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Field Specific Nitrogen Fertilizer Requirement for Sugarbeet (Beta Vulgaris L.) Grown on a Misteguay Silty Clay Soil in Michigan

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FIELD SPECIFIC NITROGEN FERTILIZER REQUIREMENT FOR SUGARBEET (*BETA VULGARIS* L.) GROWN ON A MISTEGUAY SILTY CLAY SOIL IN MICHIGAN

By

Gladis M. Zinati

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ABSTRACT

FIELD SPECIFIC NITROGEN FERTILIZER REQUIREMENT FOR SUGARBEET (*BETA VULGARIS* L.) GROWN ON A MISTEGUAY SILTY CLAY SOIL IN MICHIGAN

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Optimum and economic sugarbeet production without polluting the environment requires an accurate estimate of the fertilizer N required. The main goal of this study was to develop a model that predicts N fertilizer needs by rain-fed sugarbeet grown on a Misteguay silty clay (fine, illitic (calcareous), mesic, Aeric Endoaquent) soil. In the development of the model temporal and spatial distribution of ^{15}N in the soil and temporal pattern of N uptake were measured. Long term aerobic laboratory incubation studies were conducted to measure cumulative net N mineralization and hence to predict cumulative net N mineralization in the field. Models predicting daily soil-water balance, daily N leached and daily uptake were developed. Root yields and quality parameters as affected by N fertilizer rates were evaluated. Nitrogen fertilizer efficiency was determined. Mineral N concentration was highest in the 30 cm depth after 1-week after application. At the point of application, atom % ^{15}N excess declined with time at all depths. Ten cm lateral movement of the tracer ^{15}N from point of injection was detected at 75 cm and 120 cm deep at 4-weeks after application. Nitrogen uptake and ^{15}N uptake by sugarbeet from various depths followed a typical S-shaped pattern. Percent N derived from the tracer as well as N uptake by sugarbeet were recovered from all depths but most effectively from the top 30 cm depth. Data from the cumulative net N mineralization (N_m) in laboratory incubation was fitted to linear and exponential models. Rates of mineralization in both models were adjusted for field air temperatures and values of N_m were corrected to soil moisture (W). Predicted cumulative net N mineralizations in the field were 92.9 and 120 kg ha^{-1} for 1993 and 1994 growing seasons, respectively. Estimated amounts of mineral N leached were 6.9 kg ha^{-1} for 1993 and 35.7 kg ha^{-1} for 1994. Both models predicted the field cumulative net N mineralized (N_t) well in both years. Root yield and recoverable sugar per hectare increased significantly as N rates increased reaching a maximum at 134 kg N ha^{-1}. Recoverable sucrose per megagram, % sucrose and clear juice purity (CJP) decreased with increased N rates applied in both seasons. Nitrogen fertilizer needs model took the form: $N_f = [N_{up}(\text{opt}) - e_m (N_t + N_{min})]/e_f$. N_{up} (opt.) was higher (217 kg ha^{-1}) in 1994 than that in 1994 (178 kg ha^{-1}). e_m was 0.83 in 1993 whereas 0.65 in 1994. e_f was 0.62 in 1993 and 0.82 in 1994. N_{min} was 43.9 and 55.3 kg ha^{-1} in 1993 and 1994, respectively. This work suggests that for optimum returns N fertilizer requirement for sugarbeet, N_f, is 103 kg ha^{-1} in moderate weather years and 126 kg ha^{-1} in wet or humid years.

DEDICATION

Since I was a little girl I always had the feeling that I will discover something very important and precious. Years passed, I grew up and that feeling never left me. I did not know what I will discover but I kept looking. I traveled thousands miles. I left my home country, Lebanon, in 1990 to pursue a Ph.D. degree in Crop and Soil Sciences at Michigan State University. Evidently, I found that I was not only working towards the degree but also searching for what I should discover.

Finally, I found the most precious, priceless treasure I was looking for.

I found

THE TRUTH
I AM WHO I AM

Dear Lord,
I dedicate this piece of work to YOU- ALMIGHTY.

For there is no one in this universe would give me what you give me
and accept me as I am. YOU are with me from the beginning of my life,
YOU protect me and nurture me with YOUR Love and Kindness.
YOU never leave me even when I leave YOU.
YOU love me unconditionally, bless me with Knowledge, Wisdom, Health, Wealth and Protection.
YOU are so gentle and never force yourself on me, but YOU let me know YOU,
taste YOU and accept YOU with my own free will.

My Lord, my heavenly Father, I thank YOU for teaching me Forgiveness, Love, Patience, Obedience, Joy and above all Trusting in YOU. YOU give me eyes to see and ears to hear THE TRUTH. YOU let me understand who I am and why I am here on earth. Thank YOU for always BEING with me, surrounding me with YOUR Holy Angels and for my Guardian Angel Leelayo who all minister to me.

My God, finding YOU is a treasure. May YOU Lord continue with me to submit myself to YOU completely with all my mind and all my heart. To be YOUR "Follower" is what I am aiming for. It is a title that I would be proud to carry and be known for.

With proud, Lord I dedicate this work to YOU and hope it will be a doorway to Eternity.

ACKNOWLEDGMENT

"Tomorrow is the first day of the rest of your life, what do you want to do?", Dr. Christenson said to me one day. These words had deep meaning and were the turning point in my life. I am indebted to you, Dr. Donald Christenson, my advisor and committee member, for your mentoring, patience, moral and financial support, time and input you showed during the years I worked with you.

I am thankful for my committee members: Dr. Boyd Ellis, Dr. Darryl Warncke and Dr. Irvin Widders for their time, effort and interest throughout the completion of my dissertation.

My gratitude to Dr. Dave Harris who was the raw model for patience, kindness and simplicity. Thank you for the unlimited hours of analytical and technical support and for training me to use the mass spectrophotometer for this project. I am also thankful to Dr. Joe Ritchie for helping me on the water balance model that was an integral part of the project.

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Chapter 1

GENERAL INTRODUCTION

Nitrogen is an essential constituent of proteins, amides, amino acids, coenzymes, nucleic acids, certain hormones and chlorophyll of plant cells. In sugarbeet (*Beta vulgaris* L.), N is important in sucrose synthesis and in many reactions involving the utilization of sucrose as an energy source for plant growth and cell maintenance. Insufficient N limits yield while excess N (higher than 180 kg ha^{-1}) reduces recoverable sugar by suppressing sucrose concentration and increasing impurities in the sugarbeet juice (Hills and Ulrich, 1971). Decreased root sucrose concentration with increased N application is generally attributed to the tops becoming the dominant photosynthate sink at the expense of the roots. Increased impurities may result from many factors but are generally associated with higher N uptake that increases the nonsucrose, soluble solids (Carter, 1985).

Nitrogen taken up by sugarbeet during the season comes from mineral N present in the spring, N mineralized during the growing season and fertilizer N. Determination of the amount of mineral N and N mineralized during the growing season is essential in designing fertilizer N recommendations which provide adequate but not excessive N. Mineral N can be assessed with routine extraction by M KCl. Estimation of mineralizable N is usually done by conducting a laboratory incubation under standard conditions. However, these types of studies are not readily applicable to routine soil testing for fertilizer recommendations.

The manner in which N is mineralized during incubation may follow one of four patterns (Tabatabai and Al-Khafaji, 1980): i) immobilization of N during the initial period of incubation followed by mineralization in the later period; ii) a rate of release that decreases with time; iii) a steady linear release with time over the whole period of incubation, or iv) a rapid release during the first few days followed by a slower linear rate of release.

Models describing the latter two patterns have received the most attention in the literature. Obviously, iii above is a linear (zero order) equation and can be fit with linear regression. This model gives a rate of release, but does not give a value understood to be mineralization potential. Addiscott (1983) and Tabatabai and Al-Khafaji (1980) found linear relationships N mineralized and time. The latter authors reported an average Q_{10} of 3.0 for N mineralization of some major soil series in Iowa. However, Beauchamp et al. (1986) suggested that Tabatabai's data showed some curvilinearity during the early stages of incubation.

Stanford and Smith (1972) used a first order exponential equation to describe mineralization on a wide range of soils. They used a first-order exponential equation: $N = N_o (1- \exp(-kt))$ which estimated mineralizable N with respect to time, rate of mineralization (k) and N mineralizable potential N_o. Beauchamp et al. (1986) modified this equation to take into account an "easily" mineralized N fraction (Ne) often seen during the incubation of air dried soil. The model took on the form N = [No - (No- Ne) exp (-kt)], where N, No, k and t are defined as before and Ne is the N fraction released during the first 7 days of incubation. This N released (Ne) is attributed to microbes killed as a result of drying the soil (Richter et al., 1982). However, Beauchamp et al. (1986) attributed Ne as an experimental artifact and not part of the true No. Consequently, they concluded that their model allowed for the existence of this fraction and thereby gave a better fit of the first order rate model with the experimental data. They further suggested that either their model be applied with air-drying pretreatment or freezing or field-moist pretreatments should be considered to provide better accuracy.

Using a mass balance approach for evaluating N availability to crops requires measurement of losses as well as assessment of mineralization. Nitrogen may be lost from soil from soil through denitrification, NH_3 volatilization, leaching and erosion (Stevenson, 1986). Armstrong et al. (1986) noted that denitrification and leaching may cause loss of NO_3-N before it is taken up by the crop. Leaching is generally greatest during cool seasons when precipitation exceeds evaporation when downward movement in summer is restricted to periods of heavy rainfall. The magnitude of NO_3 leaching is difficult to estimate and depends on a number of variables, including quantity of NO_3, amount and time of rainfall, infiltration and percolation rates, evapotranspiration, water holding capacity of the soil and presence of growing plants (Stevenson, 1986). Shaffer et al. (1991) developed a N leaching model that estimates the daily soil N potential for leaching. The model required initial mineral N present and daily estimates of water drained, N mineralization and N uptake by the plant.

An accurate estimation of fertilizer N is required for optimum and economic sugarbeet production without polluting the environment. This estimation requires prediction of N supply from soil organic matter as well as soil N losses. Models for predicting fertilizer N requirement for use in N recommendations for sugarbeet under Michigan conditions are not yet developed.

This study examined field specific N fertilizer requirement for rain-fed sugarbeet grown on a Misteguay silty clay soil in Michigan. Specific objectives of this study were to:

1. determine the temporal and the spatial distribution of applied ^{15}N fertilizer in microplots on a Misteguay silty clay soil.
2. determine the temporal uptake of N by sugarbeet from various depths.
3. determine the efficiency of fertilizer recovery using non-isotopic linear regression and isotopic methods.
4. predict cumulative net N mineralization in the field from a long term aerobic laboratory incubation study.
5. predict N fertilizer needs by sugarbeet grown under rain-fed conditions on a Misteguay silty clay soil in Michigan utilizing:
    a. daily soil-water balance
    b. daily soil N leached
    c. daily N uptake by sugarbeet
    d. daily net N mineralization.

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Chapter 2

TEMPORAL AND SPATIAL DISTRIBUTION OF ^{15}N TRACER AND TEMPORAL PATTERN OF ^{15}N UPTAKE BY SUGARBEET FROM VARIOUS DEPTHS

Assessment of nitrogen fertilizer needs for sugarbeet requires a knowledge of the amount of N available from the soil profile and specially below the plow layer. Sander (1974) suggested that nitrate in the soil profile occurs primarily from unused or carryover N fertilizer. The amount of N released from the more stable organic matter complex in soils varies greatly from soil to soil depending on past cropping history, weather and other factors. Furthermore, the amount of NO_3-N that accumulates will vary greatly depending on precipitation, irrigation practices and application methods. Armstrong et al. (1986) mentioned that the contributions of residual mineral N and mineralized N to the total N uptake by sugarbeet vary considerably with soil type and season. Kaiser and Heinemeyer (1993) found that the soil surface layer is the most biologically active site for agricultural ecosystem processes. Soil near the surface is exposed to the largest nutrient and energy inputs and undergoes larger diurnal and seasonal changes in temperature and moisture than the deeper underlying soil. These factors have a considerable influence on soil microorganisms.

We further need to know the temporal distribution of this uptake since excessive N late in the season may be very detrimental to the final yield of sugar. Baldwin and Davis (1966) noted that excess N fertilizer applied would result in a lower sucrose content. Studies by Last and Haggard (1985) indicated that irrigated sugar beets had reduced amino-N concentrations which could be attributed to moist soil conditions that allowed N to be taken up and used for growth during summer. However, in unirrigated crops N was taken up later in the growing season and was stored in the root as amino nitrogen. Anderson et al. (1972), utilizing ^{15}N, showed that sugarbeet took up more N from deeper soil layers if the surface soil NO_3 concentration was low. They also found out that sugarbeet could effectively use NO_3-N from depths greater than 135 cm. They indicated that N fertilization management must be optimized to maximize sucrose content as well as root biomass yield. Waern and Persson (1982) examined N uptake by oats grown on heavy clay soil in Uppsala, Sweden, using ^{15}N labeled NO_3-N that was placed on soil surface and at depths of 25, 70 and 110 cm. Their results showed that the above ground portion of oat plants removed ^{15}N labeled N from 25 cm deep one month after sowing, from 70 cm seven weeks after sowing and from 110 cm deep before harvest. About 80 percent of labeled nitrogen placed on the surface and at a 25 cm depth was recovered in the above ground portion of the plants at harvest. Sixty and 45 percent of nitrogen placed at a depth of 70 cm and 110 cm was recovered at harvest, respectively. As described by Linden (1981 and 1982), the utilization of mineral N in deeper layers in the soil profile depends on root depth which is closely connected with the soil structure in the horizons in question. Also when uptake has ceased, soil mineral N reserves usually were depleted down to one meter in loam and clay soils. He also reported that for winter wheat and sugarbeet, N has often been utilized down to 1.5m.

Linden (1980) found that the largest concentrations of NH_4NO_3 were in the top soil (usually 5-20 kg ha^{-1} within 0-20 cm). In the subsoil there were generally small amounts of NH_4NO_3 which didn't vary appreciably with depth. Ventura and Yoshida (1978) found very little movement of ^{15}N labeled NH_4-N from the site of placement. They concluded that the availability of N from point-placed fertilizer was restricted mostly to the rice plants adjacent to the point of placement. Panda et al. (1988) studied the vertical and horizontal movement of N (100 kg ha^{-1}) in flooded soils. They applied N as broadcast urea or urea supergranules placed near the rice transplants. The surface-broadcast N was found mostly in the top 5 cm of soil and there was a small vertical movement of N to 5-10 cm. With broadcast applications, the NH_4- N concentration was 40-68 mg kg^{-1} soil in the top 0-5 cm of soil within the first 3-6 days, decreased at a faster rate from the 6^{th} to 12^{th} day and then at a slower rate up to the 32^{nd} day. With point placement of 1-g urea granules, the fertilizer N was found mostly at the 5-10 cm depth and within 2.5 cm horizontal distance from point of placement, compared with 5 cm for 2.5-g granules.

Barber (1962) and Savant and De Datta (1979) reported that the transport of NH_4 in soil was a diffusion-controlled process. Reddy et al. (1980) reported that movement of NH_4-N was along a concentration gradient, but the diffusion coefficient was very low compared with nitrate. This might explain the slight upward and downward or lateral movement of N from point-placed urea supergranules. Any latter movement was proportional to the amount applied. The disappearance of NH_4-N from the region of placement might be attributed mainly to plant uptake but might also be due to diffusion, convection and fixation by clay minerals (Savant et al., 1982). Owing to the limited mobility of N from point-placed urea supergranules, it would be necessary to ensure uniformity of placement for the benefit of the rice crop. Savant and De Datta (1980) studied the in-situ distribution patterns of NH_4-N and ^{15}N uptake by wetland rice in a dry season. Two-gram urea supergranules were placed at 5-, 10-, and 15-cm soil depths in wetland rice plots. The ammonium concentration gradients near placement sites showed that the NH_4 movement was slow and in general, downward > lateral > upward from deep placement sites of urea supergranules in a wetland Maahas clay. Ammonium concentrations decreased with time largely due to plant uptake and the ^{15}N uptake followed the S-shaped pattern.

Studying the distribution patterns of ^{15}N in the soil was accompanied by certain assumptions such as, the tagged N was uniformly mixed with soil and was distributed throughout the layer where the labeled N was applied. The work here is designed to measure the distribution after application at a confined spot. In addition, studying the temporal pattern of N uptake by sugarbeet would aid in knowing when, how much and at what rate the plants were absorbing N from soil. Therefore, the present experiments were designed to study the 1) the temporal and spatial distribution of ^{15}N tracer applied at different depths and 2) the temporal pattern of uptake of N by sugarbeet from various application depths.

MATERIALS AND METHODS

Study Site

Studies to determine the dynamics of applied ^{15}N fertilizer in soil and its uptake by sugarbeet were conducted in 1991 at the Saginaw Valley Bean and Beet Research Farm in Saginaw county, Michigan (43° 4' N, 84° 6' W). The soil is classified as a Misteguay silty clay (fine, illitic (calcareous), mesic, Aeric Endoaquent).

Cultural Practices

In both experiments, the soil was fall plowed to 22 cm depth in 1990. It was tilled once with a field cultivator to 7 cm deep in spring of 1991. Ammonium nitrate (34-0-0) was surface broadcasted to plots at planting time at a rate of 90 kg ha^{-1}. Sugarbeet (Mono-Hy-E-4) were planted in 71 cm rows on May 3rd of 1991 and thinned to 20 cm within row spacing.

Temporal and Spatial Distribution of ^{15}N in Soil

Microplots 40.3 x 80.6 cm in size containing 4 sugarbeet plants were established. Seven holes were dug in each microplot using a soil probe of 2 cm diameter. These holes were spaced 10 cm around the two middle sugarbeet plants in each microplot. One month after planting 10 ml solution of 7 mg of ^{15}N concentration, as an equimolar of $K^{15}NO_3$ and $(^{15}NH_4)_2SO_4$ (99.7% ^{15}N), was applied in each hole (Figure 1). The ^{15}N was applied at 30, 75 and 120 cm deep in a randomized complete block design with 4 replications. Subsoil was used to refill the holes upon ^{15}N application. Soil samples with and without ^{15}N were collected from the south side of the microplot (Figure 1).

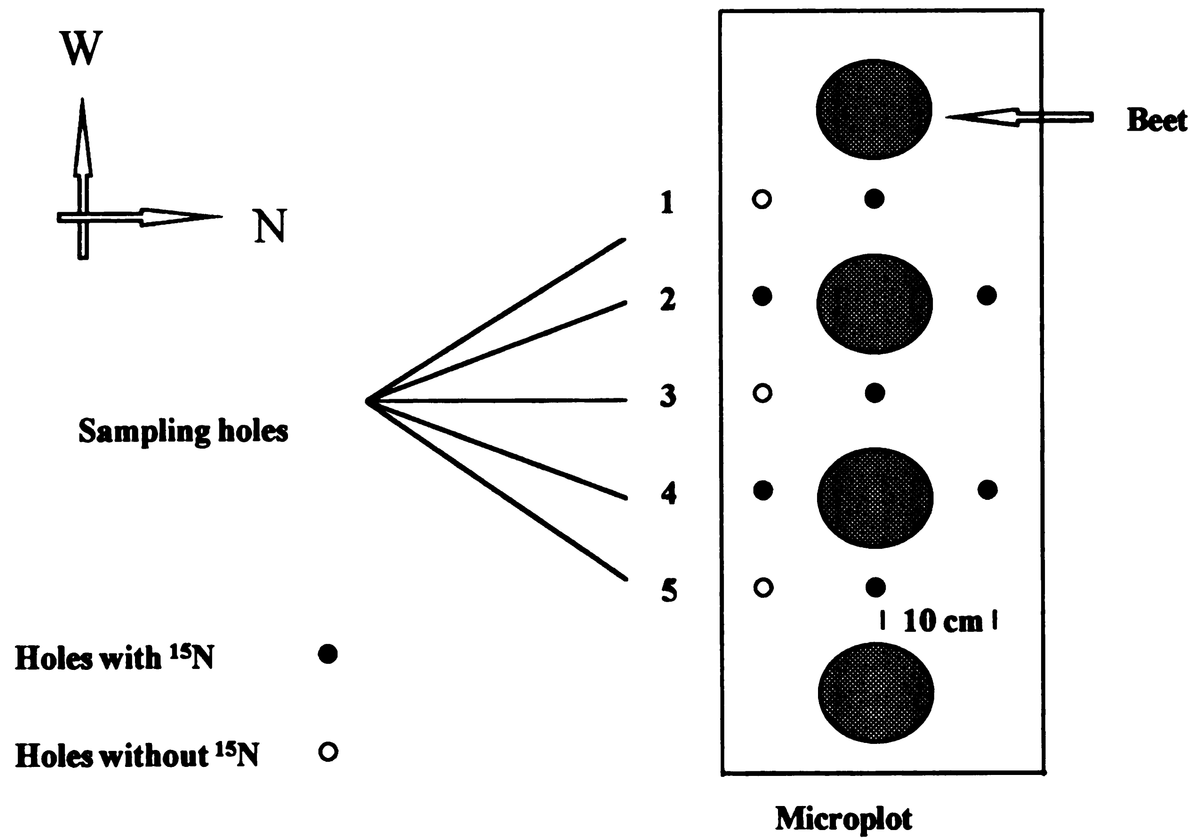

Figure 1. Schematic diagram of a microplot containing four sugarbeet plants and holes with and without ^{15}N tracer applied in 1991.

These samples were taken from 15-45, 60-90 and 105-135 cm depth on the 1st, 4th and 12th week after application. The four adjacent plants in each microplot were harvested in the first week of October of 1991. Soil samples and sugarbeet plants were processed and analyzed as described in plant and soil processing and analysis procedures section.

Temporal Pattern of N Uptake by Sugarbeet

A second study was conducted to determine the temporal pattern of N uptake by sugarbeet. Ten ml of a solution containing 7 mg of N of an equimolar mixture of $K^{15}NO_3$ and $(^{15}NH_4)_2SO_4$ as ^{15}N (99.7%) was placed in each of 4 holes dug in microplots containing 1 sugarbeet plant (Figure 2). These holes were spaced 10 cm from the sugarbeet plant. Labeled N, ^{15}N, was applied one week before each plant sampling. It was applied at the surface, 30, 60, 90, 120 and 150 cm depth in a randomized complete block design with 6 replications. The surface treatment had a metal frame 20 cm x 20 cm installed to a depth of 12 cm. Plant samples were collected 3, 6, 9, 12, 15 and 18 weeks after planting. One plant per microplot per treatment was harvested. The collected plants were processed and analyzed as described below in the following section.

Plant and Soil Processing and Analysis

Soil samples and plant material were handled and analyzed similarly in all experiments of this chapter and the following studies.

Soil preparation and analysis

Soil samples were air-dried, ground to pass through a 2 mm sieve. Ten grams of ground soil was shaken with 50 ml of M KCl (Keeney et al. 1982) for 1 hour and filtered through a Whatman #5 filter paper. The extracts were split into two parts. One part was

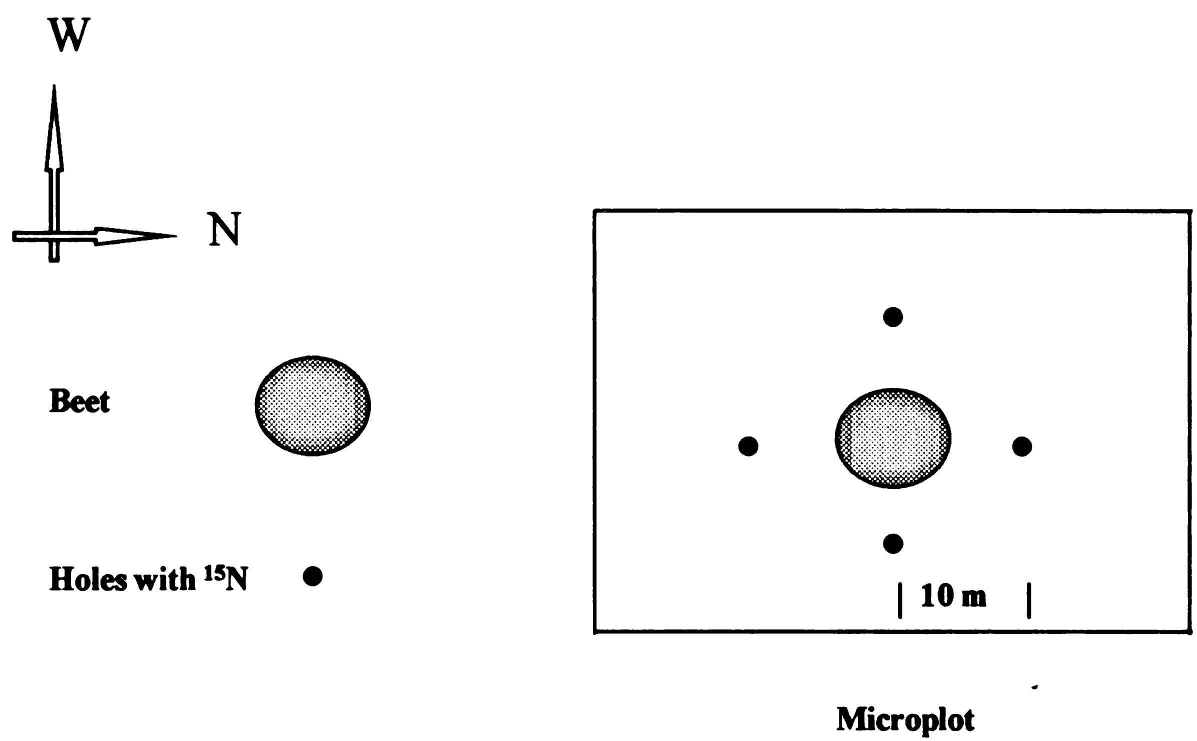

Figure 2. Schematic diagram of a microplot containing one sugarbeet plant and four holes with ^{15}N tracer applied in 1991.

used to analyze for mineral N (NH_4 and NO_3) using an Flow Injection Analyzer (Prokopy, 1993). The other part of the extract was used to determine ^{15}N atom % on a mass spectrometer. This was achieved by a diffusing technique presented by Brooks et al. (1989). In this technique Davardas alloy was used to reduce NO_3-N in the extracted sample to NH_4-N and volatalize it by increasing the solution pH with MgO. The ammonium was trapped on a $FeSO_4$ impregnated paper disc. At the end of the 7th day of diffusion the discs were dried at 65 °C and pelleted in tin capsules for analysis.

Plant processing and analysis

Sugarbeet plant samples were split into leaf, petiole and root. The leaves and petioles were washed in water, dried at 60 to 65 °C, weighed, ground to pass through a 0.5 mm screen. The fresh weight of each whole root was recorded. A root sub-sample was taken by cutting the whole root in half and scrapping approximately 50 g of beet tissue from the exposed face of the sugarbeet. Root dry weight was calculated from the wet and dry weights of the 50 g subsamples and the fresh weight of the root. Dried sub-samples were ground and saved for analysis. A ground plant sample containing 100 mg of N was pelleted in tin capsule for ^{15}N atom % analysis.

RESULTS AND DISCUSSION

Temporal and Spatial Distribution of ^{15}N in Soil

Mineral N concentration declined at all depths for the 1- and 12- weeks samplings (Table 1). At the 30 cm depth N declined from over 14 mg kg^{-1} to less than 6 mg kg^{-1} between one and 4 weeks after application. There was no further decline at this depth by week 12. There was a similar decline at 75 cm ranging from 10 mg kg^{-1} to less than 2 mg kg^{-1} between 1- and 12-weeks after application. The decline with time at 120 cm was less pronounced than at the other depths.

Table 1. Mineral N concentration (mg kg^{-1}) at 30, 75 and 120 cm deep on soil samples taken at 1-, 4- and 12-weeks after application on a Misteguay silty clay soil.

	Depth (cm)		
Sampling	30	75	120
1- week	14.22	9.85	6.47
4-weeks	4.28	6.24	4.45
12-weeks	5.49	1.93	2.63

$LSD_{(\alpha = 0.05)} = 4.043$

Atom percent excess one week after application was less in the 30 cm layer than in the lower depths (Figures 3-5). At point of application atom % ^{15}N excess declined with time at all depths (Figures 3-5). This could be attributed to several reactions involving N. Among these were mineralization-immobilization-turnover, leaching, denitrification, fixation in clay minerals and plant uptake. While there are no data to support any one of these pathways, it would seem that any of these mechanisms could play a major role in this decline. One of the objectives of this work was to determine lateral movement of tracer ^{15}N from point of injection with time. Ten cm lateral movement of ^{15}N from point of injection was detected at 75 and 120 cm deep at the 4-weeks after application sampling (Figures 4 and 5).

Temporal Pattern of N Uptake by Sugarbeet

Nitrogen uptake curve followed the typical S-shaped pattern for plant growth when total N uptake by sugarbeet from various depths was plotted against time of sampling (Figure 6). The rate of N uptake increased markedly between 3 and 6 weeks after planting and held somewhat constant until 15 weeks after planting when uptake of N was ceased. Fifteen weeks after planting (3rd week of August 1991) marked the period when the sugarbeet began to direct energy to storage of sugar rather than vegetative growth. There was senescence of older leaves and leaf loss due to mechanical damage which might account for the small decline in total N between 15 and 18 weeks.

Uptake of ^{15}N was negligible at all depths up to 6 weeks after planting (Figure 7). After that point there was a general increase in the amount of ^{15}N uptake until the 12 weeks after planting at all depths. Nine weeks after application, the plants picked ^{15}N from the surface more significantly than deeper depths. Uptake of ^{15}N reached maximum by the 12th week after application in the top 90 cm soil layer. Although there was a

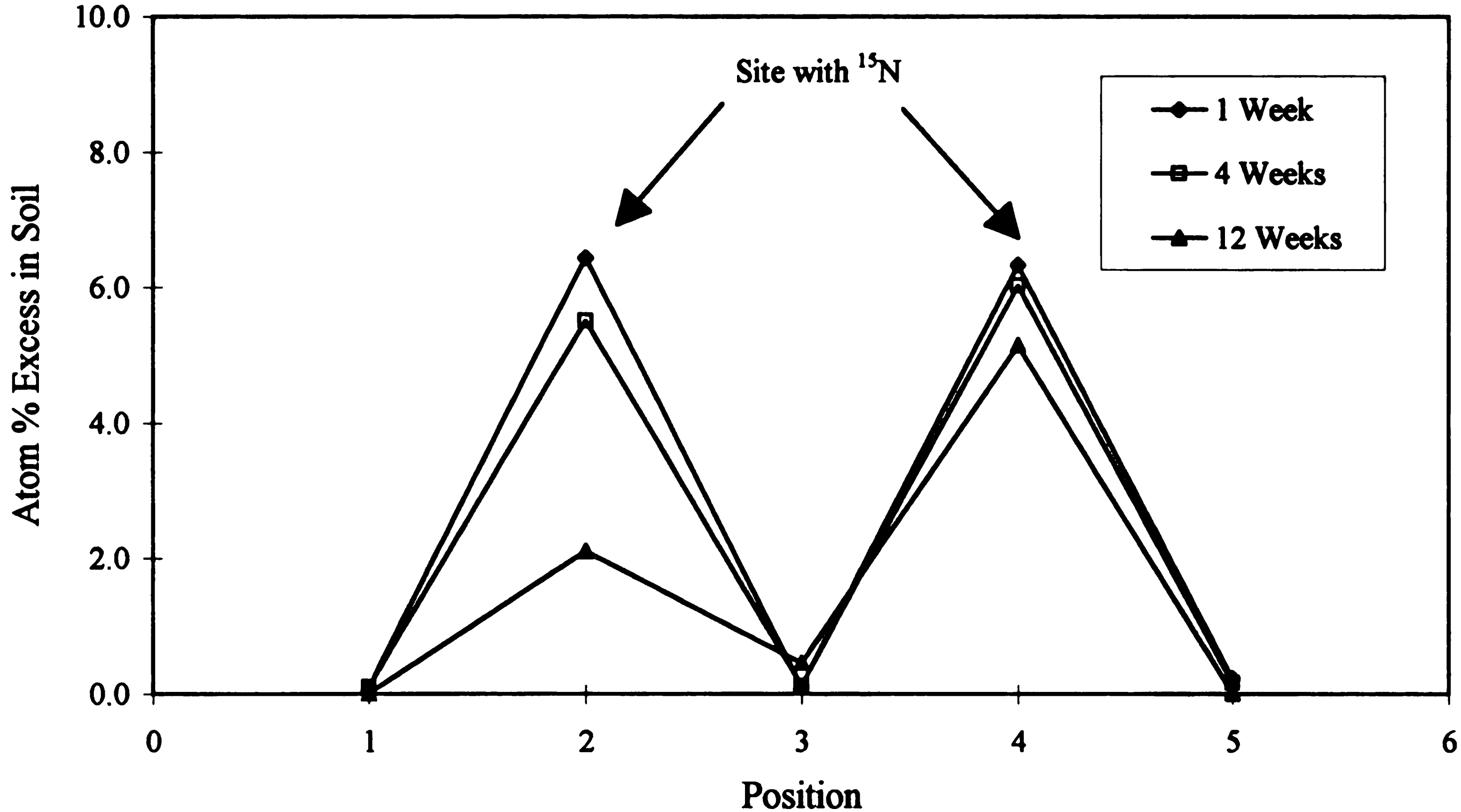

Figure 3. Atom percent ^{15}N excess in mineral N at the 30 cm depth, 1, 4 and 12 weeks after ^{15}N application on Misteguay silty clay soil in 1991.

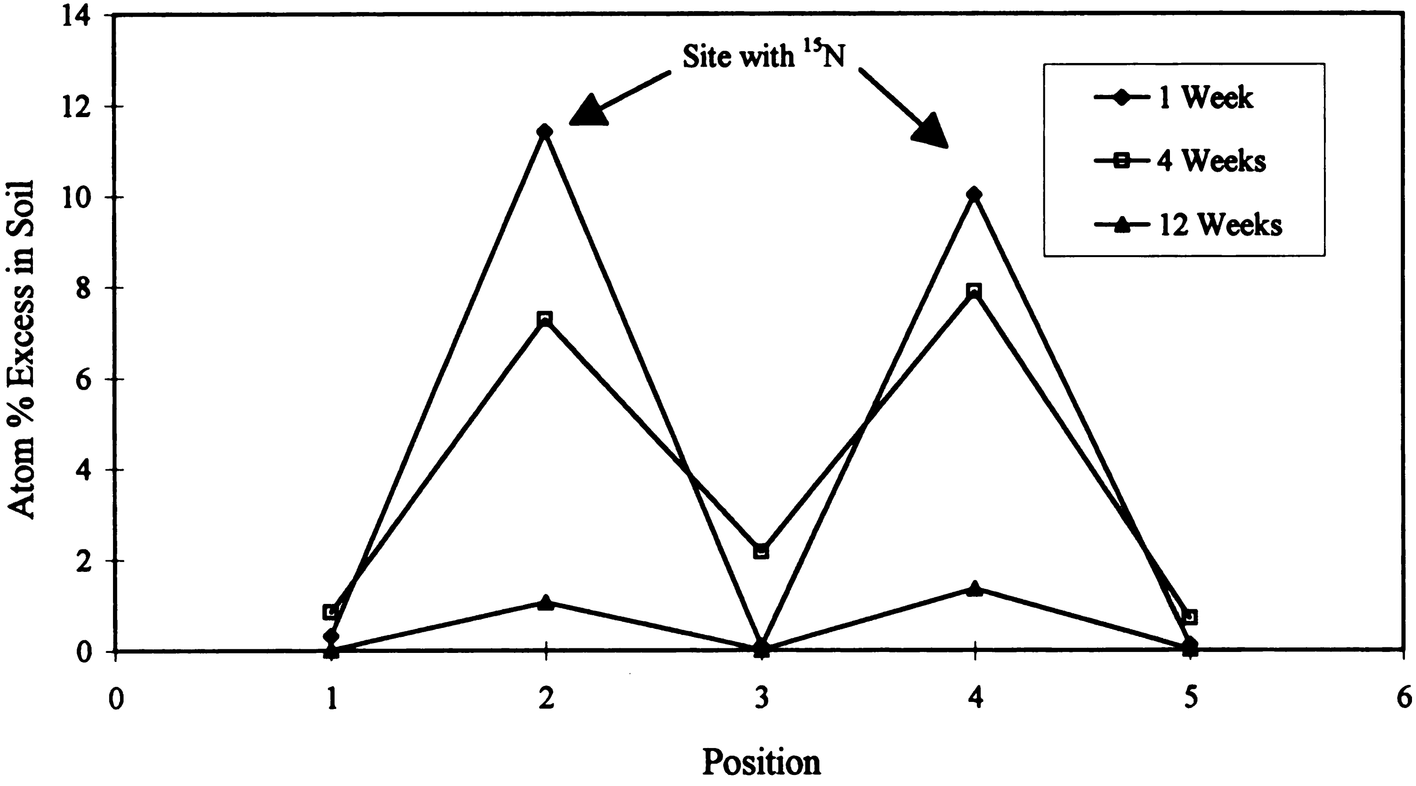

Figure 4. Atom percent ^{15}N excess in mineral N at the 75 cm depth, 1, 4 and 12 weeks after ^{15}N application on a Misteguay silty clay soil in 1991.

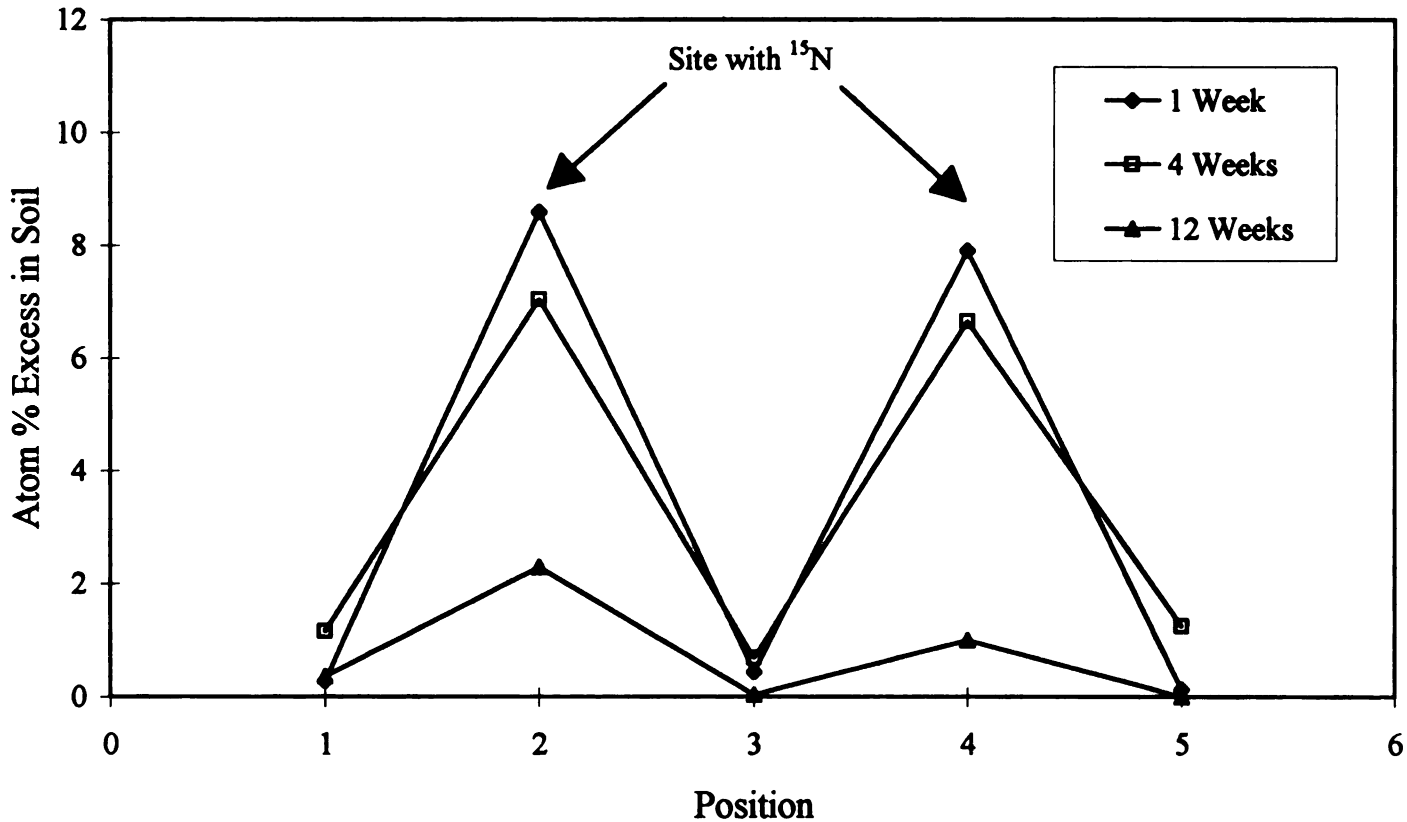

Figure 5. Atom percent ^{15}N excess in mineral N at the 120 cm depth, 1, 4and 12 weeks after ^{15}N application on a Misteguay silty clay soil in 1991.

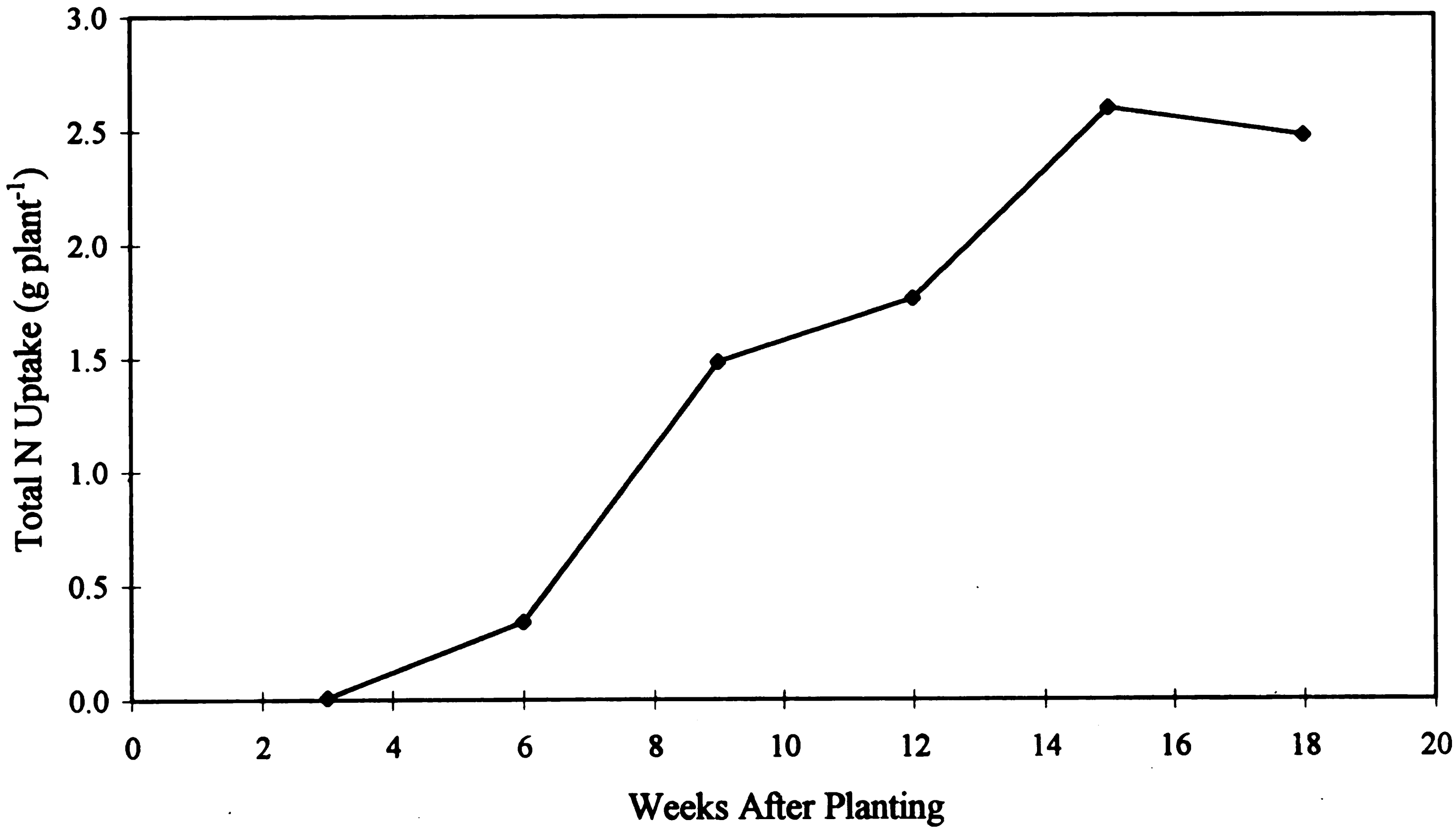

Figure 6. N uptake by sugarbeet grown on a Misteguay silty clay soil in 1991.

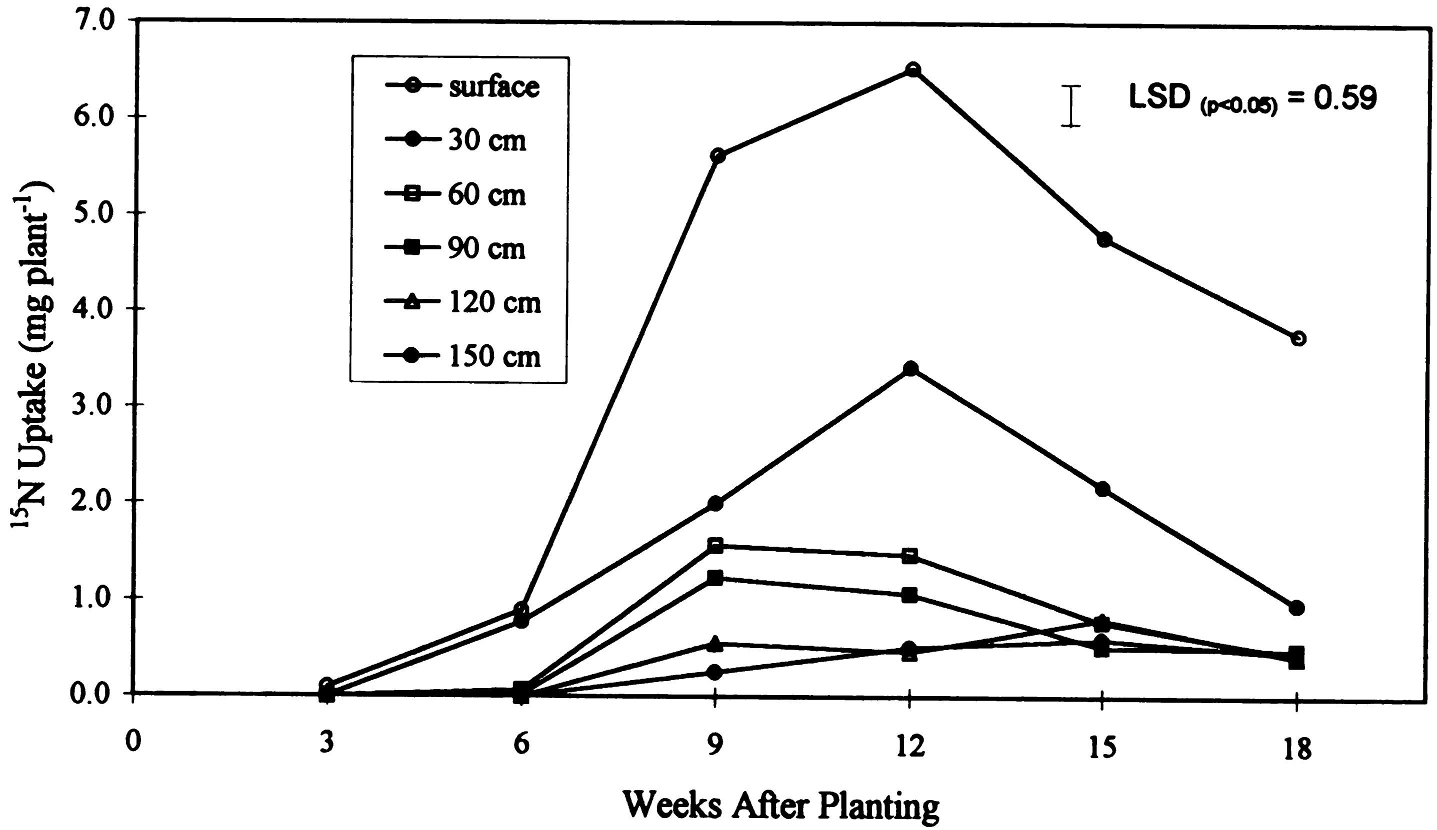

Figure 7. Tracer ^{15}N uptake by sugarbeet grown on a Misteguay silty clay soil in 1991.

significant decline in ^{15}N uptake from the top 30 cm layer sugarbeet continued to pick ^{15}N from deeper layers between 12th and 18th weeks after application. This decline could be due to the dry period between July 26 and August 16 (Christenson et al., 1991) and/or the roots were more active in exploring more soil volume at deeper layers than at the top 30 cm layer. In general, uptake from the surface applied ^{15}N was somewhat greater than for the other depths and there was no significant difference in the amount of tracer taken up from depths greater than 30 cm after the 2nd sampling. Uptake of ^{15}N by sugarbeet followed the typical S-shaped pattern. This is in agreement with the findings reported by Savant and de Datta (1980) on ^{15}N uptake by rice. Comparing the patterns total N uptake and ^{15}N uptake we found that they were similar.

Percent N derived from tracer ^{15}N applied at various depths was shown in Figure 8. At 3 weeks after planting there was a higher amount derived from the surface with a negligible quantity from the 30 cm depth. From week 6 through week 15 there was a fairly constant amount derived from the surface applied tracer. The amount from the 30 cm depth increased from the 3 week level across weeks 6 through 12. In the last two samplings, there were negligible amount from 30 cm and below. Therefore, sugarbeet plants recovered ^{15}N most effectively from the surface layer throughout the growing season and from the top 30 cm layer between the 2nd and the 4th samplings.

Percent N taken up by sugarbeet from various depths was plotted against time of sampling (Figure 9). N uptake was primarily from the surface after 3 weeks of planting and from the top 30 cm layer at 6 weeks after planting. This pattern continued till end of the season. However, 18 weeks after planting N uptake was almost equal from each layer.

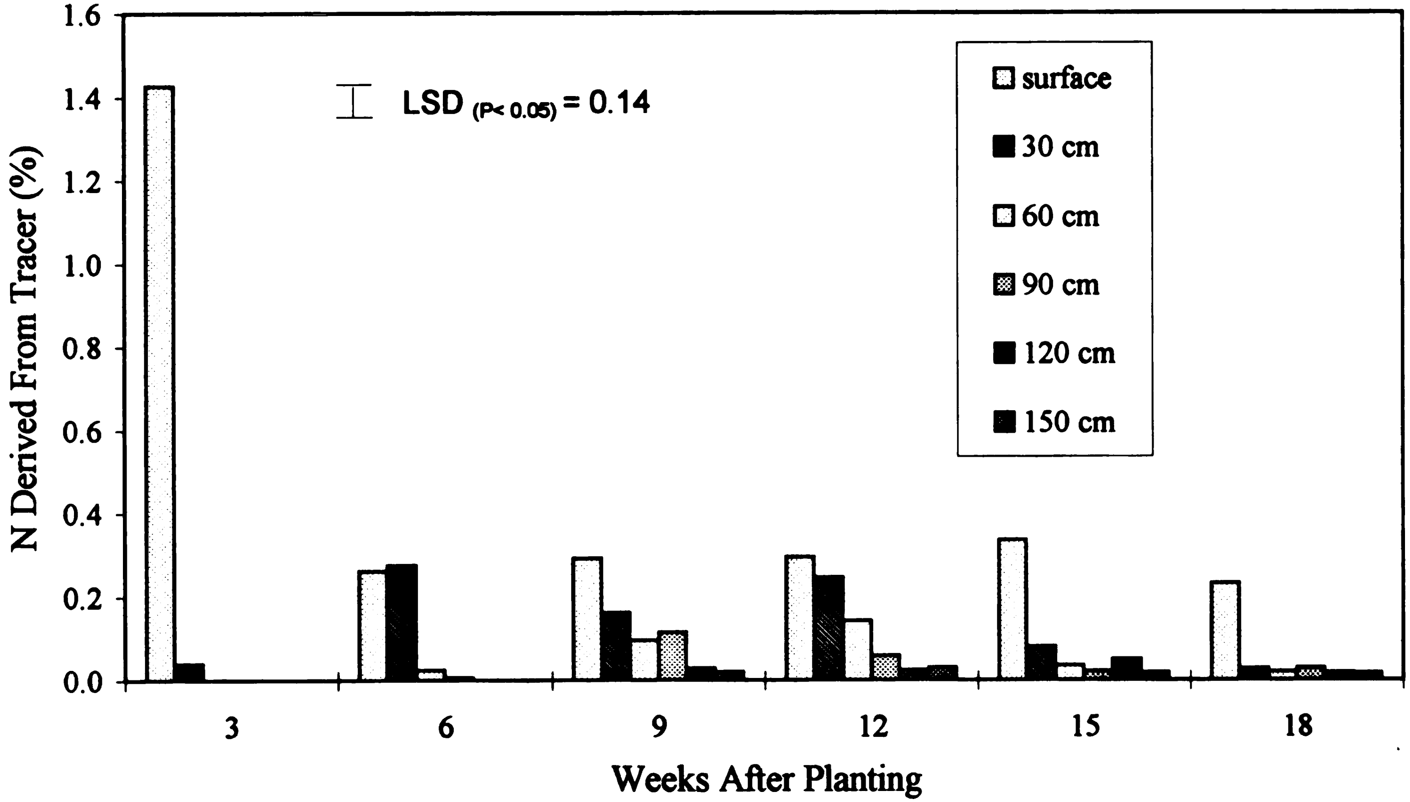

Figure 8. Percent N derived from tracer ^{15}N applied at various depths on a Misteguay silty clay soil in 1991.

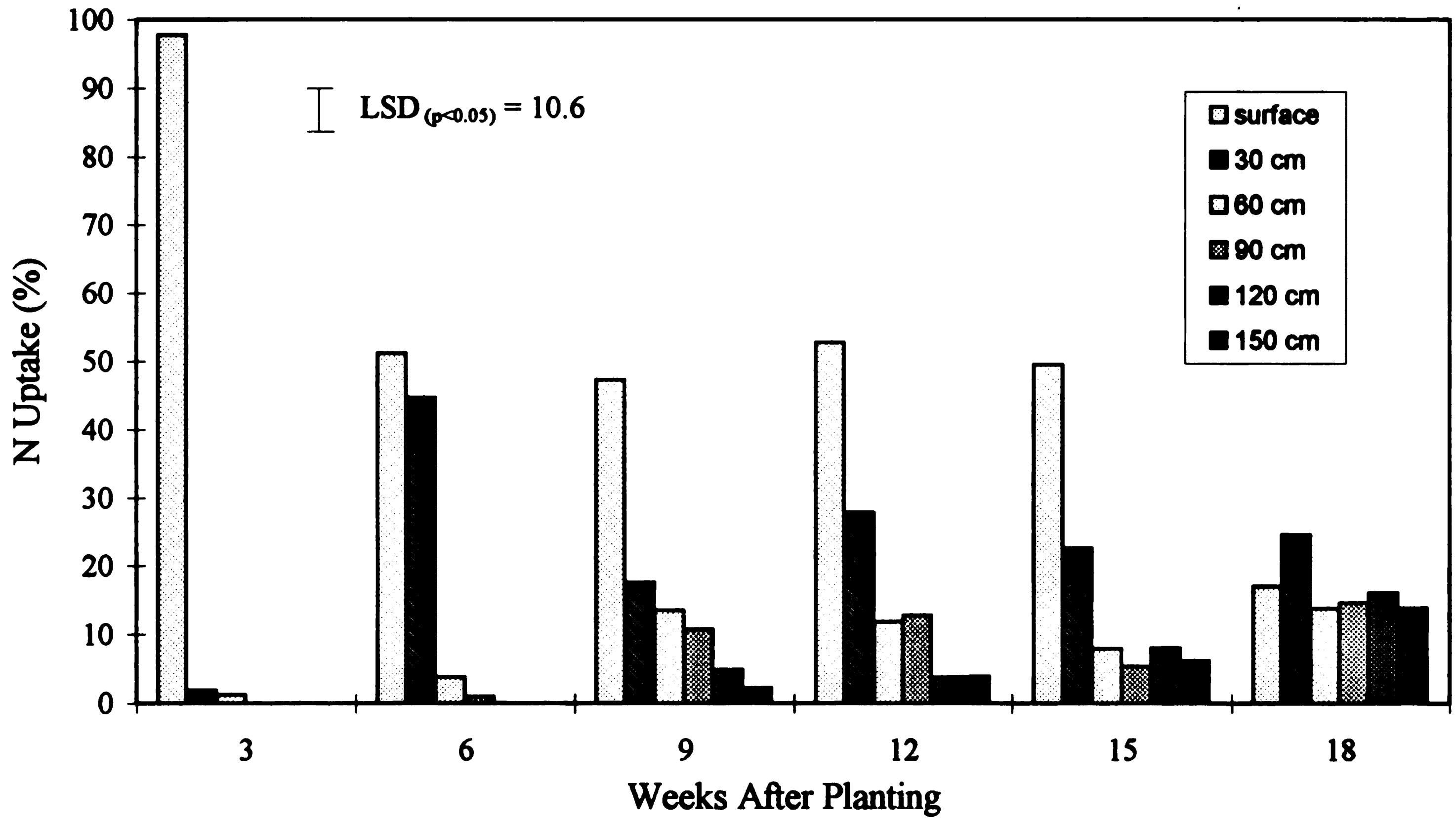

Figure 9. Percent N uptake by sugarbeet from various depths on Misteguay silty clay soil in 1991.

SUMMARY

Results of temporal and spatial distribution of ^{15}N in soil experiment showed that soil mineral N was highest in the 30 cm depth after 1-week after application. It decreased with time at all depths except at 4-week sampling (Table 1).

Ten cm lateral movement of the tracer ^{15}N from point of injection was detected at deeper depths at 4-weeks after application. Atom % ^{15}N excess in soil declined at all depths with time (Figure 3-5). Results of temporal pattern of N uptake by sugarbeet experiment showed that the total N uptake and ^{15}N uptake followed a typical S-shaped pattern.

Percent N derived from the tracer was recovered from all depths but most effectively from the top 30 cm depth. Percent N uptake by sugarbeet from various depths was mostly from the surface and 30 cm deep. Thus, these results suggest that while sugarbeet recover N from deeper depths, the N available in the top 30 cm is the most important in sugarbeet nutrition. These results, in part, agreed with Anderson et al. (1972) in that N was taken up by sugarbeet plants from deeper depths as 135 cm and with Kaiser and Heinemeyer (1993) in that the soil surface layer is the largest nutrient input to sugarbeet.

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Chapter 3

ESTIMATION OF CUMULATIVE NET N MINERALIZATION IN THE FIELD FROM A LABORATORY INCUBATION STUDY

Nitrogen fertilizer management is an important aspect of crop production practices because of the relatively large amount of N required by plants and N mobility in the soil. One of the first steps towards accurate N fertilizer recommendations is the ability to predict the quantity of N mineralized from soil organic matter which may be available for plant uptake. Matus and Rodriguez (1994) showed that N mineralized during a growing season comes from soil organic matter and recent organic inputs.

Two terms need to be defined, N mineralization and N immobilization. *Nitrogen mineralization* is defined as the transformation of organic N to NH_4, NH_3 and NO_3 ions. The process is performed by heterotrophic soil organisms that utilize nitrogenous organic substances as an energy source. *Nitrogen immobilization* is defined as the transformation of inorganic N compounds (NH_4, NH_3, NO_3, NO_2) into the organic state. Microorganisms and higher plants assimilate inorganic N by transforming it to organic N constituents of their cells and tissues, the soil biomass. The two processes work in opposite directions, building up and breaking down organic matter, respectively. The difference between the two processes will be a net effect, *net mineralization, or net immobilization* (Stevenson, 1985).

Bremner (1965) found that the reliability and reproducibility of methods for measuring soil N mineralization determine their suitability for assessing the potential ability of soils to provide N for crop growth. Control of water content during incubation was regarded as a major problem for soils having a wide range in water-holding capacities. Keeney and Bremner (1967) attained optimal water content by adding a constant level of water to the incubated soil samples. Stanford (1968) showed the existence of two general pools of organic N in soils. The first pool is decomposed relatively easily through microbial action. The second pool, however, is somewhat resistant to further rapid decomposition and contributes a small proportion of N mineralization during a short-term incubation or even within a cropping season. Keeney and Bremner (1966), Hanaway and Ozus (1966) and Cornforth (1968) found that both aerobic and anaerobic incubation gave values that correlated highly with N uptake by corn in the greenhouse (r^2 = 0.93 and 0.89, respectively). Similarly, Gasser and Kalembasa (1976) found a very high correlation (r^2 = 0.98) between N mineralized anaerobically (7 days, 40 °C) and aerobically, and these indexes correlated equally well with N uptake by ryegrass (r^2 = 0.93). Stanford (1982) reported that most of the earlier studies emphasized developing methods of soil N evaluation based on short-term incubation under controlled conditions and calibration with yield responses to field and greenhouse N. Westerman and Crothers (1980) found that using a buried polyethylene bag technique had potential for monitoring the soil N-mineralization process during the cropping season and for estimating N uptake by crops.

Indigenous available N is derived mainly from mineralization of soil organic matter (Biederbeck et al., 1984). It has been frequently observed that N mineralization is lower in fine-textured soils than in coarse-textured soils (Van Veen et al., 1985; Cartroux et al., 1975, Hassink, 1994). In addition, Bonde and Rosswall (1987); Bonde et al. (1988) and Clay and Clapp (1990) have reported increased N mineralization in soils supplied with fertilizer. When fertilizer N is added to soil, it interacts with the indigenous soil N sometimes increasing the mineralization of soil N, a phenomenon known as "priming effect" (Westerman and Kurtz, 1974, Domaar, 1975). Allison (1966), Azam et al. (1991) and Jenkinson et al. (1985) also showed in pot experiments that using increasing amounts of fertilizer N increased the amount of added N immobilized in the soil. An increase in the amount of soil N in the harvested crop has not always been evident. Coleman et al. (1983) showed that soil microbes play a key role in mineralization and immobilization processes because of their ability to serve as a source and sink of soil nutrients and as a "driving force" of nutrient availability. Ammonium rather than NO_3 is the N source preferred by microorganisms in the immobilization reactions in soil (Gainey, 1936; Rice and Tiedje, 1989).

Nielsen and Jensen (1986) postulated microbial immobilization as the main process explaining the disappearance of N soon after fertilizer application. Similarly, Messier et al. (1979) found that fertilizer N considered to be immobilized at the beginning of the growing season started to remineralize later during the season. Alexander et al. (1977) found that N immobilization in soil results from microbial assimilation of NH_4 and NO_3 into proteins, nucleic acids and other organic complexes contained within microbial cells. Only a small fraction (< 15%) of the N immobilized in organic forms usually becomes available to plants from one growing season to the next (Stevenson, 1986).

Stanford et al. (1974) showed that short term N mineralization may be heavily influenced by microbial biomass and recently incorporated residues relative to mineralizable fractions of soil organic N. The presence of high C:N ratio residue also affects the net mineralization that occurs in short-term incubations (Chichester et al., 1975). Fredrickson et al. (1982) showed that crop residues with a wide C:N ratio, when mixed with the soil, immobilize inorganic N from both fertilizer and soil sources. Studies by Wagger et al. (1985) showed that 15% of wheat residue N and 33% of sorghum residue N were mineralized after one cropping season. Net mineralization differences among these crop residues may be attributed to both the C:N ratio and chemical composition of these plant materials. Soil texture and the addition of fertilizer N influenced the initial rate of mineralization, particularly with wheat residue. Power and Doran (1988) indicated that N contained in crop residues can contribute a significant amount of N to the next crop and residues from leguminous crops often contribute substantially more than nonleguminous crops. The extent of decomposition of organic compounds in soil is greater with higher C mineralization rate as reported by Nyhan (1976) and Roper (1985) or with higher temperature (Pal et al., 1975; Kralova et al., 1980 and Donnelly et al., 1990). Norman et al. (1990) found that in soils where residues with low C:N ratios were applied there was less N recovered from the soil organic fraction at harvest. This was accompanied by larger amounts of N mineralized from residue. Kanamori and Yasuda (1979) investigated the mineralization and immobilization of tracer N ($K^{15}NO_3$) applied to soil together with two types of organic matters. They compared the decomposition rates of added herbaceous organic matter (e.g. rice straw and peat moss) vs. those of woody organic matter (sawdust and bark) in an incubation experiment for three months at 30 °C. With C:N ratio of 56, 44, 268 and 579 the decomposition rates were 41, 5, 7 and 5% for rice straw, peat moss, softwood-sawdust and softwood-bark, respectively. The data showed that the peat moss and bark were highly resistant to the action of microorganisms. Immobilization of N fertilizer incubated with organic matter was quite slow. Kirkham and Bartholomew (1954 and 1955) derived theoretical equations for following nutrient transformations in soil using tracer data. Immobilization of N from a homogenous inorganic N pool into which labeled N had been added and mineralization of N into the pool were used. The authors made three assumptions in their work for finding analytical solutions to the differential equations: (i) both isotopes of NH_4 and NO_3 behave the same in soil, (ii) immobilized labeled inorganic N is not remineralized and (iii) rates of immobilization and mineralization are constant during the interval between successive measurements. The differential equation derived for calculation of gross immobilization was: $i\Delta t = (AT_1 - AT_2)$ [ln (AL_1/AL_2)/(ln (AT_1/AT_2)] where $i\Delta t$ is the gross immobilization during an interval time, AT_1 is the total amount of labeled and unlabeled NH_4-N at start of interval time, AT_2 is the total amount of labeled and unlabeled NH_4-N at end of interval time, AL_1 is the labeled NH_4-N at start of interval time and AL_2 is the labeled NH_4-N at end of interval. Also, gross immobilization can be calculated as the difference of gross mineralization from net mineralization.

The effects of temperature and moisture factors on N mineralization and soil respiration have been studied simultaneously and several researchers found that there are interactions between these two factors (Wildung et al., 1975; Kowalenko and Cameron, 1976 and Cassman and Munns, 1980). However, Kladivko and Keeney (1987) indicated that soil N mineralization is not governed by temperature and moisture interactions. Ellert and Bettany (1992) indicated that N mineralization within individual growing seasons may be more sensitive to fluctuations in moisture and temperature than it is to the size of the mineralizable pool.

Gestel et al. (1993) concluded that soil drying and rewetting promoted the turnover of C derived from added plant material and that this increase in C cycling was mainly due to enhanced turnover of microbial products.

Smith et al. (1994) indicated that the degree to which plants can extract fixed NH_4 depended on the extent to which they lower NH_4 and K concentrations in the vicinity of the roots. In addition, their results indicated relatively little fixed NH_4 was released using conventional laboratory available N indexes. Further research needs to focus on quantifying the degree to which fixed NH_4 is available under actual crop growth conditions. Such information would help establish whether fixed N credits need to be used in conjunction with soil N tests.

Nitrogen Mineralization Potential (N_o)

Stanford and Smith (1972) presented the concept of soil N mineralization potential, N_o. N_o is a definable soil characteristic which may be of value in estimating N supplying capacities of soils under specified environmental conditions. Moreover, N_o provided a common basis for evaluating various chemical and biological availability indexes under a broad range of soil conditions for making quantitative estimates of N mineralization in the field. Mineralization potential was estimated from the cumulative amounts of N mineralized under optimal conditions of soil water and temperature based on the assumption that N mineralization obeyed the first-order kinetics' equation: $\log (N_o - N_t) = \log N_o - kt/2.303$. N_t denotes the cumulative amount of N mineralized during a specified period of incubation, t, and k is the rate constant.

Gianello and Bremner (1986) and Smith and Stanford (1971) showed that soil organic matter was not as good a measure of potentially available N as some chemical extraction methods. Cabrera and Kissel (1988a) showed that N mineralization potential was closely related to total amount of organic N and C in soils, but other studies showed no such relationship (Tabatabai and Al-Khafaji, 1980). Carlyle et al. (1990) identified organic P as an useful index of potentially mineralizable N for sandy soils. Simard and N'dayegamiye (1993) determined the N mineralization potential and mathematical models that can properly describe the dynamics of the mineralization process in 20 meadow soils from Quebec. The cumulative mineralization curves in most soils were characterized by a sigmoidal pattern and near-linear release with time after 20 wk. The total amount of mineralizable N and the potential mineralization rate were very closely correlated with the total amounts of C or N ($r^2 > 0.73$; $P < 0.01$).

Studies showed that soil N mineralization potential would be affected by climatic factors such as moisture supply and temperature (Cassman and Munns, 1980 and Myers et al., 1982). In addition, El-Harris et al. (1983) showed that there were large differences in N mineralization potential and rate of mineral N production for fall vs. spring soil sampling in the Pacific Northwest. Differences in N mineralization potential due to tillage were greater in the spring than in the fall. Cumulative N mineralized, N mineralization potential and rate of N mineralized increased with no significant increase in soil C when fertilizer N application was increased. Carter and Rennie (1984) compared the effects of zero and conventional tillage systems on N transformations of Chernozemic soils in Western Canada. The results suggested that the differences in tillage did not cause marked changes in the soil N cycle.

The effect of soil disturbance was also studied and it was found that in disturbed soil cores N_o was lower than in undisturbed cores. Potentially mineralizable N may be overestimated by drying and sieving the samples before incubation (Cabrera and Kissel, 1988b) or by the bias introduced into the estimation of the parameters as the time of incubation increases (Dendooven, 1990).

Campbell et al. (1991) indicated that the product of N_o and k yielded the initial potential rate of N mineralization which was higher for the cultivated than for the undisturbed soil cores. The initial potential rate of N mineralization had been proposed as a criterion for the definition of soil organic matter quality. Moreover, Juma et al. (1984) conducted incubation studies on Saskatchewan soils to determine the suitable mathematical equation and its parameters describing the net N mineralization in soil. They found that the data fitted to either hyperbolic or first order equations. The kinetic parameters, potentially mineralizable (N_o) and time required for ½ N_o to mineralize (T), were determined by non-linear least squares (NLLS) method. The hyperbolic No values ranged from 51 to 429 μg N g^{-1} soil while the T values ranged from 7.3 to 45.8 weeks. The No and k (net N mineralization rate constant) of the first order equation ranged from 35 to 255 μg N g^{-1} soil and 0.036 to 0.164 wk^{-1}, respectively. Both equations accurately predicted the amount of net N mineralized over a 14 week incubation. However, the parameter estimates of potentially mineralizable N and mineralizable N half-life were dependent upon the model used.

Determining the long-term mineralization capacity of soils is laborious, expensive and time-consuming (Stanford, 1982). The relative significance of N derived from the various mineralizable sources may well differ with short and long-term measurements. These considerations may help explain why attempts at relating short-term N mineralization data to N uptake by a particular crop or a succession of crops grown on different soils under uniform conditions have met with varying degrees of success.

Nitrogen Mineralization Rate (*k*)

Investigators used a variety of incubation techniques to estimate net nitrogen mineralization and net nitrification rates in forest soil. Methods differed in these ways: 1) site of incubation, field versus laboratory; 2) pre-incubation treatment, sieving versus no sieving; and 3) length of incubation. Each method offers advantages and disadvantages, but there was no reference method against which to measure mineralization rates (Adams et al., 1989; Eno, 1960; Nadelhoffer et al., 1983; Raison et al., 1987 and Vitousek and Matson, 1985). Depletion of highly labile organic matter substrate, NH_4 accumulation and NH_3 volatilization all could potentially act to decrease measured mineralization rates with increasing incubation times (Kaiser and Heinemeyer, 1993).

Studies showed that rate of N mineralization was dependent on cropping practices (Campbell and Souster 1982; El-Harris et al., 1983) tillage intensity (El-Harris et al., 1983), crop residues (Smith and Sharpley, 1990) and fertilizer application (Janzen 1987). Soudi et al. (1990) conducted a study to determine the influence of soil depth on N mineralization rate and its relationship with total N and amino acid N contents for eight representative soils of the subarid zone of Morocco. Nitrogen mineralization was evaluated in a 16 week laboratory incubation study. Individual samples were leached periodically to extract the mineralized N. Results suggested that N mineralization varied among the soils studied and the decrease of mineralization rate in a given soil was attributed to decreased biodegradability of the organic compounds with depth. The decrease of amino acid N (aspartic acid, glycine, lysine, alanine and histidine) content with depth was relatively greater than the decrease of total N. This might be due to trapping of amino acids in complex organic compounds. These compounds such as quinones and phenols were less decomposable by biological processes with increased depth.

Soil matric potential had a significant effect on the rate of net mineralization. Both net ammonification and nitrification rates declined from an optimum value near field capacity as the soil dried (Reichman et al., 1966; Campbell and Biederbeck, 1972). The rate of decrease was more rapid with nitrification than with ammonification. Ammonification, unlike nitrification, continued at soil matric potentials below the permanent wilting point (Robinson, 1957). By implication therefore, soils with an increasingly greater initial soil matric potential (wetter) would show progressively smaller increases in mineralization rate upon wetting (Pilbeam et al., 1993).

Fungi and bacteria play an important role in N transformations (Stevenson, 1986). An important factor determining the rate of N mineralization is the C:N ratio of the microbes as well as that of their substrate. When bacteria decompose organic matter, more inorganic N is released from the organic matter when the bacteria have a higher C:N ratio of 6 rather than 4 (De Rutier, 1993). In comparison of six grassland soils it was found that the C:N ratio of the microbial biomass was higher in sandy soils than in loams and clays and was positively correlated with the N mineralization rate per unit of microbial biomass N (Hassink et al., 1993).

Plant materials would decay with different rates depending on their C:N ratio and lignin content. In the early stages of decomposition rapid N mineralization was expected in crop residues with low C:N ratio and low lignin content (Parton et al., 1987). As time of incubation increased, lower mineralization rates were observed (Hunt, 1979). Attiwill and Adams (1993) reported that studies done on European soils showed that there was a generally slower rate of mineralization under field conditions compared with laboratory conditions, and slower rates in forest soils compared with agricultural soils. These slow rates of mineralization were often associated with a lack of nitrification. In addition, soil disturbance increased mineralization rates for a relatively short period. This was followed by a longer period in which net mineralization decreased, sometimes to the point where inorganic N was immobilized for 1-2 years. Mineralization rates and soil pools of inorganic N were similar to those before the disturbance. The fact that the competition for NH_4 by heterotrophic microorganisms ensured that nitrification depended on the rate of ammonification which in turn was strongly influenced by the C:N ratio of the organic substrates. When the C:N ratio of agricultural crop residues exceeded 25:1 there would be no net mineralization of N and NH_4-N would be immobilized.

Grace et al. (1993) reported that increases in N mineralization associated with cultivation had been attributed to the destruction of aggregates and exposure of organic materials previously inaccessible to microbial attack. The microbial biomass itself was identified as a significant source of N. Increased soil NO_3-N due to cultivation may also be due to higher potential for nitrification, lower rates of N immobilization or less potential for N loss through denitrification.

Several incubation studies indicated that a flush of mineralization would be detected following soil sieving (Hassink, 1992 and Nordmeyer and Ritcher, 1985). Piccolo et al. (1994) showed that higher net N mineralization and nitrification rates were measured in laboratory and *in situ* incubations of sieved soil, compared with in situ incubation of intact soil cores. Rates calculated in seven-day incubations were higher than determined by longer incubations. Sieving may increase N mineralization and/or decrease N immobilization compared with intact cores.

Large soil moisture fluctuations created potential problems in interpreting measured net N mineralization rates. Tube or buried bag methods with intact cores minimized soil disturbance that may affect transformation rates, but the carbon inputs caused by severing of live roots might influence transformation rates. Methods that utilize sieved soil created artificial soil conditions but eliminated most carbon inputs from freshly severed roots. Because rates of net N mineralization and net nitrification in intact core methods varied widely and were often near zero, incubations of sieved soil served as a better index of N availability. The possibility still existed, however, that rates of net mineralization and nitrification were substantially altered by sieving. Changes could result from either enhanced mineralization of organic matter following sieving, or from reduced immobilization after the removal of roots and large, poorly decomposed organic matter fragments.

Incubation studies by Beloso et al. (1993) showed that in a non-fertilized soil, N mineralization increased continuously from the beginning of the incubation. Nitrogen mineralization showed no signs of leveling off at the end of the incubation although a decrease in N mineralization rate was detected after week 2 of incubation. Ladd et al. (1994) showed that fertilizer N application didn't impair soil mineralization activities, expressed in percentage of soil organic C and N. Carbon and N mineralization rates per unit of microbial biomass C increased in the fertilized soils. Nitrogen fertilizer application increased the annual return of plant residues but had no effect on percentage mineralization rates. The results suggested that the decreased biomass C contents in fertilized soil was due specifically to increased rates of conversion of C from the biomass pool to the non-biomass pool.

Singh and Singh (1994) found that the increase in N mineralization in straw + fertilizer treatment was 97% greater than the control (no fertilizer and residue added) at same moisture level. Nitrogen mineralization was greatest during the wet period of the year. It increased exponentially within the range of 5-23% soil moisture content in Indian drylands. In conclusion, combined input of straw and fertilizer enhances N mineralization rate resulting in a larger available N pool. This would increase the N supply even during the period when fertilizer application was not feasible due to low moisture in dryland farming conditions.

Soil N Losses

Soil N losses may include a) leaching of NO_3-N from the rooting zone and into the groundwater, b) denitrification when microbes uses NO_3-N rather than oxygen and thereby reduces N primarily to N_2O or N_2 gas into the atmosphere, c) volatilization of NH_4-N from fertilizers and manures, d) erosion of surface N (Meisinger and Randall, 1991). Denitrification and leaching may cause nitrate-N to be lost before it is taken up by the crop (Armstrong et al., 1986).

These losses are a continuing concern for farmers and for society. The agricultural community must reduce these losses and be responsible for the soil and water resources and improve crop N-use efficiency and farm profitability. Shaffer et al. (1991) developed a N leaching model that estimates the daily soil N potential for leaching. The model required daily water drained, daily N mineralization, daily N uptake by the plant and initial mineral N.

Fertilizer N requirement of a crop depends in part on the amount of N mineralized from soil organic N before and during growth. Any attempt to predict requirement by modeling techniques needs some form of model for mineralization. Since mineralized N may be leached when it is nitrified, it is important that the model should also include nitrification of NH_4 and be compatible with an appropriate leaching model (Addiscott, 1983). Measurements or estimates of other N losses such as denitrification, volatilization and erosion should be included in N needs predicting models whenever they apply.

Nitrogen Mineralization Prediction Models

The need for rapid and reliable methods of assessing soil N availability motivated most short-term incubation studies of soil N mineralization (Harmsen and Van Schreven, 1955, Bremner 1965). In early studies of long-term N mineralization capabilities of soils, samples were continuously incubated in bottles or flasks. In 1955, Stanford and Hanway proposed measurement of NO_3 production in soils by a method that permitted carrying out series of incubations with a single set of soil samples. Stanford and Smith (1972) conducted a study to assess long-term mineralization in 39 soils differing widely in chemical and physical properties. Cumulative net N mineralization was linearly related to the square root of time ($t^{1/2}$) throughout the 30 weeks of intermittent incubation with most of the soils tested. The quantity of soil N mineralized in a given time was dependent upon temperature, available water, rate of oxygen replenishment, pH, amount and nature of plant residues and level of other nutrients. This work was further evaluated in relation to uptake of N by sudangrass in a greenhouse experiment using ^{15}N labeled fertilizer. The findings showed that with a Q_{10} of 2, the mineralization rate (*k*) didn't differ significantly among soils between 5 to 35 °C. This indicates that the organic sources of mineralizable N were similar despite wide variations in origin and management history of the soils. Amounts of soil organic N mineralized during cropping plus the mineral N present initially in the soils correlated highly with amounts of soil N taken up by whole plants (Stanford et al., 1973). Stanford et al. (1974) demonstrated that N_o could be reliably estimated from the amount of N mineralized during 2-week incubations following preliminary incubations of 1 to 2 weeks. In addition, the rate constant *k* was influenced markedly by temperature and soil water content. Miller and Johnson (1964) found that the optimum matric suction for N mineralization ranged from 0.15 to 0.5 bar. Stanford and Epstein (1974) studied the relationships between soil N mineralization, soil water content and matric suction on nine soils. Highest N mineralization rates occurred between a matric suction of 1/3 and 0.1 bar.

Tabatabai and Al-Khafaji (1980) compared the N and S mineralization of 12 major soil series in Iowa. Field moist samples collected from 0-15 cm were incubated at 20 and 35 °C for 26 weeks. They found that cumulative amounts of N and S mineralized were linear with time of incubation. The rate of N mineralization, however, was greater than the rate of S mineralization and temperature had a marked effect on organic N and S mineralization in soils. The linear relationship obtained for cumulative N mineralized at 20 and 35 °C and time of incubation did not support the finding of Stanford and Smith (1972) that cumulative N mineralization is related to $t^{1/2}$. In addition, Addiscott (1983) showed that mineralization of soil organic N measured in laboratory incubation experiments on Rothamsted soils with contrasting histories could be expressed by the simple zero-order relationship $N_t = kt$ in which N_t is the amount of N mineralized in time t. The approach in which N_o was evaluated with first-order kinetics, as proposed by Stanford and Smith (1972), could not be applied to these data.

Hadas et al. (1986) conducted an incubation experiment on 38 different soil samples collected from various places in Israel. The samples were incubated for 32 weeks at a constant temperature of 35 °C and a moisture content of water-holding capacity. The study was to evaluate the contribution of different soil layers of mineral N of the whole root zone and to relate the rate parameters obtained to various soil N factors. They found that the soil layers of 60-120 or 60-160 cm contributed about 30% of the N mineralized in the whole soil profile. In addition, the total N weighted with respect to soil layer depth was the best estimate of N mineralized in soil profiles. Bonde and Rosswall (1987) evaluated three models to describe the kinetics of N mineralization during incubation: (i) first-order, (ii) two-component (sum of two first-order models), and (iii) a simplified special case of the two-component model. The latter model offered the best description of the curves of accumulated mineral N. Cabrera and Kissel (1988a) studied the N mineralized in disturbed and undisturbed soil samples. A double exponential model fitted disturbed samples; whereas, a single exponential model was required for undisturbed samples. For each soil, the amount of N mineralized in disturbed samples was larger than in undisturbed samples at any time.

Cabrera and Kissel (1988b) dried ground samples of 3 soil series and incubated them at 35 °C for a total of 252 days to evaluate a method that predicts N mineralized from soil organic matter under field conditions. To predict N mineralized in the field, the rate constants of mineralization were adjusted for soil temperature. In addition, predicted amounts of N mineralized, N mineralization potentials and adjusted rate constants were further adjusted by soil water content. The water content factor used was similar to that proposed by Myers et al. (1982): W = (WC - AD)/(OWC - AD) where WC is soil water content, AD is water content of air-dry soil (calculated as 50% of the water content at -1.5 MPa) and OWC is the optimum water content (assumed to be that at -0.02 MPa). However, this factor only accurately predicted the amount of N mineralized in 104 days in fallow plots and significantly overpredicted by 67 to 343% the amount of N mineralized in the field. Overprediction may be attributed to improper soil water content factor, drying, grinding and sieving of the samples before incubation. On the other hand, Campbell et al. (1984) developed a model that predicted the amount of net N mineralized during a growing season when soil was incubated in plastic bags placed in incubators or buried in the field. The basic equation used was: $N_t = N_o (1 - \exp(-kt))$ where N_t is cumulative N mineralized, N_o is the potentially mineralizable N determined at an assumed optimum temperature of 35 °C and optimum moisture (-0.03 to -0.01 MPa), k is the rate constant at optimum moisture and temperature and t is time. Campbell et al. (1988) used the model to estimate net N mineralized *in situ* under cropped-dryland, cropped-irrigated and summer fallow conditions. Model output showed good agreement to field measurements especially for the first 45-60 days, but thereafter tended to underestimate the measured data particularly under cropped-dryland conditions. The model was not dynamic since it didn't allow for N_o to be replenished continuously by N derived from decomposition of fresh residues and rhizosphere microbial biomass. This might explain the underestimation. Other sources of possible discrepancy could be imprecision in measuring the mineralization of N and in estimating the parameters in the model. In addition, the model underestimated the amount of N mineralized whenever the soil became very dry and then rewetted by rainfall. This was because the latter process resulted in large flushes in mineral N *in situ* while in laboratory estimates of N_o and k, this effect was not adequately simulated.

El Gharous et al. (1990) showed that single exponential and hyperbolic models can be used to estimate N_o and k values. On these arid and semiarid Moroccan soils the active fraction of total N ranged from 7 to 22% and 10 to 36% for the exponential and the hyperbolic models, respectively.

Simard and N'dayegamiye (1993) suggested that for accurate prediction of soil N availability, it was important to select a model that would simulate the behavior of N mineralization for a wide range of soils. They conducted incubated studies on 20 meadow soils for 55.4 weeks at 20 °C. Results showed that the cumulative mineralization curves in most soils were characterized by definite lags or a sigmoidal pattern and near-linear release with time after 20 weeks. The data were best described by the Gompertz equation: $N_m = N_o e^{-he^{-kt}} - N_o e^{-h}$, where, N_m is the cumulative amount of mineralized N, t is the time, k is the rate constant, N_o is the amount of potential mineralizable organic N and h is a proportionality constant of the equation.

Matus and Rodriguez (1994) developed a model that predicted the release of N from a range of soils in different agricultural zones with large variations in fresh organic inputs, weather conditions and soil types. The model avoided the use of the potentially mineralizable N of Stanford and Smith (1972). In addition, results showed that N mineralization heavily depended on environmental factors such as soil temperature and moisture content. The effect of temperature on N mineralization is given by : $K_2(T_a) = K_2(T_o) * \exp(0.0616 * (T_a - T_o)$, where $K_2(T_a)$ is the constant decay rate K_2 adjusted to the temperature T_a ($5<T_a<35$ °C) and $K_2(T_o)$ is the rate K_2 at temperature T_o ($5<T_0<35$ °C). Cavalli and Rodriguez (1975) indicated that the relationship between soil moisture and N mineralization was linear between field capacity and permanent wilting point. Thus, $K_2(W_a) = K_2(W_o) * (1.11 * (W_a/W_o) - 0.138)$, where $K_2(W_a)$ is the rate constant K_2 adjusted to the soil moisture W_a and $K_2(W_o)$ is the rate K_2 at soil moisture W_o. Goncalves and Carlyle (1994) showed that the influence of soil temperature or moisture on net N mineralization could be explained using simple exponential functions. It was possible to predict net N mineralization from simple models of the form: $N_{min} = ON * \exp^{(-kt * TF * MF)}$ where N_{min} is the quantity of N mineralized from an organic N pool ON, k (an index of organic matter quality) is the rate constant for mineralization of ON, t is the time period, and TF and MF are temperature and moisture factors that modify the value of k in response to soil moisture and temperature.

Seneviratne et al. (1994) presented a new theory based on the diffusion of NH_4 ions during incubation to predict potentially mineralizable N (N_o) in soils. Their model predicted N_o more accurately and more easily than the conventional one-pool exponential model of Stanford and Smith (1972).

Limited information was available on N fertilizer recommendation on sugarbeet based on estimation of amount of N mineralized from soil organic matter. The objective of this work was to develop a model to predict cumulative net N mineralization under field conditions from a long-term aerobic incubation experiment.

MATERIALS AND METHODS

During 1993 and 1994 two field experiments were established at the Saginaw Valley Bean and Beet Research Farm, Saginaw County, Michigan (43° 4' N, 84° 6' W) on a Misteguay silty clay soil (fine, illitic (calcareous), mesic, Aeric Endoaquent). Soil samples from the 1993 check plots (0 kg N ha^{-1}) were used in a laboratory long-term aerobic incubation experiment. Data from the laboratory incubation experiment were used to predict cumulative net N mineralization in the field, (N_t). The latter was tested using 1994 field experiment data.

Field Experiment

In springs of 1993 and 1994 six N fertilizer rates (0, 33, 67, 100, 134 and 168 kg N ha^{-1}) were applied prior to planting sugarbeet (*Beta vulgaris* L.). The experiments was arranged in a randomized complete block design with six and four replications for 1993 and 1994 growing seasons, respectively. The plot size was 3 m x 21 m. In April 17 of 1993, just before spring tillage, , twenty composite soil cores (1.87 cm in diameter) at 0-22 cm deep were collected from the check plots. Soil cores were placed on ice, transported to the laboratory and stored at 4°C. At the same time, undisturbed soil cores (7.5 cm x 7.5 cm) were also collected from the check plots to determine the field capacity (- 0.033 MPa) following the procedure outlined by Klute (1986).

In both years, plant and soil samples were collected for N analysis. Four adjacent plants were harvested from each plot in October. Plant samples were processed, ground and analyzed for total N using the processing and analysis procedure outlined in Chapter 2.

Soil samples were taken periodically from the check plots at 0-22 cm and 22-45 cm deep. They were collected on the third day after each rainfall in excess of 35 mm. Samples were taken 10 times during the growing season. Gravimetric moisture content was determined on a subsample by drying at 110 °C. The remaining soil sample was air-dried, ground and analyzed for mineral N and total N using the preparation and analysis procedures outlined in Chapter 2.

Water Balance Model

Daily weather data (solar radiation, minimum and maximum air temperature and rainfall), were collected at the Saginaw Valley Bean and Beet Research Farm, Michigan for both years. In addition, leaf area index (LAI) (Christenson et al., 1993 and Xu, 1991), soil moisture limits of each layer and root length data were used to run the water balance *Salus* model (Dadoun and Ritchie, 1993). The predicted daily soil moisture content at each depth of sampling was then used to estimate the daily moisture content (W).

Long-Term Aerobic Incubation Experiment

Some modifications were done on the approach suggested by Cabrera and Kissel (1988b) and Stanford et al. (1974). These modifications included the i) use of moist and sieved soil rather than dry and ground soil, ii) incubation of the soil samples at 25 rather than 35 °C, iii) extraction of the whole soil sample placed in the tube rather than leaching the same sample periodically, iv) use of soil moisture factor where the optimum moisture is considered 75% field capacity rather than 50% and v) no preincubation for 2 weeks.

The soil samples were partially air-dried prior to sieving (6 mm). After sieving, moisture content was determined. Duplicate samples of moist soil (20 g dry weight) from each of the 6 replications were placed in a 50 ml orange capped centrifuge plastic tubes and 40 μg ^{15}N was added per tube. To aid in aeration of the soil, 4 pin-holes were drilled in the lid placed on the tube. Soils were aerobically incubated at 25 °C and were maintained at 75% field capacity by periodically adding water.

Sampling for N analysis (mineral N and atom % ^{15}N) was done on the following days: 0, 3, 7, 10, 20, 35, 50, 70, 90, 120, 160, 200, 273 and 329. In addition, on zero, samples without ^{15}N were extracted and analyzed for mineral N and atom % ^{15}N using the preparation and analysis procedure outlined in Chapter 2.

N Mineralization Models

Microsoft Excel Solver option (Microsoft Excel, 1995) was used to fit the cumulative net N mineralization (N_m) data of laboratory incubation to linear and one-pool exponential models. The linear equation is denoted by:

$$N_m = k\,t + c \qquad [3.1]$$

and the exponential equation is of the form:

$$N_m = N_o\,(1 - \exp(-kt)) \qquad [3.2]$$

where N_m is cumulative net N mineralization in time t, N_o is the pool of mineralizable N, k is the rate of mineralization in linear and exponential models and c is a constant.

Prediction of N Mineralized in the Field

The linear and exponential models were used to predict N mineralized in the field (N_t). Findings of Stanford and Smith (1972) showed that Q_{10} of the mineralization rate, k, did not differ significantly from 2 among soils in the temperature range of 5 to 35 °C. In this study, the rates of mineralization (k) of both models were adjusted to field air temperature using Q_{10} of 2 and 2.2 to determine the effect on cumulative net mineralization would be. With a Q_{10} of 2, for example, k was corrected using the following equation:

$$k_1 = k * 2^{((T_{daily} - T_{incubation})/10)} \qquad [3.3]$$

where k_1 is the adjusted rate constant of mineralization to air temperature, k is the rate constant of mineralization from the model, T_{daily} is the averaged daily air temperature and $T_{incubation}$ is the soil incubated temperature (°C).

The predicted amount of N mineralized (N_t) was then corrected for soil moisture using the equation:

$$W = \text{daily soil water content / optimum soil moisture content} \qquad [3.4]$$

The optimum soil moisture content was considered the moisture content at which the soil was incubated (75% field capacity). Field capacity was determined on undisturbed cores equilibrated at - 0.033 MPa. Hence, the equations for predicted cumulative N mineralized in the field (N_t) using the linear and the exponential models were of the form, respectively:

$$N_t = W(k_l t) + c \quad [3.5]$$

$$N_t = W\, N_o\, (1 - \exp(-k_l t)) \quad [3.6]$$

The predicted cumulative net N mineralization was then compared to the calculated cumulative net N mineralization in the field for both years. The calculated net N mineralized over the growing season was determined at both depths using the following equation:

$$\text{N mineralized} = (\text{Mineral } N_{end} + \text{Plant } N_{uptake}) - \text{Mineral } N_{start} \quad [3.7]$$

where Mineral N_{end} is measured soil mineral N in the field at the end of the season, Plant N_{uptake} is measured total N taken up by plant at harvest and Mineral N_{start} is measured soil mineral N in the field at the beginning of the season.

Prediction of Soil Mineral N Losses

Excessive rainfall during the growing season might lead to losses of soil mineral N from the soil profile. These losses might include denitrification and/or leaching. The prediction of potential leached N depended on the predicted cumulative N mineralization in the field, water balance and N uptake models. It considered N lost through volatilization and/or erosion to be negligible. Two approaches were used to predict the amount of soil mineral N available for leaching during the 1993 and 1994 growing seasons. The first approach depended on two parameters, namely, the average soil N concentration per *interval of time* and the total water drained *per interval*. The equation used:

$$\text{N leached} = \sum_{1}^{n} (\text{Avg. soil } \textit{solution} \text{ N conc.} * \text{Total water drained}) \quad [3.8]$$

where n is the number of intervals. The interval is defined as the midpoint between two soil N sampling dates thereby making the sampling point an average value. The N concentration in the soil solution was estimated using the measured soil mineral N divided by the total water volume. The water volume was considered as the sum of the soil water at field capacity and the water drained from the soil. Data for daily water drained were generated and validated from the water balance module of the *Salus* model. These daily values were totaled for each interval. The summation of the products of averaged soil N concentration per interval and the total water drained per interval is the N potentially leached from soil profile. The second approach is a complete soil N balance that depends on predicted daily plant N uptake, predicted soil N mineralization and predicted daily soil N available for leaching. For each day, the soil N mineralization and N uptake were used to update the previous day soil N to determine the soil N before leaching. The latter was used to determine leaching for that day. After leaching was determined, the soil N was updated to be used for the following day and so on. Daily or periodic N uptake by sugarbeet were not available. Only one sampling was taken at harvest.

Shaffer et al. (1991) suggested that the amount of N taken up by plants may vary with available N, but the shape of the curve was constant. N uptake from the temporal pattern of ^{15}N uptake by sugarbeet study (Chapter 2) was fitted to the following logistic (sigmoid) curve (Burghes et al., 1982):

$$N(t) = A/(1 + \exp(a - k\,t)) \qquad [3.9]$$

where N(t) is the daily N uptake, A is the total N uptake, t is time in days, and a (unitless) and k (kg day $^{-1}$) are constants. The constants a and k were determined using the linear programming Solver utility option of MS Excel and were 6.73 and 0.112, respectively. They were used to predict the daily N uptake during 1993 and 1994 seasons.

The predicted daily soil N mineralization at Q_{10} 2 was used to predict the N potential for leaching. The daily soil N potential for leaching is determined using the equation by Shaffer et al. (1991):

$$\text{N leached} = \text{NAL} * (1 - \exp((-k * \text{total water drained}) / \text{porosity}) \qquad [3.10]$$

where daily values of water drained amounts were generated and validated from the water balance module of *Salus* model. The constant k is the leaching coefficient (unitless) equivalent to 1.2 (Keeney and Follett, 1991). Soil porosity for the 45 cm depth was 20.7 cm and was calculated from bulk density. NAL is the mineral N available for leaching (kg ha^{-1}). It was estimated using the following equation:

$$\text{NAL} = N_f + N_t + N_{min} - N_{up} - N_d - N_v - N_e \qquad [3.11]$$

where N_f is the N from fertilizer, N_t is the N mineralization in the field, N_{min} is the initial soil mineral N, N_{up} is the N uptake in treated plot, N_d is denitrified N, N_v is volatilized N and N_e is N lost through erosion.

Losses of N due to denitrification, volatilization and erosion were assumed to be negligible. Justification for these assumptions was validated by the fraction of mineral N in the plant (e_m), that accounted for these losses. Hence, N available for leaching at day 1 would be calculated by using Eq. [3.11]: NAL (day 1) = N_{min} (day 0) + N_t (day 1) - N_{up} (day 1) and then N available for leaching at day 2 would be calculated the same: NAL (day 2) = NAL (day 1) + N_t (day 2) - N_{up} (day 2). NAL for subsequent days were calculated in the same manner. The total mineral N leached during the growing season was computed by summing the leaching obtained at each day.

Prediction of Atom % ^{15}N in Mineral N

Mineral N from the incubation study was extracted and analyzed for atom % ^{15}N following the extraction and analysis procedures described in Chapter 2. The measured values were compared to the predicted values of atom % ^{15}N in mineral N using the following equation:

$$y_t = ((X_t * 0.37) + (Y * 99))/(X_t + Y) \qquad [3.12]$$

where y_t is the predicted atom % ^{15}N in mineral N at time t, X_t is the initial mineral N + predicted N mineralized at time t (mg kg^{-1}), Y is the mass of ^{15}N added (mg kg^{-1}), 99 is atom % of tracer used and 0.37 is atom % in mineral N before addition of tracer. Predicted and measured atom % ^{15}N in mineral N were plotted against time of incubation.

In addition, gross N immobilization rate was estimated between any two intervals of time ($i\Delta t$) using a modified equation of Kirkham and Bartholomew (1945 and 1955):

$$i\Delta t = (a_1 - a_2)\,[\ln (a_1 * (b_1 - 0.37)/100)/(a_2 * (b_2 - 0.37)/100)]/[\ln (a_1 / a_2)] \qquad [3.13]$$

where a_1 is the predicted mineral N at start of the interval, a_2 is the predicted mineral N at end of the interval, b_1 is the predicted atom % in mineral N at the start of the interval, b_2 is the predicted atom % in mineral N at the end of the interval. Hence, gross mineralization is calculated as the sum of gross immobilization and net mineralization.

RESULTS AND DISCUSSION

Incubation Experiment

Data from the laboratory incubation study showed that the cumulative net N mineralization (N_m) fitted to a linear and one-pool exponential models (Figures 1 and 2). Cumulative net N mineralization (N_m) increased with time of incubation without leveling off appreciably in both models which was in agreement with Beloso et al. (1993) results. Rate of mineralization (*k*) was 0.152 mg kg^{-1} day^{-1} and coefficient of determination (r^2) was 0.974 for the linear fit. For the exponential model, rate of mineralization was 0.00337 mg kg^{-1} day^{-1} and coefficient of determination (R^2) was 0.988. The exponential model had an additional parameter known as the potentially mineralizable nitrogen, N_o, of 73.1. It was determined at an assumed optimum temperature of 25 °C and optimum moisture of - 0.03 Mpa. The exponential model doesn't allow for N_o to be replenished continuously by N derived from decomposition of fresh residues and rhizosphere microbial biomass. Both models were used to predict cumulative net N mineralization in the field.

Field Experiment

Soil bulk density determined on undisturbed cores was 1.38 g cm^{-3}. The soil field capacity volumetric moisture content was 41.4%. Soil moisture content and soil mineral N were measured on check plots at 0-22 cm and at 22-45 cm deep during the 1993 and 1994 growing seasons. Rainfall during the growing season was less (368 mm) in 1993 than in 1994 (514 mm). Rainfall from mid of May until the 7th of June totaled approximately 40 mm (Figure 3).

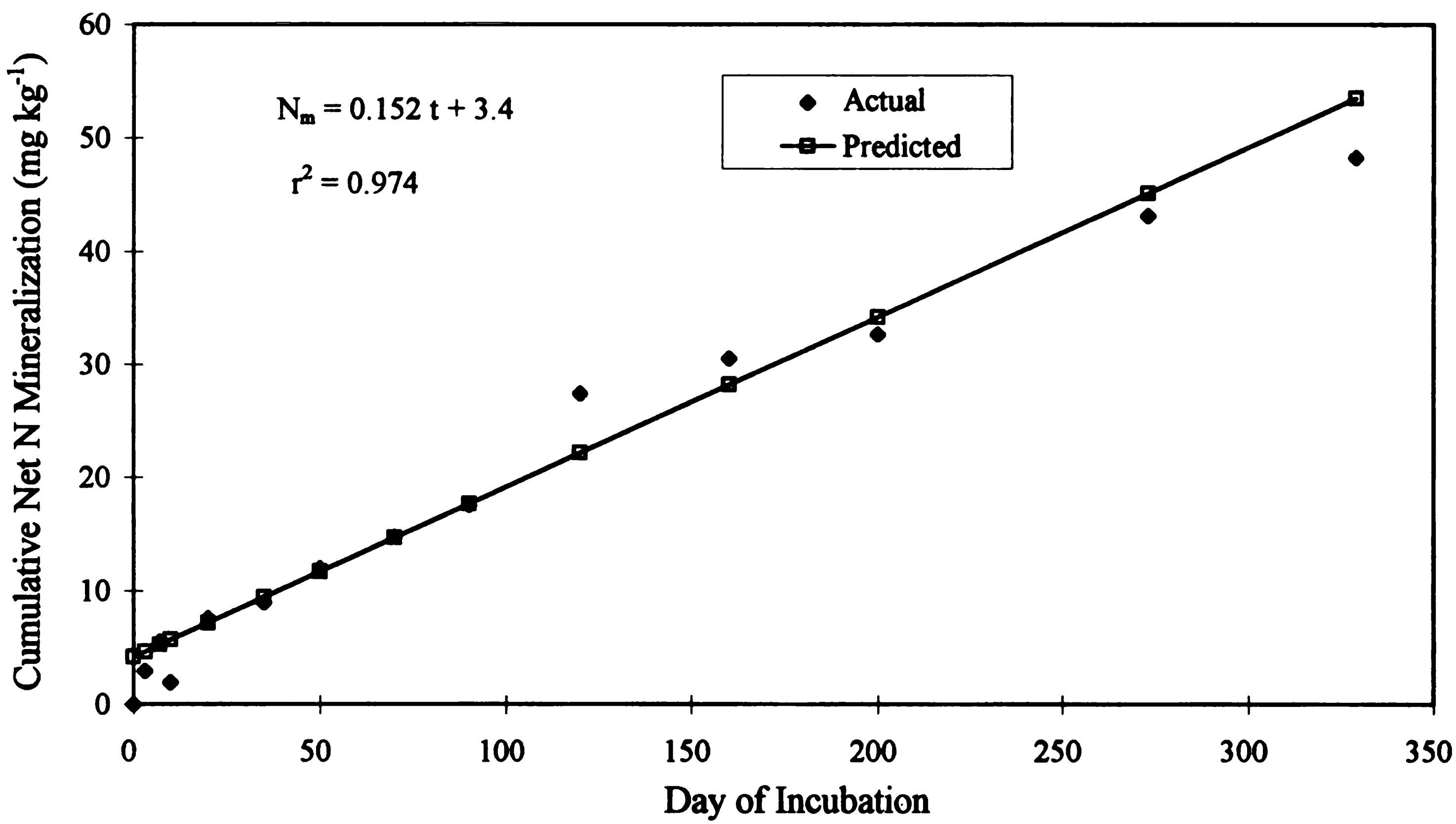

Figure 1. A linear fit of cumulative net N mineralization of laboratory incubated Misteguay silty clay soil samples with time in 1993.

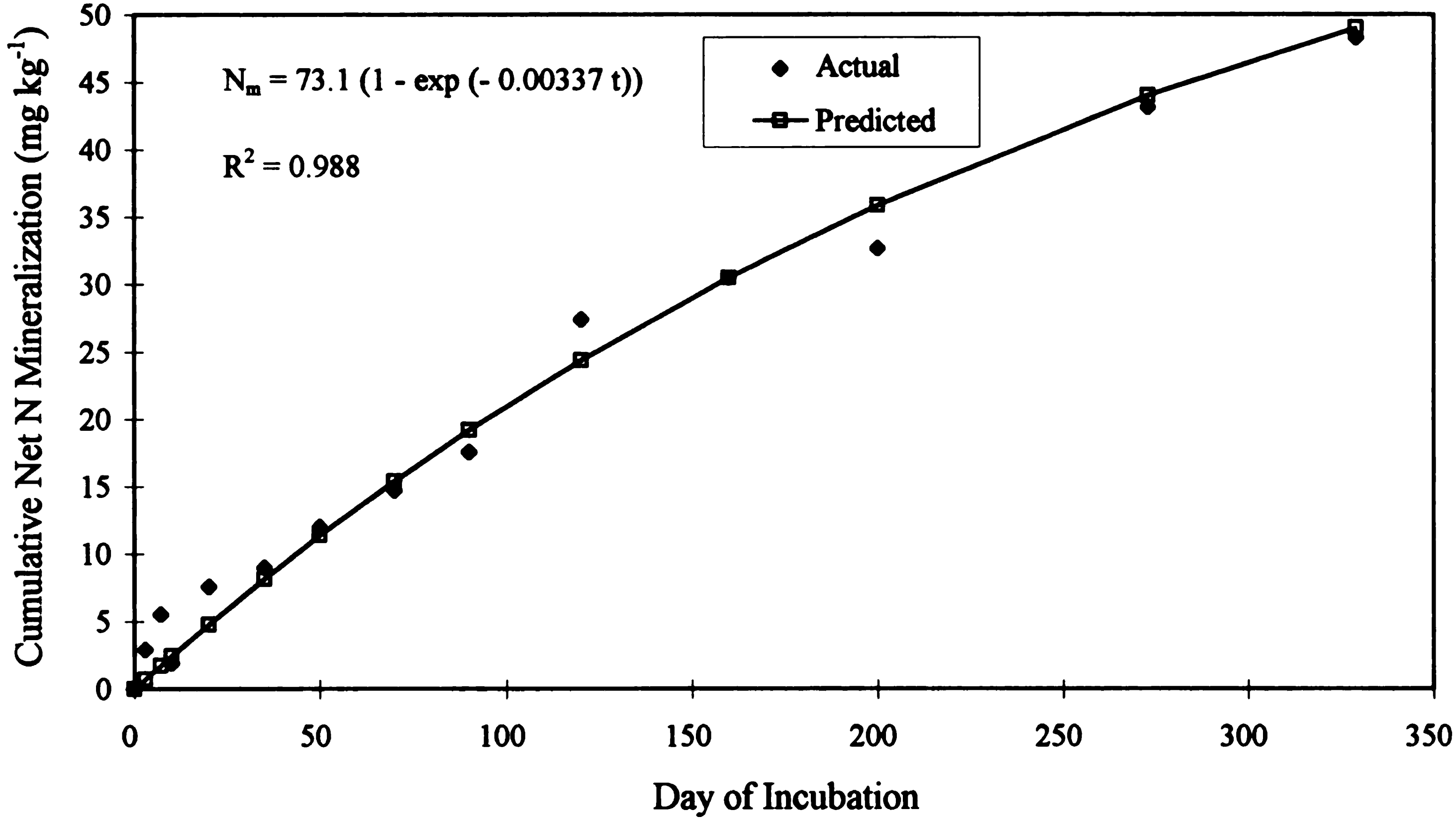

Figure 2. **An exponential fit of cumulative net N mineralization of laboratory incubated Misteguay silty clay soil samples with time in1993.**

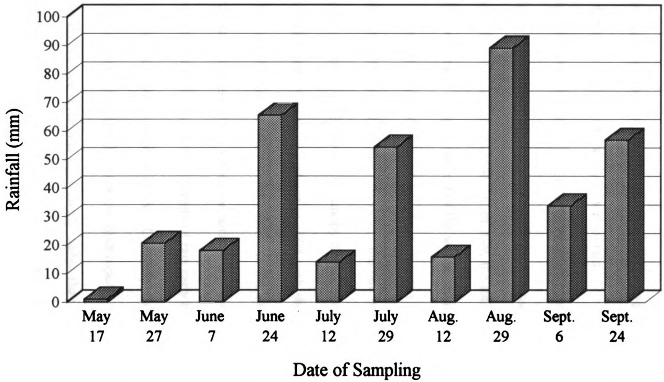

Figure 3. Rainfall during the interval between samplings on a Misteguay silty clay soil during the 1993 growing season.

This was followed by 65 mm by the 24th of June. Then there was a drier period of approximately one month with less than 15 mm of rain. Between July 12 and July 29 the plots received over 50 mm followed by another month long dry period with less than 20 mm of rain. The same pattern was repeated and there was nearly 90 mm of rain between August 12 and August 29 followed by nearly a month with less rain (August 29 to September 6). Then by the 24th of September there was approximately 55 mm of rain.

This rainfall pattern influenced the relative moisture content in the surface compared to the subsoil (Figure 4). Moisture content of the surface was equal to or greater than the subsoil until the first of July. From then until the 29th of July, the subsoil had equal or greater water content than the surface soil. During the rest of the season, moisture content was similar in the two horizons. The faster growing rate of sugarbeet crop and the warmer temperatures dried the surface soil during the month of July. Evidently the rain between July 12 and August 12 kept the surface more moist, probably due to canopy closure during this period.

The rainfall pattern was more uniform in 1994 with shorter periods with little rainfall (Figure 5). This kept the surface more moist relative to the subsoil during the whole season. There was never an extended period where the surface was drier than the subsoil (Figure 6). As will be seen later in the discussion the intensity of rain early in May as well as between June and mid July promoted greater leaching of N. Generally, when the soil moisture content exceeded the field capacity it would dry to below field capacity within 2 to 3 days. Mineral N concentration in the surface layer was significantly higher than in the subsoil during June and early August of the 1993 growing season (Figure 7). In both layers mineral N increased until late June, then it declined dramatically until end of July or early August where it remained fairly constant the rest of the season. The increase in soil mineral N between May 17 and June 24

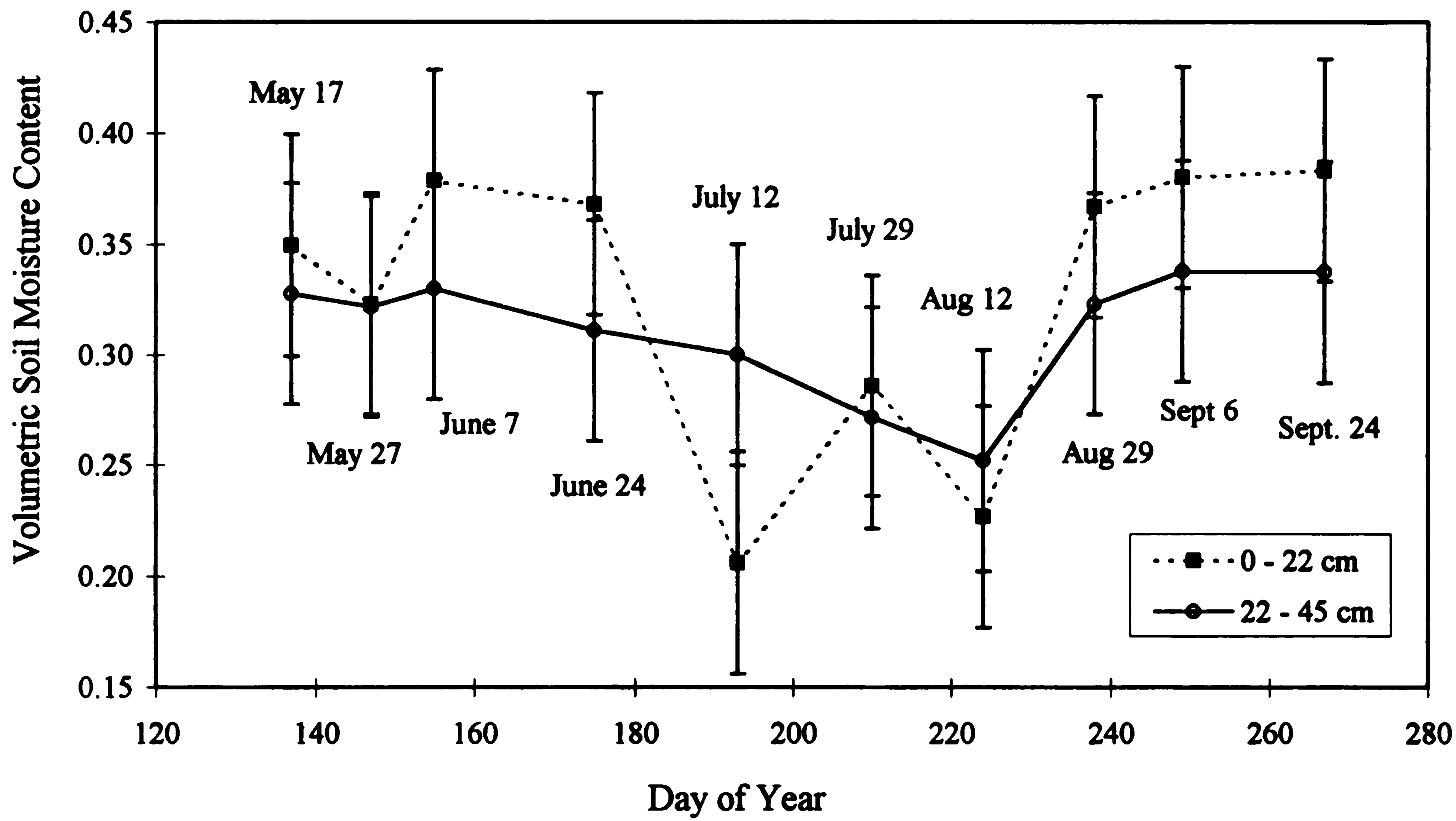

Figure 4. Volumetric moisture content of Misteguay silty clay soil during the 1993 growing season. Dates listed represent samplings after significant rainfall periods. The vertical line at each data point represents the standard error of the mean.

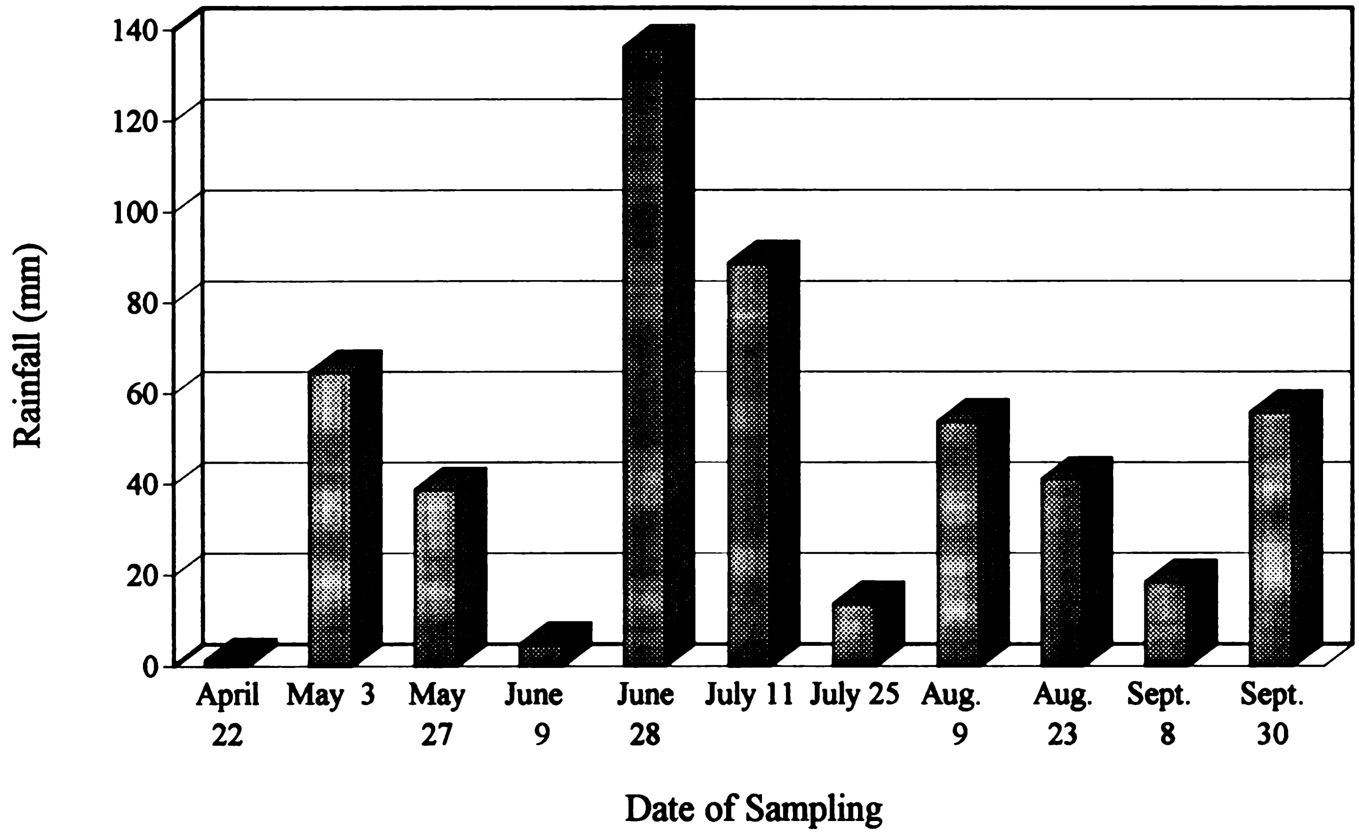

Figure 5. Rainfall during the interval between samplings on a Misteguay silty clay soil during the 1994 growing season.

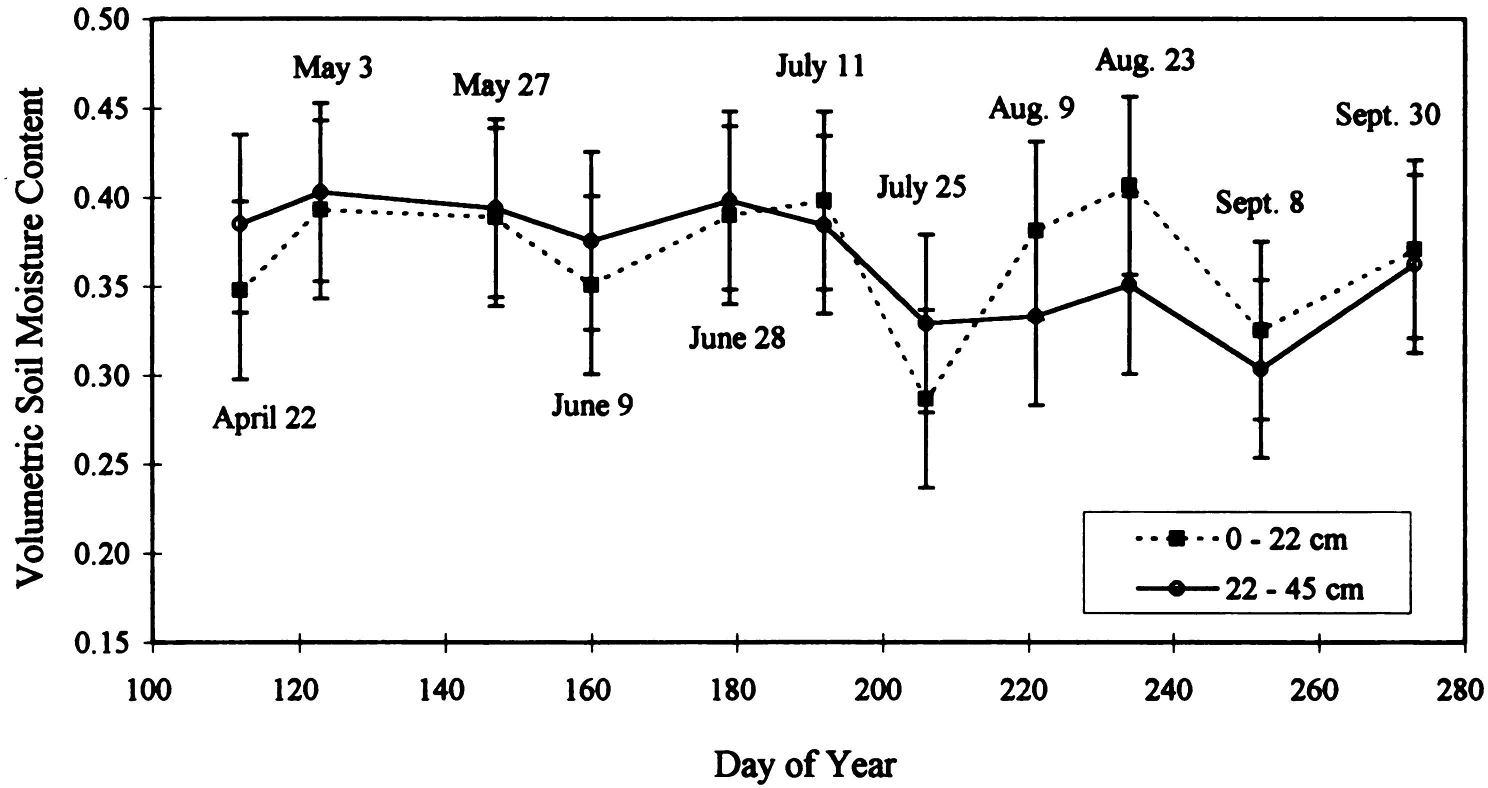

Figure 6. Volumetric soil moisture content of Misteguay silty clay soil during the 1994 growing season. Dates listed represent samplings after significant rainfall periods. The vertical line at each data point represents the standard error of the mean.

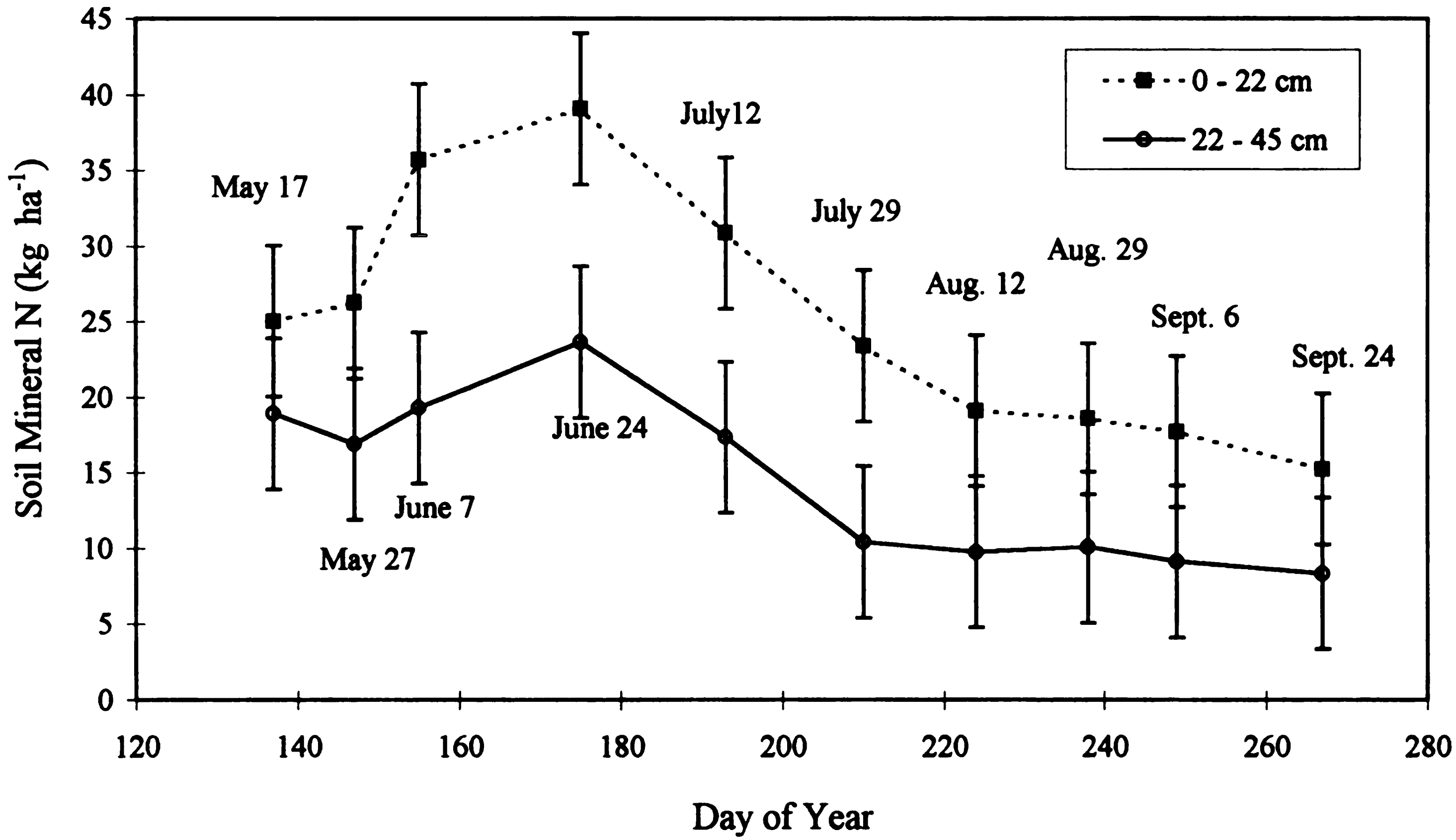

Figure 7. Soil mineral N of unfertilized Misteguay silty clay soil during the 1993 growing season. The vertical line at each data point represents the standard error for the mean.

was probably due to mineralization and nitrification of previous crop residues and to low N uptake by small sugarbeet plants. Mineralization and nitrification of decomposed organic material were enhanced by warmer temperatures, increased activity of nitrifying organisms and rainfall. The dramatic decline in mineral N after June was probably due to the higher N uptake by sugarbeet plants relative to soil mineralization.

The pattern of soil mineral N in 1994 growing season was similar to that of 1993 except in the first quarter of the season where the mineral N concentration in the subsoil was greater than that of the surface layer (Figure 8). This was due to heavy rainfalls of 104 mm (April 22 and May 27) and negligible to low N uptake by the small sugarbeet plants. Soil mineral N was leached from the surface layer to the subsoil layer and perhaps to the deeper layers (Figure 8). Soil mineral N increased in both layers until early June, decreased dramatically until July 11 and remained constant until the end of the season. The reasons for the increase of soil mineral N in 1994 were the same as those discussed for 1993. However, the decline of soil mineral N was due to high N uptake by plants (Figures 9 and 10) and leaching. During June 136 mm of rain fell followed by 89 mm during the first 10 days of July. In all likelihood this leached considerable amounts of mineral N. Measurements of leached soil mineral N were not taken during any of the growing seasons. However, a model to predict the daily mineral N leached from 0-45 cm depth for both growing seasons was developed. The estimated amount of soil mineral N leached was 6.92 kg ha^{-1} and 35.7 kg ha^{-1} during 1993 and 1994 growing seasons, respectively.

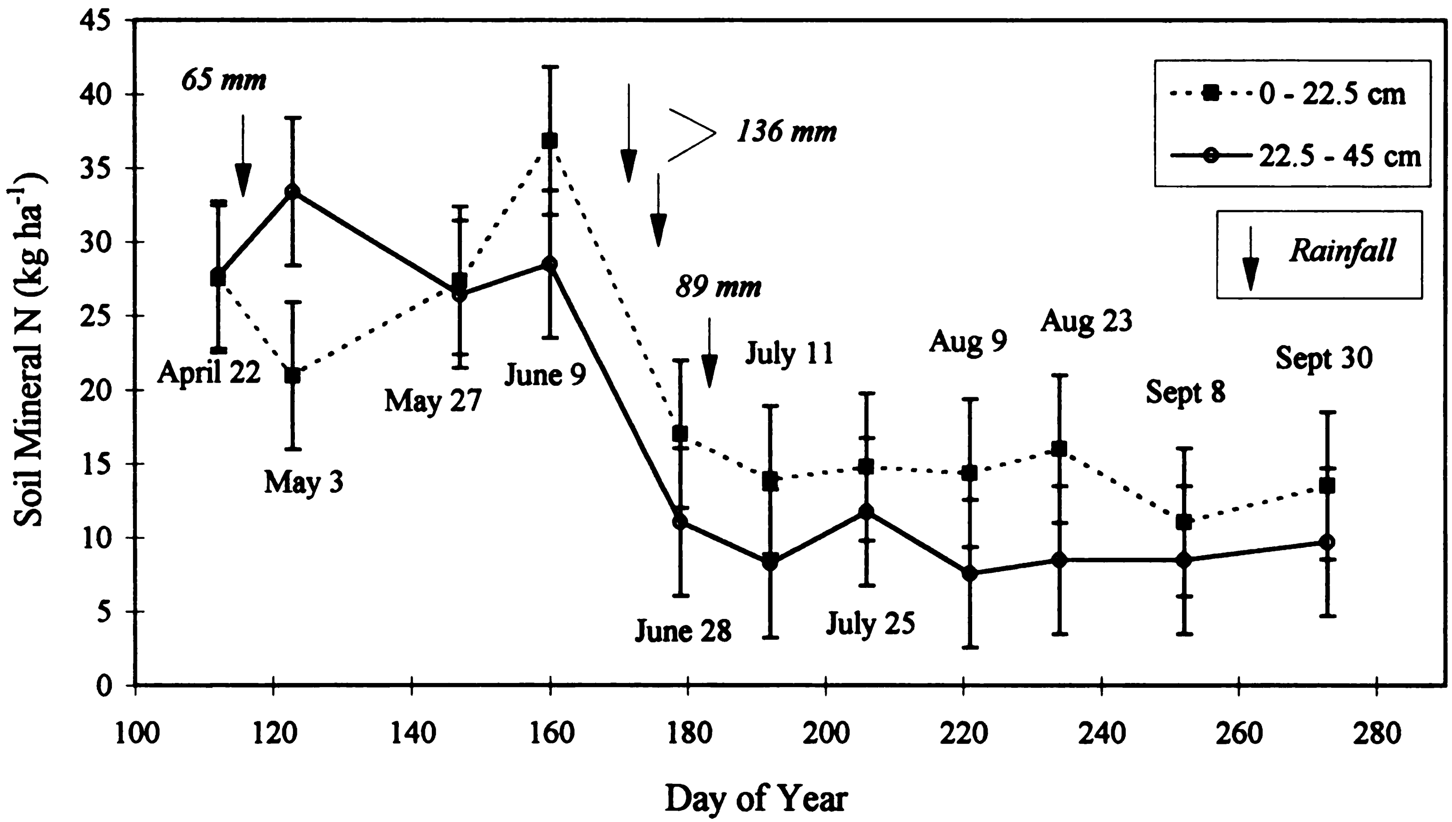

Figure 8. Soil mineral N of unfertilized Misteguay silty clay soil during the 1994 growing season. The vertical line at each data point represents the standard error for the mean.

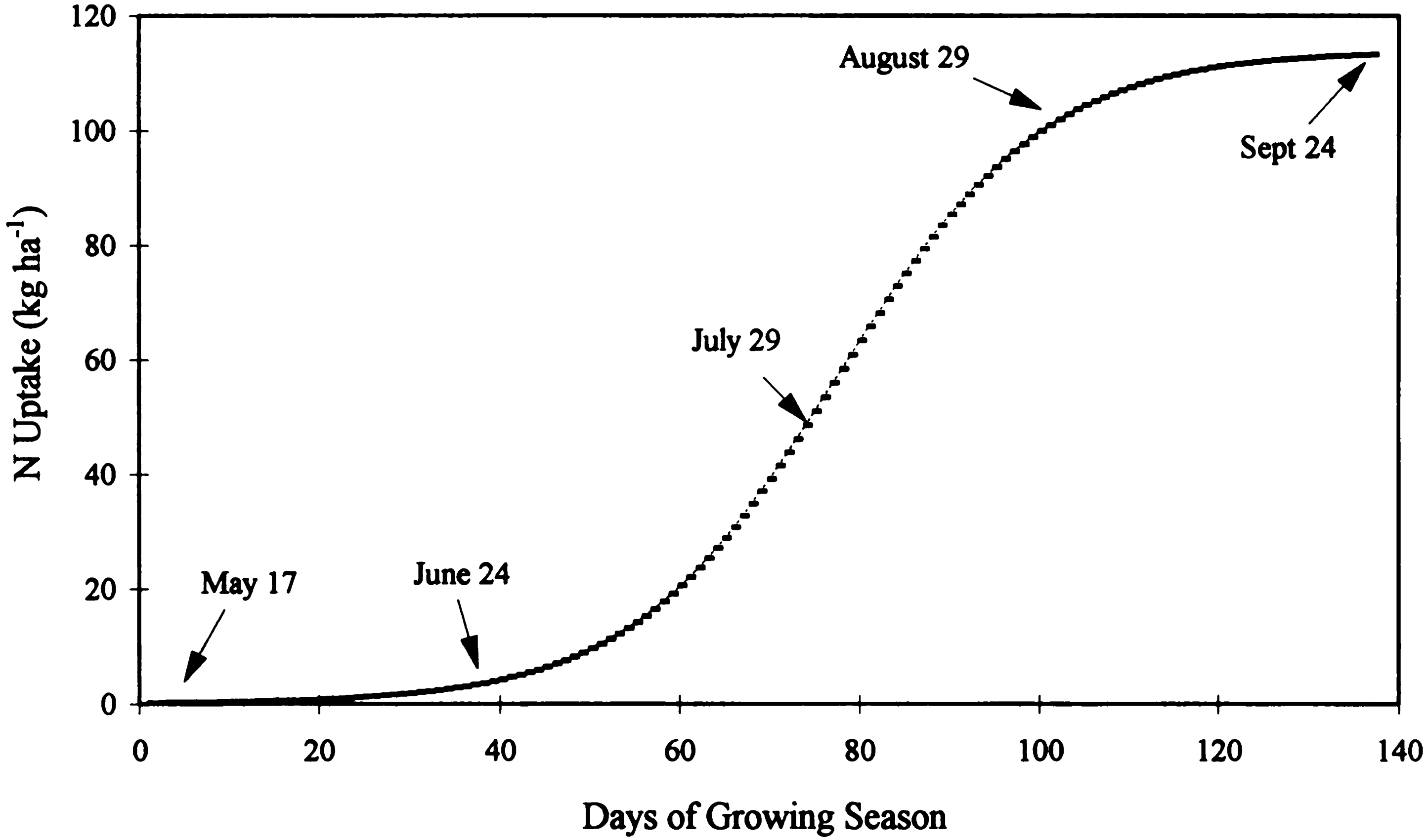

Figure 9. Predicted cumulative N uptake by sugarbeet grown on unfertilized Misteguay silty clay soil in 1993.

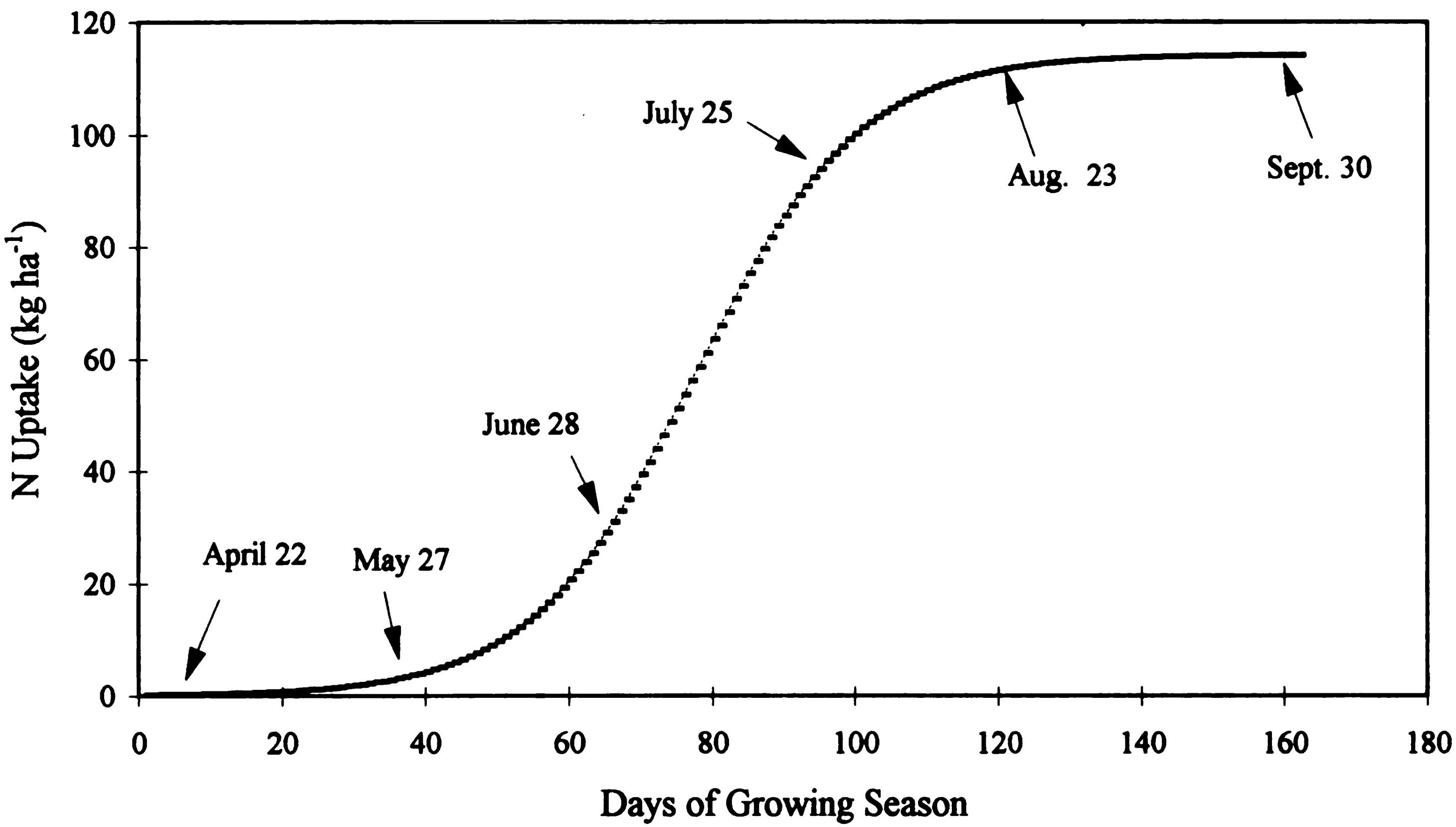

Figure 10. Predicted cumulative N uptake by sugarbeet grown on unfertilized Misteguay silty clay soil in 1994.

Prediction of Field Cumulative Net N Mineralization

Prediction of field cumulative net N mineralization (N_t) required the adjustment of N_m in both models. This was achieved by modifying the rate of mineralization (k) for both models to daily field air temperatures using Eq. [3.3]. N mineralized in the 0-45 cm layer was estimated by total mineral N weighted with respect to depth similar to Hadas et al. (1984). After correcting N_m for soil moisture (W) using Eq. [3.4], N_t was fitted to Eq. [3.5] and [3.6] for linear and exponential functions, respectively. Soil N mineralization is governed by temperature and moisture effects in a growing season during drying and rewetting cycles (Wildung et al., 1975; Kowalenko and Cameron, 1976; Cassman and Munns, 1980; Ellert and Bettany, 1992 and Gestel et al., 1993). This agrees with the findings of the field experiment of 1994, where adjusting for temperature and moisture factor increased N_t by around 10 to 12 kg ha^{-1} in both models at Q_{10} of 2 or 2.2. However, that adjustment did not change N_t in 1993 because there were no major drying and rewetting cycles to influence soil N mineralization. Values of N_t using both models at Q_{10} of 2 and 2.2 are shown in Tables 1 and 2. The calculated cumulative net N mineralized in the field during the growing season of 1993 and 1994 was 93.5 kg ha^{-1} and 84.1 kg ha^{-1}, respectively (Tables 1 and 2). Some uncertainty is expected due to imprecision in collecting and measuring soil mineral N, N uptake and calculating the measured mineralization of N. This uncertainty could also lead to some imprecision in estimating the parameters in both models and in predicting the N mineralization in the field.

In 1993, the predicted cumulative net N mineralization (N_t) value (Table 1) was close to the calculated one (93.5 kg ha^{-1}). In 1994, adding the estimated amount of mineral N leached (35.7 kg ha^{-1}) to the calculated cumulative net N mineralized (84.1 kg ha^{-1})

Table 1. Predicted field cumulative net N mineralization values after adjustment for air temperature and soil moisture (*W*) using linear and exponential models at Q_{10} 2 and 2.2 in 1993.

	Linear		Exponential	
Q_{10}	$k_l t + c$	$W(k_l t + c)$	$N_o(1 - \exp(-k_l t))$	$W N_o(1 - \exp(-k_l t))$†
	kg h a^{-1}			
2.0	83.7	82.7	94.0	92.9
2.2	80.6	79.6	90.3	89.1

† Calculated cumulative mineral N in the field was 93.5 kg ha^{-1} in 1993.

Table 2. Predicted field cumulative net N mineralization values after adjustment for air temperature and soil moisture (*W*) using linear and exponential models at Q_{10} 2 and 2.2 in 1994.

	Linear		Exponential	
Q_{10}	$k_l t + c$	$W(k_l t + c)$	$N_o(1 - \exp(-k_l t))$	$W N_o(1 - \exp(-k_l t))$†
	kg ha^{-1}			
2.0	96.0	107	108	120
2.2	92.5	103	104	116

† Calculated cumulative mineral N in the field was 84.1 kg ha^{-1} in 1994.

brought the latter value close to the predicted value of 120 kg ha^{-1} (Table 2). These models predicted the cumulative net mineralization in the field well which is contrary to Cabrera and Kissel (1988b). The models used by the mentioned authors overpredicted the amount N mineralized in the field by 67 to 343 %. The possible reasons for better prediction here are: i) using moist soil samples rather than dried ground samples in the incubation study ii) sieving the soil rather than using non-sieved intact cores where roots are not removed and iii) using correct adjustment for soil moisture.

Prediction of Leached Soil Mineral N

The constants a and k determined for 1991 N uptake were used in Eq. [3.9] to predict the daily N uptake in both seasons. Predicted cumulative N uptake for both years were similar (Figures 9 and 10). Although sugarbeet were planted 25 days earlier in 1994 than in 1993 yet the total N uptake was the same (114 kg ha^{-1}) in both years.

In 1994, predicted cumulative N mineralization in the field was 36 kg ha^{-1} greater than the calculated value. A model to predict soil mineral N leaching was developed to test that difference. Using Eq. [3.8] for the first approach showed that the predicted amount of leached N was 10.0 and 16.1 kg ha^{-1} for 1993 and 1994 growing seasons, respectively. However, the second approach (Eq. [3.10]) showed that predicted amount of mineral N leached was 6.92 kg ha^{-1} and 35.7 kg ha^{-1} for 1993 and 1994 growing seasons, respectively. The two approaches yielded insignificant losses to leaching during the 1993 growing season. Results showed that using the first approach underestimated the soil N leached in 1994, whereas the second approach was comparable with the value found by calculating the difference between the predicted and the calculated N mineralization in 1994 (Table 3). It is apparent that the second approach is more comprehensive and accounts for major N transformations and fluxes that occur during the season. The drawback of the first approach is that soil N was measured only when greater than 35 mm of rain fell and consequently all the N buildup due to mineralization especially at the beginning of the season was not accounted for. Mineral N in soil samples was assumed to be the average soil N for the interval. If periodic and more frequent measurements of soil N were done, the two approaches might have been more similar.

Table 3. Predicted soil mineral N leached from 0-45 cm deep during the 1993 and 1994 growing seasons using 2 approaches of estimation.

Approach	Predicted N leached	
	1993	1994
	---------- kg ha^{-1} ----------	
Approach 1†	10.05	16.1
Approach 2‡	6.92	35.7

† Approach 1: using average mineral N concentration per interval, equation [3.8].
‡ Approach 2: using Shaffer's et al. (1991) equation [3.10].

Prediction of Atom % ^{15}N in Mineral N

Predicted atom % ^{15}N in mineral N at each sampling was determined using Eq. [3.12]. Curves showing measured and predicted atom % ^{15}N in mineral N are shown in Figure 11. Measured and predicted atom % ^{15}N in mineral N declined rapidly until the 20th day of the incubation and then decreased at a constant rate for the rest of the incubation period. Predicted atom % ^{15}N in mineral N was almost double the measured value from the beginning until the 20th day of incubation. Reasons for overprediction might be attributed to i) added amount of atom % ^{15}N not beeing thoroughly mixed with soil, ii) preferential fixation of ^{15}N by soil microorganisms and iii) fixation of NH_4-N in clays. Mixing didn't appear to be the case since the entire soil sample was extracted. A short incubation experiment was run for 4 days to test whether labeled N was fixed by clay minerals. Two sets of soil samples were used, a control with no ^{15}N added and a set treated with ^{15}N. At the end of the incubation each set was split into two and extracted with KCl or water. Results showed that labeled N was not fixed in clay minerals. Although we could not explain the discrepancy up to day 20, we could estimate the gross immobilization between any two intervals of time using Eq. [3.13]. The decline in immobilization rate was probably due to the easily decomposed substrates that were used by the microbes and not immobilized as much. Table 4 showed the predicted immobilization rate values. Gross rate of mineralization is 25.8 % greater than net mineralization rate (Figure 12). Immobilization rate had a small effect on N budget of this soil. Immobilization rate at the beginning of incubation decreased to 1/10 of initial value by the end of the incubation.

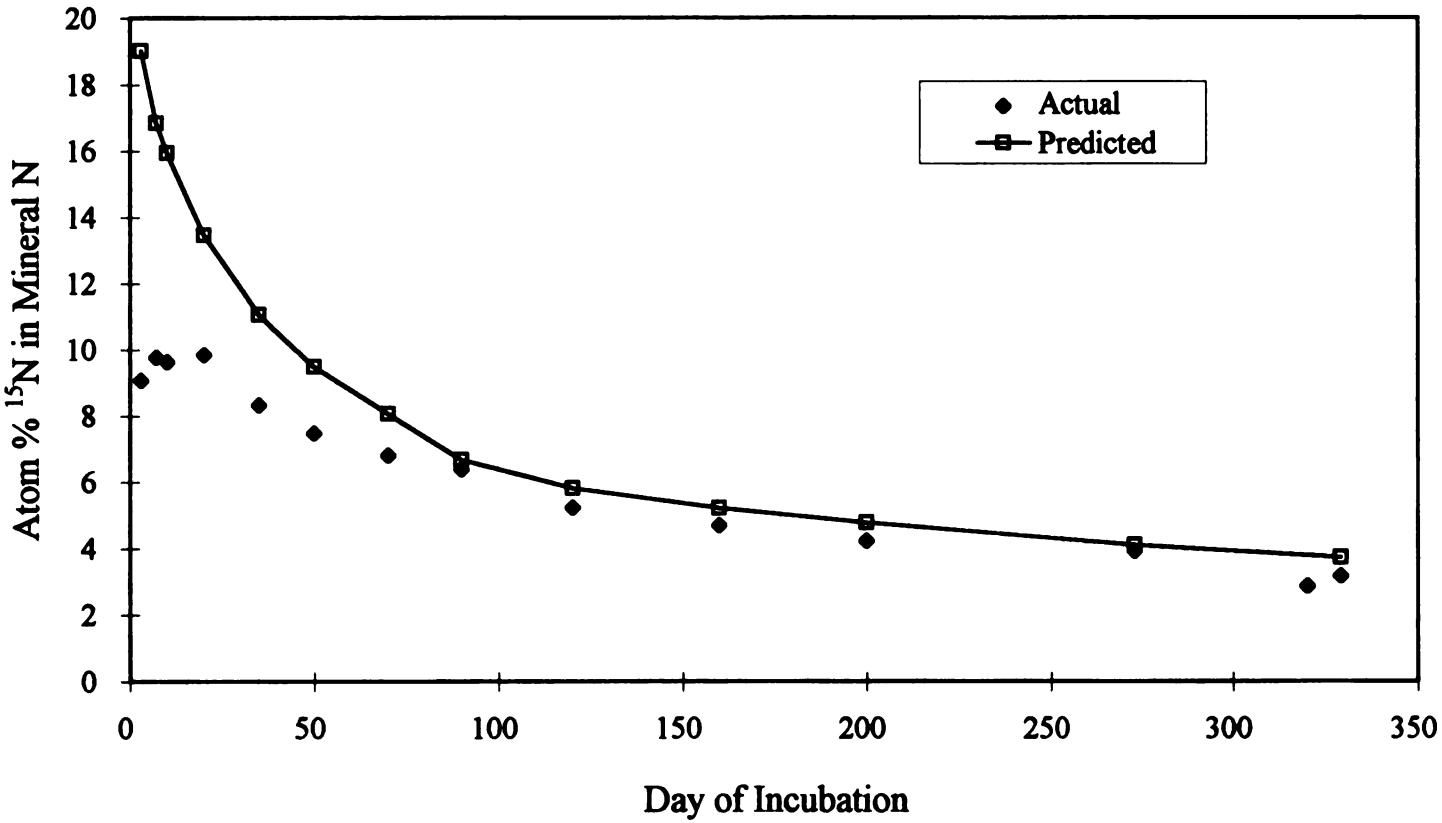

Figure 11. Predicted and measured atom % ^{15}N in mineral N of unfertilized Misteguay silty clay soil samples incubated in 1993.

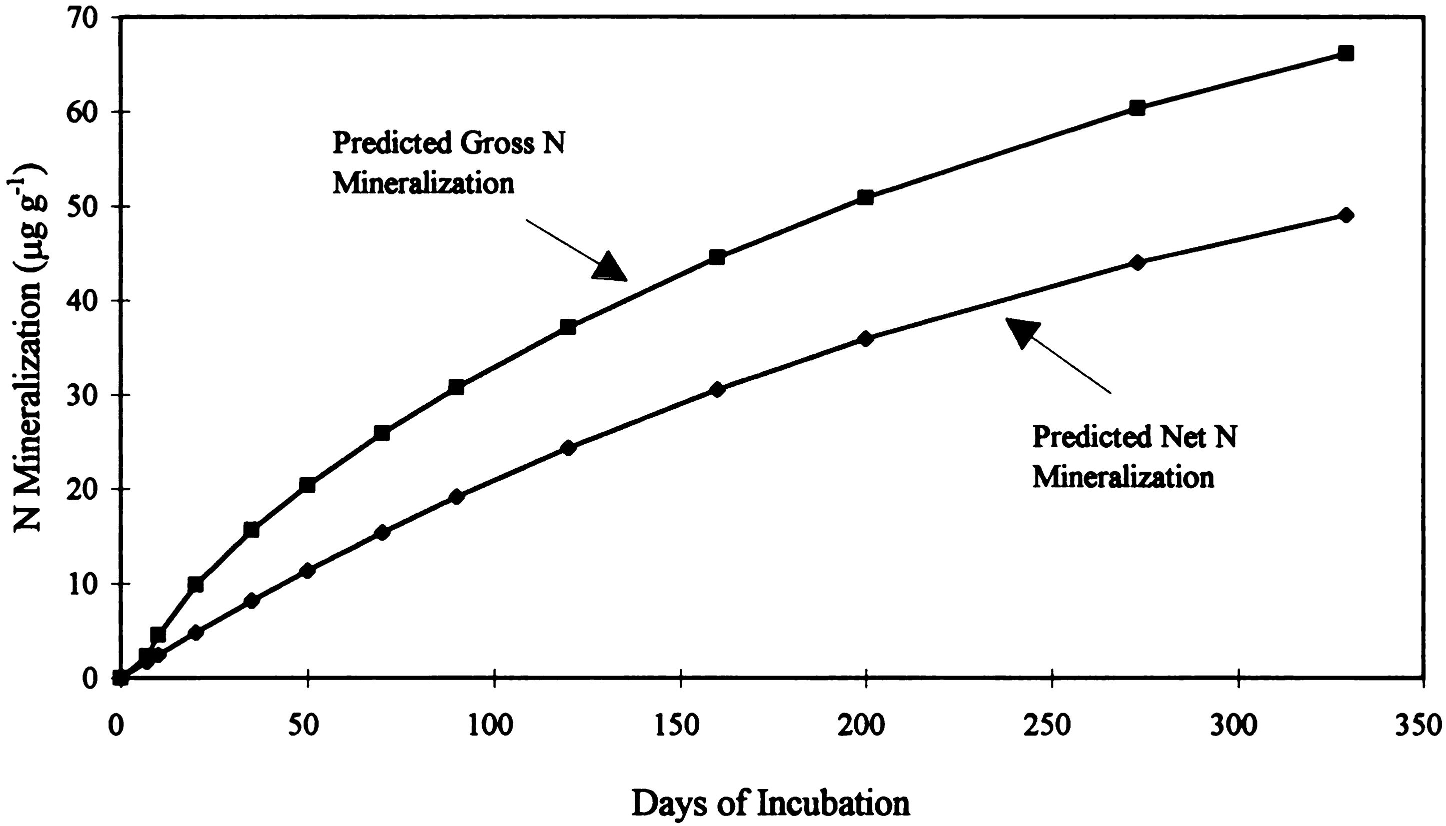

Figure 12. Gross and net N mineralization of unfertilized Misteguay silty clay soil incubated in 1993.

Table 4. Predicted gross N immobilization rates for 1993 incubation experiment.

Interval time	Predicted gross N immobilization
---- Day ----	------- $\mu g\ g^{-1}\ day^{-1}$ ------
5	0.828
8.5	0.604
15	1.744
27.5	2.093
42.5	1.667
60	1.761
80	2.019
105	1.552
140	1.223
180	0.991
236.5	1.685
301	1.051

SUMMARY

Nitrogen fertilizer recommendations for sugarbeet requires the quantification of N mineralized from soil organic matter which may be available for plant uptake. This quantification could be achieved by predicting field cumulative net N mineralization based on laboratory incubation study. A long-term laboratory incubation study was conducted in 1993. In addition, two field experiments were conducted on a Misteguay soil at the Bean and Beet Research Farm, Saginaw, in 1993 and 1994.

Cumulative net N mineralization (N_m) data from the incubation study was fitted to linear and one-pool exponential models (Figures 1 and 2). N_m increased with time of incubation without leveling off at the end of the incubation period. This agrees with Beloso et al. (1993). Rates of mineralization (*k*) were 0.152 mg kg^{-1} day^{-1} and 0.00337 mg kg^{-1} day^{-1} for linear and exponential models, respectively. Potentially mineralizable nitrogen, N_o, was 73.1 in the exponential model. The exponential model didn't allow for replenishment of N_o continuously by N derived from decomposition of fresh residues and rhizosphere microbial biomass.

The total rainfall was 368 mm during the 1993 growing season. The rainfall pattern of the 1993 growing season showed that each heavy rainfall period was followed by a light one (Figure 3). In 1993, the surface soil layer (0-22 cm) generally tended to be equal or slightly wetter than the subsoil layer (22-45 cm), except during the mid season between end of July and early August (Figure 4). During the 1994 growing season total rainfall was 514 mm. The rainfall pattern was that each two heavy rainfall periods were followed by a light one (Figure 5). The surface soil was equal in moisture relative to that of subsoil (Figure 6).

Mineral N concentration in the surface layer was higher than the subsoil during June and early August for the 1993 growing season. In both layers the soil mineral N increased until late June, then declined dramatically until end of July and it leveled off after that (Figure 7).

Increases in field mineral N during the 1993 and 1994 early in the growing seasons were attributed to mineralization and nitrification of previous crop residues and to low N uptake by sugarbeet plants. Mineralization and nitrification of decomposed organic material were enhanced by warmer temperatures, increase in activity of nitrifying organisms and soil moisture content. The dramatic decline in mineral N after June was mainly due to the higher N uptake by sugarbeet plants relative to soil mineralization and nitrification. The pattern of field soil mineral N in 1994 growing season was similar to 1993 except in the first quarter of the season (Figure 8) where soil mineral N was lost from the surface to the deeper layers (Figure 8). A model was developed to predict the amount of N lost during the growing seasons based on predicted field N mineralization, predicted daily N uptake and water balance models. N leached during 1993 growing season was considered insignificant. However, losses of mineral N from the rooting zone early during the 1994 season were mainly due to high rainfall events during April and July. The estimated leached amount of field mineral N was 35.7 kg ha^{-1} for that year.

Cumulative N uptake in check plots of 1993 and 1994 growing seasons are shown in Figures 9 and 10.

The calculated cumulative net N mineralized during the growing season was 93.5 kg ha^{-1} and 84.1 kg ha^{-1} for 1993 and 1994 growing seasons, respectively. Lack of precision in collecting soil samples, measuring soil mineral N and determination of N uptake at harvest may lead to uncertainty in calculating N mineralization in the field, estimating the parameters in both models and in predicting N mineralization in the field.

Rates of mineralization in linear and exponential models were modified to field air temperatures at Q_{10} of 2 and 2.2 for both years using Eq. [3.3]. Values of N_t were corrected for soil moisture (W) using Eqs. [3.5] and [3.6] and were presented in Tables 1 and 2. The linear and exponential models predicted the field cumulative net N mineralized (N_t) in 1993. The two models were used to test the prediction of field cumulative net N mineralized in 1994. Adding the estimated leached soil mineral N (35.7 kg ha^{-1}) to the calculated cumulative net N mineralized during the season (84.1 kg ha^{-1}) brought the latter value close to the predicted value (120 kg ha^{-1}). Linear and exponential models predicted the cumulative net N mineralization in the field from a long-term aerobic incubation of Misteguay silty clay soil equally well.

Predicted atom % ^{15}N in mineral N at each sampling was determined using Eq. [3.12]. Measured and predicted atom % ^{15}N in mineral N declined rapidly at the beginning until the 20th day of the incubation then decreased at a constant rate (Figure 11). Predicted atom % ^{15}N in mineral N was almost double the measured value from the beginning of the incubation until the 20th day. The overprediction during that period of incubation might be attributed to immobilization of ^{15}N by soil microorganisms. Although we can not explain the discrepancy up to day 20, still we can estimate the gross immobilization between any two intervals of time

(Figure 12) using the modified equation by Kirkham and Barholomew (1945 and 1955). Gross rate of mineralization was 25.8 % greater than net mineralization rate.

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Chapter 4

PREDICTING NITROGEN FERTILIZER NEEDS FOR SUGARBEET GROWN ON MISTEGUAY SILTY CLAY SOIL IN MICHIGAN

Greater use of nitrogen fertilizer has been a major factor in increasing yields of arable crops. Nevertheless, there is concern within the sugar industry that too much N is currently being applied to the sugar beet (*Beta vulgaris* L.) crop because excessive N has deleterious effects on the quality which reduces the profitability for both the grower and the processor. In particular, beet given too much fertilizer N contains smaller concentrations of sugar and higher concentrations of α-amino N compounds, both of which decrease the efficiency of sucrose extraction.

Mineral N taken up during the course of sugar beet growth comes from three main sources: that present in the soil in spring, soil organic N mineralized during the growing season and that applied as fertilizer. Denitrification and leaching may cause nitrate-N to be lost before it is taken up by the crop (Armstrong et al., 1986).

Residual N, N mineralized from soil organic sources during the growing season and individual crop needs must be considered when predicting the N fertilizer required. Adams et al. (1983) mentioned that, as with any agricultural crop, an important cultural decision faced by the sugar beet producer is the appropriate rate of fertilizer application.

The question of appropriate fertilization rates had been extensively investigated by agronomists. The producer's actual rate of application might reflect information obtained from soil test reports, extension agronomists and fertilizer suppliers as well as the producer's own experiences and expectations concerning plant response and crop price.

For sugar beets, a typical measure of fertilizer response is root yield. For some producers, root yield appears to be of primary concern, rather than recoverable sucrose, even though returns are ultimately based on recoverable sucrose production. The decision as to the economically appropriate fertilization rate should be keyed to the response of recoverable sucrose to fertilizer, not simply root yield.

Halvorson and Hartman (1988) studied the effects of tillage systems on N requirements for optimum yield and quality of sugarbeet grown on a furrow-irrigated silty clay loam soil. They found that application of N significantly increased root yield as well as gross and recoverable sucrose yields, but reduced sucrose concentration of sugarbeet root and clear juice purity of all tillage treatments. They recommended that a N fertilizer rate of 112 kg ha^{-1} can be used for sugarbeet produced with reduced-tillage systems.

Nitrogen Recovery Efficiency (NRE)

Westerman and Kurtz (1974) suggested that there were four methods to calculate fertilizer N recovery by crops. These were the i) difference method, ii) unlabeled regression (N uptake vs. N rates applied- slope of the relationship between N uptake and applied N rates), iii) isotopic method (^{15}N recovered in plants), iv) labeled regression (^{15}N recovery in plants vs. N rates applied and where the intercept was considered theoretically as zero).

The most common method for determining fertilizer nitrogen recovery efficiency was the difference method. It was calculated as the difference in amount of fertilizer N taken up by the crop in fertilized and unfertilized plots divided by the amount of fertilizer N rate applied. Alternatively, if the experiment involved rates of N fertilizer, recovery might also be calculated by linear regression of N uptake by the crops with rate of applied N. This method might be vitiated by the priming effect, which results in increased uptake of N from soil organic matter in fertilized plots, causing an over estimation of NRE (Hauk and Bremner, 1976). Both of these methods were indirect and would not distinguish between fertilizer N and soil N. The assumption was that immobilization-mineralization and other N transformations during the course of the experiment were the same for both treated and control plots. Obviously this was an erroneous assumption and could account for gross differences between recovery calculated by nonisotopic and isotopic techniques (Westerman and Kurtz, 1974). In addition, Rao et al. (1991) reported that the increased availability of soil N in fertilized plots had been attributed to: (i) stimulation of microbial activity by addition of N fertilizer, (ii) nitrification of NH_4 fertilizers, causing acid hydrolysis of soil organic substances, (iii) changes in the plant's physiological processes induced by fertilizer N, (iv) osmotic effects and (v) increased root growth in fertilized plots.

The isotopic dilution technique was used by many workers to determine NRE by direct measurement of ^{15}N-labeled fertilizer taken up by the plant. This method was influenced by pool substitution of ^{15}N for ^{14}N, which could result in erroneous NRE estimations. This substitution leaves less ^{15}N available for plant uptake and so N recoveries estimated by this method might be low and could result in erroneous NRE estimation when substitution is not accounted for quantitatively.

Low and Piper (1957) studied the uptake of ^{15}N-labeled ammonium sulfate and urea N in ryegrass grown under greenhouse conditions. They found that N uptake calculated by the difference method was greater than the amount calculated by the ^{15}N tracer method. The difference method indicated that 37.5% of the applied N was taken up compared to 28% uptake calculated by the ^{15}N method. Terman and Brown (1968) stated that the commonly used difference method was oversimplified and didn't effectively characterize the efficiency of applied N. In addition, they stated that labeling techniques offered no distinct advantage over nonisotopic techniques in most routine N efficiency studies if multiple rates were compared. Zamyatina et al. (1968) determined the efficiencies of fertilizer N use in small field plots by difference method were higher than those obtained by the ^{15}N method. Applications of fertilizer N in greenhouse and laboratory experiments had been reported to stimulate, depress or have no effect on the mineralization of soil N (Westerman and Kurtz, 1973). In 1974, the same authors used 4 methods to estimate the recovery of fertilizer N by Sudax (sorghum-sudangrass hybrid) grown under field conditions. They found that on average the difference method over-estimated recovery of urea and oxamide N in sudangrass by 30% when compared to the isotopic tracer method. Similarly, nonisotopic linear regression of total N in crops on rates of N over-estimated recovery of urea and oxamide N when compared to linear regressions of isotopically-labeled fertilizer N. Westerman and Kurtz (1974) concluded that recoveries by nonisotopic methods were more likely to coincide with recoveries from isotopic method when only one harvest of the crop was considered and when N removed in the crop was small or when mineralizable N in the soil was low. In their opinion, a simpler and probably better method to determine the N recovery efficiency was from the difference between the total N uptake on fertilized and unfertilized plots. Recoveries measured in this way were usually constant over a considerable range of N fertilizer rates although they vary substantially among sites and crops.

Similarly, a pot study by Rao et al. (1991) to estimate the N-recovery efficiency by spring wheat showed that the NRE estimation by the isotopic method averaged 20% lower than the difference method, although the two estimations were strongly correlated (r^2= 0.94).

Models for Estimating N Fertilizer Requirement

The fertilizer N requirement of a crop depends in part on the amount of N mineralized from soil organic N before and during growth. Any attempt to predict the requirement by modeling techniques thus needs modeling of N mineralization. Since mineralized N may be leached when it is nitrified, it is important that the model should also include nitrification of ammonium ions and be compatible with an appropriate leaching model (Addiscott, 1983).

One model developed in France for estimating the N fertilizer requirement of winter wheat (Viaux 1980, Reemy and Viaux 1982) was :

$bY = (N_m + M_s + M_r + M_o + F) C$ where:

Y is expected yield, b is total N per unit yield of grain, N_m is mineral N in soil at the end of winter to the depth of soil to which the crop roots finally penetrate, M_s is N mineralized from the soil organic matter, M_r is N mineralized from residues of a previous crop, M_o is N mineralized from organic manures, F is fertilizer N to be applied and C is the efficiency of utilization.

Nitrogen balance systems for giving advice on fertilizer use had also been developed in the United States (Stanford 1973, 1982; Carter et al., 1976). Carter et al. (1976) developed a model where the inputs were the potential crop yield, profile mineral N at the start of the growing season and a recovery factor.

Sugarbeet, a rainfed crop, is grown on a wide diversity of soils and management practices in Michigan. These practices include crop rotations of legumes, returning crop residues and application of animal manures. In Michigan, researchers reported the effect of crop rotation on increasing yields of sugarbeet (Cook et al., 1946; Robertson et al., 1965 and 1977; Christenson, 1989; Christenson et al., 1991).

Optimum and economic sugarbeet production without polluting the environment requires an accurate estimation of the fertilizer N required. In view of this concern, it is necessary to have a prediction of N supply from soil organic matter for making fertilizer N recommendations for sugarbeet production. Models for predicting fertilizer N needs for sugarbeet under Michigan conditions are not developed yet.

The objective of this study was to develop a model to predict N fertilizer requirement for sugarbeet grown on a Misteguay silty clay soil. This model was based on N leaching, N uptake and N mineralization models that were developed and discussed in Chapter 3.

MATERIALS AND METHODS

This chapter will cover root yield, quality and estimation of each parameter that constitutes the prediction model for N fertilizer needs on sugarbeet.

In 1993 and 1994 two field experiments were established at the Saginaw Valley Bean and Beet Research Farm, Saginaw County, Michigan (43° 4' N, 84° 6' W). Sugarbeet were planted after dry bean (*Phaseolus vulgaris* L.) on a Misteguay silty clay soil (fine, illitic (calcareous), mesic, Aeric Endoaquent) in both years. Nitrogen as NH_4NO_3 was broadcast prior to sugarbeet planting in both years. Nitrogen rates were 0, 33, 67, 100, 134 and 168 kg N ha^{-1}. The plot size was 3 x 21 m and the experiment was placed in a randomized complete block design. There were 6 replications in 1993 and 4 in 1994. At the end of each season four sugarbeet plants were harvested, processed and analyzed for total N using the processing and analysis procedures mentioned in Chapter 2.

Root Yield and Quality

Root yield was determined by harvesting two-10 m rows in 1993 and one-19 m row in 1994. Sugar quality was determined by selecting twenty average size beet roots from each plot for juice extraction. These beets were sliced and the juice extracted from the resulting pulp was immediately frozen. The frozen juice was analyzed for clear juice purity and sucrose concentration as described by Dexter et al. (1967) and Caruthers and Oldfield (1961), respectively. Recoverable sugar per hectare and per megagram were calculated using the following equations based on the work of Dexter et al. (1967) and modified by Michigan Sugar Company (Dr. Zielke, personal communication)[1]:

$$RWST = [(\%S * 18.4 - 22) * (1 - (60/(CJP - 3.5)))]/0.4 \quad [4.1]$$

$$RWSH = RWST * RY \quad [4.2]$$

where RWST is the recoverable white sugar per megagram, %S is the percent sugar, CJP is the clear juice purity, RWSH is the recoverable white sugar per hectare and RY is the root yield (Mg ha^{-1}).

Nitrogen Uptake (N_{up})

Nitrogen uptake was estimated at harvest by removing 4 evenly spaced beet plants. The plants were divided into leaves, petioles and roots. They were processed as described in Chapter 2. Nitrogen was determined using a C/N analyzer. Ground plant material (2-3 mg for leaf, 5-6 mg for petiole and 8-11 mg for root tissue) was pelletized prior to analysis.

Modeling N Fertilizer Needs

The N fertilizer needs model consists of five independent variables and takes on the form:

$$N_f = [N_{up}(\text{opt}) - e_m (N_t + N_{min})]/e_f \quad [4.3]$$

where: N_f is predicted fertilizer N rate (kg N ha^{-1}), N_{up}(opt) is plant N uptake at an optimum N rate (kg ha^{-1}), e_m is fraction of mineral N recovered by plant, N_t is predicted field net N mineralization (kg ha^{-1}), N_{min} is measured mineral N at the beginning of the

[1] Dr. Richard Zielke, Director of Research, Michigan Sugar Company, Carrollton, Michigan.

season (kg ha^{-1}) and e_f is fertilizer N efficiency. It was assumed that predicted net N mineralization in the field in check plots was the same as in the fertilized plots and the mineral N at the beginning of the season was also the same in treated and nontreated plots. Fraction of mineral N recovered by the plant (e_m) was also considered to be constant in treated and non-treated plots and accounted for any N not used by the crop such as the residual N at the end of the growing season (N_r) and leached N (N_l).

Soil mineral N (N_{min} and N_r)

Soil samples from 0-22 and 22-45 cm deep were taken periodically during each growing season from the center of each check plot. They were processed and analyzed for mineral N (NH_4 and NO_3) using the methods and analysis described in Chapter 2. Mineral N at the beginning of growing season (N_{min}) was used in N fertilizer needs prediction model and that at the end of the season (N_r) was measured but not used in the model.

Predicted field N mineralization (N_t)

Data from 1994 were used to test the prediction equations. Extensive details of results and conclusions on the cumulative N mineralization in the field were presented in Chapter 3.

Plant N uptake at optimum N rate ($N_{up}(opt)$)

Four adjacent plants were harvested from each plot in October of 1993 and 1994. Plant samples were separated, into leaves, petioles and roots. They were processed (cleaning, drying and grinding) using the processing procedure outlined in Chapter 2. Pellets containing ground plant material (2-3 mg for leaves, 5-6 mg for petioles and 8-11 mg for roots) were analyzed for total N on a C/N analyzer.

Optimum N rate was determined from the first derivative of the equation of recoverable sugar per hectare versus applied N rate. Then, N uptake at the optimum N rate was determined from a plot of N uptake versus N rate. The values of N uptake at optimum N rate were then used in Eq. [4.3] to predict N fertilizer needs on sugarbeet for 1993 and 1994 growing seasons.

Fraction of mineral N recovered by plant (e_m)

Based on Eq. [4.3] the fraction of mineral N recovered by plant, e_m, was determined using the following equation:

$$e_m = (N_{up} - (e_f * N_f))/(N_t + N_{min}) \qquad [4.4]$$

N uptake from the check plots (N_{up}), fertilizer N rate (N_f) in check plots, predicted cumulative N mineralization in the field (N_t) and soil mineral N at the beginning of the growing season (N_{min}) were used to determine e_m.

Nitrogen fertilizer efficiency (e_f)

Nitrogen fertilizer efficiency (e_f) was determined by non-isotopic linear regression method in both years and isotopically in 1993. Using the non-isotopic method, e_f was determined from the slope of the linear regression line of N uptake as a function of applied fertilizer N rate. Isotopic determination was made in a separate experiment on the same soil. NRE (e_f) was calculated using the equations suggested by Rennie and Rennie (1983):

$$\%Ndft = \text{atom } \%\ ^{15}N \text{ excess in plant/atom } \%\ ^{15}N \text{ excess in tracer} \quad [4.5]$$

$$NRE = (\%Ndft * \text{ plant total N })/\text{rate of N fertilizer applied} \quad [4.6]$$

Prediction of N fertilizer rate (N_f)

Using all the above mentioned parameters N fertilizer rate was predicted using the following equation:

$$N_f = [N_{up} (\text{ opt. N rate }) - N_{up} (\text{ 0 N rate })]/e_f \quad [4.7]$$

RESULTS AND DISCUSSION

The 1993 and 1994 growing seasons were different which affected yield of sugarbeet. The yield tended to be greater in 1994. However, the pattern of response to applied N was similar in both years. The optimum N rate was 128 kg ha^{-1} for both years. Sugarbeet quality (percent sugar and recoverable sugar per Mg) declined with increasing N rate both years. The different weather patterns for the two years played a significant role in the differences between the two years. However these factors did not affect clear juice purity (CJP) as it would be shown in the following sections of this chapter.

Root Yield and Quality

In 1993 and 1994, root yield and recoverable sugar per hectare increased with increasing N rate reaching a maximum at 134 kg N ha^{-1} (Tables 1 and 2). Recoverable sucrose per megagram, % sucrose and CJP decreased with increasing N rates applied in both growing seasons. In addition, root yield, recoverable sugar and % sucrose tended to be higher in 1994 than 1993 at the same N fertilizer rates applied. However, CJP values tended to be similar for both seasons. The 1994 season was warmer and there was more rainfall (Christenson et al., 1994).

Model Variables Determinations

N_f was predicted using Eqs. [4.3] or [4.7] and N_t was predicted using equation [3.6] as shown in Chapter 3. N_{min} was measured and N_{up}, e_f and e_m were calculated using Eq. [4.4]. N_{up} (opt) was determined using equations in Figures 1 and 3 for 1993 and Figures 2 and 4 for 1994. e_f was determined as the slope of the regression equations in Figures 5 and 6 for 1993 and 1994, respectively. In the following sections, results of each variable for both years will be presented in details.

Soil mineral N (N_{min} and N_r)

Table 3 showed the mass of mineral N in check plots at the beginning (N_{min}) and at the end of the growing season (N_r) for both years. N_{min} was less in the 1993 than in 1994. N_{min} was used in Eq. [4.4] to calculate e_m and in turn in Eq. [4.3] to predict N fertilizer needs by sugarbeet, N_f. The mass of N at the end of the season (N_r) in 1993 was not different from that of 1994. N_r was measured but not used in the model.

Predicted field N mineralization (N_t)

The cumulative net mineralization in the long-term aerobic incubation experiment, N_m, was fitted to two models. Both models, N mineralization rates (*k*), N mineralization potential (N_o) as well as r^2 or R^2 are presented in Table 4. The regression curves are shown in Figures 1 and 2 of Chapter 3. Cumulative net mineralization (N_t) in the field for 1993 and 1994 were predicted by correcting N_m for temperature and soil moisture. N_t for 1993 and 1994 at Q_{10} 2.0 were 92.9 kg ha^{-1} and 120 kg ha^{-1}, respectively (Table 5). The 1994 N_t tended to be greater than 1993. This was due to warmer air temperatures and moisture conditions during 1994 growing season (Christenson et al., 1994) that indirectly increased the microorganisms activities to mineralize the decomposed crop residues.

Plant N uptake at optimum N rate (N_{up})

In 1993 and 1994, N uptake increased significantly as N rates increased reaching a maximum at 134 kg ha^{-1} (Tables 1 and 2). Maximum N uptake in the 1994 growing season was 30% more than in 1993.

The optimum N rate was determined from the regression equation in Figures 1 and 2 for 1993 and 1994, respectively. N uptake at the optimum N rate was determined from the equation in Figures 3 and 4 for 1993 and 1994, respectively. N uptake at optimum N rate was 178 kg ha^{-1} and 217 kg ha^{-1} for 1993 and 1994 growing seasons, respectively (Table 5). These values were used in Eq. [4.3] to predict N fertilizer needs (N_f).

Table 1. Root yield, N uptake, recoverable sugar per hectare (RWSH), recoverable sugar per ton (RWST), sucrose and clear juice purity (CJP) of sugarbeet as affected by nitrogen rate on a Misteguay silty clay soil, 1993.

Nitrogen Rate	Root Yield	Nitrogen Uptake	RWSH	RWST	Sucrose	CJP
kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg Mg^{-1}	------------ %	-----------
0	59.8	114	7500	125	17.3	94.2
33	61.6	124	7515	122	17.0	93.8
67	65.8	141	7870	120	16.9	93.3
101	65.2	141	7810	120	16.7	93.7
134	69.5	189	8020	116	16.4	93.2
168	68.5	222	7780	114	16.0	93.4
$LSD_{(P < 0.05)}$	3.61	33.8	455	3.65	0.29	0.85

Table 2. Root yield, N uptake, recoverable sugar per hectare (RWSH), recoverable sugar per ton (RWST), sucrose and clear juice purity (CJP) of sugarbeet as affected by nitrogen rate on a Misteguay silty clay soil, 1994.

Nitrogen Rate	Root Yield	Nitrogen Uptake	RWSH	RWST	Sucrose	CJP
kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg Mg^{-1}	----------- %	----------
0	68.5	114	9050	132	18.1	94.4
33	76.4	135	9940	130	17.8	94.5
67	79.5	176	10305	130	17.9	94.1
101	81.8	176	10420	128	17.8	93.6
134	85.3	236	10635	125	17.4	93.6
168	84.2	247	10500	125	17.5	93.4
$LSD_{(P < 0.05)}$	4.39	49.7	797	5.41	0.59	0.78

Table 3. Mass of soil mineral N at 0-45 cm deep in check plots of a Misteguay silty clay soil in 1993 and 1994 growing seasons.†

Year	Season	Mass
		------ kg ha^{-1} ------
1993	Beginning (N_{min})	43.9 (2.4)
	End (N_r)	35.8 (0.6)
1994	Beginning (N_{min})	55.3 (2.0)
	End (N_r)	23.2 (0.7)

† Numbers in parantheses are standard errors of the means. Means are average of 6 replications for 1993 and of 4 replications for 1994.

Table 4. Equations and coefficients of determination (r^2 or R^2) of linear and exponential models of cumulative net N mineralization predicted on check plots of a Misteguay silty clay soil in an aerobic incubation experiment in 1993.

Model	Equation	r^2 or R^2
Linear	$0.152\,t + 3.4$	0.979
Exponential	$73.1\,(1 - \exp(-0.00337\,t))$	0.988

Table 5. Predicted and measured model parametrs†, N_{up}, N_t, N_l, N_{up} (opt.), N_f, e_m and e_f at Q_{10} of 2.0 for 1993 and 1994 growing seasons.

Year	N_{up}	N_t	N_{up} (opt.)	N_f	e_m	e_f
	----------	----------	kg ha^{-1}	----------		
1993	114	92.9	178	103	0.83	0.62
1994	114	120	217	126	0.65	0.82

† N uptake in check plots (N_{up}); predicted net mineralization (N_t); plant N uptake at optimum N rate (N_{up} (opt.)); predicted N rate (N_f); fraction of mineral N recovered by plant (e_m) and N fertilizer efficiency (e_f).

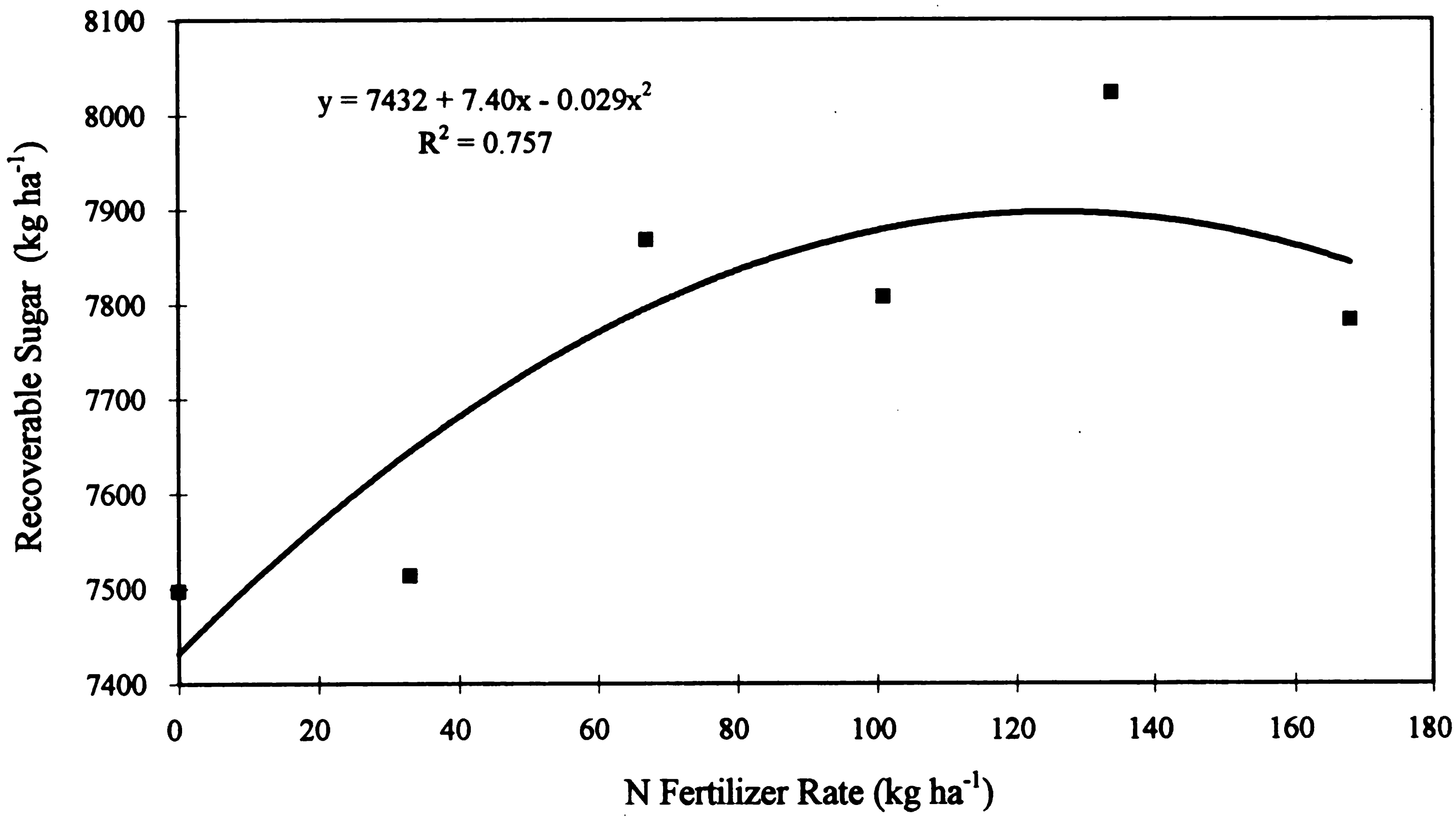

Figure 1. Recoverable sugar as affected by N fertilizer rate applied in 1993.

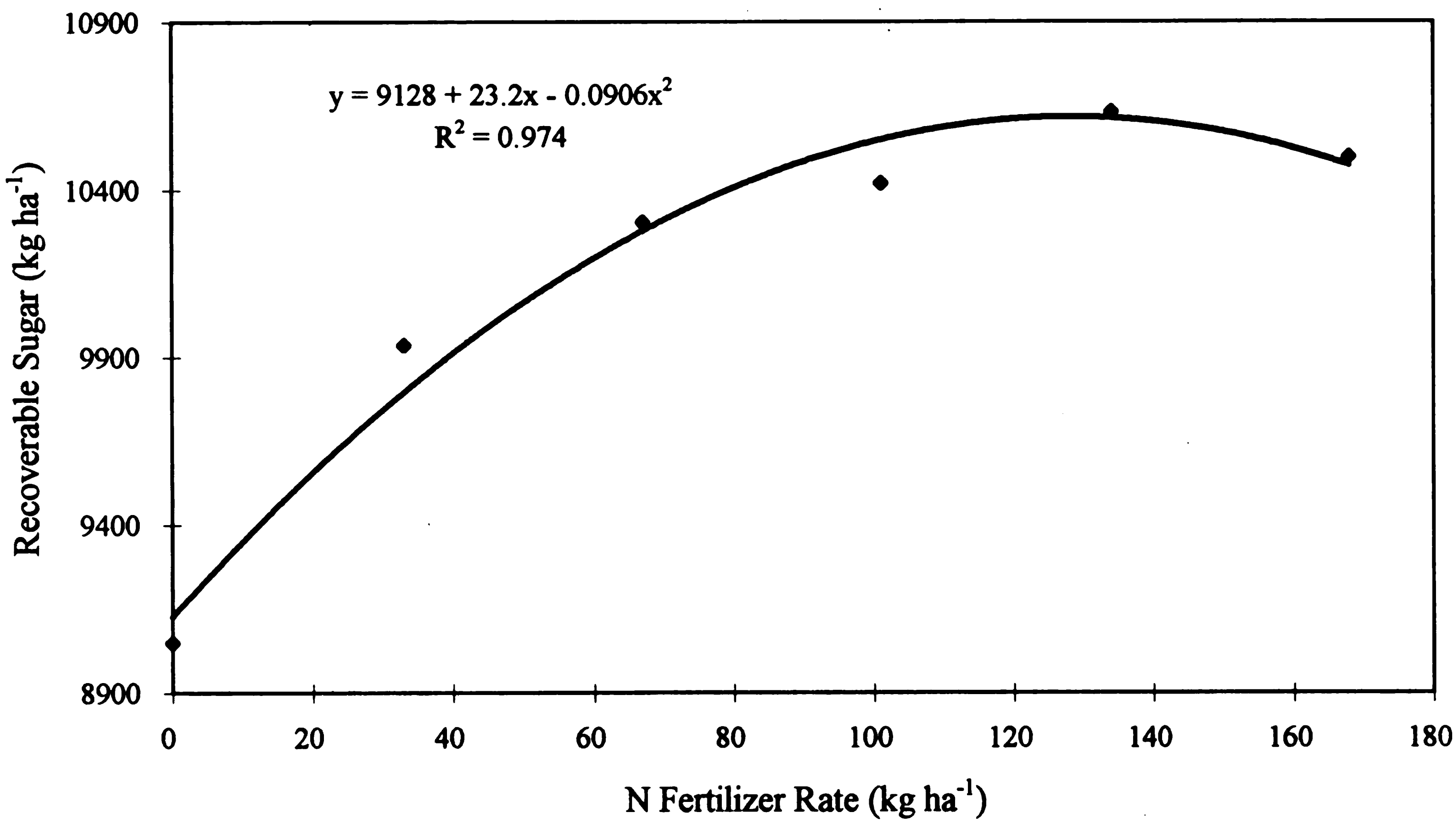

Figure 2. Recoverable sugar as affected by N fertilizer rate appied in 1994.

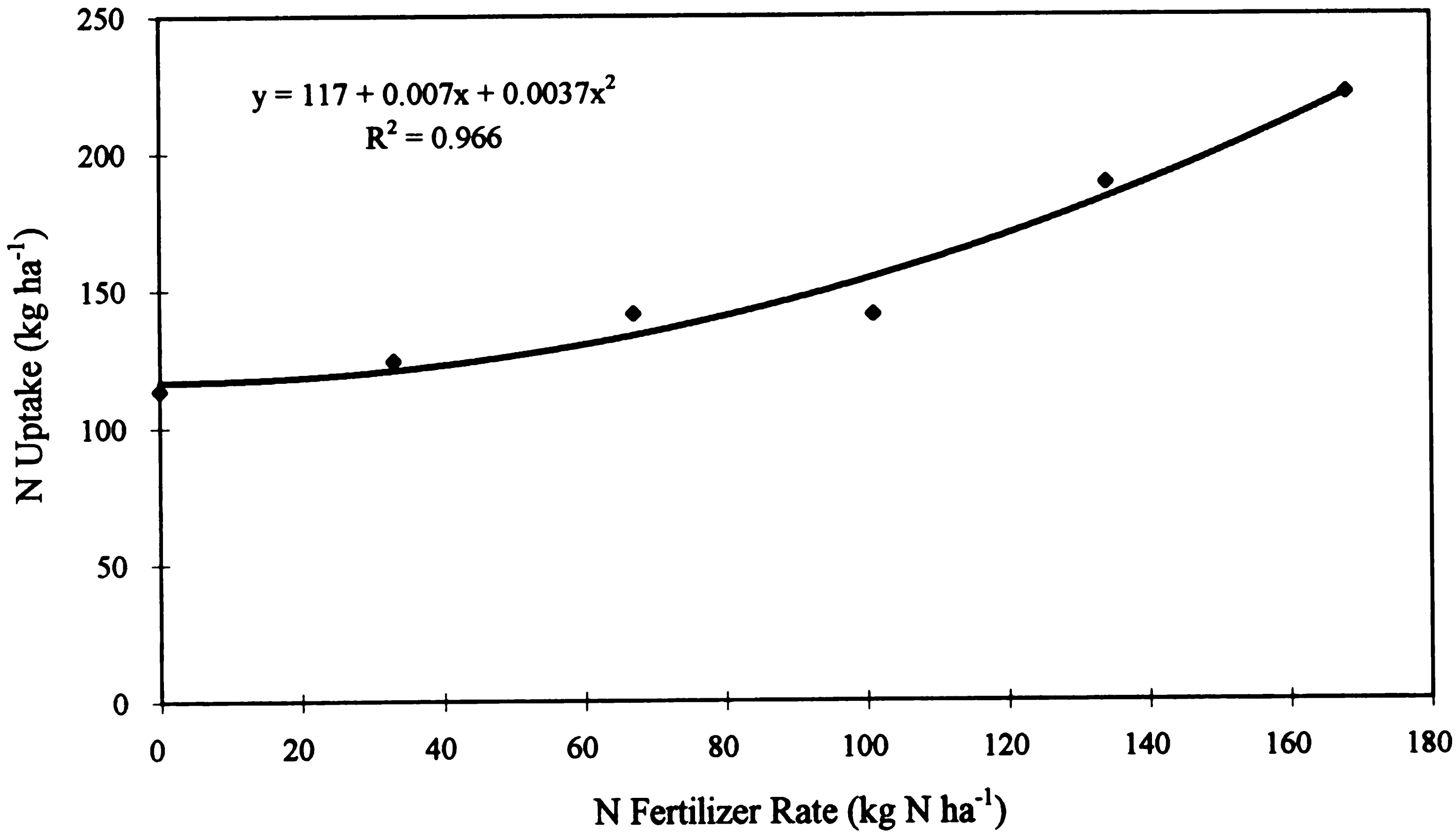

Figure 3. N uptake by sugarbeet as affected by N fertilizer rate applied in 1993.

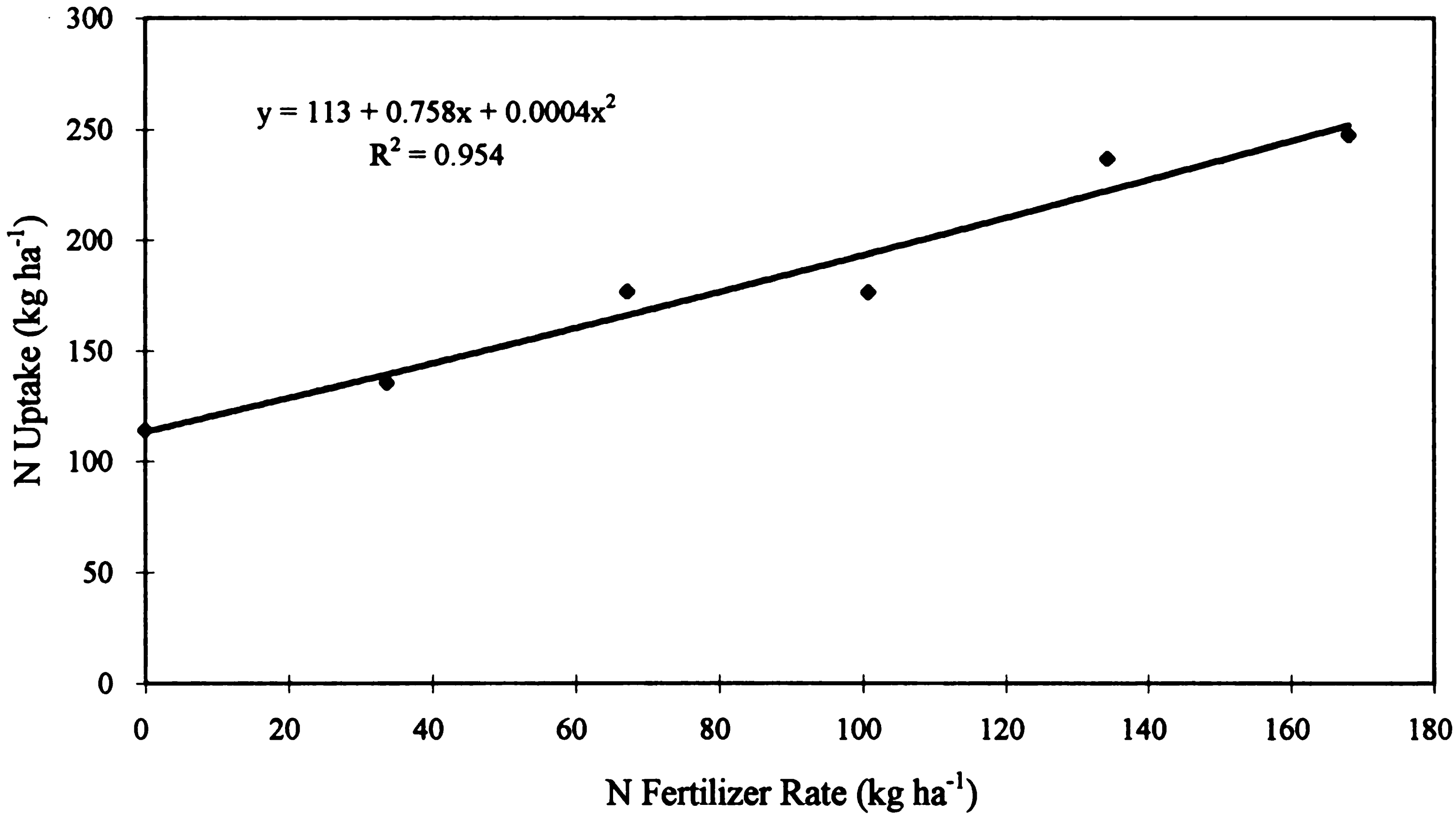

Figure 4. N uptake as affected by N fertilizer rate applied in 1994.

Fraction of mineral N recovered by plant (e_m)

The fraction of mineral N recovered by plant, e_m, is calculated using Eq. [4.4]. Values of e_m at Q_{10} 2.0 for 1993 and 1994 growing seasons are shown in Table 5. The fraction of mineral N recovered by plant, e_m, accounted for any soil mineral N not used by the crop during the growing season. This fraction was higher for 1993 than 1994. This could be either due to higher predicted values of field N mineralization or predicted N leached than should be. These values were used in Eq. [4.3] to predict N fertilizer needs by sugarbeet, N_f.

N recovery efficiency (e_f)

Using the non-isotopic linear regression method nitrogen fertilizer efficiency, e_f was determined as the slope of the regression line of N uptake as a function of applied fertilizer N rate (Figures 5 and 6). Nitrogen fertilizer efficiency, e_f, tended to be lower in 1993 compared to 1994 (Table 5). This was due to higher rainfall and warmer air temperatures. These two factors increased soil N mineralization and plant growth rate. This suggests that e_f is a moisture and temperature dependent parameter. Nitrogen fertilizer efficiency, e_f, determined by non-isotopic linear regression method was 0.62 and 0.4 when determined by isotope N fertilizer in 1993.

Prediction of N fertilizer rate (N_f)

Equations [4.3] or [4.7] were used to predict N fertilizer rate. Predicted N fertilizer rate, N_f, was 103 kg ha^{-1} in 1993 and 166 kg ha^{-1} in 1994 (Table 5). An increase in N fertilizer beyond the optimum rate would add to production costs. The excess N would be either left in soil at end of season, exposed for denitrification and/or leaching. The model suggested that 103 kg N ha^{-1} is an optimum fertilizer N rate to be applied for optimum returns in moderate weather years and 126 kg N ha^{-1} in wet or humid years.

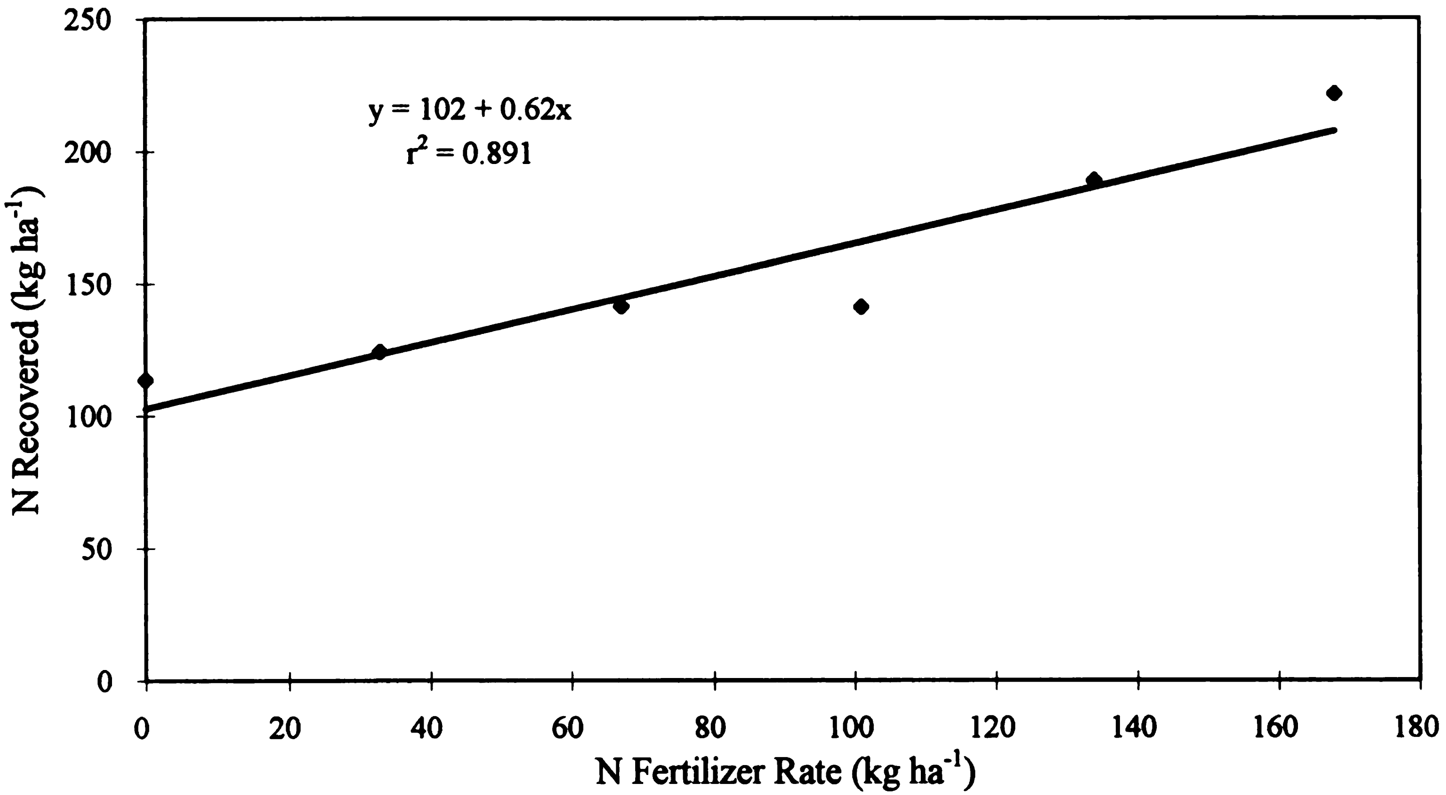

Figure 5. N recovery efficiency (e_f) as the slope of the regression line of N uptake as affected by N fertilizer rate applied in 1993.

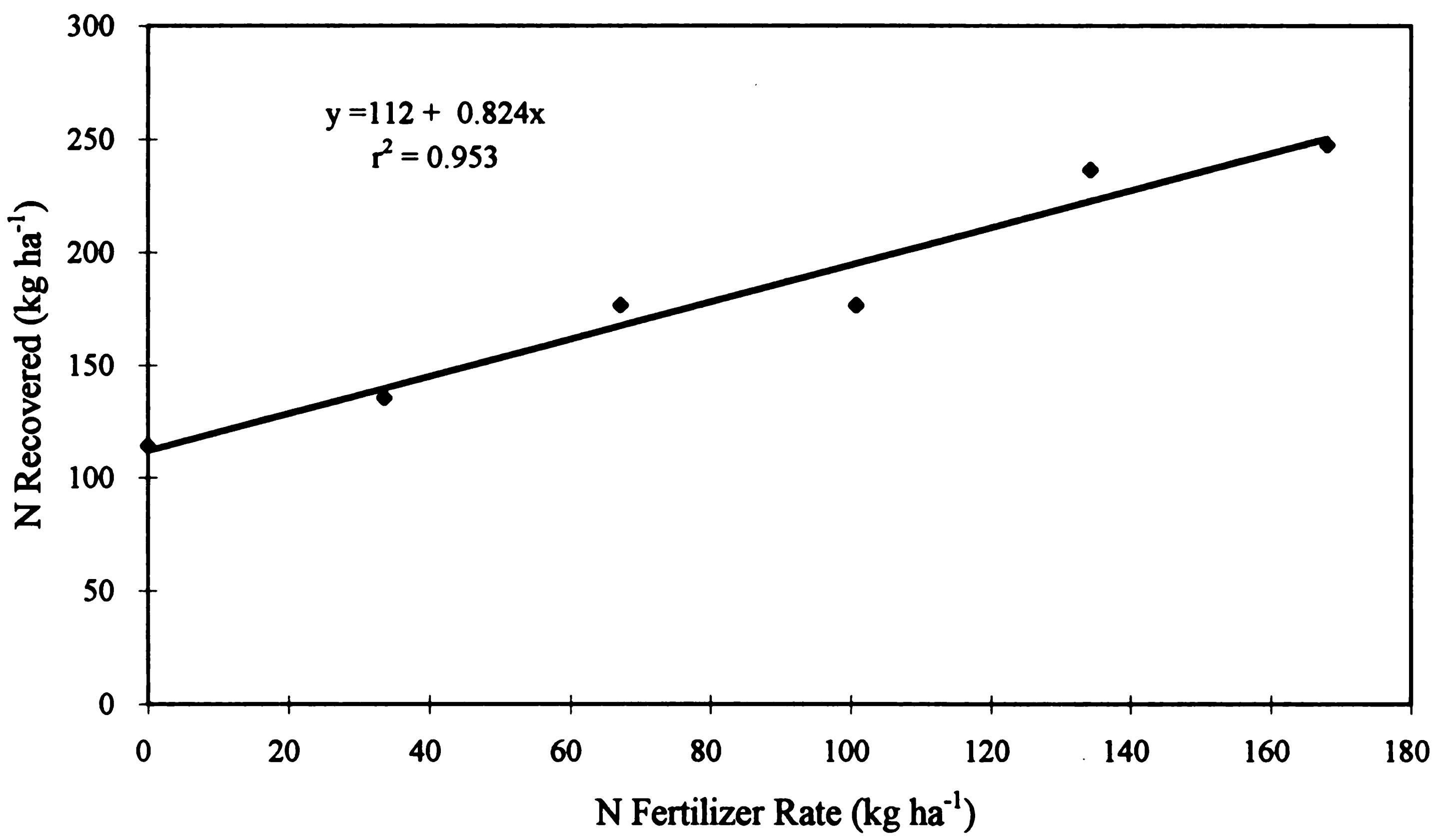

Figure 6. N recovery efficiency(e_f) as the slope of the regression line of N uptake as affected by N fertilizer rate applied in 1994.

SUMMARY

Excessive use of N has deleterious effects on the quality of the harvested beet which makes the crop less profitable for both growers and processors. Optimum and economic sugarbeet production without polluting the environment requires an accurate estimate of the fertilizer N required. In N balance models, N fertilizer requirement is effectively calculated as the demand of the crop for N less the sum of the inorganic N in the soil at beginning of the season and an estimate of the total amount mineralized during the growing season. Prediction of N supply from soil organic matter is necessary for evaluation of N fertilizer needs on rain-fed sugarbeet production in Michigan. Nitrogen supply of Misteguay silty clay soil from soil organic matter in Michigan was predicted. Results were presented in Chapter 3 and were used in a working model with seven independent variables and one dependent variable using Eq. [4.3]. The model predicted N fertilizer needs of sugarbeet. Initial soil mineral N, soil N processes and weather factors have a big influence on yield, N uptake by crops, crop quality, fraction of mineral N recovered by plants and on prediction of N fertilizer needs.

In 1993 and 1994, root yield and recoverable sugar per hectare increased significantly as N rates increased and reaching a maximum at 134 kg N ha^{-1} (Tables 1 and 2). An increase in N rate from 134 to 168 kg N ha^{-1} didn't increase the root yield and recoverable sugar per hectare significantly in both years (Tables 1 and 2). Recoverable sucrose per megagram, % sucrose and CJP decreased with increased rates applied in both growing seasons (Tables 1 and 2). In addition, the values of root yields, recoverable sugar per hectare and per megagram and % sucrose tended to be higher in 1994 compared to those of 1993 at same N fertilizer rates applied. However, CJP values were similar both years. The reasons behind this increase could be attributed to warmer temperatures, higher rainfall, increased soil microorganisms activities, more mineralization of soil organic residues and higher initial soil mineral N in 1994 growing season compared to that of 1993.

Nitrogen fertilizer needs model consisted of seven independent variables and took on the form: $N_f = [N_{up} - e_m (N_t + N_{min})]/e_f$

where N_f is predicted fertilizer N rate (kg N ha^{-1}), N_{up} is plant N uptake at an optimum N rate (kg ha^{-1}), e_m is fraction of mineral N recovered by plant, N_t is predicted field net N mineralization (kg ha^{-1}), N_{min} is measured mineral N at the beginning of the season (kg ha^{-1}) and e_f is N fertilizer efficiency.

Table 3 showed the mass of soil mineral N in check plots at the beginning (N_{min}) and at the end (N_r) of the growing season for both years. N_{min} for 1993 growing season was lower than that of 1994 growing season at 0-45 cm deep. However, N_r of 1993 growing season was higher than that of 1994 at same depth.

Cumulative net mineralization in the field, N_t, for 1993 and 1994 were predicted by modifying N_m for temperature and soil moisture. N_t for 1993 and 1994 at Q_{10} 2.0 were 92.9 kg ha^{-1} and 120 kg ha^{-1}, respectively (Table 5). N_t was higher in 1994 than in 1993. This was due to warmer temperatures and more rainfall during the 1994 growing season that indirectly increased the microorganisms activities to mineralize the decomposed crop residues.

The optimum N rate was determined from the regression equation in Figures 1 and 2 and N uptake at the optimum N rate was determined from the equation in Figures 3 and 4. N uptake at optimum N rate was 178 kg ha^{-1} and 217 kg ha^{-1} for 1993 and 1994 growing seasons, respectively (Table 5).

The fraction of mineral N recovered by plant (e_m) at Q_{10} 2.0 for 1993 was 0.83 0.65 for 1994 (Table 5). e_m accounted for any soil mineral N not used during the growing season.

In 1993 and 1994, N uptake increased significantly as N rates increased and they were maximum at 134 kg ha^{-1} (Tables 1 and 2). Maximum N uptake in 1994 growing season was 30% more than in 1993. Using the non-isotopic linear regression method nitrogen fertilizer efficiency, e_f, was determined as the slope of the regression line of N uptake as a function of applied fertilizer N rate (Figures 5 and 6). e_f was lower in 1993 as compared to that of 1994 (Table 5). This was due to more rainfall and warmer air temperatures that in turn increased soil N mineralization and plant growth rate. This suggests that e_f is a moisture and temperature dependent parameter. Nitrogen fertilizer efficiency, e_f, determined by non-isotopic linear regression method was 0.62 and 0.40 when determined by isotope N fertilizer in 1993.

Equation [4.7] was used to predict required N fertilizer rate for optimum N uptake. N_f was 103 kg ha^{-1} in 1993 and 126 kg ha^{-1} in 1994 (Table 5). With higher N fertilizer efficiency the plant N uptake was higher and hence the N fertilizer needed was greater in 1994 as compared to that of 1993.

Applying N fertilizer in excess of the optimum N rate would be costly and non-profitable. In addition, mineral N left in soil as residual mineral N after harvest and not taken up by plants would be lost as denitrification or leaching. The results suggest that 103 kg N ha^{-1} is an optimum fertilizer N rate to be applied for optimum returns in moderate weather years and 126 kg N ha^{-1} in wet or humid years. These recommendations are done under rain-fed sugarbeet grown on a Misteguay silty clay soil. The N fertilizer needs model predicted the fertilizer required for sugarbeet well.

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Chapter 5

SUMMARY AND CONCLUSIONS

Optimum and economic sugarbeet production without polluting the environment requires an accurate estimate of the fertilizer N required. This entails evaluating the amount of mineral N present in the soil at the beginning of the season and the amount of N released from soil organic matter during the growing season. It seemed that modeling would be the best approach since models to predict N fertilizer needs by rain-fed sugarbeet are not developed yet.

The main goal of this study was to develop a model that predicts N fertilizer needs by sugarbeet grown in rain-fed system on a Misteguay silty clay soil. The field studies were located on the Saginaw Valley Bean and Beet Research Farm in Saginaw County, Michigan (43° 4' N, 84° 6' W).

In the development of the model, temporal and spatial distribution of ^{15}N in the soil and temporal pattern of N uptake were measured. Long term aerobic laboratory incubation studies were conducted to measure cumulative net N mineralization and hence to predict cumulative net N mineralization in the field. Models predicting daily soil-water balance, daily N leached and daily N uptake were developed. Root yields and quality parameters as affected by N fertilizer rates were evaluated.

Nitrogen fertilizer efficiency was determined.

The results were summarized as follows:

Temporal and Spatial Distribution of ^{15}N in Soil

1. Mineral N concentration was highest in the 30 cm depth after 1-week after application.
2. Mineral N concentration decreased with time at all depths except at 4-weeks after application. The decline with time at 120 cm was less pronounced than at the other depths.
3. At point of application, atom % ^{15}N excess declined with time at all depths.
4. One week after application, atom % ^{15}N excess was less in the 30 cm layer than in the lower depths.
5. Ten cm lateral movement of the tracer ^{15}N from point of injection was detected at 75 cm and 120 cm deep at 4-weeks after application.

Temporal Pattern of N uptake by Sugarbeet

1. Nitrogen uptake and ^{15}N uptake by sugarbeet from various depths followed a typical S-shaped pattern.
2. Fifteen weeks after planting (3rd week of August 1991) marked the period when sugarbeet began to direct energy to storage of sugar rather than vegetative growth.
3. Percent N derived from the tracer was recovered from all depths but most effectively from the top 30 cm depth.
4. Eventhough N was taken from depths to 120 cm, N was taken up mainly from the surface 30 cm.

Estimation of Cumulative Net N Mineralization in the Field from a Laboratory Incubation Study

1. Data from the cumulative net N mineralization (N_m) in laboratory incubation study was fitted to linear and exponential models.

2. Rate of mineralization was 0.152 mg kg^{-1} day^{-1} and coefficient of determination was 0.974 for linear fit. These parameters were 0.00337 mg kg^{-1} day^{-1} and 0.988 for exponential fit, respectively.

3. The potential N mineralization (N_o) for Misteguay silty clay soil was 73.1. This was determined at optimum temperature and moisture of 25 °C and -0.03 Mpa, respectively.

4. Rainfall during the growing season was less (368 mm) in 1993 than in 1994 (514 mm).

5. The rainfall pattern in 1993 influenced the relative moisture content in the surface (0-22 cm) compared to the subsoil (22-45 cm). Moisture content of the surface soil was equal or greater than the subsoil except during the month of July where the surface soil had equal or less water content than the subsoil.

6. The rainfall pattern in 1994 was more uniform with shorter periods with little rainfall.

7. The surface soil was more moist relative to the subsoil during the whole season of 1994.

8. Mineral N concentration was significantly higher in the surface layer than in the subsoil during June and early August of 1993. In both layers, mineral N

concentration increased until late June and then declined dramatically until end of July where it remained fairly constant the rest of the season.

9. The increase in soil mineral N during the growing season of 1993 was due to mineralization of soil organic matter whereas the decrease was due to higher N uptake by sugarbeet relative to N mineralization.

10. The pattern of soil mineral N in the 1994 growing season was similar to that of 1993 in the except in the first quarter of the season where mineral N concentration was greater in the subsoil layer than in the surface layer. This was due to heavy rainfall (104 mm) during a short period of time and negligible to low N uptake by small sugarbeet plants.

11. The reasons behind the increase of soil mineral N in 1994 growing season were the same as those in 1993. However, the decline was due to leaching in addition to high N uptake by plants relative to soil N mineralization.

12. Predicted field cumulative net N mineralization (N_t) based on long-term incubation of Misteguay silty clay soil took the following forms: $N_t = W(k_l t) + c$ and $N_t = W N_o (1- \exp(-k_l t))$ for linear and exponential models, respectively. N_o is potential mineralizable N, k_l is the adjusted rate of mineralization to air temperature, W is soil moisture correction and c is constant.

13. The calculated cumulative net N mineralization in the field was 93.5 and 84.1 kg ha^{-1} for 1993 and 1994 growing seasons, respectively.

14. Using the N balance approach suggested by Shaffer's et al. (1991), predicted amounts of N leached during 1993 growing season was considered insignificant

(6.9 kg ha^{-1}). However, estimated N leached in 1994 growing season was 35.7 kg ha^{-1}.

15. The addition of the estimated leached amounts of soil mineral N (35.7 kg ha^{-1}) in 1994 to the calculated cumulative net N mineralization (84.1 kg ha^{-1}) brought the latter value close to the predicted value (120 kg ha^{-1}).

16. Measured and predicted atom % ^{15}N in mineral N declined rapidly at he beginning until the 20th day of the incubation then decreased at a constant rate.

17. Predicted atom % ^{15}N in mineral N was almost double the measured value from the beginning of the incubation until the 20th day. The overprediction could be attributed to immobilization of ^{15}N by soil microorganisms that wasn't accounted for in the measured value.

18. Gross rate of mineralization was 25.8% greater than net N mineralization rate.

Predicting Nitrogen Fertilizer Needs on Sugarbeet Grown on Misteguay Silty Clay Soil in Michigan

1. Root yield and recoverable sugar per hectare increased significantly as N rates increased and they were maximum at 134 kg N ha^{-1} in 1993 and 1994.

2. Recoverable sucrose per megagram, % sucrose and clear juice purity (CJP) decreased with increased rates applied in both growing seasons.

3. Nitrogen fertilizer needs model took the following form:

$$N_f = [N_{up}(\text{opt}) - e_m (N_t + N_{min})]/e_f$$

where: N_f is predicted fertilizer N rate (kg N ha^{-1}), N_{up}(opt) is plant N uptake at an optimum N rate (kg ha^{-1}), e_m is fraction of mineral N recovered by plant, N_t is predicted field net N mineralization (kg ha^{-1}), N_{min} is measured mineral N at the beginning of the season (kg ha^{-1}) and e_f is N fertilizer efficiency.

4. Optimum N uptake by sugarbeet was 178 kg ha^{-1} and 217 kg ha^{-1} for the 1993 and 1994 growing seasons, respectively.

5. Fraction of mineral N recovered by plant (e_m) was 0.83 and 0.65 for 1993 and 1994 growing seasons, respectively. e_m accounted for any soil mineral N not used by the plants during the growing seasons.

6. Using the exponential model and at Q_{10} of 2 predicted field net N mineralization (N_t) was 92.9 kg ha^{-1} and 120 kg ha^{-1} for 1993 and 1994, respectively.

7. The measured mineral N at the beginning of the season (N_{min}) was less (43.9 kg ha^{-1}) in 1993 than that in 1994 (55.3 kg ha^{-1}).

8. N fertilizer efficiency (e_f) was 0.62 in 1993 whereas it was 0.82 in 1994.

9. Optimum fertilizer N rate recommended for rain-fed sugarbeet grown on a Misteguay silty clay soil was 103 kg N ha^{-1} in moderate weather years and 126 kg N ha^{-1} in wet or humid years.

This work showed that fertilizer N requirement could be predicted in both dry and wet seasons if the appropriate adjustments were made to selected coeffientients. These adjustments included the modification of N mineralization rate k for air temperatures and correction of N_m for soil moisture W.

This model should be tested on other soils and crops. It requires weather, soil and plant data to predict the N fertilizer needed. However, we realize that this model like any other model is used after the harvest. Would it be possible to use this model at the beginning rather than at the end of the season? This can be achieved only after conducting experiments to get average values for optimum N uptake by the crop and the N fertilizer efficiency on a particular soil. Then Eq. [4.7], $N_f = [N_{up}(opt) - N \text{ (no fertilizer)}]/ef$, can be used to predict the required N fertilizer to be applied during the growing season.