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UNIVERSITY OF ALBERTA

FATE OF ^{15}N-LABELLED NITROGEN FERTILIZERS APPLIED TO ARTIFICIALLY-ERODED SOILS

BY

RUPA PRADHAN

A THESIS SUBMITTED TO

THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

DEPARTMENT OF SOIL SCIENCE

EDMONTON, ALBERTA

SPRING 1995

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TITLE OF THE THESIS: **FATE OF ^{15}N-LABELLED NITROGEN FERTILIZERS APPLIED TO ARTIFICIALLY-ERODED SOILS**

DEGREE: **MASTER OF SCIENCE**

YEAR THIS DEGREE GRANTED: 1995

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled FATE OF ^{15}N-LABELLED NITROGEN FERTILIZERS APPLIED TO ARTIFICIALLY ERODED SOILS submitted by RUPA PRADHAN in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE

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To Shri Vithuraya, Ista Devata Of My Heart

ABSTRACT

There is a general trend to apply fertilizers uniformly across the fields regardless of their differences in nutrient status and degree of erosion. Overfertilization of eroded soils may lead to fertilizer losses from the plant-soil system. Loss of N fertilizer is of major environmental concern. Two field experiments were conducted in 1991 and 1992 at Josephburg (Black Chernozem) and Cooking Lake (Gray Luvisol) to study the fate of ^{15}N-labelled N fertilizer applied to artificially eroded soil. The experimental design was split plot, with three erosion levels (0-, 10- and 20- cm) as main-plot treatments and two ^{15}N-labelled N fertilizers (urea and KNO_3 both at 5 atom % abundance at 150 kg N ha^{-1}) and one control as sub-plot treatments. The plots were sown to barley (Hordeum vulgare L.) cv.Duke. The study also examined erosion-crop productivity relationships, effectiveness of two N sources on restoring productivity of eroded soils, and variations in natural ^{15}N abundance in artificially eroded soil. Barley yields were lowest in the 20 cm cut, at both sites. Addition of fertilizer N improved yields and N uptake of barley at all levels of erosion. Barley yields of 20 cm artificially-eroded soils were increased to the yield levels of non-eroded and non-fertilized soils with KNO_3 at both sites and with urea only at Josephburg. The yields of 20 cm eroded plots did not attain the levels of non-eroded soils under same fertilizer treatment. Barley yields were partly affected by late sowing in 1991 and relatively low precipitation in 1992. Plant response to added N increased with increasing levels of erosion. Mass balance of added ^{15}N suggested large N losses. In two years, at Cooking Lake 14 to 38% and at Josephburg 38 to 53% of the added N were not accounted by the ^{15}N mass balance. By mid September 1991, with KNO_3 about 20 to 27% of added N had been lost from eroded treatments at Cooking Lake and with both N sources at Josephburg. During the period between harvests, N losses were higher from the artificially-eroded soils and was greatest with KNO_3 (46.5 kg ha^{-1}) at Josephburg. At Cooking Lake, N losses were minimum with urea in the 20-cm cut. Denitrification was likely the major mechanism of N loss due to waterlogging of soil as a result of heavy rainfall in 1991 and spring thaw in 1992. Measurement of high values of δ^{15}N for soil

NO_3-N and plant N also suggested denitrification. Although soil recovery of added N at Cooking lake in 1991 occurred mostly in the surface 15 cm, there was an evidence of downward movement of N down to 75 cm depth (2.5 kg ha^{-1}). In conclusion, crop productivity of eroded soils may be improved by adding increased amounts of commercial fertilizers but at the same time it may result in large losses of fertilizer.

ACKNOWLEDGMENTS

This part of my thesis is the most enjoyable to me personally, since I get the privilege to acknowledge those individuals and organizations who have assisted me in a variety of ways. I would like to begin by expressing my heartfelt gratitude to my Supervisor, Dr. R.C. Izaurraulde for his immense support and guidance throughout the project. He was an excellent instructor, motivator and overseer of the project. I am equally grateful to Dr. M. Nyborg for his constant help, scholarly suggestions, and constructive criticisms in building up of this thesis. This project would have faltered significantly without his feedback.

I would like to thank Dr. S.S. Malhi for his keen interest and valuable suggestions on development of this thesis and for providing me with much "food for thought". My sincere thanks to Dr. R.D. Hauck, Dr. W.B. McGill and Dr. D.J. Pluth for answering all my inquiries about ^{15}N. I thank Dr. J.P. Tewari for his participation as an external examiner and providing helpful suggestions on my thesis.

My work in artificially eroded soils would not have been possible without the assistance of Zhixiong Zhang in the field. I thank him sincerely for being the "main muscle" of my project. I gratefully acknowledge Lenz Haderline and Dick for their help in installing (hammering) the steel frames into the soil and soil sampling. I also thank Mrs. Zhixiong Zhang for assisting me during harvesting and in drying and weighing the plant samples at Ellerslie farm. I must recognize and thank Monica Molina-Ayala and John Konwicki for their friendship and their assistance in laboratory analysis. Acknowledgments are also due to Chung Nguyen for her great help during the statistical analysis of my data. I also owe sincere thanks to Clive Figueiredo and Chung Ngyuen for their much patient instruction and invaluable help in ^{15}N mass spectrometer analysis of plant and soil samples.

I would like to acknowledge Cristina-Quiroga Jakas for her moral support and kind friendship. Sincere thanks and appreciation to Pramod and Rita Shreshtha, Roshan and Kalpana Chitrakar, and Hridaya and Uttara Bajracharya for their support and encouragement. I thank all my FOP friends for making my stay most comfortable.

Financial aid for the project was provided by Environmental Sustainability Initiative (ESI), Parkland Agricultural Research Initiative (PARI) and National Soil Conservation Program (NSCP). Financial support for my expenses was graciously provided by these organizations and Department of Renewable Resources (formerly Soil Science) in the form of Graduate Research and Teaching Assistantships. I must acknowledge International Students Center at University of Alberta and especially Doug Weir for financial support, friendship and invaluable help during my early days in Canada.

Completion of any degree is always accompanied by acquaintances and long-term friendships that tend to make the frustrating moments more endurable. To those individuals, I offer a most sincere *thank you.* The warm and trusting friendships of Lynette and Myron Esak; Regi and Joi Mathew have always been a great welcome in my life. The warm and selfless love of Mrs. Vanalata Upadhaya have always been a great comfort in my work.

My family back in Kathmandu valley........my parents, Gokul and Babajyan; my brothers, Gem, Om, Suraj and Diwaker; and my sister Shobha all deserve thanks for their love, continued support and enthusiasm.

Sincere thanks and love to my best friend and husband Nilesh for his love and patience, for providing me with inspiration *extraordinaire*, and for being my *Himalayas* during the moments of anxiety.

My questions, though, extend beyond the bounds of science. Only few know me well enough to understand that statement. I am most thankful to *Lord Vitthala,* the God of my life for all that I have been given and *Acharya Vinoba Bhave* for guiding me on right track in my spiritual endeavors.

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CHAPTER 1

INTRODUCTION

Wind and water erosion are major forms of soil degradation in the Canadian prairies. Soil erosion leads to a reduction of topsoil thickness. Topsoil is a layer of variable thickness pedogenically associated with the 'A' horizon. Topsoil thickness varies from few centimeters to about 40 to 45 cm but it is usually not thicker than one third of the total solum (A+B horizons). Topsoil is considered an important parameter determining soil quality and productivity (Power et al., 1981). Loss of topsoil often leads to an exposure of infertile subsoil, a layer normally deficient in plant nutrients (primarily N and P), low in organic mater, biological activity and water holding capacity and high in bulk density (Eck et al., 1965; Batchelder and Jones, 1972; Power et al., 1981; Frye et al., 1982; Dormaar et al, 1986; Tanaka and Aase, 1989). Low organic C concentration of eroded soils is associated with lighter soil colors and in turn with cooler soil temperatures (Tanaka and Aase, 1989). Hence, the subtle and drastic deterioration of soil quality ultimately reduces productivity. However, in early stages of the erosion process the negative effects of topsoil loss may go unnoticed due to advanced technology such as improved genotypes, increased use of fertilizers and more efficient herbicides (Krauss and Allmaras, 1982).

An understanding of erosion-crop productivity relationships is essential to develop cost-effective measures of erosion control. A common approach to develop such relationship has been the use of artificial erosion or desurfacing technique. Substantial yield reductions have been reported using this method (Battison et al., 1983; Morrison and Shaykewick, 1987; Ripley et al., 1961; Shafiq et al., 1988; Tanaka and Aase, 1989; Larney et al., 1995). Crop productivity of artificially eroded soils could be restored by adding nutrients, primarily N and P (Englestad and Shrader, 1961; Morrison and Shaykewick, 1987; Shafiq et al., 1988; Malhi et al., 1994; Izaurralde et al., 1995). In many cases, however, crop yields obtained on severely-eroded soils could not be improved to the yield levels of non- or slightly-eroded soils (Frye et al., 1982; Massee and Waggonner, 1985; Mielke and Schepers, 1986; Malhi et al., 1994; Izaurralde et al., 1994).

Cultivated fields often exhibit signs of erosion by wind and water such as changes in soil tilth and color, or in uneven plant growth (De Jong et al., 1983; De Jong, 1988; Rennie, 1986; Howitt, 1991). There is a trend, however, to apply fertilizers uniformly to fields regardless of their difference in nutrient status and degree of erosion. This may result in fertilizer application at rates equal to or either greater or lower than optimum levels. Overapplication of fertilizer N to eroded soils may result in losses from the plant-soil system. Loss of fertilizer N through denitrification, volatilization and leaching poses a serious environmental concern. Gaseous loss of N (nitrogen oxides such as NO, NO_2 and N_2O) through denitrification contributes to the increase in greenhouse-gas levels and hence global warming (Wang et al, 1976). On the other hand, leaching of nitrates below the root zone impairs the quality of ground water.

Several studies have been conducted to understand and quantify erosion-crop productivity relationships but little has been done on studying the fate of N fertilizers applied to eroded soils. There is a need therefore to improve our understanding of the environmental impact of restoring the productivity of the eroded soils with N fertilizers.

OBJECTIVES

The objectives of this thesis were: (i) to assess the relative efficiency of two N source (urea and potassium nitrate) in restoring the productivity of two artificially-eroded soils; (ii) to determine the fate of these sources in the plant-soil system using ^{15}N mass-balance technique, and (iii) to ascribe losses of N using the difference method, downward movement of soil nitrate, and variations in natural in ^{15}N abundance of artificially-eroded soils.

In Chapter 2, effects of artificial erosion and N source on crop productivity of two soil types of north-central Alberta are reported. Fate of ^{15}N-labelled fertilizer N applied to artificially-eroded soils is reported in Chapter 3. The variations in natural ^{15}N abundance of plants and soils where soils had been artificially-eroded are described in Chapter 4.

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CHAPTER 2

BARLEY PRODUCTIVITY AS INFLUENCED BY ARTIFICIAL EROSION AND N FERTILIZER SOURCE

2.1 Introduction

Topsoil is an important parameter determining soil quality and hence crop productivity (Power et al., 1981). Reduced crop production of eroded soils has been found to be associated with a deterioration of properties or conditions of soils such as bulk density, soil tilth, organic matter, availability and amounts of nutrients and water-holding capacity (Eck et al., 1965; Batchelder and Jones, 1972; Frye et al., 1982; Dormaar et al., 1986; Tanaka and Aase, 1989). Various studies have indicated that topsoil loss may result in either subtle or dramatic reductions of crop yield (Lyles, 1975; Frye et al., 1982; Battison et al., 1983).

Studies on erosion-crop productivity relationships using artificial erosion techniques have indicated a negative correlation between crop yield and topsoil thickness (Ripley et al., 1961; Battison et al., 1983; Morrison and Shaykewick, 1987; Larney et al., 1995). In some studies, crop yields on artificially-eroded soils were partially or totally restored with N and P fertilizers (Engelstad and Shrader, 1961; Morrison and Shaykewick, 1987; Shafiq et al., 1988; Tanaka and Aase, 1989). The level of restoration, however, varied with soil type, climate, crop type and level of management (Langdale and Schrader, 1982; Morrison and Shaykewick, 1987). Crop yields of eroded soils can be improved with the addition of N and P fertilizers but they may not attain the yield levels reached by crops growing on non- or slightly-eroded soils (Frye et al., 1982; Massee and Waggoner, 1985; Meilke and Schepers, 1986). The yield response to fertilizer N in eroded soils may also vary with the source used (i.e., nitrate-based or ammonium-based fertilizer).

The objectives of this study were: (1) to determine the effect of artificial erosion on crop productivity of two soil types of north-central Alberta, and (2) to assess the effectiveness of two N fertilizers in restoring the productivity of artificially-eroded soils.

2.2 Materials and Methods

2.2.1 Site and Soil Description

Field experiments were conducted in 1991 and 1992 at Cooking Lake (Site 1) and Josephburg (Site 2), Alberta. Both sites are located approximately 20 km east of Edmonton (53° 34'N, 113°33'W). The soil at Site 1 is an Orthic Gray Luvisol and has an A horizon 15-cm thick. The soil at Site 2 is an Eluviated Black Chernozem of the Angus Ridge series. Its A horizon (A_p+ A_h) is 30 cm thick. Both soils lie on glacial-till parent material. The sites are located on a 2% slope and have similar growing season precipitation (May-August). The long-term (30 year) average growing season precipitation is 288 mm at Site 1 and 265 mm at Site 2.

2.2.2 Management History

Recent soil management at Site 1 consisted of growing oats intercropped with field peas in rotation with barley. Cattle manure was applied regularly on this field at an approximate rate of 5 Mg ha^{-1} yr^{-1}. The fertility program was complemented with annual additions of fertilizer N at 60 kg ha^{-1} and fertilizer P at 10 kg ha^{-1}. At Site 2, soil management consisted of a canola-wheat-barley rotation. The recent fertilizer program used fall-applied N at 60 kg ha^{-1}. Phosphorous was applied with the seed at 15 kg ha^{-1}.

2.2.3 Field Experiment

The experiment consisted of a factorial combination of three levels of artificial erosion and three levels of N source arranged in a split plot design. Topsoil removal (0, 10 and 20 cm) were assigned as main plot treatments. Within each main plot two ^{15}N-labelled N fertilizers and one control were randomly assigned. The N fertilizers used were urea and KNO_3 at a rate of 150 kg N ha^{-1}. The atom % ^{15}N abundance was 5.62 for KNO_3 and 5.63 for urea. Each treatment was replicated four times.

The artificial erosion levels (soil cuts or topsoil removal) were established in the fall of 1990 by removing topsoil with an excavator with a grading bucket in 10 cm depth increments from 0 to 20 cm. Two steel frames were installed within each subplot in order to account for plant N uptake and soil N distribution of the applied ^{15}N (for ^{15}N mass balance study reported in Chapter 3) during a two year period. The frames were installed adjacent to each other. Each frame was 18 cm tall, 46 cm long and 46 cm wide. The frames were driven 13 cm into the soil leaving 5 cm above the soil surface. A spirit level was used to ensure that the frames were installed as level as possible.

A total of 72 frames at each site were sown to barley cv. Duke on 6 June 1991 at a rate of 90 kg ha^{-1}. Each frame had two seed rows spaced 23 cm apart. The seeds were sown 2 cm deep into the soil. The ^{15}N-labelled N fertilizer was banded 5-cm deep midway between the seed rows. Fertilizer P as triple superphosphate (TSP) was applied to each seed row at 10 kg P ha^{-1}. The experiment was weeded by hand but the pulled weeds were left on the soil.

Barley was harvested at maturity on 2 September 1991 for determination of above ground biomass. Harvesting was done manually by cutting the plant stem just above the soil surface. The plant samples (which included harvested barley plants and all the weed biomass retained within the frames) were placed in brown paper bags, dried at 65°C for 36 hours. After drying the plant samples were allowed to equilibrate at room temperature and humidity and later weighed for yield determination.

Soil samples were taken on 15 September 1991 on one set of frames to proceed with the ^{15}N mass-balance study (reported in Chapter 3). The second set of frames was sown again to barley on 10 May 1992. In order to account for the residual ^{15}N recovery from the previous application of ^{15}N-labelled fertilizer the N source used in 1992 were not labelled with ^{15}N. Therefore, urea, KNO_3 and TSP were applied at the same rates and with the same methods as in 1991. Barley was harvested at maturity on 7 August 1992 and the plant samples were dried and weighed for biomass as described for 1991.

2.2.4 Soil Characteristics

Bulk density (D_b) values were determined 'in situ" for the 0-10 cm layer with MC1 gamma probe (Moisture/Density Gauge, CPN Co., 2830 Howe Rd., Martinez, California, USA). The values for deeper soil layers were obtained from the Soil Inventory Map Attribute File-Alberta Soil Layer Digital Data (1989). Physical and chemical soil properties were obtained from analytical determination on soil samples taken prior to sowing from a neighboring experiment (Main Fertility) having same erosion levels (Izaurralde et al., 1993). The analytical methods used to determine the chemical and physical soil properties are described by Izaurralde et al. (1993).

2.3 Data Analysis

Barley N uptake was calculated with the equation:

$$\text{Barley N uptake (kg ha}^{-1}\text{)} = \frac{(\%\text{ N in barley}) \times (\text{barley yield kg ha}^{-1})}{100}$$

Fertilizer use efficiency (FUE) was determined as:

$$\text{FUE} = \frac{(\text{N uptake in fertilized treatment} - \text{N uptake in the control})\ (\text{kg ha}^{-1})}{\text{N applied (kg ha}^{-1}\text{)}}$$

where N applied = 150 kg N ha^{-1}

2.4 Statistical Analysis

The barley yield and N uptake data were analyzed with the statistical package SAS (SAS Inst. Inc. 1987). The statistical model used was split plot design. Missing observations in the data set were dealt by PROC GLM. The homogeneity of error

was tested by plotting the residuals against the predicted values using PROC

the normality of the error was tested using PROC UNIVARIATE. Least significant differences (LSD) were used to compare the barley yield and N source main effects.

2.5 Environmental Conditions

Growing season precipitation (May to August) in 1991 was 274 mm at Site 1 and 277 mm at Site 2. Rainfall in June was above normal in June at both sites with 103 mm at Site 1 (normal is 77 mm) and 90 mm at Site 2 (normal is 78 mm). In 1992, the growing season precipitation was very low (almost half of the normal) total rainfall from May to June was 168 mm at Site 1 while at Site 2 it was 147 mm.

2.6 Results

2.6.1 Soil Characteristics

Soil compaction increased with increasing levels of erosion (Tables 2.1 and 2.2). At Site 1, D_b of the surface 10 cm sampling depth increased from 1.25 Mg m^{-3} in the 0 cm cut to [illegible] Mg m^{-3} in the 20 cm cut. While at Site 2, for the same sampling depth D_b increased from 1.17 Mg m^{-3} in the 0 cm cut to 1.31 Mg m^{-3} in the 20 cm cut.

As the levels of erosion increased total C, total and mineral N , extractable P, and water holding capacity decreased (Tables 2.1 and 2.2). At Site 1, the surface soil layer of the 10 cm and 20 cm cuts had, respectively, 50% and 62% lower mineral N than that present in the 0 cm cut (Table 2.1). At Site 2, the 20 cm cut had 45% lower mineral N than that in the 0 cm cut (Table 2.2). At Site 1, the organic C concentration in the surface 10 cm of the 20 cm cut was 75% lower than that present in the 0 cm cut. Whereas at Site 2, organic C was only 38% lower in the 20 cm cut than that found in the 0 cm cut, in the surface 10 cm.

2.6.2 Barley Dry Matter Yield in 1991

At both sites, topsoil removal and N fertilizer significantly affected the dry matter yields of barley (Table 2.3). Barley yields, averaged over all fertilizer treatments decreased as levels of topsoil removal increased (Table 2.3). At both sites, yields were lowest in the 20 cm cut without N fertilization (Appendix 2.1). The effects of topsoil removal on dry matter yields of barley were more severe at Site 1 than at Site 2, as the average barley yields on the former decreased sharply with the increase in the levels of erosion (Appendix 2.1). With no fertilizer addition, the dry matter yields ranged from 440 to 3200 kg ha^{-1} at Site 1 and from 2000 to 4000 kg ha^{-1} at Site 2.

At both sites, barley yields, averaged over all topsoil removal treatment were greater on fertilized treatments than on control treatments (Table 2.3). Also at both sites, KNO_3 gave 10 to 50% higher dry matter yields than that obtained with urea at all levels of topsoil removal (Appendix 2.1).

At Site 1, with both N sources, the yield levels of 20 cm eroded soils were 78 to 90% greater than those obtained without N addition in the same cut (Appendix 2.1). Similarly, the yield levels of 10 cm cut were increased by 65 to 70% with urea and KNO_3. The barley dry matter yields were highest (6000 kg ha^{-1}) in the 10 cm cut with KNO_3 fertilizer (Appendix 2.1). With KNO_3, the dry matter yields in the 20 cm cut were slightly higher (3900 kg ha^{-1}) than those obtained in the 0 cm cut (3200 kg ha^{-1}) without N fertilization. Whereas with urea, barley yields in the 20 cm cut were about 36% lower than those obtained in 0 cm cut without N fertilization (Appendix 2.1). There was a Cut x N interaction at Site 1 at $p \leq 0.1212$ but it did not alter the trends stated in the main effects of Cut and N (Appendix 2.1).

At Site 2, both N sources improved yields of barley grown on the 10 and 20 cm eroded soils by 50 to 60% over that obtained without N fertilization. Potassium nitrate fertilizer increased barley yields in the 20 cm of topsoil removal treatment by 23% over that obtained in the 0 cm of topsoil removal treatment without N. With urea, barley yields of 20 cm cut erosion were similar to those of the non-eroded soils with no N (Appendix 2.1).

2.6.3 Barley Dry Matter Yield in 1992

At both sites, barley dry matter yields were affected by the depth of topsoil removal and N fertilizer (includes residual N from 1991 addition and N fertilizer added in the second year) (Table 2.4). At both sites barley yields averaged over all fertilizer treatments decreased with increasing levels of erosion (Table 2.4). Yield trends were similar to those observed in 1991 (Appendix 2.2). The N addition increased barley yields significantly over the control, at all levels of artificial erosion (Table 2.4.). Both N sources gave somewhat similar crop yields at all levels of erosion (Appendix 2.2).

At both locations, barley yields were remarkably higher in the second year as compared to those obtained in the first year in all treatments (Appendices 2.1 and 2.2). In most of the treatments on average, barley yields tended to be higher at Site 1 than at Site 2. At Site 1, however, barley yields in the 20 cm cut without N were about 27% lower than those obtained in the similar treatment at Site 2 (Appendix 2.2).

At Site 1, barley dry matter yields varied from 2200 to 8700 kg ha^{-1} in the control. Potassium nitrate gave surprisingly higher dry matter yields (8900 kg ha^{-1}) in the 20 cm artificially-eroded soils than in the 10 cm topsoil removal (7700 kg ha^{-1}) treatment (Appendix 2.2). With KNO_3, the barley yields in the 20 cm cut were somewhat similar to those in the 0 cm cut without N addition, and with urea the yields in the 20 cm erosion were slightly lower than those in the 0 cm erosion.

At Site 2, the barley yield trend was similar to that of the first year (Appendices 2.1 and 2.2). The dry matter yields ranged from 3000 to 5900 kg ha^{-1} in the treatments with no N addition. With KNO_3, the barley yields on the 20 cm artificially eroded soils were 20% higher than those obtained on the non-eroded soils without N. Whereas with urea, the yields in the 20 cm cut were only 11% higher than those obtained in the 0 cm cut with no N fertilization (Appendix 2.2).

2.6.4 Barley N uptake in 1991 and 1992

Topsoil removal and N source significantly affected barley N uptake in both years and both locations (Table 2.5 and 2.6). Barley N uptake decreased linearly with depth of topsoil removal (Appendices 2.3 and 2.4). It was noted at both sites that, barley N uptake appeared to be remarkably higher in 1992 than in 1991 (Appendix 2.2). Addition of N increased barley N uptake significantly over the control at all levels of topsoil removal (Tables 2.5 and 2.6).

Site 1:

In 1991, both KNO_3 and urea produced similar plant N uptake in the 0 and 10 cm cuts, but in the 20 cm cut however, KNO_3 gave 16% higher N uptake than urea (Appendix 2.3). With KNO_3, the N uptake by barley in the 20 cm cut was about 23% higher than that obtained in the 0 cm cut without N addition.

In 1992, the trend was different, with urea inducing 8 to 15% higher N uptake than with KNO_3 at all depths of topsoil removal, except for the 20 cm cut, where KNO_3 gave 10% higher N uptake than urea (Appendix 2.4).

Site 2:

The barley N uptake trend was similar in both years. Potassium nitrate gave notably higher N uptake than urea at all levels of topsoil removal (Appendices 2.3 and 2.4). In 1991, with KNO_3, N uptake by barley was 15% higher in the 20 cm cut than that obtained in the 0 cm cut without N addition. Whereas in 1992, both N source gave about 30 to 40% higher N uptake in the 20 cm cut than that obtained in the 0 cm cut with no N addition (Appendix 2.4).

2.6.5 Fertilizer Use Efficiency (FUE) of Barley in 1991 and 1992

At Site 1 in 1991, FUE with both N source increased with increasing levels of erosion. At Site 2, however, the trend was opposite (Fig. 2.5). At Site 1, FUE ranged from 0.14 to 0.32 with KNO_3, and with urea it varied from 0.14 to 0.26. Whereas, at Site 2, the FUE ranged from 0.24 to 0.18 with KNO_3, and with urea it varied from 0.21 to 0.14.

In 1992, the FUE values were relatively higher than those in 1991. At Site 1, the FUE values were lowest in the 10 cm cut, and maximum in the 20 cm cut with both N sources (Appendix 2.5). At Site 2, the FUE trend was similar to that of the previous year (Appendix 2.5).

2.7 Discussion

The substantial reduction of barley yields and N uptake with increased levels of topsoil removal were likely associated with a deterioration of physical, chemical and biological soil properties. Topsoil removal exposed subsoil layers which were compact and low in plant nutrients (especially in N and P), organic C, and water holding capacity. Similar results were reported by others (Dormaar et al., 1986; Shafiq et al., 1988; Tanaka and Aase, 1989 and Malhi et al., 1994).

The relatively lower barley yields obtained at Site 1 than at Site 2 in 1991, were probably due to intrinsic properties of Gray Luvisols. This was evident from the relatively lower values of mineral N and organic C measured in the Gray Luvisol than those in the Black Chernozem.

Overall, lower yields obtained at both sites in 1991, may have been due to late sowing of barley in that year. The relatively higher yields of barley obtained at Site 1 than at Site 2 in 1992, might have been due to greater amount of moisture stored in the soil profile at Site 1 than at Site 2, from the previous year's heavy precipitation. In 1991, the soils at Site 2 had supported better plant growth (yields were higher at Site 2 than at Site 1) and likely used more moisture during that year. Whereas, comparatively less fertile soils at Site 1 supported less plant growth and retained in turn greater amounts of unused soil moisture. Also, in 1992, the precipitation received during May to June was only 38% of the normal at Site 2 while at Site 1, it was 55% of the normal.

Reduced N uptake by barley with increased artificial erosion may have been due to reduced N mineralization of eroded soil. Decreased N mineralization potentials were measured with the increasing erosion levels in a laboratory experiment conducted with the same soils and five artificial erosion levels (0-, 5-, 10-, 15-, and 20-cm) (Izaurralde et al.,1993). There was a positive correlation between N uptake and amounts of N-mineralized over the growing season. Similar results were found in a greenhouse experiment with barley grown on artificially eroded soils of the Malmo and Peace Hills series (Malhi et. al., 1994). The overall higher N uptake of barley obtained in the 1992, was probably due to timely sowing and resultant higher yields in that year.

Although N fertilizer additions improved barley yields and N uptake at all levels of artificial erosion, the response to added N was greatest from barley growing on the 20 cm cut due to low plant N availability in this treatment. Several researchers (Soper et al., 1971; Carson et al., 1974; Walker, 1975; and Nyborg and Malhi, 1990) have reported increased crop response to applied N, when the level of extractable NO_3-N was low.

At Site 1, the increased FUE values with increasing levels of erosion, indicated that the crop use of added N in less productive soils was more prominent than in more productive soils (Site 2). At Site 2, the decreasing trend of FUE values with increasing levels of erosion might have been either due to partial immobilization of the added N soon after its application or its loss from the soils.

Nitrogen fertilization with KNO_3 improved the yields and N uptake of barley growing on the 20 cm cut plots to the levels of non-fertilized non-eroded soils. These results agree with those reported by Dormaar et al. (1988). Whereas, from a similar study using N and P fertilizers, barley grain yields of fertilized eroded plots were reported to be lower than those of non-fertilized non-eroded plots (Izaurralde et al., 1994). However, under the same fertilizer treatment, barley yields of fertilized 20 cm cut plots were lower than those of 0 cm cut plots.

The lower yields and N uptake values with urea than KNO_3 in most topsoil removal treatments were probably the result of the direct availability of KNO_3 to plants whereas urea was available to plants only after hydrolysis to form NH_4. I speculate that, the low biological activity expected in artificially eroded soils might not have been sufficient to provide urease enzyme for a rapid hydrolysis of urea. In addition lower yields and N uptake values observed with urea were probably the result of the band placement of N fertilizer (pers. comm. S.S. Malhi). Potassium nitrate is quickly mobile and thus plant roots reach it soon. By comparison NH_4 from urea (after hydrolysis) is only slowly mobile in the soil and consequently roots have to grow to reach the NH_4. The distance for root to encounter NH_4 could be considerable since the distance between the seed row and fertilizer band was 12 cm.

The high pH and NH_3 toxicity from urea hydrolysis on barley root seedling growth were considered to be minimal because urea was banded 12 cm away from the seed rows. Also, acidic environment produced from TSP dissolution might have reduced the NH_3 toxicity by reducing soil pH (Fan and MacKenzie, 1995).

2.8 Conclusions

Yields and N uptake of barley decreased with topsoil removal. Barley dry matter yield and N uptake were lowest in the 20 cm topsoil removal treatment. Nitrogen fertilizer addition improved barley yields and N uptake at all levels of topsoil removal. Barley yields of the 20 cm artificially-eroded soils were increased to the yield levels of non-eroded and non-fertilized soil with KNO_3 at both sites and with urea at Site 2. Barley yields and N uptake were greater with KNO_3 than with urea in most erosion treatments. Fertilizer use efficiency increased with greater erosion at Site 1 but trend was opposite at at Site 2. Barley yields and uptake were, affected by soil type, time of sowing and growing season precipitation.

Table 2.1. Characteristics of the Gray Luvisol Soil at Site 1 (Izaurralde et al.,1993)..

Cut	Sampling Depth	Field Capacity	Bulk Density	Sand	Silt	Clay	pH	Extractable P	Total P	Mineral N	Total N	Organic C
cm	cm	$m^3 m^3$	Mg m^{-3}		g kg $^{-1}$					mg kg^{-1}		g kg^{-1}
0	0-10	0.336	1.25	450	330	220	6.5	40	840	16	3000	33.8
	10-20	0.257	1.30	440	370	190	6.4	10	570	9	1390	14.0
	20-30	0.241	1.36	430	350	220	5.9	3	380	7	1000	8.0
	30-60	0.244	1.50	410	280	310	5.5	3	400	6	600	6.9
	60-90	0.238	1.50	0.41	0.31	0.28	6.8	1	460	3	500	6.1
10	0-10	0.274	1.30	440	350	210	6.4	12	540	8	1700	18.0
	10-20	0.252	1.38	430	340	230	6.1	1	400	6	1000	9.0
	20-30	0.257	1.47	420	300	280	5.8	1	370	5	830	8.0
	30-60	0.257	1.50	410	290	300	6.1	1	400	4	610	7.4
	60-90	0.258	1.50	410	310	280	7.8	1	500	4	520	8.4
20	0-10	0.252	1.38	430	330	240	6.2	2	480	6	930	8.5
	10-20	0.253	1.45	420	310	270	5.6	3	440	5	850	7.3
	20-30	0.256	1.49	410	290	300	5.5	1	430	4	720	6.7
	30-60	0.253	1.50	410	300	290	6.5	1	520	4	500	6.3
	60-90	0.256	1.50	410	210	280	7.9	1	520	4	470	7.7

Table 2.2. Characteristics of the Black Chernozem Soil at Site 2 (Izaurralde et al.,1993) .

Cut	Sampling Depth	Field Capacity	Bulk Density	Sand	Silt	Clay	pH	Extractable P	Total P	Mineral N	Total N	Organic C
cm	cm	m^3 m^3	Mg m^{-3}		g kg^{-1}					mg kg^{-1}		g kg^{-1}
0	0-10	0.375	1.17	400	300	300	6.6	23	800	11	3600	40.2
	10-20	0.365	1.21	400	300	300	6.7	18	750	12	2960	36.8
	20-30	0.287	1.31	400	300	300	6.6	3	480	9	1250	14.0
	30-60	0.235	1.44	420	260	310	6.7	3	400	6	510	5.3
	60-90	0.224	1.58	440	290	280	6.6	1	410	7	450	4.7
10	0-10	0.356	1.24	400	300	300	6.7	14	720	10	2850	34.3
	10-20	0.292	1.31	410	290	300	6.5	3	560	8	1420	16.3
	20-30	0.263	1.37	420	270	310	6.5	5	440	9	1040	11.6
	30-60	0.235	1.48	430	270	300	6.4	1	350	7	580	6.0
	60-90	0.228	1.60	440	290	280	7.7	1	440	7	440	5.7
20	0-10	0.321	1.31	410	290	300	6.8	12	640	6	2050	25.0
	10-20	0.251	1.37	420	280	310	6.6	4	550	5	750	7.7
	20-30	0.237	1.41	430	270	300	6.5	4	520	7	610	6.3
	30-60	0.229	1.52	430	280	290	6.6	4	440	6	500	4.8
	60-90	0.229	1.60	440	290	280	8.0	2	490	7	460	6.0

Table 2.3. Effects of artificial erosion and N source (applied at 150 kg N ha^{-1}) on dry matter yield of barely in 1991.

	Site	
Treatment	1	2
	kg ha^{-1}	
Cut (cm)		
0	4757a	5889a
10	4332a	4515ab
20	2111b	3706b
Fertilizer source		
Check	1808c	2920c
KNO_3	5141a	6002a
Urea	4250b	5187b

Analysis Of Variance

Source	df	Mean Square	Pr>F	df	Mean Square	Pr>F
Rep	3	3.2E6		3	2.2E6	
Cut	2	2.3E7	0.0174	2	1.5E7	0.0256
Error (a)	6	2.7E6		6	2.0E6	
N source	2	3.6E7	0.0001	2	2.9E7	0.0001
Cut x N source	4	1.7E6	0.1212	4	1.2E6	0.9498
Error (b)	17[†]	8.0E5		17[†]	7.1E5	

a,b Means followed by the same letter for among cuts means and between N source means are not significantly different at 5% probability level to the least significant difference test (LSD).

[†] Both sites had one missing observation.

Table 2.4. Effects of artificial erosion and N source (applied at 150 kg N ha^{-1}) on dry matter yield of barely in 199[illegible]

Treatment	Site 1	Site 2
	kg ha^{-1}	
Cut (cm)		
0	11200a	8692a
10	7107b	7357a
20	6397b	5637b
Fertilizer source		
Check	5004b	4339b
KNO_3	9531a	8965a
Urea	10169a	8383a

Analysis Of Variance

Source	df	Mean Square	Pr>F	df	Mean Square	Pr>F
Rep	3	7.5E6		3	9.1E6	
Cut	2	8.1E7	0.0001	2	2.8E7	0.0110
Error (a)	6	1.2E6		6	2.7E6	
N source	2	9.5E7	0.0001	2	7.6E7	0.0001
Cut x N source	4	4.0E6	0.4674	4	3.4E5	0.8983
Error (b)	18	7.7E7		18	2.3E7	

a,b Means followed by the same letter for among cuts means and between N source means are not significantly different at 5% probability level to the least significant difference test (LSD).

Table 2.5. Effects of artificial erosion and N source (applied at 150 kg N ha^{-1}) on N uptake by barely in 1991.

Treatment	Site 1	Site 2
	kg ha^{-1}	
Cut (cm)		
0	57.8a	65.2a
10	49.6ab	46.0b
20	36.5b	38.4c
Fertilizer source		
Check	24.2b	29.8b
KNO_3	61.5a	62.4a
Urea	58.3a	57.3a

Analysis Of Variance

Source	df	Mean Square	Pr>F	df	Mean Square	Pr>F
Rep	3	93.5		3	26.7	
Cut	2	1261.3	0.0335	2	2272.7	0.0002
Error (a)	6	199.9		6	50.0	
N sourcce	2	4954.6	0.0001	2	3538	0.0001
Cut x N source	4	191.4	0.2513	4	34.9	0.4998
Error (b)	17[†]	129.1		17[†]	39.96	

a,b Means followed by the same letter for among cuts means and between N source means are not significantly different at 5% probability level according to the least significant difference test (LSD).

[†] Number of missing observation in data: Site 1=1; Site 2 = 1.

Table 2.6. Effects of artificial erosion and N source (applied at 150 kg N ha^{-1}) on N uptake by barely in 1992.

Treatment	Site 1	Site 2
	kg ha^{-1}	
Cut (cm)		
0	156.3a	111.5a
10	95.1b	92.5ab
20	85.8b	75.2b
Fertilizer source		
Check	56.1b	44.7c
KNO_3	134.9a	124.2a
Urea	146.2a	110.3b

Analysis Of Variance

Source	df	Mean Square	Pr>F	df	Mean Square	Pr>F
Rep	3	760.9		3	768.5	
Cut	2	15919.3	0.0001	2	3954.7	0.0129
Error (a)	6	185.7		6	404.0	
N source	2	26148.7	0.0001	2	21615.2	0.0001
Cut x N source	4	275.1	0.7226	4	67.7	0.7347
Error (b)	15[†]	529.2		18[†]	134.77	

a,b Means followed by the same letter for among cuts means and between N source means are not significantly different at 5% probability level according to the least significant difference test (LSD).

[†] Number of missing observation in data: Site 1=3; Site 2 = none.

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CHAPTER 3

FATE OF ^{15}N-LABELLED NITROGRN FERTILIZERS APPLIED TO ARTIFICIALLY-ERODED SOILS.

3.1 Introduction

Crop productivity of artificially eroded soils could be restored by adding commercial fertilizers, particularly N and P (Englestad and Shrader, 1961; Morrison and Shaykewick, 1987; Shafiq et al., 1988; Tanaka and Aase, 1987; Malhi et al., 1994; Izaurralde et al., 1994). In many cases, however, crop yields of extremely eroded soils could not be brought up to the yield levels attained in non- or slightly-eroded soils (Frye et al., 1982; Massee and Waggoner, 1985; Mielke and Schepers, 1986; Malhi et al., 1994; Izaurralde et al., 1994).

Cultivated fields often exhibit various degrees of erosion by wind and water (De Jong et al., 1983; De Jong, 1988; Rennie, 1986; Howitt, 1991). Soil erosion induces variability in soil properties and, in turn may produce a variable yield response to fertilizer application. Uniform application of fertilizer on a field may result in application of rates equal to or either greater or lower than optimum levels. From an economic point of view an optimum level of fertilizer application is defined as the rate at which marginal returns are maximized. From an environmental point of view, an optimum fertilizer application results when losses from the plant-soil system are minimal. The loss of fertilizer N through denitrification, volatilization and leaching is a serious environmental concern. Gaseous losses of N as nitrogen oxides (NO, N_2O, NO_2) through denitrification contribute to the greenhouse gas problem and therefore to global warming (Wang et al., 1976). On the other hand, leaching of nitrate below the root zone impairs ground water quality.

Various field and laboratory experiments conducted in different regions of Alberta, have indicated that denitrification is a major mechanism of N loss, particularly during early spring thaw of surface soil (Malhi and Nyborg, 1983; Nyborg et al., 1990; Heaney et al., 1992). Those studies have also indicated that little movement of nitrates occur below 30 cm soil depth. Research in Alberta has been conducted to understand and quantify the erosion-crop productivity relationship (Larney et al., 1995), but little has been done to understand the fate of N fertilizers applied to eroded soil.

The objective of this study was to find the fate of ^{15}N-labelled fertilizer N applied to artificially-eroded soil. The ^{15}N-labelled fertilizers were used to account for N the in plant-soil system for a period of two years and to estimate N losses. The study also explored the downward movement of the added ^{15}N in eroded-and non-eroded soils by measuring the ^{15}N-in total N and in nitrate (NO_3-N) at various soil depths.

3.2 Materials and Methods

Site and soil description, management history and field experiment (includes experimental layout, plant harvest) are described in Chapter 2.

3.2.1 Soil Sampling Procedure

After dry matter yield determination in 1991 the plant samples were ground to pass a 2 mm sieve. Soil samples were taken on 15 September 1991 on one set of frames at the following depth intervals: 0-15, 15-30, 30-45, 45-60, and 60-75 cm. The sampling technique varied with the depth interval sampled. For the 0-15 cm depth all soil was removed from the frames, mixed well in a wheel barrow, and a representative sample removed. For the second depth (15-30 cm) soil samples were taken by combining three cores (diagonally across the frame) by using a 2 cm diameter coring tube. Below the 30 cm depth, two to three cores (2- or 3.2-cm diameter) were taken diagonally across the frame with a hydraulic, truck-mounted sampler. The individual cores were then combined to form one set of samples per frame. The soil samples were placed in aluminum trays and air dried at room temperature (22 °C). The soil samples were then mixed and ground to pass 2 mm sieve.

The second set of frames was sown again to barley on 11 May 1992. In order to account for the residual ^{15}N recovery (from the previous year's ^{15}N-labelled N application) non-labelled N was applied at 150 kg N ha^{-1} either as KNO_3 or urea and P at 10 kg P ha^{-1} as TSP. Soil sampling was done after harvest on 15 August 1992 as decribed above. Plant and soil samples were processed as described above.

3.2.2 Chemical Analysis of Plant and Soil Samples

Determination of ^{15}N in total N in plants and soils:

The 2 mm ground samples of plant and soil were manually homogenized and then subsamples of plant and soil were pulverised separately, in a vibrating-ball mill (Retsch, Type MM2, Brinkmann Instruments Co., Toronto, Ontario, Canada), as required for sample preparation for mass spectrometer analysis. Ethanol was used to chemically clean the mill after vacuum cleaning (Binkley et al., 1985). The finely ground plant and soil samples were analysed for total N and atom % ^{15}N abundance in total N using an Automatic Nitrogen Analyzer (ANA) 1500 coupled to a Stable Isotope Ratio Analyzer (SIRA) 10 Mass Spectrometer (VG Inorganic, Astonway, Middlewich, Cheshire, England). The mass spectrometer comprises of an automated Dumas system (Carlo Erba) for total N and a flow-through system of the nitrogen gas so generated for isotope ratio analysis using a triple collector system.

Determination of ^{15}N in mineral N in soil:

Soil samples of 0-15 cm, 15-30 cm, and 30-45-cm depths were analysed for mineral N (NO_3 and NH_4). Approximately 20 g of a ground soil subsample were shaken with 100 mL of 2M KCl for one hour and the supernatant liquid was filtered through Whatman filter paper no. 42. Soil NO_3 and NH_4 were then determined by a colorimetric method, using a Technicon Auto Analyzer (Technicon Industrial Systems, 1973a and 1973b). The Dumas combustion method requires a minimum of 50 μg N per sample for accurate ^{15}N diffusion anaylsis of ^{15}N in mineral N. Therefore, the mass of extracted soil samples was increased for profile samples of lowest mineral N. Low concentration (<

1ppm) of mineral N was found below 45-cm depth, and so ^{15}N diffusion analysis was conducted only for the 0-15, 15-30, and 30-45 cm depths.

Based on preliminary analyses of the KCl extract for mineral N, the soil extracts were analyzed for ^{15}N in NO_3-N and NH_4-N using ^{15}N-diffusion technique as modified by Brooks et al. (1989). Briefly, 40 to 60 mL of KCl extract were placed in a 120 mL specimen container and a glass-filter disc saturated with 10 µL of 2.5M $KHSO_4$ was suspended above the solution in a thin (0.35 mm) steel wire. For the determination of ^{15}N in NH_4, approximately 0.2 g of MgO was added to the extract after suspending the acid ($KHSO_4$) soaked disc. The container was then quickly capped and the mixture manually shaken for one minute. The mixture was carefully shaken so that it did not touch the suspended glass-filter disc. The container was then left for a period of six days, during which the NH_3 gas evolved from NH_4-N was trapped by $KHSO_4$ in the glass-filter disc. For the determination of ^{15}N in NO_3-N, the container was left uncapped for 48 hours after MgO addition to let the NH_3-N dissipate. After adding approximately 0.4 g of Devarda's alloy, the container was capped and left for six days, to collect the NO_3-N in the extract as NH_3 on the acid-soaked glass-filter disc. After six days the discs were removed and placed in a tray, and allowed to dry in a desiccator with silica gel as the drying agent. The dried discs (diffused samples) were then placed directly in the ANA-SIRA 10 Mass Spectrometer for N and ^{15}N analysis.

For soil samples with low mineral N two to four specimen containers (depending upon the mineral N concentration) were used per soil sample with 40 to 60 mL of KCl extract in each. The rest of the procedure followed was as described above except, upon drying, the discs of the same soil sample were pooled together while placing them in the mass spectrometer.

3.3 Data analysis

Plant and soil recovery of applied ^{15}N in plants and soil was calculated from the ^{15}N abundance in plant and soil samples by using the following equations:

% Recovery of applied N in plant =

$$\frac{(\%\text{N plant}) \times (\text{yield kg ha}^{-1}) \times (\text{atom \% }^{15}\text{N excess of total N in plant sample})}{(150 \text{ kg N ha}^{-1}) \times (\text{atom \% }^{15}\text{N excess of fertilizer})} \text{...............(1)}$$

% Recovery of applied N in soil =

$$\frac{(\%\text{N soil}) \times (\text{kg soil ha}^{-1}) \times (\text{atom \% }^{15}\text{N excess of total N in soil sample})}{(150 \text{ kg N ha}^{-1}) \times (\text{atom \% }^{15}\text{N excess of fertilizer})} \text{.....................(2)}$$

where,

(i) Atom % ^{15}N excess of total N in plant or soil =

atom % ^{15}N abundance of total N in plant or soil of fertilized plot - atom % ^{15}N abundance of total N in plants or soil of control plot.

(ii) Atom % ^{15}N excess of fertilizer = atom % ^{15}N abundance of fertilizer - atom % ^{15}N abundance of atmosphere (0.3663 %)

% Recovery of applied N as NO_3-N and NH_4-N in soil =

$$\frac{(\%\text{MN soil}) \times (\text{kg soil ha}^{-1}) \times (\text{atom \% }^{15}\text{N excess of MN in soil}))}{(150 \text{ kg N ha}^{-1}) \times (\text{atom \% }^{15}\text{N excess of fertilizer})} \text{................................(3)}$$

where,

(i) MN denotes either NO_3-N or NH_4-N.

(ii) Atom % ^{15}N excess of MN =

atom % ^{15}N abundance of soil NO_3-N or NH_4-N of fertilized plots - atom % ^{15}N abundance of soil NO_3-N or NH_4-N of control plots

Mass balance of the applied ^{15}N was calculated by replacing the missing observations in plant and soil recovery data, by the SAS estimates from analysis of variance, using PROC GLM as described below in statistical analysis. The amount of ^{15}N which could not be accounted from mass balance was assumed to be lost from the plant-soil system.

3.4 Statistical Analysis

The plant and soil data were analysed with the general linear models procedure (PROC GLM) in SAS version 6.08 (SAS Inst. Inc. 1987). The statistical model used was split plot design. Missing observations in the data were dealt by PROC GLM. Recovery of ^{15}N in total N and mineral N in soil at various sampling depths were analysed by ANOVA for each depth. Cumulative recoveries were analysed separately. The homogeneity of error variance was tested by plotting the residuals against the predicted values using PROC PLOT, and the normality of the error was tested using PROC UNIVARIATE. The protected Fisher's Least Significant Difference (LSD) test was used for mean separations.

ANOVA tests were not run for the unaccounted fraction of applied ^{15}N because the missing observations that had been replaced with SAS estimates resulted in the loss of 4-5 error degrees of freedom. Average values with their respective standard errors are presented and discussed instead.

3.5 Results

3.5.1 Plant Recovery of Applied ^{15}N

In 1991, topsoil removal did not significantly affect the plant recovery of added ^{15}N at either site (Table 3.1). The N source effect was significant at Site 2 only where the recovery was 15% higher with KNO_3 than with urea. Overall, plant uptake of applied N was higher at Site 1 than at Site 2 (Appendix 3.1).

In 1992, at neither site were the effects of topsoil and N source on the recovery of residual ^{15}N in plants significant (Table 3.2). The residual N recovery in plants was quite similar with KNO_3 and urea in the 0 and 10 cm cut but in the 20 cm cut it tended to be greater with urea than with KNO_3 (Appendix 3.1).

3.5.2 Soil Recovery of ^{15}N in total N

Soil recovery of total ^{15}N in the 0 to 75 cm depth interval was calculated from the ^{15}N recovered at various soil depths (0-15, 15-30, 30-45, 45-60, 60-75 cm).

In 1991, the ANOVA tests for both sites indicated no significant effect of neither artificial erosion nor N source on the recovery ^{15}N in total soil N (Table 3.3). At Site 1, the recovery of ^{15}N in urea-treated soil was greater than that in KNO_3-treated soil. At Site 2, the recovery of ^{15}N in soil, tended to increase ($p < 0.068$) with increasing levels of topsoil removal (Appendix 3.2).

At both sites, the recovery of residual ^{15}N in the soil, when averaged over all the topsoil removal treatments was significantly greater with urea than with KNO_3 (Table 3.4). At both sites in 1992 there was no effect of artificial erosion on soil recovery of residual ^{15}N (Table 3.4). The N-source effect, however, was significant at both sites (Table 3.4). At both locations, the recovery of residual ^{15}N increased with increasing depth of topsoil removal with urea (Appendix 3.2). At Site 1, there was a significant interaction between erosion level and N source (Table 3.4) but it did not alter the main effect results (Appendix 3.2).

3.5.3 Unaccounted Fraction of Applied ^{15}N From the Plant-Soil System:

At both sites, the ^{15}N mass balance suggested substantial losses of N from the plant-soil system during the two years (Appendices 3.4 and 3.5). In both years, unaccounted ^{15}N at Site 1 varied from 14 to 38% while at Site 2 it varied from 38 to 53% (Appendix 3.3).

Unaccounted Fraction of Applied ^{15}N During the 1991 Growing Season:

The ^{15}N mass balance indicated that, by mid-September 1991, approximately 20 to 27% of the added N had been lost from the artificially eroded soils receiving KNO_3 at Site 1 and with both N source at Site 2 (Appendix 3.3). At Site 1, with urea application, only 8 to 10% of the added N was lost from the artificially eroded soils during the 1991 growing season (Appendix 3.3). At both locations, however, the major loss (29 to 35%) of added N was from non eroded soils, with both N sources (Appendix 3.3).

Unaccounted Fraction of Applied ^{15}N During the Period Between Harvests:

For the unaccounted fraction of applied ^{15}N between harvests (from 2 September 1991 to 15 August, 1992) we subtracted the unaccounted fraction of added ^{15}N during the growing season in 1991 from the total unaccounted fraction of added ^{15}N in two years. With both N sources at both sites, losses of residual ^{15}N from artificially eroded soils were higher than from non-eroded soils (Appendix 3.3). At Site 1, the loss of added N between the two harvests in the 20 cm cut was larger with KNO_3 (13.6 kg ha^{-1}) than with urea (6.2 kg ha^{-1}); while in the 10 cm cut it was higher with urea (30.4 kg ha^{-1}) than with KNO_3 (21.4 kg ha^{-1}). At Site 2, the N losses between harvests from 10- and 20-cm artificially-eroded soils fertilized with KNO_3 were 3.8 and 13.7 kg ha^{-1} greater than those occurred during the first growing season.

The two year average of ^{15}N loss suggested that there was little difference among the eroded and non-eroded treatments with KNO_3 at Site 1 and with urea at Site 2 (Appendix 3.3). At both sites, loss of added N over two years was higher with KNO_3 than with urea. The N loss was lowest at Site 1 with urea (21.3 kg ha^{-1}) from the 20 cm topsoil removal treatment, and maximum at Site 2 with KNO_3 (79 kg ha^{-1}) from 20 cm topsoil removal treatment.

3.5.4 Soil Profile Distribution of Total ^{15}N Retained in Soil

Site 1, 1991:

The statistical analysis for ^{15}N recovery at different soil depths (0-15 cm, 15-30 cm, 30.45 cm, 45-60 cm, and 60-75 cm), indicated that topsoil removal was significant only at 15-30 cm and 30-45 cm soil depths, while the N source effect was significant only at 0-15 cm soil depth (Table 3.5). In 15-30 cm and 30-45 cm depths, the recovery of added ^{15}N averaged over both N sources increased significantly with increasing levels of erosion. Soil recovery of added ^{15}N averaged over all erosion treatments was significantly greater with urea than with KNO_3, in surface 15 cm (Table 3.5).

In most cases, the added ^{15}N that remained in soil was found primarily in the 0-15 cm depth except in the 20 cm cut plots fertilized with KNO_3 where the ^{15}N recovered in the surface 15 cm depth was lower than that found in the 15-30 cm depth (Table 3.5). However, it was noted that within three months of N application (June 6 to September 15), a considerable accumulation of ^{15}N occurred in the 45-75 cm depth. For instance, at the 60-75 cm depth recoveries of ^{15}N in the 10- and 20-cm cut treatments were 1 and 2.5 kg ha^{-1}, respectively. The recovery of applied ^{15}N in deeper layers (30-75 cm) of artificially eroded soils was greater than that of non-eroded soil (Table 3.5). With both N sources, the soil recovery of ^{15}N below the 45-cm depth in non-eroded soils was less than 1 kg ha^{-1}, (Table 3.5).

In the surface 15 cm, the soil recovery of ^{15}N in KNO_3-treated plots tended to decrease with increasing depth of topsoil removal, but the trend was opposite with urea (Table 3.5). In the 20 cm cut, the soil recovery of ^{15}N was notably greater with KNO_3 than with urea at depth intervals of 15-30, 30-45, and 45-60 cm (Table 3.5).

Site 1, 1992:

The topsoil removal effect was significant at 0-15, 15-30, and 30-45 cm soil depths while the N source effect was significant only at the 0-15 cm depth (Table 3.6). The residual ^{15}N recovery in the soil followed a similar trend to that of the first year, i.e., the N recovery in deeper soil layers was greater in artificially eroded soil (Table 3.6). In the 0-45 cm depth interval, the recovery of residual ^{15}N averaged over both N sources increased significantly with increasing levels of erosion. In the 0-15 cm depth, the residual ^{15}N recovery averaged over all erosion levels was significantly greater with urea than with KNO_3 (Table 3.6).

In the 0 cm cut, the recovery of ^{15}N averaged over both N sources, in the 15-30, 30-45, 45-60, 60-75 cm soil depths, was substantially greater in 1992 than in 1991 (Tables 3.5 and 3.6). Whereas, in the 10- and 20-cm cuts, recoveries of ^{15}N in 30-45, 45-60, 60-75 cm soil depths were somewhat lower than those in 1991 (Table 3.6).

Site 2,1991:

The recovery of applied ^{15}N in soil at various depths was not significantly affected by either topsoil removal or N source (Table 3.7). In most cases, however the recovery of added ^{15}N averaged over both fertilizer treatments was greater in artificially eroded than non-eroded soil (Table 3.7).

As at Site 1, most ^{15}N was recovered in the surface 15 cm depth of all treatments. Topsoil removal increased the downward movement of applied ^{15}N particularly in the 10 cm topsoil removal treatment (Table 3.7). In this treatment, the ^{15}N recovery averaged over both N sources, ranged from 2.8 to 1.2 kg ha^{-1}, in the 45-75 cm depth interval. However, there was little accumulation of ^{15}N below 30- and 45- cm soil depths in the non-eroded and 20 cm eroded treatments respectively (Table 3.7).

Site 2, 1992:

Statistical analyses indicated that topsoil removal did not affect the residual ^{15}N recovery at different soil depths. Except for the 0-15 cm depth, N source did not significantly affect soil ^{15}N recovery (Table 3.8).

In the 0- and 20-cm cut at depths deeper than 30 cm soil recovery of ^{15}N increased from 1991 to 1992 (Tables 3.7 and 3.8). In the 20 cm topsoil removal, N recovery in the 30-75 cm depth interval was 2 kg ha^{-1} greater than that recovered in the previous year. Similarly, for the same depth interval, the ^{15}N recovery in the non-eroded treatment was about 2.5 kg ha^{-1} greater than that recovered in the first year (Tables 3.7 and 3.8). Whereas, in the 10 cm cut, soil recoveries of residual ^{15}N were somewhat lower than those recovered in the previous year, in the 30-45, 45-60 and 60-75 cm depths (Tables 3.7 and 3.8).

3.5.5 Recovery of ^{15}N in Soil NO_3-N at Various Depths, in 1991

Site 1:

Nitrogen source did not significantly affect the recovery of ^{15}N in soil NO_3-N in first three depth intervals. The topsoil removal effect was significant only in the 15-30 cm depth interval (Table 3.9).

In most cases, a greater proportion of ^{15}N recovered in soil NO_3-N remained within the 0-15 cm depth, nevertheless, the recovery of ^{15}N in NO_3-N in the 20 cm cut, from KNO_3 was notably lower in the 0-15 cm depth than that recovered either in the 15-30 cm or in the 30-45 cm depth (Table 3.9). At the 15-45 cm depth interval, the recovery of ^{15}N in soil NO_3-N from both N sources tended to increase with increasing level of erosion, (Table 3.9). At the 30-45 cm depth interval the recovery of ^{15}N in NO_3-N was 1.3 kg ha^{-1} in the 10 cm cut, while it was 3.7 kg ha^{-1} in the 20 cm cut .

Site 2:

Artificial erosion and N source did not affect soil recovery of ^{15}N in NO_3-N at none of the three depths sampled, except for the 15-30 cm depth interval where the topsoil-removal effect was significant (Table 3.10). At the 15-30 cm soil depth, the soil recovery of ^{15}N in NO_3-N was greater in eroded soils than in non-eroded soils (Table 3.10). As at Site 1, the soil recovery of ^{15}N in NO_3-N occurred mostly within the surface 15 cm depth (Table 3.10), except for the 10 cm cut where the average recovery in the 30-45 cm depth was 1.4 kg ha^{-1}.

3.5.6 Recovery of ^{15}N in Soil NH_4-N at Various Depths in 1991

Site 1:

Soil recovery of ^{15}N in NH_4-N within the first two depths was significantly affected by the level of artificial erosion and N source (Table 3.11). The recovery of ^{15}N in soil NH_4-N in the first two soil depths increased significantly with increasing amounts of topsoil removal. In the 0-15 and 15-30 cm depths, the soil recovery of ^{15}N in NH_4-N averaged over all erosion treatments was significantly greater with urea than with KNO_3

(Table 3.11). For all treatments, the average soil recovery of ^{15}N in NH_4-N below 15 cm depth was negligible (< 0.1 kg ha^{-1}).

Site 2:

The effects of topsoil removal and N source on recovery of ^{15}N in NH_4-N in soil were significant only in the 0-15 cm depth (Table 3.12). As at Site 1, all treatments had negligible soil recoveries of ^{15}N in NH_4-N below 15-cm depth. In the 0-15 cm depth, soil recovery of ^{15}N in NH_4-N averaged over both N sources in the 20 cm cut was significantly greater than in 10 cm cut (Table 3.12). Recovery of ^{15}N in NH_4-N in soil from urea was greater than with KNO_3 (Table 3.12). Overall, a greater proportion of ^{15}N recovered in mineral N at various depths was present as NO_3 than as NH_4 (Tables 3.9, 3.10, 3.11, and 3.12).

3.5.7 Recovery of ^{15}N in Soil NO_3-N and NH_4-N in 1992

At both sites, recoveries of ^{15}N in mineral N below 15-cm depth were insufficient to conduct ^{15}N diffusion analyses. Therefore, only soil recoveries of ^{15}N in mineral N for the first depth were statistically analysed (Tables 3.13 and 3.14).

At both sites, the greatest proportion of the ^{15}N recovery in soil mineral N occurred as nitrate (Tables 3.13 and 3.14). At neither location did topsoil removal and N source affect recovery of ^{15}N in soil NO_3-N (Tables 3.13 and 3.14). The recovery of ^{15}N in NH_4-N in soil was significantly affected by the level of artificial erosion at Site 1, while it was affected by type of N source at both sites (Tables 3.13 and 3.14).

The recovery of ^{15}N in soil NH_4-N averaged over erosion levels was significantly greater with urea than with KNO_3 (Tables 3.13 and 3.14). At Site 1, the soil recovery of ^{15}N in NH_4-N was significantly greater in the 20 cm cut than either in the 0- or 10-cm cuts (Table 3.13). Unexpectedly in the 20 cm cut, the soil recovery of ^{15}N in NO_3-N with urea was greater than with KNO_3 (Tables 3.13 and 3.14).

3.5.8 Immobilization of Applied ^{15}N in Soil

The amount of added ^{15}N immobilized by soil (i.e., ^{15}N in total N in soil minus ^{15}N in mineral N in soil) was calculated for the first three depths (0-15, 15-30,. 30-45 cm depths) and a cumulative value obtained for the 0-45 cm depth interval in 1991 only.

At both sites, artificial erosion and N source effects were not significant on the recovery of ^{15}N in immobilized soil N (Tables 3.15 and 3.16). At Site 1 the average recovery of ^{15}N in immobilized N was larger than ^{15}N in mineral N. At Site 2, ^{15}N in immobilized N was relatively lower than ^{15}N in mineral N. At both sites, immobilization of added N tended to be larger with urea than with KNO_3 (Tables 3.15 and 3.16) Overall, N immobilization at Site 1 was greater than at Site 2.

3.6 Discussion

Sustained and sufficient plant nutrient uptake depends upon favorable growth conditions. Of these, good soil physical, chemical and biological properties are paramount. In addition to the type of crop, the level of management and climatic conditions are also major determinants of crop growth. In both years and both sites, I found that plant recovery of fertilizer N was not affected by erosion level. In 1991, however, total plant N uptake at both sites was proportionately higher in the 10- and 20-cm artificially eroded soils than in non-eroded soils. As the N supplying power of sites decreased with erosion (Izaurralde et al., 1993), plants growing on eroded soil derived proportionately more N from the fertilizer sources. The range of these proportions at Site 1, was 49-58, 63-66, and 70-78% for the 0-, 10-, and 20-cm cuts (Appendix 3.6). At Site 2, the ranges were lower than at Site 1 (44-48, 56-58, and 58-64% for 0-, 10- and 20-cm cuts). Due to the use of non-labelled fertilizer N in 1992 it was not possible to apportion the total plant N uptake to soil N, residual N, or non-labelled N.

The higher plant response to added N measured at Site 1 was probably due to comparatively low plant-available N of Gray Luvisols (Site 1) (Chapter 2, Table 2.1 and 2.2). The surprisingly higher plant fertilizer recovery observed in 1992 with urea in the 20 cm cut may had been induced by increased amounts of unused urea.

Immobilization of added N was relatively higher at Site 1 than at Site 2. This was probably due to the decreased mineralization potentials of the Gray Luvisol (Izaurralde et. al., 1993). At both sites, preferential use of NH_4 than NO_3 by heterotrophs may have induced relatively higher immobilization measured with urea than with KNO_3 (Aulakh and Rennie, 1984).

At Site 1, the lower soil N recovery with KNO_3 than with urea in the 20 cm cut was probably caused by; (i) lower N immobilization by soil, (ii) higher plant uptake of KNO_3 (higher FUE was noted with KNO_3 than with urea) (Chapter 2), (iii) a likely greater N loss. Regardless of time of application, Nyborg et al. (1990) also reported higher soil recovery of added N with urea than with KNO_3, from an experiment conducted on a Gray Luvisol at Breton (Alberta) using ^{15}N-labelled urea and KNO_3. At Site 1, the interaction effect between erosion level and N source on soil recovery of ^{15}N in total N measured in 1992 also indicated that the amounts of added N remaining in soil could have been influenced by the type of N source and degree of erosion.

Regardless of N source, the retention of added N in soil at Site 2 in 1991, appeared to increase with increasing levels of erosion. This may have been due to partial immobilization of the added N by soil soon after its application and its subsequent release during the period when crop demand for N was low (i.e., plant maturity). This was suggested by a higher recovery of ^{15}N in mineral N than in immobilized N in the 0-45 cm depth range after harvest in 1991. At Site 2, the rapid immobilization of the added N by the artificially-eroded soils was probably associated with the high organic C content. Even after the removal of 10- and 20- cm of topsoil, the upper 10 cm of exposed soils had between 85 and 62% of the organic carbon present in the non-eroded soil.

In most cases, the accumulation of ^{15}N primarily in the first 15 cm soil depth and the limited leaching in the non-eroded soils in the first year, were in agreement with previous studies conducted in northern and central Alberta (Malhi and Nyborg, 1983; Nyborg et al., 1990; Heaney et al., 1992).

At Site 1, downward movement of added ^{15}N into the soil recorded in 1991 was quite prominent in both erosion levels particularly in the 20 cm cut. This may have been probably due to the downward flow of the added N through large cracks of the exposed B_t horizon. Moreover, a heavy rainfall totalling 103 mm in June, immediately after sowing, likely enhanced the downward flow of added N.

Generally, it would be anticipated that topsoil removal would decrease NO_3 leaching by decreasing N mineralization and nitrification due to lower levels of soil organic C expected in eroded soils (Paul and Clark, 1989). The results obtained in this study indicated a reverse trend. With both N sources, the recovery of ^{15}N in soil NO_3-N in the 15-30 and 30-45 cm soil depths at Site 1 increased with increasing levels of erosion. However, the relatively greater downward movement of NO_3 into soil with KNO_3 than with urea, in the 20 cm cut at Site 1, suggests a lack sufficient biological activity for a rapid hydrolysis and nitrification of urea.

In 1992, the increase in the residual ^{15}N recovery observed at both sites below the 45-cm depth in the 0 cm cut and, in the 20 cm cut at Site 2, suggested that downward movement of residual N from upper layers had progressed during the period between harvests.

The N losses estimated for non-eroded and artificially-eroded soils during the first growing season by ^{15}N mass balance were much higher than those reported by others from different field experiments under normal field conditions and with ^{15}N-labelled fertilizers added in spring. On a Black Chernozem at Innisfail, Nyborg et al. (1990) estimated N losses during the growing season, at 12% with urea and at 16 % with KNO_3. On a Gray Luvisol at Breton, the N losses from spring applied N were estimated at 44% for urea and at 90% for KNO_3. From an experiment conducted in three irrigated soils, Bole and Gould (1986) reported N losses from spring-applied urea mixed within the top 10 cm of soil to vary between 11 to 21%. Fiegenbam et al. (1984) reported average of 5 to 20% of N losses with KNO_3 by the end of the first growing season, a season during which crop growth was limited by insufficient rainfall.

In this study, the relatively high losses of residual ^{15}N from artificially eroded soils that occurred between harvests were likely due to the substantial amounts of added N remaining in soil. At Site 2, the increased losses of residual ^{15}N with KNO_3, from the 10-

and-20 cm soil cuts in the second year may have been due to relatively higher amounts of mineralized N retained in soil after the first growing season. Nyborg et al. (1990) also reported results from an field experiment where the overwinter N losses with KNO_3 were larger than with urea. A study conducted by Heaney et al. (1992) on a Black Chernozem and a Gray Luvisol reported N losses ranging from 74 to 87% for winter-applied ^{15}N labelled KNO_3.

An analysis of environmental conditions in 1991 and the soil profile distribution of added N at harvest suggests denitrification as the major process determining the N losses occurred during the first growing season. In June 1991, prolonged and intensive rainfalls caused waterlogging in the plots and apparently enhanced denitrification of the added N.

The N losses that occurred during the period between harvests were also ascribed to denitrification. The soil profile distribution of the added ^{15}N in the second year, indicated some leaching up to 75-cm in the non-eroded soils but the amounts of ^{15}N recovered were small. Meanwhile, in the eroded soils, the amounts of residual ^{15}N recovered in deeper soil layers did not vary much from those recovered in the previous year. In addition to this, much of the added N remaining in soil occurred primarily in the 0-15 cm depth. These results indicated that N loss through leaching was minimal. According to several researchers (Ferguson et. al., 1964; Satrz, 1969) the surface soil becomes saturated during the soil thaw in early spring due to impeded drainage caused by underlying frozen subsoil. Despite low soil temperatures, this saturated surface soil apparently creates anaerobic conditions which enhance denitrification activity. Since most of the added N retained by the soil after the 1991 growing season was in the surface 15 cm, it is reasonable to assume it was denitrified during thawing of the surface soil in the early spring of 1992. This supports the findings of Malhi and Nyborg (1983), Aulakh and Rennie (1984), Bole and Gould (1986), Nyborg et al. (1990), Heaney et al. (1992), and Laidlaw (1993).

The N losses through volatilization were considered minimal since the fertilizers were banded 5 cm deep into the soil. The N losses through surface runoff and lateral movement of the added N in the surface 13 cm were restricted by the walls of the steel frames. The lateral movement below 13 cm was considered to be minimal based on the findings by Malhi and Nyborg (1983) and Heaney (1992).

The relatively large losses of N estimated in this study was also due to the application of N at rates higher than that needed for optimum yield. Reddy and Reddy (1993) found greater N losses with higher rates of ^{15}N-labelled ammonium nitrate fertilizer applied to corn. Crop yields of eroded soils cannot be improved by simply adding more nutrients because soil physical and chemical properties also play a major role in crop growth (Chapter 2). Due to the comparatively poor plant growth observed in the eroded soils I surmised much of the applied N was subjected to loss.

3.7 Conclusions

In conclusion, plant recovery of fertilizer N was not affected by various erosion levels. Artificial erosion induced an increase in the plant recovery of added N. In 1991, soil retention of the added N appeared to be higher in eroded soils than in non-eroded soils due to relatively higher N losses from the non-eroded soils. The N losses occurred during the first growing season were substantial with KNO_3 at Site 1 and with both N sources at Site 2. The N losses between harvests were higher from eroded soils and were maximum with KNO_3 at Site 2. With urea, the N losses were minimal from the eroded soils at Site 1. The N losses were assumed to occurr through denitrification, due to waterlogged soil conditions as a result of heavy rainfall in the first year and early spring thaw in the second year. Since in most cases, soil ^{15}N recovery was primarily in the surface 15 cm, N losses through leaching were assumed to be small. Exceptionally, at Site 1, the fast downward movement of the added N noted up to 75 cm depth in 10-and 20-cm erosion levels in 1991 indicated that although, small in amount, part of added N was possibly lost through leaching. Within a very short period, the recovery of nitrates in the 15-45 cm depth interval at Site 1 was maximum under the 20 cm soil cut. The soil at Site 2 appeared to have less potential for leaching. Large N losses were also due to the application of N at rates higher than that needed for optimum yield.

This study showed that the fate of added N does not solely depend upon the severity of erosion but also on prevailing environmental conditions, soil type, type and rate of amendment, and the level of management.

Table 3.1. Effects of artificial erosion and N source (applied @ 150 kg N ha^{-1}) on ^{15}N recovery by barley in 1991.

Treatment	Site 1	Site 2
	kg ha^{-1}	
Cut (cm)		
0	34.9a	35.4a
10	40.8a	32.1a
20	38.3a	28.6a
N source		
KNO_3	40.5a	34.3a
Urea	35.6a	29.7b

	Analysis Of Variance					
Source	df	Mean Square	Pr>F	df	Mean Square	Pr>F
Rep	3	47.6		3	74.5	
Cut	2	69.8	0.5224	2	94.0	0.0764
Error (a)	6	96.3		6	23.1	
N source	1	127.7	0.1493	1	115.4	0.0111
Cut x N source	2	65.5	0.3232	2	17.2	0.2579
Error (b)	8†	50.2		8†	10.7	

a,b Means followed by the same letter for among cuts means and between N source means are not significantly different at 5% probability level according to the least significant difference test (LSD).

† Number of missing observations in data: Site 1=1; Site 2=1.

Table 3.2. Effects of artificial erosion and N source (applied @ 150 kg N ha^{-1}) on ^{15}N recovery by barley in 1992.

Treatment	Site 1	Site 2
	kg ha^{-1}	
Cut (cm)		
0	13.5a	14.3a
10	12.5a	15.9a
20	20.8a	12.4a
N source		
KNO_3	13.8a	13.1a
Urea	17.4a	15.4a

Analysis Of Variance

Source	df	Mean Square	Pr>F	df	Mean Square	Pr>F
Rep	3	166.1		3	13.1	
Cut	2	98.1	0.1111	2	23.8	0.5702
Error (a)	6	30.3		6	38.5	
N source	1	40.3	0.1708	1	32.3	0.3507
Cut x N source	2	53.9	0.1115	2	74.0	0.1203
Error (b)	6†	16.7		9†	27.4	

a,b Means followed by the same letter for among cuts means and between N source means are not significantly different at 5% probability level according to the least significant difference test (LSD).

† Number of missing observations in data: Site 1= 3; Site 2= none.

Table 3.3. Soil recovery of ^{15}N in total N in the 0-75 cm depth (cumulative of 0-15, 15-30, 30-45, 45-60, and 60-75 cm depths) in 1991.

Treatment	Site 1	Site 2
	kg ha^{-1}	
Cut (cm)		
0	70.4a	65.1a
10	84.3a	84.9a
20	84.1a	86.7a
N source		
KNO_3	67.8b	79.5a
Urea	91.4a	77.7a

Analysis Of Variance

Source	df	Mean Square	Pr>F	df	Mean Square	Pr>F
Rep	3	200.7		3	51.9	
Cut	2	486.1	0.1786	2	980.7	0.0677
Error (a)	6	208.9		6	224.9	
N source	1	3008.7	0.0512	1	14.5	0.6875
Cut x N source	2	459.5	0.4815	2	54.0	0.5487
Error (b)	8[†]	573.1		6[†]	81.3	

a,b Means followed by the same letter for among cuts means and between N source means are not significantly different at 5% probability level according to the least significant difference test (LSD).

[†] Number of missing observations in data: Site 1=1; Site 2=3.

Table 3.4. Soil recovery of ^{15}N in total N in the 0-75 cm depth (cumulative of 0-15, 15-30, 30-45, 45-60, 60-75 cm depths) in 1992.

Treatment	Site 1	Site 2
	kg ha^{-1}	
Cut (cm)		
0	49.8a	38.9a
10	45.5a	43.9a
20	58.5a	41.1a
N source		
KNO_3	42.2b	34.1b
Urea	60.4a	48.6a

Analysis Of Variance

Source	df	Mean Square	Pr>F	df	Mean Square	Pr>F
Rep	3	116.9		3	41.0	
Cut	2	264.0	0.1261	2	50.0	0.6720
Error (a)	6	88.5		6	117.4	
N source	1	1491.5	0.0018	1	1263.2	0.0194
Cut x N source	2	424.6	0.0199	2	77.4	0.6259
Error (b)	6†	52.6		9†	156.7	

a,b Means followed by the same letter for among cuts means and between N source means are not significantly different at 5% probability level according to the least significant difference test (LSD).

† Number of missing observations in data: Site 1=3; Site 2=none.

Table 3. 5. Soil recovery of ^{15}N in total N at different soil depths Site 1 in 1991.

	Depths of topsoil removal (cuts) (cm)			N source
Treatment	0	10	20	means
	kg ha^{-1}			
		0-15 cm depth†		
KNO_3	60.3	48.5	17.5	42.1
Urea	69.5	63.8	84.2	72.5
Cut means	64.9	56.2	50.9	
		15-30 cm depth†		
KNO_3	4.0	14.0	24.0	14.0
Urea	2.0	22.0	11.3	11.8
Cut means	3.0	18.0	17.7	
		30-45 cm depth†		
KNO_3	1.5	5.8	16.3	7.9
Urea	1.0	8.3	5.3	4.9
Cut means	1.3	7.1	10.8	
		45-60 cm depth†		
KNO_3	0.8	2.8	4.3	2.6
Urea	0.8	2.0	1.9	1.6
Cut means	0.8	2.4	3.1	
		60-75 cm depth†		
KNO_3	0.3	1.3	2.3	1.3
Urea	0.5	1.0	2.5	1.3
Cut means	0.4	1.2	2.4	

† LSD$_{0.05}$

- Between N source means: 0-15 = 19.6; 15-30 = NS; 30-45 = NS; 45-60 = NS; 60-75 = NS.
- Among cuts means: 0-15 = NS; 15-30 = 13.4; 30-45 = 5.2; 45-60 = NS; 60-75 = NS.
- Among cuts for the same N source: 0-15 = 33.1; 15-30 = 14.4; 30-45 = 8.2; 45-60 = 2.6; 60-75 = 1.9.

Table 3.6. Soil recovery of ^{15}N in total N at different soil depths at Site 1 in 1992.

Treatment	Depths of topsoil removal (cuts) (cm) 0	 10	 20	N source means
	kg ha^{-1}			
		0-15 cm depth†		
KNO$_3$	35.8	18.1	22.0	25.3
Urea	44.7	32.3	48.8	41.9
Cut means	40.2	25.2	40.2	
		15-30 cm depth†		
KNO$_3$	5.3	9.0	6.4	7.0
Urea	3.3	8.9	12.6	8.3
Cut means	4.3	9.0	9.5	
		30-45 cm depth†		
KNO$_3$	3.7	5.0	5.8	4.8
Urea	2.8	4.3	5.3	4.1
Cut means	3.3	4.7	5.5	
		45-60 cm depth†		
KNO$_3$	1.6	4.2	3.9	3.2
Urea	1.8	3.6	2.1	2.5
Cut means	1.7	3.9	3.0	
		60-75 cm depth†		
KNO$_3$	1.5	2.1	2.1	1.9
Urea	1.0	1.7	1.5	1.4
Cut means	1.3	1.9	1.8	

† LSD$_{0.05}$

- Between N source means: 0-15 = 7.9; 15-30 = NS; 30-45 = NS; 45-60 = NS; 60-75 = NS.
- Among cuts means: 0-15 = 8.5; 15-30 = 3.5; 30-45 = 1.2; 45-60 = NS; 60-75 = NS.
- Among cuts for the same N source: 0-15 = 13.4, 15-30 = 3.5; 30-45 = 1.7; 45-60 = 1.8; 60-75 = NS.

Table 3.7. Soil recovery of ^{15}N in total N at different soil depths at Site 2 in 1991.

Treatment	Depths of topsoil removal (cuts) (cm)			N source means
	0	10	20	
	kg ha^{-1}			
		0-15 cm depth		
KNO_3	53.8	75.5	69.0	66.1
Urea	59.2	68.5	73.8	67.2
Cut means	56.5	72.0	71.4	
		15-30 cm depth†		
KNO_3	9.3	8.5	13.3	10.4
Urea	4.5	9.8	5.9	6.7
Cut means	6.9	9.2	9.6	
		30-45 cm depth†		
KNO_3	0.5	1.8	1.3	1.2
Urea	0.8	3.8	1.8	2.1
Cut means	0.7	2.8	1.6	
		45-60 cm depth†		
KNO_3	0.8	0.4	0.5	0.6
Urea	0.5	1.9	0.3	0.9
Cut means	0.7	1.2	0.4	
		60-75 cm depth†		
KNO_3	1.0	1.3	0.8	1.0
Urea	0.3	1.0	0.3	0.5
Cut means	0.6	1.2	0.6	

† $LSD_{0.05}$

- Between N source means: 0-15 = NS; 15-30 = NS; 30-45 = NS; 45-60 = NS; 60-75 = NS.
- Among cuts means: 0-15 = NS; 15-30 = NS; 30-45 = NS; 45-60 = NS; 60-75 = NS.
- Among cuts for the same N source: 0-15 = 18.4; 15-30 = NS; 30-45 = 2.7; 45-60 =0.6; 60-75 = NS.

Table 3.8. Soil recovery of ^{15}N in total N at different soil depths at Site 2 in 1992.

	Depths of topsoil removal (cuts) (cm)			N source
Treatment	0	10	20	means
	kg ha^{-1}			
		0-15 cm depth†		
KNO_3	16.5	19.8	15.0	17.1
Urea	33.0	33.8	39.0	35.3
Cut means	24.8	26.8	27.0	
		15-30 cm depth†		
KNO_3	7.0	8.8	7.3	7.7
Urea	5.8	8.3	5.5	65
Cut means	6.4	8.6	6.4	
		30-45 cm depth†		
KNO_3	2.5	6.5	3.3	4.1
Urea	3.0	2.3	4.0	3.1
Cut means	2.8	4.4	3.7	
		45-60 cm depth†		
KNO_3	2.8	3.0	2.5	2.8
Urea	2.0	2.0	2.5	2.2
Cut means	2.4	2.5	2.5	
		60-75 cm depth†		
KNO_3	2.8	2.0	2.8	2.5
Urea	2.5	1.8	0.5	1.6
Cut means	2.7	1.9	1.7	

† $LSD_{0.05}$

- Between N source means: 0-15 = 7.9; 15-30 = NS; 30-45 = NS; 45-60 = NS; 60-75 = NS.
- Among cuts means: 0-15 = NS; 15-30 = NS; 30-45 = NS; 45-60 = NS; 60-75 = NS.
- Among cuts for the same N source: 0-15 = NS; 15-30 = NS; 30-45 = 3.6; 45-60 = NS; 60-75 = NS.

Table 3.9. Soil recovery of ^{15}N in NO_3-N at different soil depths at Site 1 in1991.

Treatment	Depths of topsoil removal (cuts) (cm) 0	10	20	N source means
	kg ha^{-1}			
		0-15 cm depth[†]		
KNO_3	14.6	20.2	2.5	12.4
Urea	10.0	14.9	12.3	12.4
Cut means	12.3	17.5	7.4	
		15-30 cm depth[†]		
KNO_3	0.8	5.5	13.1	6.5
Urea	0.2	8.5	10.1	6.3
Cut means	0.5	7.0	11.6	
		30-45 cm depth[†]		
KNO_3	0.0	1.2	6.3	2.5
Urea	0.1	1.5	1.2	0.9
Cut means	0.1	1.3	3.7	

[†] $LSD_{0.05}$

- Between N source means: 0-15 = NS; 15-30 = NS; 30-45 = NS.
- Among cuts means: 0-15 = NS; 15-30 = 8.1; 30-45 = NS.

Table 3.10. Soil recovery of ^{15}N in NO_3-N at different soil depths at Site 2 in 1991.

Treatment	Depths of topsoil removal (cuts) (cm) 0	10	20	N source means
	kg ha^{-1}			
		0-15 cm depth†		
KNO_3	37.3	53.5	42.3	44.4
Urea	27.7	26.2	43.9	32.6
Cut means	32.5	40.0	43.1	
		15-30 cm depth†		
KNO_3	1.0	13.9	9.3	8.0
Urea	0.4	4.2	8.5	4.4
Cut means	0.7	9.0	9.0	
		30-45 cm depth†		
KNO_3	0.6	0.8	0.4	0.6
Urea	0.1	1.9	0.7	0.9
Cut means	0.3	1.4	0.6	

† $LSD_{0.05}$

- Between N source means: 0-15 = NS; 15-30 = NS; 30-45 = NS.
- Among cuts means: 0-15 = NS; 15-30 = 6.2; 30-45 = NS.

Table 3.11. Soil recovery of ^{15}N in NH_4-N at different soil depths at Site 1 in 1991.

	Depths of topsoil removal (cuts) (cm)			N source
Treatment	0	10	20	Means
	kg ha^{-1}			
		0-15 cm depth†		
KNO_3	0.7	0.4	0.5	0.6
Urea	2.5	7.2	12.6	7.5
Cut means	1.6	3.8	6.6	
		15-30 cm depth†		
KNO_3	0.0	0.0	0.3	0.1
Urea	0.1	0.7	0.8	0.5
Cut means	0.1	0.4	0.5	
		30-45 cm depth†		
KNO_3	0.0	0.0	0.0	0.0
Urea	0.0	0.1	0.1	0.1
Cut means	0.0	0.1	0.1	

† $LSD_{0.05}$

- Between N source means: 0-15 = 3.9; 15-30 = 0.3; 30-45 = NS.
- Among cuts means: 0-15 = 3.7; 15-30 = 0.3; 30-45 = NS.

Table 3.12. Soil recovery of ^{15}N in NH_4-N at different soil depths at Site 2 in 1991.

Treatment	Depths of topsoil removal (cuts) (cm) 0	10	20	N source means
		kg ha^{-1}		
		0-15 cm depth[†]		
KNO_3	0.2	0.3	0.3	0.3
Urea	2.7	1.4	4.3	2.8
Cut means	1.5	0.9	2.3	
		15-30 cm depth[†]		
KNO_3	0.0	0.0	0.0	0.0
Urea	0.0	0.5	0.4	0.3
Cut means	0.0	0.2	0.2	
		30-45 cm depth[†]		
KNO_3	0.0	0.0	0.0	0.0
Urea	0.0	0.1	0.1	0.1
Cut means	0.0	0.1	0.1	

[†] $LSD_{0.05}$

- Between N source means: 0-15 = 0.9; 15-30 = NS; 30-45 = NS.
- Among cuts means: 0-15 = 0.9; 15-30 = NS; 30-45 = NS.

Table 3.13. Soil recovery of ^{15}N in mineral N in the 0-15 cm depth at Site 1 in 1992.

	Depths of topsoil removal (cuts) (cm)			N source
Treatment	0	10	20	means
	kg ha^{-1}			
		^{15}N-NO$_3$[†]		
KNO$_3$	1.5	1.0	0.3	0.9
Urea	1.2	0.8	3.0	1.7
Cut means	1.3	0.9	1.6	
		^{15}N-NH$_4$[†]		
KNO$_3$	0.1	0.1	0.2	0.1
Urea	0.4	0.4	4.3	1.7
Cut means	0.2	0.3	2.3	

[†] LSD$_{0.05}$

- Between N source means: ^{15}N-NO$_3$ = NS; ^{15}N-NH$_4$ = 1.0.
- Among cuts means: ^{15}N-NO$_3$ = NS; ^{15}N-NH$_4$ = 1.4.

Table 3.14. Soil recovery of ^{15}N in mineral N in the 0-15 cm depth at Site 2 in 1992.

Treatment	Depths of topsoil removal (cuts) (cm) 0	10	20	N source means
	kg ha^{-1}			
		^{15}N-NO$_3$†		
KNO$_3$	1.6	1.7	0.3	1.2
Urea	1.2	1.0	1.2	1.2
Cut means	1.4	1.4	0.8	
		^{15}N-NH$_4$†		
KNO$_3$	0.1	0.1	0.1	0.1
Urea	0.5	0.4	1.2	1.7
Cut means	0.3	0.3	0.6	

† LSD$_{0.05}$

- Between N source means: ^{15}N-NO$_3$ = NS; ^{15}N-NH$_4$ = 0.3.
- Among cuts means: ^{15}N-NO$_3$ = NS; ^{15}N-NH$_4$ = NS.

Table 3.15. Soil recovery of ^{15}N in total N, mineral N and immobilized N in the 0-45 cm depth (cumulative of 0-15, 15-30 and 30-45 cm depths) at Site 1 in 1991.

Treatment	Depths of topsoil removal (cuts) (cm) 0	 10	 20	N source means
		Total ^{15}N (kg ha^{-1})†		
KNO_3	65.8	68.1	57.6	63.9
Urea	72.9	93.7	100.4	89.0
Cut means	69.4	80.9	79.0	
		Mineral ^{15}N (kg ha^{-1})†		
KNO_3	37.9	7.9	19.6	21.8
Urea	22.0	45.3	27.6	31.6
Cut means	29.9	26.6	23.6	
		Immobilized (kg ha^{-1})^{15}N†		
KNO_3	27.9	60.2	38.0	42.1
Urea	50.9	48.4	72.8	57.4
Cut means	39.4	54.3	55.4	

† $LSD_{0.05}$

- Between N source means: Total ^{15}N = 23.28; Mineral ^{15}N = NS; Immobilized ^{15}N = NS.
- Among cuts means: Total ^{15}N = NS; Mineral ^{15}N = NS; Immobilized ^{15}N = NS.

Table 3.16. Soil recovery of ^{15}N as total N , mineral N and immobilized N in the 0-45 cm depth interval (cumulative of 0-15, 15-30 and 30-45 cm depths) at Site 2 in 1991.

	Depths of topsoil removal (cuts) (cm)			N source means
Treatment	0	10	20	
		Total ^{15}N (kg ha^{-1})†		
KNO_3	63.8	85.7	83.8	77.6
Urea	64.8	77.3	87.7	76.6
Cut means	64.0	81.5	85.7	
		Mineral ^{15}N (kg ha^{-1})†		
KNO_3	39.2	65.0	47.5	50.5
Urea	31.0	33.8	59.4	41.4
Cut means	35.1	49.4	53.4	
		Immobilized ^{15}N (kg ha^{-1})†		
KNO_3	24.1	21.7	31.3	25.7
Urea	33.9	43.1	30.0	35.7
Cut means	29.0	32.4	30.6	

† $LSD_{0.05}$

- Between N source means: Total ^{15}N = NS; Mineral ^{15}N = NS; Immobilized ^{15}N = NS.
- Among cuts means: Total ^{15}N = NS; Mineral ^{15}N = 14.6; Immobilized ^{15}N = NS.

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CHAPTER 4

VARIATIONS IN NATURAL ^{15}N ABUNDANCE OF ARTIFICIALLY ERODED SOILS.

4.1 Introduction

The variations in natural ^{15}N abundance have been measured in various nitrogen-containing substances (White and Yagoda, 1950; Smith and Hudson, 1951; Hoering, 1955; Junk and Svec, 1958; Cheng et al., 1964; Bokhoven and Theeuwen, 1966; Riga et al., 1971). Variations in ^{15}N abundance in the biosphere is usually within ±10 δ units, where one δ unit is equal to about 0.00037 atom % ^{15}N (Hauck, 1973). These variations result from isotope effects on biological and chemical reactions (Hauck and Bremner, 1976). The isotope effect arises from mass differences of stable or radioactive isotopes (Hauck and Bremner, 1976).

The biologically induced isotope effect in soils is caused by microbial discrimination against the heavier isotope, ^{15}N, by micro-organisms. Biological discrimination leads to N isotope fractionation during fixation of atmospheric N_2 by bacteria (Hoering, 1955; Delwiche and Steyn, 1970), nitrification of ammonium (Delwiche and Steyn, 1970), and during denitrification of nitrate (Wellman et al, 1968). If the biological or chemical reactions go to completion the N isotope ratio does not change. Since that condition is rarely found, usually slight variations in the ^{15}N concentration occurs. A slight increase in the ^{15}N concentration of ammonium and residual nitrates was found during nitrification and denitrification (Hauck and Bremner, 1976).

Crops often have lower $\delta^{15}N$ than the total soil N (Cheng et al., 1964; Ledgard, 1984 and Sutherland et al., 1991). During transformations of plant and soil N, ^{14}N is mineralized preferentially due to biological discrimination against ^{15}N. The mineralized

^{14}N is either taken up by the plants or subjected to loss more quickly than ^{15}N and thus the substrate becomes enriched with ^{15}N.

Variations in $\delta^{15}N$ in soil differ among published reports. Field studies have reported that soil surface horizons usually have positive $\delta^{15}N$ values (Cheng et al., 1964; Delwiche and Steyn, 1970; Kohl et al., 1971; Feigin et al., 1974a,b), while other studies have shown that $\delta^{15}N$ of total soil N increased with depth (Riga et al., 1971; Mariotii et al., 1980; and Ledgard et al., 1984).

Isotopic enrichment of residual nitrates have been attributed to microbial denitrification (C[illegible] et al, 1977; Mariotti et al., 1981; Böttcher et al., 1990). In Saskatchewan, Karamanos and Rennie (1980) found greater $\delta^{15}N$ values of NO_3-N in the surface horizons of poorly drained lowland profiles than in the surface of well-drained upland profiles. They suggested that the higher values of $\delta^{15}N$ of NO_3-N were obtained in part because of denitrification activity in the low-lying profiles.

Several researchers (Hauck, 1973; Rennie et al., 1976; Karamanos and Rennie, 1978, 1981) have suggested the use of natural variations of ^{15}N abundance of plant and soil samples for studying N cycling processes. At present, the information obtained from variations in natural ^{15}N abundance is qualitative but with further research and study on isotope fractionation accompanying the N transformations in various ecosystems, more quantitative information from natural variations in ^{15}N may become available (Hauck and Bremner, 1976; Rennie, 1976; Nommik et al., 1993).

The objectives of this report were: (a) to find the ^{15}N abundance of plants and soils where soils had been artificially eroded (b) to discover if any variations in natural ^{15}N abundance could be used to explain N losses from artificially eroded soils.

4.2 Materials and Methods

Soil and site description, management history, field experiments and chemical analyses are described in Chapter 2 and 3. The plant and soil samples of the plots with no N addition were used.

4.3 Data Analysis

The variations in natural ^{15}N abundance ($\delta^{15}N$) of the plant and soil samples were calculated by using the following equation:

$$\delta^{15}N =$$

$$\frac{\text{atom \% }^{15}\text{N abundance of the sample - atom \%}^{15}\text{N abundance of atmosphere}}{\text{atom \%}^{15}\text{N abundance of atmosphere}} \times 1000$$

where atom ^{15}N abundance of the atmosphere = 0.3663%

4.4 Results and Discussion

There were only slight variations in the isotopic composition of the total soil N in different soil depths at all erosion levels (Tables 4.1 and 4.2). In 1991, the $\delta^{15}N$ values for the total soil N ranged from + 5 to + 8 at both sites, while in 1992 the values ranged from + 6 to +10 at Site 1 and from + 5 to + 9 at Site 2 (Tables 4.1 and Tables 4.2). In the first year, the $\delta^{15}N$ of total soil N tended to decreased slightly with increasing soil sampling depths at all erosion levels, while in the second year there was no such trend (Tables 4.1 and 4.2). These results were in contrast to those of Riga et al. (1971), Mariotii et al. (1980) and Ledgard et al. (1984), who found increases in $\delta^{15}N$ with depth. Overall, the $\delta^{15}N$ values for total soil N obtained in this study support the findings of Rennie et al. (1976). They reported only slight variations in the $\delta^{15}N$ values of total soil N at different soil depths (up to 75 cm depth) of a Brown Chernozem and a Dark Gray Luvisol.

At both sites, the $\delta^{15}N$ values for NO_3-N in 1991 at all erosion levels were unusually large from 15 to 30 cm and from 30 to 45 cm (i.e. depths 2 and 3) (Table 4.3). In the 0 to 15 cm depth (i.e. depth 1), the $\delta^{15}N$ values of soil NO_3-N were in the range of +3 to +11 units. At depths 2 and 3, the isotopic composition of soil NO_3-N varied from +16 to +85 at Site 1 while at Site 2 it ranged from +9 to +33, depending upon the depth of artificial erosion. The δ^{15}N values of NO_3-N obtained for depths 2 and 3, in the 20 cm erosion, had high variability among replications (Appendix 4.1). In most cases, however, the δ^{15}N of soil NO_3-N tended to increase with increasing soil sampling depths for any erosion level. These δ^{15}N values of NO_3-N were greater than those of the total soil N. These results differed from those obtained by Feigin et al. (1974a), Delwiche and Steyn (1970), and Edwards 1973. Those studies showed that isotopic enrichment of soil NO_3-N was consistently lower than that of total soil N. The results of this study were much greater than those of Rennie et al. (1976) for various soil depths in a Dark Brown Chernozem. Rennie et al. (1976), however, found a sudden increase in δ^{15}N values of NO_3-N deeper in the soil profile studied. The δ^{15}N value of NO_3 was + 11 for the surface 15 cm soil but decreased consistently with depth to + 3 at the 180 cm soil depth. Below that depth, however, the values became greater again to as high as 8.5 δ units at 270 cm depth.

The large values of δ^{15}N for soil NO_3-N in depths 2 and 3 may have been the result of rapid denitrification. In June 19[illegible], prolonged and intensive rainfalls caused waterlogging of soil in the plots and apparent denitrification (Chapter 3). Karamanos and Rennie (1980) found high values of δ^{15}N [illegible] soil NO_3-N (+34.6 and +15) for an uncultivated, poorly drained and saline soil and they attributed these high values to denitrification. Bremner and Tabatabai (1973) reported that virgin soils have lower δ^{15}N values than cultivated soils. The experimental sites of this study had been under cultivation for more than 40 years and received during that period, regular application of cattle manure and/or commercial fertilizer (management history in Chapter 3). Soil management, therefore, may explain why the δ^{15}N values of this study were higher than those obtained by Karamanos and Rennie (1980) in a poorly drained virgin soils.

The δ^{15}N values of NH_4-N for different soil depths at various erosion levels in 1991 varied from -2 to + 9 at Site 1 and from +2 to +46, at Site 2 (Table 4.4). At Site 1, the δ^{15}N values of soil NH_4-N tended to decrease with soil depth at all erosion levels. At

Site 2, the particularly high $\delta^{15}N$ values of NH_4-N (+46) at 15-30 cm depth, in 10 cm artificially-eroded soil, reflected an extreme variation among replications (Appendix 4.2). Overall, the isotopic enrichment of soil NH_4-N for 15-30 and 30-45 cm depths was lower than that of NO_3-N for the same depths. The higher recovery of ^{15}N enriched NO_3-N than ^{15}N enriched NH_4-N suggested the possibility of active denitrification (Hauck, 1973; Chien et al., 1977).

The isotopic enrichment of plant (whole above ground part) N in two years varied from +8 to +26 at Site 1 and it ranged from +9 to +20 at Site 2 (Tables 4.5 and 4.6). The $\delta^{15}N$ of plant N tended to increase with increasing levels of erosion, only in the first year (Tables 4.5 and 4.6). The plant $\delta^{15}N$ values were greater (by approximately +2 to +15 δ units) than the soil $\delta^{15}N$ values, depending on the level of erosion (Tables 4.1, 4.2, 4.5 and 4.6). However, Cheng et al. (1964), Ledgard et al. (1984) Rennie et al. (1976), and Sutherland et al. (1991) found that $\delta^{15}N$ values of plant N was often lower than that of total soil N.

The high values of plant $\delta^{15}N$, particularly in the first year were probably caused by extensive denitrification of ^{14}N in soil NO_3-N in June (discussed in Chapter 3). Since most of the ^{14}N in soil NO_3-N was denitrified soon after sowing, plants might have assimilated the enriched NO_3-N, and consequently this was reflected in elevated values of plant $\delta^{15}N$. Similarly, Doughton et al. (1991) concluded that increased $\delta^{15}N$ of barley (Hordeum vulgare L.) was the result of extensive microbial denitrification of NO_3-N before seeding and throughout the growing season.

4.5 Conclusions

Isotopic enrichment of total soil N varied little among soil depths, among erosion levels, and between the sites. The large $\delta^{15}N$ values of soil NO_3-N measured in the artficially-eroded soils were attributed to extensive microbial denitrification. The relatively lower $\delta^{15}N$ values of soil NH_4-N than of NO_3-N supported the hypothesis of loss via denitrification. Plant $\delta^{15}N$ values greater than those of total soil N reflected denitrification of ^{14}N enriched NO_3-N in early growth stages and consequent assimilation of ^{15}N enriched NO_3-N.

Although the interpretation of variations in natural ^{15}N abundance of soils and plants are qualitative, the findings support the hypothesis that N losses through denitrification from artificially-eroded soils were highly influenced by environmental conditions.

Table 4.1 The δ ^{15}N values for total soil N in artificially-eroded soils at Site 1.

Depth of soil erosion (cm)	Soil sample depth (cm)	Year	
		1991	1992
0	0-15	7 ± 0.17[‡]	7 ± 0.40
	15-30	7 ± 0.11	7 ± 0.38
	30-45	7 ± 0.18	8 ± 0.44
	45-60	7 ± 0.14	10 ± 0.73
	60-75	6 ± 0.10	8 ± 0.29
10	0-15	7 ± 0.10	8 ± 0.41
	30-45	6 ± 0.12	8 ± 0.10
	45-60	7 ± 0.27	8 ± 0.62
	60-75	6 ± 0.14	7 ± 0.54
20	0-15	8 ± 0.20	6 ± 0.27
	15-30	7 ± 0.12	9 ± 0.23
	30-45	7 ± 0.18	8 ± 0.35
	45-60	6 ± 0.12	7 ± 0.10
	60-75	5 ± 0.09	7 ± 0.15

[‡] Values following ± represent the standard error of estimate.

Table 4.2 The $\delta\ ^{15}N$ values for total soil N in artificially-eroded soils at Site 2.

Depth of soil erosion (cm)	Soil sample depth (cm)	Year	
		1991	1992
0	0-15	7 ± 0.18[‡]	7 ± 0.12
	15-30	7 ± 0.25	8 ± 0.20
	30-45	7 ± 0.20	7 ± 0.13
	45-60	6 ± 0.46	8 ± 0.10
	60-75	6 ± 0.16	7 ± 0.25
10	0-15	7 ± 0.23	8 ± 0.18
	15-30	7 ± 0.17	8 ± 0.06
	30-45	6 ± 0.17	8 ± 0.30
	45-60	5 ± 0.28	5 ± 0.30
	60-75	5 ± 0.31	5 ± 0.12
20	0-15	7 ± 0.29	8 ± 0.20
	15-30	7 ± 0.17	8 ± 0.15
	30-45	7 ± 0.07	9 ± 0.17
	45-60	6 ± 0.19	7 ± 0.26
	60-75	6 ± 0.19	6 ± 0.42

[‡] Values following ± represent the standard error of estimate.

Table 4.3 Recovery of NO_3-N and corresponding $\delta\ ^{15}N$ in artificially-eroded soils at Sites 1 and 2 in 1991.

Depth of soil erosion (cm)	Soil sample depth (cm)	Site 1 NO_3-N (kg ha^{-1})	 $\delta\ ^{15}N$	Site 2 NO_3-N (kg ha^{-1})	 $\delta\ ^{15}N$
0	0-15	15	3 ± 2‡	9	3 ± 4
	15-30	3	29 ± 7	4	9 ± 5
	30-45	2	39 ± 12	2	17 ± 4
10	0-15	5	11 ± 3	13	5 ± 1
	15-30	2	30 ± 2	4	17 ± 14
	30-15	2	16 ± 4	2	9 ± 2
20	0-15	4	8 ± 2	18	6 ± 4
	15-30	3	72 ± 37	4	27 ± 18
	30-45	2	85 ± 41	4	33 ± 13

‡Values following ± represent the standard error of estimate.

Table 4.4 Recovery of NH_4-N and corresponding $\delta\ ^{15}N$ in artificially-eroded soils at Sites 1 and 2 in 1991.

		Site 1		Site 2	
Depth of soil erosion	Soil sample depth	NH_4-N	$\delta\ ^{15}N$	NH_4-N	$\delta\ ^{15}N$
(cm)	(cm)	(kg ha^{-1})		(kg ha^{-1})	
0	0-15	14	8± 2‡	7	6 ± 1
	15-30	5	-2 ± 3	6	7 ± 1
	30-45	6	4 ± 1	4	6 ± 2
10	0-15	6	9 ± 1	10	6 ± 1
	15-30	8	2 ± 1	4	46 ± 26
	30-45	5	3 ± 1	4	2 ± 1
20	0-15	4	7 ± 2	4	4 ± 6
	15-30	5	9 ± 1	5	9 ± 2
	30-45	4	5 ± 2	5	18 ± 12

‡ Values following ± represents the standard error of estimate.

Table 4.5 Above ground plant N uptake and corresponding $\delta\ ^{15}N$ as affected by artificial erosion at Site 1 .

Depth of soil erosion	1991		1992	
	N	$\delta\ ^{15}N$	N	$\delta\ ^{15}N$
(cm)	(kg ha^{-1})		(kg ha^{-1})	
0	43	9 ± 0.24[‡]	97	11 ± 0.75
10	23	11 ± 0.54	49	8 ± 0.75
20	7	26 ± 5.0	23	14 ± 3.0

[‡] Values following ± represents the standard error of estimate.

Table 4.6 Above ground plant N uptake and corresponding $\delta\ ^{15}N$ as affected by artificial erosion at Site 2 .

Depth of soil erosion	1991		1992	
	N	$\delta\ ^{15}N$	N	$\delta\ ^{15}N$
(cm)	(kg ha^{-1})		(kg ha^{-1})	
0	42	9 ± 0.11[‡]	60	11 ± 0.75
10	25	20 ± 4.0	43	9 ± 0.5
20	22	12 ± 2.0	31	11 ± 0.5

[‡] Values following ± represents the standard error of estimate.

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CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

5.1 Focal Points of this Research

Although detailed conclusions for each topic of thesis are provided at the end of each chapter, noteworthy points will be briefly described here. The main conclusion was that crop productivity on artificially eroded soils was improved by increasing the rate of fertilizer application but, at the same time, resulted in large losses of N from the plant-soil system.

Topsoil loss often results in reduced soil quality and productivity and hence crop production. Removal of various depths of topsoil exposed soils which were compact, low in plant nutrients especially N and P, and low in water holding capacity. This deterioration of soil quality reduced yield and N uptake by barley (Chapter 2). The decreased contribution of native soil N to plant N uptake with increasing levels of erosion (Chapter 3) confirmed the poor N status of the artificially-eroded soils.

This research supported the concept that effectiveness of any amendment in restoring the crop productivity of eroded soils depends on factors like; (a) soil type, (b) type of fertilizer, (c) climatic conditions, (d) crop, and (e) level of management (Morrison and Shaykewick, 1987; Tanaka and Aase, 1987). Yields and N uptake of barley were improved by the addition of N fertilizers at all levels of erosion (Chapter 2). In both years, however, plant N fertilizer recovery was not significantly affected by the level of erosion but in 1991 proportionately greater amounts of added N were taken up by barley growing in eroded soils than that in non-eroded soils. This indicated that eroded soils had lower plant available N than non-eroded soils (Chapter 3). Similarly, the higher fertilizer use efficiency measured at Site 1 than at Site 2, with both N sources, suggested an increased plant response to added N in less productive soils (Gray Luvisol). The type of N fertilizer also influenced the restoration of crop productivity of eroded soils. Barley yields of the 20 cm artificially eroded soils were increased to the yield levels of non-eroded and non-fertilized soil with KNO_3 at both sites and, with urea only at Site 2. However, under the same fertilizer treatment barley yields of 20 cm eroded soils were lower than that of non eroded soils. Late sowing of barley was assumed to be one of the reasons for the relatively low biomass yield obtained in the first year at both locations.

The application of N fertilizers improved the productivity of artificially eroded soils but at the cost of substantial N losses (Chapter 3). In two years, the percentage of added N not accounted by the ^{15}N mass balance was 14 to 38% at Site 1 and 38 to 53% at Site 2 (Chapter 3).

By mid-September 1991 approximately 20 to 27% of the N added as KNO_3 had been lost from the artificially eroded soils at Site 1 and with both N sources at Site 2. At both locations, since the accumulation of the added N was primarily in the first 15 cm soil depth, the N losses during the first four months were assumed to occur mainly via denitrification. The N losses via denitrification were probably enhanced by waterlogged soil conditions as a result of heavy rainfall. Although direct measurements of denitrification were not made, the hypothesis of denitrification losses was greatly supported by the high $\delta^{15}N$ values (+16 to +85, at Site 1 and +9 to +33, at Site 2) of soil NO_3-N in artificially eroded soils (Chapter 4). The relatively lower $\delta^{15}N$ values of soil NH_4-N than that of NO_3-N gave further evidence for N loss through denitrification. In addition, elevated plant $\delta^{15}N$ values (which was greater than that of soil $\delta^{15}N$) reflected denitrification of ^{14}N in soil NO_3-N in early growth stages and consequent accumulation of ^{15}N enriched NO_3-N (Chapter 4).

At Site 1, although most of the added N retained in soil was recovered in the surface 15-cm, fast downward movement of N was noted in the eroded soils during the first growing season (Chapter 3). Leaching was also thought to have contributed partly to the N losses in the first year, at Site 1, since, in the 20 cm of artificially eroded soils, almost 2.5 kg ha^{-1} of added N were recovered as total soil N in the 60-75 cm depth.

During the period between harvests, losses of residual ^{15}N were greater from the artificially eroded soils than from non-eroded soils. This was probably due to a comparatively greater soil retention of added N in eroded than in non-eroded soils in the first year (Chapter 3). Since most of the added N retained by the soil was primarily in the surface 15 cm, the N losses obtained for the period between harvests, were assumed to have occurred mainly through denitrification during the spring thaw period of 1992 (Chapter 3).

With KNO_3, major N losses from the artificially-eroded soils seemed to occur immediately after N application at Site 1, and during the early spring thaw period at Site 2. Overall, KNO_3 gave greater N losses from the artificially-eroded soils, at both locations (Chapter 2 and 3). The large N losses obtained in this study, were also thought to be due to the application of greater than the recommended rates of fertilizer N (Chapter 3).

5.2 Practical Implications

Our results showed that restoration of crop productivity of the maximum eroded soils was possible by applying large doses of fertilizer N but at the same time resulted in substantial losses of N. The N losses occurred mainly to the atmosphere, through denitrification. The proportion of N lost as N_2O may have important consequence for environmental quality in that N_2O contributes to global warming and depletes stratospheric ozone.

The major implication of this research is that, to minimize fertilizer loss and improve crop production, restoration programs should optimize the rates of fertilizer application according to degree of erosion, soil type, crop type, and level of management.

This research has supported, from an environmental point of view (i.e., N losses), that preventing erosion will always be better than curing it.

5.3 Recommendations for future work

The findings of any research on any topic always allow us to extend and verify more on that topic or on any other topic related directly or indirectly to it. This research gave some helpful suggestions on restoring the crop productivity of eroded soils. At the same time it also gave us the knowledge to focus on various areas like:

(i) Quantitative measurement of gaseous loss of N from eroded soils:

The ^{15}N mass balance technique gave us estimates of unaccounted N losses from the artificially eroded soils. On the basis of soil profile distribution of total soil N we assumed the major N loss to be through denitrification. The variations of natural ^{15}N abundance of artificially eroded soils gave further evidence of denitrification loss from the eroded soils. Since the estimates of N losses obtained from this study were more qualitative or semi quantitative I realized the need to quantify the gaseous loss of N from eroded soils, in a large scale. Further research should measure the N losses through denitrification from: (a) soils with varying degree of erosion, (b) cultivated and uncultivated soils, and (c) fertilized and unfertilized soils.

(ii) Mineralization potential of the soil under study:

Mineralization of N or C could be used as indexes of the activity of soil microbial biomass. This study did not measure the N mineralization potential of the soils thus future research could involve laboratory measurements of N mineralization potential of the soils under study. This should include the measurement of ^{15}N in the microbial biomass. Measurement of biological activity of eroded soils may also help explain the possible loss of gaseous N from subsoils.

(iii) Soil-specific farming:

Soil-specific farming appears to be an appropiate technology to optimize fertilizer application to soils with varying degree of erosion and nutrient requirements. Soil-specific farming is a farm management system that takes into account the variability of soil and microclimate conditions that occur within most fields. In this management, fertilizers, pesticides, crop varieties, and management practices are precisely matched with land and climate attributes (Neilsen et al., 1992). This practice could therefore help reduce waste and contribute to energy conservation and environmental protection. I suggest the need to assess the efficiency of soil-specific farming when applied to fields with varying degree of erosion.

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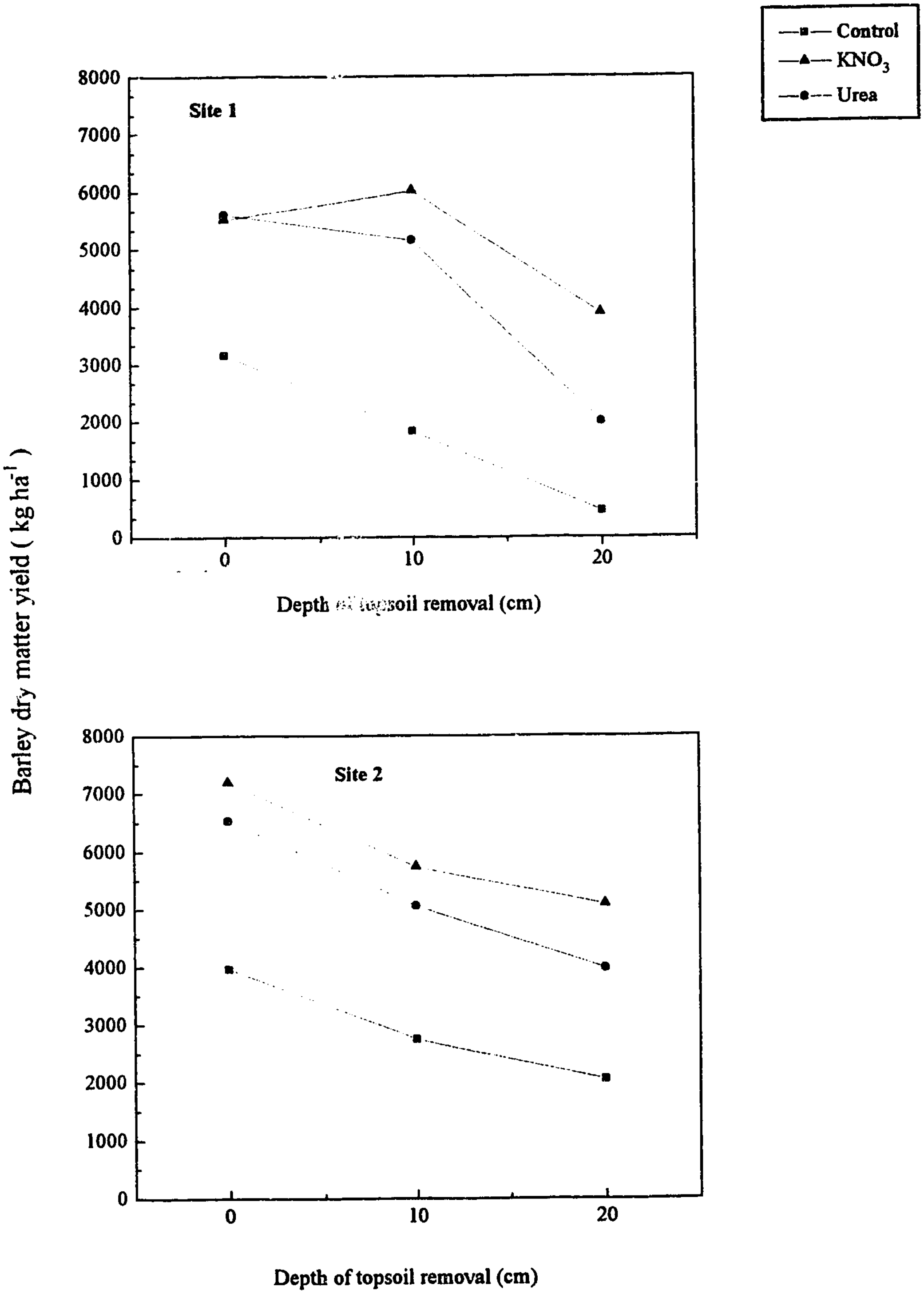
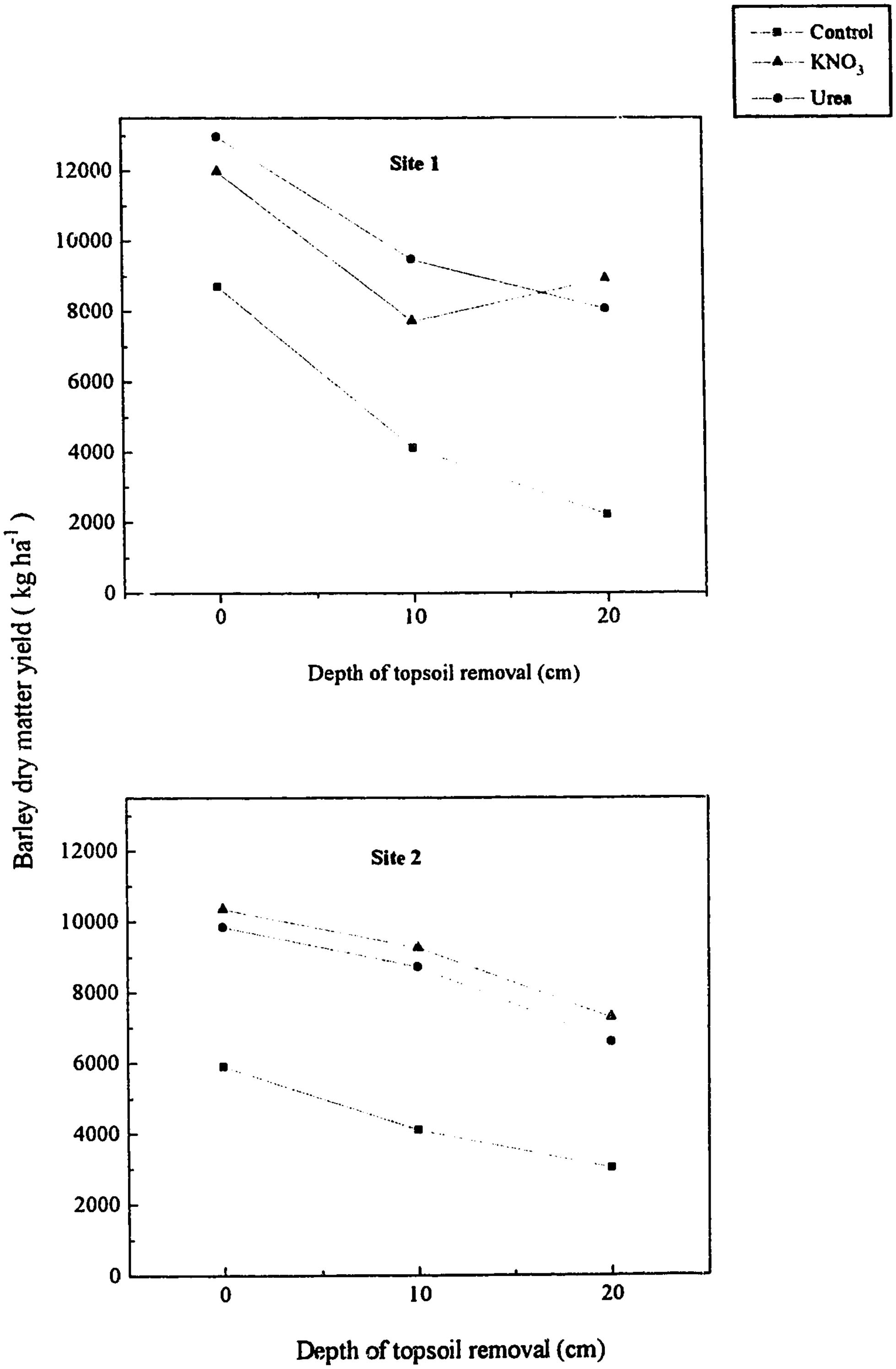
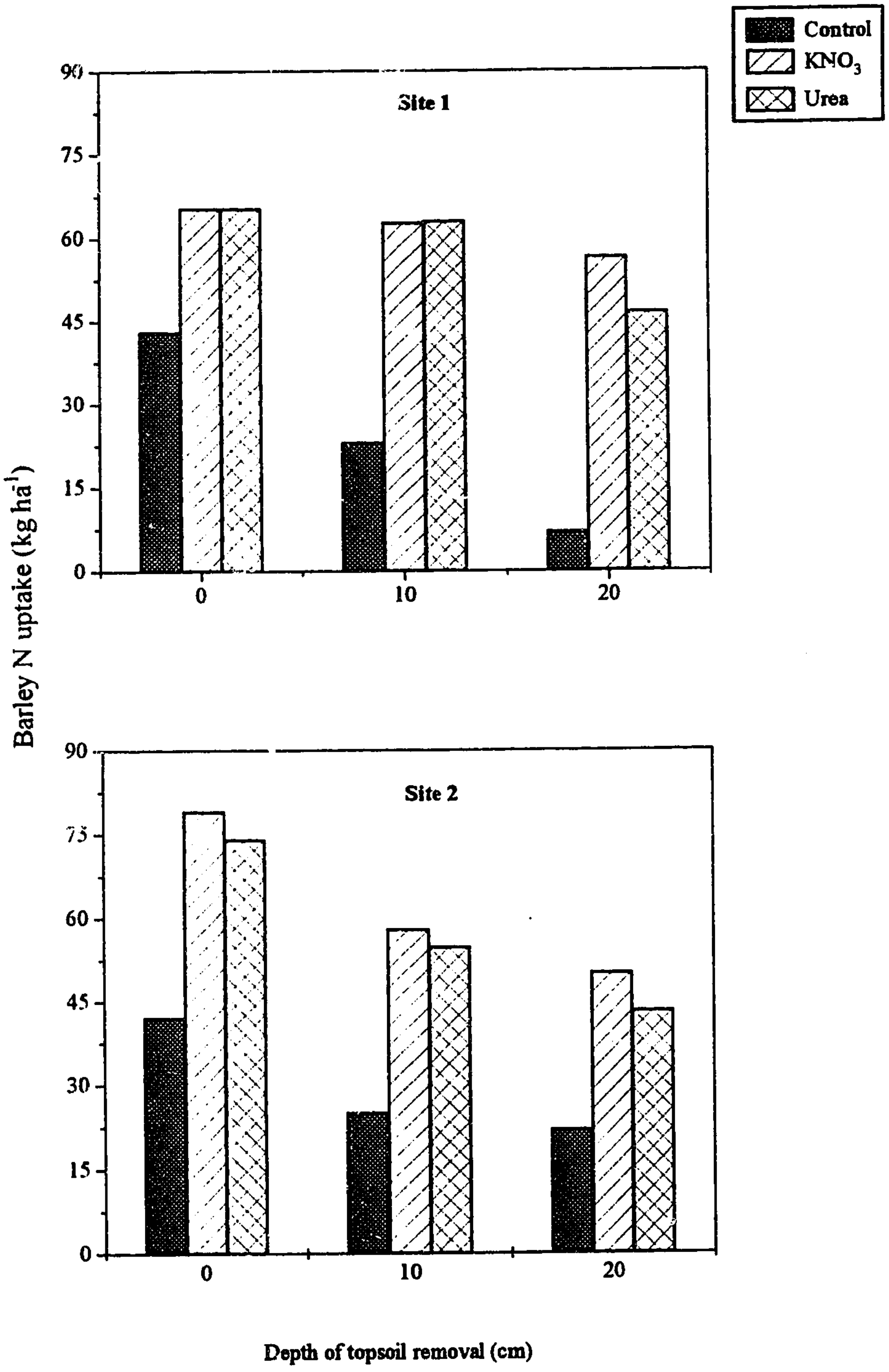
APPENDICES



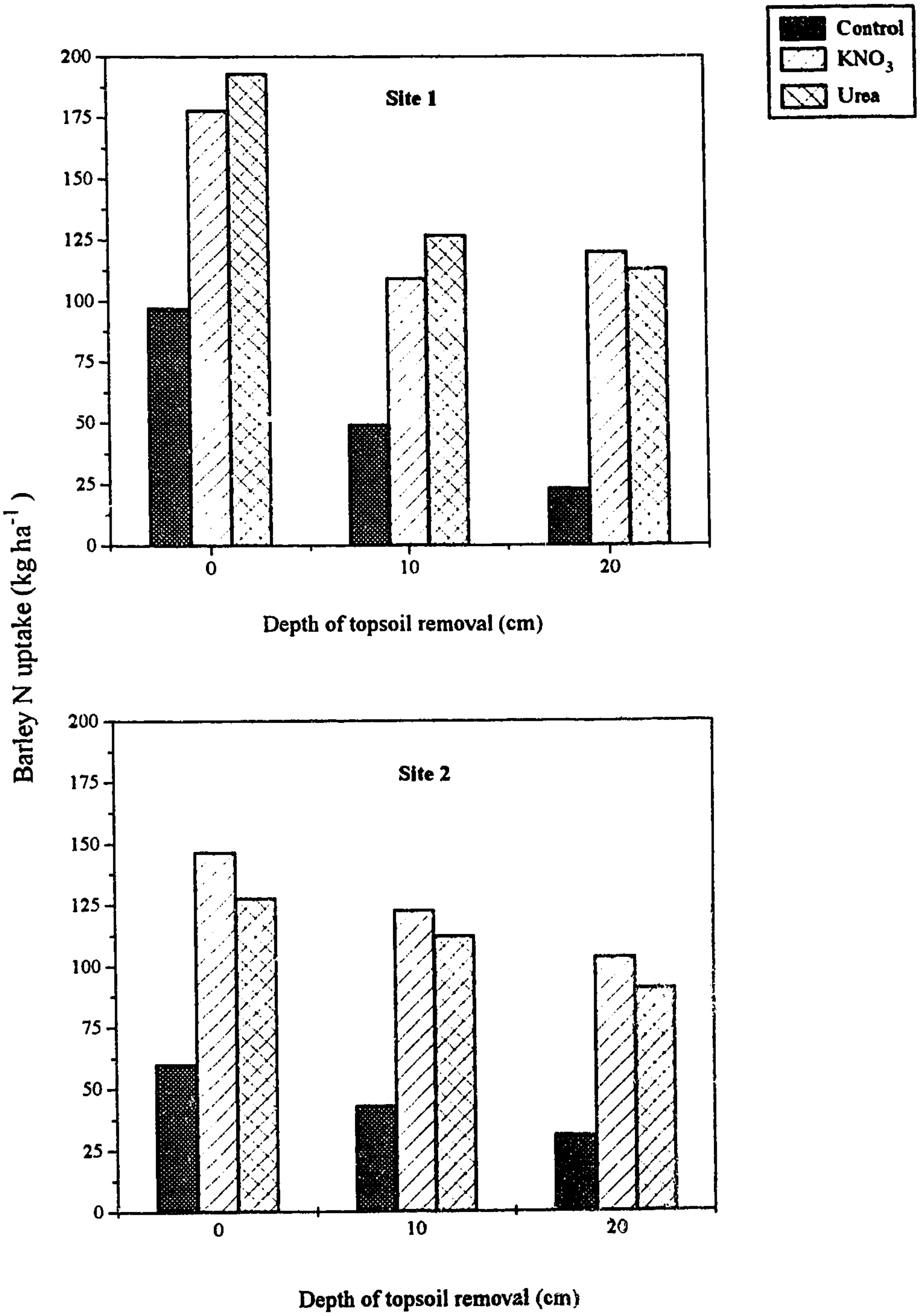
Appendix 2.1. Effect of artificial erosion and N source on dry matter yield of barley at Sites 1 and 2 in 1991.



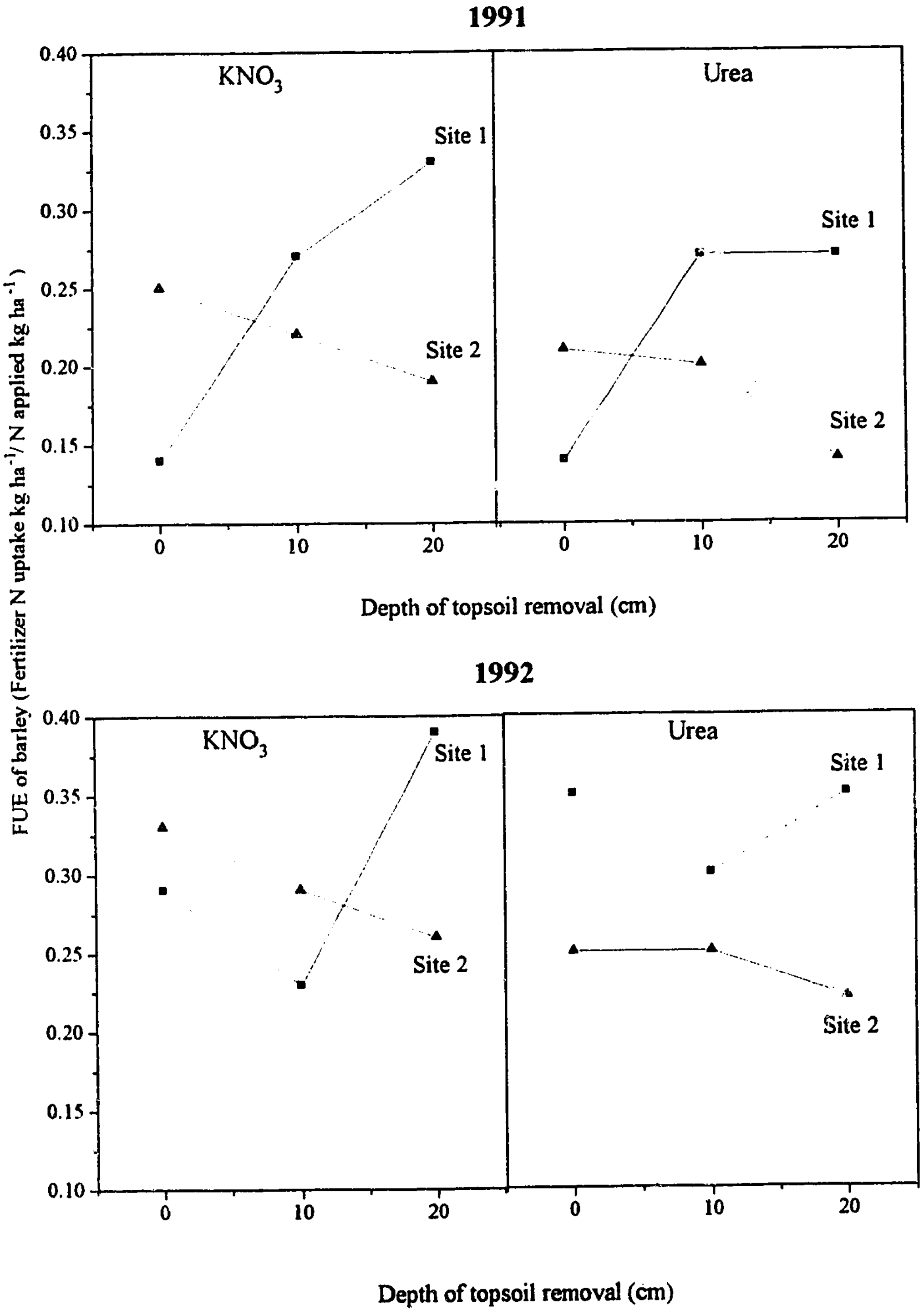
Appendix 2.2. Effect of artificial erosion and N source on dry matter yield of barley at Sites 1and 2 in 1992.



Appendix 2.3. Effect of artificial erosion and N source on barley N uptake at Sites 1 and 2 in 1991.



Appendix 2.4. Effect of artificial erosion and N source on barley N uptake at Sites 1 and 2 in 1992.



Appendix 2.5. Effects of artificial erosion and N source on fertilizer use efficiency (FUE) of barley, at Sites 1 and 2, during 1991-1992.

Appendix 2.6

Barley dry matter yields as affected by artificial erosion and nitrogen fertilizer source at Site 1 and Site 2, in 1991.

Depth of topsoil removal (cm)	Treatment	Dry matter yield (kg ha^{-1}) Site 1	Site 2
0	Control	3200	4000
10	Control	1800	2800
20	Control	440	2100
0	KNO_3	5500	7200
10	KNO_3	6000	5700
20	KNO_3	3900	5100
0	Urea	5600	6500
10	Urea	5200	5100
20	Urea	2000	4000

Barley dry matter yields as affected by artificial erosion and nitrogen fertilizer source at Site 1 and Site 2, in 1992.

Depth of topsoil removal (cm)	Treatment	Dry matter yield (kg ha^{-1}) Site 1	Site 2
0	Control	8700	5900
10	Control	4100	4100
20	Control	2200	3000
0	KNO_3	12000	10400
10	KNO_3	7700	9300
20	KNO_3	8900	7300
0	Urea	13000	9800
10	Urea	9500	8700
20	Urea	8100	6600

Appendix 2.7

Barley N uptake as affected by artificial erosion and nitrogen fertilizer source at Site 1 and Site 2, in 1991.

Depth of topsoil removal (cm)	Treatment	N uptake (kg ha^{-1}) Site 1	Site 2
0	Control	43	42
10	Control	23	25
20	Control	7	22
0	KNO_3	65	79
10	KNO_3	63	58
20	KNO_3	56	50
0	Urea	65	74
10	Urea	63	55
20	Urea	47	43

Barley N uptake as affected by artificial erosion and nitrogen fertilizer source at Site 1 and Site 2, in 1992.

Depth of topsoil removal (cm)	Treatment	Dry matter yield (kg ha^{-1}) Site 1	Site 2
0	Control	97	60
10	Control	49	43
20	Control	23	31
0	KNO_3	179	147
10	KNO_3	109	123
20	KNO_3	121	103
0	Urea	193	127
10	Urea	127	112
20	Urea	113	91

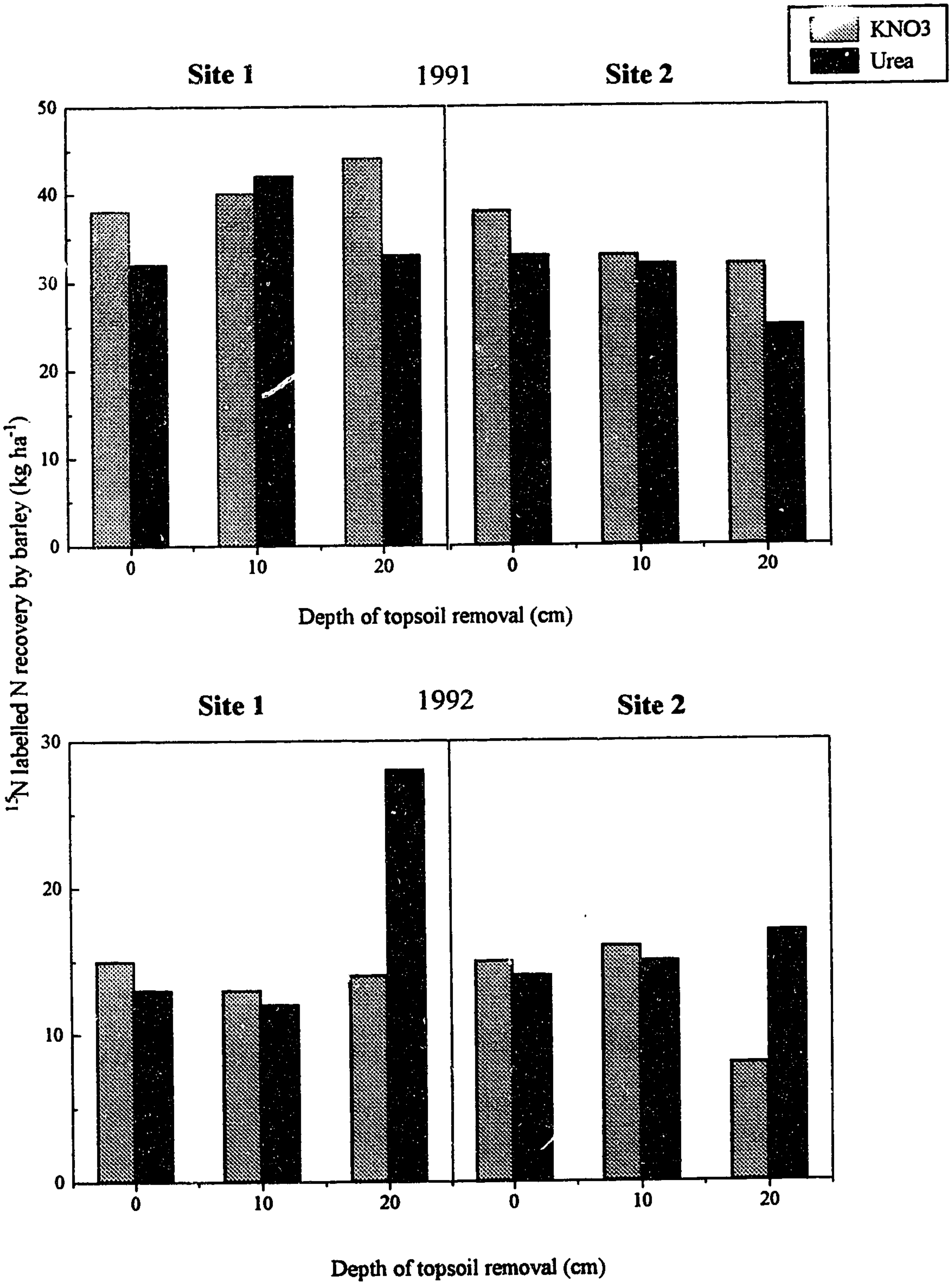
Appendix 2.8

Fertilizer use efficiency (FUE) of barley as affected by artificial erosion and nitrogen fertilizer source at Site 1 and Site 2, in 1991.

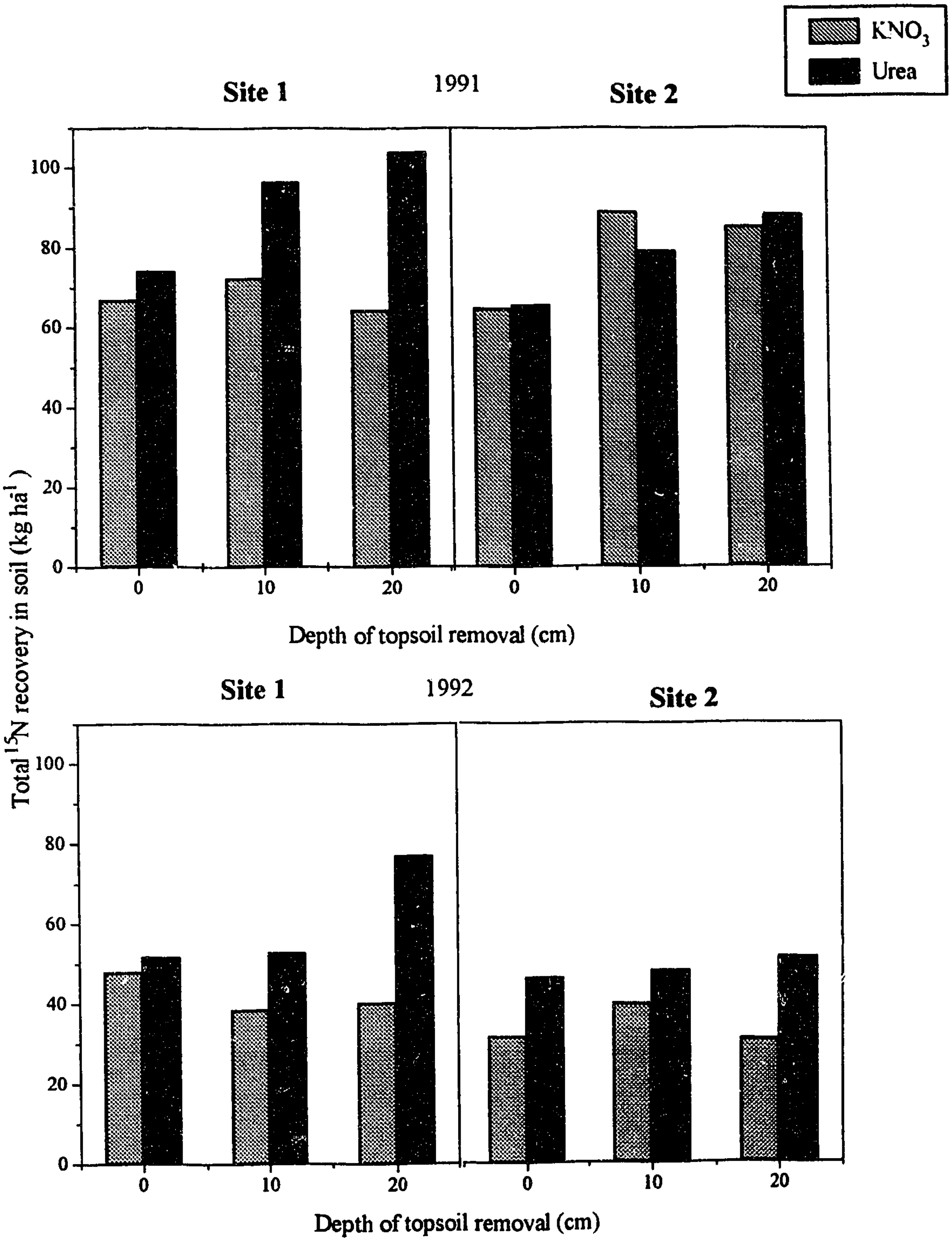
Depth of topsoil removal (cm)	Treatment	FUE Site 1	FUE Site 2
0	KNO_3	0.14	0.24
10	KNO_3	0.26	0.22
20	KNO_3	0.32	0.18
0	Urea	0.14	0.21
10	Urea	0.26	0.20
20	Urea	0.26	0.14

Fertilizer use efficiency (FUE) of barley as affected by artificial erosion and nitrogen fertilizer source at Site 1 and Site 2, in 1992.

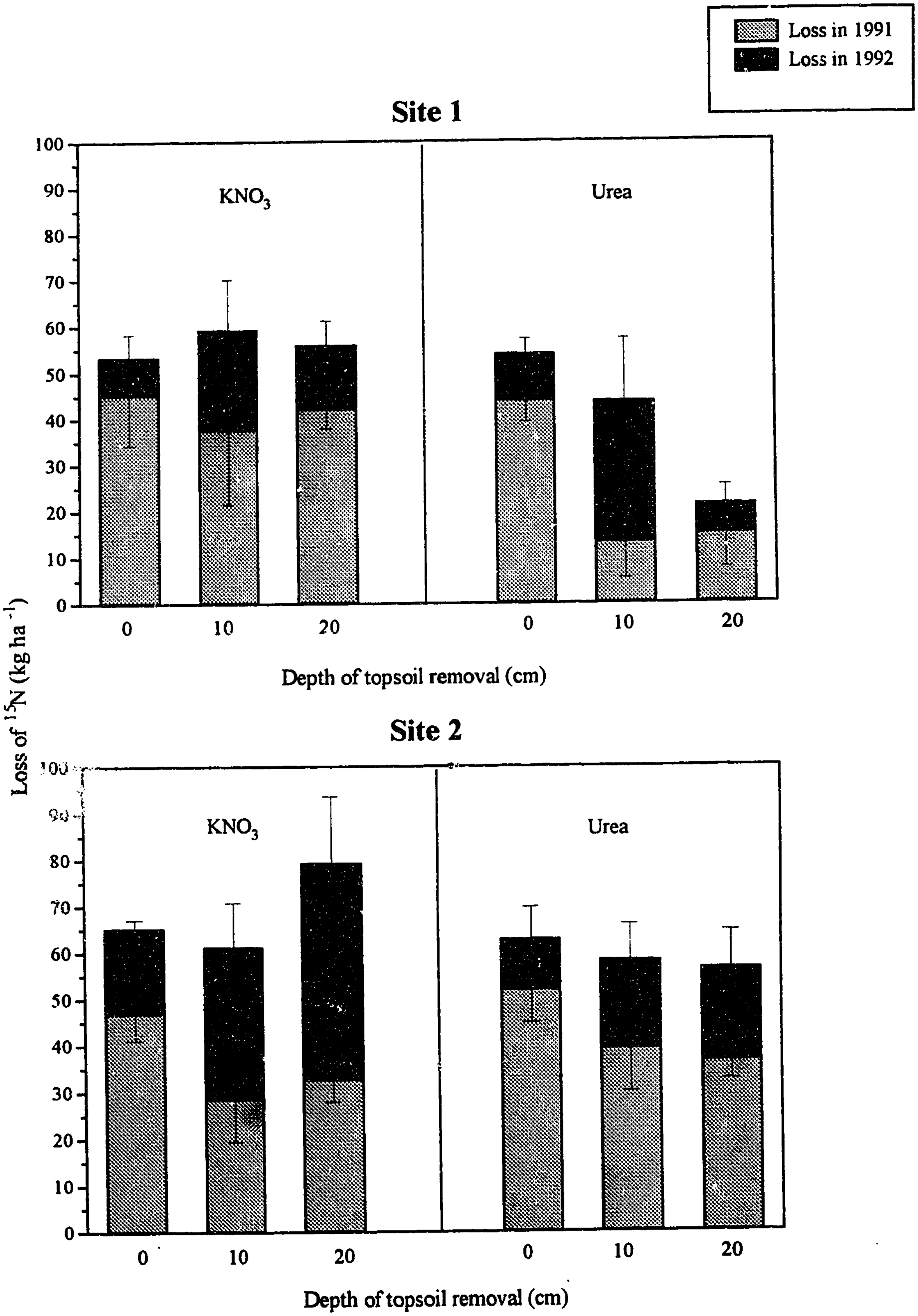
Depth of topsoil removal (cm)	Treatment	FUE Site 1	FUE Site 2
0	KNO_3	0.29	0.33
10	KNO_3	0.23	0.29
20	KNO_3	0.39	0.27
0	Urea	0.35	0.25
10	Urea	0.30	0.25
20	Urea	0.56	0.21



Appendix 3.1. Effects of topsoil removal and N source on ^{15}N recovery in barley, in 1991-1992.



Appendix 3.2. Effects of topsoil removal and N source on total ^{15}N recovery in soil (0-75 cm depth).



Appendix 3.3. Loss of applied ^{15}N from the plant-soil system, during 1991-1992.
Note: Vertical lines in each column indicate the magnitude of the standard error associated with the N loss estimate.

Appendix 3.4

Mass balance of applied ^{15}N at Site 1 in 1991-1992.

	Depth of topsoil removal (cm)		
Treatment	0	10	20
Year		**1991**	
		Soil ^{15}N recovery	
KNO_3	66.8 ±7.6	72.2±17.8[‡]	64.3±2.6
Urea	73.9±4.1	96.3±10.4	103.9±6.2
		Plant ^{15}N recovery	
KNO_3	37.8±4.7	40.1±4.5	43.6±2.0
Urea	32.1±5.0	41.6±2.4	33.1±4.5
		^{15}N Unaccounted for/loss	
KNO_3	45.4±11.1	37.7±16.2	42.2±4.2
Urea	44.0±4.6	13.3±7.9	15.1±7.5
Year		**1992**	
		Soil ^{15}N recovery	
KNO_3	47.9±3.7	38.4±5.3	40.2±6.3
Urea	51.6±3.6	52.7±5.9	76.9±3.0
		Plant ^{15}N recovery	
KNO_3	14.5±2.5	13.0±5.5	13.9±3.9
Urea	12.4±1.2	12.0±3.8	27.7±3.7
		^{15}N Unaccounted for/loss	
KNO_3	7.9±5.0	21.4±11.1	13.6±5.4
Urea	10.0±3.3	30.4±13.6	6.2±4.1
		Total unaccounted ^{15}N loss in two years	
KNO_3	53.3	59.1	55.8
Urea	54.0	43.7	21.3

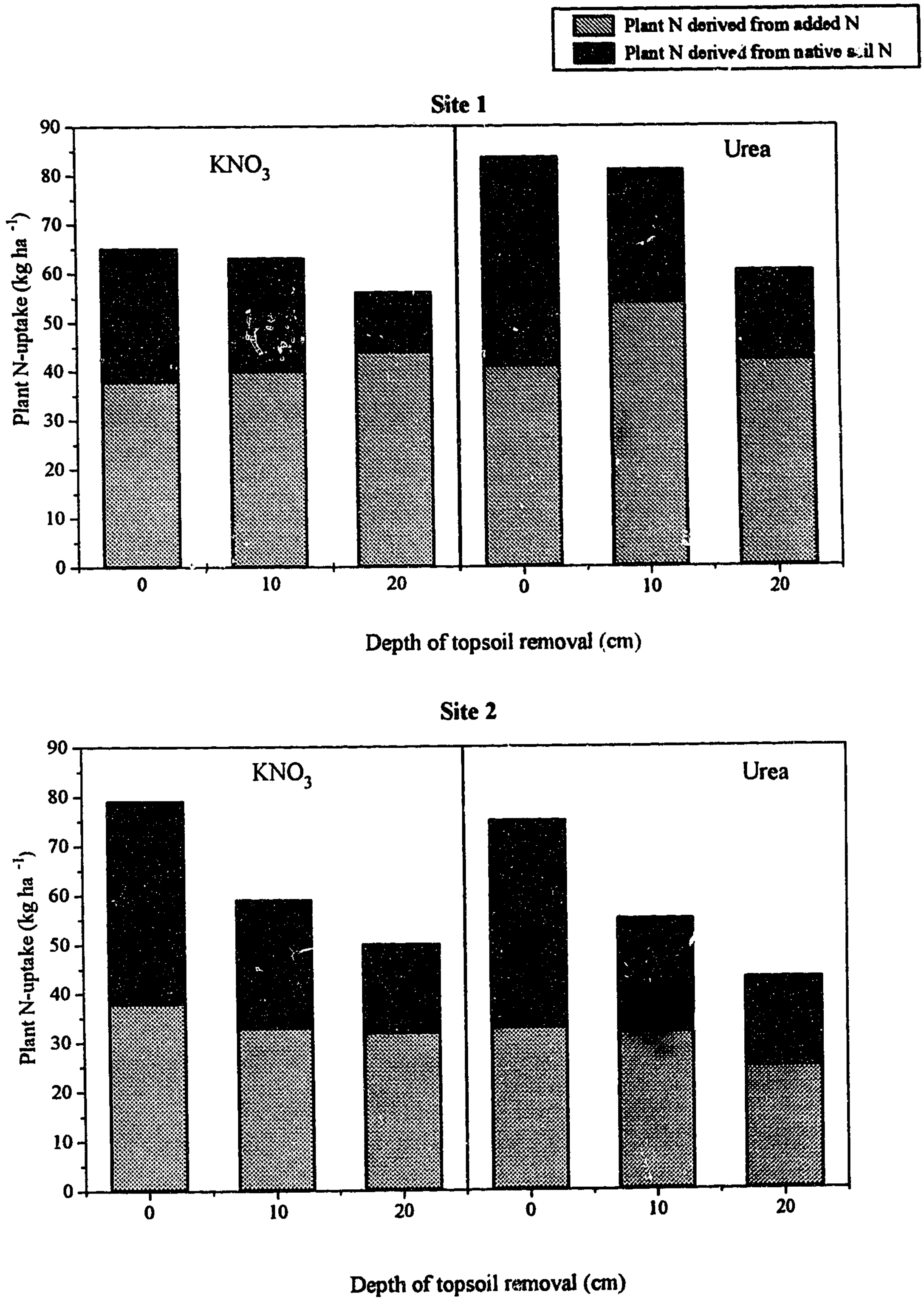
[‡] Values following ± represents the standard error of estimate.

Appendix 3.5

Mass balance of applied ^{15}N at Site 2 in 1991-1992.

	Depth of topsoil removal (cm)		
Treatment	0	10	20
Year		**1991**	
		Soil ^{15}N recovery	
KNO_3	64.7 ±5.1[†]	88.8±6.3[‡]	85.1±6.4
Urea	65.5±5.9	79.1±5.5	88.3±5.0
		Plant ^{15}N recovery	
KNO_3	38.4±2.7	32.5±3.5	32.1±2.0
Urea	32.5±1.2	31.6±3.9	25.1±2.4
		^{15}N Unaccounted for/loss	
KNO_3	47.0±5.8	28.7±9.2	32.8±4.9
Urea	52.0±7.1	39.3±9.3	36.6±4.1
Year		**1992**	
		Soil ^{15}N recovery	
KNO_3	31.5±5.3	39.8±4.8	30.9±7.7
Urea	46.3±4.9	48.0±2.9	51.4±6.7
		Plant ^{15}N recovery	
KNO_3	14.9±2.3	16.5±2.3	7.8±4.5
Urea	13.7±0.9	15.3±3.0	17.1±1.4
		^{15}N Unaccounted for/loss	
KNO_3	18.2±1.9	32.5±9.6	46.5±14.4
Urea	10.8±6.9	18.9±7.8	19.8±8.2
		Total unaccounted ^{15}N loss in two years	
KNO_3	65.2	61.2	79.3
Urea	62.8	58.2	56.4

[‡] Values following ± represents standard error of estimate.



Appendix 3.6. Contribution of added N and soil derived N to barley N uptake at different depths of topsoil removal, in 1991.

Appendix 4.1 The delta 15N values for soil NO3-N at Sites 1 and 2.

Depth of soil erosion (cm)	Replication	Soil sampling depth (cm)	Site 1 Delta 15N	Site 2 Delta 15N
0	1	0-15	7.4	6.3
0	2	0-15	-0.3	9.3
0	3	0-15	2.5	-9.6
0	4	0-15	2.2	5.2
10	1	0-15	31.7	3.8
10	2	0-15	41.8	4.1
10	0	0-15	34.4	7.9
10	4	0-15	8.2	2.7
20	1	0-15	35.2	-3.3
20	2	0-15	30.3	2.7
20	3	0-15	17.5	9.0
20	4	0-15	74.8	14.9
0	1	15-30	6.3	7.1
0	2	15-30	8.2	6.6
0	3	15-30	21.3	22.1
0	4	15-30	9.0	0.3
10	1	15-30	29.5	10.1
10	2	15-30	35.5	-4.4
10	3	15-30	26.5	5.2
10	4	15-30	27.3	58.1
20	1	15-30	12.3	5.7
20	2	15-30	13.1	79.7
20	3	15-30	12.3	6.0
20	4	15-30	28.4	16.4
0	1	30-45	5.7	16.4
0	2	30-45	8.5	12.8
0	3	30-45	12.3	9.6
0	4	30-45	6.0	28.1
10	1	30-45	161.1	9.3
10	2	30-45	-7.1	4.1
10	3	30-45	36.3	9.3
10	4	30-45	96.6	14.5
20	1	30-45	200.4	33.3
20	2	30-45	52.1	26.8
20	3	30-45	77.5	5.2
20	4	30-45	11.5	68.3

Appendix 4.2 The delta 15N values for soil NH4-N at Sites 1 and 2, 1991.

Depth of soil erosion (cm)	Replication	Soil sampling depth (cm)	Delta 15N	Delta 15N
0	1	0-15	2.7	5.2
0	2	0-15	7.1	5.7
0	3	0-15	13.1	9.0
0	4	0-15	10.1	5.5
10	1	0-15	-2.7	6.6
10	2	0-15	4.1	4.4
10	0	0-15	-0.3	7.1
10	4	0-15	-10.3	10.4
20	1	0-15	4.6	5.2
20	2	0-15	1.6	3.0
20	3	0-15	2.2	11.7
20	4	0-15	6.3	4.4
0	1	15-30	6.8	8.2
0	2	15-30	12.8	6.3
0	3	15-30	9.8	4.6
0	4	15-30	7.9	6.6
10	1	15-30	4.1	10.6
10	2	15-30	3.8	7.6
10	3	15-30	-1.1	121.2
10	4	15-30	-0.5	46.4
20	1	15-30	5.5	1.1
20	2	15-30	-0.8	1.1
20	3	15-30	4.7	1.9
20	4	15-30	3.0	3.5
0	1	30-45	3.3	8.7
0	2	30-45	11.5	-14.2
0	3	30-45	7.9	10.9
0	4	30-45	7.1	9.6
10	1	30-45	8.2	10.9
10	2	30-45	10.6	14.7
10	3	30-45	10.9	4.9
10	4	30-45	6.3	5.5
20	1	30-45	9.0	54.6
20	2	30-45	4.6	8.2
20	3	30-45	1.6	4.4
20	4	30-45	6.3	4.4