ABSTRACT

Ph.D. B. CASPAR WARNAARS Soil Science

SOIL FACTORS AFFECTING CORN (*ZEA MAYS* L.) ROOT GROWTH, FERTILIZER NITROGEN UPTAKE AND NITROGEN LEACHING LOSSES IN THREE QUEBEC SOILS

Increases in mechanical impedance, as measured by a root shaped penetrometer, caused decreases in corn root growth in sands and soils.

Restricted root systems of corn, mainly caused by high impedance levels in a fine sandy loam and clay, were more efficient in utilizing native soil N than less restricted root systems growing in a sandy loam with low levels of impedance. Fertilizer N recoveries ranged from 26% on the fine sandy loam and clay to 37% on the sandy loam.

Fertilizer N increased both top and root dry matter production, the effect on root growth was greater in soils with low impedance levels.

Most residual fertilizer N in the soil was in the inorganic form after crop harvest. Higher levels of nitrates in the soil in late September were associated with applications of fertilizer N in June rather than in April or May.

Leaching losses of N were negligible in 1971 due to low rainfall. Precipitation from crop harvest to mid-December was insufficient to recharge the soil to a depth of 100 cm.

Suggested short title

CORN ROOT GROWTH, SOIL CONDITIONS

AND NITROGEN UTILIZATION

Warnaars

SOIL FACTORS AFFECTING CORN (ZEA MAYS L.) ROOT GROWTH,

FERTILIZER NITROGEN UPTAKE AND NITROGEN LEACHING

LOSSES IN THREE QUEBEC SOILS

by

Benjamin Caspar Warnaars

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Doctor of Philosophy

Department of Soil Science
McGill University
Montreal

August 1972

ACKNOWLEDGEMENTS

Financial support from the Quebec Agricultural Research Council and the Canadian Department of Agriculture in the form of a Graduate Assistantship is greatfully acknowledged.

The author wishes to express his sincere gratitude to Dr. A.F. MacKenzie, Professor and Chairman of the Department of Soil Science and Dr. B.P. Warkentin, Professor in the Department of Soil Science, for their encouragement and for many useful discussions during the course of the experimental work.

I am indebted to Dr. B.W. Eavis, O.A.S. Horticulturist, Ministry of Agriculture, Barbados, for his assistance with the experimental work dealing with root growth.

It is a pleasure to acknowledge the help of Mr. Alex Schumacher who corrected some of the English grammar and style.

I extend special appreciation to Yvonne and Papoef who somehow managed to type this dissertation in this neat and final form.

FOREWORD

The original results of the investigation are not all presented in this dissertation. Mean values of these results are used in tables and figures to illustrate differences between soil types and treatments. The large volume of the original results are mainly presented on computer sheets and may be obtained, upon request, from the Department of Soil Science, McGill University.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Figure		Page

CHAPTER III

INTRODUCTION

The primary source of nitrogen (N) for plant growth is in elemental form, but neither this nor the organic N compounds which form the bulk of the soil N are directly available to plants. Instead they have to rely on the inorganic N forms which are present in only small amounts in the soil. Therefore plant growth is often limited by N supply especially at critical growth stages. This leads farmers to apply excessive quantities of readily available inorganic N fertilizer in an attempt to ensure maximum yield. A large proportion of this added N can escape as nitrate through drainage into waterways and becomes a pollutant. Factors affecting the availability of soil N by plants and the conservation of applied N by the soil are therefore relevant to the eutrophication problem. Management of this N system requires knowledge of the major N reactions within the soil-plant continuum on any crop production system. The proportion of added N recovered by crops may depend *inter alia* on root growth and distribution which is affected by soil physical conditions. The latter also influence the retention and movement of inorganic N in the soil and therefore losses through drainage into streams and lakes.

The series of experiments described in this thesis were designed to test several hypotheses concerning root distribution and N utilization by corn (*Zea mays* L.).

In the first chapter, the effects on seedling root growth of soil physical properties in sands and soil varying in moisture content is considered, showing the important effects of mechanical impedance (measured by a root shaped penetrometer), aeration and moisture availability. Because of the complexity of the field situation and the interactions due to climatic variations this aspect was studied in the laboratory under simplified controlled conditions.

The second chapter concerns the effect of the size of the root system of corn on the utilization of fertilizer N and native soil N in the field. The hypothesis being tested was that a deep and extensive root system would utilize proportionally more fertilizer N and less native soil N than a restricted root system since soil N is mineralized mainly in the top soil.

The third chapter examines the effect of time of fertilizer N applications on potential losses from the field. The hypothesis being tested was that potential losses of fertilizer N would be greater with late applications than with early applications because smaller amounts of late applications may be immobilized or absorbed by the plant as compared to earlier applications.

These field experiments were carried out on three soil types varying in texture and root impedance levels. Corn was chosen because of its increasing importance in Quebec agriculture, its superior yield of dry matter and its dependence on high rates of N fertilization for maximum yield. Ammonium nitrate fertilizer was used as a source of N.

CHAPTER I

MECHANICAL IMPEDANCE, AERATION AND MOISTURE AVAILABILITY INFLUENCING SEEDLING ROOT GROWTH

LITERATURE REVIEW

Root growth can be restricted by mechanical impedance, poor aeration or moisture stress. The significance of each factor varies with the composition of the soil, its moisture content and structure.

The soil matrix exerts an influence on plant root development through the impedance it offers. The physical condition of the soil has an important influence on other factors involved in root development, such as aeration and water movement, and it is therefore difficult to isolate the direct effects of mechanical impedance. In a review of literature, Lutz (1952) made an effort to separate the effects of impedance.

Under controlled laboratory conditions Gill and Miller (1956) studied direct effects of mechanical impedance on root growth, showing that increasing compression resulted in slower root growth of corn. Wiersum (1957) found that depth of root penetration decreased as rigidity of sand pores increased. He concluded that a root is only able to penetrate a rigid pore having a diameter exceeding that of a young root.

Mechanical impedance in soils have often been determined with root shaped penetrometers (Pfeffer, 1893; see Gill and Bolt, 1955; Wiersum, 1957; Phillips and Kirkham, 1962; Taylor and Gardner, 1963). Eavis (1965) found a highly significant positive relation between root force and penetrometer resistance force. However, root forces were four to eight times smaller than the equivalent stresses on the root shaped penetrometer. The reason of this difference could not be explained but may have been due to differences in skin friction.

Many experiments have been reported which show that increases in soil bulk density decrease root growth (Barley and Greacen, 1967; Gerard and Metha, 1971; Wilkinson and Duff, 1972). Phillips and Kirkham (1962) found that an increase in bulk density associated with an increase in mechanical impedance, decreased corn seedling growth. However, bulk density alone does not seem to determine root penetration but pore size distribution and water content must also be considered. Evidence was clearly demonstrated by Taylor and Gardner (1963) and Eavis (1965) that decreasing matric potential increased mechanical impedance at one bulk density. Thus the magnitude of soil bulk density effects upon root penetration depended on the soil moisture content. It was concluded that soil strength, measured by penetrometer, not bulk density was the critical impedance factor controlling root penetration.

The relationship between soil water potential and seedling root growth was evaluated by Gingrich and Russell (1956) and Peters (1957) who concluded that the reduction in corn root elongation was entirely due to decreasing soil moisture contents. The validity of this conclusion can now be questioned after the findings of Taylor and Gardner (1963) and Eavis (1965) that decreasing moisture contents also increases mechanical impedance. The effect of soil water potential on corn root elongation could therefore have been a combination of the two factors.

Inadequate soil aeration causing a decrease in root growth can in most situations be traced to excess soil water, either alone or in combination with high soil densities. Gingrich and Russell (1956) found that at low water suctions, oxygen concentration was most critical, needing to be above 10.5% for maximum growth. Maximum growth occurred at about -1 bar soil water potential.

Eavis (1972) recently made an attempt to separate and identify effects attributable to mechanical impedance, aeration and water availability on root growth of pea seedlings. He found that mechanical impedance increased both with bulk density and water potential and that an aeration effect was detected in soils having less than 30, 22 and 11% gas filled pore space at low (1.1 g cm^{-3}), medium (1.4 g cm^{-3}) and high (1.6 g cm^{-3}) bulk densities respectively. He indicated that a large number of small pores would be more effective than smaller number of large pores in reducing the effect of a liquid barrier around the root. Severe symptoms associated with restricted water availability were found only at potentials at about -10 bars. He concluded that in loose soil pea root growth is suppressed through aeration effects only, at soil water potentials larger than -0.1 bar, and in compacted soil by both mechanical impedance and bad aeration. Root growth is restricted by mechanical impedance only at potentials ranging from -0.1 bar to -10 bar, and by both moisture stress and impedance at potentials smaller than -10 bar regardless of composition. Optimal conditions for pea root growth was found at bulk density of 1.0 g cm^{-3} at potentials ranging from -0.1 bar to about -4.0 bar.

The experimental results contained in the literature generally emphasize the important role of water in root growth. Not only does it influence the factors previously mentioned, but also controls soil temperature and nutrient uptake.

The experiments described here show that variations in mechanical impedance and aeration, effect seedling root growth in sands and soil with differing moisture content(1).

Because of the complexity of the field situation, and the interactions caused by climatic variations the experiments were carried out under controlled laboratory conditions. An attempt was made to separate these factors influencing root growth so as to give a better background understanding. A simple method of measuring mechanical impedance by a root shaped penetrometer was employed and evaluated for subsequent field samples.

This investigation was carried out under the direction of Dr. B.W. Eavis, a visiting lecturer in the department of Soil Science.

---

(1)This part of the study is written up separately as a paper entitled "Soil Physical Conditions Affecting Seedling Root Growth: 2. Mechanical impedance, aeration and moisture availability as influenced by grain size distribution and moisture content in silica sands". Warnaars, B.C. and B.W. Eavis. 1972. Plant and Soil, 36: In Press.

MATERIALS AND METHODS

The grain size distributions of three grades of pure silica sand obtained from St. Donat deposits, Montreal, Canada are given in Figure 1.

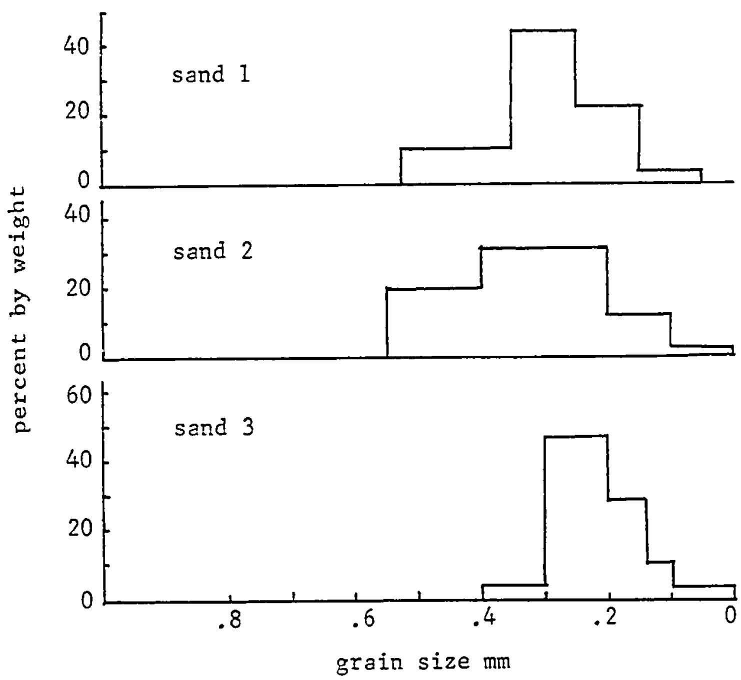

Figure 1: Grain size distribution of three silica sands. Histogram shows percentage by weight retained by different sized sieves.

The dry sands were scooped into wide acrylic cylinders 8.0 cm diam x 7.5 cm long, thus preventing the separation and layering of different grain sizes which occurs if the sands are poured. The base of each cylinder was cast in plaster of Paris and even packing was obtained by gently tapping the cylinder three times on the laboratory bench.

Soil water potential was controlled by placing the saturated sand columns on ceramic one bar tension plates maintained at different suctions. The columns were allowed to equilibrate with the applied suction over 48 hours before planting. The 18 treatments combining six water potentials with three sand grades are shown in Table 1. There were five replications.

Table 1: Sand grades and soil water potentials used as treatments in the experiments.

Sand grade	Water potential (-cm of water)								
1	5,	10,	15,	20,	30,	40			
2	5,		15,	20,	30,	40,	50		
3	5,		15,		30,		50,	70,	100

(Water potential values are for mid-point of sand column)

Each sand column was planted with five to ten germinated pea (*Pisum sativum* L. Alaska), corn (*Zea mays* L. Warwick SL 209) and grass (*Lolium perenne* L.) when the seedling radicles were one cm long (pea and corn) or 0.25 cm long (grass). The seedlings were fixed on the top surface of the sand columns and radicles grew into the sands for 48 hours at $21^{\circ}C \pm 1^{\circ}C$. The root growth taking place was identified by a Congo red stain mark made behind the growing region at the time of planting. The root was cut at this position at the end of the experiment and root length and fresh weight were determined, the roots being weighed again after drying for 12 hours at $50^{\circ}C$.

Bulk density and moisture content of the sands were measured and estimates made of the volumetric proportions of gas, water and solid mineral matter in each treatment (Figure 2).

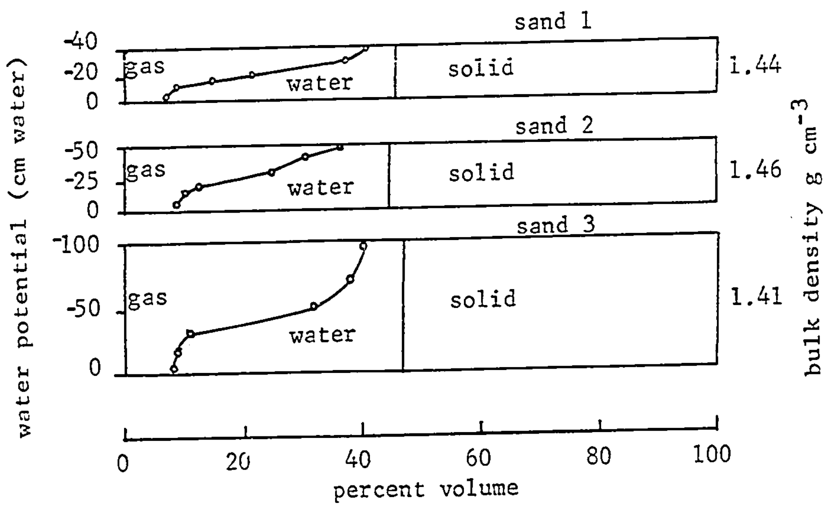

Figure 2: Volume proportions of solid, water and gas in three sands at six soil water potentials.

Penetrometer resistance in the sands was determined using a top-loading balance method (Eavis, 1972) and a stainless steel penetrometer probe (Figure 3) similar in size and shape to the pea and corn root tip, one or two mm long and one mm in diameter at its widest point. The probe, supported by a vice, was driven through the sand in one mm stages to a depth of 15 mm and the forces registered on the balance after equilibration at each stage were averaged.

In a second experiment pea root growth alone was compared in loose sand (approximate grade 3) and in a sandy loam soil. The sand and soil were loosely placed in flexible pouches attached to the surface of vertically positioned ceramic tension plates held at soil water potentials -10, -30, -70, -100, -140 and -210 cm of water. The root grew either in the soil or in the sand at a distance of about 1 cm from the ceramic plate. In this experiment effects of mechanical impedance were minimized by careful placement of the media. There were five replications and temperature was $20^{o}C \pm 2^{o}C$.

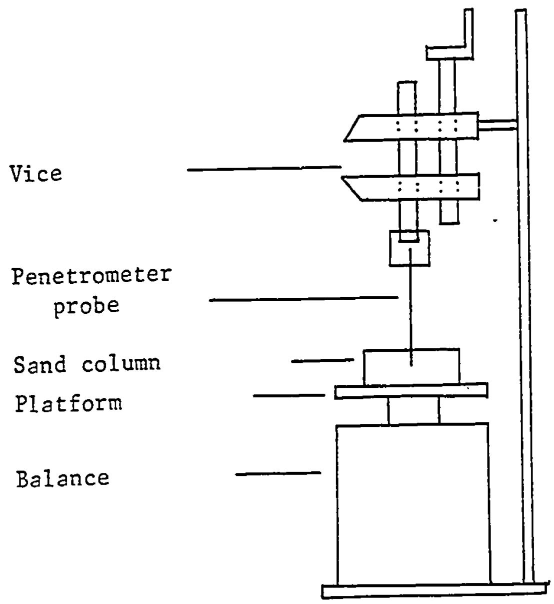

Figure 3: Top loading balance method for determining penetrometer resistance after Eavis (1972).

RESULTS AND DISCUSSION

Bulk densities of the sands packed dry were between 1.41 and 1.46 g cm^{-3} (Figure 2). Water content varied from 6 percent to 40 percent v/v and gas filled pore volume from 8 to 40 percent.

Root length (Figure 4a) and fresh weight (Figure 4b) of pea, corn and grass after 48 hours growth varied both with sand grade and with water potential. Maximum root elongation was 4.7 cm or 0.10 cm/h for peas, 6.6 cm or 0.14 cm/h for corn and 2.0 cm or 0.04 cm/h for grass. In the worst treatments root elongation was about 40 percent less in each case. Figure 4c also shows that the ratio fresh weight per unit length of root also varied, indicating differences in root diameter.

Possible effects on root growth due to nutrition, mechanical impedance, aeration and water availability are now discussed.

In preliminary experiments there was no significant difference between root elongation in sands wetted with distilled water and sands wetted with complete nutrient solution. Distilled water was therefore used in these experiments. Differences in nutrition between sands are unlikely since the sands originated from the same mineral deposit.

Penetrometer measurements were able to give some indication of mechanical impedance effects. Penetrometer resistance (Figure 5) decreased with increase in moisture content.

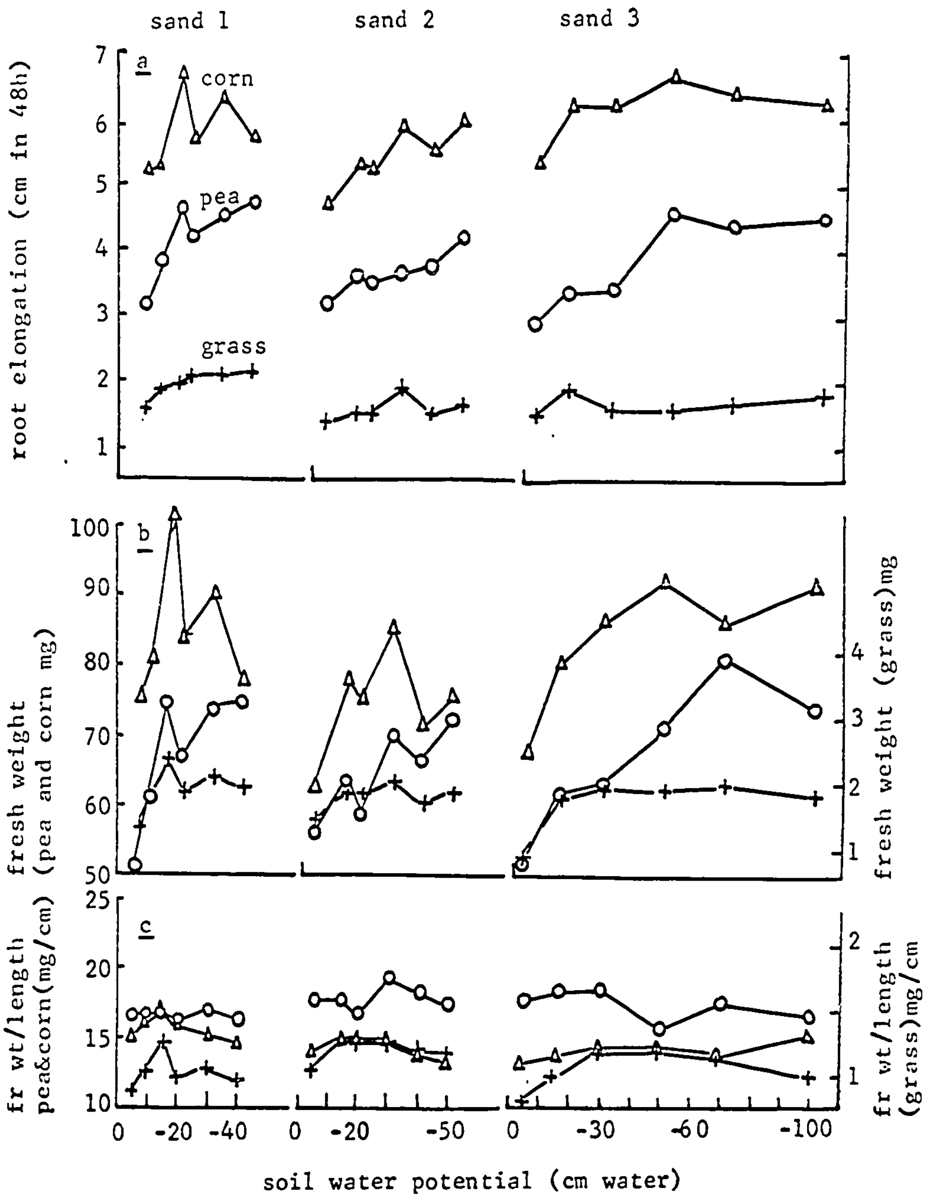

Figure 4: Root elongation, fresh weight and fresh weight per unit length for pea, corn and grass grown for 48 hours in three sands at six soil water potentials.

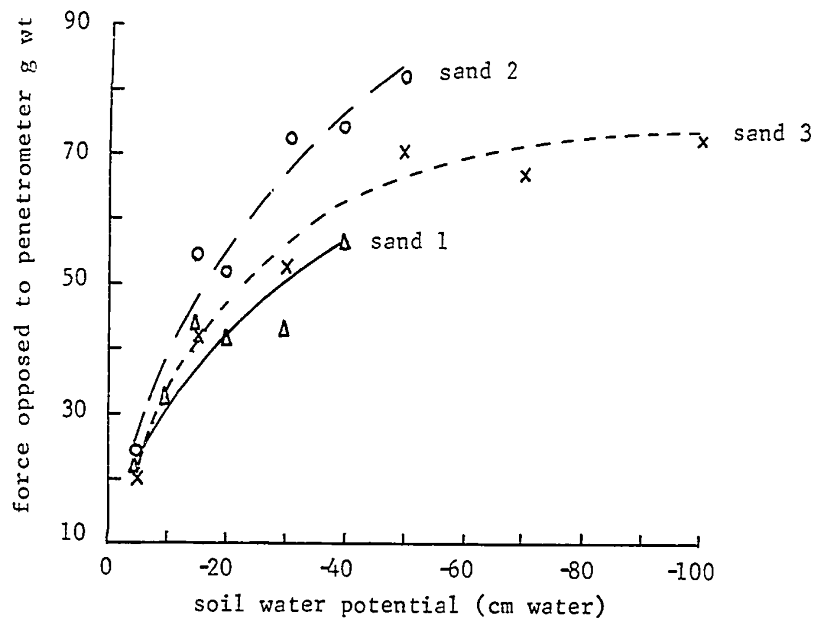

Figure 5: Penetrometer resistance in the three sands at six soil water potentials. Diameter of probe at its widest point was 1 mm.

Straight vertically orientated evenly tapered normal roots were produced, in all treatments, indicating a well balanced stress distribution over the root tip. It is now possible to identify the factors affecting growth using the method outlined by Eavis and Payne (1968) and Eavis (1972). The dotted line in Figure 6a shows the rate of decrease in pea root elongation with penetrometer resistance that is the expected effect of mechanical impedance acting singly on pea root elongation with aeration and moisture availability not limiting. The slope of this curve probably differs for corn and grass but a trend similar to that shown in Figure 6 would be expected. There are insufficient points for an accurate plot. The

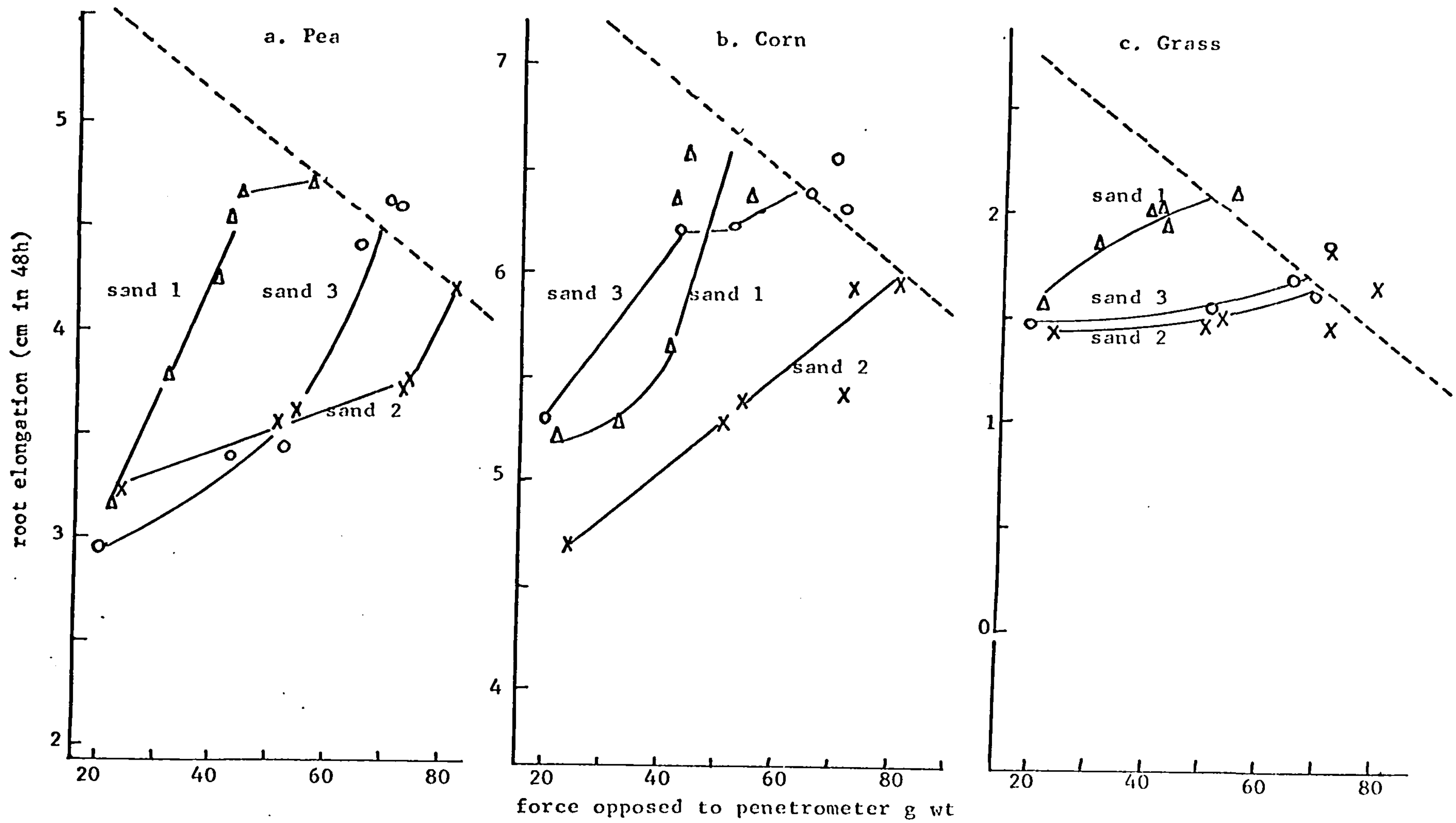

Figure 6: Root elongation plotted against penetrometer measurements. The slope of the dotted line indicates expected trend when mechanical impedance is the only factor involved. Solid lines indicate an 'aeration' effect.

longest roots were produced in the three driest treatments (Figure 6), indicating that moisture availability was unlikely to be limiting. Even in the best treatments root elongation was not maximum, the dotted line indicating that if a lower level of mechanical impedance had existed a greater elongation rate would have occurred. Pea root elongation was at least 20 percent less than that expected under ideal conditions (Eavis, 1972).

Many points do not fall on the dotted line, the roots being shorter as penetrometer force decreased in the wetter sands (Figure 6), an effect which is opposite in direction to that expected from mechanical impedance and moisture stress. An aeration effect is thus identified. The gas filled pore volume (Figure 2) in each sand decreases from between 30 to 40 percent for points in which there is no aeration effect to a minimum of 8 to 10 percent depending on sand grade and moisture content. The aeration effect therefore occurs even when a considerable fraction of the pore space is drained. This suggests that diffusion of oxygen or toxic substances to and from the root is chiefly affected by the spatial distribution of water and gas spaces near the root rather than by diffusion resistance through the gas filled pores.

In the second experiment the interpretations given previously for effects of aeration and moisture availability in the sands were further examined by comparing pea root elongation at six soil water potentials in a sandy loam soil and in a fine sand. Effects of mechanical impedance were virtually eliminated by placing the sand or the soil in a very loose condition in flexible pouches attached to vertically positioned ceramic plates. The similarity between root elongation rates at -70, -100, -140, and -210 cm of water (Figure 7) shows that although moisture contents in the sand and soil differed greatly (Figure 7b) at a given water potential, there was no difference due to availability of water attributable either to potential or moisture content. These results do not support Peters' (1957) hypothesis in which he claims that water absorption by seedling roots is directly influenced by both the potential and moisture content of the media. It is probable that the indirect effect of mechanical impedance which was not recognized as a factor of importance at the time of his experiments, was partly responsible for the effects he described.

Figure 7a shows that at -10 and -30 cm of water, root elongation was depressed in the soil, again supporting the contention that aeration effects are correctly identified. In the loose sand at a much lower moisture content this effect was eliminated. An aeration effect was also obtained when the roots were grown without soil, down the surface of a bare vertical ceramic tension plate at low water potentials. This observation also supports the hypothesis that small changes in the thickness and shape of water films around the root can produce the effect attributed to poor aeration.

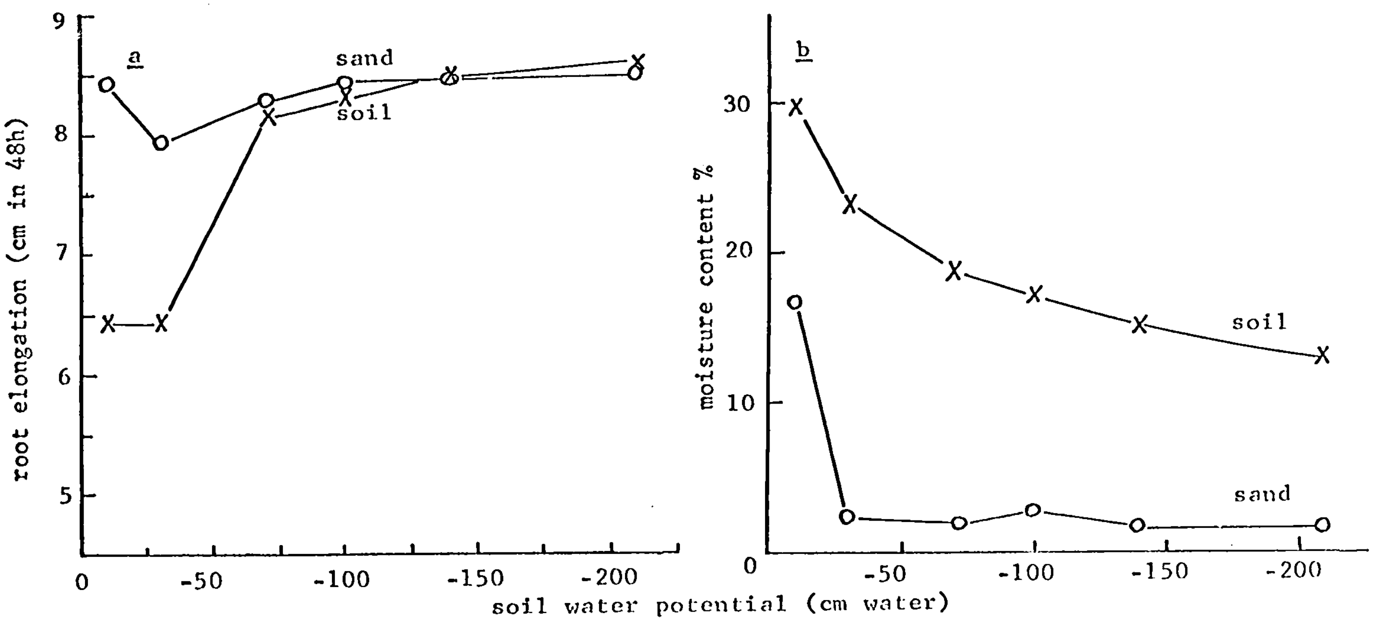

Figure 7: Root elongation in loose sandy loam soil compared with elongation in loose sand, at similar soil water potentials but at different moisture contents.

CONCLUSIONS

Straight, well formed, normal roots were produced in the sands, but due to mechanical impedance effects the rate of pea root elongation was at least 20 percent less than that expected under ideal conditions. Corn and grass root elongation rates were also less than maximum. Effects due to poor aeration occurred in the sands containing less than 25 percent gas filled pore volume.

No evidence for any effect due to water availability could be found, in sands and a sandy loam.

Similar response patterns were obtained for pea, corn and grass root growth but possible differences need examining over a wider range of variation.

A root shaped penetrometer provided a satisfactory method of measuring differences in mechanical impedance. It proved to be a practical and quick method and may be used on a large number of samples from the field.

CHAPTER II

UTILIZATION OF FERTILIZER NITROGEN BY CORN SHOOTS AND ROOTS IN THREE SOILS DIFFERING IN TEXTURE AND MECHANICAL IMPEDANCE

LITERATURE REVIEW

There is a vast amount of literature available on the fate of N applied to soils. Excellent reviews have been published by Allison (1955, 1966) and can be found in "Soil Nitrogen" edited by Bartholomew and Clark (1965).

Corn stover and grain yields are generally increased by N fertilization and rates of application will tend to increase as nitrogenous fertilizers inevitably become relatively cheaper. In the early days experimenters used rates of 50 - 70 kg N ha^{-1} (Black et al., 1947), but present day applications may run as high as 400 kg N ha^{-1}. There is evidence that even higher rates may be profitable in the future. In addition to achieving yield increases, high rates of fertilizer N hasten maturity under Quebec conditions (MacKenzie, 1966[(1)]). Timing of fertilizer N applications for corn has also been of interest in recent years, as there is some practical advantage to apply N in the fall. However the efficiency of utilization of fall applied N is generally low, as shown by Stevenson and Baldwin (1969) in Ontario, Sadler (1967) in Quebec and in many parts of the U.S.A. (Nelson and Uhland, 1955). Exceptions can be found in certain parts of Minnesota and Iowa (Nelson and Uhland, 1955), and Illinois (Welch et al., 1971).

Van der Paauw (1962) indicated the importance of winter rainfall in temperate climates on the amount of nitrogen available to crops in the next season. He suggested that fertilizer recommendations should

---

(1) Soil fertility research at Macdonald College, mimeo graphed annual report, Department of Soil Science, McGill University.

be reduced by 20 - 30% in case of low rainfall during the preceding winter and increased by 30 - 40% after winters of high rainfall. Bouldin et al. (1971) showed that summer sidedress of N is more efficient than spring plowdown in New York, both in terms of yield response and fertilizer N recovered by the above ground dry matter. Summer sidedress in their work coincided with the period of rapid N uptake by corn.

It has been shown by Viets (1960) and Broadbent and Chapman (1950) that the recovery of fertilizer N by the corn plant will generally decrease with increasing rates of applications, although some contradictions have been mentioned by Allison (1966) and Viets (1960). Olson et al. (1970) demonstrated the recovery of fertilizer N by corn plants ranged from 20 - 40%. Owens (1960) and Allison (1966) further mentioned that in field experiments the amounts of applied N recovered by crops plus the amount retained by the soil ranges from 70 - 95%, thus leaving 5 - 30% which may be lost through leaching and denitrification.

The validity of calculating plant N recovery by the difference method, as postulated by Viets (1960) and Allison (1966) can be questioned since it assumes that applied N will not change the soil N release pattern as measured in the control plot. Several authors have shown that the addition of fertilizer N can stimulate mineralization of soil N (Broadbent, 1965; Libois, 1965; Chabonnes et al., 1964). Harmsen and Kolenbrander (1965) attributed this increase to a stimulation of the disintegration of organic matter, resulting in an accumulation of inorganic N. Broadbent and Nakashima (1971) attributed the increase to a possible extraction of organic N by the salt application, and soluble N then being quickly mineralized. The exact mechanism is not known. Most authors agree that the effect is only of short duration, in the order of one or two weeks.

In well aerated soils with no restrictive zones, corn roots can penetrate to a depth of more than 150 cm (Fehrenbacher et al., 1967). Foth (1962) showed a depth of penetration just after tasseling of 75 cm. Under such conditions, it is possible for corn plants to utilize accumulated NO_3 in the subsoil since it remains virtually unchanged where there is hardly any biomass activity (Lathwell et al., 1970). Drastic alterations in the soil profile with a root impeding layer such as a plow sole or a pan layer may restrict root penetration through lack of oxygen or high mechanical impedance levels. These layers make it impossible for the corn plants to utilize soil or fertilizer N, which may have been moved to the subsoil. Harmsen and Kolenbrander (1965) mentioned that inorganic N can move 20 - 30 cm per 10 cm of rain.

It is unfortunate that most studies on fertilizer N recovery by the plant have omitted root development studies because low recoveries could well have been associated with a poor or restricted root system.

Taylor and Gardner (1963) showed that the effects of compaction on root penetration varied with the soil moisture content, and was explained in terms of soil strength, or mechanical impedance effects as measured by a needle penetrometer.

Van Diest (1969) mentioned that increasing amounts of N in a nutrient solution will at first increase root growth rate until a maximum is reached; the addition of more N will reduce the rate of root growth, but the top growth of a wide variety of crops including corn will continue to increase. Similar findings were mentioned by Viets (1960, 1965) and Whitehead (1970) for grass root and top growth in the field. Brouwer, mentioned by Viets (1965), explained that if N is present in high amounts, corn plant tops use so much of the carbohydrate for top growth that there is little or none left over for translocation to the roots, thus explaining the reduction in root growth rates. There is also some evidence that fertilizer N may increase grass root uptake activity (Whitehead, 1970).

The present field study was designed to determine whether corn plants with a restricted root growth would utilize more soil N relative to fertilizer N and conversely if corn plants with a more extensive root system would utilize more fertilizer N relative to soil N.

MATERIALS AND METHODS

Three soil types with differing textures were selected on the Macdonald College farm. These had been classified as St. Benoit sandy loam (72% sand; 22% silt; 6% clay), Chicot fine sandy loam (45% sand; 45% silt; 10% clay) and St. Rosalie clay (25% sand; 33% silt; 42% clay). The experiments were laid out in a randomized block design with three replications using four rows of corn per plot. Corn variety Warwick SL 209 was seeded May 18 using a two row drill, and a constant population of 64,000 plant ha^{-1} was maintained. Phosphorus and potassium were applied uniformly at the rate of 100 kg ha^{-1} of P_2O_5 and K_2O, phosphorus being placed 5 cm below and beside the seed and potassium was broadcast. Nitrogen was applied as ammonium nitrate at 300 kg N ha^{-1} on April 29, May 18 or June 3, and compared with no N applied. Nitrogen was broadcast and worked into the top soil. The experiment was carried out in 1971.

Corn tops and roots were sampled on June 15; July 14; August 10 and on September 18, the final harvest date. A 10 m^2 area was kept for final harvest. Root samples were collected using a metal frame with a mesh wire grid of 5 x 10 x 20 cm in dimension. Two or four root samples were taken per plot between two corn plants in the row. Careful visual observations were made on depth of root penetration at each sampling, and depth of sampling was adjusted accordingly. Root samples from the top 20 cm were kept separate from subsoil samples. The slabs of soil with roots were left in the metal frame to soak overnight in water. Soil was washed from the roots using a fine water spray. The method employed was a modification of one described by Schuurman and Goedewagen (1971). The roots were blotted dry and the fresh weight was obtained. A sample was taken for dry matter determinations, and another sample was stored in a glass jar in formalin solution for future root diameter measurements. Root diameters were measured using a projection microscope, and the quadratic mean of at least 100 roots was calculated for each sample. However, due to large variations and erratic results, this part of the experiment was abandoned.

Corn shoot and root samples were oven-dried at 70°C for dry matter determinations. The dried samples were ground in a Wiley mill for total N determinations using the sulphuric-peroxide digestion technique converting combined N to ammonium (NH_4) (Linder and Harley, 1942; Miller and Miller, 1948). Ammonium was determined by the Technicon auto analyzer, using an alkaline phenolhypochlorite test described by O'Brien and Fiore (1962).

Nitrogen uptake was estimated as the amount of N contained in the root and shoot portions of the plant material at given yields. Recovery of fertilizer N was the difference between N uptake from fertilized and unfertilized plots expressed as a percentage of the amount applied to the soil.

Soil moisture and inorganic N sampling commenced on April 28 and continued at monthly intervals. A soil auger was used to sample each plot at 10 and 20 cm depth intervals down to 100 cm, but only the determinations from the top 20 cm were used in this experiment. Soil samples were immediately analyzed for ammonium (NH_4) and nitrate (NO_3) using a wet sample K Cl extraction technique as suggested by Bremner (1965) and modified by MacKenzie and Trenholm (1972)[(1)].

[(1)]Mimeo reports on methods of analysis used by the Department of Soil Science, McGill University.

Net mineralization or immobilization was calculated using the following simplified equation:

$$ANM = PN + (SNF - SNB)$$

ANM = apparent net mineralization in kg ha^{-1}

PN = Plant N uptake during a specified growth period (= one month) kg ha^{-1}

SNF = Soil inorganic N ($NH_4^+ + NO_3^-$) at the end of the growth period (= one month) kg ha^{-1}

SNB = Soil inorganic N ($NH_4 + NO_3^-$) at the beginning of the growth period (= one month) kg ha^{-1}

A positive value indicates an apparent net mineralization, a negative value a net immobilization.

Soil bulk density and soil moisture content, on oven dry weight basis (100°C), were determined on undisturbed soil cores, 7 cm in diameter and 10 cm long. The soil was sampled to a depth of 50 cm on May 8; June 8 and August 29. The mechanical impedance of the fresh undried samples was measured with a root shaped penetrometer similar in size and shape to a corn root tip (Figure 1). The force encountered during penetration was measured using the top-loading balance method (Figure 2) described in the previous chapter. It was observed mainly in the clay that it sometimes took up to 5 minutes for the force registered on the balance to reach a steady state after each 1 mm penetration.

Field capacity (F.C.) and permanent wilting point (P.W.P.) values were estimated using Staple's (1969) and Shaykewich (1968) data who used similar textured soils.

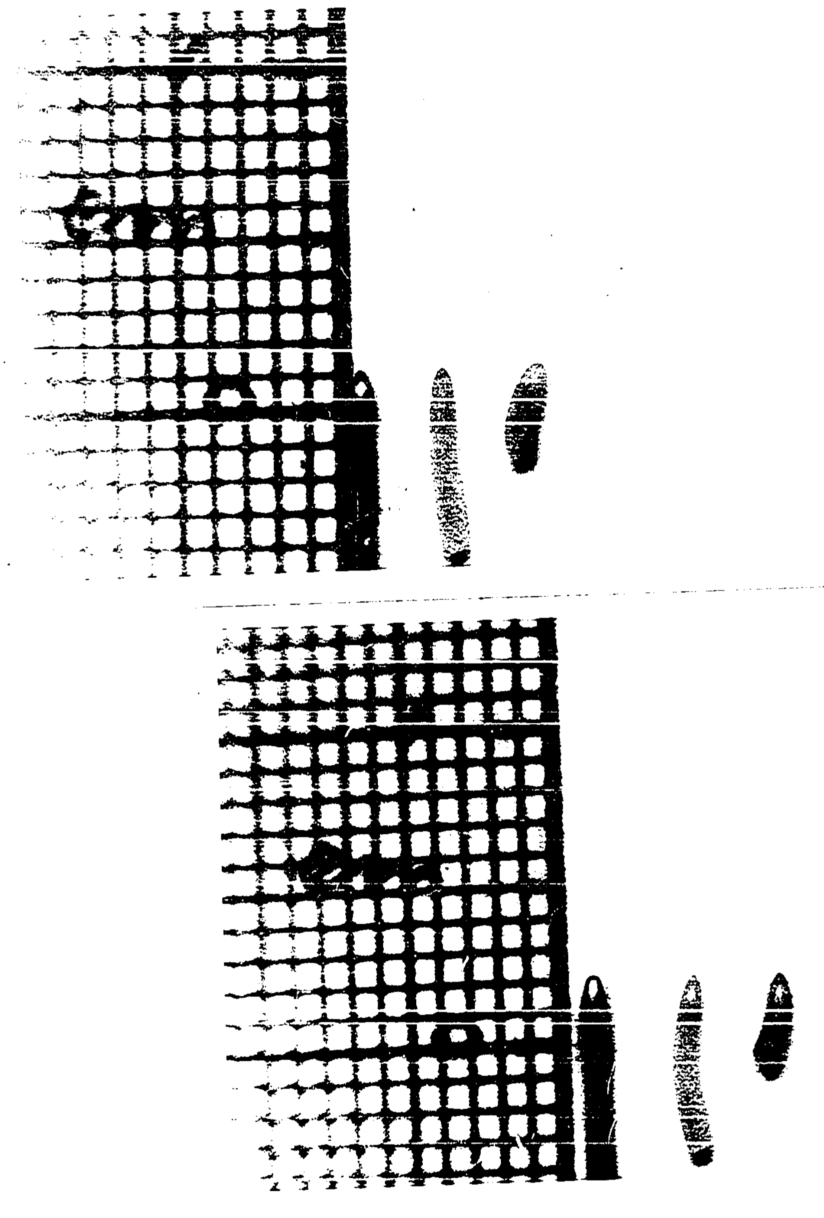

Figure 1: Two corn seedling roots and two root shaped penetrometers (1 mm diameter, 1 and 2 mm long) used to measure mechanical impedance in soil columns.

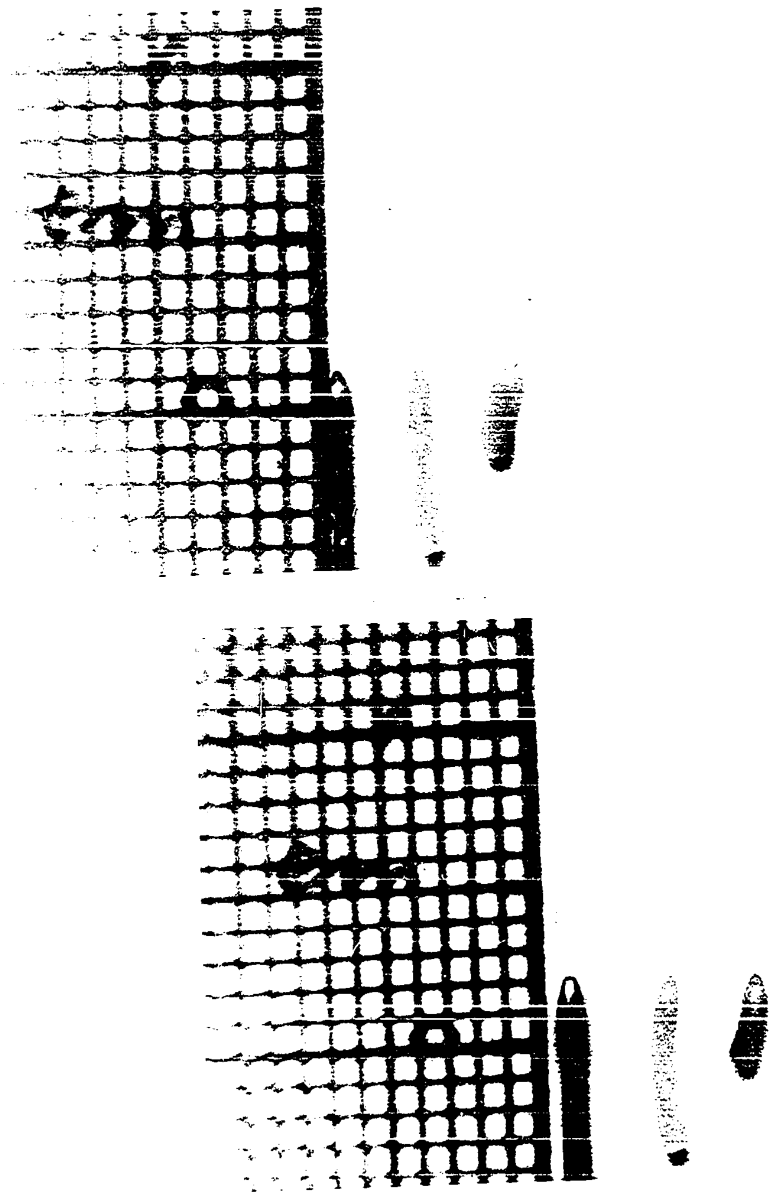

Figure 1: Two corn seedling roots and two root shaped penetrometers (1 mm diameter, 1 and 2 mm long) used to measure mechanical impedance in soil columns.

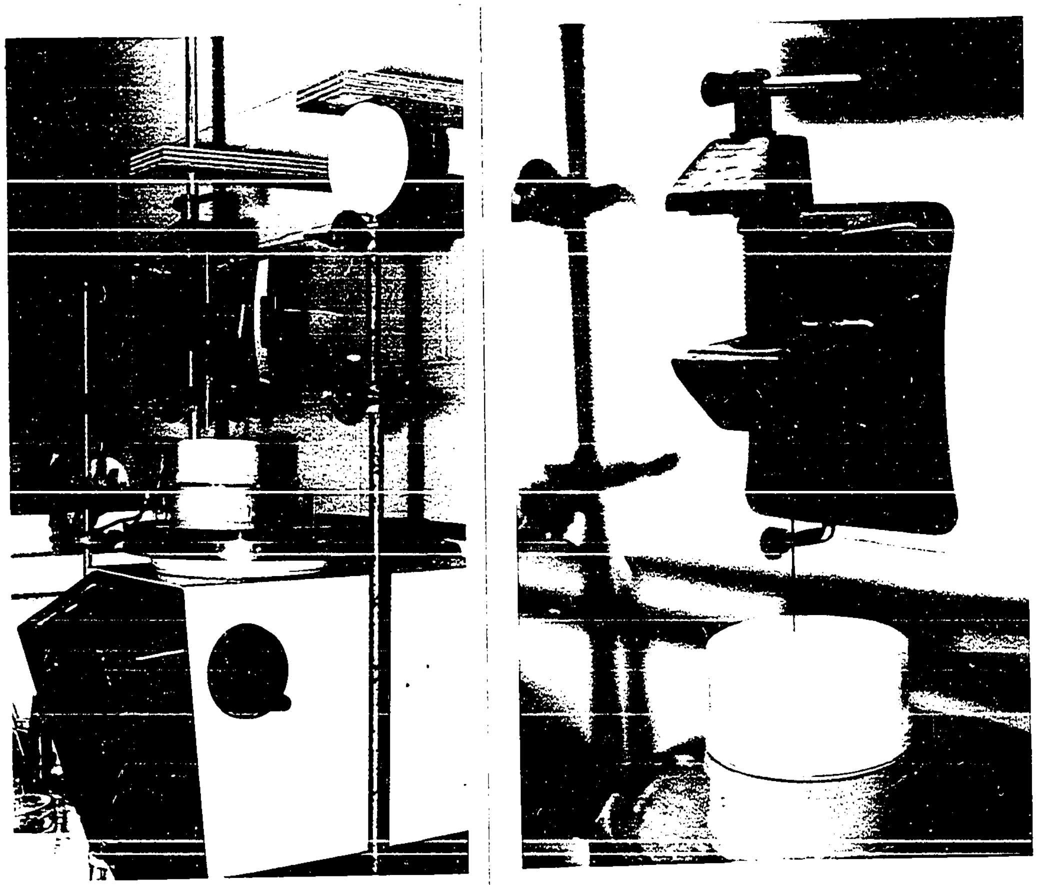

Figure 2: Top loading balance method for measuring penetrometer resistance in a soil column. Each full turn of the vice represents 1 mm of penetration.

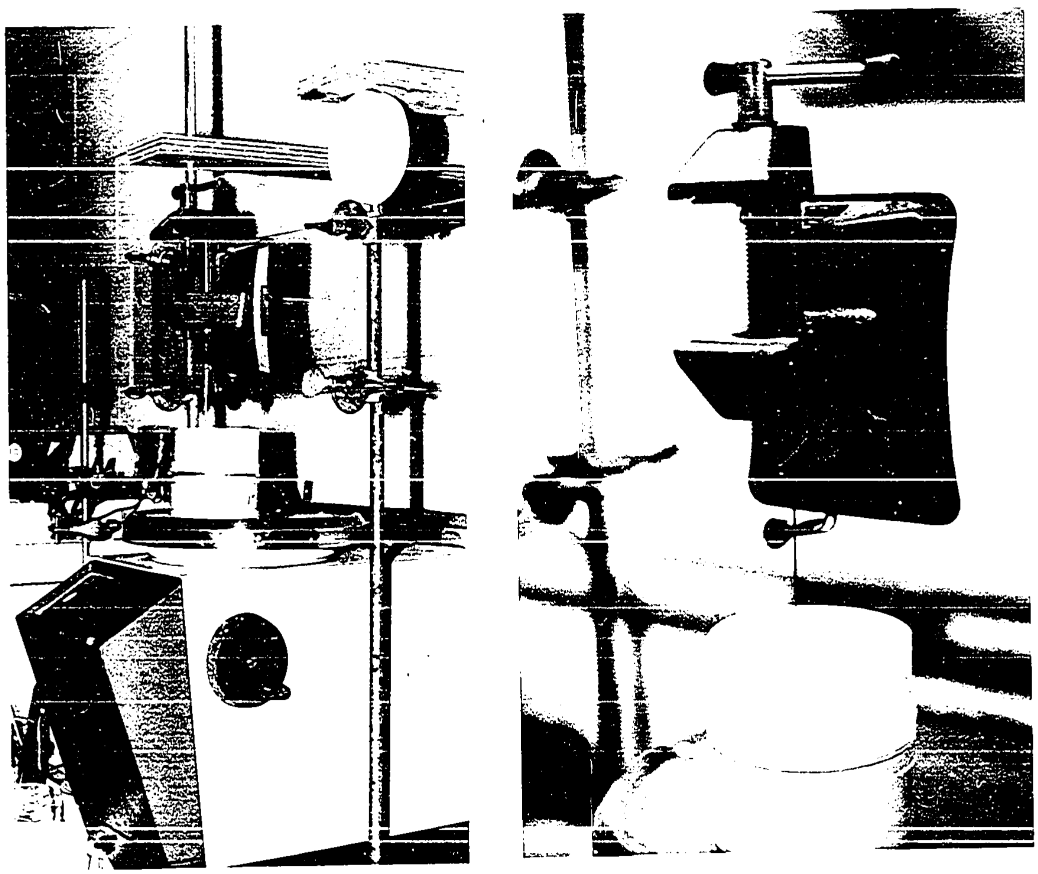

Figure 2: Top loading balance method for measuring penetrometer resistance in a soil column. Each full turn of the vice represents 1 mm of penetration.

RESULTS AND DISCUSSION

1) Dry matter accumulation

a) Corn Top Growth

Nitrogen fertilization significantly increased the above ground dry matter production of corn on all soil types (Table 1, Figure 3). Time of nitrogen application had no effect on yield response (Table 1), because dry matter production started to accumulate to a significant degree only after mid-July (Figure 3), about 2 weeks after the latest application in June.

Table 1: Corn grain yields (15% moisture) and stover dry matter yields affected by time of nitrogen application on three soil types.

Nitrogen applied	St. Benoit sandy loam stover	St. Benoit sandy loam grain	Chicot fine sandy loam stover	Chicot fine sandy loam grain	St. Rosalie clay stover	St. Rosalie clay grain
	kg ha^{-1}					
None	3835 a	2522 a	4802 a	4522 a	3432 a	4672 a
April 29	5385 b	7137 bc	5284 b	7263 b	4793 b	7825 bc
May 18	5086 b	6710 b	5780 b	7263 b	4892 b	7733 b
June 2	5523 b	6640 b	5639 b	7187 b	4778 b	7208 b
Significance level	*	**	*	**	*	**
L.S.D. (5%)	1150	1458	679	1612	1304	1401

* Significant response at the 5% level of significance
** Significant response at the 1% level of significance
Mean values followed by the same letter were not statistically different at the 5% level of significance.

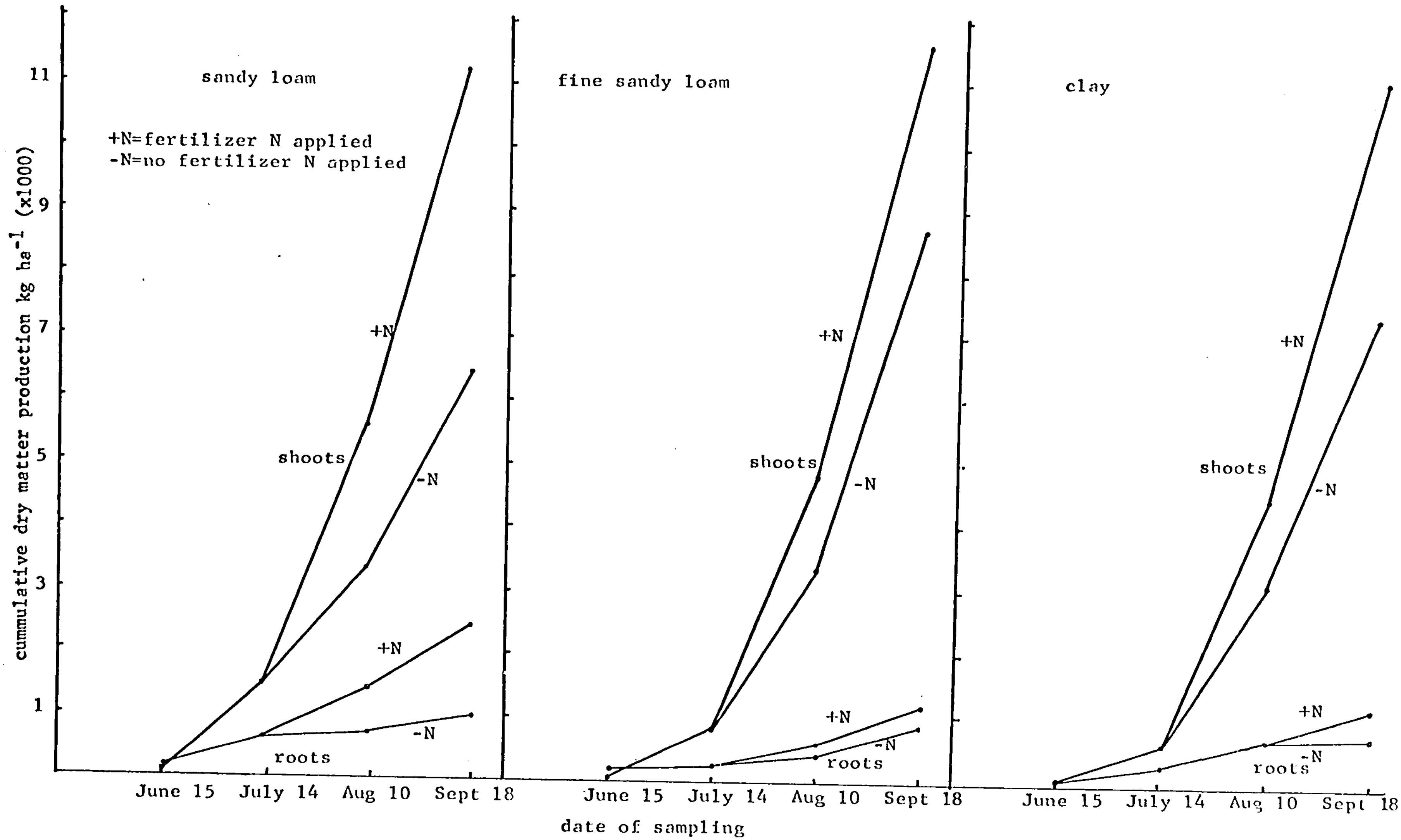

Figure 3: Cummulative dry matter production of corn shoots and roots affected by N fertilization on three soils.

Slow post emergent growth rates (about May 30) were mainly attributed to cool weather conditions which are considered normal for this time of the year[1]. Most daily mean temperatures during June were below 15 - 18^{o}C, a faster initial growth rate was observed on the sandy loam site presumably because of higher top soil temperatures. Top soil temperatures in June on the sandy soil ranged from 14 - 22^{o}C compared to 11 - 18^{o}C on the clay soil. In view of the slow initial growth rates, applied N had no effect on dry matter production of corn in the first two months after seeding (Figure 3). It can be assumed that there was an adequate supply of soil N during this period as N uptake was about 5 kg ha^{-1} for all sites (Figure 4) and inorganic N (NH_4 + and NO_3^-) ranged from 35 - 16.5 kg ha^{-1} depending on the site (Figure 5, 6 and 7).

The effect of applied N on dry matter accumulation was evident after mid-July (Figure 3) when a closed crop surface was obtained, and the effect was maintained for about 70 days until final harvest in mid-September. Since there was no effect of time of N application the results were grouped together in Figure 3. These dry matter accumulation curves are different than those obtained by Hanway (1962a), in that the slope of the line after July 14th was much steeper. Hanway obtained 50% of total dry matter yields by mid-July, under Iowa conditions whereas less than 10% of total dry matter was produced in the present experiment. The reason for the difference must presumably be due to differences in climatic conditions. Nitrogen fertilizer during the period of rapid

---

(1) R.H. Douglas, Agricultural Physics Department, McGill University, personal communications.

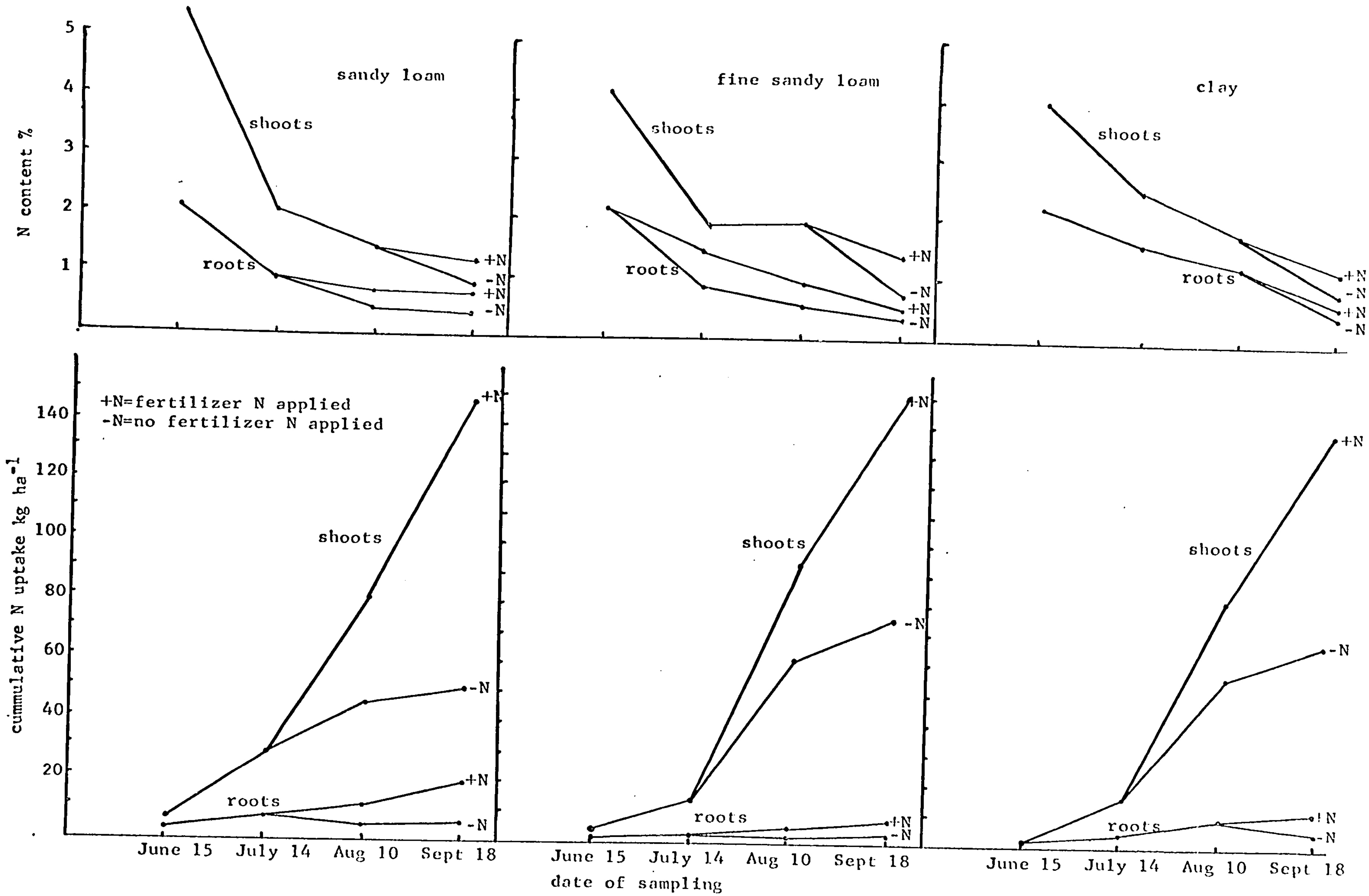

Figure 4: The effect of applied N on N content of corn shoots and roots and cummulative N uptake on three soils.

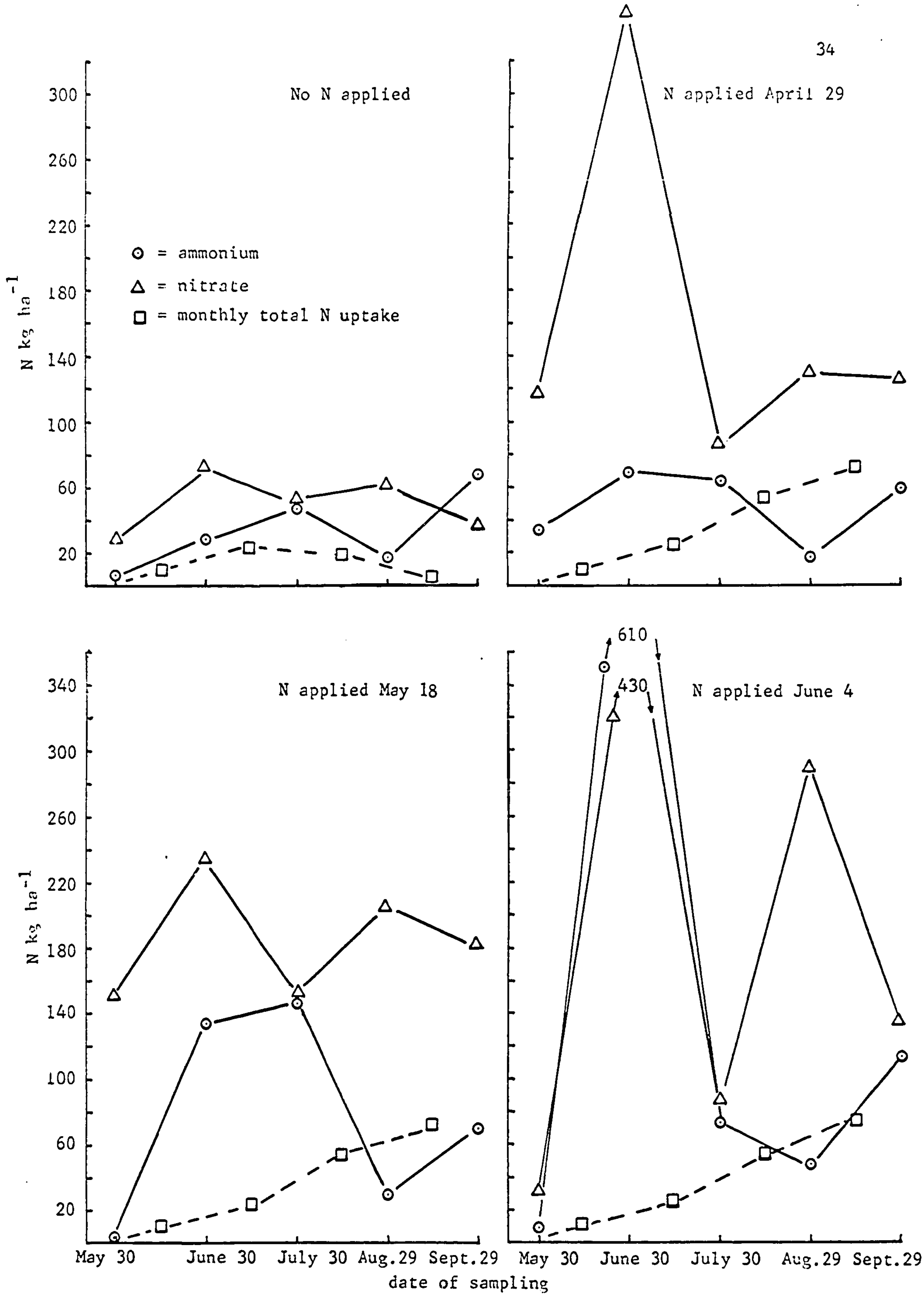

Figure 5: Ammonium and nitrate contents in the top 20 cm soil layer, during the 1971 growing season, influenced by time of N application and total monthly N uptake by corn on a St. Benoit sandy loam.

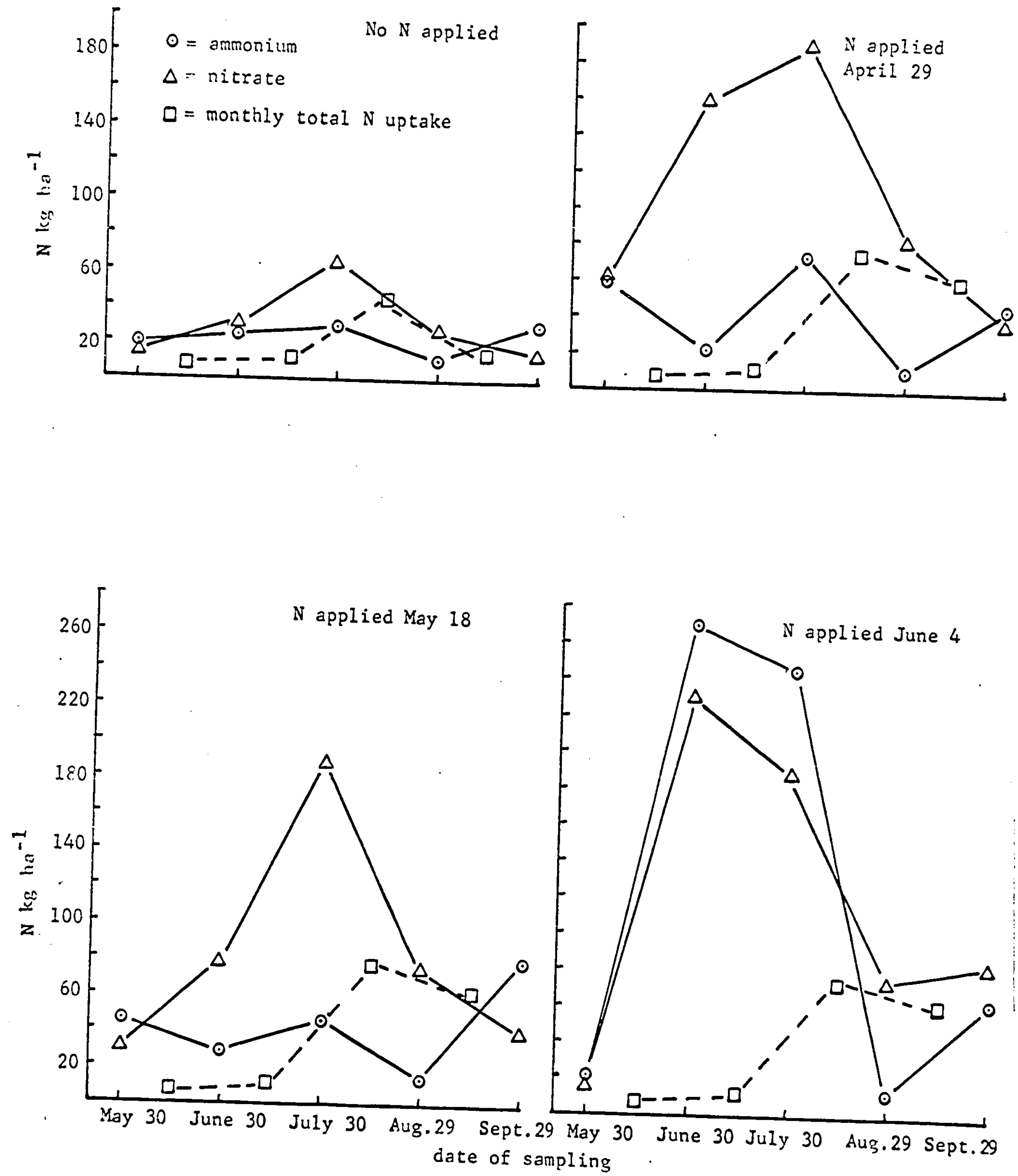

Figure 6: Ammonium and nitrate contents in the top 20 cm soil layer, during the 1971 growing season, influenced by time of N application and total monthly N uptake by corn on a Chicot fine sandy loam.

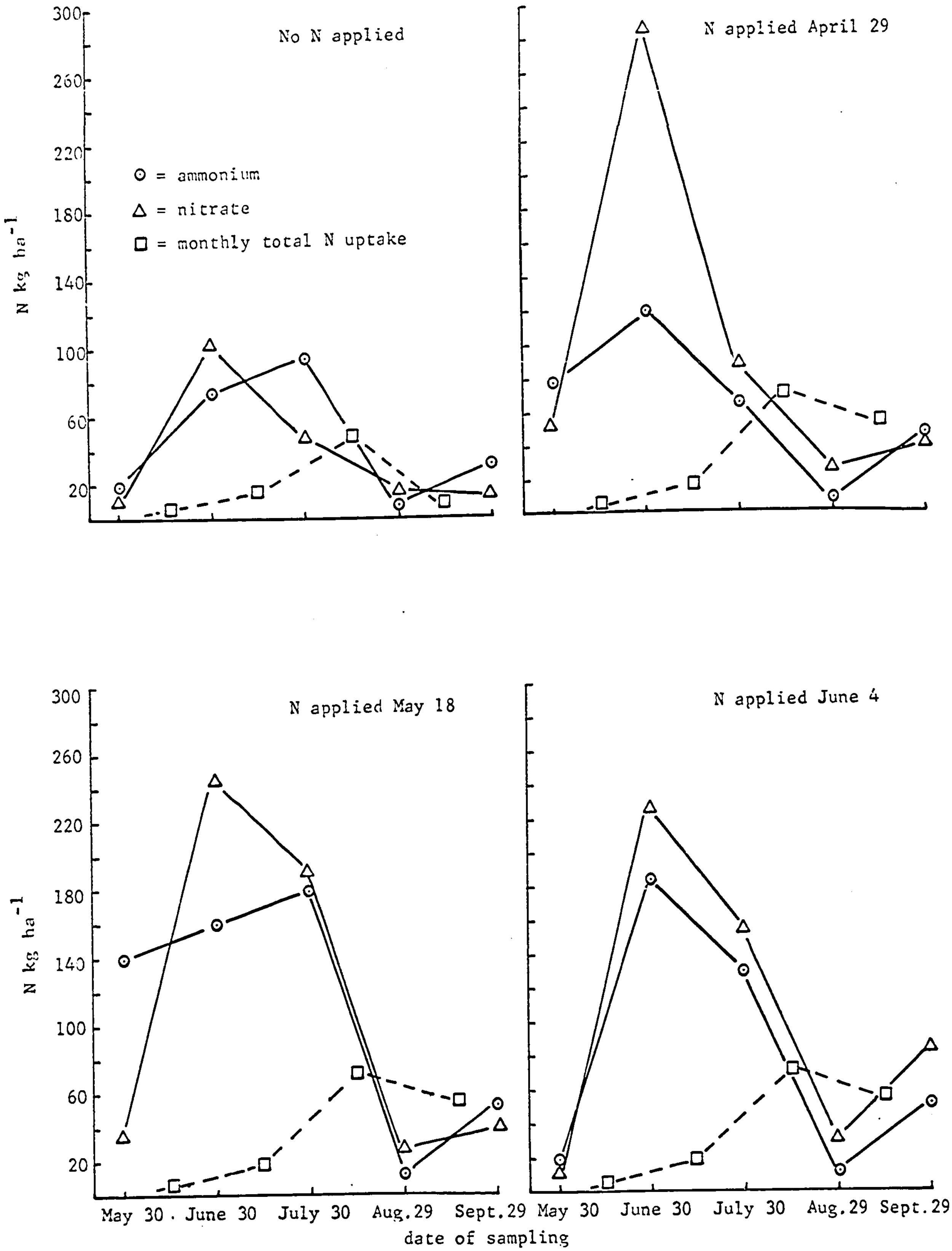

Figure 7: Ammonium and nitrate contents in the top 20 cm soil layer, during the 1971 growing season, influenced by time of N application and total monthly N uptake by corn on a St. Rosalie clay.

growth after mid-July increased dry matter accumulation by 97% on the sandy loam, 53% on the clay and 38% on the fine sandy loam (Table 2).

Table 2: Corn growth rates during the 70 days of rapid growth from July 10 to September 18, 1971 as affected by N fertilization on three soils.

Site	No N	N applied	Increase	% Increase
	kg ha^{-1} day^{-1}			
Sandy loam	70	138	68	97%
Clay	98	150	52	53%
Fine sandy loam	112	155	43	38%

The reason for these differences in N response is not clear, since the bulk of the inorganic (NH_4 and NO_3) soil N observed in July was similar for all soils and in August a higher level of inorganic N was observed in the sandy loam (Figure 5, 6 and 7). The uptake of N may have varied because of differences in moisture uptake or because of possible effects of N movement varying with soil type. In June, July and August soil moisture contents of the top 20 cm of the sandy loam and clay soils were close to permanent wilting point and slightly higher values were observed in the fine sandy loam (Figure 8). At soil moisture contents close to permanent wilting point, flow of soil water is slower in a coarse textured soil than in a fine textured one, (Warkentin, 1970; Shaykewich, 1968; and Gardner, 1965b). Slow nutrient movement with soil water to the plant roots into the transpiration stream may have accentuated N deficiency in the St. Benoit sandy loam on plots receiving no applied N. Whilst more soil N could be taken up in the transpiration stream in the fine sandy loam and clay, in which there was a faster rate of soil water movement. Although further research is required to investigate this, the practical implication is that at low soil moisture contents higher rates of fertilizer N are required than at higher moisture contents.

	F.C.(est)	P.W.P.(est)
sandy loam:	23%	10%
fine sandy loam:	28%	13%
clay:	30%	16%

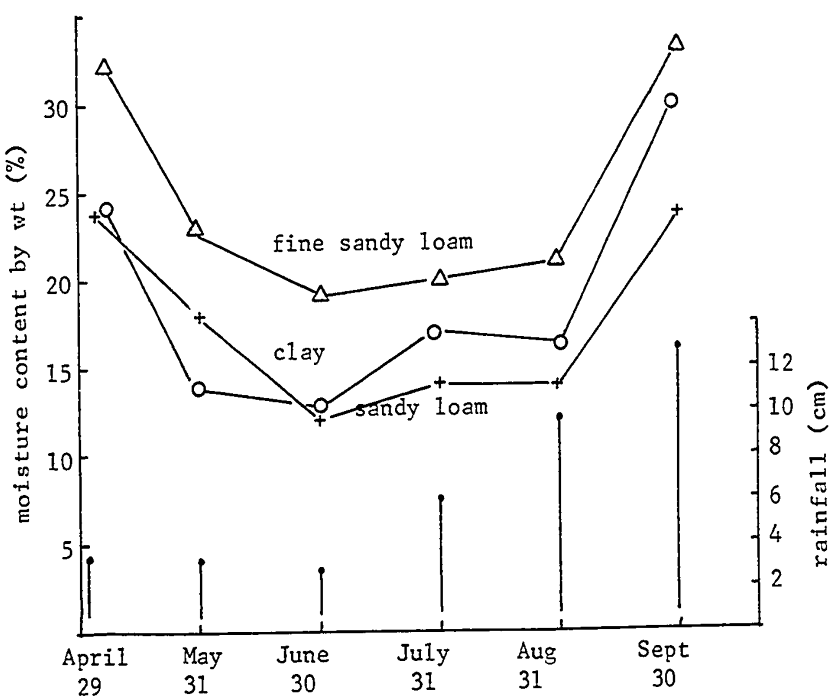

Figure 8: Soil moisture contents of the top 20 cm of three soils during the 1971 growing season and monthly rainfall.

The maximum growth rates obtained (Table 2) fall below maximum dry matter accumulation rates of 200 - 240 kg ha^{-1} day^{-1} obtained by de Wit (1970) for 100 days for various crops not limited by water or nutrient supply and growing under similar climatic conditions. For maximum corn production, available water in the soil should be held at about -0.5 bar soil water potential during the period of rapid growth (Haise and Hagan, 1967). Stanhill and Vaadia (1967) found that soil water potential at about -1 bar reduces fresh weight production of many crops. They found that at low evaporative conditions the decrease was 25% and at high evaporative conditions the decrease was 50% of maximum growth.

b) Corn Root Growth

The effect of N fertilization on root growth was particularly large in the sandy loam, where an increase of 155% was observed, in comparison to only 34% and 48% respectively on the fine sandy loam and clay soil (Figure 3 and Table 3).

Table 3: Final corn root dry matter yields in the top soil and in the subsoil affected by N fertilization on three soil types.

Nitrogen applied	sandy loam topsoil 0-20cm	sandy loam subsoil 20-40cm	fine sandy loam topsoil 0-20cm	fine sandy loam subsoil 20-40cm	clay topsoil 0-20cm	clay subsoil 20-40cm
	kg ha^{-1}					
None	706 a	258 a	840	138	696 a	88
May 18	2128 b	300 ab	1056	105	1065 b	63
June 2	1740 b	528 b	975	147	1140 b	111
Significance level	**	*	N.S.	N.S.	*	N.S.

N.S. Non significant response
* Significant response at the 5% level of significance
** Significant response at the 1% level of significance
Mean values followed by the same letter were not statistically different at the 5% level of significance.

Variation in the degree of aeration could not have been a major cause for the large differences in soil types since soil moisture contents remained close to permanent wilting point throughout most of the growing season (Figure 8). Furthermore, at low soil moisture contents, shoot growth is more affected than root growth and an excess of carbohydrates not utilized for top growth would be available for root growth (Viets, 1965; Peters and Runkles, 1967). Effects of soil moisture content on root growth may be either due to mechanical impedance or lack of water. There is substantial evidence that mechanical impedance (Figure 9) was the dominant factor for the spectacular difference in root growth between the sandy loam and both the fine sandy loam and clay soils.

Mean mechanical impedance levels, as measured by the root shaped penetrometer, ranged from 75 grams mm^{-2} for the sandy loam to 160 and 200 gram mm^{-2} respectively on the fine sandy loam and clay soils. Impedance generally increased with depth, especially at the 10 and 20 cm zone which was associated with the plow sole (Figure 9). A very high impedance level of 428 gram mm^{-2} on the fine sandy loam was associated with a pan layer. In the plots receiving fertilizer N, lower impedance was associated with root penetration down to 45 cm or deeper on the sandy loam but root growth was restricted on the other soils as very few roots were observed below 30 cm in the clay and 35 cm in the fine sandy loam (Figure 10). There seemed to be an inverse relationship between mechanical impedance, depth of penetration and root yield, but this could not be verified due to the lack of points.

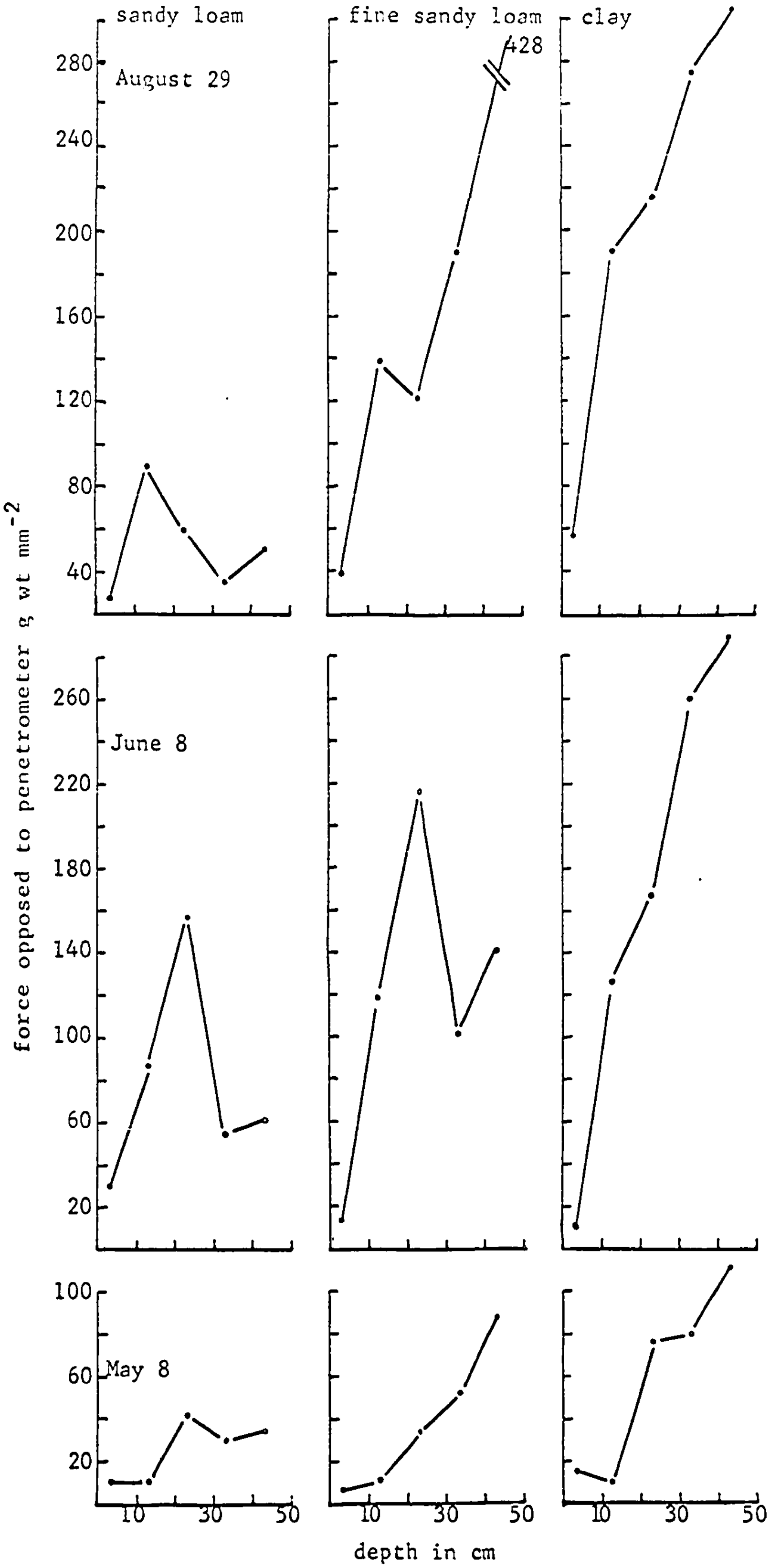

Figure 9: Penetrometer resistance variations with depth in three soils on three dates in 1971.

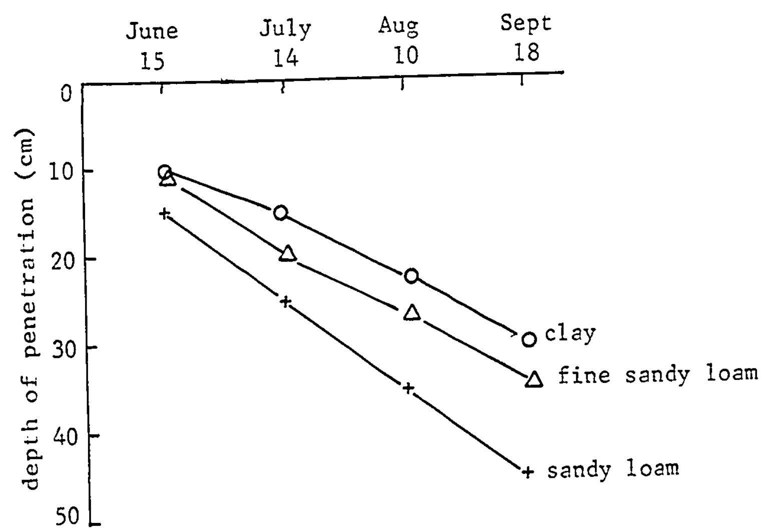

Figure 10: Depth of corn root penetration in three soils receiving fertilizer N during the 1971 growing season.

Due to the limited number of observations, valid comparisons of penetrometer resistance with soil moisture, bulk density and soil texture could not be made, although the trends were consistent with the previous chapter results. The proportion of the final fresh root weight found in the top 20 cm of the soil was 92% in the clay, 85% in the fine sandy loam and 75% in the sandy loam.

It is concluded that applied N resulted in increased root growth and that the effect was larger at low mechanical impedance than in those soils with high impedance levels. Top growth did not seem to be limited by restricted root growth on any of these soils as final maximum dry matter yields were similar.

2) Fertilizer N and release of soil N

Maximum levels of inorganic N were found at the end of June for most soils and fertilizer treatments (Figure 5, 6 and 7). These findings are consistent with those observed by Sadler (1967). On the fine sandy loam, maximum values were obtained late in July (Figure 6), because this soil remained colder and wetter for a longer time than the sandy loam and drained clay soil. Ice was still observed in the subsoil of the fine sandy loam in June, thus mineralization must have been delayed.

After, maximum apparent net mineralization was reached by the end of June net immobilization prevailed during July and August on the clay and sandy loam (Table 4).

On the fine sandy loam net immobilization was only apparent in August because of delayed mineralization. On the other soils however, it is assumed that inorganic N was immobilized during July and August as estimated leaching losses were negligible and denitrification was assumed to be minimal due to the aerobic conditions in the soils. Allison (1966) and Harmsen and Kolenbrander (1965) mention that there is conclusive evidence that mineralization under cropped land is retarded and that applied N is immobilized because of an increase in decomposable matter from roots and root excretion. Goring and Clark (1948) mentioned that an increase in immobilization and decrease in mineralization, on cropped land as compared to uncropped land, was due to an increase of microbial population in the rhizosphere. In spite of the fact that the total biomass activity increased, they found no increase in those bacteria responsible for N mineralization, as a result of which they suggested a net immobilization. At the end of the growing season, when root activity decreases, microbial population in the rhizosphere decreases

Table 4: Apparent net mineralization (+) or immobilization (-) in the top 20 cm soil layer influenced by N fertilization on three soil types during the 1971 growing season.

Nitrogen applied	St. Benoit sandy loam June 29	July 30	Aug 28	Sept 28	St. Rosalie clay June 29	July 30	Aug 28	Sept 28	Chicot fine sandy loam June 29	July 30	Aug 28	Sept 28
						kg ha^{-1}						
No N	+42	+20	-5	+14	+151	-4	-77	+126	+27	+58	-33	+18
April 29	+296	-240	+56	+106	+282	-209	-53	+98	+73	+101	-101	+53
May 18	+232	-22	-5	+88	+220	+6	-268	+102	+42	+147	-74	+91
June 2	+1018	-690	+141	-201	+386	-88	-178	+144	+453	-45	-272	+117

(Harmsen and Kolenbrander, 1965) resulting in an increase in net mineralization. Similar results were obtained in the present experiment on all soils (Table 4) when net mineralization was observed again in September after net immobilization in August.

A sampling error may have contributed to the erratic results observed on the sandy loam (Figure 5 and Table 4). This could be due to the sand from the surface being disturbed in augering and thus contaminating the deeper samples.

Application of fertilizer N in late April and mid-May did not seem to have increased net mineralization as was observed by several authors (Broadbent and Nakashima, 1971; Harmsen and Kolenbrander, 1965; Chabannes et al., 1964). About 50 - 60% of the applied N was apparently immobilized by the end of May (Figure 5, 6 and 7). This could be attributed to the presence of readily decomposable crop residues of corn stubble and roots from the previous year's crop, estimated at about 1500 kg ha^{-1} of dry matter. Most of the available mineral soil N may have been utilized for decomposition, along with the applied inorganic N, causing a biological immobilization.

The application of fertilizer N in early June notably increased the release of soil N on the sandy loam and to some extent on the fine sandy loam by late June (Table 4 and Figure 5 and 6). Harmsen and Kolenbrander (1965) mentioned that the addition of fertilizer N stimulates the disintegration of organic matter, resulting in an increased accumulation of inorganic N. Broadbent and Nakashima (1971) attributed the increase in mineralization by the addition of salts to a possible extraction of organic N by the salt in solution. The organic N rendered soluble is then readily mineralized.

However, the increase in the release of inorganic N (NH_4 and NO_3) on plots receiving fertilizer N in June was only of short duration as net immobilization was observed at subsequent sampling dates.

It is concluded that maximum levels of inorganic N found in June must be due to an increase in soil temperature and an initial flush of bacterial activity. Net immobilization over mineralization occurred during most of the summer before net mineralization was observed again at the end of the growing season in September.

3) <u>Plant uptake and recovery of fertilizer N</u>

Nitrogen content (N%) of the corn shoots and roots decreased with time (Figure 4). Similar observations were reported by Hanway (1962b). Young corn plants must have contained high proportions of protoplasm in relation to structural components such as cellulose and lignin. Young plants have also the ability to store soluble N as amino acids for future use (Viets, 1965). Fertilizer N increased the N content of shoots and roots mainly in the later part of the growing season (Figure 4), although the effects on N content of the roots were eratic.

The amounts of N accumulated in the plants not supplied with fertilizer N (roots and shoots combined) varied from 57 kg ha^{-1} on the sandy loam to 73 and 80 kg ha^{-1} for the clay and fine sandy loam respectively (Figure 4 and Table 5). Maximum uptake occurred generally from July 14 to August 10 (Table 5), on the clay and fine sandy loam; on the sandy loam maximum uptake occurred about a month earlier. Silking time was during the last week of July on all soil types. The difference in the sandy loam was attributed to more favourable soil moisture conditions in June and higher soil temperatures for plant growth than on the other two soils, thus enabling more plant growth while accumulating more N. Low soil moisture conditions during most of July and August (Figure 8) may have decreased nutrient movement to the plant roots more in the coarse textured soil than in the finer textured soils.

Soil water movement at soil water potentials near permanent wilting point is slower in coarse textured soils than in fine textured soils (Warkentin, 1970). This may have produced a lower N yield from plots receiving no fertilizer N in the sandy loam. This slower rate of movement may not have been an important factor on plots receiving fertilizer N where similar N yields were obtained from all soil types.

Table 5: Nitrogen uptake influenced by fertilizer N and fertilizer N recovery on three soils.

	June 15	July 14	Aug 10	Sept 18	Total	Fertilizer N recovery
	kg ha^{-1}					
	sandy loam					
No N applied	10	25	16	6	57	37% (110 kg ha^{-1})
N applied 300 kg ha^{-1}	10	26	55	76	167	
	clay					
No N applied	2	16	50	5	73	26% (78 kg ha^{-1})
N applied 300 kg ha^{-1}	2	16	75	58	151	
	fine sandy loam					
No N applied	8	8	50	14	80	26% (79 kg ha^{-1})
N applied 300 kg ha^{-1}	8	8	85	58	159	

The applied N more than doubled total N uptake in most cases (Table 5). Maximum rate of N uptake on the clay (75 kg ha^{-1}) and fine sandy loam (85 kg ha^{-1}) was also from July 14 to August 10 and decreased to 58 kg ha^{-1} from August 10 to crop harvest September 18. These findings were in general agreement with Hanway's (1962a) work in Iowa, where he found that at silking time about 60% of N was accumulated. On the sandy loam rate of N uptake increased during the growing season (Figure 4 and Table 5) until maximum rate of uptake

(76 kg ha^{-1}) was reached from August 10 to final harvest. Nitrogen uptake rates seemed to follow dry matter accumulation and root depth penetration, indicating that the mechanism of N uptake may have been by root interception, rather than by mass flow.

Using the difference method to calculate fertilizer N recovery as postulated by Viets (1960) and Allison (1966), 37% N was recovered on the sandy loam compared to 26% on the other soils (Table 5). This difference may have been due to differences in root development in these soils. The deeper and more extensive root system in the sandy loam must have been in contact with more fertilizer N than the restricted root systems in both other soils. A root system restricted mainly to the topsoil is also in the zone of maximum biological activity and thus N mineralization. Jansson (1958), who worked with labelled N found an increase in soil N uptake by crops by an increase in mineral N applied to the soil. Thus supporting the hypothesis that soil organisms use both soil N and fertilizer N indiscriminately (Allison, 1966).

CONCLUSIONS

Nitrogen fertilizer increased corn dry matter production by 97% on a sandy loam, 53% on a clay and 38% on a fine sandy loam. These variations in response, associated with soil type, were mainly attributable to yield differences between the control plots since similar yields were recorded between the N fertilized plots.

Yield differences between the control plots could also have been caused by variations in soil moisture availability. The lowest dry matter yields (6400 kg ha^{-1}) were obtained on the sandy loam when soil moisture levels were close to the estimated permanent wilting point during the period of rapid corn growth from July 15 to August 31. The next lowest dry matter yields (8000 kg ha^{-1}) were obtained from the clay which also had a moisture content in the top-soil close to permanent wilting point. In this case however, water movement may have occurred from the subsoil where higher moisture contents were measured and this was not the case in the sandy loam. The highest yielding (9100 kg ha^{-1}) control plots were on the fine sandy loam and this could have resulted from the higher soil moisture content during the growing season.

Differences in the yield of dry matter between the control plots could also have been caused by the influence of low soil moisture content on nutrient movement. The slower movement of N with soil water may have enhanced N deficiency in the sandy loam more than in the clay where the rate of soil water movement is generally regarded as being higher.

Another reason for the yield differences between control plots may have been the differences in N mineralization between the three soils. Maximum net mineralization in the sandy loam and clay soils occurred by the end of June when corn plants were still small and not yet in the period of rapid growth and net immobilization prevailed during most of July and August. On the fine sandy loam however, maximum net mineralization occurred a month later due to moisture and temperature conditions which were unfavourable for maximum biological activity early in the spring. The corn crop was in its period of rapid growth by the end of July and immobilization was only apparent in August. Therefore there may be an advantage to delay the period of maximum net mineralization to coincide with the crop maximum growth rate.

Applied fertilizer N increased corn above ground dry matter yields to the same level on all three soils (about 11500 kg ha^{-1}). The increase in root growth, caused by fertilizer N, may have offset some of the harmful effects of low soil moisture. In the sandy loam, the effect of slower movement of N with soil water, from the soil to the root and into the transpiration stream may have been eliminated because the mechanism of nutrient uptake could have been root interception rather than mass flow.

Timing of N applications had no effect on yield response because N was not limiting in the early stages of growth. The period of rapid growth occurred after July 14, five weeks after the latest application in June.

Final root yields were similar on the control plots of all three soils. Fertilizer N increased root yields by 155% in the sandy loam, 48% in the clay and 34% in the fine sandy loam. Mechanical impedance, as measured by a root shaped penetrometer, was the dominant factor causing the differences in root yield between the soils on plots receiving fertilizer N. Deep (45 cm) and more extensive root systems on the sandy loam were associated with mean impedance levels of about 75 grams mm^{-2}. Root systems restricted to the top 30 and 35 cm were associated with mean impedance levels of about 200 and 160 grams mm^{-2} in the clay and fine sandy loam soils respectively.

Fertilizer N recovery in the corn plant was higher (37%) on the sandy loam than on the fine sandy loam and clay soils (26%). The larger root systems in the sandy loam must have been in contact with more fertilizer N than the restricted root systems. Root growth restricted to the topsoil remains in the zone of maximum biological activity where soil N is mineralized. Proportionally more soil N could therefore be taken up by a shallow root system than by a deeper root system.

In conclusion, deep and extensive root systems are required to utilize fertilizer N (mainly as nitrate) in the subsoil which may otherwise contaminate ground water. If however, maximum use of native soil N is required, then perhaps a shallower root system is sufficient.

CHAPTER III

THE EFFECT ON LEACHING OF THE TIMING OF FERTILIZER NITROGEN APPLICATIONS ON THREE QUEBEC SOILS

LITERATURE REVIEW

The rate of application of nitrogeneous fertilizers to corn often exceeds the rate of removal in the harvested crop (Allison, 1966). As a result of this, the excess of mobile inorganic N mainly as nitrate may become a contaminant in ground water or streams thus endangering the environment. Therefore N utilization, its accumulation and loss through the soil is of very special interest.

Certain amounts of inorganic N, mainly as nitrate (NO_3), are nearly always present in the surface soil, even during winter months (van Schreven, 1958). Water is the major agent in the transportation of this and other soluble ions in the profile. The conditions of movement of soil water through the soil and into the transpiration stream has been well documented (Bolt *et al.*, 1970; Gardiner, 1960, 1965b), and the main processes involved in the movement of N through the soil solution have been shown to be mass flow and diffusion.

Mass flow is the movement of inorganic N or other salts which takes place because of the movement of water. The rate at which this flow occurs in the profile, described approximately by Darcy's law, depends on gradients in hydraulic potential and the capillary conductivity, and varies *inter alia* with moisture content and soil texture (Staple, 1965; Rose, 1965; Warkentin, 1970). Hydraulic conductivity generally increases as soil moisture content increases (Staple, 1965, 1969), but once saturation has occurred in a non swelling soil, hydraulic conductivity is mainly dependent upon voids ratio and geometry, and is much larger than unsaturated hydraulic conductivity (Warkentin, 1970). Conductivity values for coarse textured soils are larger for fine textured soils except when moisture contents are very low, near the permanent wilting point, when the reverse is true. Downward migration of soluble substances due to rainfall depends not only on the amount of rain, but also on the texture and soil water content at field capacity. The higher the moisture content at field capacity, the smaller is the loss of dissolved N to deeper layers for any amount of rainfall. Therefore inorganic N moves downward more readily in sandy soils than in clays (Russell, 1961). Kolenbrander (1969) in the Netherlands found less than two percent loss of fertilizer N in drainage water from clay soils (more than 35% clay), but that more than 20% of applied N could be leached out of sandy soils (0-10% clay).

In the absence of hydraulic gradients or transpiration induced water flow, nitrate moves mainly by diffusion, this takes place in response to a concentration gradient. The diffusion coefficient of the soil to nitrate is less than that for pure water because:
1) diffusion is restricted to that part of the soil volume which is occupied by water, and thus varies according to the soil moisture content (Romkens and Bruce, 1964); 2) because water filled voids in the soil are never straight capillaries the diffusion depends on a tortuosity factor (Viets, 1967 and Gardner, 1965a) this also being dependent on the water content (Frissel _et al_., 1970). The transport of nitrate by mass flow and ion diffusion are considered additive (Barber, 1962; Nye, 1968).

Positive correlations between N movement and rainfall were found by van Brug (1970) and Wetselaar (1962). Van Brug (1970) found this correlation only where there was a high rate of fertilizer N application. Wetselaar (1962) found that for every inch of rainfall a mean movement of nitrate of 1.075 inches on a fallow clay loam receiving 23.7 inches of rain during a six month period. Harmsen and Kolenbrander (1965) found a downward displacement of nitrate per 100 mm rainfall of 45 cm in a sandy soil, 30 cm in a loam and 20 cm for a clay soil. The difference between these values can probably be attributed to the fact that Wetselaar started with a soil having a moisture content around the permanent wilting point whilst Harmsen and Kolenbrander began with a moisture content corresponding to field capacity.

Upward movement of N may occur when water is evaporated from the soil surface and as water is transpired through plants. This upward movement may supply the plant with N from the subsoil (Van der Paauw, 1962). Herron et al. (1968) working with a well aerated Nebraska loess soil found that 41% of applied ammonium nitrate was recovered by corn plants when placed at about 45 cm depth, and 61% was recovered when placed at about 140 cm depth. This would be consistent with de Roo and Wiersum's (1963) observation that in sufficiently aerated soils the ability of plant roots to absorb nutrients does not decrease with depth. Under dry soil conditions however, nitrate N may be moved to the top inch of the soil making it unavailable for the plant (Wetselaar, 1961). In uncropped soil this upward movement is limited to the upper 50 cm of the soil (Wetselaar, 1961).

The effect of cropping on N losses in drainage effluent was measured by Bolten et al. (1970) who found 11% loss of applied N to continuous corn in Ontario and less than 1% loss in drainage water from a blue-grass sward. Small leaching losses of fertilizer N on pastures were also reported by Whitehead (1970) in Britain. However, Woldendorp et al. (1966) in the Netherlands found that as much as 50 or 60% of applied N could be lost in drainage effluent from permanent pastures in the fall and winter.

Numerous other papers on soil nitrogen movement have been published (Allison, 1965, 1966). Gardner (1965a) and de Wit and van Keulen (1970) have developed emperical equations to describe N movement in the soil. Using theoretical considerations, de Wit and van Keulen have successfully developed computer simulation models for salt transport in the soil using a C.S.M.P. computer language.

Many pot or soil column studies in the laboratory were carried out to study N movement (Jansson, 1958, 1963; Steward and Eck, 1958; Romkens and Bruce, 1964). Leaching losses have generally been measured in lysimeter experiments or in controlled field drainage plots by measuring N in the effluent water. A few N movement experiments have been published comparing uncropped land (Wetselaar, 1961, 1962) and cropped land (Gasser, 1959, 1961; Linville and Smith, 1971).

Little is known about the exact paths that water and salts take in moving through a soil (Thomas, 1970) leaching can be appreciable when the soil is at field capacity and when precipitation exceeds evapotranspiration. Hence most leaching losses occur between the fall and spring (Olsen et al., 1970). Most workers concluded that during the summer months applied nitrate seldom moves out of range of the plant roots.

Methods of decreasing the loss of nitrate N out of the soil-plant continuum into ground water supply through control of nitrification rate, slow release fertilizers and nitrification inhibiters has not yet been widely used (Broadbent, 1971). Bouldin et al. (1971) found that in New York, summer sidedress of fertilizer N caused the least amount of loss. Summer sidedress was applied just before the period of maximum N uptake by corn in late June. However, N applied in spring or early summer does not seem to cause differences in yield response in Ontario (Stevenson and Baldwin, 1969) or Quebec (Sadler, 1967).

It was the purpose of this experiment to show how the losses of fertilizer N varied when applied in April, May or early June. Due to the short growing season in Quebec, smaller amounts of late applications may be immobilized or absorbed by the plant as compared to earlier applications.

MATERIALS AND METHODS

An experiment was conducted in 1971 in which the movement of inorganic N (NO_3) was estimated to a depth of 100 cm in three different soil profiles. The three soils were classified as St. Benoit sandy loam (72% sand, 6% clay), Chicot fine sandy loam (45% sand, 10% clay) and St. Rosalie clay (25% sand, 42% clay). Corn plots laid down on these soils received 300 kg N as ammonium nitrate on April 29, May 18 or on June 3 and were compared with control plots receiving no N. A randomized block design with three replications was used and details of the experimental lay-out are given in Chapter II.

At monthly intervals, starting on April 28 one 100 cm deep soil profile was sampled per plot using a soil sample auger which was 20 cm long and 5 cm in diameter. The top 20 cm of the soil was sampled in two 10 cm intervals, but subsequent sampling was done at 20 cm intervals to a depth of 100 cm. Soil samples were put in plastic coated soil sample bags, sealed and transported to the laboratory for analysis the following day. The samples were analyzed for ammonium and nitrate using the wet sample extraction technique as suggested by Bremner (1965) and modified by MacKenzie and Trenholm (1972)(1). The last sampling was carried out December 15 under a 18 - 20 cm snow cover. Subsamples for soil moisture determinations were oven dried at about 90°C for 48 hours, but because the results obtained from these were inconsistent and erratic this data was not used to calculate potential soil water movement. Top soil values only were used.

(1)Mimeo reports on methods of analysis used by the Department of Soil Science, McGill University.

Bulk density core samples were taken down to a depth of 50 cm in early May, early June and late August. The variations in volume proportions of solid, water and air of the three soils are shown in Figure 1. Bulk density values were used to calculate inorganic N content in kg N ha^{-1}. Field capacity (F.C.) and permanent wilting point (P.W.P.) values were estimated using Staple's (1969) and Shaykewich (1968) data who used similar textured soils.

Data on precipitation and class A pan evaporation were obtained from a weather station nearby, within a mile of each experimental site. Potential evapotranspiration for corn was calculated by multiplying class A pan evaporation by a transpiration factor[(1)]. The factors were for early June 0.7; late June 0.8; early July 0.9; late July and early August 1.0; late August 0.9 and early September 0.8. These factors corresponded with those mentioned by de Wit (1970).

Statistical analysis and standard errors of the difference between two means were calculated for nitrate concentrations with respect to both depth and time. High sampling errors were generally found and the coefficient of variability was often about 25% or higher.

---

(1) B.P. Warkentin, Professor of Soil Physics, in the Department of Soil Science; personal communications.

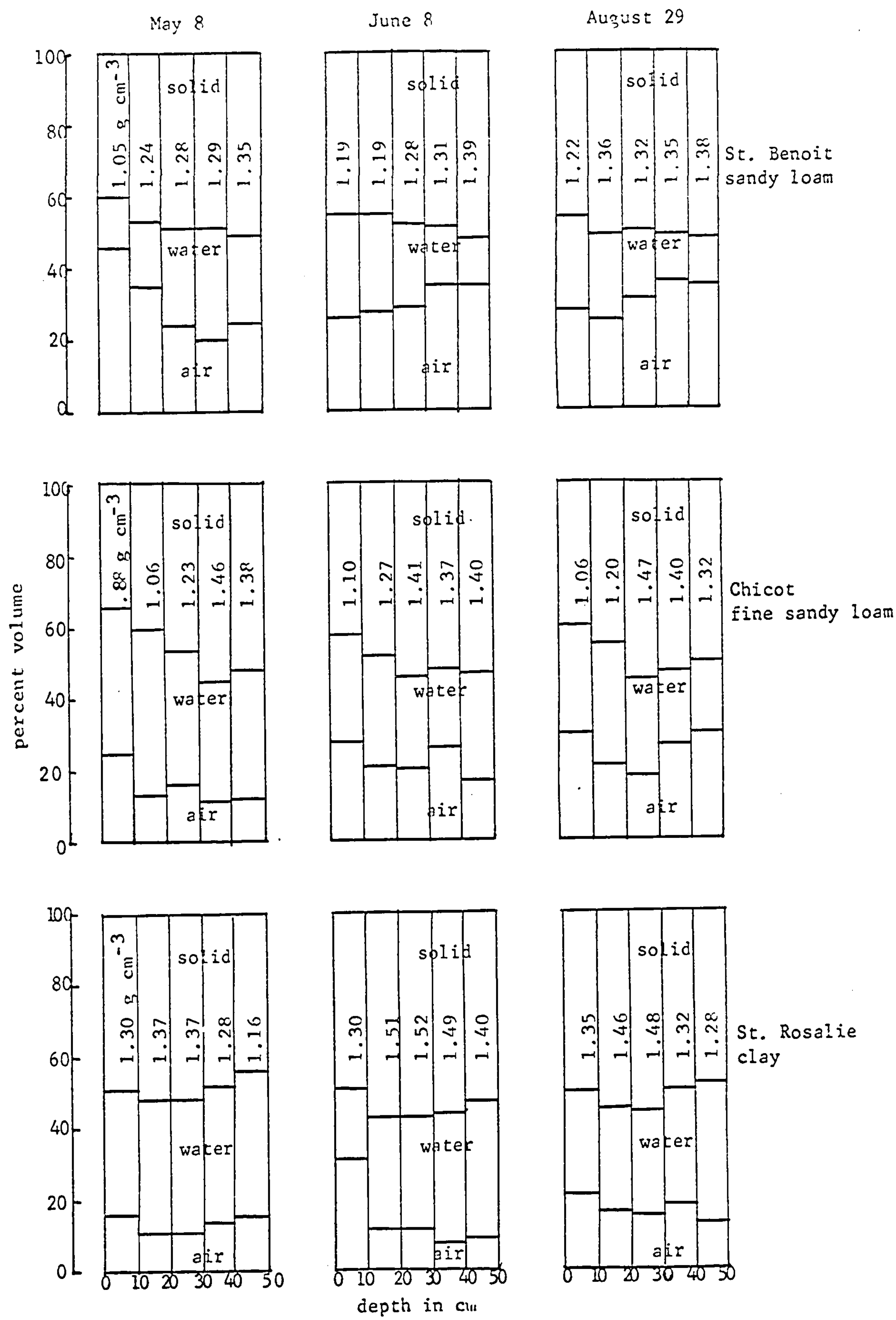

Figure 1: Volume proportions of solid, water and air variations with depth in three soils on three dates. (Bulk density values for each depth are mentioned in the figure).

RESULTS AND DISCUSSION

In April the total amount of inorganic N (NH_4 and NO_3) found between 0 and 100 cm depth in the three soils was small, varying from 100 kg ha^{-1} to 150 kg ha^{-1} (Table 1). Nitrate N levels were low and never exceeded 10 ppm at any depth (Figure 2, 3 and 4). The soil moisture contents of the top soil (Figure 5) were at or above the estimated field capacity by the end of April, just after the snow cover melted. Soil conditions were at this time therefore optimal for nitrate leaching losses. Later, during May, low rainfall and rapid drying of the top soil, particularly after seedbed preparation, must have slowed down or stopped downward water movement, and a potential gradient between the dry topsoil and the wetter subsoil may have caused some upward movement of soil water.

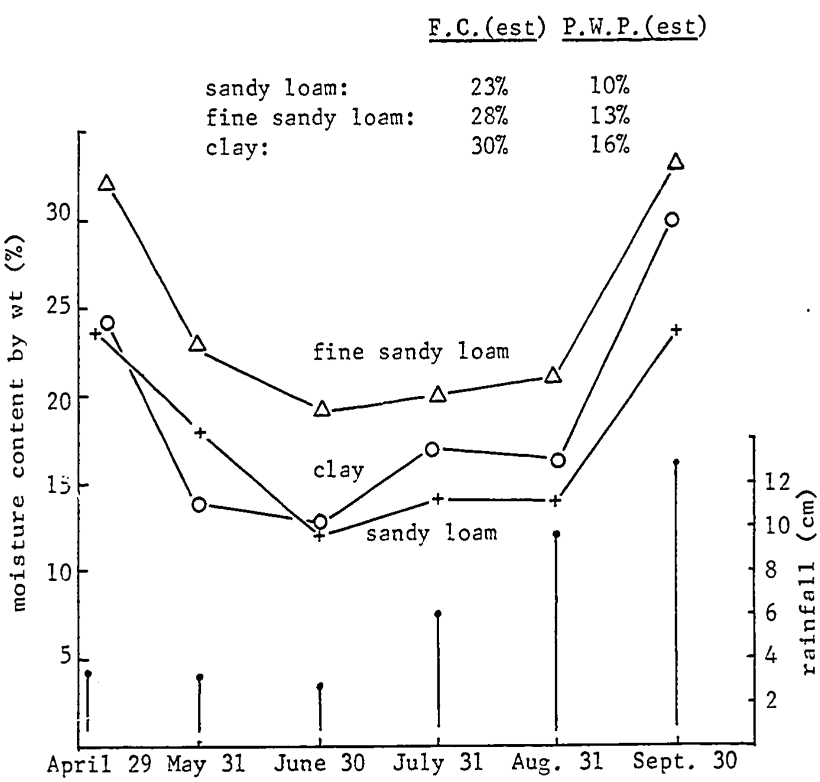

Figure 5: Soil moisture contents of the top 20 cm of three soils during the 1971 growing season and monthly rainfall.

Table 1: Inorganic N (NH_4 + NO_3) contents in a 100 cm profile of three soils affected by time of N fertilization in 1971.

Nitrogen applied	Sampling date	Sandy loam NH_4	NO_3	Total	Fine sandy loam NH_4	NO_3	Total	Clay NH_4	NO_3	Total
		kg ha^{-1}								
None	April 28	91	36	127	83	20	103	137	19	156
	May 30	44	144	188	95	91	186	163	56	219
	June 30	123	234	357	120	171	292	315	315	630
	July 30	270	220	490	160	286	446	460	218	678
	Aug. 29	62	252	314	55	98	152	48	57	105
	Sept. 28	333	206	539	234	109	343	181	106	287
	Dec. 15	161	181	342	189	123	312	126	54	180
April 29	April 28	91	36	127	83	20	103	137	19	156
	May 30	85	298	383	171	180	351	271	106	377
	June 30	214	691	904	147	499	646	426	587	1012
	July 30	222	326	548	328	769	1087	494	284	778
	Aug. 29	51	347	398	71	267	338	53	88	141
	Sept. 28	322	427	749	370	205	575	199	117	316
May 18	April 28	91	36	127	83	20	103	137	19	156
	May 30	133	402	535	160	130	290	462	62	523
	June 30	320	623	943	170	313	483	514	631	1145
	July 30	350	305	655	243	445	688	536	466	1002
	Aug. 29	70	430	500	64	202	266	51	82	133
	Sept. 28	381	506	887	416	220	636	257	139	396
June 2	April 28	91	36	127	83	20	103	137	19	156
	May 30	44	144	188	95	91	186	163	56	219
	June 30	1190	1141	2335	508	554	1062	461	425	886
	July 30	354	428	771	428	458	896	426	339	765
	Aug. 29	146	658	804	63	217	280	56	98	154
	Sept. 28	378	474	832	362	326	688	272	240	512
	Dec. 15	136	390	525	136	214	350	139	85	224

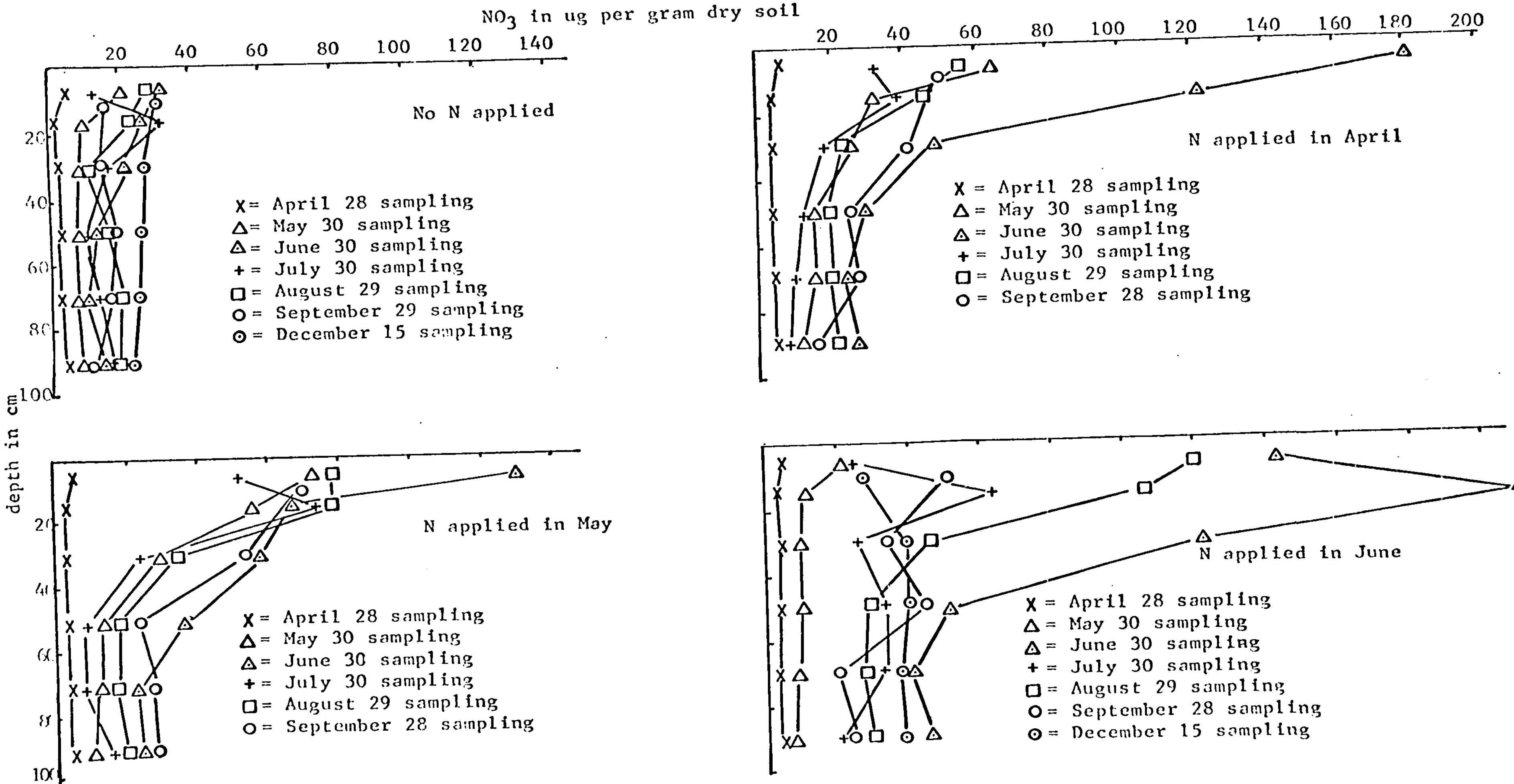

Figure 2: Time of nitrogen fertilizer application and its effect on nitrate distribution in the 100 cm soil profile before, during and after the corn growth period on a St. Benoit sandy loam.

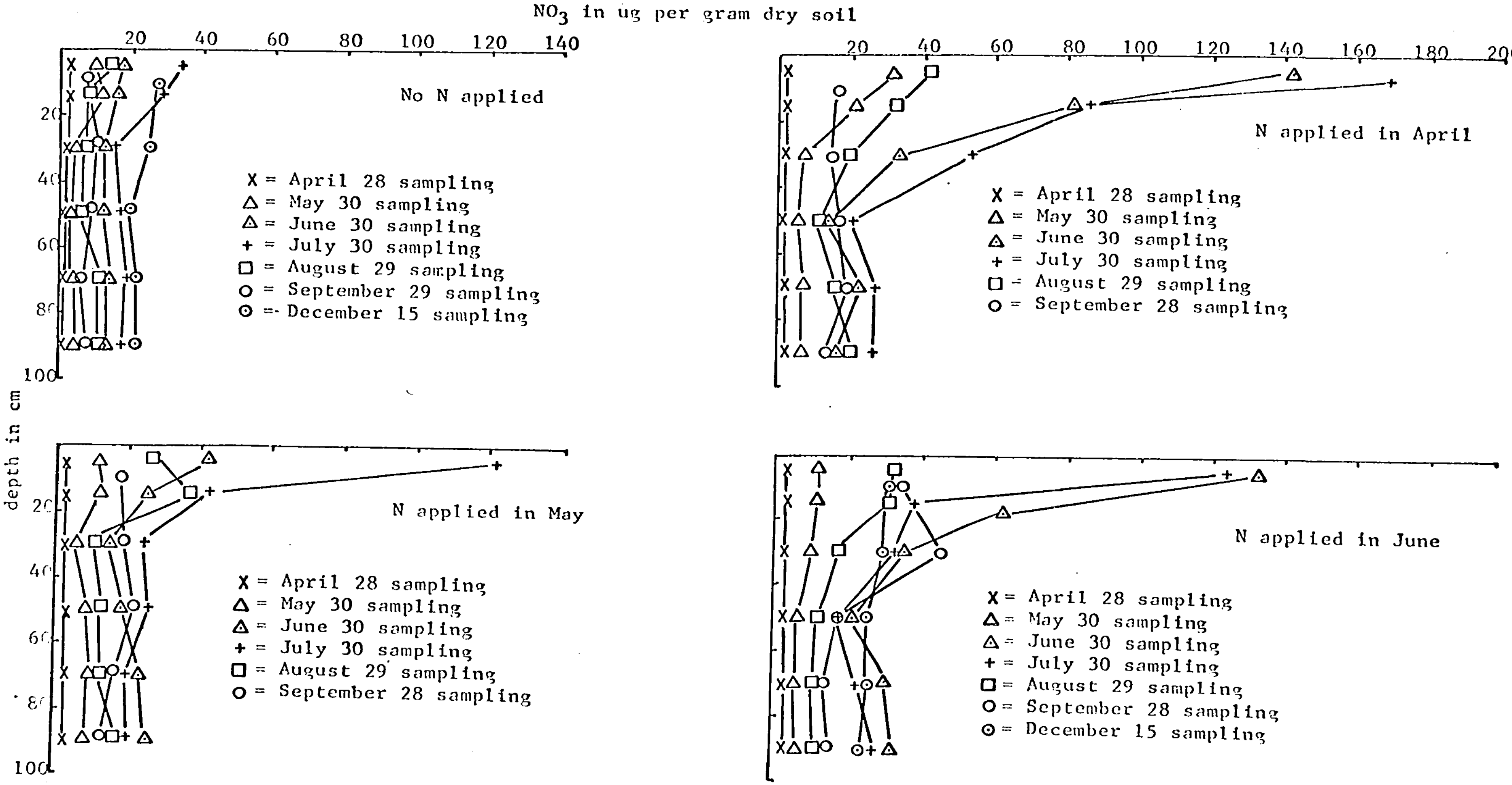

Figure 3: Time of nitrogen fertilizer application and its effect on nitrate distribution in the 100 cm soil profile before, during and after the corn growth period on a Chicot fine sandy loam.

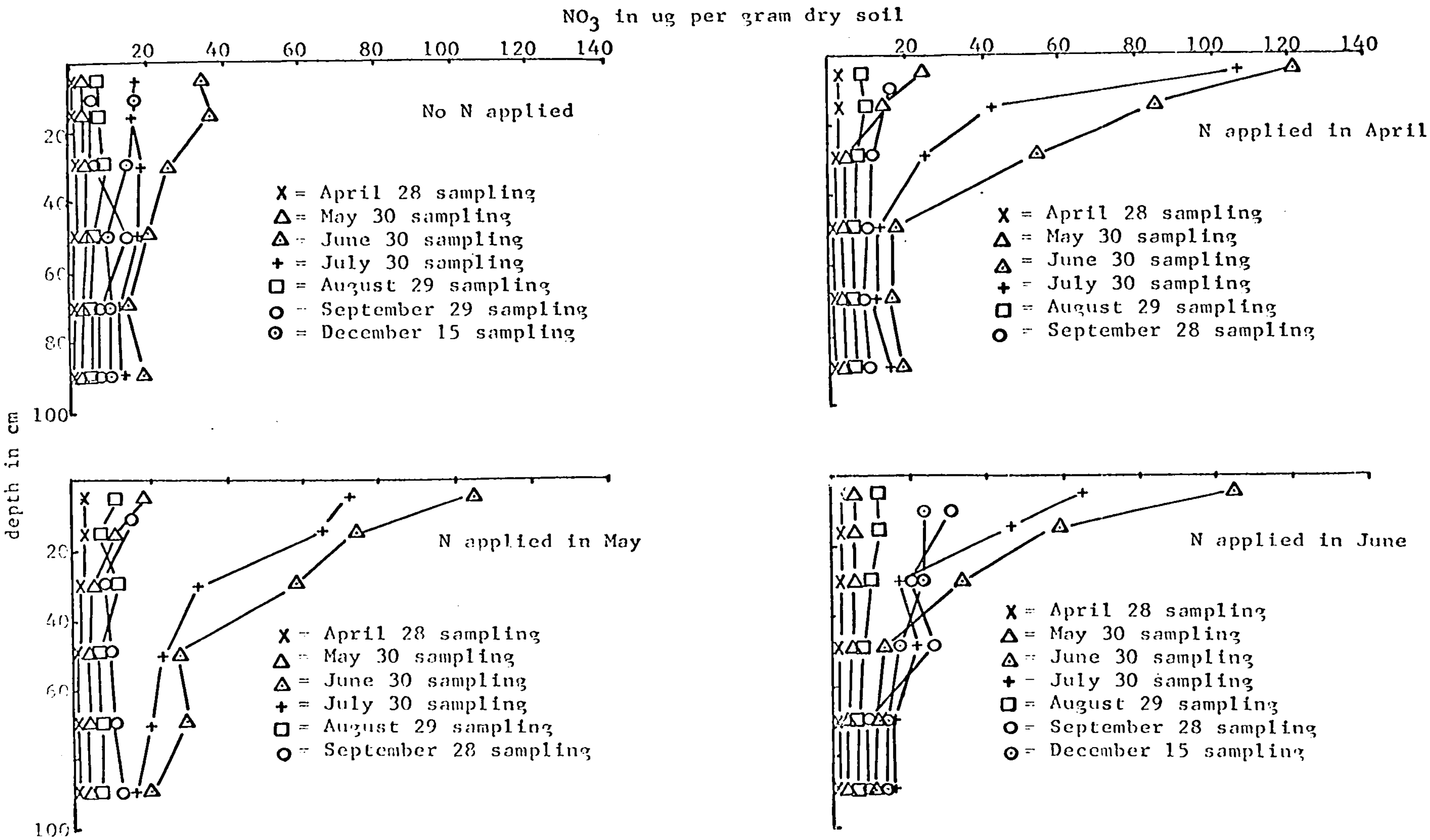

Figure 4: Time of nitrogen fertilizer application and its effect on nitrate distribution in the 100 cm soil profile before, during and after the corn growth period on a St. Rosalie clay.

After emergence on June 1st potential evapotranspiration was larger than precipitation for most of the growing season (Figure 6).

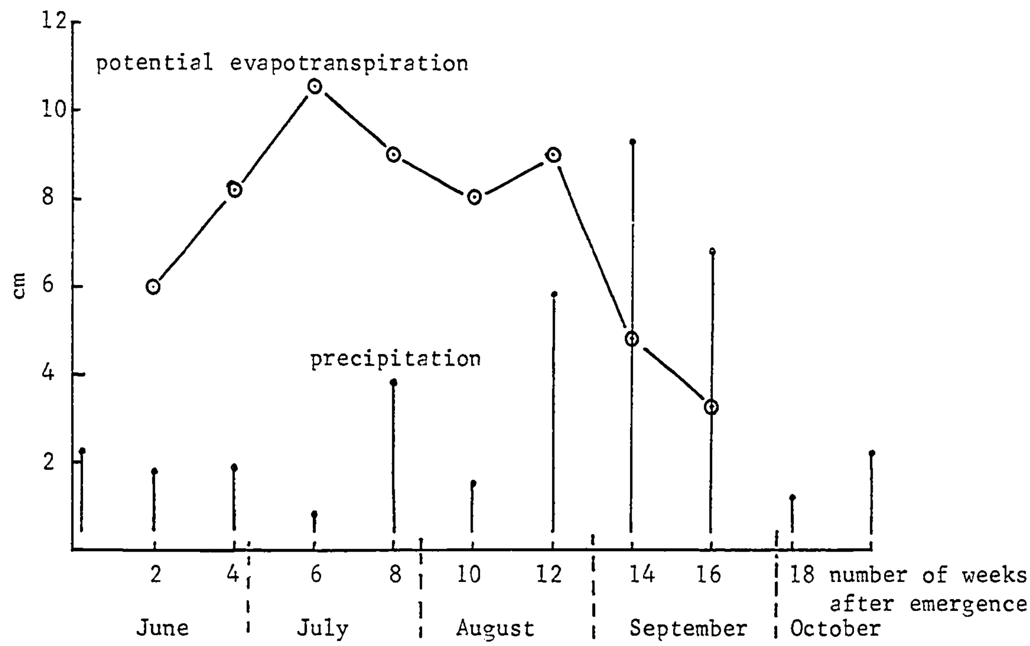

Figure 6: Precipitation and potential evapotranspiration for corn at two week intervals in the 1971 growing season.

Thus downward water movement would not have occurred during this period. An increase in precipitation in August to a maximum of about 10 cm by early September, was associated with a decrease in potential evapotranspiration. This caused an excess of about 4.2 cm water early in September and a 3.7 cm excess in mid-September. Topsoil moisture was thus recharged again to about field capacity (Figure 5). It was calculated that between 2.4 and 2.5 cm of water was required to bring the sandy loam and fine sandy loam back to the estimated field capacity while 3.3 cm was required for the clay. More water would have moved in the subsoil of the sandy loam (5.5 cm) than in the clay (4.6 cm). Low rainfall in October (3.2 cm) and November (5 cm) may not have caused much soil water movement through the soil profile since total estimated evaporation in October and November was about 4 cm (Ferland, 1969). Thus the excess of precipitation was 4.2 cm of water by the end of November. Assuming that the topsoil remained at field capacity during this time, the excess of precipitation could have percolated down the profile to recharge the subsoil from about permanent wilting point to field capacity. Knowing the bulk density of the soils (Figure 1) and approximate values of soil moisture content of the subsoil it was calculated that by the end of November about 75 cm of the 100 cm sandy loam soil profile was recharged to field capacity, and about 60 cm of both the fine sandy loam and clay soils. Precipitation, mainly as snowfall (about 35 cm), in the later part of November up to final sampling date December 15 made it difficult to calculate further recharge of the profiles as most of the snow remained as permanent cover. It is assumed that none of the 100 cm soil profiles were completely recharged to field capacity by mid-December.

It is therefore concluded that N leaching losses could have occurred during April when snow cover was melting, but that these losses were negligible during most of the growing season due to low rainfall and high potential evapotranspiration. When soil moisture content again reached field capacity in the top soil in September, N leaching out of this zone could have occurred, especially towards the end of the month and then more in the sandy loam than in the clay. Subsequent leaching may have been limited by low rainfall in October and November. These observations were consistent with the findings of Bouldin et al. (1971) and Olsen et al. (1970).

The application of fertilizer N in April, May or June particularly increased the inorganic N content of the top 20 to 40 cm in all three soils (Table 1 and Figures 2, 3 and 4). The effect was more pronounced with nitrate than with ammonium levels, indicating that microbial life may have preferred the ammonium source over the nitrate source; similar observations were mentioned by Allison (1966) and Jansson (1958). However, ammonium fixation could also have taken place, but the two processes are difficult to separate.

The effect of applied N was particularly evident during the time of maximum net mineralization in June or July. Plant uptake and net immobilization reduced the inorganic N levels until a minimum was reached at the end of August. It was assumed that loss of N through denitrification or leaching were negligible during most of the growing season due to low rainfall. It was calculated that after crop harvest at the end of September 189 kg fertilizer N was still left in the sandy loam (based on 37% crop recovery); with 222 kg left in the fine sandy loam and the clay (26% recovery). At the sampling in late September an amount equal to this residual fertilizer N was found to be back in the inorganic form on the sandy loam and fine sandy loam regardless of time of application (Table 2). The increase of inorganic N was often higher than expected, but this could have been due to contamination of subsoil samples with soil from the top, especially in the sandy loam.

In the clay soil almost half of the calculated amount of residual

N was apparently immobilized by the end of September on plots receiving N in April and May (Table 2). On the plots receiving N in June all the calculated residual fertilizer N was still found in the inorganic form, mainly as nitrate. By the end of September it was generally observed that the highest nitrate levels were found on the plots receiving fertilizer N in June in all soils.

Table 2: The effect of applications of nitrogen fertilizer on the inorganic N content of 100 cm deep profiles of three soils on September 29, two weeks after crop harvest.

Treatment		Sandy loam	Fine sandy loam	Clay
			kg ha^{-1}	
No N applied	NH_4	333	243	181
	NO_3	206	109	106
	Tot	539	343	287
N applied in April	NH_4	322	370	119
	NO_3	427	205	117
	Tot	749	575	316
N applied in May	NH_4	381	416	257
	NO_3	506	220	139
	Tot	887	636	396
N applied in June	NH_4	378	362	272
	NO_3	474	326	240
	Tot	852	688	512
Calculated residual fertilizer N		189	222	222

It is concluded that during the period up to December 15 fertilizer N was not leached out of the 100 cm profile, since most of the calculated residual fertilizer N after cropping was accounted for. There was some indication that accumulation of nitrate N occurred at a depth of 40 to 60 cm in the profile by the end of September (Figure 2, 3 and 4). Fertilizer N applied in June to the clay resulted in higher concentrations of nitrate in the 100 cm profile in September than earlier applications. This effect did not occur on the sandy loam and fine sandy loam.

By mid-December the effect of the fertilizer N applications on inorganic N content was negligible for all soils except the sandy loam (Table 1). In this nitrate levels of the plots receiving N in June was double the level in the control plot. The inorganic N levels in the 100 cm profile in the plots which received fertilizer N generally decreased by about 300 kg N ha^{-1} compared to a 100 - 200 kg N ha^{-1} decrease in the control plots. The relative importance of losses through denitrification or immobilization can only be determined by N^{15} tracer; however, leaching must have been small due to low rainfall in October and November.

CONCLUSIONS

Fertilizer N applications greatly increased inorganic N content in all soils, and leaching losses were negligible since potential evapotranspiration exceeded precipitation during most of the growing season.

The corn crop removed 78 kg fertilizer N ha^{-1} on the fine sandy loam and clay and 111 kg on the sandy loam. At the end of September an amount of N equal to the residual fertilizer N was still present in the inorganic form, particularly as nitrate in 100 cm soil profiles. These conditions might be considered potentially hazardous for the pollution of underground water. The increased precipitation in September caused soil moisture to reach field capacity and nitrate may have moved to the subsoil at a depth of 40 to 60 cm by October or November. Once this has accumulated in the subsoil it is likely to remain there unchanged until subsequent downward movement of water occurs. In the subsoil, microbiological activity is minimal, thus immobilization or denitrification is considered negligible. An attempt to estimate water movement through the profile was unsuccessfull due to a poor sampling technique.

A better sampling technique is required, and the use of undisturbed soil cores rather than a soil auger is suggested, so that contamination of the subsoil sample by topsoil is prevented. A separate set of soil samples should be taken for soil moisture determinations at different depths.

There were indications that applications of N in early June increased residual nitrate concentrations in September more than early spring applications on the clay soil where most of the residual N from the early applications was immobilized by September.

The data obtained in the present study indicate that fertilizer N in excess of that removed by corn, increases the potential for downward movement of nitrate. This potential is greater in a sandy soil than in a clay soil, and greater in a wet season than in a dry season.

PERSPECTIVE

The problem of accurately forecasting the quantities of additional nitrogen fertilizer needed by any crop is very difficult, but it must ultimately be determined by the total crop requirement and the amount of N which will be supplied by the soil. The previous three chapters have focussed on factors related to this problem with specific reference to three different Quebec soils on which corn was grown.

The study showed two other important factors affecting root growth were aeration and mechanical impedance. Aeration decreases as the soil moisture content increases and once critical levels have been surpassed, root growth will be restricted. Simultaneously however, mechanical impedance will decrease with an increase in soil moisture.

A field study was made in which three soils of various textures were used. Under the conditions of the experiment, where there was low rainfall and low soil moisture content and thus no influence of the aeration factor, the differences in root development were attributable to differences in levels of mechanical impedance. In a sandy soil, with low impedance levels, deep root systems developed and more fertilizer N and less native soil N was taken up than in either a loam or a clay soil. The restricted root systems in the latter two soils caused a greater absorption of native soil N than of fertilizer N. On the basis of this observation it seems that plants with deep root systems may absorb more fertilizer N for a given yield to plants with restricted root systems under conditions similar to those encountered in this experiment. However, further research is required to substantiate these findings over a wider range of soil conditions.

The residual fertilizer N which is present as nitrates in the subsoil, but is outside the rooting zone may eventually be subject to leaching. The principal factors which determine the rate of movement of these accumulated nitrates are the amount of rainfall and the soil moisture content at field capacity. The movement of residual fertilizer nitrate into drainage effluent was probably negligible in 1971 when conditions of low rainfall were experienced.

In conclusion, factors restricting root growth can reduce fertilizer N uptake and may increase N leaching losses, thus causing a pollution hazard.

CONTRIBUTIONS TO KNOWLEDGE

1. The force opposed to a root shaped penetrometer, measured in gram weight mm^{-2} in undisturbed soil cores from the field, was related to corn root growth and development and by inference to mechanical impedance.

2. Root elongation rates in pure silica sands never reached maximum levels as a result of mechanical impedance effects. A reduction of root growth due to poor aeration occurred in sands containing less than 25 percent gas filled pore volume. Thus sand is not an ideal rooting medium.

3. In sandy soils with low impedance, providing easy penetration for corn roots, more fertilizer N was utilized than in fine textured soils with restricted corn root systems. Maximum utilization of native soil N occurred in fine textured soils where root systems were restricted mainly to the topsoil.

4. It was found that applied N increased both root growth and top growth, and that the effect on root growth was greater in soils with low mechanical impedance than in soils with high levels of impedance. Top growth was unaffected by mechanical impedance levels.

5. It was found that maximum net N mineralization in the soil occurred before maximum corn plant growth rate under Quebec

climatic conditions. Hence the timing of large fertilizer N applications had no effect on yield from the end of April to mid-June.

6. Late applied N could increase the potential leaching losses of nitrates from residual fertilizer N left in the inorganic form after crop removal.

BIBLIOGRAPHY

Allison, F.E. 1955. The enigma of soil nitrogen balance sheets. Advance. Agron. 7:213-250.

Allison, F.E. 1965. Evaluation of incoming and outgoing processes that affect soil nitrogen. In W.V. Bartholomew and F.E. Clark (eds.) Soil nitrogen. Agronomy 10:573-606. Amer. Soc. of Agron., Madison, Wis. U.S.A.

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

Barber, S.A. 1962. A diffusion and mass-flow concept of soil nutrient availability. Soil Sci. 93:39-50.

Barley, K.P., and E.L. Greacen. 1967. Mechanical resistance as a soil factor influencing the growth of roots and underground shoots. Advance. Agron. 19:1-43.

Bartholomew, W.V., and F.E. Clark (eds.). 1965. Soil nitrogen. Agronomy 10. Amer. Soc. of Agron., Madison, Wis. U.S.A.

Black, C.A., L.B. Nelson, and W.L. Pritchett. 1947. Nitrogen utilization by wheat as affected by rate of fertilization. Soil Sci. Soc. Amer. Proc. 11:393-396.

Bolt, G.H., A.R.P. Janse, and F.F.R. Koenings. 1970. Algemene Bodemkunde. (In Dutch) Syllabus of Kandidaatscollege. Agricultural Univ., Wageningen, The Netherlands.

Bolton, E.F., J.W. Aylesworth, and F.R. Hore. 1970. Nutrient losses through tile drains under three cropping systems and two fertility levels on a Brookston clay soil. Can. J. Soil Sci. 50:275-279.

Bouldin, D.R., W.S. Reid, and D.J. Lathwell. 1971. Fertilizer practices which minimize nutrient loss. Cornell University Conference on Agricultural Waste Management. 1971:25-35.

Bremner, J.M. 1965. Inorganic forms of nitrogen. In C.A. Black (ed.) Methods of soil Analysis II. Agronomy 9:1179-1238. Amer. Soc. of Agron., Madison, Wis. U.S.A.

Broadbent, F.E. 1965. Effect of fertilizer nitrogen on the release of soil nitrogen. Soil Sci. Soc. Amer. Proc. 29:692-696.

Broadbent, F.E. 1971. Nitrogen in soil and water. In L.R. Webber (ed.) Nitrogen in soil and water. Proc. Guelph University Symposium. Guelph, Ontario, Canada.

Broadbent, F.E., and H.D. Chapham. 1950. A lysimeter investigation of gains, losses and balance of salts and plant nutrients in an irrigated soil. Soil Sci. Soc. Amer. Proc. 14:261-269.

Broadbent, F.E., and T. Nakashima. 1971. Effect of added salts on nitrogen mineralization in three California soils. Soil Sci. Soc. Amer. Proc. 35:457-460.

Brug, P.F.J. van. 1970. The seasonal response of grassland herbage to nitrogen. Neth. Nitrogen Techn. Bull. 8. Agricultural Bureau, The Hague, The Netherlands.

Chabannes, J., G. Barbier, and J. Driad. 1964. More observations on the spring mineralization of soil N. (In French) C.R. Acad. Agric. Fr. 50:874-881.

Diest, A. van. 1969. Soil fertility. Syllabus of lectures. Int. Agric. Centr. Wageningen, The Netherlands.

Eavis, B.W. 1965. Soil physical conditions and root growth. Ph.D. Thesis. Univ. of Reading, Reading, U.K.

Eavis, B.W., and D. Payne. 1968. Soil physical conditions and root growth. In W.J. Whittington (ed.) Root growth. Proc. 15th Easter School in Agric. Sci. 315-338. Butterworths, London, U.K.

Eavis, B.W. 1972. Soil physical conditions affecting seedling root growth: 1. Mechanical impedance, aeration and moisture availability as influenced by bulk density and moisture levels in a sandy loam soil. Plant and Soil, 36: In Press.

Fehrenbacher, J.B., B.W. Ray, and J.D. Alexander. 1967. Root development of corn, soybeans, wheat, and meadow in some contrasting Illinois soils. Illinois Res. 9:2:3-5.

Ferland, M. 1969. Evapotranspiration potentielle au Québec. Naturaliste Can. 96:601-619.

Foth, H.D. 1962. Root and top growth of Corn. Agron. J. 54:49-52.

Frissel, M.J., P. Poelstra, and P. Reiniger. 1970. Chromatographic transport through soils. Plant and Soil. 33:161-176.

Gardner, W.R. 1960. Dynamic aspects of water availability to plants. Soil Sci. 89:63-73.

Gardner, W.R. 1965a. Movement of nitrogen in soil. In W.V. Bartholomew and F.E. Clark (eds.) Soil nitrogen. Agronomy 10:550-572. Amer. Soc. of Agron., Madison, Wis. U.S.A.

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

Gasser, J.K.R. 1959. Soil nitrogen. IV. -Transformations and movement of fertilizer nitrogen in a light soil. J. Sci. Food Agric. 10:192-197.

Gasser, J.K.R. 1961. Transformation, leaching and uptake of fertilizer nitrogen applied in autumn and spring to winter wheat on a heavy soil. J. Sci. Food Agric. 12:375-380.

Gerard, C.J., and H.C. Mehta. 1971. Influence of a root crop on physical properties of a medium-textured soil. Agron. J. 63:889-895.

Gill, W.R., and G.H. Bolt. 1955. Pfeffer's studies of the root growth pressures exerted by plants. Agron. J. 47:166-168.

Gill, W.R., and R.D. Miller. 1956. A method for study of the influence of mechanical impedance and aeration on the growth of seedling growth. Soil Sci. Soc. Amer. Proc. 20:447-453. 1956.

Gingrich, J.R., and M.B. Russell. 1956. Effects of soil moisture tension and oxygen concentration on the growth of corn roots. Agron. J. 48:515-520.

Goring, C.A.I., and F.E. Clark. 1948. Influence of crop growth on mineralization of nitrogen in the soil. Soil Sci. Soc. Amer. Proc. 13:261-266.

Haise, H.R., and R.M. Hagan. 1967. Soil, plant, and evaporative measurements as criteria for scheduling irrigation. In R.M. Hagan, H.R. Haise, and T.W. Edminster (eds.) Irrigation of agricultural lands. Agronomy 11:577-606. Amer. Soc. of Agron., Madison, Wis. U.S.A.

Hanway, J.J. 1962a. Corn growth and composition in relation to soil fertility:II. Uptake of N, P, and K and their distribution in different plant parts during the growing season. Agron. J. 54:217-222.

Hanway, J.J. 1962b. Corn growth and composition in relation to soil fertility:III. Percentages of N, P, and K in different plant parts in relation to stage of growth. Agron. J. 54:222-229.

Harmsen, G.W., and G.J. Kolenbrander. 1965. Soil inorganic nitrogen. In W.V. Bartholomew and F.E. Clark (eds.) Soil nitrogen. Agronomy 10:43-92. Amer. Soc. of Agron., Madison, Wis. U.S.A.

Herron, G.M., G.L. Terman, A.F. Drier, and R.A. Olsen. 1968. Residual nitrate nitrogen in fertilized deep loess-derived soils. Agron. J. 60:477-482.

Jansson, S.L. 1958. Tracer studies on nitrogen transformations in soil with special attention to mineralization-immobilization relationships. Ann. Roy. Agr. Coll. Sweden 24:101-361.

Jansson, S.L. 1963. Balance sheet and residual effects of fertilizer nitrogen in a 6-year study with N15. Soil Sci. 95:31-37.

Kolenbrander, G.J. 1969. Nitrate content and nitrogen loss in drainwater. Neth. J. Agric. Sci. 17:246-255.

Lathwell, D.J., D.R. Bouldin, and W.S. Reid. 1970. Effects of nitrogen fertilizer applications in agriculture. Cornell University Conference on Agricultural Waste Management. 1970:192-206.

Libois, A. 1965. A study of the evolution of mineral N in a bare soil in the Dijon region. (In French) C.R. Acad. Agric. Fr. 51:546-551.

Linder, R.C., and C.P. Harley. 1942. Scientific apparatus and laboratory methods. A rapid method for determination of nitrogen in plant tissue. Science. 96:565-566.

Linville, K.W., and G.E. Smith. 1971. Nitrate content of soil cores from corn plots after repeated nitrogen fertilization. Soil Sci. 112:249-255.

Lutz, J.F. 1952. Mechanical impedance and plant growth. In B.T. Shaw (ed.) Soil physical conditions and plant growth. Agronomy 2:43-71. Academic Press, New York, New York, U.S.A.

Miller, G.L., and E.E. Miller. 1948. Determination of nitrogen in biological material. Anal. Chem. 20:481-488.

Nelson, L.B., and R.E. Uhland. 1955. Factors that influence loss of fall-applied fertilizers and their probable importance in different sections of the United States. Soil Sci. Soc. Amer. Proc. 19: 492-496.

Nye, P.H. 1968. Processes in the root environment. J. Soil Sci. 19:205-215.

O'Brien, J.E., and J. Fiore. 1962. Automation in sanitary chemistry: III. Ammonia determination by automatic analysis. Wastes Eng. 33:352-353.

Olsen, R.J., R.F. Hensler, O.J. Attoe, S.A. Witzel, and L.A. Peterson. 1970. Fertilizer nitrogen and crop rotation in relation to movement of nitrate nitrogen through soil profiles. Soil Sci. Soc. Amer. Proc. 34:448-452.

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

Paauw, F. van der. 1962. Effect of winter rainfall on the amount of nitrogen available to crops. Plant and Soil. 16:361-380.

Peters, D.B. 1957. Water uptake of corn roots as influenced by soil moisture content and soil moisture tension. Soil Sci. Soc. Amer. Proc. 21:481-484.

Peters, D.B., and J.R. Runkles. 1967. Shoot and root growth as affected by water availability. In R.M. Hagan, H.R. Haise, and T.W. Edminster (eds.) Irrigation of agricultural lands. Agronomy 11:373-388. Amer. Soc. of Agron., Madison, Wis. U.S.A.

Phillips, R.E., and D. Kirkham. 1962. Soil compaction in the field and corn growth. Agron. J. 54:29-34.

Romkens, M.J.M., and R.R. Bruce. 1964. Nitrate diffusivity in relation to moisture content of non-adsorbing porous media. Soil Sci. 98:332-337.

Roo, H.C. de, and L.K. Wiersum. 1963. Root training by plastic tubes. Agron. J. 55:402-405.

Rose, C.W. 1965. Movement of water in soils. In Agricultural physics. Pergamon Press. Sydney, Australia.

Russell, E.W. 1961. The nitrogen cycle in the soil. In Soil conditions and plant growth. 9th ed. Longmans publishing Co., London, U.K.

Sadler, J.M. 1967. The effect of time and rate of nitrogen fertilization of corn on the nitrogen balance in some Quebec soils. M.Sc. Thesis McGill University, Montreal, Canada.

Schreven, D.A. van. 1958. Experiments on nitrogen mineralization in soil (In Dutch) Van Zee tot Land. 26:26-52. English Summary.

Schuurman, J.J., and M.A.J. Goedewagen. 1971. Methods for the examination of root systems and roots. ISDN 90 220 03248 Pu. Doc. Wageningen, The Netherlands.

Shaykewich, C.F. 1968. Availability of water for plant growth in three Quebec soils. Ph.D. Thesis McGill University, Montreal, Canada.

Stanhill, G., and Y. Vaadia. 1967. Factors affecting plant responses to soil water. In R.M. Hagan, H.R. Haise, and T.W. Edminster (eds.) Irrigation of agricultural lands. Agronomy 11:446-458. Amer. Soc. of Agron., Madison, Wis. U.S.A.

Staple, W.J. 1965. Moisture tension, diffusivity, and conductivity of a loam soil during wetting and drying. Can.J. Soil Sci. 45:78-86.

Staple, W.J. 1969. Comparison of computed and measured moisture redistribution following infiltration. Soil Sci. Soc. Amer. Proc. 33:840-848.

Stevenson, C.K., and C.S. Baldwin. 1969. Effect of time and method of nitrogen application and source of nitrogen on the yield and nitrogen content of corn (Zea mays L.). Agron. J. 61:381-384.

Steward, B.A., and H.V. Eck. 1958. The movement of surface-applied nitrate into soils at five moisture levels. Soil Sci. Soc. Amer. Proc. 22:260-262.

Taylor, H.M., and H.R. Gardner. 1963. Penetration of cotton seedling tap roots as influenced by bulk density, moisture content, and strength of soil. Soil Sci. 96:153-156.

Thomas, G.W. 1970. Soil and climatic factors which affect nutrient mobility. In Nutrient mobility in soils: accumulation and losses: Soil Sci. Soc. Amer. Special publ. 4:1-20.

Viets, F.G., Jr. 1960. Recovery of fertilizer nitrogen on irrigated and dryland soils of the western United States. Trans. 7th Intern. Cong. Soil Sci. 2:486-493.

Viets, F.G., Jr. 1965. The plant's need for and use of nitrogen. In W.V. Bartholomew and F.E. Clark (eds.) Soil nitrogen. Agronomy 10:503-549. Amer. Soc. of Agron., Madison, Wis. U.S.A.

Viets, F.G., Jr. 1967. Nutrient availability in relation to soil water. In R.M. Hagan, H.R. Haise, and T.W. Edminster (eds.) Irrigation of agricultural lands. Agronomy 11:458-471. Amer. Soc. of Agron., Madison, Wis. U.S.A.

Warkentin, B.P. 1970. Soil physical properties. Syllabus of lectures. Dept. of Soil Sci. McGill Univ., Montreal, Canada.

Welch, L.F., D.L. Mulvaney, M.G. Oldham, L.V. Boone, and J.W. Pendleton. 1971. Corn yields with fall, spring, and sidedress nitrogen. Agron. J. 63:119-123.

Wetselaar, R. 1961. Nitrate distribution in tropical soils:I. Possible causes of nitrate accumulation near the surface after a long dry period: Plant and Soil 15:110-120.

Wetselaar, R. 1962. Nitrate distribution in tropical soils:III. Downward movement and accumulation of nitrate in the subsoil. Plant and Soil 16:19-31.

Whitehead, D.C. 1970. The role of nitrogen in grassland productivity. Commonwealth Bureau of Pastures and Field crops, Hurley, U.K. Bull. 48.

Wiersum, L.K. 1957. The relationship of the size and structural rigidity of pores to their penetration by roots. Plant and Soil 9:75-85.

Wilkinson, J.F., and D.T. Duff. 1972. Rooting of *Poa annua* L., *Poa pratensis* L., and *Agrostis palustris* Huds. at three soil bulk densities. Agron. J. 64:66-68.

Wit, C.T. de. 1970. Grondslagen plantaardige productie. (In Dutch) Syllabus of lectures. Theoretical production ecology, Agricultural Univ., Wageningen, The Netherlands.

Wit, C.T. de, and H. van Keulen (eds.) 1970. Simulation of transport processes in soils. Theoretical Production Ecology. Agricultural Univ., Wageningen, The Netherlands.

Woldendorp, J.W., K. Dilz, and G.J. Kolenbrander. 1966. The fate of fertilizer nitrogen on permanent grassland soils. Proc. 1st Gen. Mtg. Europ. Grassl. Fed. 1:53-76.

LUCTOR ET EMERGO