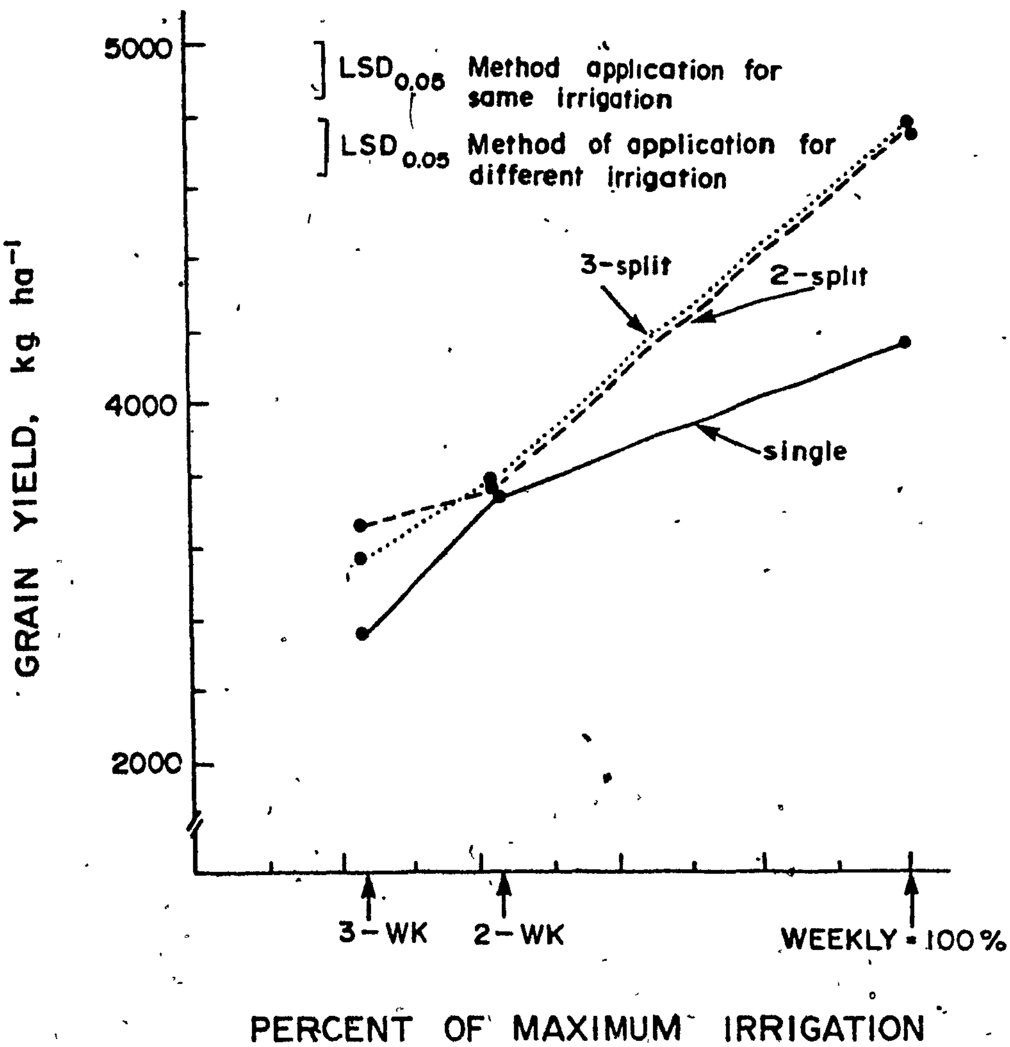

Fig. 3.5 Grain yields of wheat grown in the 1982 experiment as affected by irrigation schedule and method of nitrogen fertilizer placement

At every two or three week irrigation schedules, water stress was the main yield-limiting factor. Hence, no benefit of method of N application was observed with these two irrigation schedules. However, when irrigation was applied on a weekly basis, split applications produced significantly higher grain yields (Fig. 3.5). The results from the 1983 experiment were in close agreement (Table 3.4), considering that the method of N fertilizer placement in 1982 was simple broadcasting. The results in Table 3.4 suggest that benefit of split application under water stress was obtained only when the initial portion of the fertilizer was broadcast and incorporated. Further, with reduced amounts of irrigation, single application of the high N rate tended to enhance water stress with the exception of the late broadcast, where actually a benefit of a single application of 150 kg N ha^{-1} was obtained under stress. In 1984 only one irrigation regime was implemented.

High N rates applied in two portions did not enhance water stress unless the initial portion of the fertilizer was side-banded (Table 3.5). Comparison of yield reduction with side-banded urea under stress (Table 3.5) suggested that even the initial portion of 50 kg N ha^{-1} was harmful to the plant. High N rates did not produce any significant increase in the grain yield under the weekly irrigation regime, except when the fertilizer was broadcast. This indicates that, with the exception of broadcasting, the placement methods examined led to an efficient utilization of urea N by non-stressed wheat.

Under weekly irrigation, the greatest benefit of split application in 1983 was obtained when the initial portion of the fertilizer was broadcast two weeks after seeding (Table 3.4). This corresponded with the maximum

Table 3.4 Benefit of split application of nitrogen fertilizer placement methods on the basis of irrigation schedule and nitrogen rate in 1983.

Placement method	% yield increase by split N application	
	75 kg ha^{-1}	150 kgN ha^{-1}
Weekly irrigation		
Broadcast	16	20
Broadcast and incorporation	21	16
Side-banding	20	18
Late broadcast	29	18
Irrigation every two weeks		
Broadcast	none[1]	none
Broadcast and incorporation	36	35
Side-banding	none	none[1]
Late broadcast	6 n.s.[2]	none
Irrigation every three weeks		
Broadcast	7 n.s.	none
Broadcast and incorporation	20	38
Side-banding	5 n.s.	none
Late Broadcast		

[1] In these treatments a significant ($P < 0.05$) decrease was actually obtained

[2] n.s. = non-significant

Table 3.5 Effect of nitrogen rate and placement on the grain yield of wheat under various irrigation regimes in 1983.

Irrigation schedule	% change in grain yield with application of high N rate[1]							
	Broadcast		Broadcast and incorporation		Side-banding		Late broadcast	
	Single	2-split	Single	2-split	Single	2-split	Single	2-split
Weekly	+17	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Every 2-wk	-13	n.s.	-11	n.s.	-12	-10	n.s.	n.s.
Every 3-wk	-10	n.s.	-15	n.s.	-24	-21	+21	n.s.

1. $$\%\ \text{change} = \frac{\text{Yield}_{150}\ (\text{kg N ha}^{-1}) - \text{Yield}_{75}\ (\text{kg N ha}^{-1})}{\text{Yield}_{75}\ (\text{kg N ha}^{-1})} \times 100$$

yield obtained by any method of N fertilizer placement and/or application in all treatments (Fig 3.6). In 1984, the greatest benefit of split application was obtained when the initial portion of the fertilizer was broadcast and incorporated (Table 3.6 and 3.7). This again may reflect the different water regime implemented in the last year of the experiment. Higher yields with the late broadcast placement method may be associated with reduced N fertilizer losses during the early stages of wheat growth at which N is taken up by the plant at relatively low rates (Olson and Kurtz, 1982). When the average grain yield was obtained from all irrigation schedules, the best method of placement was broadcast and incorporation.

3.4 Conclusions

Weekly irrigation of wheat at rates of 70% of the total class A pan evaporation during the whole irrigation interval and throughout the growing season was superior to irrigation schedules which included shifting to either every two week or every three week (at 60 and 50% of the total class A pan evaporation during the whole irrigation interval, respectively) irrigation at tillering. Split applications of urea fertilizer at rates of 50 kgN ha^{-1} at seeding and minimum of 25 kg N ha^{-1} topdressed at the tillering stage produced maximum yields. Although no apparent benefit was obtained by employing various methods of urea fertilizer application and placement when every two or three week irrigation schedules were followed, different methods of placement (broadcast or broadcast and incorporation prior to seeding, side-banding at seeding and broadcast two weeks after seeding) and different methods of application (single, two or three split)

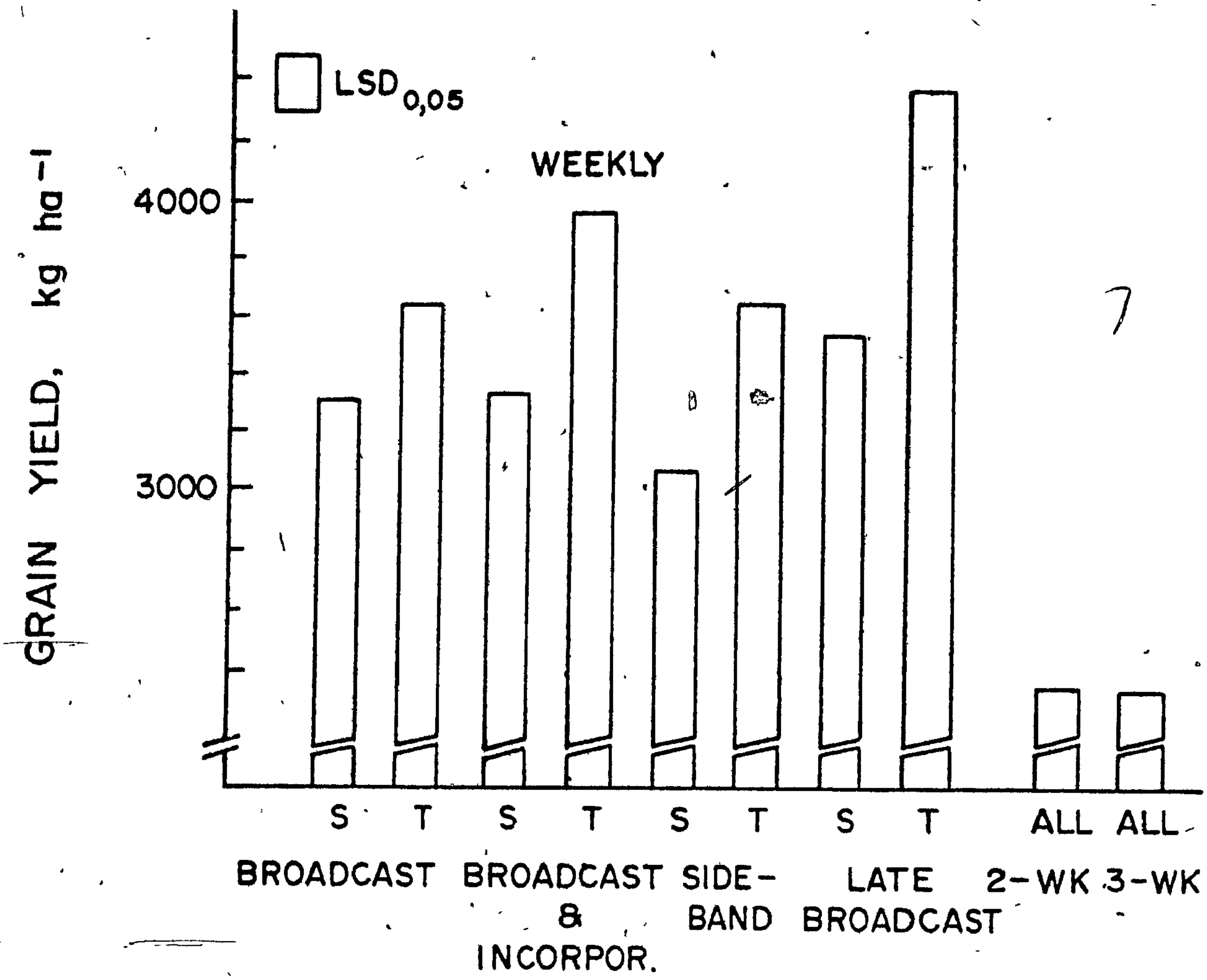

Fig. 3.6 Grain yields obtained by the weekly irrigation schedule in 1983 as affected by the method of nitrogen application (S = single, T = two split) and placement (average yields of all treatments for the every two and every three week irrigation schedules are presented for visual comparison only

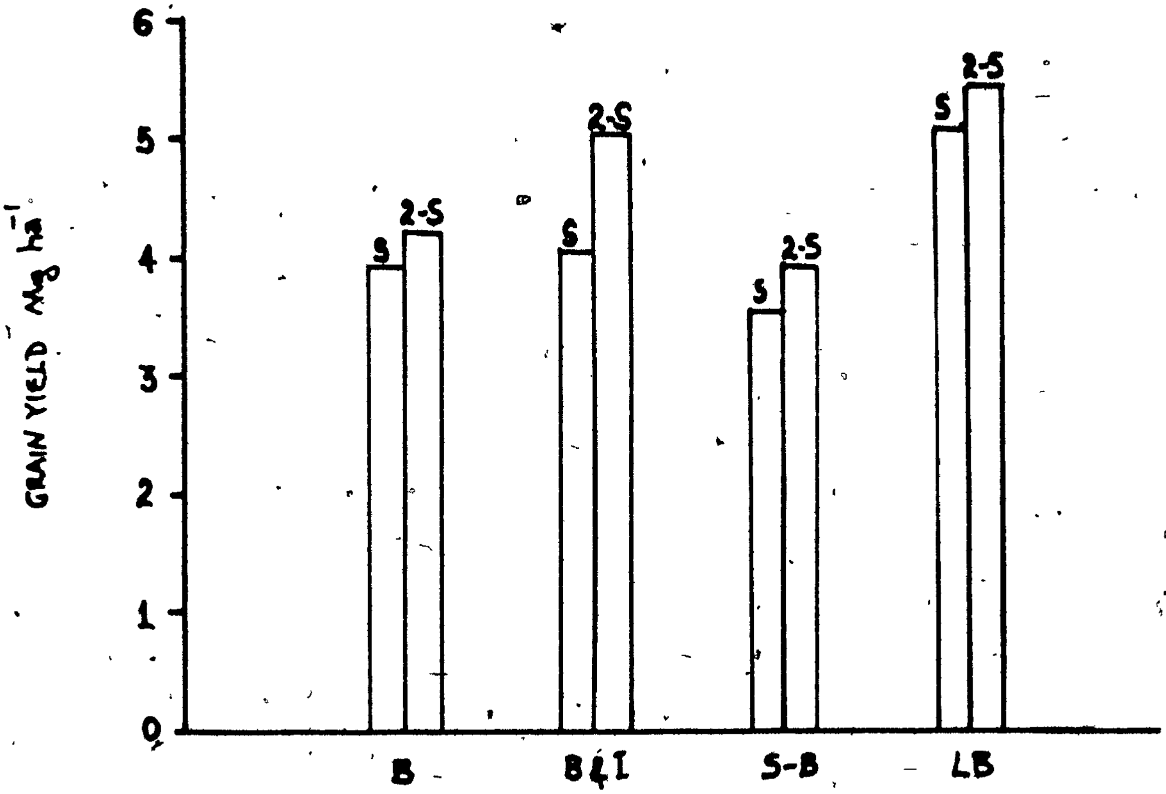

Fig. 3.7 Grain yields obtained in 1984 as affected by the method of nitrogen application and placement. (B = broadcast, B&I = broadcast and incorporation, S-B = side band, LB = late broadcast, S = single, 2-S = two-split)

Table 3.6 Benefit of split application on the basis of nitrogen fertilizer placement methods and nitrogen rate in 1984.

Placement method	% yield increase by split N application	
	75 kg N ha^{-1}	150 kg N ha^{-1}
Broadcast	none	19
Broadcast and incorporation	23	26
Side-band	13	9
Late application	7	8

produced different yields when the weekly irrigation schedule was followed. Hence, maximum yields at weekly irrigation were obtained with split application of N fertilizer of which the initial portion was either broadcast two weeks after seeding or was broadcast and incorporated prior to seeding. Highest yields in this 3-year study were obtained when weekly irrigation of wheat was employed at rates 85% of the total class A pan evaporation during the whole irrigation interval.

4. EFFECT OF IRRIGATION SCHEDULES AND REGIMES ON WHEAT YIELD

4.1 Introduction

The need for water conservation in Zambia during the dry season (May to October) is of utmost importance to the country's economy. Since Zambia has embarked on a major agricultural expansion program, the need for increased acreage of irrigated crops has received high priority. This, however, must be combined with a more rational and efficient use of water and fertilizer (Section 3).

Earlier work at the National Irrigation Research Station, at Nanga, Zambia could not lead to final recommendations due to a number of obstacles encountered, especially with proper measurement of soil moisture. However, Aeppli (1977) concluded that although with 14 days irrigation interval high wheat yields are possible under normal conditions, reduced irrigation intervals might be particularly effective at least during seasons with higher temperatures than usual. A three-year investigation was therefore carried out to study the effect of irrigation intervals on the grain yield of wheat (Triticum aestivum L.). The effect of different irrigation regimes, rates and methods of N placement on the yields of irrigated wheat have been already reported in Section 3. However, in that section no considerations were given to soil moisture and water use efficiency. The objective of this Section is to analyze the soil moisture and irrigation data from the first set of experiments (Section 3) and arrive at recommendations for rational and efficient use of irrigation water.

4.2. Materials and Methods

Three field experiments were conducted in three crop years (1982, 1983 and 1984) on a sandy clay loam soil at the National Irrigation Research Station at Nanga, Zambia. The characteristics of this soil and experimental design are described in Section 3. In summary, wheat (Triticum aestivum L. cv EMU'S) was sown in each year. A heavy pre-sowing irrigation was applied each season to saturate the field to a depth of 1.2 m. Blanket application of 60 kg P_2O_5 ha^{-1} was applied prior to sowing in each of the three years. The experiment in 1982 was a partly randomized split plot design with irrigation treatments as the main plots and N application (single, two-split and three-split) as subplots. In 1983, a completely randomized split-split plot design was followed with irrigation treatments as main plots, N rate (75 and 150 kg N ha^{-1}) as subplots and method of N placement (broadcast or broadcasting and incorporation prior to sowing, side banding at sowing and broadcasting two weeks after sowing) and application (single and two-split) as sub-subplots. The irrigation regimes in each of the three years were implemented at tillering and included: (i) irrigation on a weekly basis (W) at the rate of 70% of the total class A pan evaporation during the whole irrigation interval; (ii) every two weeks irrigation (2-W) at 60% of the total class A pan evaporation during the whole irrigation interval; and (iii) every three weeks irrigation (3-W) at 50% of the total class A pan evaporation during the whole irrigation interval. In 1984 the experiment was a split-split plot in a completely randomized block design with N rates (75 and 150 kg N ha^{-1}) as main plots, methods of application (single and split) as subplots and methods of placement (identical to the 1983 experiment) as the sub-subplots.

Irrigation was on a weekly basis at 85% of class A pan evaporation during the whole irrigation interval. The dates of sowing, irrigation and harvesting are given in Table 4.1.

The class A pan evaporation and relative humidity were determined on a daily basis. Twelve-neutron probe access tubes were installed per irrigation treatment. Soil water content was determined gravimetrically for the 0-15 cm depth and with a neutron moisture meter thereafter to a depth of 1.4 m before and after irrigation and at the time of harvest. Apparent field water use was calculated from these soil moisture data for each irrigation schedule. The data reported here therefore do not include outgoing flux of water at the 1.4 m soil depth. Grain yields were measured for all treatments (Section 3). The effect of the method of N placement and application have been discussed in the preceding section.

4.3 Results and Discussion

Grain yields of wheat increased with shorter irrigation intervals for both 1982 and 1983 (Fig. 4.1). Multiple linear regression revealed that the greater loss in yield was due to amounts of irrigation water applied ($P < 0.01$) rather than interval of application. This contradicts the results of Aeppli (1977) who found irrigation increased intervals reduced yields dramatically, whereas reduced irrigation amounts had no significant effects. He attributed the loss of yield to reduced effective rooting depth and the amount of water stored in the soil available for the crop as a result of inadequate soil preparation.

Table 4.1 Dates of sowing, irrigation and harvesting

Crop year	Date of sowing	First differential irrigation			Last irrigation			Number of			Date of harvest
		W	2-W	3-W	W	2-W	3-W	W	2-W	3-W	
1982	28 May	20 July	28 July	4 Aug.	15 Sept.	8 Sept.	15 Sept.	9	4	3	12 Oct.
1983	9 June	10 Aug.	17 Aug.	24 Aug.	28 Sept.	21 Sept.	21 Sept.	6	3	2	28 Oct.
1984	2 June	27 July	-	-	22 Sept.	-	-	9	-	-	15 Oct.

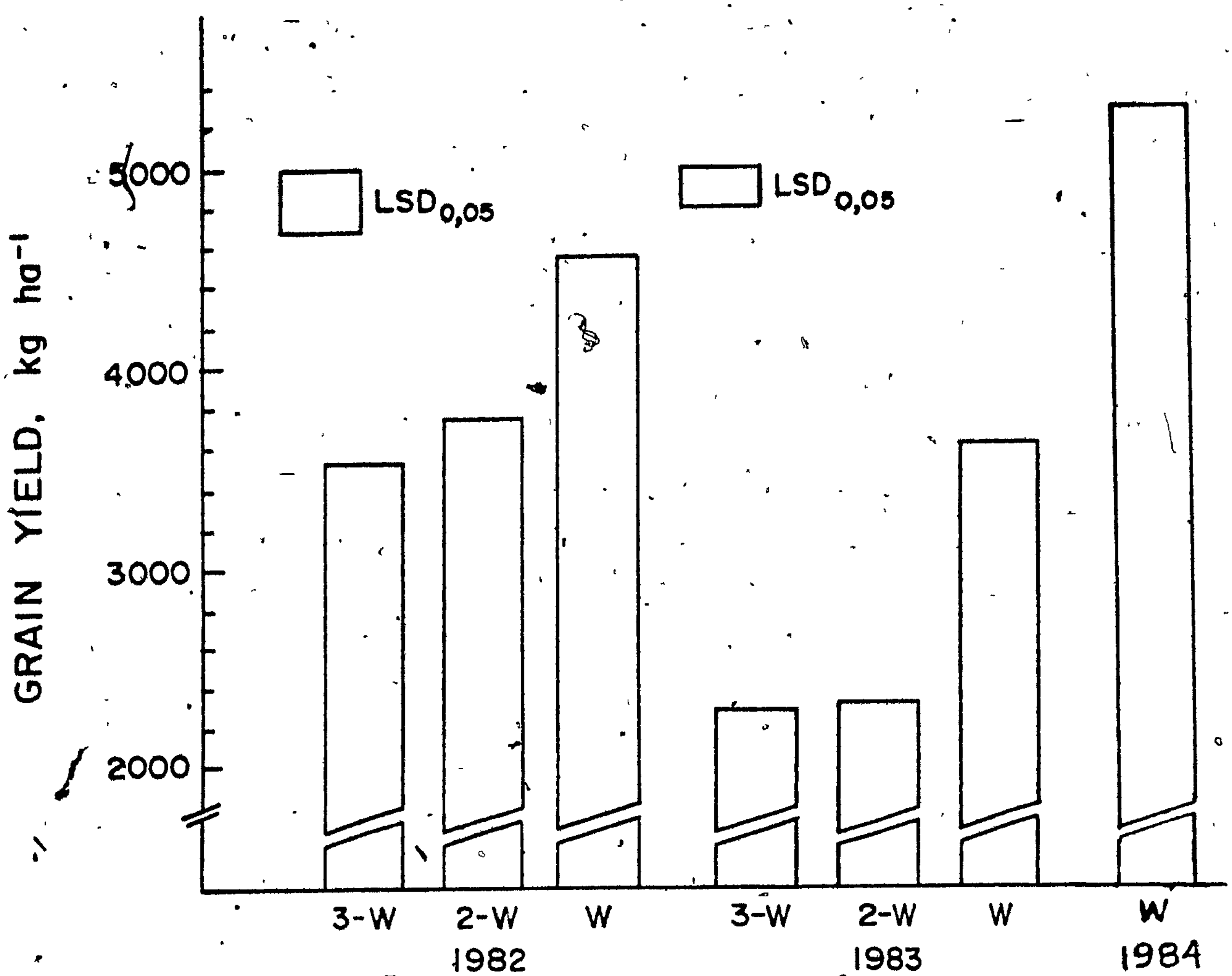

Fig. 4.1 Average effect of irrigation schedule on grain yield of wheat

The cumulative pan evaporation on a weekly basis and average weekly relative humidity for 1982 and 1983 seasons are shown in Fig. 4.2. Pan evaporation for the period of June to September was almost identical in the 1982 and 1983 experiments. Hence, the only major difference in the two experiments as far as water requirements are concerned was the date of sowing as well as the date of initiation of differential irrigation (Table 4.1). Total pan evaporation during the growing season amounted to 636.3 and 674.1 mm in 1982 and 1983, respectively. The total irrigation applied in 1982 as per the three irrigation schedules was W: 406.4 mm, 2-W: 329.0 mm and 3-W 321.6 mm. However, that in 1983 was significantly less due to a brief interruption in irrigation and amounted to W: 311.1 mm, 2-W: 229.9 mm and 3-W: 214.9 mm. This explains the significantly lower yields obtained in 1983.

The effect of N rate and method of N placement as well as interaction between irrigation schedule and N rate and method of N placement have been discussed in detail (Section 3).

An attempt was made here to describe wheat grain yields as a function of amount of water based on the realization that water was the main yield limiting factor. A close linear relationship ($r = 0.972$, $P < 0.01$) was found between the depth of irrigation in mm in the 1.4-m soil profile and the weekly cumulative pan evaporation for the weekly irrigation schedule in 1982:

$$Y = - 0.58 + 0.645 X \qquad [4.1]$$

where,

Y = depth of irrigation water in mm

X = weekly pan evaporation in mm

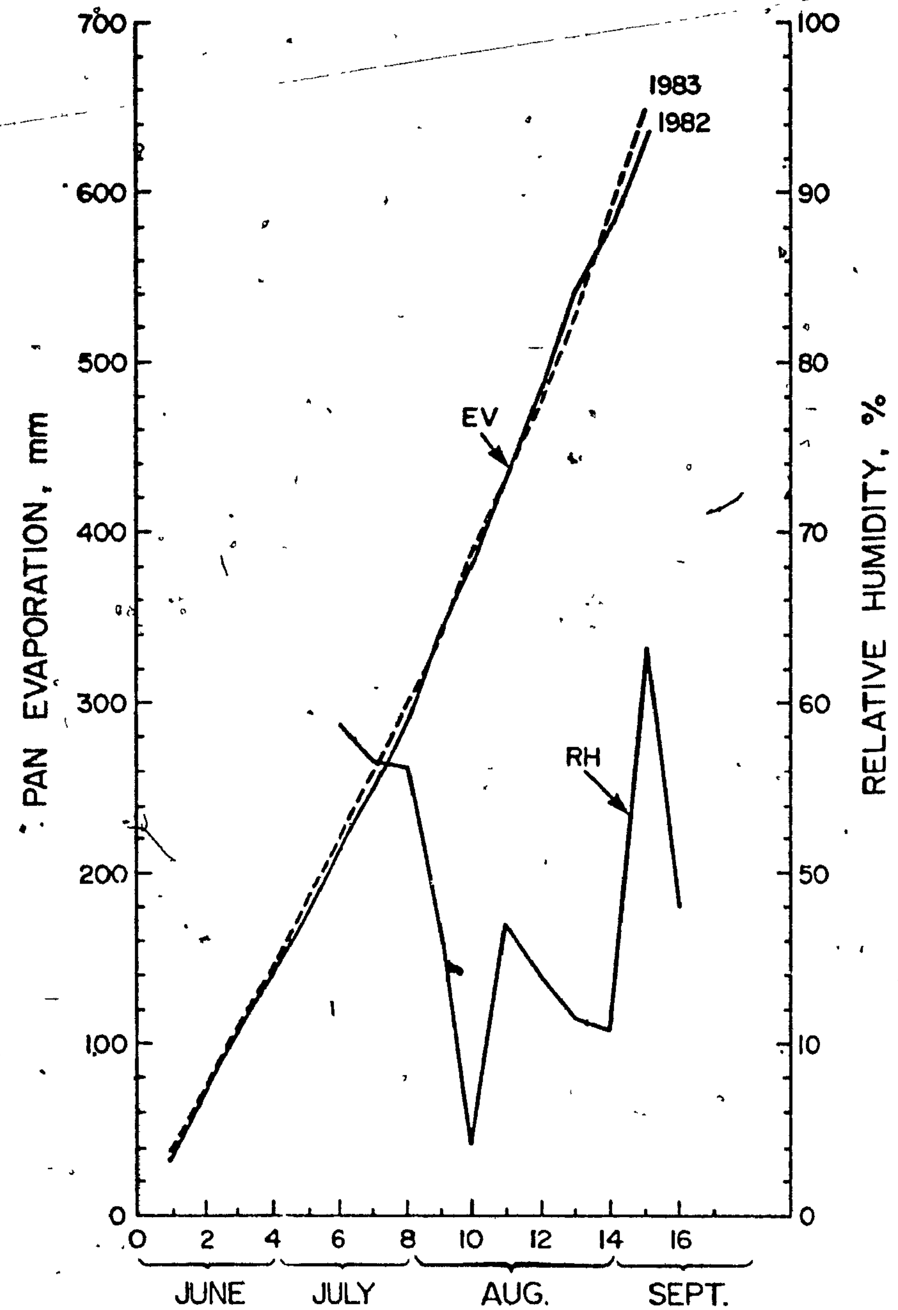

Fig. 4.2 Cummulative pan evaporation on a weekly basis and relative humidity during the growing season

Although Eq. [4.1] has no universal value, it allowed us to make some useful comparisons among the various treatments. An attempt was made initially to predict the depth of irrigation water for the 2-W and 3-W treatments in 1982 and all the irrigation treatments in 1983. Details of this prediction are presented in Table 4.2 for the 1982 data only as those for 1983 led to similar trends. There was a close agreement between the predicted depth of irrigation water and the actual depth determined from neutron moisture meter readings for the 2-W treatment only (Table 4.2). The large discrepancy between the predicted and actual values in the 3-W treatment (Table 4.2) suggests that the efficiency of the every three week irrigation schedule was much lower compared to the other two irrigation treatments. The lower efficiency could be attributed to water losses due to run-off. These losses, of course, could not be predicted from Eq. [4.1].

Simple linear regression between grain yields and actual depth of irrigation water for the 1982 data revealed a close relationship ($r = 0.999$, $P<0.01$) between these two variables:

$$Y = 1068 + 9.3\,X \qquad [4.2]$$

where,

Y = actual grain yield in kg ha^{-1}

X = actual depth of irrigation water in mm

The relationship between grain yield and predicted depth of irrigation water was also significant ($P<0.05$) but the intercept was negative:

$$Y = -400.5 + 13.18\,X \qquad [4.3]$$

hence, implying that Eq. [4.3] introduces large errors at low amounts of applied water.

Table 4.2 Relationship between applied irrigation and depth of irrigation in 1982

Week of Irrigation	Weekly: Applied (mm)	Weekly: Irrigation dept (mm) Predicted	Weekly: Irrigation dept (mm) Actual	Every two weeks: Applied (mm)	Every two weeks: Irrigation depth (mm) Predicted	Every two weeks: Irrigation depth (mm) Actual	Every three weeks: Applied (mm)	Every three weeks: Irrigation depth (mm) Predicted	Every three weeks: Irrigation depth (mm) Actual
1st.	24.9	-	22.3	-	-	-	-	-	-
2nd	29.3	-	26.3	56.4	42.2	40.1	-	-	-
3rd	32.9	-	29.8	-	-	-	62.3	56.8	45.4
4th	31.3	-	28.3	55.0	50.0	48.1	-	-	-
5th	35.8	-	32.5	-	-	-	-	-	-
6th	35.4	-	32.1	61.0	55.8	52.9	73.2	67.1	54.2
7th	38.9	-	35.3	-	-	-	-	-	-
8th	27.8	-	25.0	57.2	52.2	49.3	-	-	-
9th	40.8	-	37.0	-	-	-	76.8	70.4	55.7
SUBTOTAL	297.1		268.6	219.7	200.4	190.4	212.3	194.3	155.3
Irrigation prior to differential program	102.0		102.0	102.0	102.0	102.0	102.0	102.0	102.0
Rainfall	7.3		7.3	7.3	7.3	7.3	7.3	7.3	7.3
TOTAL	406.4		377.9	329.0	309.7	299.7	321.6	303.6	264.6
Unaccounted	-		28.5	-	19.3	29.3	-	18.0	57.0
Irrigation efficiency,%	-		93.0	-	94.0	91.1	-	94.4	82.3

The relationship between predicted grain yields for both 1982 and 1983 experiments and the grain yields actually obtained is illustrated in Fig 4.3.

Irrigation in this experiment was applied strictly as a function of total pan evaporation during the whole irrigation interval. It has been shown (Prihar et al., 1974; Singh et al., 1979) that the use of fixed depth of irrigation and cumulative pan evaporation (W/PAN-E) ratios is a valuable tool in rational irrigation scheduling of wheat. Hence, great savings of irrigation water may be achieved especially by eliminating irrigation at later stages of wheat growth. The IW/PAN-E ratio in our experiment was maintained at 0.64, which is below the minimum value of 0.75 recommended by Prihar et al., (1974). This may have led to comparatively lower yields in our experiments. Since the irrigation schedule followed in these experiments was a direct function of pan evaporation and since there was a direct relationship between grain yields and soil moisture data, the loss in the average yield by not applying the minimum IW/PAN-E can be calculated from Eq. [4.1] and [4.2]. This loss was approximately 0.7 Mg ha^{-1} and could have been compensated by applying weekly irrigation at a rate of 85% of the total pan evaporation during the whole irrigation interval. Assuming that soil fertility is maintained at optimum and, hence, water is the only yield limiting factor and that irrigation efficiency is maintained at 94%, the maximum yield that could possibly be obtained by applying water at 100% of pan evaporation during the whole irrigation interval on a weekly basis would probably be in the order of 5.5 to 6.0 Mg ha^{-1} depending on the sowing date. The 1984 experiment was carried out at 85% of class A pan

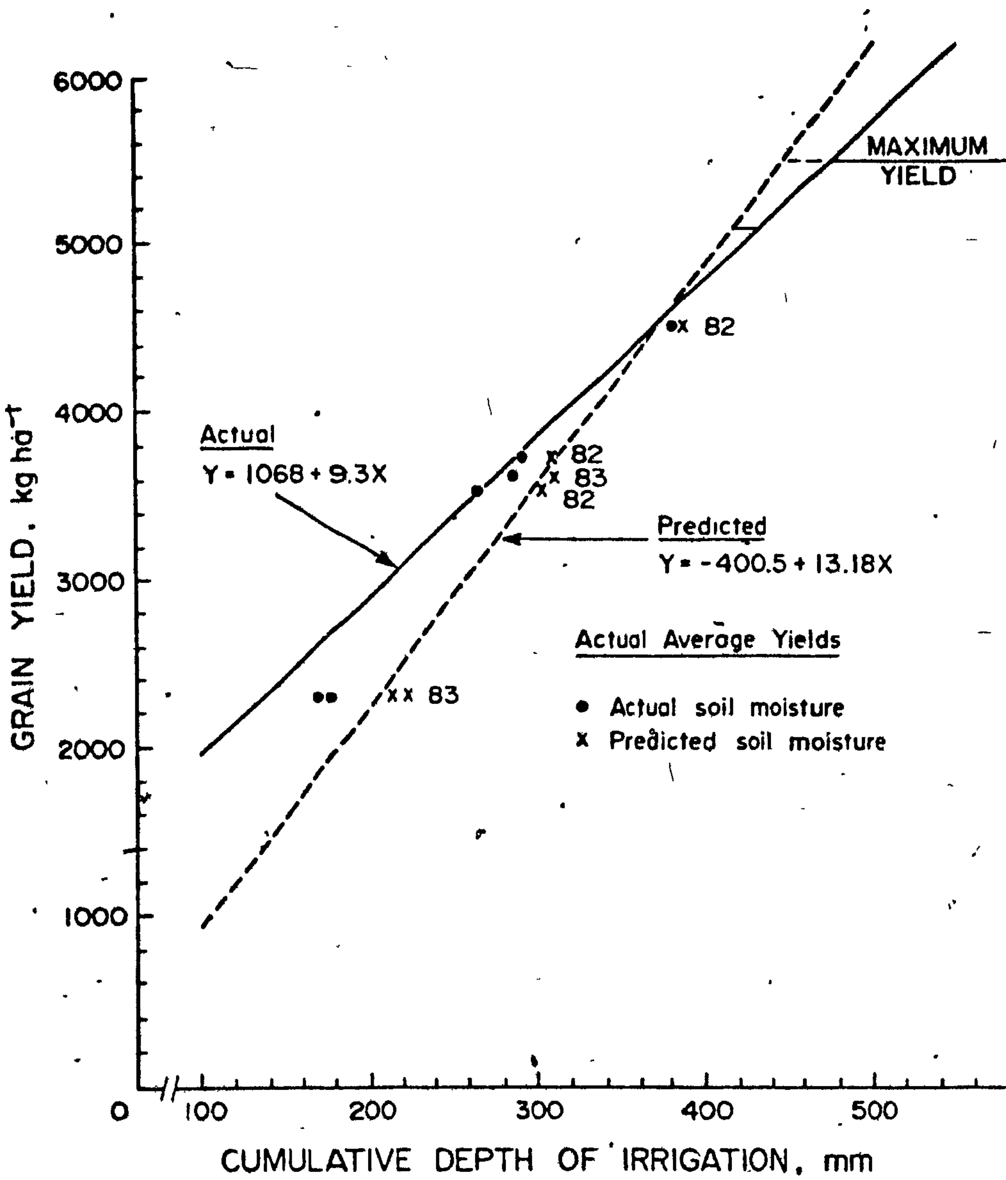

Fig. 4.3 Relationship between grain yield of wheat and cummulative depth of irrigation in mm

evaporation following the conclusions of the previous 1982 and 1983 seasons. Results of the 1984 season are in agreement with this hypothesis (Fig. 4.1), i.e. high grain yields of wheat where obtained with the weekly irrigation at 85% of class A pan evaporation. The study of Aeppli (1977) corroborates our results (Table 4.3). The amount of water use by the wheat crop in that experiment was only an estimate since soil moisture in the root zone could not be determined.

The data of an experiment carried out at Mt Makulu (Soil Research Coordination Report, 1981) with irrigation applied every week confirms these conclusions. The mean for the wheat stover and grain yield was 10.6 and 6.1 Mg ha^{-1} respectively. The amount of irrigation water applied was not exactly determined. The higher grain yields of wheat possibly reflects the higher fertilizer status and moisture retention properties of the soil.

The apparent water use by wheat increased with shorter irrigation intervals (Table 4.4). Water use efficiency was maximum with the every three week irrigation schedule in both years. Apparent water use in Mg ha^{-1} of grain produced per cm of water ranged from 0.120 to 0.134 in 1982 and 0.116 to 0.127 in 1983. This demonstrates that irrigation water efficiency increases with longer intervals between two successive irrigations. However, apparent water use values have been calculated using actual soil moisture data and, hence, do not compensate for the efficiency of the irrigation itself. Moreover, the loss in yield with longer intervals between irrigations is too large to warrant their implementation. For example, improvement of apparent water use efficiency by 10% in 1982

Table 4.4 Apparent water use of wheat in different irrigation treatments

Irrigation schedule	Apparent water use 1982	Apparent water use 1983	Apparent water use efficiency 1982	Apparent water use efficiency 1983
	cm		Mg grain ha^{-1} per cm water	
W	38.0	31.0	0.120	0.116
2-W	30.0	19.5	0.125	0.119
3-W	26.5	18.5	0.134	0.127

Table 4.3 Yield of irrigated wheat Mg ha^{-1} (Aeppli, 1977)

Interval days	% of pan evaporation		
	100%	80%	60%
7	5.28	5.25	5.22
14	3.98	3.64	3.70
21	3.40	3.15	3.42

led to yield decreases of 18%, whereas a similar increase in apparent water use efficiency in 1983 caused a 36% decrease in the grain yield.

The results of this study in combination with those reported in Section 3 suggest that split application of N of which the initial portion is either broadcast and incorporated prior to sowing or broadcast two weeks after sowing in combination with weekly irrigation applied at a rate of at least 85% of the total pan evaporation during the whole irrigation interval can lead to satisfactory wheat grain yields with relative conservation of irrigation water.

5. UTILIZATION OF ^{15}N-UREA FERTILIZER BY IRRIGATED WHEAT IN ZAMBIA

5.1 Introduction

Fertilizer along with complementary inputs will continue to play a significant role in accelerating agricultural growth in Zambia. The increasing cost of fertilizers, especially nitrogen, will necessitate reforms and commitment in several areas: (i) improvement of fertilizer efficiency and productivity, (ii) risk reduction of fertilizer use through appropriate fertilizer recommendations and management, (iii) improvement of crop response to applied fertilizer through the development and transfer of fertilizer-responsive crop varieties, and, (iv) expansion of irrigation. Since Zambia imports N fertilizers to meet the shortfall in domestic production, efficient use of N fertilizers is of utmost importance to the country.

The transitory nature of N in soil, its tendency for loss from soil, acceleration of the acidification process and its potential for becoming a pollutant of water and air demands that N receive a higher management level than any other of the primary and secondary nutrients.

For cereals, maximum efficiency of fertilizer N is obtained when fertilizer is applied shortly before the period of most rapid growth and greatest demand by the crop permitting ready uptake (Olson et al., 1964; Herron et al., 1971; Hucklesby et al., 1971; Welch et al., 1971; Miller et al., 1975).

Efficient application of fertilizer can be attained through adjustment of (i) rate of application, (ii) time of application, (iii) method of placement, and, (iv) water management. Efficiency in crop use of fertilizer N generally decreases with increasing application rates. Correspondingly, the economic return from each added unit of N declines so that fertilizer N is not recommended beyond where the cost of the last fertilizer increment is equal to the price return of the additional yield produced (Olson and Kurtz, 1982).

Depending on soil and climatic conditions, N application has been divided into two or more increments during the growing season for maximum fertilizer efficiercy. Seasonal increments are especially favored with humid region cropping and with irrigation of sandy soils. Split applications of N reduce the opportunity for N losses through leaching, runoff, volatilization and denitrification because an active root system is present for absorbing the fertilizer N when it is applied (Olson and Kurtz, 1982). When split application of N was superior to the single application, the uptake efficiency was higher from the N applied at tillering and boot stage (IAEA, 1974). This can be at least partially attributed to the avoidance of excessive N during the vegetative growth stage and the high availability of N during grain filling. Excessive vegetative growth stimulated by excessive N levels at early growth stages uses available soil moisture at the expense of grain yield and is likely to hasten the onset of moisture stress (Olson and Kurtz, 1982).

Isotope studies on wheat fertilization (IAEA, 1974; Tomar and Soper, 1981; Carter and Rennie, 1984) showed that the best method of placement was side-banding. Nitrogen was less efficiently taken up by wheat when it was incorporated in the soil prior to sowing as compared to side-banding at planting time. Under a drier moisture regime, however, side-banding was inferior to the broadcast application (IAEA, 1974).

Contrary to expectations, broadcasting in the humid and subhumid tropics performed significantly better than either band or point placement (Mughogho and Bationo, 1985). Over all zones, point-placed urea tended to be less effective than other sources in the semiarid zone as represented by the Niger site (Vlek, 1985). Concentrated placement of urea in points or in bands may lead to increased leaching of fertilizer N due to limited access to the sorption sites of the soil. The problem is accentuated in coarse textured soils (Miller et al., 1975; Velk et al., 1980; Mughogho and Bationo, 1985).

The objective of this study was to assess the effect of various placement methods and application times examined in Sections 3 and 4 on the efficiency of urea-N use by irrigated wheat in Zambia.

5.2 Materials and Methods

The comparison of application times and placement methods of ^{15}N-urea under various irrigation schedules was conducted in 1982 and 1983 at adjacent sites on a nearly level sandy clay loam at the National Irrigation Research Station at Nanga, Zambia. The soil belongs to the Mazabuka series, which includes chromic luvisols or Dystric Nitosols (FAO-UNESCO) or Typic Haplustalfs (USDA) occurring on elevated sites under miombo Savannah of moderate rainfall. They are deep well-drained soils with a characteristic argillic B horizon developed over calcium-silicate schists. The soil had a pH of 5.5, CEC of 7 cmols(+) kg^{-1} and total N content of 80 mg kg^{-1}. The experimental designs for the two years have been described in detail in Section 3. In summary, wheat (Triticum aestivum L., cv. EMU'S) was grown each year. A heavy pre-sowing irrigation was applied each season to saturate the field to a depth of 1.2 m. Phopshorus was broadcast at a rate of 60 kg P_2O_5 ha^{-1} each year prior to sowing. The experiment in 1982 was a partly randomized split plot design with irrigation (non-randomized component) treatments as the main plots and N application time (single, two-split and three-split totaling 150 kg N ha^{-1}) (randomized component) as subplots (Table 5.1). In 1983, a completely randomized split-split plot design was utilized with irrigation treatments as main plots, N rate (75 and 150 kg N ha^{-1}) as subplots and N placement method (broadcast, broadcast and incorporation prior to sowing, banding-2.5 cm to the side of the seed row at sowing and broadcast two weeks after sowing) and N application time (single and two-split) as sub-subplots (Table 5.2). The irrigation regimes in both years were implemented at tillering and included: (i) irrigation on a weekly basis at the rate of 70% of the total class A pan evaporation during the whole irrigation interval; (ii) every two weeks irrigation at 60% of the total class A pan evaporation during the whole irrigation interval; and, (iii) every three weeks at 50% of the total class A pan evaporation during the whole irrigation interval.

The ^{15}N-urea treatments were applied in microplots (1.5 m X 1.5 m in 1982 and 0.6 m X 0.6 m in 1983) within the subplots and sub-subplots of the 1982 and 1983 experiments, respectively. The ^{15}N-urea was applied to all treatments in the 1982 experiment and only to the 150 kg N ha^{-1}

Table 5.1. Nitrogen fertilizer program for the 1982 experiment

Method of application	Time of application and amount of fertilizer		
	At seeding	At 4 weeks after seeding	At 7 weeks after seeding
	kg ha^{-1}		
One portion	150*[1]	--	--
Two portions	75*	75	--
	75	75*	--
Three portions	50*	50	50
	50	50*	50
	50	50	50*

1 * indicates labelling with 0.96 atom % ^{15}N excess urea-N. Thus, two and three microplots were used per treatment for the two and three portions, respectively

Table 5.2. Nitrogen fertilizer program for the 1983 experiment

Method of placement	Time of application and amount of fertilizer		
	At seeding	At 2 weeks after seeding	At tillering[1]
	kg ha $^{-1}$		
Broadcast and incorporation	150*[2]	--	--
	50*	--	100
	50	--	100*
Side-banding	150*	--	--
	50*	--	100
	50	--	100*
Late broadcast	--	150*	--
	--	50*	100
	--	50	100*

1 Topdressing was broadcast in all cases

2 * indicates labelling with 0.96 atom % ^{15}N excess urea-N. Thus, two microplots were used in the split application treatments

broadcast and incorporation, side-band and late broadcast treatments in the 1983 experiment.

Samples for grain and straw yield determination were harvested from a 1.5 m^2 (4 rows 1.5 m long) area in 1982 and 1 m^2 area in 1983. An area half the linear dimensions of the microplots (0.75 m X 0.75 m in 1982 and 0.30 m X 0.30 m in 1983) was harvested in the centre of each microplot for ^{15}N assay.

All plant samples from both field experiments were dried at 60 °C to constant weight and ground to pass a 425-um sieve. The straw samples from all microplot replicates of both experiments were composited for each treatment. Total N content was determined using a modified semi-micro Kjeldahl procedure (Rennie and Paul, 1971). After Kjeldahl analysis, the distillate was acidified with 0.5 M H_2SO_4 and concentrated for ^{15}N analysis. Assay for atom % ^{15}N was carried out in a Micromass 602E mass spectrometer.

To assess relative differences in N efficiency, the percent N derived from fertilizer (%Ndff) and the percent utilization of fertilizer N by wheat were determined. Analyses of variance for replicated parameters were calculated assuming a randomized split plot design for both years.

5.3 Results and Discussion

Dry matter (DM) yields in both years were significantly higher with the weekly than the every two or three week irrigation schedule (Tables 5.3 and 5.4). DM yields from every two or three week irrigation schedules were statistically the same in both years suggesting that water stress was

Table 5.3. Effect of irrigation schedule and method of urea application on DM yield of wheat grain and straw in the 1982 experiment

Water	Method of application	DM yield	
		Grain	Straw
		$Mg\ ha^{-1}$	
Weekly	Single	4.14	8.56
	2-split	4.56	7.74
	3-split	4.68	8.27
2-weeks	Single	3.34	6.62
	2-split	3.93	6.76
	3-split	3.85	6.42
3-weeks	Single	3.70	5.62
	2-split	3.53	6.34
	3-split	3.57	6.93
	Significance		
Irrigation		**	*
Application		*	ns
Irrigation X application		ns	ns

**, * and ns = Significant at P<0.01, P<0.05 and not significant, respectively

Table 5.4. Effect of irrigation schedule and method of urea application and placement on DM yield of wheat grain and straw in the 1983 experiment

Water	Method of application and placement	Yield	
		Grain	Straw
		Mg ha^{-1}	
Weekly	B & I[@] - single	3.64	5.30
	B & I - split	4.22	5.77
	Sideband - single	3.34	5.73
	Sideband - split	3.95	4.91
	Late - single	3.89	7.58
	Late - split	4.58	6.35
2-week	B & I - single	2.08	4.70
	B & I - split	2.81	4.03
	Sideband - single	2.72	3.62
	Sideband - split	2.36	3.65
	Late - single	2.31	3.23
	Late - split	2.26	3.64
3-week	B & I - single	2.02	2.90
	B & I - split	2.78	2.59
	Sideband - single	2.62	3.63
	Sideband - split	2.68	2.12
	Late - single	2.66	2.51
	Late - split	2.34	2.84
	Significance		
Irrigation		**	**
Placement		**	ns
Irrigation X Placement		**	*

@ B & I = broadcast and incorporation

**, * and ns = Significant at P<0.01, P<0.05 and not significant, respectively the main yield limiting factor. However, DM yields in 1983 were lower than those in 1982, which was associated with a 2-week interruption of the irrigation schedules during the growing season. Plants under the every two or three week irrigation schedules exhibited visual signs of water stress during both growing seasons.

Split applications of urea-N produced significantly higher yields than a single application in both years (Tables 5.3 and 5.4). Under water stress benefit of split applications of urea-N was obtained only with two splits and when the initial portion of the fertilizer was broadcast and incorporated (Tables 5.3 and 5.4). Under weekly irrigation, the greatest benefit of split application in 1983 was obtained when the initial portion of the fertilizer was broadcast and incorporated or broadcast two weeks after sowing (Table 5.4).

Total N uptake by grain was significantly affected by irrigation schedule and time and method of application (Tables 5.5 and 5.6). Uptake of fertilizer N under the weekly irrigation schedule was higher than under the every two or three week irrigation schedules in both years.

Split application of fertilizer N produced significantly higher uptake of N in both years (Tables 5.5 and 5.6). However, orthogonal contrasts of the irrigation X placement or time of application interactions in 1983 revealed that there was no benefit of split application on uptake of N into wheat grain (Table 5.6) when the crop was under water stress and the initial portion of N was side-banded or applied two weeks after sowing.

Table 5.5. Effect of irrigation schedule and method of urea application on total uptake into the grain and straw and % Ndff in the grain of wheat in the 1982 experiment

Water	Method of application	Total uptake Grain	Total uptake Straw	Total uptake Total	%Ndff[@] Grain
		kg N ha^{-1}			
Weekly	Single	83.47	85.59	169.06	41.80
	2-split	105.71	82.87	188.58	17.94/17.50[#]
	3-split	109.22	107.49	216.61	9.12/12.90/16.56[+]
2-week	Single	67.39	66.20	133.59	41.21
	2-split	88.47	72.29	160.76	16.74/14.79
	3-split	89.34	70.06	159.40	9.67/13.84/15.72
3-week	Single	71.54	63.50	135.04	42.48
	2-split	77.43	67.77	145.20	15.72/16.37
	3-split	78.43	75.52	153.95	9.67/12.30/17.61
	Significance				
Irrigation		**			
Application		**			
Irrigation X application		*			

@ Average of six replicates
# 1st split/2nd split
+ 1st split/2nd split/3rd split
** and * Significant at $P<0.01$ and $P<0.05$, respectively

Table 5.6. Effect of irrigation schedule and method of urea application and placement on total uptake into the grain and straw and % Ndff in the grain of wheat in the 1983 experiment

Water	Method of application and placement	Total uptake			%Ndff@
		Grain	Straw	Total	Grain
		kg N ha^{-1}			
Weekly	B & I# - single	77.35	56.74	134.09	35.37
	B & I - split	115.45	66.36	181.81	7.57/21.98+
	Sideband - single	76.64	54.18	130.82	32.83
	Sideband - split	90.80	53.96	144.76	10.17/27.18
	Late - single	100.06	81.84	181.90	35.98
	Late - split	125.19	53.45	178.64	7.77/32.77
2-week	B & I - single	48.80	50.27	99.07	33.63
	B & I - split	86.81	46.36	133.17	5.70/21.57
	Sideband - single	67.75	35.84	103.59	29.72
	Sideband - split	59.20	40.12	99.32	7.65/22.49
	Late - single	45.78	34.87	80.65	33.58
	Late - split	54.34	39.26	93.60	9.36/29.26
3-week	B @ I - single	51.75	31.06	82.81	38.17
	B @ I - split	67.44	29.82	97.26	10.55/20.25
	Sideband - single	59.71	35.94	95.65	31.44
	Sideband - split	63.09	23.27	86.36	11.27/19.33
	Late - single	69.39	27.09	96.48	32.33
	Late - split	64.55	30.65	95.20	9.62/28.03

	Significance
Irrigation	**
Placement	**
Irrigation X Placement	*

@ Average of four replicates
# B & I = broadcast and incorporation
+ 1st split/2nd split
**, * Significant at $P<0.01$ and $P<0.05$, respectively

The % Ndff was similar for the two broadcasting placement methods independently of the water regimes in both years. Side-banding, however, of urea-N in 1983 resulted in slightly lower % Ndff values than either of the broadcasting methods. This is in agreement with average data by the International Atomic Energy Agency (1974) from a study carried out in fifteen different countries. They are, however, in sharp contrast to those reported for non-irrigated Canadian prairie soils (Carter and Rennie, 1984), where low water regimes resulted in "positional unavailability" of the broadcast fertilizer.

In spite of the similar % Ndff values at various water regimes for fertilizer N placement methods, percent utilization of N by wheat was significantly affected by irrigation schedules and the time and method of N application (Tables 5.7 and 5.8). Utilization of N by wheat grain was significantly higher under weekly than under every two or three week irrigation schedules in both years. There was a statistically significant main effect of split applications of urea-N on uptake of N into the grain but orthogonal contrasts of the noted interactions revealed that benefits from split applications on grain DM yields were significant only under the weekly irrigation schedule and with broadcast application under the every two week irrigation schedule.

In evaluating the irrigation schedules for these experiments, it was observed (Section 4) that class A pan evaporation rates were identical in both years of the experiment and differences in the mean yields between the two years of the experiment were attributed to different seeding times and water regimes. Hence, combination of the data from both years to

Table 5.7. Effect of irrigation schedule and method of urea application on fertilizer uptake and % utilization by wheat grain and straw in the 1982 experiment

Water	Method of application	Fertilizer uptake			Utilization	
		Grain	Straw	Total	Grain	Total
		kg N ha^{-1}			%	
Weekly	Single	34.85	15.49	50.34	23.23	33.56
	2-split	37.39	13.26	50.65	24.93	33.77
	3-split	42.00	17.09	59.09	28.00	39.39
2-week	Single	27.76	11.99	39.75	18.51	26.50
	2-split	27.78	11.56	39.34	18.52	26.23
	3-split	35.38	11.14	46.52	23.59	31.01
3-week	Single	30.39	11.49	41.88	20.26	27.92
	2-split	24.72	10.84	35.56	16.48	23.71
	3-split	31.13	12.00	43.13	20.75	28.75
		Significance				
Irrigation		**			**	
Application		**			**	
Irrigation X application		ns			*	

**, * Significant at $P<0.01$ and $P<0.05$, respectively

Table 5.8. Effect of irrigation schedule and method of urea application and placement on fertilizer uptake and % utilization by wheat grain and straw in the 1983 experiment

Water	Method of application and placement	Fertilizer uptake			Utilization	
		Grain	Straw	Total	Grain	Total
		kg N ha^{-1}			%	
Weekly	B & I@ - single	27.36	10.27	37.63	18.24	25.09
	B & I - split	36.00	10.62	46.62	24.00	31.08
	Sideband - single	25.16	9.81	34.97	16.77	23.31
	Sideband - split	35.59	8.63	44.22	23.73	29.48
	Late - single	36.00	14.81	50.81	24.00	33.88
	Late - split	54.66	8.55	63.21	36.44	42.14
2-week	B & I - single	16.41	9.10	25.21	10.94	17.01
	B & I - split	25.36	7.42	32.78	16.91	21.86
	Sideband - single	20.13	6.49	26.62	13.42	17.74
	Sideband - split	18.84	6.42	25.26	12.56	16.84
	Late - single	15.37	6.31	21.68	10.25	14.45
	Late - split	22.24	6.28	28.52	14.83	19.01
3-week	B & I - single	19.75	5.62	25.37	13.17	16.91
	B & I - split	21.29	4.77	26.06	14.19	17.37
	Sideband - single	19.56	6.50	26.06	13.04	17.38
	Sideband - split	19.63	3.72	23.35	13.09	15.57
	Late - single	22.43	4.90	27.33	14.95	18.22
	Late - split	25.65	4.90	30.55	17.10	20.37
		Significance				
Irrigation		**			**	
Placement		**			**	
Irrigation X Placement		*			*	

@ B & I = broadcast and incorporation
**, * Significant at P<0.01 and P<0.05, respectively

assess the effect of irrigation water and %Ndff on grain DM yields was considered valid. Only the data from the broadcast and incorporation treatments were utilized, since this application method was common in both years. The following regression model was used:

$$Z = a + bX + cY + dXY$$

where, Z = grain DM yield in Mg ha^{-1}, X = irrigation water in mm, Y = %Ndff values, and, a, b, c, d = coefficients.

A response surface was drawn for the irrigation (Section 4) and % Ndff (Tables 5.5 and 5.6) limits in this study (Fig. 5.1) and the following equation derived from the experimental data:

$$Z = -15.726 + 0.0665X + 0.3898Y - 0.00137XY \quad (R^2 = 0.96)$$

The response surface shows that, under the conditions of these experiments, grain DM yield was primarily a function of available water and was affected by %Ndff only at low water regimes. Increasing %Ndff at low water regimes resulted in increased grain DM yields but this increase did not compensate for yield loss due to restricted moisture.

5.4 Conclusions

Weekly irrigation of wheat at rates 70% of the total class A pan evaporation during the whole irrigation interval and throughout the growing season resulted in higher fertilizer N utilization and efficiency as measured by crop uptake and isotope dilution parameters compared to every two or every three week irrigation at 60 and 50% of class A pan evaporation during the whole irrigation interval, respectively. Maximum fertilizer N utilization and grain DM yields were obtained with weekly

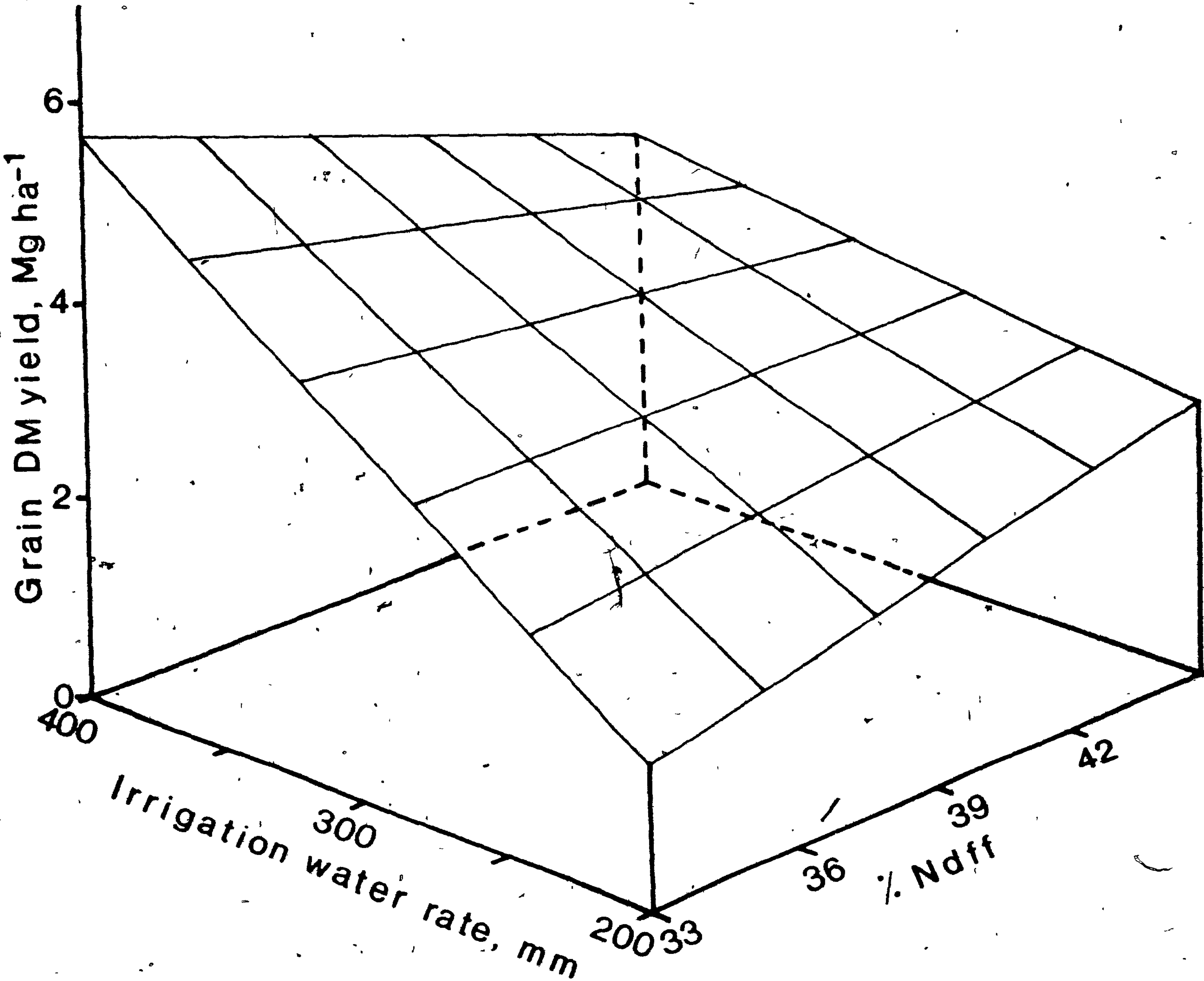

Figure 5.1 Effect of irrigation rate and %Ndff on the grain dry matter (DM) yield of wheat.

irrigation and split application of urea-N. Yield independent criteria (%Ndff) for any fertilizer placement method were independent of water regime, thus leading to the conclusion that N utilization was primarily a function of water availability.

6. NITROGEN FIXATION BY SOYBEANS (Glycine max L.) IN ZAMBIA

6.1 Introduction

Grain legumes are an important component in the agricultural cropping systems in Zambia, since they provide a significant protein source for both human and animal consumption. Soybeans (Glycine max L.) are being introduced as a cash crop to small scale producers who have only groundnut Arachis hypogea L.), beans (Phaseolus vulgaris L.), cowpeas (Vigna unguiculata L.) and bambara groundnut (Voanzeia subterranea L.) as legumes for rotation in their farming systems. The traditional legumes have agronomic limitations for expansion (Javaheri and Nkumbula, 1984). Soybeans, on the other hand, have a relatively good yield potential and also possess resistance to disease and insect attack. Little is known, however, about the nitrogen fixing capacity of different soybean cultivars adapted to Zambian conditions. Without an accurate measure of the N_2 fixing capacity in the field, no baseline exists to assess the present agronomic significance and impact of N_2 fixation.

Quantifying N_2 fixation by the isotope dilution method requires reference to a non-fixing control. This generally involves labelling the soil with ^{15}N (organically or inorganically) and calculating the amount of N_2 fixed by isotope dilution (Fried and Middleboe, 1977; Fried et al., 1983; Rennie, 1984). The ^{15}N concentration in the non-fixing plant provides an integrated measure of the isotopic composition of the soil and/or fertilizer derived nitrogen. The reference criteria for N_2 fixation studies have been extensively discussed by Fried et al. (1983), Rennie (1979; 1984; 1986) and Rennie and Rennie (1983).

The objectives of this study were to compare and select the most appropriate non-fixing control for estimating N_2 fixation by soybeans and assess yields and N_2 fixation for soybeans in Zambia.

6.2 Materials and Methods

Experiments to quantify N_2 fixation by soybeans in Zambia were conducted at the National Irrigation Research Station, Nanga, Zambia. These experiments were designed to evaluate the choice of non-fixing control plants to quantify N_2 fixation by ^{15}N dilution and the ability of three soybean cultivars to support symbiotic fixation by Bradyrhizobium japonicum.

The characteristics of the Typic Haplustalf soil on which the experiments were carried out have been described in Section 3.

Two methods of incorporating ^{15}N labelled materials were utilized, namely application ^{15}N-labelled organic material and application of ^{15}N-labelled inorganic fertilizer. The former method was utilized in choosing non-legume reference crops for estimating N_2 fixation by ^{15}N dilution and the latter in assessing nonnodulating soybean cultivars for their suitability to serve as reference crops for estimating N_2 fixation as well as in selecting soybean cultivars for their ability to fix N_2.

The experimental sites were pre-irrigated, then ploughed and disced to prepare a uniform seedbed. Macro and microelements were applied as a blanket application of 50 kg P ha^{-1} as triple super phosphate, 60 kg K ha^{-1} as K_2SO_4, 18 kg Mg ha^{-1} as $MgSO_4$, 0.08 kg Mo ha^{-1} as Mo_2O_3, 0.3 kg B ha^{-1} as Na_3BO_4 and 3 kg Zn ha^{-1} as $ZnSO_4$.

In the first experiment the plots were organically labelled with molasses as a carbon source and ^{15}N urea as the N source (Legg and Sloger, 1975). ^{15}N-labelled urea at 4.56 atom % ^{15}N excess was applied at a rate of 100 kg N ha^{-1}. The required amount of molasses for each replication was diluted in 7 litres of water as a 1:1 molasses:water mixture and uniformly sprayed on the surface of the soil. The molasses were applied in three separate applications at weekly intervals prior to seeding. The final C:N ratio was calculated to be 100:1. The plots received 14 mm of irrigation three times a week. Control plants included Finger millet (Eleusine corocana L.), Pearl millet (Panicum glaucum L.), Rhodesgrass (Chloris gayana L.) and a non-nodulating soybean cultivar (Glycine max cv. D68-0099) supplied by Dr. Carter, USDA, North Carolina. The nodulating soybean Glycine max cv. Magoye, a local cultivar, was inoculated with a mixture of B. japonicum strains MM48 and US110.

The experiment (control plants and sampling dates) was arranged in a completely randomized block design with four replications. The experimental plots were planted on 6 December 1983 at a seeding rate of 40 seeds m^{-1} row for soybeans. The grasses were planted at 10 kg ha^{-1}. Soybean seeds were inoculated with a liquid suspension of a mixture of US110 and MM48 B. japonicum strains to ensure 10^6 cells per seed.

The treatments of the second experiment are summarized in Table 6.1. The experiment was arranged in a completely randomized factorial design. In

Table 6.1. Components of the experiment for selection of nonnodulating soybean cultivars as reference crops by ^{15}N isotope diltution and of fixing cultivars for their ability to support N_2 fixation by *R. japonicum*

Cultivars	Inoculi	Fertilizer N rates
		kg N ha^{-1}
Nodulating		
Bossier	US110	20 and 100
Magoye	MM48	
Santa Rosa		
Nonnodulating		
Clark RJ1	US110	20 and 100
D68-0099	MM48	
N77		

each plot, one treatment of the fixing plant was inoculated with US110 while the other treatment of the same cultivar was inoculated with MM48 *B. japonicum* strain, a local isolate. Urea was applied at two levels, 20 kg N ha^{-1} at 4.56 atom % ^{15}N excess and 100 kg N ha^{-1} at 0.96 atom % ^{15}N excess. The soybeans were planted on 6 December 1983 at 40 seeds per meter row. Rows of nonnodulating cultivars were alternated with rows of nodulating cultivars in all cases.

Irrigation was applied to both experiments to ensure uniform emergence and (200 mm) during December and January dry spells to ensure good crop growth.

Plants were harvested at four different sampling dates (Table 6.2). On each sampling date, a composite sample from a 0.15 m section of each row (5 plants) of nodulating and corresponding non-nodulating varieties of soybeans was obtained. No attempt was made to collect abscised leaves and petioles. At harvest, one m^2 area from each plot was harvested to assess final dry matter yields. Straw, pods/hulls and seed plant parts were separated, oven dried at 60 °C to constant weight ground to pass a 425 um sieve and weighed. Total N content was determined using a modified semi-micro Kjeldahl procedure (Rennie and Paul, 1971). After analysis the distillate was acidified with 0.05 M H_2SO_4 and concentrated for ^{15}N assay on a NIO5 emission spectrometer using the lithium hypobromite oxidation procedure.

Nitrogen fixation estimates for all sampling dates were based on the total aboveground plant parts and were calculated using the isotope dilution formula (Rennie and Rennie, 1983):

Table 6.2. Growth stages of soybean (<u>Glycine max</u> L.) at which harvests were taken.

Harvest	Days after planting	Magoye	Non-nodulating cultivars Bossier and Santa Rosa
1	46	begining bloom	mid-bloom
2	69	mid-bloom	pod production
3	76	pod production	bean development
4	84	bean development	beans full size physiological maturity

$$\%Ndfa = \left(1 - \frac{\text{atom \% } ^{15}N \text{ excess}_{(fixing)}}{\text{atom \% } ^{15}N \text{ excess}_{(non\text{-}fixing)}}\right) X\ 100$$

and,

$$N_2 \text{ fixed} = \left(1 - \frac{\text{atom \% } ^{15}N \text{ excess}_{(fixing)}}{\text{atom \% } ^{15}N \text{ excess}_{(non\text{-}fixing)}}\right) X\ N \text{ yield}_{(fixing)}$$

Nitrogen derived from fertilizer (Ndff) was calculated from:

$$\%Ndff = \frac{\text{atom \% } ^{15}N \text{ excess}_{(plant)}}{\text{atom \% } ^{15}N \text{ excess}_{(fertilizer)}} X\ 100$$

The percent utilization of applied fertilizer N, i.e., the percent fertilizer use efficiency (%FUE) was calculated from:

$$\%FUE = \frac{\%Ndff\ X\ N \text{ yield } (kg\ N\ ha^{-1})}{N \text{ application rate } (kg\ N\ ha^{-1})} X\ 100$$

The 'A' value as an index of soil N availability to indicate the suitability of each non-fixing control was calculated from:

$$\text{'A' value} = \frac{\%Ndfs}{\%Ndff} X\ N \text{ application rate } (kg\ N\ ha^{-1})$$

where, Ndfs = 100 - (%Ndff + %Ndfa)

6.3 Results and Discussion

Dry matter (DM) and N yields of all crops grown on plots that received ^{15}N-labelled organic material are presented in Tables 6.3 and 6.4. The N yield of Finger millet and Rhodesgrass remained significantly lower than that of Magoye throughout the growing period (Table 6.4). The yield of the nonnodulating cultivar became significantly lower than Magoye 69 days after planting (DAP) and remained as such thereafter. In contrast, N yield of Pearl millet was equal or significantly higher than the nodulating cultivar throughout the growing period. Nitrogen uptake of all reference crops peaked at 76 DAP, while that of the nodulating cultivar was still increasing at 84 DAP.

In choosing the appropriate reference crop the following factors (Fried et al., 1983) were considered:

a. Absence of N_2-fixing activity. Inspection of the fixing crop revealed massive nodulation, while there were no nodules on the nonnodulating cultivar.

b. Relative feeding pattern of standard and fixing crop. Although the reference and the N_2-fixing crops do not have to absorb the same quantity of total N, both should absorb similar ratios of available N from soil and fertilizer (Fried et al., 1983). Of the three non-legume reference crops, only Pearl millet consistently fulfilled this requirement (Table 6.5).

c. Time of growth of reference and fixing crop. The "A" values of the soil as determined using the nonnodulating cultivar increased sharply with time (Table 6.6). It is apparent that Finger millet and Rhodesgrass were

Table 6.3. Dry matter yields of soybeans and non-nodulating control plants at the four harvest times

Crop	Harvest 1	Harvest 2	Harvest 3			Harvest 4		
	Whole plant	Whole plant	Straw	Pods/ hulls	Seed	Straw	Pods/ hulls	Seed
	g 5 plants^{-1}							
Magoye	32.4a^{+}	79.3b	77.7b	2.1b	--	86.6b	17.1a	--
Non-nodulating	27.7a	30.9c	28.6c	10.1a	16.1	16.5c	11.1a	12.4
Finger millet	4.6c	6.4c	11.8d	--	--	3.4d	--	--
Pearl millet	15.2b	160.9a	197.8a	--	--	284.8a	--	--
Rhodesgrass	7.5bc	18.2c	16.3d	--	--	17.8c	--	--

$^{+}$ Mean values followed by the same letter in same column are not significantly different at $P<0.05$.

Table 6.4. Nitrogen yields of soybeans and non-nodulating control plants at the four harvest times

Crop	Harvest 1	Harvest 2	Harvest 3			Harvest 4		
	Whole plant	Whole plant	Straw	Pods/ hulls	Seed	Straw	Pods/ hulls	Seed
	g 5 plants^{-1}							
Magoye	0.53a[+]	0.79b	1.39b	0.06b	--	1.48b	0.42a	--
Non-nodulating	0.37a	0.45c	0.29c	0.13a	0.61	0.14c	0.13b	0.50
Finger millet	0.07b	0.08c	0.19cd	--	--	0.04c	--	--
Pearl millet	0.44a	1.96a	2.75a	--	--	3.32a	--	--
Rhodesgrass	0.11b	0.18c	0.23d	--	--	0.36c	--	--

+ Mean values followed by the same letter in same column are not significantly different at $P<0.05$.

Table 6.5. Atom % ^{15}N excess in soybeans and non-nodulating control plants at the four harvest times

Crop	Harvest 1	Harvest 2	Harvest 3			Harvest 4		
	Whole plant	Whole plant	Straw	Pods/ hulls	Seed	Straw	Pods/ hulls	Seed
Magoye	0.39c+	0.21d	0.20b	0.22b	--	0.19c	0.18b	--
Non-nodulating	0.76a	0.45bc	0.53a	0.44a	0.51	0.41a	0.45a	0.48
Finger millet	0.55b	0.50b	0.36b	--	--	0.36b	--	--
Pearl millet	0.71a	0.58a	0.51a	--	--	0.49a	--	--
Rhodesgrass	0.57b	0.43c	0.34a	--	--	0.31b	--	--

\+ Mean values followed by the same letter in same column are not significantly different at $P<0.05$.

Table 6.6. Comparison of possible non-legume crops as reference for estimating N_2 fixation by ^{15}N isotope dilution

Crop	Ndff	Ndfa	"A" value
	——— % ———		kg N ha^{-1}
<u>Harvest 1</u>			
Magoye	8.6	48.9+	494
Finger millet	12.1	-	726
Pearl millet	15.6	-	541
Rhodesgrass	12.5	-	700
<u>Harvest 2</u>			
Magoye	4.6	52.3	936
Finger millet	12.5	-	700
Pearl millet	11.0	-	809
Rhodesgrass	9.4	-	964
<u>Harvest 3</u>			
Magoye	4.4	58.2	808
Finger millet	7.9	-	1166
Pearl millet	11.1	-	801
Rhodesgrass	7.5	-	1233
<u>Harvest 4</u>			
Magoye	4.2	59.6	888
Finger millet	7.9	-	1166
Pearl millet	10.7	-	83[illegible]
Rhodesgrass	6.8	-	1371

+ Nonnodulating D68-0099 cultivar used as a reference crop.

exploring different soil volumes compared to the fixing cultivar and Pearl millet, both of which apparently were exploring similar soil volumes. To calculate data in Table 6.6, the assumption was made that the nodulating and nonnodulating cultivars had similar growth patterns. This apparently was not the case, since the nonnodulating cultivar was progressing through growth stages at a faster pace than the nodulating one (Table 6.2). Further, the N uptake patterns of all crops over the sampling intervals (Fig. 6.1) would suggest that Pearl millet was more suitable as a reference crop in these experiments.

The nonnodulating cultivar and Pearl millet yielded higher estimates of symbiotic N_2 fixation throughout the growing period with an exception at harvest 2 (Table 6.7). The %Ndfa had increased by the second sampling (69 DAP) and remained relatively constant for the nonnodulating cultivar and Pearl millet but declined for Finger millet and Rhodesgrass (Table 6.7).

Only the data for the first and fourth harvests are reported for the second experiment. No significant differences for any measured parameter due to inoculation of nonnodulating soybean cultivars with B. japonicum US110 or MM48 strains were obtained, hence the average values for the two inocula are presented (Tables 6.8, 6.9 and 6.10). At anthesis, atom % ^{15}N excess and %Ndff of the nonnodulating soybean cultivars were statistically the same for all cultivars but were significantly affected by N application rate (Table 6.8). At maturity, although atom % ^{15}N excess in various plant parts of nonnodulating cultivars was significantly affected by cultivar and N rate, % Ndff values were significantly affected by N rate only (Table 6.10). Therefore, at this growth stage all nonnodulating cultivars exhibited more or less similar characteristics.

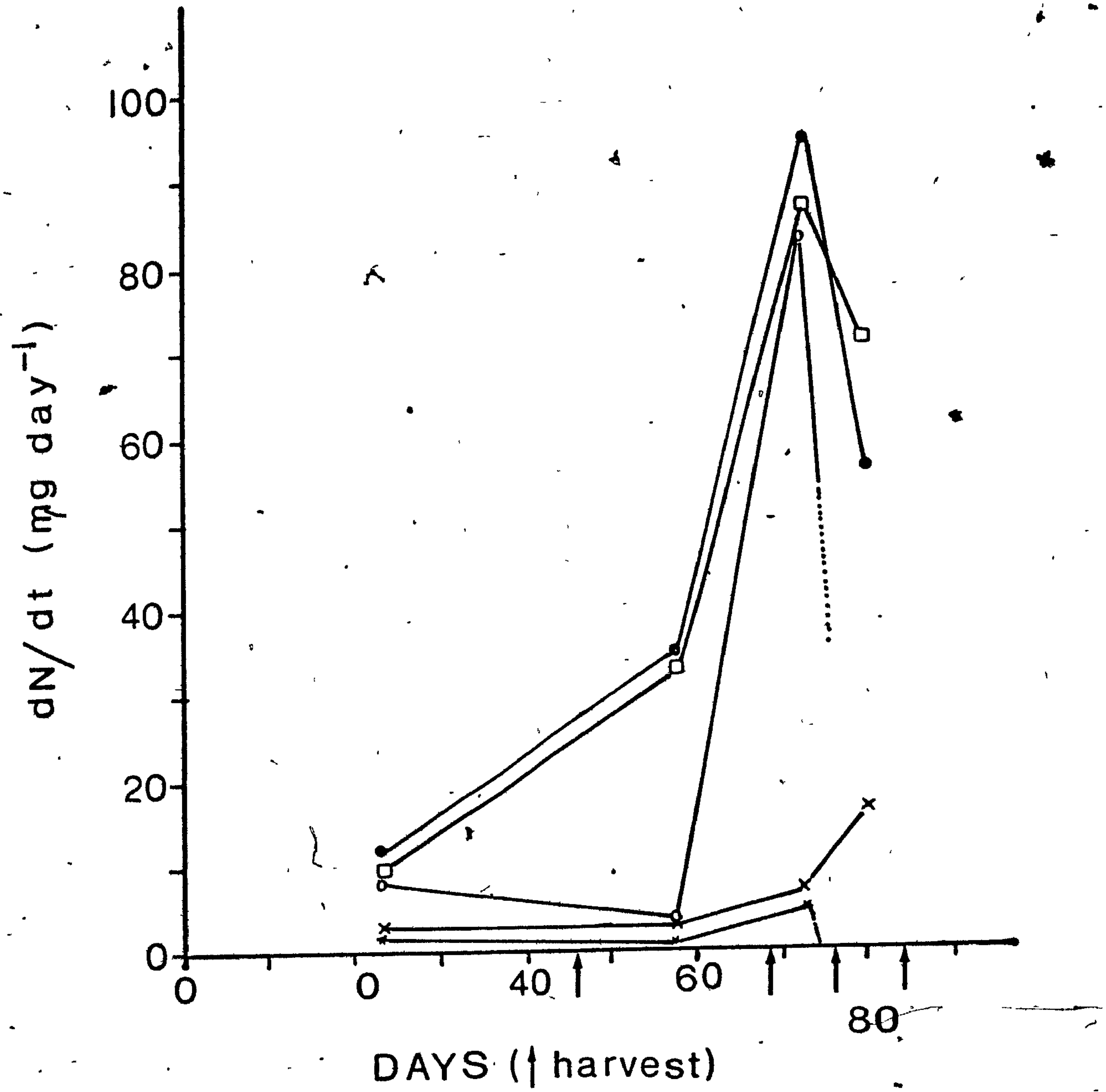

Figure 6.1 Changes in Nitrogen uptake by Glycine max cv. Magoye ( ) and D68009 (o) and non-fixing reference crops (*Eleuisine corocana L., Panicum glaucum L., and x Chloris gayana L.) between sampling intervals during the growing season.

Table 6.7. Percent Ndfa in soybeans estimated from various control plants at the four harvest times

Control	Harvest 1	Harvest 2	Harvest 3#	Harvest 4#
Non-nodulating	48.9a+	52.3b	58.2a	59.6a
Finger millet	45.4a	62.7a	44.3b	40.9b
Pearl millet	29.5b	56.9a	57.2a	60.7a
Rhodesgrass	31.9b	49.5b	41.3b	38.7b

\# Weighted values for all plant parts.

\+ Mean values followed by the same letter in same column are not significantly different at $P<0.05$.

Table 6.8. Dry matter and nitrogen yield and N isotope characteristics of non-nodulating soybean cultivars at 46 days after planting

Cultivar	Nitrogen rate	Dry matter yield	Nitrogen yield	Atom % ^{15}N excess	Ndff	Fertilizer use efficiency
	$kg\ ha^{-1}$	$Mg\ ha^{-1}$	$kg\ ha^{-1}$		%	
RJ1	20	2.15	40	0.58	12.7	25.4
	100	3.11	64	0.44	45.6	29.1
D68	20	3.48	54	0.56	12.2	33.1
	100	3.30	73	0.44	46.5	37.8
N77	20	3.28	59	0.54	11.9	35.1
	100	2.82	45	0.43	44.5	20.0
			Significance			
Cultivar		**	*	ns	ns	**
N rate		*	**	**	***	**
Cultivar X N rate		**	***	ns	ns	***

***, **, * and ns = Significant at $P<0.001$, $P<0.01$, $P<0.05$ and not significant, respectively.

Table 6.9. Dry matter and nitrogen yield of non-nodulating soybean cultivars 84 days after planting

Cultivar	Nitrogen rate	Dry matter				Nitrogen			
		Straw	Pods	Seed	Total	Straw	Pods	Seed	Total
	kg ha^{-1}	Mg ha^{-1}				kg ha^{-1}			
RJ1	20	1.2	0.6	1.7	3.5	5	4	53	62
	100	4.6	1.3	1.5	7.4	32	9	52	94
D68	20	2.2	1.3	2.1	5.1	19	7	74	100
	100	1.9	1.0	2.5	5.4	16	10	87	113
N77	20	2.0	0.7	2.1	4.8	12	5	60	77
	100	4.2	1.2	3.3	8.7	31	9	100	139
		Significance							
Cultivar		*	ns	**	**	*	**	**	**
N rate		**	*	**	**	**	**	*	**
Cultivar X N rate		**	*	*	***	**	ns	**	ns

***, **, * and ns = Significant at P<0.001, P<0.01, P<0.05 and not significant, respectively.

Table 6.10. Nitrogen isotope characteristics of non-nodulating soybean cultivars 84 days after planting

Cultivar	Nitrogen rate	Atom % ^{15}N excess			Ndff	Fertilizer use efficiency
		Straw	Pods	Seed		
	kg ha^{-1}				%	%
RJ1	20	0.33	0.48	0.56	12.3	68.0
	100	0.31	0.41	0.52	45.0	47.9
D68	20	0.44	0.36	0.39	8.7	43.6
	100	0.39	0.27	0.47	45.9	51.9
N77	20	0.30	0.53	0.55	11.1	43.0
	100	0.22	0.46	0.39	37.0	51.4
			Significance			
Cultivar		*	**	*	ns	*
N rate		*	*	**	***	**
Cultivar X N rate		**	ns	*	ns	**

***, **, * and ns = Significant at P<0.001, P<0.01, P<0.05 and not significant, respectively.

The type of inoculum had no significant effect on any of the plant parameters determined for nodulating cultivars at anthesis except N yield (Table 6.11). Dry matter and N yields at this stage were statistically the same for all cultivars but N yields were significantly affected by N application rate. With the exception of Bossier, application of 100 kg N ha^{-1} actually resulted in lower N yields. Calculation of % Ndfa values using either of the three nonnodulating cultivars as a reference crop showed that N_2 fixation was for the most part inhibited at this high N application rate. Further, use of any of the three nonnodulating cultivars as a reference crop resulted in similar %Ndfa estimates, except at 100 kg N ha^{-1} application rate, at which D68-0099 led to higher estimates for Bossier and Magoye. Since active fixation was taking place only at 20 kg N ha^{-1} application rate and because all three nonnodulating cultivars were exploring similar soil volumes (Table 6.12) any of them would be a suitable reference crop at anthesis. Of the three fixing soybean cultivars Magoye yielded the highest %Nfda values (40-50%) at this growth stage (Table 6.11).

Contrary to anthesis, the DM yields of the three cultivars were statistically different 84 DAP (Table 6.13). Magoye yielded the highest total DM yield but no seeds had been formed at sampling time. However, DM yields of this cultivar taken at a later date and at full maturity were in the order of 3.7 Mg seed ha^{-1}. The type of inoculum continued to have no effect on DM yields through to this stage but significantly affected N yields. Total DM yields were, except in one case, statistically lower with 100 kg N ha^{-1} application rates, thus suggesting that DM yield benefits from

Table 6.11. Comparison of soybean cultivars at 46 days after planting for their ability to support symbiotic N_2 fixation at Nanga, Zambia

Cultivar	Inoculum	Nitrogen rate	Dry matter yield	Nitrogen yield	Atom % ^{15}N excess	Ndff	Fertilizer use	Ndfa		
								RJ1	D68	N77
		$kg\ ha^{-1}$	$Mg\ ha^{-1}$	$kg\ ha^{-1}$	%					
Bossier	US110	20	3.37	62	0.47	10.3	32.0	18.6	15.3	13.4
		100	5.14	82	0.40	41.4	34.2	9.1	20.5	7.0
	MM48	20	4.66	80	0.38	8.3	33.2	34.6	32.0	30.4
		100	5.31	113	0.53	55.0	61.8	-20.6	-5.5	-23.4
Magoye	US110	20	4.53	99	0.34	7.4	36.4	42.0	39.6	38.2
		100	4.36	82	0.39	40.6	33.1	10.9	22.0	8.8
	MM48	20	4.95	131	0.26	5.7	37.2	41.1	48.5	39.8
		100	3.18	69	0.48	50.0	34.5	16.9	13.5	11.5
Santa Rosa	US110	20	4.95	113	0.35	7.7	43.4	21.1	31.0	19.3
		100	4.05	79	0.58	60.4	47.7	-0.9	-5.0	-7.4
	MM48	20	4.26	104	0.36	7.9	41.0	18.3	28.5	16.4
		100	4.72	98	0.51	53.1	52.0	11.3	7.7	5.5
					Significance					
Cultivar			ns	ns	***	***	-	***	***	***
Inoculum			ns	*	ns	ns	-	ns	ns	ns
N rate			**	***	***	***	-	*	*	ns
Cultivar X inoculum			ns	ns	ns	***	-	ns	ns	ns
Cultivar X N rate			ns	ns	***	***	-	***	***	***
Inoculum X N rate			ns	*	ns	ns	-	ns	ns	ns
Cultivar X inoculum X N rate			*	**	***	***	-	***	***	***

***, **, * and ns = Significant at $P<0.001$, $P<0.01$, $P<0.05$ and not significant, respectively.

Table 6.12. 'A'-values for nodulating cultivars of soybean calculated on the basis of the non-nodulating cultivars at 46 days after planting

Non-nodulating cultivar	Fertilizer rate	'A'-values
	kg N ha^{-1}	
RJ1	20	138
D68	20	144
N77	20	148

Table 6.13. Dry matter and nitrogen yield of nodulating soybean cultivars 84 days after planting

Cultivar	Inoculum	Nitrogen rate	Dry matter				Nitrogen			
			Straw	Pods	Seed	Total	Straw	Pods	Seed	Total
		$kg\ ha^{-1}$	$Mg\ ha^{-1}$				$kg\ ha^{-1}$			
Bossier	US110	20	7.0	1.7	3.5	12.1	53	13	116	182
		100	6.4	1.8	3.3	11.5	62	18	107	187
	MM48	20	6.6	1.4	3.4	11.4	44	12	117	174
		100	4.6	0.9	1.7	7.2	67	18	63	148
Magoye	US110	20	10.8	1.6	-	12.4	193	13	-	206
		100	9.8	1.9	-	11.7	192	44	-	236
	MM48	20	15.4	1.6	-	17.0	289	41	-	330
		100	10.7	1.2	-	11.9	170	22	-	192
Santa Rosa	US110	20	9.3	1.4	1.1	11.8	78	16	41	136
		100	4.3	1.0	1.3	6.7	49	16	49	114
	MM48	20	4.7	1.1	0.7	6.4	77	16	26	117
		100	8.5	1.2	1.8	11.5	133	21	71	225
Significance										
Cultivar						***				***
Inoculum						ns				*
N rate						***				ns
Cultivar X inoculum						***				**
Cultivar X N rate						*				***
Inoculum X N rate						ns				ns
Cultivar X inoculum X N rate						***				***

***, **, * and ns = Significant at P<0.001, P<0.01, P<0.05 and not significant, respectively.

N_2 fixation were not, for the most part, compensated by this N application rate in spite of similar N yields (Table 6.13).

Estimates of %Nfda using Clark RJ1 and N77 as reference at 20 kg N ha^{-1} crops were similar and considerably higher than those arrived at using D68-0099 as a reference (Table 6.14). This reflects differences in maturity dates as D68-0099 is an early maturing cultivar and had reached senescence at this sampling time. This is also reflected in the "A" values for the three nonnodulating cultivars at 84 DAP; whereas those for the two former cultivars were similar to each other and had not considerably changed since 46 DAP, that of the latter had considerably increased (Tables 6.12 and 6.15). On the basis of %Ndfa and fertilizer use efficiency values at 84 DAP, Magoye was by far superior to Bossier and Santa Rosa in supporting N_2 fixation by B. japonicum. When this cultivar was inoculated with B. japonicum MM48 strain yielded the highest amount of N_2 fixed at 225 kg N ha^{-1}.

6.4 Conclusions

Nonnodulating soybean (Glycine max) cultivars Clark RJ1 and N77 or in their absence Pearl millet (Panicum glaucum L.) appear to be the best reference crops for estimating N_2 fixation using the ^{15}N isotope dilution technique in Zambia. A local soybean fixing cultivar (Glycine max L. cv. Magoye) rated highest among three cultivars tested for its ability to support symbiotic N_2 fixation under the experimental conditions.

Table 6.14. Comparison of soybean cultivars for their ability to support symbiotic N_2 fixation 84 days after seeding

Cultivar	Inoculum	Nitrogen rate	Atom % ^{15}N excess			Ndfa			Ndff	Fertilizer use efficiency
			Straw	Pods	Seed	RJ1	N77	D68		
		kg ha^{-1}				%				
Bossier	US110	20	0.22	0.37	0.54	18.7	15.4	-8.7	9.5	86.5
		100	0.33	0.38	0.38	18.1	-0.1	18.3	37.3	69.8
	MM48	20	0.13	0.40	0.34	45.3	43.1	26.9	6.6	57.4
		100	0.43	0.44	0.42	2.4	-19.3	2.7	44.7	66.2
Magoye	US110	20	0.16	0.19	--	69.7	68.5	59.5	3.6	37.1
		100	0.25	0.25	--	43.5	31.0	43.7	25.7	60.7
	MM48	20	0.15	0.32	--	68.8	67.6	58.4	3.7	61.1
		100	0.24	0.37	--	42.8	30.1	43.0	26.1	50.1
Santa Rosa	US110	20	0.22	0.37	0.40	45.3	43.1	26.9	6.4	43.5
		100	0.22	0.44	0.33	32.2	17.1	32.4	30.9	35.2
	MM48	20	0.20	0.36	0.36	51.5	49.6	35.3	5.7	33.3
		100	0.32	0.37	0.29	27.8	11.7	28.0	32.9	74.0
Significance										
Cultivar			***	***	***	***	***	***		
Inoculum			ns	***	***	ns	**	ns		
N rate			***	**	***	***	**	***		
Cultivar X inoculum			ns	ns	***	ns	**	ns		
Cultivar X N rate			***	ns	***	***	***	ns		
Inoculum X N rate			***	ns	***	ns	***	***		
Cultivar X inoculum X N rate			***	ns	***	***	***	***		

***, **, * and ns = Significant at P<0.001, P<0.01, P<0.05 and not significant, respectively.

Table 6.15. 'A'-values for nodulating cultivars of soybean calculated on the basis of the non-nodulating cultivars at 84 days after planting

Non-nodulating cultivar	Fertilizer rate	'A'-values
	kg N ha^{-1}	
RJ1	20	151
D68	20	207
N77	20	157

7. WHEAT YIELDS IN MAIZE-WHEAT AND SOYBEAN-WHEAT ROTATIONS

7.1 Introduction

Grain legumes play an important role in agricultural systems since they provide a significant source of protein for both human and animal consumption. In addition, they provide an inexpensive source of fixed N for the crop itself as well as for subsequent crops in crop rotations. This is of importance to developing countries since the fertilizer N costs are increasing and consequently the fertilizer supply to farmers is being reduced. Thus, biological N fixation is a viable alternative for these countries, where escalating energy costs render the use of synthetic N products prohibitive.

Legumes are known to increase soil N levels (National Academy of Science, 1979; Ladd et al., 1981; Reddy et al., 1986). Consequently they improve the productivity of subsequent cereal crops (Singh and Awasthi, 1978). Legume materials contribute only a small portion of the available N pool. Their main value appears to be long term, i.e., in their capacity to maintain or increase concentrations of soil organic N to be decomposed at relatively slow rates in the following years (Ladd et al., 1981).

Section 6 dealt with establishing a baseline for N_2-fixation of soybean cultivars adapted to Zambian conditions. This Section will examine the agronomic significance and impact of N_2-fixation when soybeans are included in rotations.

The objectives of this study were to evaluate (i) amounts of N fixed by two soybean (Glycine max L.) cultivars at two levels of P in the first crop season of a rotation, and (ii) the residual effect of applied N and P fertilizers or biologically fixed N_2 on wheat growth in a soybean-wheat (*Triticum aestivum* L.) and a maize (*Zea mays* L.)-wheat rotation.

7.2 Materials and Methods

A two crop season experiment was carried out at the National Irrigation Research Station, Nanga, Zambia. The characteristics of the Haplustalf soil at the site have been described in Section 3.

Maize (*Zea mays* L. cv. MM502) and three cultivars of soybeans (*Glycine max* L.) were planted on 23 December, 1983. Maize was planted at 25 cm stations with an interrow spacing of 80 cm. The legume cultivars (Bossier, Magoye and Chappewa) were planted at 15 cm spacings with an interrow spacing of 40 cm. A liquid suspension of *Bradyrhizobium japonicum* inoculum strain US110 was applied over the seeds to ensure 10^6 cells per seed and covered immediately. Irrigation was applied to ensure uniform emergence and during January-February dry spells for maximum crop growth.

The experiment in the first year of the rotation was arranged in a completely randomized block design with six replications. The yield plot for the fixing legume cultivars was 6 m X 4.8 m. The isotope subplot for the fixing (Bossier and Magoye) and non-fixing (Chappewa) cultivars was 2.4 m X 2.4 m. The yield plot for the cereal (Maize) was 8.4 m X 4.8 m.

Micronutrients were applied as a blanket application of 80 g Mo_2O_3, 80 g $CuSO_4$ and 8 kg $ZnSO_4$ ha^{-1}. All plots received 70 kg K and 27 kg S ha^{-1}, respectively as K_2SO_4. Chappewa started flowering 30 days after emergence. This necessitated taking sequential harvests of tissue samples from rows instead of plots in the ^{15}N subplots. The first harvest was 42 days and the second 72 days after planting. Harvest of soybeans for grain was taken on 18 April, 1984. Maize straw and grain was harvested on 24 April, 1984.

In the second crop season, wheat (Triticum aestivum L. cv. EMU's') was planted on 5 May, 1984. The wheat was drilled at 20 cm interrow spacing. Pre-irrigation was applied seven days prior to seeding to establish a homogeneous moisture profile. A weekly irrigation at 70 % of total class A pan evaporation during the whole irrigation interval was applied. The experiment was a completely randomized block design with six replications. The yield subplot for the wheat was 6 m X 4.8 m. The rotations and the N and P fertilizer program involved are summarized in Table 7.1. Macro- and micronutrients were applied at the same rates as for the first crop of the rotation. Wheat straw and grain were harvested on 5 September, 1984.

All plant tissue samples were dried at 65 °C and ground in a Wiley mill to pass 425 um sieve. Analysis for total N was carried out using a modified semi-micro Kjeldahl procedure (Rennie and Paul, 1971). ^{15}N assay was carried out in a 602E Micromass mass spectrometer. Total P was determined by the vanadomolybdophosphoric acid method (Olsen and Sommers, 1982). ^{32}P was first concentrated as magnesium ammonium phosphate [$Mg(NH_4)PO_4.6H_2O$] and counting was carried out in a Geiger Muller counting system. Isotopic parameters were calculated by the methods described by Rennie and Paul (1971).

Table 7.1. Fertilizer P and N treatments of two season rotations in Zambia

First season crop followed by *Triticum aestivum* L. cv. EMU's'	First season Nitrogen	First season Phosphorus	Second season Nitrogen	Second season Phosphorus
	kg ha^{-1}			
Glycine max L. cv. Bossier	20⁺	0	60	30⁺⁺
	20	30	60	30
Glycine max L. cv. Magoye	20	0	60	30
	20	30	60	30
Zea mays L. cv. MM502	20	0	60	30
	20	30	60	30
	60	0	60	30
	60	30	60	30

+ All nitrogen treatments in first season were ^{15}N-labelled with 4.56 atom % ^{15}N excess.

++ All P treatments in second season were ^{32}P-labelled .

7.3 Results and Discussion

No significant differences in the total amount of dry matter (DM) yields between the two fixing soybean cultivars were obtained at 42 days after planting (Table 7.2). There was a significant interaction of both cultivars and P on atom % ^{15}N and %Ndff, the latter owing to a significant reduction in %Ndff value for Magoye. Maximum N_2 fixation at this sampling was attained by Magoye (Table 7.2).

At 72 days after planting there was still no significant difference in straw DM yield between the two fixing cultivars (Table 7.3). Bossier being an earlier maturing cultivar (100 days to maturity) than Magoye (125 days to maturity) had set seed, while the latter was at pod set. This is reflected in the total DM yield for Bossier (Table 3). The total N yield, however, was statistically the same reflecting higher N concentrations in the Magoye straw. Both fixing cultivars responded to P application (Table 7.3).

Atom % ^{15}N excess of Magoye was significantly lower than that of Bossier (Table 7.4). Estimates of N_2 fixation using Chappewa as a reference crop suggested that Magoye was superior in its ability to support N_2 fixation by B. japonicum (Table 7.4), which is consistent with the results of Section 6. Up to 50% of N was derived from fixation. There was no significant effect of P on ^{15}N enrichment of both cultivars (Table 7.4).

The 'A' values for both fixing (Bossier and Magoye) and the non-fixing (Chappewa) soybean cultivars were similar (Table 7.5). The cultivars were exploring similar soil volumes and by implication took N of

Table 7.2. Comparison of soybean cultivars for their ability to support symbiotic N_2 fixation by <u>B</u>. <u>Japonicum</u> at 42 days after planting

Cultivar	P rate	Yield: Dry matter	Yield: Nitrogen	Atom % ^{15}N excess	Ndfa[1]	Ndff
		g 5plants^{-1}	mg 5plants^{-1}		%	%
Bossier	0	3.29	82.4	0.4211	15.1	9.2
	30	3.56	78.5	0.4240	16.6	9.3
Magoye	0	2.92	69.9	0.3246	34.6	7.1
	30	3.22	84.1	0.4827	5.0	10.6
				Significance		
Cultivar		ns	ns	ns	ns	ns
Phosphorus		ns	ns	**	***	**
Cultivar X P		ns	ns	***	***	**

1 nonnodulating cultivar Chappewa used as a reference crop.
***, **, * and ns = Significant at P<0.001, P<0.01, P<0.05 and not significant, respectively.

Table 7.3. Dry matter and nitrogen yield of soybean cultivars 72 days after planting

Cultivar	P rate	Dry matter yield				Nitrogen yield (total)
		Straw	Pods	Seeds	Total	
	kg ha^{-1}		Mg ha^{-1}			kg ha^{-1}
Bossier	0	4.5	1.3	0.4	6.2	87.6
	30	4.9	1.2	0.6	6.7	98.2
Magoye	0	4.3	0.1	-	4.4	76.4
	30	6.1	0.1	-	6.5	94.5
				Significance		
Cultivar		ns	***	-		ns
Phosphorus		**	ns	**		*
Cultivar X P		ns	ns	-		ns

***, **, * and ns = Significant at $P<0.001$, $P<0.01$, $P<0.05$ and not significant, respectively.

Table 7.4. Comparison of soybean cultivars for their ability to support N_2 fixation by *B. japonicum* 72 days after planting

Cultivar	P rate	Atom % ^{15}N excess	% Ndff	%Ndfa[1]
	kg ha^{-1}			
Bossier	0	0.3088	6.8	36.7
	30	0.2982	6.5	39.0
Magoye	0	0.2393	5.2	50.9
	30	0.2647	5.8	45.9
		Significance		
Cultivar		***	ns	***
Phosphorus		ns	ns	ns
Cultivar X P		ns	ns	ns

1 Nonnodulating cultivar Chappewa used as a reference crop
*** and ns = Significant at $P<0.001$ and not significant at $P<0.05$.

Table 7.5. 'A' values for nonnodulating and nodulating soybean cultivars

Cultivar	P rate	Ndff	"A" value
	kg ha^{-1}	%	kg N ha^{-1}
Chappewa	0	10.7	167
	30	10.7	166
Bossier	0	6.8	162
	30	6.5	166
Magoye	0	5.3	167
	30	5.8	167

the same isotopic ratio, therefore, Chappewa was considered an appropriate reference crop (Fried et al., 1983).

At final harvest at maturity, Magoye produced significantly higher grain DM yield than Bossier and Chappewa (Table 7.6), which is consistent with the findings in Section 6. The level of P did not significantly influence the final grain DM yield for all cultivars (Table 7.6). Although Chappewa flowered much earlier than Bossier and Magoye, it appears to have the same yield potential as Bossier (Table 7.6).

Maize responded to P application (Table 7.7), the maximum DM seed yield being obtained with 30 kg P ha^{-1} at 60 kg N ha^{-1} (Table 7.7). Similar yield increases have been reported by Safaya (1976). Stover yields followed the same trend.
The maize cultivar used (MM 502) is an early maturing, drought tolerant hybrid, recently released. This study has shown its potential in achieving high yields at low levels of N (20 kg ha^{-1}). The standard maize hybrid SR 52 is a late maturing one (175 days to maturity) and requires a higher N input level. The response of MM 502 to P means that P fertilizers have to be applied to obtain high yields.

In the second crop season, the levels of P and N fertilizers applied to the wheat grown on various treatments from the first season were identical (Table 7.1). Hence, any differences in the DM yield could be attributed to the previous crop and fertilizer history. The highest wheat DM yield was obtained when the previous crop was the fixing legume Bossier (Table 7.8). DM yields were lower when wheat was preceded by maize, especially where no fertilizer was applied. Similar results were obtained

Table 7.6. Grain DM yields of soybean cultivars

Cultivar	P rate	DM yield
	$kg\ ha^{-1}$	$Mg\ ha^{-1}$
Bossier	0	2.48
	30	2.51
Magoye	0	3.53
	30	3.71
Chappewa	0	2.71
	30	2.28

Significance of contrasts

		Bossier 0	Bossier 30	Magoye 0	Magoye 30	Chappewa 0	Chappewa 30
Bossier	0	-	ns	**	**	ns	ns
	30		-	**	**	ns	ns
Magoye	0			-	ns	**	**
	30				-	**	**
Chappewa	0					-	ns
	30						-

Table 7.7. Dry matter yields of maize in first season of the rotation.

P rate	N rate	Dry matter yield: Stover	Dry matter yield: Grain
kg ha^{-1}		Mg ha^{-1}	
0	20	6.23b[1]	4.09
	60	5.21b	3.62
30	20	5.43b	4.05
	60	9.52a	5.43

Significance of contrasts

P	N	Stover P 0, N 20	Stover P 0, N 60	Stover P 30, N 20	Stover P 30, N 60	Grain P 0, N 20	Grain P 0, N 60	Grain P 30, N 20	Grain P 30, N 60
0	20	-	ns	ns	**	-	ns	ns	**
	60		-	ns	**		-	ns	**
30	20			-	**			-	**
	60				-				-

Table 7.8. Wheat grain DM yields in the second season of the rotation

Crop in first season	Fertilizer program: First season P rate	First season N rate	Second season P rate	Second season N rate	Grain DM yield
	kg ha^{-1}				Mg ha^{-1}
Bossier	0	20	30	60	4.18
	30	20	30	60	4.32
Magoye	0	20	30	60	3.43
	30	20	30	60	3.73
Maize	0	20	30	60	3.01
		60	30	60	2.79
	30	20	30	60	3.12
		60	30	60	3.19

Significance of contrasts

			Bossier 0	Bossier 30	Magoye 0	Magoye 30	Maize 0 20	Maize 0 60	Maize 30 20	Maize 30 60
Bossier		0	-	ns	*	*	**	**	**	**
		30		-	**	*	**	**	**	**
Magoye		0			-	ns	ns	**	ns	ns
		30				-	ns	**	ns	ns
Maize	0	20					-	ns	ns	ns
		60						-	ns	ns
	30	20							-	ns
		60								-

by Reddy et al. (1986) and Singh and Awasthi (1978) for rye, maize and wheat, which produced higher yields following tropical legumes than cereals.

Application of P fertilizer to crops in the first year of the rotation had no significant effect on wheat grain DM yields. Further, the type of crop in the first year of the rotation (legume or cereal) or P application rate did not significantly affect the P levels in wheat grain (Table 7.9). A mean value of 0.2 % P in wheat straw showed a sufficient amount of P for wheat growth (Ozanne, 1980). Percent P derived from fertilizer (%Pdff) values ranged from 8.8 to 20.5 %. Plants rarely recover more than 20% of the applied P in a single season (Black, 1968; Stewart et al., 1983). The %Pdff was higher when wheat was preceded by the legume cultivar Bossier that had not received P fertilization (Tables 7.9 and 7.10). Phosphorus application to Bossier and maize (20 kg N ha^{-1}) in the first season of the rotation led to significantly lower %Pdff values of freshly applied P to the subsequent wheat crop compared to treatments where no P was applied in the first season of the rotation. The contribution of previously applied P may be inferred from the fertilizer P uptake by wheat grown subsequent to the corresponding treatments (Tables 7.9 and 7.10). No differences in %Pdff values were obtained for Magoye possibly due to more P being recovered by wheat as leaf fall from this crop. Magoye was the biggest and most vigorously growing of the two legumes.

The 'A' value appeared to be a function of the residual effect of P applied in the first year of the rotation and was highest for Bossier and

Table 7.9. Phosphorus levels and isotopic characteristics of wheat in the second season of the rotation[+]

First season						
Crop	Fertilizer program		P	Pdff	P Fertilizer uptake	'A' value
	P rate	N rate				
	kg ha^{-1}		%		kg P ha^{-1}	
Bossier	0	20	0.19	20.5	1.76	125
	30	20	0.20	14.3	1.34	196
Magoye	0	20	0.21	12.6	0.99	208
	30	20	0.20	14.8	1.22	174
Maize	0	20	0.19	15.0	0.90	170
		60	0.19	13.5	0.79	200
	30	20	0.21	8.8	0.56	314
		60	0.20	12.5	0.86	228

+ Statistical comparison of data in this Table is given in Table 7.10.

Table 7.10. Significance of contrasts among P levels, %Pdff, fertilizer P uptake and 'A' values of wheat in the second season of the rotation

	Bossier 0	Bossier 30	Magoye 0	Magoye 30	Maize 0 20	Maize 0 60	Maize 30 20	Maize 30 60
				%Pdff				
Bossier 0	-	ns	***	**	**	***	**	**
30		-	***	**	*	***	**	**
Magoye 0			-	ns	*	ns	ns	*
30				-	ns	*	ns	ns
Maize 0 20					-	*	ns	ns
60						-	ns	ns
30 20							-	ns
				Fertilizer P uptake				
Bossier 0	-	*	**	*	**	**	***	**
30		-	*	ns	*	*	**	*
Magoye 0			-	*	ns	ns	*	ns
30				-	*	*	**	*
Maize 0 20					-	ns	*	ns
60						-	*	ns
30 20							-	*
				'A' value				
Bossier 0	-	ns	***	**	*	***	**	**
30		-	***	**	*	***	***	**
Magoye 0			-	ns	*	ns	*	ns
30				-	ns	ns	*	ns
Maize 0 20					-	ns	*	ns
60						-	*	ns
30 20							-	ns

maize at the lower N application rate (20 kg N ha^{-1}). At the higher N application rate (60 kg N ha^{-1}), the 'A' value did not increase with P application because of the high maize yield (Table 7.7) and the consequent increased uptake of fertilizer P (Tables 7.9 and 7.10). Maize leaves deposited on the soil surface may supply the soil with more P than legumes, especially after P fertilization (Hargrove, 1985). This study has shown that the 'A' value for P appears sensitive enough to allow detection of residual P. The 'A' value is an inverse measure of the effectiveness of a fertilizer (IAEA, 1983). The increase in grain DM yields of wheat preceded by Bossier cannot be explained by the presence of of residual P, since differences in residual P were not reflected in the DM yield of the subsequent wheat crop.

Legumes are known to increase the soil N levels (National Academy of Sciences, 1979) and consequently the productivity of succeeding cereal crops (Singh and Awasthi, 1978). Reddy et al. (1986) indicated 50 kg N ha^{-1} to have been added by senescent leaves of tropical legumes and to some extent roots and nodules. The increase in wheat yields after Bossier could either be due to residual N through biological N_2 fixation by the previously grown legumes or to a better utilization of soil moisture (Stewart et al., 1983; Dick, 1984; Power et al., 1985; Reddy et al., 1986).. This simple approach is complicated by the complex influence of legumes with respect to cycling of other nutrients, soil water status, soil temperature, soil structural changes, changes in soil microflora and fauna etc (Hargrove, 1985). However, the highest wheat DM yields were obtained when the preceding crop had the least soil N requirements (Table

7.11). This is confirmed by the highest total N uptake of wheat when the preceding crops were legumes (Table 7.12). Thus, grain benefits of wheat grown in rotation with legumes in this study could be attributed to biologically fixed N by the preceding crop.

Table 7.11 Nitrogen derived from atmosphere, fertilizer and soil by crops in the first season of the rotation+

Crop	N rate	Ndfa	Ndff	Ndfs	Total
		kg ha^{-1}			
Bossier	20	61	11	82	154
Magoye	20	108	12	105	225
Maize	20	-	12	108	120
Maize	60	-	34	108	142

\+ Data calculated assuming N isotopic values at final harvest were same as 72 days after planting.

Table 7.12 Total N uptake of wheat in the second season of the rotation

First season			Total N uptake
Crop	Fertilizer program		
	P rate	N rate	
	—— kg ha^{-1} ——		kg ha^{-1}
Bossier	0	20	141
	30	20	124
Magoye	0	20	132
	30	20	120
Maize	0	20	100
		60	87
	30	20	114
		60	117
Significance			
Crop			**
Phosphorus			ns
Nitrogen (maize)			ns

** and ns = Significant at $P<0.001$ and not significant, respectively.

8. SUMMARY AND CONCLUSIONS

The objectives of this study were to arrive at efficient use of two most valuable resources in Zambian agriculture, water and nitrogen. A number of field experiments were conducted over a period of three years at the National Irrigation Research Station in Nanga, Zambia to arrive at efficient management of water for irrigating wheat and of two major inputs to the nitrogen cycle, i.e. N fertilizer and N_2 fixation. The water efficiency component was tackled by evaluating various irrigation schedules that would provide maximum wheat yields with minimum water losses. The nitrogen efficiency component was studied in a series of experiments, where maximum efficiency of fertilizer N or N from fixation was achieved by proper placement and time of application of fertilizer N or selection of soybean cultivars with maximum fixing capacity under Zambian conditions, respectively.

The efficient use of water and fertilizer N was studied in a three year experiment on a Typic Haplustalf soil with pH 5.5, CEC of 7 cmoles (+) kg^{-1} and total N content of 0.8 g kg^{-1}.

Three irrigation schedules were adopted for the first two years of the study, namely, (i) every week irrigation at a rate of 70% of the total class A pan evaporation during the whole irrigation interval, (ii) every two weeks irrigation at 60% of the total class A pan evaporation during the whole irrigation interval, and (iii) every three weeks irrigation at 50% of the total class A pan evaporation during the whole irrigation interval.

Nitrogen fertilizer in all experiments was in urea form. In the first year of the experiments the time of application of fertilizer N was the main focus. Urea-N was applied either as a single application at 150 kg N ha^{-1} prior to seeding; or, as a two-split with half of the fertilizer applied prior to seeding and half at four weeks after emergence; or, as a three-split with one third applied prior to seeding, one third at four weeks and one third at seven weeks after emergence. The fertilizer in all cases was ^{15}N-labelled in such a way as to allow assessment of the utilization of the N from each application.

In the second year of the study, in addition to time of N application, four methods of fertilizer N placement were assessed. Data from the first year of the study had suggested that there was no benefit of a three-way split of the fertilizer compared to the two-split application. Therefore, only single (75 or 150 kg N ha^{-1}) and two-split applications were evaluated. Single application of which the initial portion of the split application of the fertilizer (50 kg N ha^{-1}) was either simply broadcast or broadcast and incorporated prior to seeding, placed in a narrow band 2.5 cm to the side of the seeding row, or broadcast two weeks after emergence. In this year, the ^{15}N-labelled fertilizer treatments were applied to microplots within the major plots and only for the broadcast and incorporation, side-band and late broadcast methods of placement.

Designing the third year experiments followed the experience obtained through the first two years of experimentation for which the following results were obtained:

Irrigation on a weekly basis led to higher wheat yields than irrigation every two or three weeks. Although water efficiency increased with larger intervals between irrigation, the efficiency of the irrigation was drastically decreased. Hence, overall, maximum efficiency of water without sacrificing maximum yields was obtained with the weekly irrigation.

Grain yields were primarily a function of water availability and for each level of water availability a function of fertilizer placement and time of application. Split application of fertilizer N resulted in significant benefits. When water was not a limiting factor broadcasting techniques followed by incorporation of the fertilizer or applied after the crop had established itself provided maximum efficiency of fertilizer N use. In the latter cases, where maximum efficiency of fertilizer N was achieved, grain yields were a function of the depth of irrigation water in mm or indirectly of the evapotranspiration demands.

Calculations using the data from the first two years of the experiment led to the conclusion that maximum efficiency of water yields that would provide maximum grain yields could be achieved by increasing the amount of irrigation water for the weekly application to 85% of class A pan evaporation over the whole irrigation interval. This hypothesis was tested in the third year of the study. Methods and times of fertilizer N application were maintained as in the second year of the experiment. Indeed the predicted maximum yields of 5.5 - 6.0 Mg ha^{-1} for the wheat variety used (Triticum aestivum cv. EMU's') were obtained in these experiments.

Yield independent isotopic criteria (% N derived from fertilizer) for any fertilizer placement method in these studies was independent of water regime, thus leading to the conclusion that N utilization was primarily a function of water availability.

To assess the contribution of N from atmospheric N_2 fixation by legumes, assessment of N_2 fixation by preferred Zambian legumes must be documented. This initial step involved selection of appropriate non-fixing reference crops that would allow estimating N_2 fixation using the ^{15}N isotope dilution technique. Thus a series of experiments were carried out utilizing ^{15}N isotope labelling techniques to evaluate local and imported nonnodulating soybean varieties along with a number of non-legume crops. Organic material (molasses) amended with ^{15}N-urea or ^{15}N-urea fertilizer were used. A time-dependent sampling scheme was devised to monitor crop growth characteristics and availability of N sources throughout the growing season. This allowed for choices of reference crops suitable for estimating N_2 fixation by soybeans by ^{15}N isotope dilution either at specific growth stages or over the entire growing season. In choosing the appropriate reference crop absence of N_2-fixing activity, relative feeding pattern of standard and fixing crops and time of growth of reference and fixing crops were evaluated.

Nonnodulating soybean (Glycine max) cultivars Clark RJ1 and N77 or in their absence Pearl millet (Panicum glaucum L.) appeared to be the best reference crops for estimating N_2 fixation using the ^{15}N isotope dilution technique in Zambia.

A local soybean fixing cultivar (Glycine max cv. Magoye) rated the highest among three cultivars tested for its ability to support symbiotic N_2 fixation by Bradyrhizobium japonicum under the experimental conditions. When this cultivar was inoculated with B. japonicum MM48 strain it fixed 225 kg N ha^{-1}. Therefore, it would be most recommended for inclusion in rotations by farmers in Zambia.

The superiority of Magoye was confirmed in another study, where three soybean cultivars, two fixing (Bossier and Magoye) and a non-fixing (Chappewa) were planted along with maize (Zea mays cv MM502) as first crops in a two season rotation. All crops received two levels of P (0 and 30 kg. ha^{-1}) and the legumes 20 kg N ha^{-1}, whereas maize 20 and 60 kg N ha^{-1}. Chappewa was used as a reference crop for estimating symbiotic N_2 fixation in the fixing soybean cultivars. After all crops were harvested, all plots received 30 kg P ha^{-1} and 60 kg N ha^{-1} and were seeded to wheat (Triticum aestivum cv. EMU's) as a second season crop. There were no benefits from residual P from the first season on wheat grain yields. However, the yields of wheat grown on plots where fixing legumes had grown the previous year were significantly higher than those where maize had preceded. The superiority of the soybean-wheat rotation over the maize-wheat rotation was attributed to residual N from biological N_2 fixation by the preceding legume crop.

This study was limited to an area in Zambia where climatic conditions are conducive for irrigated wheat cropping during the dry and cool (May to October) season. Although the fertilizer placement methods and times of application could be directly applicable for rainfed wheat, growth of the latter has not been very successful in Zambia with the exception of certain localities in the north of the country. However, the country has a tremendous potential to develop irrigation and as such inclusion of soybeans in other rotation schemes, primarily involving maize (Zea mays L.), can prove a definite asset for the Zambian agriculture as a whole.

REFERENCES

Aeppli, H. 1977. National Irrigation Research Station - end of contract. Report Ministry of Lands and Agriculture, Republic of Zambia. Publ. National Irrigation Research Station, Mazabuka, Zambia.

Aina, P.Q. 1980. Influence of soil moisutre. Soil compaction and K fertilization of maize (Zea mays L.) grown on two soils. Z. Pflanz. Bod. 143: 317-323.

Alaerts, M., Badj, M. and Feyen, J. 1985. Comparing the performance of root-water-uptake models. Soil Sci. 139: 289-296.

Allison, F.E. 1963. Losses of gaseour nitrogen from soils by chemical mechanisms involving nitrous acid and nitrites. Soil Sci. 96: 404.

Allison, F.E. 1966. The fate of nitrogen applied to soils. Adv. Agron. 18: 219-258.

Allison, F.E. 1973. Soil organic matter and its role in crop production. Elsevier Sci. Pub. Co., N.Y.

Allison, F.E., Carter, J.N. and Sterling, L.D. 1960. The effect of partial preasure of oxygen on denitrification in soil. Soil Sci. Soc. Am. Proc. 24: 283-285.

Allison, F.E. and Doetsch, J.H. 1951. Nitrogen gas production by the reaction of nitrites with amino acids in slightly acidic media. Soil Sci. Soc. Am. Proc. 15: 163-166.

Allison, F.E., Doetsch, J.H. and Sterling, L.D. 1952. Nitrogen gas formation by interaction of nitrites and amino acids. Soil Sci.

74: 311-314.

Arkley, R.J. 1963. Relationships between plant growth and transpiration. Hilgardia. 34: 559-584.

Azzi, G. 1922. Critical period of wheat as regards rain. Int. Rev. Sci. Practice Agr. 13:1184-1185.

Bailey, L.D. and Beauchamp, E.G. 1973. Effects of moisture, added NO_3^- and macerated roots on NO_3^- on transformation and redox potential in surface and sub surface soils. Can. J. Soil Sci. 53: 219-230.

Baldocchi, D.D., Verma, S.B. and Rosenberg, N.J. 1981. Mass and energy exchanges of a soybean canopy under various environmental regimes. Agron. J. 73: 706-710.

Baligar, V.C. and Patil, S.V. 1968. Effect of initial soil moisture and temperature on volatile losses of ammonia with the application of urea to soils. Mysore J. Agric. Sci. II: 85-93.

Barber, S.A. and MacKay, A.D. 1985. Sensitivity Analysis of the Parameters of a Mechanistic Methematical Model Affected by Changing Soil Moisture. Agron. J. 77: 528-531.

Barber, S.A., Walker, J.M. and Vasey, E.H. 1963. Mechanisms for the movement of plant nutrients from the soil and fertilizer to the plant root. J. Agric. Food Chem. 11: 204-207.

Barley, K.P. 1963. Influence of soil strength on growth of roots. Soil Sci. 96: 175-180.

Barley, K.P. and Naidu, N.A. 1964. The performance of three Australian wheat varieties at high levels of nitrogen supply. Aust. J. Agric. Anim. Husb. 4: 39-48.

Barrada, Y. 1965. Application of the neutron moisture meter in Proceedings of the Symposium on the Use of Isotopes and Radiation in Soil-Plant Nutrition Studies. International Atomic Energy Agency, Ankara, 28 June - 2 July, 1965.

Bergersen, F.J. and Turner, G.L. 1983. An evaluation of ^{15}N methods for estimating nitrogen fixation in a subterranean clover - perenial ryegrass sward. Aust. J. Agric. Res. 34: 391-401.

Betlack, M.K. 1979. Accumulation of intermediates during denitrification-kinetic mechanisms and regulation of assimilatory nitrate uptake. PhD thesis. Michigan State Univ. Microfilms. Ann. Arb. Mich. (Diss. 80: 06083).

Bierhuizen, J.F. and Slatyer, R.O. 1965. Effect of atmospheric concentration of water vapour and CO_2 in determining transpiration - photosythesis relationships of cotton leaves. Agric. Meteorol. 2: 259-270.

Black, C.A. 1968. Soil-plant relationships. Wiley and Sons, New York.

Blaney, H.F. and Criddle, W.D. 1966. Determining consumptive use for water developments. ASCE Irrig. and Drain. Spec. Conf. Proc. Nov. 2-4, pp. 1-34.

Blasco, M.L. and Cornfield. 1966. Volatilization of nitrogen as ammonia from acid soils. Nature (London) 212: 1279-1280.

Boatwright, G.O. and Haas, H.J. 1961. Development and composition of spring wheat as influenced by nitrogen and phosphorus fertilization. Agron. J. 53: 33-36.

Bouwmeester, R.J.B. and Vlek, P.L.G. 1981. Rate control of ammonia volatilization from rice paddies. Atmos. Environ. 15: 131-140.

Bouweester, R.J.B., Vlek, P.L.G. and Stumpe, J.M. 1985. Effect of environmental factors on ammonia volatilization from a urea-fertilized soil. Soil Sci. Soc. Am. J. 49: 376-381.

Brar, S.S., Miller, R.H. and Logan, T.J. 1978. Some factors affecting denitrification in soils irrigated with wastewater. J. Water Pollut. Control Fed. 50: 709-717.

Bremner, J.M. 1957. Studies on soil humic acids. II. Observations on the estimations of free amino groups. Reactions of humic acid and lignin preparations with nitrous acid. J. Agric. Sci. 48: 352-353.

Bremner, J.M. and Douglas, L.A. 1971. Decomposition of urea phosphate in soils. Soil Sci. Soc. Am. Proc. 35: 575-578.

Bremner, J.M. and Fuhr, F. 1966. Tracer studies of the reaction of soil organic matter with nitrite. pp 376-346 in The Use of Isotopes in Soil Organic Matter Studies. Pergamon Press, Inc., Elmsford, N.Y.

Bremner, J.M. and Shaw, K. 1958. Denitrification in soil. II. Factors affecting denitrification. J. Agric. Sci. 51: 39-52.

Broadbent, F.E. and Clark, F.E. 1965. Denitrification. pp 344-359 in W.V. Bartholomew and F.E. Clark (eds) Soil Nitrogen. Am. Soc. Agron., Madison, Wis.

Broadbent, F.E., Nakashima, T. and Chang, G.Y. 1983. Response to comments by Fried and Broeshart (1983) on paper "Estimation of nitrogen fixation by isotope dilution in field and greenhouse experiments". Agron. J. 75: 718.

Brun, L.J., Prunty, L., Larsen, J.K. and Enz, J.W. 1985.

Evapotransiration and soil water relationships for spring wheat and soybean. Soil Sci. 139: 547-552.

Burford, J.R. and Bremner. J.M. 1975. Relationships between the denitrification capacities of soils and total water soluble and readily decomposable soil organic matter. Soil Biol. Biochem. 7: 389-394.

Burford, J.R. and Millington, R.J. 1968. Nitrous oxide in the atmosphere of a red brown earth. 9th International Congress of Soil Science, II: 505-511.

Businger, J.A. 1956. Some remarks on Penman's equation for the evapotranspiration. Neth. J. Agr. Sci. 4: 77-80.

Campbell, N.E.R. and Lees, H. 1967. The nitrogen cycle in soil biochemistry. in A.D. McLaren and G.H. Peterson (eds) Soil Biochemistry. Marcel Dekker, Inc., New York, N.Y.

Carneiro, C. and de Jong, D.E. 1985. In situ determination of the slope of the calibration curve of a neutron probe using a volumetric technique. Soil Sci. 139: 250-254.

Carter, J.N., Bennet, O.L. and Pearson, R.W. 1967. Recovery of fertilizer nitrogen under field conditions using ^{15}N. Soil Sci. Soc. Amer. Proc. 31: 50-56.

Carter, M.R. and Rennie, D.A. 1984. Crop utilization of placed and broadcast N_{15} urea fertilizer under zero and conventional tillage. Can J. Soil Sci. 64:563-570.

Chao, T. and Kroontje, W. 1964. Relationships between ammonia volatilization, ammonia concentration and water evaporation. Soil.

Sci. Soc. Proc. 28: 393-395.

Cooke, G.W. 1967. The control of soil fertility. Lockwood and Son, London.

Chichester, F.W. 1977. Effects of increased fertilizer rates on nitrogen content of runoff and percolate from monolith lysimeters. J. Env. Qual. 6: 211-216.

Craswell, E.T. and Martin, A.E. 1974. Effect of moisture content on denitrification in a clay soil. Soil Biol. Biochem, 6: 127-129.

Craswell, E.T. and Martin, A.E. 1975. Isotopic studies of nitrogen balance in a cracking clay. II. Recovery of Nitrate N-15 added to columns of packed soil and microplots growing wheat in the field. Aust. J. Soil Res. 13: 53-61.

Craswell, E.T. and Vlek, P.L.G. 1980. Research to reduce losses of fertilizer nitrogen form wetland rice soils. Fertilizer Association of India (FAI) Annual Seminar, Dec. 4-6, 1980. New Delhi. India.

Danso, S.K.A. 1986. Review: Estimation of N_2-fixation by isotope dilution: An appraisal of techniques involving ^{15}N enrichment and their application - Comments. Soil Biol. Biochem. 18: 243-244.

Dastur, R.H. 1924. Water content factor in photosynthesis. Ann. Bot. 38: 779-788.

Dastur, R.H. and Desai, B.L. 1933. The relation between water-content, chlorophyll-content, and the rate of photosynthesis in some tropical plants at different temperatures. Ann. Bot. 47: 69-88.

Day, A.D. and Intalap, S. 1970. Some effects of soil moisture stress on the growth of wheat. Agron. J. 62: 27-49.

Deibert, E.J., Bijeriego, M. and Olson, R.A. 1979. Utilization of ^{15}N fertilizer by nodulating and non-nodulating soybean isolines. Agron. J. 71: 717-723.

Dennis, D.B., Verma, S.B. and Rosenberg, N.J. 1985. Water use efficiency in a soybean field: Influence of plant water stress. Agr. and Forest Meteorology 34 (1984): 53-65.

de Wit, C.T. 1958. Transpiration and crop yields. Versl. Landbouwk. Onderz. 64.6 Inst. Biol. Chem. Res. Field crops and Herbage, Wageningen, The Netherlands.

Dick, W.A. 1984. Influence of long-term tillage and crop rotation combinations on soil enzyme activities. Soil Sci. Soc. Am. J. 48: 569-574.

Domenach, A.M., Chalamet, A. and Pachiaudi, C. 1979. Estimation de la fixation d' azote par le soja a l' aide de deux methodes d' analyses isotopiques. C.R. Hebd. Seances Acad. Sci. 289: 291-293.

Doorenbos, J. and Pruitt, W.D. 1977. Crop water requirements. Irrig. and Drain. FAO, Rome, 144 pp.

Dowdell, R.J. and Smith, K.A. 1974. Field studies of the soil atmosphere. II Occurence of nitrous oxide. J. Soil Sci. 25: 231-238.

Du Plessis, M.C.F. and Kroontje, W. 1964. The relationship between pH and ammonium equilibrium in soil. Soil Sci. Soc. Am. Proc. 28: 751-754.

Du Plessis, M.C.F. and Kroontje, W. 1966. The effect of carbon dioxide on the chemisorption of ammonia by base saturated clays. Soil. Sci.

Soc. Am. Proc. 30: 693-696.

Dugas, W.A., Upchurch, D.R. and Ritchie, J.T. 1985. A weighing lysimeter for evapotranspiration and root measurements. Agro. J. 77: 821-825.

Ekpete, D.M. and Cornfield, A.H. 1965. Effect of pH and addition of organic materials on denitrification losses from soil. Nature (London) 208: 1200.

Ernest, J.W. and Massey, H.F. 1960. The effects of several factors on volatilization of ammonia formed from urea in soil. Soil Sci. Soc. Am. Proc. 24: 87-90.

Fenn, L.B. 1975. Ammonia volatilization from surface applications of ammonium compounds on calcareous soils: III. Effects of mixing low and high loss ammonium compounds. Soil Sci. Soc. Am. Proc. 39: 366-368.

Fenn, L.B. and Escarzaga, R. 1977. Ammonia volatilization from surface application of ammonium compounds on calcareous soil: VI. Effects of initial soil water content and quality of applied water. Soil Sci. Soc. Am. J. 41: 358-363.

Fenn, L.B. and Kissel, D.E. 1973. Ammonia volatilization from surface application of ammonium compounds on calcareous soils: I General Theory. Soil Sci. Soc. Am. Proc. 37: 855-859.

Fenn, L.B. and Kissel, D.E. 1975. Ammonia volatilization from surface application of ammonium compounds on calcareous soils: 4 Effect of calcium carbonate content. Soil Sci. Soc. Am. Proc. 39: 631-633.

Fenn, L.B. and Kissel, D.E. 1976. The influence of cation exchange capacity and depths of incorporation on ammonia volatilization from ammonium compounds applied to calcareous soils. Soil Sci. Soc. Am. J. 40: 394-398.

Fenn, L.B. and Miyamoto, S. 1981. Ammonia loss and associated reactions of urea in calcareous soils. Soil Sci. Soc. Am. J. 45: 537-540.

Fewson, C.A. and Nicholas, D.J.D. 1961. Utilization of nitrate by micro-organisms. Nature 190: 2-7.

Fried, M. and Broeshart, H. 1975. An independent measurement of the amount of nitrogen fixed by a legume crop. Plant Soil 43: 707-711.

Fried, M., Danso, S.K. and Zapata, F. 1983. The methodology of measurement of N_2 fixation by non-legumes as inferred from field experiments with legumes. Can. J. Microbiol. 29: 1053-1062.

Fried, M. and Dean, L.A. 1952. A concept concerning the measurement of available soil nutrient. Soil Sci. 73: 263-271.

Fried[illegible] and Middleboe, V. 1977. Measurement of amount of nitrogen fixed by a legume crop. Plant Soil 74: 713.715.

Fried, M., Soper, R.J. and Broeshart, H. 1975. ^{15}N-Labelled single-treatment fertility experiments. Agron. J. 67: 393-396.

Gandhi, A.P. and Paliwal, K.V. 1976. Mineralization and gaseous loss of nitrogen from urea and ammonium sulfate in salt-affected soil. Plant Soil 45: 247-255.

Gardner, W.R. 1965. Dynamic aspects of water availability to plants. Ann. Rev. Plant Physiol. 16: 323-342.

Gardner, W.R. and Ehlig, D.F. 1962. Some observations on the movement of water to plant roots. Agron. J. 54: 453-456.

Gardner, W. and Kirkham, D. 1952. Determination of soil moisture by neutron scattering method of measuring soil moisture. Soil Sci. 73: 391-401.

Gerretsen, F.C. and De Hoop, H. 1957. Nitrogen losses during nitrification in solutions and in acid sandy soils. Can. J. Microbiol. 3: 359-380.

Gilliam, J.W. and Gambrell, R.P. 1978. Temperature and pH as limiting factors in the loss of nitrate from saturated Atlantic coastal plain soils. J. Environ. Qual. 7: 526-532.

Gingrich, J.R. and Russell, M.B. 1957. A comparison of effects of soil moisture tension and osmotic stress on root growth. Soil Sci. 84: 185-194.

Haahr, V. and Olgaard, P.L. 1965. Comparative experimental and theoretical investigations of the neutronic method for measuring the water content in soil in Proceedings of the Symposium on the Use of Isotopes and Radiation in Soil-Plant Nutrition Studies. International Atomic Energy Ag., Ankara, 28th June - 2nd July, 1965.

Haan, C.T., Johnson, H.P. and Brakensick, D.L. 1982. Hydrological modeling of small watersheds. ASAE Monograph. No. 5, Amer. Soc. Agric. Engin. St. Joseph, Michigan.

Ham, G.E. and Caldwell, A.C. 1978. Fertilizer placement effects on soybean seed yield, N_2 fixation, and ^{32}P uptake. Agron. J. 70: 779-783.

Hamid, A. and Sarwar, G. 1976. Effect of split application on N uptake by wheat from ^{15}N labelled ammonium nitrate and urea. Exp. Agric. 12: 189-193.

Hanks, R.J. 1983. Yield and water-use relationships. An overview. pp 393-441 in H.M. Taylor, W.R. Jordan and T.R. Sinclair (ed), Limitation to Efficient Use in Crop Production. Am. Soc. Ag., Madison, WI.

Hargrove, W.L. 1985. Influence of tillage on nutrient uptake and yield of corn. Agron. J. 77: 763-768.

Hargrove, W.L., Kissel, D.E. and Fenn, L.B. 1977. Field measurements of ammonia volatilization from surface applications of ammonium salts to a calcareous soil. Agron. J. 69: 473-476.

Hauck, R.D. 1971. Quantitative estimates of nitrogen-cycle processes - Concepts and review. pp 65-80. in Nitrogen-15 in Soil-Plant Studies. Proc. of a Research Coordination Meeting, Sofia, Bulgaria. 1-5 Dec., 1969. Int. Atomic Energy Ag. Vienna.

Hauck, R.D. 1973. Nitrogen tracers in nitrogen cycle studies - past use and future needs. J. Environ. Qual. 2: 317-327.

Hensler, R.F. and Attoe, O.J. 1970. Rural sources of nitrates in water. in V.L. Snoeyink (ed). Nitrate and Water Supply: Source and Control. Proc. of the 12th Sanitary Engr. Conf., Urbana, Ill. 11-12 Feb., 1970. University of Illinois, Urbana.

Henzell, E.F. 1971. Recovery of nitrogen from four fertilizers applied to Rhodes grass in small plots. Aust. J. Exp. Agric. Anim. Husb. 11: 420-430.

Herron, G.M., Dreier, A.F., Floverday, A.D., Colville, W.L. and Olson, R.A. 1971. Residual mineral N accumulation in soil and its utilization by irrigated corn. Agron. J. 63: 322-327.

Hillel, D. 1982. Introduction to Soil Physics. Academic Press, N.Y.

Hira, G.G. and Singh, N.T. 1977. Observed and predicted rates of phosphorus diffusion in soils of varying bulk density and water content. Soil Sci. Soc. Am. J. 41: 537-540.

Howell, T.A. and Hiler, E.A. 1975. Optimization of water use efficiency under high frequency irrigation. I. Evapotranspiration and yield relationship. Transactions of the ASAE.

Hucklesby, D,P., Brown, C.M., Howell, S.E. and Hageman, R.H. 1971. Late spring application of nitrogen from efficient utilization and enhanced production of grain protein of wheat. Agron. J. 63: 274-276.

Inoue, K., Uehijima, Horie, T. and Iwakere, S. 1975. Studies of the energy and gas exchange within crop canopies. X. Structure of turbulence in rice crop. J. Agric. Meteor. 31: 71-82.

International Atomic Energy Agency. 1974. Isotope studies on wheat fertilization: Results of four-year co-ordinated research programme. Techninical Report series No. 157.

International Atomic Energy Agency. 1983. A guide to the use of nitrogen-15 and radioisotopes in studies of plant nutrition: Calculation and interpretation of data. TECDOC-288, Vienna.

Jain, N.K., Maurya, D.P. and Singh, H.P. 1971. Effects of time and method of applying nitrogen to dwarf wheats. Exp. Agric. 7: 21-26.

Javaheri, F. 1982. Naturally nodulating cultivars of soyabean in Zambia.

Javaheri, F. and Nkumbula, S. 1984. Soyabean production by small schale farmers in Zambia. Zambian Ministry of Agriculture and Water Development Report 5pp.

Johnson, V.A. 1953. Environmental factors affecting plant height in winter wheat. Agron. J. 45: 505-508.

Johnson, V.A., Dreier, A.F. and Grabouski, P.H. 1973. Yield and protein responses to nitrogen fertilizer of two winter wheat varieties differing in inherent protein content of their grain. Agron. J. 65: 259.

Jones, CP.L. and Adam, J. 1975. Effects due to the type of glass used in the discharge tubes on the calibration of emission spectrometers for the measurement of nitrogen -15. Analyst 100: 891-895.

Kezer, A. and Robertson, D.W. 1927. The critical period of applying irrigation water to wheat. Am. Soc. Agron. J. 19: 80-116.

Kezer, A., and Sackett, W.G. 1931. Soil investigations at the Colorado Station. Colorado Agr. Exp. Sta. Rpt. 1391: 13-14.

Khalifa, M.A. 1973. Effects of nitrogen on leaf area index, leaf area duration, net assimilation rate and yield of wheat. 1973. Agron. J. 65: 253-256.

Khan, D.H. and Rashid, G.H. 1971. Losses of nitrogen from urea in some soils of East Pakistan. Exp. Agric. 7: 107-112.

Khan, M.F.A. and Moore, A.W. 1968. Dinitrification capacity of some Alberta Soils. Can. J. Soil Sci. 48: 89-91.

Kolenbrander, C.J. 1972. Eutrophication from agriculture with special reference to fertilizers and animal waste. pp 305-327. in Effects of Intensive Fertilizer Use on the Human Environment. FAO Soils Bull. No. 16 Rome.

Kresge, C.B. and Satchell, D.P. 1960. Gaseous loss of ammonia from nitrogen fertilizers applied to soil. Agron. J. 52: 104-207.

Kundler, P. 1970. Utilization, fixation and loss of fertilizer nitrogen (Review of international results of the last 10 years basic research). Albrecht-Thaer-Arch. 14: 191-210.

Ladd, J.N., Oades, J.M. and Amato, M. 1981. Distribution and recovery of nitrogen from legume residues decomposing in soils sown to wheat in the field. Soil Biol. Biochem. 13: 251-256.

Legg, J.O. and Meisinger. 1982. Soil nitrogen budgets. pp 503-566. in F.J. Stevenson, J.M. Bremner, R.D. Hauck; D.R. Koeney Series, Amer. Soc. Agron. Madison, Wis.

Legg, J.O. and Sloger, C. 1975. A tracer method for determining symbiotic nitrogen fixation in field studies. pp 661-666 in Proceedings of the Second International Conference on Stable Isotopes E.R. Klein and P. D. Klein, (eds). Oak Brook, Illinois.

MacNeal, B.L. and Pratt, P.F. 1978. Leaching of nitrate from soils. pp 195-230 in P.F. Pratt (ed). Proc. Natl. Conf. on Management of Nitrogen in Irrigated Agric. Sacramento, Cal. 15-18 May, 1978. Univ. of California, Riverside.

MacRae, I.C., Ancajas, R.R. and Salandanan, S. 1968. The fate of nitrate nitrogen in some tropical soils following submergence. Soil Sci. 105: 327-334.

Mahtab, S.K., Godfrey, C.L., Swoboda, A.R. and Thomas, G.W. 1971. Phosphorus diffusion in soils. I. The effect of applied P, clay content, and water content of soil. Soil Sci. Soc. Am. Proc. 35: 393-397.

Martin, J.P. and Chapman, H.D. 1951. Volatilization of ammonia from surface fertilized soils. Soil Sci. 71: 25-34.

Meyer, R.D., Olson, R.A. and Rhoades, H.F. 1961. Ammonia losses from fertilized Nebraska soils. Agron. J. 53: 241-244.

Miller, H.F., Kavanaugh, J. and Thomas, G.W. 1975. Time of N application and yields of corn in wet, alluvial soils. Agron. J. 67: 401-404.

Mirreh, M.F. and Ketcheson, J.W. 1973. Influence of soil water matrix potential and resistance to penetration or corn root elongation. Can. J. Soil. Sci. 53: 383-388.

Moe, P.G. 1967. Nitrogen losses from urea as effected by altering soil urease activity. Soil Sci. Soc. Am. Proc. 31: 380-382.

Moliboga, A.I. 1928. Critical moisture periods for wheat and barley. Exp. Sta. Rec. 58: 734.

Molz, F.J. and Remson, I. 1970. Extraction-term models of soil moisture use of transpiring plants. Water Resour. Res. 6: 1346-1356.

Morel, A. and Sisley, P. 1927. Constitution of the azo compounds of the silk fibers. Soc. Chim. Fr. Bull. 41: 1217-1224.

Monteith, J.L. 1965. Evaporation and environment. pp 205-234 in G.E. Fogg (ed.) The state and Movement of Water in Living Organisms. Academic Press, New York, NY.

Mughogho, S.K. and Bationo, A. 1985. Management of N fertilizers for tropical African soils. IRDC symposium on the management of N and P fertilizers in sub-saharan Africa. March 25-28. Lome, Togo.

Myers, R.J.K. and Paul, E.A. 1971. Plant uptake and immobilization of ^{15}N-labelled ammonium nitrate in a field experiment with wheat. pp 55-64 in Nitrogen-15 in Soil Plant Studies. International Atomic Energy Agency. Vienna, Austria.

National Academy of Sciences. 1979. Tropical legumes: Resources for the future. National Academy of Sciences, Washington, D.C.

Nelson, D.W., and Bremner, J.M. 1969. Factors affecting chemical transformations of nitrite in soils. Soil Biol. Biochem. 1: 299-239.

Olsen, S.R. and Sommers, L.E. 1982. Phosphorus. pp 403-430 in R.H. Miller, D.R. Keeney (ed). Methods of Soil Analysis, Part 2. 2nd edition: Am. Soc. Agron. Inc., Madison, Wis.

Olson, R.A., Dreier, A.F., Thompson, C. and Frank, K., and Grabouski, P.H. 1964. Using fertilizer nitrogen effectively on grain crops. Nebr. Agric. Exp. Stn. Bull 479: 10-14.

Olson, R.A. and Kurtz, L.T. 1982. Crop N requirements, utilization and fertilization in pp 567-604 F.J. Stevenson, R.C. Dnauer, K.E. Gates and M. Stelly (eds) nitrogen in Agricultural soils. Am. Soc. Agron., Madison, Wis.

Overrein, L.M. and Moe, P.G. 1967. Factors effecting urea hydrolysis and ammonia volatilization in soil. Soil Sci. Soc. Am. Proc. 31: 57-61.

Owens, L.D. 1960. Nitrogen movement and transformation in soils as evaluated by a lysimeter study utilizing isotopic nitrogen. Soil Sci. Soc. Am. Proc. 24: 372-376.

Ozanne, P.G. 1980. Phosphate nutrition of plants - A general treatise. pp 559-589 in F.E. Khassavuch, E.C. Sample and E.J. Kamprath (eds.) The Role of Phosphorus in Agriculture. Am. Soc. Agron., Madison, WI

Payne, W.J. 1973. Reduction of nitrogenous oxides by microorganisms. Bacteriol. Rev. 37: 409-452.

Pelton, W.L., King, K.M. and Tanner, C.B. 1960. An evaluation of the Thornwaite and mean temperature method for determining potential evapotranspiration. Agron. J. 52: 387-395.

Penman, H.L. 1948. Natural evaporation from open water, bare soil, and grass. Proc. Royal Soc. Ser. A No. 1032, 193: 120-145.

Penman, H.L. 1956. Estimating evaporation. Am. Geophys. Union. 4: 9-29.

Peters, D.B. 1977. Water uptake of corn roots as influenced by soil moisture content and soil moisture tesion. Soil Sci. Soc. Am. J. 43: 880-883.

Phillip, J.R. 1957. The physical principles of soil water movement during the irrigation cycle. Proc. Int. Cong. Irrig. Drain. 8: 125-154.

Philpot, J.S. and Small, P.A. 1938. The action of nitrous acid on phenols. Biochem. J. 32: 534-541.

Pilot, L. and Patrick, W.H. 1972. Nitrate reduction in soils. Effect of soil moisture tension. Soil Sci. 114: 312-316.

Power, J.F., Doran, J.W. and Wilhelm, W.W. 1986. Uptake of nitrogen from soil, fertilizer and crop residues by no-till corn and soybean. Soil Sci. Soc. Am. J. 50: 137-142.

Pratt, P.F., Davis, S. and Sharpless, R.G. 1976. A four year field trial with animal manures. I. Nitrogen balances and yield. Hilgardia 44: 99-112.

Priestley, C.H.B. and Taylor, R.J. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Monthly Weather Rev. 100: 81-92.

Prihar, S.S., Gajri, P.R. and Narang, R.S. 1974. Scheduling of irrigation to wheat using pan evaporation. Indian J. Agric. Sci. 44: 567-571.

Rashid, G.H. 1977. The volatilization losses of nitrogen from added urea in some soils of Bangladesh. Plant Soil 44: 567-571.

Reddy, K.C., Soffes, A.R. and Prine, G.M. 1986. Tropical legumes for green manure. I. Nitrogen production and the effects on succeeding crop yields. Agron. J. 78: 1-4.

Rennie, D.A. and Paul. E.A. 1971. Isotope methodology and techniques in soil-plant nutrition and plant physiology. University of Saskatchewan Press. Saskatoon, Sask. 142 pp.

Rennie, D.A. and Fried, M. 1971. An interpretive analysis of the significance in soil fertility and fertilizer evaluation of N-15 labelled fertilizer experiments conducted under field conditions. Int. Symposium on Soil - Fertilizer Evaluation, I.S.S.S. Com. II and IV New Delhi.

Rennie, D.A., Paul, E.A. and Johns, L.E. 1976. Natural N-15 abundance of soil and plant samples. Can. J. Soil Sci. 56: 43-50.

Rennie, R.J. 1979. Comparison of ^{15}N-aided methods for determining symbiotic dinitrogen fixation. Rev. Ecol. Biol. Sol. 16 (4):

455-463.

Rennie, R.J. 1982. Quantifying dinitrogen fixation in soybeans by N-15 isotope dilution: The question of the nonfixing control plant. Can. J. Bot. 60: 856-861.

Rennie, R.J. 1984. Comparison of nitrogen balance and ^{15}N isotope dilution to quantify N_2 fixation in field-grown legumes. Agron. J. 76: 785-790.

Rennie, R.J. 1986. Advantages and disadvantages of N-15 isotope dilution to quantify dinitrogen fixation in field-grown legumes - a critique. pp 43-58 in Field Measurement of Dinitrogen Fixation and Denitrification, SSSA Spec. Pub. No. 18.

Rennie, R.J. 1986. Comparison of methods of enriching a soil with nitrogen-15 to estimate dinitrogen fixation by isotope dilution. Agron. J. Vol. 78: 158-163.

Rennie, R.J. and Dubetz, S. 1984. Multistrain vs. single strain Rhizobium japonicum inoculants for early maturing (00 and 000) soybean cultivars: N_2 fixation quantified by ^{15}N isotope dilution. Agron. J. 76: 498-502.

Rennie, R.J. and Kemp, G.A. 1983. N_2-fixation in field beans quantified by ^{15}N isotope dilution. II. Effect of cultivars of beans. Agron. J. 75: 645-649.

Rennie, R.J. and Kemp, G.A. 1984. ^{15}N determined time course for N_2 fixation in two cultivars of field bean. Agron. J. 76: 146-154.

Rennie, R.J. and Rennie, D.A. 1983. Techniques for quantifying N_2

fixation in association with non legumes under field and greenhouse conditions. Can. J. Microbiol. 29: 1022-1035.

Rennie, R.J., Rennie, D.A. and Fried, M. 1978. Concepts of ^{15}N usage in dinitrogen fixation studies. pp 107-133 in Isotopes in Biological Dinitrogen Fixation, International Atomic Energy Agency, Vienna.

Reuss, J.O. and Smith, R.L. 1965. Chemical reactions of nitrites in acid soils. Soil Sci. Soc. Am. Proc. 29: 267-270.

Rice, W.A. 1966. The role of anacrobiosis in asymbiotic nitrogen fixation in soil. M.Sc. Thesis. Ueniv. of Saskatchewan, Saskatoon.

Robertson, D.W., Kezer, A., Sjogren, J. and Koonce, D. 1934. Stuides on the critical period for applying irrigation water to wheat. Colorado Agr. exp. Sta. Bull. 11, 43 p.

Rolston, D.E., Fried, M. and Goldhamer, D.A. 1976. Denitrification directly from nitrogen and nitrous oxide gas fluxes. Soil Sci. Am. J. 40: 259-266.

Rolston, D.E., Hoffman, D.L. and Toy, D.W. 1978. Field measurement of denitrification: I. Flux of N_2 and N_2O. Soil Sci. Soc. Am. J. 42: 863-869.

Rolston, D.E., Broadbent, F.E. and Goldhamer, D.A. 1979. Field measurement of denitrification: II. Mass balance and sampling uncertainty. Soil Sci. Soc. Am. J. 43: 703-708.

Ruschel, A.P., Vose, P.B., Victoria, R.L. and Salati, E. 1979. Comparison of isotope techniques and non-nodulating isolines to study the effect of ammonium fertilization on dinitrogen fixation in soybean, Glycine max L., Plant Soil 53: 513-525.

Ryden, J.C. and Lund, L.J. 1980. Nature and extent of directly measured denitrification losses from some irrigated vegetable crop production units. Soil Sci. Soc. Am. J. 44: 505-511.

Safaya, N.M. 1976. Phosphorus-zinc interaction in relation to absorption rates of phosphorus, zinc, copper, manganese and iron in corn. Soil Sci. Am. J. 40: 719-722.

Shields, J.A., Paul, E.A., Lowe, W.E. and Parkinson, D. 1973. Turnover of microbial tissue in soil under field conditions. Soil Biol. Biochem. 5: 753-764.

Shih, S.F. 983. Evapotranspiration and water use efficiency of sweet corn. Winter meeting of Am. Soc. Agric. Eng. Chicago, Ill.

Sinclair, T.R., Bingham, G.E., Lemon, E.R. and Allen, L.H. Jr. 1975. Water use efficiency of a field-grown maize during moisture stress. Plant Physiol. 56: 245-249.

Singh, K.K. and Awasthi, O.P. 1978. Maintenance of soil fertility in the hills with incorporation of legumes in cropping sequencies. Ind. J. Agric. Sci. 48: 41-46.

Singh, N.T., Vig, A.C., Singh, R. and Chaudhary, MR. 1979. Influence of different levels of irrigation and nitrogen on yield and nutrient uptake by wheat. Agron. J. 71: 401-404.

Slatyer, R.O. 1967. Plant-water relationships. Academic Press, New York.

Smith, C.J. and Chalk, P.M. 1980a. Gaseous nitrogen evolution during nitrification of ammonia fertilizer and nitrite transformations in soils. Soil Sci. Soc. Am. J. 44: 227-282.

Smith, C.J. and Chalk, P.M. 1980b. Fixation and loss of nitrogen during transformations of nitrite in soil. Soil Sci. Soc. Am. J. 44: 288-291.

Smith, D.H. and Clark, F.E. 1960. Volitile losses of nitrogen from acid or neutral soils or solution containing nitrite and ammonium ions. Soil Sci. 90: 86-92.

Smith, M.S. and Tiedje, J.M. 1979. Phases of denitrification following oxygen depletion in soil. Soil Biochem. 11: 261-267.

Soil Research Co-ordination Report. 1981. Mount Makulu Central Research Station. Ministry of Agriculture and Water Development, Zambia.

Stanford, G, Vander Pol, R.A. and Dzienia, S. 1975. Dinitrification rates in relation to total and extractable soil carbon. Soil Sci. Soc. Am. Proc. 39: 284-289.

Starr, J.L. and Parlange, J.V. 1975. Non-linear denitrification kinetics with continuous flow in soil columns. Soil Sci. Soc. Am. Proc. 39: 875-880.

Stefanson, R.C. 1976. Denitrification from nitrogen fertilizer placed at various depths in the soil-plant systems. Soil Sci. 121: 353-363.

Stewart, G.L. and Taylor, S.A. 1957. Field experience with neutron-scattering method of measuring soil moisture. Soil Sci. 83: 151-158.

Stewart, J.W.B., Halm, B.J. and Cole, C.V. 1973. Nutrient cycling: I. Phosphorus. Technical report No. 40. Published by Can. Comm. Int. Biol. Prog. (Matador Project), Univ. of Saskatchewan, Saskatoon.

Stillwell, M.A. and Woodmansee, R.G. 1981. Chemical transformations of urea-nitrogen and movement of nitrogen in a shortgrass prairie soil. Soil Sci. Am. J. 45: 893-898.

Storrier, R.R. 1962. The availability of mineral nitrogen in a wheat-soil - from Southern New South Wales. Aust. J. Exp. Agric. Anim. Husb. 5: 310-316.

Tanner, C.B. and Fuchs, M. 1968. Evaporation from unsaturated surfaces: A generalized combination method. J. Geophys. Res. 73: 1299-1304.

Tanner, C.B. and Jury, W.A. 1976. Estimating evaporation and transpiration from a row crop during incomplete cover. Agron. J. 68: 239-243.

Tanner, C.B. and Pelton, W.L. 1960. Potential evapotranspiration estimates by the approximate energy balance method of Penman, J. Geophys. Res. 63: 3391-3413.

Tanner, C.B. and Sinclair, T.R. 1983. Efficient water use in crop production: Research on Research. pp 1-27 in H.M. Taylor, W.R. Jordan, J.R. Sinclair (eds) Limitations to Efficient Water Use in Crop Production. Am. Soc. Agron., Madison, WI.

Terman, G.L., Parr, J.F. and Allen, S.E. 1968. Recovery of nitrogen by corn from solid fertilizers and solutions. J. Agric. Food Chem. 16: 685-690.

Tisdale, S.L., Nelson, W.L. and Beaton, J.D. 1985. Soil fertility and fertilizers. Fourth Edition, Macmillan Publ. Co., New York, NY.

Tomar, J.S. and Soper, R.J. 1981. Fate of tagged urea N in the field with different methods of N and organic matter placement. Agron. J. 73: 991-995.

Vallis, I., Henzell, E.F., Martin, A.E. and Ross, P.J. 1973. Isotopic studies on the uptake of nitrogen by pasture plants. V. ^{15}N balance experiments in field microplots. Aust. J. Agric. Res. 24: 693-702.

van Bavel, C.H.M. 1966. Potential evaporation: The combination concept and its experimental verification. Water Resour. Res. 12: 455-467.

van Cleemput, O. and Patric, Jr. W.H. 1974. Nitrate and nitrite reduction in flooded gamma irradiated soil under controlled pH and redox potential conditions. Soil Biol. Biochem. 6: 85-88.

Verhoeven, W. 1956. Some remarks on nitrate and nitrite metabolism in microorganisms in W.D. McElroy and Bentley Glass (eds) A Symposium. The Johns Hopkins Press, Baltimore, Md.

Verma, R., Singh, N. and Sarkar, M.G. 1974. Some soil properties affecting loss of nitrogen from urea due to ammonia volatilization. J. Ind. Soc. Soil Sci. 22: 80-83.

Viets, F.G., Jr. 1962. Fertilizer and efficient use of water. Adv. Agron. 14: 223-264

Viets, F.G., Jr., Humbert, R.P. Jr. and Nelson, C.E. 1967. Fertilizers in relation to irrigation practice, in R.M. Hagan et al. (ed.). Irrigation of agricultural lands. Agron. II: 1009-1023. Am. Soc. of Agron., Madison, Wis.

Vlek, P.L.G. 1985. The fertilizer nitrogen balance in tropical Africa. IDRC symposium on the management of nitrogen and phosphorus fertilizers in sub-saharan Africa. March 25-28, Lome, Togo.

Vlek, P.L.G., Byrnes, B.H. and Craswell, E.T. 1980. Effect of urea placement on leaching losses of nitrogen from flooded soils.

Plant Soil 54: 441-449.

Vlek, P.L.G., Fillery, I.R.P. and Burford, J.R. 1981. Accession, transformation, and loss of nitrogen in soils of the arid region. Plant Soil 58: 133-175.

Vlek, P.L.G. and Stumpe, J.M. 1978. Effect of solution chemistry and environmental conditions on ammonia volatilization losses from aqueous systems. Soil Sci. Am. J. 42: 416-421.

Volk, G.M. 1959. Volatile loss of ammonia following surface application of urea to turf or bare soils. Agron. J. 51: 746-749.

Volk, G.M. 1970. Gaseous loss of ammonia from prilled urea applied to slash pine. Soil Sci. Soc. Am. Proc. 34: 513-516.

Volz, M.G., Ardakani, M.S., Shulz, L.H. and Stolzy, L.H. 1976. Soil nitrate loss during irrigation: Enhancement by plant roots. Agron. J. 68: 621-627.

Volz, M.G., Belser, L.W., Ardakani, M.S. and McLaren, A.D. 1975. Nitrate reduction and associated microbial populations in ponded Hanford sandy loam. J. Environ. Qual. 4: 99-102.

Volz, M.G. and Starr, J.L. 1977. Nitrate dissimilation and population dynamics of denitrifying bacteria during short term continuous flow. Soil Sci. Soc. Am. J. 41: 991-996.

Wagner, G.H. and Zapata, F. 1982. Field evaluation of reference crops in the study of nitrogen fixation by legumes using isotope techniques. Agron. J. 74: 607-612.

Wahhab, A., Randhawo, M.S. and Alam, S.Q. 1957. Loss of ammonium sulfate under different conditions when applied to soils. Soil

Sci. 84: 249-255.

Wahhab, A. and Hussain, I. 1957. Effect of nitrogen on the growth, quality and yield of irrigated wheat in West Pakistan. Agron. J. 49: 116-119.

Wahhab, A. and Uddin, F. 1954. Loss of nitrogen through reaction of ammonium and nitrite ions. Soil Sci. 78: 119-1126.

Watkins, S.H., Strand, R.F., de Bell, D.S. and Esch, J. Jr. 1972. Factors influencing ammonia losses from urea applied to northwestern forest soils. Soil Sci. Soc. Am. Proc. 36: 354-357.

Welch, L.F., Mulvaney, D.L., Oldham, M.G., Boone, L.V. and Pendleton, J.W. 1971. Corn yields with fall, spring and sidedress nitrogen. Agron. J. 63: 119-123.

Wetselaar, R. and Farquhar, G.D. 1980. Nitrogen losses from tops of plants. Adv. Agron. 33: 263-302.

Whisler, F.D., Klute, A. and Millington, R.J. 1968. Analysis of steady state evapotranspiration from soil column. Soil Sci. Soc. Am. Proc. 32: 167-174.

Wijler, J. and Delwiche, C.C. 1954. Investigations on the denitrifying process in the soil. Plant Soil 5: 155-169.

Witty, J.F. 1983. Estimating N_2-fixation in the field using N-15 labelled fertilizer: Some problems and solutions. Soil Biol. Biochem. 15: 631-639.

Woodmansee, R.G. 1978. Additions and losses of nitrogen in grassland ecosystems. Bio Sci. 28: 448-453.

Yang, S.J. and deJong, E. 1972. Effect of aerial environment and soil water potential on the transpiration and energy status of water in wheat plants. Agron. J. 64: 574-578.

Yates, R.A. and Taylor, R.D. 1986. Water use efficiencies in relation to sugarcane yields. Soil Use and Management. Vol. 2 No.2.

Zamyatina, V.B., Borisova, N.I., Varyushkina, N.M., Burtseva, S.V. and Kirpaneva, L.I. 1968. Investigations on the balance and use of ^{15}N - tagged fertilizer nitrogen by plants in soils. Trans. 9th int. Congr. Soil Sci. 2: 513-521.

Zur, B. and Jones, J.W. 1984. Diurnal changes in instantaneous water use efficiency of a soybean crop. Agric. For. Meteorol. 33: 41-51.