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Diana L. Weigmann
Assistant Director

ABSTRACT

Research was conducted in soils of the Chesapeake Bay area to determine the effects of tillage practice and nitrogen (N) fertilizer application rates on N leaching from corn fields. Three well known computer models (NTRM, CERES-Maize, and VT-MAIZE) were tested to determine their ability to predict the distribution of N in (a) soil and crop, (b) the components of the N cycle, and (c) corn yields.

To accomplish the above objectives, two field sites were selected on agronomically important soils for either a corn (*Zea mays* L.)-wheat (*Triticum aestivum* L.)-soybean (*Glycine max* [L.] Merr.) or a continuous-corn rotation. The corn-wheat-soybean rotation was located on a Suffolk sandy loam soil (coarse loamy, siliceous, thermic Typic Hapludult) in the immediate Chesapeake Bay drainage basin. The continuous-corn rotation was located on a Groseclose silt loam soil (clayey, mixed, mesic Typic Hapludult) typical of finer-textured soils located in the upper reaches of tributaries that drain into the Chesapeake Bay. Management practices evaluated included tillage system and rate, source, and time of N application. Specifically, we looked at conventional vs. no-till; inorganic N vs. sewage sludge; preplant vs. split application of N; and a variety of N application rates. The N treatments for corn were 0, 75, 150, and 225 kg N ha^{-1} applied preplant; 150 kg N ha^{-1} applied 4 weeks after emergence; and 150 kg of mineralizable N ha^{-1} from anaerobically digested and either lime- or polymer-conditioned sewage sludge. The N treatments for wheat were 20 kg N ha^{-1} applied in the fall and 30, 60, or 90 kg N ha^{-1} applied in the spring; 60 kg N ha^{-1} split application; and 80 kg of mineralizable N ha^{-1} applied in the fall from either lime- or polymer-conditioned sewage sludge.

In the Groseclose soil, there was an increase in total yield and N uptake when sewage sludge was applied compared to the split and preplant application of inorganic N. There was no difference between polymer-or lime-conditioned sewage sludge application. Also, there were no differences between preplant and split application of N. Where no-till was used, there was an increase in both yield and N uptake compared with conventional till. In the Suffolk soil, tillage management did not influence yield or N uptake where time and source of N application were studied. This lack of response on the Suffolk soil is attributed to severe moisture deficits that were present during the growing season on this coarse-textured soil.

Nitrogen losses from the soil profile were directly related to the quantity of N remaining in the upper 1 m of the soil profile after the crop was harvested. Larger quantities of N were lost from the Groseclose soil where conventional till was employed during the first year of the study. This was attributed to enhanced mineralization where no-till was converted to conventional till and to lower yields and lower N recovery with conventional till. Losses of N tended to be higher from the conventional-till plots because of the larger quantities remaining at the end of the growing season. It should be noted that the years during which these studies were conducted were extremely dry, and the additional moisture in the Groseclose soil where no-till management was employed resulted in increased yield and increased N recovery. This study also emphasizes the need for better methods for making N recommendations for crop production.

The model performances varied from year to year and from one tillage practice to another. Because they were written for average soil and climatic conditions, they did not make satisfactory predictions in many instances. Such models require adjustment to reflect the moisture stress conditions that often prevail in this region for corn production.

Key Words: No-till, Nitrogen leaching, Denitrification, Nitrogen uptake, Sewage sludge, Computer models, Nitrogen balance, Nitrogen carryover

INTRODUCTION

I. Overview

Awareness of contamination of the basic resources essential for human survival, growth, and progress, such as water, soil, and air, has stimulated the interest of several scientific communities. Paradoxically, the environment can be contaminated and polluted with the basic commodities the scientific world produced to promote the well-being of human society and to make the world livable.

Environmental pollution is defined as contamination by compounds introduced through human activities. The definition hinges on the identifiable presence of a contaminant added by human activity (deHaan and Bolt 1979). Normally, products such as hydrocarbons, pesticides, herbicides, and heavy metals are considered to be soil pollutants. But with the advent of improved technology, by-products of well intended practices, such as wastewater treatment and nuclear power generation, have now augmented the list of potential environmental contaminants. Even nitrogen (N), when applied in excess as a component of a crop production system, has been identified as an environmental pollutant. The major concern with these substances is that they pose a potential hazard to the environment (Johnson 1971).

Lindemann and Cardenas (1984) reported the subsequent health hazards to both humans and animals due to nitrate (NO_3^-) from fertilizer application. Apart from the fact that excessive application of N fertilizers gives rise to accumulation of NO_3^- in plants, high levels of NO_3^- in drinking water are undesirable. When NO_3^- is ingested by infants that suffer from gastrointestinal upsets, it may result in a condition known as methemoglobinemia. Moreover, NO_3^- may cause carcinogenic N-nitroso compounds to form in the human gastrointestinal tract.

Enrichment of certain surface waters (primarily estuarine and coastal) may result in a number of water quality changes deemed undesirable, such as eutrophication. The effects of eutrophication include increased algal blooms, greater macrophyte growth, and O_2 depletion.

One source of potential N contamination arises from excessive or inefficient application of N fertilizers for crop production. Research indicates that there is a limit beyond which further increase in N fertilizer application does not increase crop yield (Gast et al. 1978; Broadbent and Carlton 1978). Excessive application of N occurs under conditions of improper use of N fertilizers. When this occurs, soils, plants, and the environment suffer undesirable symptoms that might not otherwise exist under normal agricultural use of soils.

The sudden and uncontrolled world population explosion since the beginning of the last century has resulted in increased food production by means of increased use of nutrients, improved grain varieties, and tillage management systems. These factors contributed significantly to the green revolution. The large increases in crop yield with increased N application have resulted in continually higher N application rates. Many states doubled their fertilizer consumption between 1960 and 1973 (Donahue et al. 1977). Unfortunately, large additions of crop nutrients to soils have increased the potential for contamination of ground and surface waters. This potential for increased contamination, in addition to the escalated energy crisis of 1974, which doubled and then continued to increase fertilizer prices, has brought about a new awareness and a critical examination of the use of commercial fertilizers. The potential for environmental degradation has placed new emphasis on research into the use of waste products such as sewage sludge as a N source and the use of best management practices (BMPs) such as selecting soils, crops, tillage practices, and fertilizer additions that would be most successful in increasing N use efficiency (NUE) and reducing N losses to surface and ground waters. Recently, soil scientists, agronomists, and environmentalists have focused their attention on the contribution of N fertilizers and management practices to nitrogen oxide emissions from and NO_3^- leaching through soils.

II. Nitrogen Sources

A. Commercial Fertilizers

Since the beginning of this century, especially during the period subsequent to World War II, both production and consumption of commercial fertilizers have increased rapidly (FAO 1973). Since N is required in large quantities for crop growth and can have a spectacular effect on crop yields, higher N application rates have been used for agricultural crops (Brady 1984).

The world consumption of N fertilizers has doubled in the last 20 years and quadrupled since the 1940s. The United States uses 8 to 12 million metric tons of N in fertilizers per year, which is 17.7% of the world total (FAO 1973). In the United States, fertilizer N use increased by 240% between 1965 and 1984 (Soileau 1988). During this same period fertilizer N consumption in Virginia increased by 175%, from 50,800 to 90,000 Mg (56,000 to 99,000 tons) (Virginia Department of Agricultural and Consumer Services 1988). Fertilizer N used for crop production in Virginia is valued at approximately $50 million.

B. Sewage Sludge

The value of sewage sludge as a crop fertilizer and land conditioner is well documented. In the Orient and in most of what are now called the "Third World" countries, it has been used for this purpose for centuries. It is only in the last century that western countries began utilizing this resource as a fertilizer. With the coming of cheaper and more efficient commercial fertilizers, sewage sludge as a fertilizer was ignored and became a burden to society; thus, a solution for its disposal was seriously sought. In recent years, however, there has been a growing interest in utilizing soil as a medium for treatment of municipal and industrial wastes (King 1973). Since sewage sludge has nutrient value, mainly N and P, its application to agricultural lands is one way of recycling these nutrients and conserving natural resources. This approach is gaining acceptance not only as a means of recycling nutrients but also as an effective means of disposing of sewage sludge. The increase in land application of sewage sludge in Virginia from less than 200 ha to more than 8,900 ha annually from 1980 to 1985 provides evidence for the increasing acceptance of this approach. Currently, Virginia farmers annually apply about 123,000 Mg (136,000 tons) of sewage sludge with approximately 4,500 Mg (4,900 tons) of N for crop production worth approximately $2.5 million. In addition to the value of N and P present in sewage sludge applied to farmlands, land application of sewage sludge may save Virginia municipalities as much as an estimated $12 million annually in operating costs.

Application of sewage sludge improves both chemical and physical properties of soils (Epstein et al. 1976) and results in favorable plant yield responses (Milke and Graveland 1972). Unfortunately, sewage sludge application can be limited with respect to land application when elevated levels of elements such as zinc, copper, nickel, lead, cadmium, and mercury are present. Some of these elements are phytotoxic while others pose a threat to animals and humans via accumulation in the food chain. On a cumulative basis, the rate at which sludge can be applied to soil may be determined by heavy metal content. On an annual basis, sewage sludge application rate is normally limited by the quantity of plant-available N present. If the amount of N mineralized is in excess of crop needs, it may result in groundwater pollution unless released from the soil profile by either denitrification or volatilization.

III. Tillage Practice

Traditionally, conventional tillage was the sole means of crop production. Some of the reasons for maintaining plowing and cultivation as a means of crop production were to establish and maintain a monoculture, to bury plant materials that had collected during the previous planting, to mix lower horizons of the soil profile with surface layers, and to loosen the surface to encourage water absorption. Recently, however, the emphasis in tillage has been shifting towards adopting minimum- or no-till practices. These procedures, generally referred to as conservation tillage, are being used to reduce time, to save fuel, to reduce labor and machinery costs, and to control erosion (Throckmorton 1986). It is estimated that at least 95% of the agronomic crops produced in the United States will be produced using conservation tillage by the year 2010 (USDA 1975).

The attractiveness of conservation tillage to farmers stems from the conservation of soil moisture, reduced soil and wind erosion, higher crop yields, and decreased energy use. But its economic impact, based primarily on higher crop yields, lower energy requirements, and reduced investment in machinery, is the basic reason for the shift from conventional to conservation tillage. Phillips et al. (1980) reported that no-till systems consume 7% less energy than conventional tillage for the production of corn. They also reported that 80% of the energy used by United States agriculture is from liquid petroleum fuels and natural gas, which makes conventional tillage economically untenable.

The use of conservation tillage was accelerated by the existence and availability of herbicides. Prior to the advent of effective herbicides, stubble mulch (a form of no-till) was practiced in the Great Plains of the United States and Canada to conserve moisture and reduce soil loss from wind erosion. However, since the 1930s and 1940s, the availability of effective herbicides has reduced the need for tillage to control weeds. Thus, conventional tillage need not be an integral part of crop production (Unger and McCalla 1980). Before this period, it was inconceivable to regress to a seemingly more primitive form of tillage (i.e., no-till) because conventional tillage had become a feature of more advanced systems of crop production.

Conservation tillage was reinstated into modern agriculture by simple but effective demonstrations by Garber (1927; as cited in Baeumer and Bakermans 1973) and Moody et al. (1961). Garber successfully oversowed a legume into an unproductive grass sod without tillage using simple techniques that demonstrated the essential features of zero tillage, i.e., growing a crop with the least possible soil disturbance. A similar experiment, but with corn, was conducted by Moody at the Virginia Agricultural Experiment Station in 1960. Thomas et al. (1973) reported that Moody "planted corn by removing plugs of soil with a soil sampling tube, dropping in a seed, and replacing the soil removed by the sampler . . . and the corn grew well." In addition, Blevins et al. (1971) reported an average yield difference of about 600 kg ha^{-1} in favor of no-till corn. Such experiments, together with the use of herbicides, helped popularize conservation tillage. Among the many possible consequences of shifting from conventional-till to no-till practices, soil erosion, soil moisture content, and crop yields seem to have occupied the attention of researchers. However, leaching and denitrification, two components of the N cycle that serve no useful nutritional function for the plant, have not received due consideration in relation to fertilizer application and crop nutritional consumption.

The impact of N application to cropland with respect to crop yield and quality and ground- and surface-water degradation needs to be considered in conjunction with BMPs such as conservation tillage. No-till is a BMP that has increased corn production. The single greatest advantage of no-till over conventional-till management with respect to crop growth is conservation of moisture by reducing evaporation, which contributes substantially to the increased yield of corn (Jones et al. 1968; Triplett et al. 1968; Blevins et al. 1971). The lower evaporation rate may promote NO_3^--N loss by leaching from the root zone, especially under saturated flow conditions. Leaching is further enhanced by the presence of cracks and macropores near the soil surface (Thomas et al. 1973). Moreover, the increased moisture present in the no-till soil profile may increase the potential for enhanced loss of N from the system as a result of increased denitrification.

Another major advantage of the no-till management system for crop production is that it is perhaps the most efficient method for reducing erosional losses of nutrients. The effect of no-till agriculture systems on erosion control is well documented. McGregor et al. (1975) observed a reduction in erosional losses from 17.5 to approximately 1.8 Mg ha^{-1} with no-till management, and Triplett and Van Doren (1977) reported as much as a 50-fold reduction in erosion in no-till management systems.

Despite the increasing popularity of conservation tillage, there is no clarity or consistency in the literature for the precise meaning of the various tillage practices. The term conservation tillage is used interchangeably with minimum tillage, reduced tillage, lo-till, mulch-till, no-till, stubble mulching, ecofallow, limited tillage, and direct drill — all of which have meanings that differ either in nuances or extent (Mannering et al. 1987). The multiplicity in terminology is partly due to the fact that these systems share common goals. Due to the lack of standardized meaning in usage, conflicting results are reported.

The Conservation Tillage Information Center (CTIC) opted for using the term conservation tillage as an umbrella term to encompass the spectrum of tillage practices used interchangeably with conservation tillage (CTIC 1982-85). The CTIC defined conservation tillage as any tillage and planting system that maintains at least 30% of the soil surface covered by residue after planting to reduce soil erosion by water. An identical definition is also used with respect to wind erosion. An extreme form of conservation tillage is no-till. No-till is defined as the introduction of seed into unplowed soil in narrow slots, trenches, or bands of sufficient width and depth for seed coverage and soil contact (Phillips et al. 1980). Weed control is accomplished primarily with herbicides. On the other hand, conventional tillage is the combined primary and secondary tillage operation normally performed in preparing a seedbed for a given crop grown in a given geographical area.

IV. Corn Yield and Nitrogen Uptake

Since the purpose of agronomic agriculture is to increase crop yield, the early successful results obtained with application of no-till seemed to satisfy this expectation, i.e. increased yield with minimum input. With regard to corn, several researchers confirmed that no-till corn performed better or as well as conventional tillage. Moody et al. (1961) and Jones et al. (1968) observed faster growth of sod-sown corn seedlings. Blevins et al. (1971) showed an average yield difference of 600 kg ha^{-1} in favor of no-till. Thomas et al. (1973) and Phillips et al. (1980) rated no-till better or just as good as conventional tillage. Averaged over a

3-year period, Wagger and Denton (1989) reported 32% higher corn grain yield due to no-till.

The positive effect of no-till on crop yield is often attributed to the larger quantities of available moisture conserved in the root zone (Triplett et al. 1968). This additional moisture enables no-till to support a crop through short-term drought periods (Blevins et al. 1971). Jones et al. (1969) and Blevins et al. (1971) showed that increased soil moisture during the growing season was the most important factor causing increased yields of corn under the killed sod mulch as compared to conventionally tilled corn.

Although many reports attributed higher yield to no-till, there are situations where conventional tillage is reported to increase corn grain yield. Soil type, prevailing climatic conditions, soil moisture, and planting date are some of the factors that play a significant role in creating the difference in yield between conventional tillage and no-till. Van Doren and Triplett (1969) reported that in clay to clay loam soil conventional tillage yielded higher corn grain, whereas in a silt loam soil no-till performed better (quoted by Baeumer and Bakermans 1973). Thomas et al. (1973) observed that, in a wet year, conventionally tilled corn with zero N applied had higher yields than the no-till corn. But in the dry years, no-till corn yields were higher. Similar results were obtained by Herbeck et al. (1986). They also noted that early planting date with conventional tillage gave higher grain yield, while increased yield with no-till was observed when the planting date was delayed by two weeks. Their experiment was conducted in a well drained silt loam soil. Moch and Erbach (1977) also reported 30% reduction in grain yield with early planting for no-till. Griffith et al. (1973) observed that conventional tillage shows more uniform emergence than no-till on somewhat poorly drained soils.

Yield reductions and other negative aspects of no-till are attributed to the residues remaining on the soil surface. Plant residues may cause reduced soil temperature or slow warming in the spring (Johnson and Lowery 1985), which may reduce plant growth and seedling emergence (Burrows and Larson 1962; Moch and Erbach 1977). Unger and McCalla (1980) reported greater N immobilization, fertility imbalance, difficulty with stand establishment, reduced seedling vigor, greater weed infestations, and release of phytotoxic decomposition products as possible reasons for the lower yields in more humid regions with no-till. Al-Darby and Lowery (1986) also reported delayed maturity for no-till corn. Another undesirable aspect of no-till is the increased soil compaction and bulk density in the surface 15 to 30 cm of the soil profile (Gantzer and Blake 1978). This may inhibit root growth and nutrient uptake of seedlings due to mechanical impedance (Bauder et al. 1981; Cochran et al. 1977).

No-till induced changes in yield are effective only in conjunction with other factors. In continuous corn, for instance, no-till showed only slightly better yield than conventional tillage on well drained soil and a reduction in yield on poorly drained soils (Griffith et al. 1973; Van Doren et al. 1976). In a 7-year experiment using high and low organic matter but poorly drained soils, Griffith et al. (1988) showed that no-till planting increased yields by up to 20% for rotation compared to continuous corn. They also showed that no-till corn yield, without rotation, was lower than conventional-till corn yields. Corn response to no-till, with regard to grain and dry matter production and N uptake, is also dependent on the type of cover crop and amount of fertilizer N applied (Wagger 1989). Studies conducted in Kentucky by Phillips et al. (1980) show that corn grain yields were higher with conventional tillage than with no-till systems where no N fertilizer was applied. In the same experiments, yields were equal when N was applied at the rate of 84 kg ha^{-1}. But application of 168 kg ha^{-1} resulted in higher yields of corn with no-tillage systems than with conventional tillage. Similar results were also observed by Thomas et al. (1973). It is frequently observed that no-till crops require more N fertilizer to attain their maximum yield than those grown by conventional techniques (Baeumer 1970; Phillips et al. 1980). Davies and Cannell (1975) stated that in 45 comparisons in the United Kingdom an additional 10 kg ha^{-1} was required to give the same yield of winter wheat after direct drilling as after plowing. In Kentucky, Phillips et al. (1980) recommend 28 kg ha^{-1} more N fertilizer to be applied for the production of no-till corn. In Virginia, Moschler recommends 20% more N for no-till corn to support 20% higher yields expected from no-till (cited in Phillips et al. 1980). Among the reasons suggested are that more denitrification, more leaching, lower mineralization, and greater weed competition occur with no-till than with conventional-till systems (Bakermans and de Wit 1970; Phillips et al. 1980).

With respect to dry matter or stover yield, available reports indicate that no-till did not perform conclusively better than conventional tillage. A six-year study of no-till and conventional-till management by Shear and Moschler (1969) showed a higher stover yield from no-till only in the first year of the study. In the remaining five years, no difference was observed. Jones et al. (1968) also reported that no-till dry matter yield was significantly less than that of conventional tillage.

In both tillage systems, the N uptake by corn requires in-depth study in order to maximize yield and minimize N loss. The most commonly reported N fertilizer response with no-till compared to conventional-till management is lower yields and lower N efficiency at lower fertilizer N rates and higher yields and higher N efficiency at higher N rates with no-till. However, the available reports are limited. Fox and Bandel (1986) discussed six hypothetical curves that depict yield or N uptake distribution with N fertilizer rate and the efficiencies associated with them.

V. Fate of Nitrogen in Soil

The inert atmospheric gas N_2 is the ultimate source of N used by plants. Since plant response to N is rapid and the quantity required by plants is relatively large, much attention has been focused on crop response to applied N. In agriculture, the ionic forms ammonium (NH_4^+) and nitrate (NO_3^-) are important because they are taken up directly by plants. In addition, NO_3^- is highly mobile in soils and thus has the potential to become an environmental pollutant.

The N in soil is either biologically fixed from the atmosphere or externally supplied as commercial fertilizers, crop residues, green and farm manures, waste products, and NO_3^- and NH_4^+ salts brought down by precipitation from the atmosphere. With the exception of inorganic N present in materials applied for crop production and that which is already present in the soil profile in either NO_3^- or NH_4^+ form, the rest must be microbially converted to NH_4^+ and NO_3^- via mineralization before it can be absorbed by crops.

In order to avoid shortage of food due to rapid population growth, modern agriculture is dependent on commercial N fertilizers. In soil, N fertilizer is subjected to a series of microbial and chemical processes. The most important of these processes are nitrification, immobilization, mineralization, and denitrification. It is generally surmised that there is no difference in nitrification rates between tillage systems as long as the moisture content remains the same. However, mineralization and immobilization data suggest that conservation tillage and conventional tillage have a steady-state level of soil N. Unless the management system is changed, the system attains an equilibrium state, apart from some temporal and spatial fluctuations. However, it is assumed that going from a conventional to a conservation system promotes immobilization, while moving from conservation to conventional tillage promotes mineralization.

It should be borne in mind, however, that the purpose of farming with regard to N fertilizers is to promote N uptake and maximize crop yield while minimizing N loss through leaching and denitrification. It is these last two processes that are of primary environmental concern, because loss of N from the farm through these processes is an economic loss to the agriculture system and a potential contaminant of ground and surface waters and of the atmosphere.

A. Denitrification in Corn Fields

An important component of the N cycle is the process known as biological denitrification. Denitrification is defined as the dissimilatory reduction of soluble NO_3^- or nitrite (NO_2^-) to gaseous N either as molecular nitrogen (N_2) or as an oxide of nitrogen (N_2O) (SSSA 1979). The products N_2 or N_2O are subsequently released to the atmosphere. Generally, NO_3^- reduction has been considered to be the major source of these products. It is, however, known that N_2 or N_2O can be produced from NO_2^- without the conversion of NO_2^- to NO_3^- (Blackmer and Bremner 1977; Bremner and Blackmer 1981). Denitrification is carried out by microorganisms that are able to use NO_3^- or NO_2^- as an electron acceptor, under anoxic conditions, as a substitute for molecular oxygen (O_2) in conventional metabolism. Denitrification is, thus, likely to occur strictly in an anaerobic (anoxic) environment. Chemical (abiotic) denitrification is another mechanism by which N may be lost in the gaseous form. In contrast to biological denitrification, it involves decomposition of NO_2. Since it is strictly chemical, it does not require the presence of microorganisms or an anoxic environment. It has been shown to occur in a well drained acid soil (Broadbent and Clark 1965; Tisdale and Nelson 1975). It is not known how much N is lost under such conditions. Chemical denitrification is believed to contribute little to gaseous N losses although field data to substantiate or negate this claim are not available (Hauck 1983).

The interest in denitrification arises from its significance to environmentalists, agronomists, and soil scientists. The purpose of N fertilizer application is to promote N uptake and crop yields; denitrification negates this purpose. Denitrification releases N from N fertilizers and natural sources and allows it to escape to the atmosphere as either N_2 or N_2O. While gaseous escape of N from N fertilizers via denitrification is an economic loss to the agricultural producer, it also is a potential environmental pollutant. When N_2O is released to the atmosphere, it promotes, through a series of reactions, the destruction of stratospheric ozone. Decrease of stratospheric ozone, in turn, allows ultraviolet radiation from extraterrestrial sources to reach the earth surface unimpeded, where it can cause skin cancer (Crutzen 1971). It may also contribute to the "greenhouse effect" caused by increased CO_2 concentration (Yung et al. 1976). When denitrification occurs in the agricultural system, it may reduce N concentrations available for leaching.

Denitrification occurs when certain minimum conditions are met. The four essential factors generally mentioned are (a) anaerobic conditions, (b) appropriate autotrophic or heterotrophic bacteria, (c) suitable oxidizable inorganic or organic material, and (d) a supply of NO_3^- or NO_2^-. The existence of anaerobic conditions should not in itself be a condition; however, when O_2 consumption rate exceeds O_2 supply rate, anoxic conditions develop. This occurs in wet soils because O_2 diffusion rate through water is seriously impeded, thus prompting the microorganisms to utilize NO_3^- or NO_2^- as an electron acceptor.

The existence of anaerobic conditions in soil for denitrification to occur may imply that the soil has to be water-saturated before denitrification takes place. This, however, may not be the only set of conditions under which denitrification occurs. When water infiltrates the soil profile (especially in a flooded situation), it flows through all pores and penetrates into all aggregates, causing a completely saturated condition. Nitrogen fertilizer supplied with water also permeates into all parts of the soil through both convection and diffusion processes. The consumption of O_2 by microorganisms at the center of the aggregates causes a N concentration gradient to form from the outside of the aggregate towards the inside (the gradient results from decreased N concentration at the center of the aggregate resulting from N loss through denitrification upon consumption of O_2). This causes a perpetual flow of N towards the center of the aggregate. When water supply from outside of the soil profile ceases, the macropores drain and only the soil aggregates (thus micropores or microsites) remain saturated (Smith 1978). Devices such as the neutron moisture probe, which are meant to indicate the mean moisture status of a soil segment, may not indicate the existence of such saturated microsites. In such situations, two phenomena take place concurrently: (a) diffusion of N towards the center of the aggregate and (b) evapotranspiration and/or drainage of water from the periphery of the soil aggregate. Despite the apparently aerobic condition that may prevail in the soil, these anaerobic microsites function as sites of denitrification since O_2 demand is high and O_2 supply is very low (Focht and Verstrate 1977).

An essential part of the study of denitrification is the estimation of N loss under field conditions. Difficulties arise due to two factors: (a) the high mobility of the denitrification products, N_2O and N_2, and (b) the failure to distinguish the N that results from denitrification from that already present in the soil atmosphere. Historically, the N loss due to denitrification was considered to be that part of the N mass balance that could not be accounted for (Allison 1955; Allison 1966). Here, it was assumed that the other components of the N cycle could be accurately evaluated. This can be a reasonable assumption especially in lysimeter studies, where every component of the N cycle, including N loss due to leaching, can be accurately estimated. However, as mentioned earlier, not every N loss is due to biological denitrification. Moreover, except for gross mass balance purposes, this approach cannot be used for studying the dynamic behavior of denitrification and the other components of the N cycle.

Two methods have been developed for direct estimation of N loss from the soil. These methods are also meant to distinguish between N that originates from denitrification and N from the soil atmosphere. These methods are (a) the use of ^{15}N (Burford and Stefanson 1973; Rolston et al., 1976) and (b) the use of acetylene (C_2H_2) to block the conversion of N_2O to N_2 (Patriquin et al. 1978; Ryden et al. 1979). In the first method, a high concentration of ^{15}N-enriched fertilizer is supplied to the soil. Then the ^{15}N concentration in the N lost from the soil is evaluated. The disadvantages in this method are that it is expensive and is limited only to the evaluation of the ^{15}N that originates from the applied fertilizer. The C_2H_2 blocking method is cheaper and can be used to measure the total N loss from denitrification. Its success depends on its ability to inhibit N_2O from being reduced to N_2.

Four methods are used for the estimation of N-flux from the soil surface: (a) the use of Fick's law, where the N concentration gradient in the soil profile and the molecular diffusion coefficient are used (Rolston et al. 1976; Delwiche et al. 1978); (b) micrometeorological techniques, where gas concentration gradient and Eddy diffusion coefficient above the soil surface are used (Lemon 1978; Hutchinson and Mosier 1979); (c) open chambers (continuous-flow) (Ryden et al. 1978; Denmead 1979); and (d) closed chambers (Rolston et al. 1979; Denmead 1979; Hutchinson and Mosier 1979).

Application of Fick's law for estimation of N_2O flux is dependent on two factors: (a) independently measured N_2O concentration gradient in the soil profile and (b) measured soil-gas diffusivity. To estimate N_2O concentration gradient, N_2O concentrations are sampled close to the soil surface. This depends on the availability of suitable equipment that can be installed near the soil surface. This approach has been applied by Burford and Millington (1968) and Burford and Stefanson (1973). The soil-gas diffusivity is calculated by allowing aknown concentration of gas to pass through an undisturbed soil sample and then solving pertinent partial differential equations subject to certain initial and boundary conditions (Rolston 1982). Limitations of this approach arise from inherent uncertainties and variability of the concentration gradients and soil-gas diffusivity within field soils (Smith 1978). The main advantage of this approach is that, if the samples are taken at several depths, it enables identification of source and sink zones for N_2O and provides information about N_2O concentration distribution within the soil profile (Delwiche et al. 1978).

Micrometeorological techniques are the preferred approach. Their main advantages are that they permit measurement of gas flux without disturbing soil processes, allow rapid sequential measurements, and minimize the problems of spatial variability (Hauck 1986). They are limited, however, by lack of accurate, precise, sensitive, and rapid gas analysis procedures (Hauck 1986; Lemon 1978). Since use of these techniques in the measurement of N_2O flux does not seem feasible, several workers have resorted to use of soil covers (chambers) as the only practical approach to the measurement of N_2O flux (Kimball 1978; Rolston 1978; Denmead 1979).

The open and closed chambers are placed on the soil surface. In the closed chamber, the increase in N concentration with time is measured and is extrapolated to estimate the total flux for a given period. The disadvantage of this approach is that the rising N concentration in the chamber may influence the N flux from the soil profile into the chamber by reducing the N concentration gradient. Thus, the total N flux may be underestimated unless the monitoring period is kept short. In the open chamber method, the diffusing N from the soil is prevented from accumulating in the chamber by inducing a continuous but low rate of air flow through the chamber. The induced flow of air, though low, may cause underpressure so that the N concentration gradient is slightly increased. Thus, the total N flux may be overestimated. Both systems are also criticized for lack of response to environmental (ambient) pressure, temperature, and humidity fluctuations (Kimball and Lemon 1971; Matthias et al. 1980). However, with adequate precautions in use, the closed and open chambers should provide simple and sensitive approaches to direct measurement of N_2O flux over short and long periods, respectively (Matthias et al. 1978; Matthias et al. 1980).

To evaluate tillage effect on the fate of N in soil, components of the N cycle must be evaluated quantitatively. Of all the components of the N cycle, only leaching of N requires an indirect estimation when field studies are conducted. Estimation of denitrification from field soils is now made possible by using C_2H_2. No-till compared to conventional-till management promotes more of the factors required for denitrification to occur. Linn and Doran (1984) reported that no-till created greater water-filled pores and caused 9.4 times higher N loss to occur through denitrification than conventional tillage. Dowdell et al. (1983) concluded that wet soils in Great Britain would lose more N to denitrification in no-till than conventional-till systems. Rice and Smith (1982), in investigating well drained soil series in Kentucky, reported that no-till soils had higher denitrification activity than conventional-till soils. Generally, the greater water content, higher microbial activity, and higher organic matter in no-till is believed to lead to higher denitrification than in conventional-till soils (Doran 1980). Other investigators attribute the lower NO_3^- contents in the profiles of untilled and poorly drained soils to denitrification (McMahon and Thomas 1976; Cannell et al. 1980; Dowdell et al. 1983).

Many studies have been conducted to estimate N loss through denitrification from either no-till or conventional-till management systems. Studies also have been conducted to determine the effect of factors such as straw incorporation (Ganry et al. 1978), rainfall (Webster and Dowdell 1982), urea (Terman 1979), pH (Broadbent and Clark 1965), air drying of soil (Pattern et al. 1980), temperature (Bremner and Shaw 1958), and water content (Goodroad and Keeney 1984). However, few studies directly comparing N loss via denitrification from no-till and conventional till have been reported.

B. Nitrogen Leaching in Corn Fields

Leaching is the downward movement of substances dissolved in percolating waters. In field soils, leaching of NO_3^- through the root zone is one of the most important mechanisms of N loss (Allison 1973). Supplied either as a component of inorganic fertilizers or generated from organic sources, NO_3^- is subject to leaching with percolating water through the root zone due to its high mobility and solubility in soil water-systems (McMahon and Thomas 1976; Cooper et al. 1984; Haghiri et al. 1978). Because NO_3^- is the most abundant inorganic N form in typical crop systems, it forms a major share of the N lost through leaching (Allison 1955). In contrast to NO_3^-, NH_4^+ leaching is normally not a problem. With respect to the combined forms of N, only NO_3^- will be leached out of soil in appreciable quantities and thus may have potentially adverse effects on groundwater, the environment, and both human and animal health (Johnson 1971).

Some factors that affect leaching of NO_3^- from a soil profile are soil texture, amount and distribution of rainfall, pH, cropping pattern, tillage practice, organic matter content, moisture status, soil temperature, and ionic mobility of the elements. In addition, processes such as immobilization, mineralization, and nitrification that influence the availability of N affect leaching. These processes are sensitive to environmental conditions, including tillage practices such as conventional till and no-till. In general, the following prerequisites are required if major N loss through leaching is to occur: (a) soil NO_3^- content is high and (b) water movement is large (Legg and Meisinger 1982). The last factor is obvious during the months of low evaporation or high rainfall. As evaporation declines after harvest, soil moisture levels increase. Subsequently, significant leaching may occur through the root zone. However, these conditions do not preclude the occurrence of NO_3^- leaching or water movement at even lower moisture levels. Soluble forms of N fertilizers can leach readily from the root zone at any time following application. The movement of NO_3^- in the soil profile is governed by NO_3^- concentration gradients as described by Fick's law, satisfying the convection-dispersion transport laws. Convective transport of NO_3^- is proportionally dependent on the rate of water flow. Thus, NO_3^- leaching is least likely to take place during summer when evapotranspiration usually exceeds precipitation and plant uptake rates are high (Allison 1973). Hubbard et al. (1984) reported that the time of maximum leaching coincides with the period of lowest evaporation and highest rainfall. Hence, leaching losses of NO_3^- are strongly influenced by seasonal effects. The effects of pH and soil temperature and texture on NO_3^- leaching are indirect through their influence on the various processes that affect formation and availability of NO_3^- for leaching. Likewise, NO_3^- leaching losses in humid temperate regions, subhumid conditions, tropical areas, grasslands, flooded soils, and forest soils are dependent on the prevailing environmental conditions.

Estimation of N leaching losses depends on the accuracy of the methods employed to monitor such losses. In contrast to the direct methods employed in estimation of denitrification losses and crop N uptake, estimations of NO_3^- leaching losses are often derived through indirect approaches. Estimates of N leaching losses are derived from mass balance studies, which require prior knowledge of N input, N losses through denitrification and crop N uptake, and changes in N stored in the soil profile, assuming that immobilization and mineralization processes remain steady (Dowdell and Cannell 1975). An alternative approach to this is the use of controlled lysimeters for more direct measurement of N loss. This approach requires accurate measurement of amounts and compositions of drainage waters. For experimental purposes, several workers have studied N leaching losses from lysimeters and tile-drains. Tyler and Thomas (1977) used lysimeters for measurement of NO_3^- and Cl^- losses from soils used for conventional and no-till corn. Haghiri et al. (1978) used lysimeters to determine the maximum rate of beef cattle manure that can be applied to soil without adversely affecting the quality of groundwater. Gast et al. (1978) used tile-drains to study NO_3^--N losses from clay loam soils. Webster et al. (1986) used lysimeters to study the fate of N fertilizers, quantitative assessment of total N uptake by the crop, losses in drainage, and effect of transient waterlogging on the growth of crops. Chichester (1977) used field lysimeters to study effects of increased fertilizer rates on N content of runoff and percolates. Although analysis of drainage water from lysimeters and tiled fields for estimation of N leaching losses has been practiced for many years (e.g., Bizzell and Lyon 1927, cited in Kilmer et al. 1974), Thomas concluded from studies in Kentucky that concentrations of tile effluents are not reliable indicators of the amounts of NO_3^- leaving a tiled field (cited in Kilmer et al. 1974). For instance, where tile drains were placed at a depth of 1.8 m, Gast et al. (1978) observed leaching of NO_3^- below the tile lines to a depth of 2.2 m. Other approaches applied in monitoring downward water and nutrient fluxes are the use of devices such as pan or tension and zero-tension lysimeters. These devices, however, have not been found to be suitable for all purposes or situations (Russel and Ewel, 1985). Studies by Haines et al. (1982) showed discrepancies in amounts of water and concentrations of ions collected by tension and zero-tension lysimeters. Van der Ploeg and Beese (1977) also concluded that suction plates (pans) were preferable to ceramic cups. The pan-type lysimeter is unsuitable for unsaturated conditions because the soil solution passes around the soil directly above the lysimeter. The zero-tension lysimeter is better suited for saturated conditions or for measuring channelled flows. Thus, the best alternative for estimation of nutrient leaching losses, especially under field conditions, is the mass-balance or difference approach as used by Legg and Meisinger (1982) and Dowdell et al. (1983).

Because NO_3^- is very soluble in water and highly mobile, it is susceptible to leaching. Various studies have been conducted to examine the extent of NO_3^- leaching when applied as an inorganic N fertilizer. Kilmer et al. (1974) reported that 6 to 10% of the N fertilizer applied was lost from a steeply sloping, fertilized, grassed watershed in western North Carolina. Studies by Quisenberry and Phillips (1976) showed that an application of 4.2 cm of water increased the water content to the 60-cm depth within 1 hr following irrigation. In their study, the initial soil profile water content was below the upper limit of the water-holding capacity of the soil. Studies by King and Morris (1974), McMahon and Thomas (1976), Gast et al. (1978), and Cooper et al. (1984) show that NO_3^- may be leached well below the rooting zone of corn. In a study on leaching, where Cl^- was used as a tracer for NO_3^-, McMahon and Thomas (1976) reported that appreciable quantities leached from a killed sod during the growing season. Chichester (1977) reported that in a lysimeter study N loss by leaching was greatest during the winter and the N flux was < 10 kg ha^{-1} yr^{-1} under meadow and more than 250 kg ha^{-1} yr^{-1} for cultivated corn. While under meadow, N concentration in the percolate did not exceed 10 mg L^{-1} NO_3^--N; percolate leaching reached 70 mg L^{-1} with cultivated corn. The difference was a function of the levels of soluble N remaining in the soil at the end of the growing season. Gast et al. (1978) reported that N lost below the root zone increased with higher application rates of inorganic N fertilizers while the N removed by the crop remained unaltered. Thus, the efficiency of crop N uptake decreased with higher application rates (Gast et al. 1978; Broadbent and Carlton 1978; Gambrell et al. 1975). Gast et al. (1978) and Broadbent and Carlton (1978) also reported that crop yields increased with increases in N application up to 150 kg N ha^{-1} and remained constant thereafter.

The amount of N in liquid sludges available for leaching is potentially quite high (King 1973). About 20 to 50% of the N in liquid sewage sludge is in the easily nitrified NH_4^+-N form. The rest is in the organic-N form (Kelling et al. 1977), with an insignificant amount in the highly mobile NO_3^--N form. Sewage sludges, however, may vary considerably both in the rate of N mineralization and in the quantity of mineralizable organic N. Several researchers have investigated the rate of organic N mineralization. Stark and Clap (1980) reported that from 2.3 to 4.2% of the added organic N mineralized in 6 weeks of incubation and 14 to 25% was mineralized in 13 weeks. The virtue in this process of slow N release is that it may not be subjected to leaching and denitrification in large quantities at the early stages of crop growth but gradually becomes available for crop uptake at the later stages of growth. This promotes increased NUE. With regard to the amount of mineralizable organic N, Magdoff and Amadon (1980) reported that mineralization to the inorganic N form varies from about 4 to more than 50% of organic N. Therefore, it is difficult to estimate accurately in advance the amount of available N that could be supplied by a given amount of sludge. Moreover, the decay factor necessary to account for the slow rate of mineralization of the remaining organic N is not often given appropriate consideration (Pratt et al. 1973; Keeney et al. 1975). Thus, due to lack of assurance of the precise quantity of mineralizable organic N, there is a tendency to apply excessive amounts of sewage sludge, which, in turn, may result in NO_3^- leaching to and contamination of ground waters. For this reason, Hinesly et al. (1971) proposed that sludge loading should be limited to less than 5 cm or less than 15 metric tons ha^{-1} when applied to land used to grow nonleguminous crops.

Hinesly et al. (1971, 1972) reported that, at relatively high loading rates of sludge, only a low percentage of the applied N was utilized by corn (*Zea mays* L.), reed canarygrass (*Phalaris arundinacia* L.), and grain sorghum (*Sorghum vulgare* Pers.). Stewart et al. (1975) observed that only 3 to 12% of the total N applied as sewage sludge was removed by a corn crop. Haghiri et al. (1978) reported the effect of a single application of beef cattle manure on corn yield and on NO_3^- leached from field lysimeter. Corn yields the first and second years reached a maximum at the 158 Mg ha^{-1} rate (dry weight), while in the fourth year the highest yield was obtained at the 316 Mg ha^{-1} rate.

The quantity of N applied beyond that required for maximum yield or that which fails to achieve the highest plant N-uptake efficiency is lost from the root zone and may not be recoverable, depending on soil properties and crop management. Recently, there has been concern that changes in agricultural practice and increased N fertilizer use may have increased leaching of NO_3^- into groundwaters. However, limited studies have been conducted that compared NO_3^- leaching loss in tilled versus untilled soils (McMahon and Thomas 1976; Phillips et al. 1980; Thomas et al. 1973; Tyler and Thomas 1977). All results indicate a potential for higher NO_3^- leaching loss with no-till management. Results from moderately fertilized grasslands, however, suggest that NO_3^- concentrations in leachates are generally low (Kilmer et al. 1974).

The higher leaching losses of N from no-till soils are often attributed to the presence of macropores and to the higher moisture content in the soil profile. Studies by Thomas and associates in Kentucky (Thomas et al. 1973) confirm that the larger number of continuous pores in no-till leads to rapid channelized water movement downward in the soil profile. Studies by Chichester (1977) and Tyler and Thomas (1977) also showed that N loss by leaching was greatest during winter when percolation rates increased and surface-applied anions would be washed into natural soil cracks and channels and flow much deeper into the soil profile. Thus, winter and spring soil conditions, when micro- and macropores are filled with water, are ideal for leaching of NO_3^-. However, although it was generally accepted that greater leaching and infiltration occur in no-till than in conventional till, these processes do not necessarily occur simultaneously. Percolation studies of surface-applied water in the field conducted by Quisenberry and Phillips (1976) showed that the location and movement of chloride in the profile indicated that a large percentage of the applied water percolated past the water initially present with little displacement of the initial water. Similar results also were obtained by Kanwar et al. (1985). In both studies, much of the water movement was in the larger pores and the water was surface-applied. The results of Tyler and Thomas (1977) were also explained in terms of macropore preferential flow of the surface-applied NO_3^- solution through the soil column. However, when the NO_3^- solution is already wetting the soil column, the displacement of NO_3^- by any surface-applied water would result in a slow leaching of NO_3^-, since the water would bypass much of the NO_3^- in the soil column. Similar reasoning was also applied by Wild (1972) and Kanwar et al. (1985) to explain their results. The contribution of macropores to leaching in unsaturated conditions, however, is questionable. Water flows from zones of higher to lower total potential. Water in unsaturated micropores is retained with lower total potential than that in macropores. Thus, water in macropores is spontaneously absorbed into micropores where the latter are unsaturated. Hence, unless macropores are continually replenished with water from the surface of the soil profile, the macropores in the soil will be empty. However, where the micropores are saturated and with positive hydrostatic pressure (e.g., where clay pans or perched water tables exist), macropores play a significant role in leaching of the soil solution through the soil profile by chanelling solutions from micropores. Therefore, the higher NO_3^- leaching loss from no-till practices under this condition is solely due to the higher moisture content in the micropores of the no-till soils.

Most studies concerning leaching have been conducted under irrigated field conditions or in lysimeters (Smika et al. 1977; Watts and Hanks 1978; Hergert 1986). There is very little information available on comparisons of leaching from no-till and conventional tillage. The works on this subject quoted most often are those by Thomas and associates in Kentucky (Thomas et al. 1973). Moreover, there have been few attempts to determine total NO_3^- leaching losses from defined areas treated with different rates of N fertilizers (Kilmer et al. 1974; Barraclough et al. 1983). In Virginia, excess loading of nutrients from agricultural activities in the Chesapeake Bay watershed has been identified as a contributor to decline in key estuarine resources (USEPA 1983). At present, there is concern about increased NO_3^- concentration in groundwater resulting from nonpoint sources of NO_3^- pollution. A reasonable alternative to minimize major N leaching losses is to adjust N fertilization to the N requirement of the crop. Other alternatives are to adopt appropriate tillage practices simultaneously with split or delayed application of N fertilizers. Although this approach is relatively easy with inorganic fertilizers, it is difficult when farmyard manures or sewage sludges are applied. However, to effectuate the desired result, studies on direct comparison of N loss due to leaching from no-till and conventional-till management systems concurrently with different N fertilizer rates and sewage sludges must be conducted. Such studies are at present lacking in the Chesapeake Bay area as well. In addition, information about the drought effects on leaching from both tillage systems is nonexistent.

VI. Use of Simulation Models to Predict the Fate of Nitrogen in Corn Fields

Models of various types are used to describe and predict the flow of water and the fate of N in porous media such as soil. Models are simplified versions of the real system and are used to simulate the excitation-response relations of the prototype system. Because the real system is complicated and complex, there exists no unique model that can be used to represent the actual system. Each model may reflect the inherent assumptions incorporated by the modeler, and the process of simulation is for predicting the response of the prototype.

The models used in the study of soil water movement and solute transport fall generally in three categories: (a) the analogues, (b) the physical models, and (c) the mathematical models. Analogues possess a similarity relation to the prototype, but they do not possess the same properties. The solution to the problem of flow in this case is based on the principle that systems belonging to an entirely different physical category are described by essentially the same equations. Examples of these are the principles used in Darcy's and Ohm's laws. Physical models are identical to the prototype, except that they are scaled down according to certain scaling laws. Their properties do not differ from the prototype, except that they are of a smaller scale. Examples of physical models are viscous flow models.

The third category of model is the mathematical model. These are quantitative expressions of the phenomenon one is observing, analyzing, or predicting. They are often presented in partial differential equation forms. Their solution for a particular problem is unique. For some real systems, numerical solutions are used mainly due to the nonlinearity, heterogeneity, or irregularity of the system. Since no process can be completely observed, any mathematical expression of a process will involve some element of stochasticism, i.e., uncertainty. However, often deterministic approaches are used. In contrast to the two previously mentioned models, which represent a real simulation system, the mathematical models represent an abstract system. Mathematical models are of primary interest for this study. Therefore, the basic concepts used in these models are discussed briefly below.

The flow of water in a porous medium such as soil is described by the macroscopic level equation, the Darcy's law, expressed as:

$$q = - K(\theta) \frac{\partial H}{\partial z} \qquad [1]$$

where q is the volumetric moisture flux, K is the hydraulic conductivity as a function of volumetric moisture content θ, Z is the distance positive downwards, and H is the hydraulic head. This equation is valid to describe soil water flow in the absence of other forces, such as thermal or electrical gradients. To represent the dynamic behavior of water flow and predict the soil-water status, the law of conservation of mass is invoked. Thus, Darcy's law is incorporated in the general flow equation to render the continuity equation. For transient cases and in the presence of an actively transpiring plant, it is expressed as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K(\theta) \frac{\partial H}{\partial z}\right) + A(z,t) \qquad [2]$$

where t is time and A(z,t) is the rate of plant root extraction of water. Equation 2 assumes water density is constant and the system is a nondeformable medium.

The flow of solutes, chemicals, or nutrients in soil is described by Fick's law, which is stated as:

$$J = -D \frac{\partial C}{\partial z} \qquad [3]$$

where J is the solute flux, D is the apparent diffusion coefficient, and C is the solute concentration. For a complete description of the system, Fick's law is used in the mass conservation equation of continuity. For a reactive solute, this is expressed as:

$$\frac{\partial (S + \theta C)}{\partial t} = D \frac{\partial^2 C}{\partial z^2} - q \frac{\partial C}{\partial z} + Q \qquad [4]$$

where S is the solute adsorbed per unit mass of the solid and Q is the solute sink-source term. In the above equation, D and q are assumed to be constant. In reality, q is nonsteady and is derived from Equation 1. In a numerical solution, there is back and forth interaction between Equations 1 and 4 so that an updated value of q can be used. The adsorption term S includes three processes: adsorption, chemical sorption, and ion exchange. It is generally referred to as sorption because it represents the selective uptake and storage of solutes in the soil system. The equations relating S and C are Freundlich, Langmuir, and linear isotherms.

For a nonreactive solute, the adsorption term S does not exist. Equation 4, thus, reduces to:

$$\frac{\partial C}{\partial t} = D' \frac{\partial^2 C}{\partial z^2} - v \frac{\partial C}{\partial z} + Q' \qquad [5]$$

where $D'=D/\theta$, $v=q/\theta$, and $Q'=Q/\theta$; v is the pore water velocity.

For nutrients such as NH_4^+,NO_3^-, and urea, the source-sink Q' represents various processes. For NH_4^+, Q' represents the sum of the terms that represent plant N uptake, N losses due to nitrification and immobilization of NH_4^+, and the N gain due to mineralization of organic matter. For NO_3^-, Q' represents the sum of the terms for plant N uptake, the N losses due to denitrification and immobilization, and the N gain due to nitrification. Where urea is used, the diffusion-convection equation, Equation 5, is written to represent, respectively, NH_4^+, NO_3^-, and urea as separate equations. Subsequently, the derived equations are coupled as a result of their transformational interdependence. The relationships among the three derived equations are linked through the time rate change of the given species, where the rates are expressed by use of kinetic sorption solutions (e.g., first-order kinetic equations).

The above equations are the basic equations used in simulating N transport in soil. Based on these equations, several authors (Smith et al. 1984; Watts and Hanks 1978; Tillotson and Wagenet 1982; DeSmedt and Wierenga 1978) have developed models that simulate N movement in soil. The modelers differ, however, in the form of the sink-source terms and the type of initial and boundary conditions they adopted. Moreover, the solutions they obtained are not very comprehensive.

Other simpler models used to describe the transport of solutes (nutrients) in soil and that do not require detailed data for execution are those developed by Burns (1974, 1975, 1976), Addiscott (1977), DeSmedt and Wierenga (1978), and Smith et al. (1984). Using the concept developed by these authors and by modifying Equations 1 to 5, Rose et al. (1982 a, b, c) derived a simple model that predicts the distribution of N in the soil profile. Rose's model, assuming that soil drains to a field capacity, predicts the position of the mean solute penetration or depth of solute peak (α) for solutes that undergo no processes other than convection, dispersion, and diffusion. Though Rose and his colleagues (Rose et al. 1982 a, b, c) start with Equations 2 and 4, they assume $S=0$ and that dispersion and diffusion are negligible. Cameron and Wild (1982) tested the simplified models of Rose, Burns, and Addiscott for their usability for field conditions. They concluded that the analytical solution given by Rose was the best, but it requires only an estimate of solute dispersivity. These modelers, however, introduce severe simplification into the system as well as into the mathematical models they used. Inherent to the underlying assumptions, the models are thus limited only to certain situations. In situations where extreme drought prevailed as in the three years our experiments were conducted, the use of their model is questionable. Moreover, they provided neither equations to represent plant N uptake and the various transformations that N undergoes in soil nor the program to run and test their model. For these reasons, after initially considering the use of Rose's model, we opted for the VT-MAIZE model developed in the Department of Crop and Soil Environmental Sciences by Newkirk and colleagues (Newkirk et al. 1988) as an improved version of the CERES-Maize model.

The NTRM model, developed by Shaffer and his colleagues (Shaffer and Pierce 1986; Shaffer and Larson 1987), the CERES-Maize, developed by Ritchie and his colleagues (Jones and Kiniry 1986), and the VT-MAIZE incorporate all relevant factors for the determination of leaching, denitrification, and plant growth and yield (i.e., climatic, soil, crop, and management factors). Moreover, these models predict the N concentrations and amounts in the different parts of the crop and the soil system. The model NTRM uses the finite difference approach to discretize Equations 2 and 4. The models CERES-Maize and VT-MAIZE, however, use a series of interrelated submodels. All these models require detailed field information for calibration.

MATERIALS AND METHODS

I. Experimental Sites

Two field sites were located in 1986 for a three-year study on agronomically important and representative soils that are used for corn production in either a corn (*Zea mays* L.)-wheat (*Triticum aestivum* L.)-soybean (*Glycine max* [L.] Merr.) or a continuous-corn rotation in the Chesapeake Bay drainage basin. The corn-wheat-soybean rotation experimental site was located on a Suffolk sandy loam soil (coarse-loamy, siliceous, thermic Typic Hapludult) with a 0 to 2% slope located in the Coastal Plain region in the Nomini Creek drainage basin of Westmoreland County, Virginia. The soil is deep, well drained (water table at approximately 12 m), and situated on a broad ridgetop at an elevation of approximately 30 m. The continuous-corn rotation experimental site was located on a Groseclose silt loam soil (clayey, mixed, mesic Typic Hapludult) with a 2 to 7% slope located in the Ridge and Valley region at Blacksburg, Virginia. This soil is well drained, gently sloping, and occurs on ridgetops. The depth to bedrock is greater than 2 m. Selected physical, chemical, and hydraulic properties of the soils used in this study are presented in Tables 1-8. Soil texture was determined by the pipet method (Day 1965). Bulk and particle densities were determined by employing the core and pycnometer methods, respectively (McIntyre 1974). The constant head method was used to measure the saturated hydraulic conductivity of the soils. The measured values generally fall within the medium to low class range (Klute and Dirksen 1986). Some of the values used in obtaining the average saturated hydraulic conductivities for the soil layers are probably influenced by the presence of some short-ranged macropores, due to the core length of the sample. The macropores may not affect the overall saturated hydraulic conductivity of the field soil, however, due to their short lengths. Cation exchange capacity (CEC) was measured by Ca saturation with subsequent displacement with Mg acetate solutions buffered at pH 7 (Rich 1961). The soil pH was determined by using a combination electrode (Tables 3 and 4). The pressure plate apparatus was used to obtain an estimate of the soil moisture characteristics for each layer of the soil profile. The saturated moisture content of each layer was then used to derive the Campbell constant b (Campbell 1974), which was required in the NTRM model. The b values decreased with increased clay content. The residual moisture content (Res) and the moisture content at field capacity (FC) were evaluated at 1.5 and .01 MPa suction, respectively.

II. Experimental Treatments

In the spring of 1986, areas of 48.8 by 42.7 m on the Suffolk soil and 42.7 by 42.7 m on the Groseclose soil were delineated as the study sites. These areas accommodated the experimental plots and included a 3.3-m buffer strip around the experimental plots. The experimental design was a split plot replicated four times. The main plot treatment was tillage and consisted of no-till and conventional till. The subplot treatment was N application and consisted of six levels at the Groseclose site and seven levels at the Suffolk site. Each subplot was 6.1 m by 4.6 m. The conventional-till treatment consisted of plowing and disking to establish a seedbed. Treatments for corn were a control (0 N), three rates of inorganic N fertilizer (75, 150, and 225 kg N ha^{-1}) applied at planting as a 30% N [Urea-ammonium nitrate (UAN)] solution, one split application of inorganic N (UAN solution) with 60 kg N ha^{-1} applied at planting and 90 kg N ha^{-1} applied 6 weeks later, and two types of anaerobically digested sewage sludge (one polymer- and the other lime-conditioned) designed to supply 150 kg of plant-available N ha^{-1} (Tables 9 and 10). The lime-conditioned sewage sludge treatment was used only on the Suffolk soil. The lime-conditioned sewage sludge was obtained from the Atlantic Treatment Plant in Virginia Beach, Virginia, and the polymer-conditioned sewage sludge from the James River Plant in Newport News, Virginia.

The chemical analyses of the sewage sludge applied to corn in 1986, 1987, and 1988 and to wheat in 1987 are shown in Tables 11 and 12. Rates of sludge applied to the two soils (Tables 9 and 10) were based on the total estimated plant availability of sludge N. Nitrogen mineralization was estimated at 25% of the total organic N during the first growing season. The availability of inorganic N (present as NH_4^+) was estimated as nil for the lime-conditioned sludge and 80% for the polymer-conditioned sludge. The 100% volatilization loss of NH_4^+-N for the lime-conditioned sludge was based on field observations by Dr. T.W. Simpson. Use of lime-conditioned sludge was discontinued after the 1987 wheat experiment because of the conversion of the treatment process at the Atlantic Plant from lime-conditioned to polymer-conditioned.

III. Cultural Practices

A. Continuous-Corn Rotation

In April 1986, lime was applied to all plots. A mixture of paraquat and atrazine was applied to kill the rye cover crop and for seasonal weed control. Furadan was applied in late April, at the time of planting corn, for insect control. Fertilizer treatment consisted of 93 kg K ha^{-1} applied to all plots and 49 kg P ha^{-1} applied to all plots except those that received sewage sludge. Nitrogen application rates are given in Table 9. Corn 'Pioneer 3192' was overplanted and thinned to 61,700 plants ha^{-1}. After the corn was harvested, rye 'Abruzzi' was seeded at 134 kg ha^{-1}. The chemical analysis for the sewage sludge used at this site is shown in Table 11. The same cultural practices used in the 1986 crop year were also employed in the 1987 and 1988 crop years. The chemical analysis for the sewage sludge used at this site is shown in Table 12.

B. Corn-Wheat-Soybean Rotation

Because the two rotations were managed almost identically, only the differences will be mentioned here. A mixture of paraquat and atrazine was applied to the soybean stubble for weed control. Fertilizer additions consisted of 74 kg K ha^{-1} applied to all plots and 39 kg P and 20 kg S ha^{-1} applied to all plots except those that received sewage sludge. Following corn harvest in 1986, the site was plowed and wheat 'Coker 916' was planted at 148 kg ha^{-1}. Fertilizer treatments for the wheat consisted of 93 kg K ha^{-1} to all plots and 49 kg P ha^{-1} to all plots except those that received sewage sludge. Nitrogen was fall-applied to all plots at the rate of 20 kg ha^{-1} except for the sewage sludge and control treatments (Table 9). Lime- and polymer-conditioned sewage sludges were applied at rates estimated to supply 80 kg ha^{-1} prior to planting wheat. The chemical analysis of the sewage sludges used for wheat are shown in Table 11. The spring application of N (as UAN solution) was applied to the wheat plots on February 26, 1987. The split N treatment plots received 30 kg N ha^{-1} on February 26, 1987, and an additional 30 kg N ha^{-1} on April 1, 1987 (Table 9). No-till soybeans 'Stafford' were planted immediately following wheat harvest in June, 1987. Corn planted in April of 1988 was the beginning of the second cycle of the rotation. The only difference in management employed in 1988 versus 1986 was the omission of the lime-conditioned sewage sludge treatment.

IV. Sample and Data Collection

A. Moisture

Tensiometers and neutron moisture meter access tubes were installed to monitor the energy status of soil water and soil water content. Twenty-four tensiometers and 24 neutron moisture meter access tubes were installed in the Suffolk soil, and 144 tensiometers and 24 neutron moisture meter access tubes were installed in the Groseclose soil. Neutron moisture probe access tubes were installed to a depth of 1.5 m; the tensiometers were installed at six different depths (15, 30, 60, 90, 120, and 150 cm). Soil moisture was monitored approximately once per month using the tensiometers and the neutron moisture meter. Neutron moisture meter readings were taken at 30-cm intervals to a depth of 1.5 m. Due to an extreme drought during the three growing seasons, limited information was collected from the tensiometers.

B. Grain and Fodder

Fodder (the aboveground plant parts excluding the grain) and grain samples were collected at physiologic maturity from all plots. Fodder yield was estimated by weighing the harvest from the two center rows in each plot. Grain yield was estimated by weighing cobs and grains from the same samples used for fodder yield estimation. The grain weight was subsequently adjusted to 155 g H_2O kg^{-1} moisture content. Silage yields (fodder + grain) were also determined for all treatments. The fodder and grain samples were dried at 70°C and ground to pass a 20-mesh (0.833-mm) sieve in preparation for N analysis. The N in plant tissue was determined by the indophenol-blue procedure following Kjeldahl digestion (Bremner and Mulvaney 1982).

C. Soil

Soil samples were collected from both Groseclose and Suffolk soils, late in the fall when mineralization and immobilization would not have been important features because of decreased soil temperature and again in the spring before temperatures were warm enough to promote mineralization and immobilization. At each site, soil samples were collected from 36 to 40 of the experimental plots. Eight shallow and two deep soil cores were collected per plot. Samples were obtained from depths of 12.5, 25, 40, 55, 70, 85, 100, 115, 130, 145, 160, 175, and 200 cm for the deep cores and 12.5 and 25 cm for the shallow cores. Subsequently, corresponding soil segments from each plot were thoroughly mixed, composited, and then bagged for analysis. Thus the total number of samples collected at each site on each sampling date ranged from 468 to 520. Following bagging, all samples were stored at 5 °C. A total of 2,305 and 2,110 samples were collected, respectively, from the Groseclose silt loam and the Suffolk sandy loam soils. The soil samples were analyzed for NH_4^+-N and NO_3^--N concentrations following extraction with 2 M KCl solution. NO_3^--N and NO_2^--N were determined colorimetrically at 540 μm as NO_2^--N using a Cu-coated Cd reduction technique (USEPA 1979). Ammonium N was determined colorimetrically using the indophenol-blue technique (USEPA 1979). These data were used for estimating N leaching and denitrification losses from the soil profile and to compare outputs from and test the predictive ability of the CERES-Maize, VT-MAIZE, and NTRM computer models.

V. Denitrification Experiments

Denitrification experiments were conducted on the Groseclose soil during the 1988 corn-growing season. To estimate and compare N loss through denitrification from both till and no-till treatments, three levels of inorganic N (0, 150, and 225 kg N ha^{-1}) and one level of sludge treatment (150 kg N ha^{-1}) were selected. In order to measure denitrification, C_2H_2 was used to block the final conversion of N_2O to N_2. When such experiments are conducted under field conditions, the soil system behaves as an open system. The substrate necessary for the biological activity (e.g., NO_3^-) is supplied from outside the system. Since the gaseous product is highly mobile, the denitrification product is also collected outside the system.

The process of applying C_2H_2 and collecting the denitrification product, N_2O, consists primarily of three parts: (a) installation of closed chambers on the soil surface, (b) installation of C_2H_2 supply tubes into the soil profile, and (c) installation of N_2O collection tubes into the soil profile.

Closed chambers were installed in 20 plots (one at the center of each plot). Each chamber consists of two parts. The lower part (an open-ended PVC tube 25.4 cm in diameter and 12.7 cm in length with a 2.5-cm wall thickness) was driven 6.5 cm into the soil. The volume above the soil surface was 3.217 L. To avoid leakage of N_2O from inside to outside through the bottom of the chamber, a small amount of bentonite was used to seal the bottom line where the tube makes contact with the soil. The upper part of the chamber (chamber cover) was constructed from a flat wooden board with the contact between the chamber and the cover being hermetically sealed. A plastic open-ended tube was placed in the center of the cover and a gas-tight seal was achieved between the cover and the tube. The external end of the tube was fitted with a rubber septum and N_2O was withdrawn from the chamber by inserting a hypodermic needle through the rubber septum. Gas samples were collected in a 3.5-ml hypodermic syringe.

Acetylene was supplied to each C_2H_2 diffusion tube through nylon tubes connected with the gas cylinder. The C_2H_2 diffusion tubes were constructed from 2-cm diameter PVC tubes. Each tube was 100 cm long and was perforated at intervals of 5 cm throughout its length in four equidistant rows around its periphery. The perforations were needed to facilitate C_2H_2 diffusion from the C_2H_2 tube to the surrounding soil. Four C_2H_2 tubes were inserted around each closed chamber at equal intervals around its circumference. Acetylene was supplied at a rate shown to effectuate N_2O reduction inhibition, 28 L in 15 min. (Ryden et al. 1979).

To estimate N_2O evolution from the soil in both space and time, gas sampling tubes were installed at six depths around the circumference of the closed chamber. The tubes were constructed from 2-cm diameter PVC tube. At the bottom of each tube, a 1-cm segment was partitioned from the rest of the tube and was hermetically closed on both ends. Its wall was then perforated, allowing gas from the soil to flow in and out freely. A 3-mm diameter nylon sample tube was inserted into this segment through its upper inner wall for sample collection.

Gas sampling tubes were installed at depths of 5, 20, 35, 55, 75, and 100 cm. After holes were dug, the tubes were inserted and the void spaces between the tube and the hole wall were filled at first with loose soil and later with bentonite to prevent gas flow through the space between the tube wall and the soil profile.

Soil gas was sampled from the closed chambers at 10-minute intervals three times before and three times immediately after C_2H_2 was applied. Short interval sampling was necessary to avoid buildup of N_2O concentration within the closed chamber (Hutchinson and Mosier 1981). Gas samples from the gas sampling tubes were taken at the end of the experiment. Gas samples were collected and transported in hypodermic syringes to the lab. In the lab, they were stored in vacuum tubes until analyzed.

The N_2O concentration was analyzed on a gas chromatograph equipped with an electron capture detector. A Porapak-Q column (2 m long, 2 mm inside and 6 mm outside diameters, and 80/100 mesh size) was used.

An inlet temperature of 60°C, a column/oven temperature of 50°C, and a detector temperature of 350°C were used. Column pressure of 27 psi and tank pressure of 60 psi were applied. Helium was used as a carrier gas. Good separation of the N_2O peak was obtained under these conditions with a retention time of approximately 1.3 minutes. For analysis, 0.5 ml of soil gas was injected into the chromatograph.

VI. Nitrogen Balances

The principle of N mass balance was applied to the data collected following the above stated procedures to estimate the N content changes in the soil profile due to crop N uptake, leaching, denitrification, and mineralization during the fall and winter months of the three years of this study. The mass balance approach is a direct bookkeeping approach to the concept of the conservation of mass. The difference between input and output of a substance (e.g., N) is the net change in the content of the same substance in the system. In order to accurately represent the effect of each process that prevailed in the system during the season considered, a layer-by-layer comparison and evaluation of the N contents in the soil profile was employed.

VII. Comparison of Computer Simulation Models

The NTRM, CERES-Maize, and VT-MAIZE models require extensive climatic, soil, and crop data. The model inputs include daily maximum and minimum air temperature, soil temperature, rainfall and irrigation amounts, pan evaporation, wind velocity, and solar radiation; soil horizon depths; soil water characteristic curves, soil water content, bulk density, soil textural composition; soil nutrient and salt concentration; N transformations; profile geometry; soil and residue reflection coefficients; random roughness; percent slope, slope length, aspect, site latitude and elevation; crop growth data; fertilizer application amounts, types, and dates; crop residue amounts and types; tillage dates and types; corn maturity class, population density, and emergence and harvest dates; soil pH; and soil hydraulic conductivity.

The required data were entered into each model and can be found in Menelik (1990). The NTRM and CERES-Maize were run on an IBM-XT PC for each N treatment level and for each tillage type. While the NTRM model has an inbuilt mechanism for handling a no-till management system, the CERES-Maize depends on differences in the bulk density between the two tillage systems. Both models run for only one N treatment at a time. In contrast, the VT-MAIZE has the capability to run all N treatments for both tillage systems and for the three years under study simultaneously as long as computer data storage memory is available.

The 2-m soil profile was segmented into 20 sections, and values for each section were entered. As output, the above models produce N leaching, denitrification, mineralization, and immobilization amounts; total dry matter, stover, and grain production; N uptake in biomass, stover, and grain; grain filling dates; transpiration amounts; root growth; NH_4^+-N and NO_3^--N distribution in the soil profile; and daily potential transpiration.

Execution time for the models varies. The VT-MAIZE was the fastest because it was run on the mainframe system. Normally, it took three to four minutes to execute the data of two to three years. The CERES-Maize and NTRM models took about 5 and 55 minutes, respectively, for each treatment using the IBM-XT PC.

In addition to managing normal inorganic N application levels, the NTRM model also is able to handle split and sewage sludge application of N and conventional till as well as no-till. The CERES-Maize model also can handle split but not sewage sludge application of N. The VT-MAIZE runs neither for split nor for sewage sludge application. Moreover, it is used only for conventional tillage systems; nevertheless, it was tested for no-till by varying the bulk density inputs.

For all three models, user's guide manuals are available. The CERES-Maize and VT-MAIZE have the easiest manuals to follow. The VT-MAIZE user's guide needs more correction than the guides for CERES-Maize. The NTRM guide is the most complicated to follow and use. It contains some ambiguous terms, and errata are quite prevalent. The output of the CERES-Maize and the VT-MAIZE models are clearer, although the VT-MAIZE required more output correction initially than the CERES-Maize. The NTRM model produces more complicated and meaningless outputs. As the authors of the NTRM stated in a disclaimer in one of the files, it indeed requires a skilled user to enter the input, run the program, and interpret the output.

Evaluation of the predictive performance (i.e., the closeness of predicted values to the actual or field-measured values) of a model requires the use of statistical methods. In this study we used (a) regressions and coefficient of determination (R^2), (b) pooled t tests, and (c) upper and lower confidence intervals. These methods were applied to each N fertilizer treatment level, tillage management system, and experimental site. Based on the outcome of these statistical approaches, each model was evaluated relative both to the measured data and to the other models. The coefficient of determination was used to show the proportion of the total variation in the model-predicted values that can be explained by the linear relationship existing between the model-predicted and field-measured data. The degree of correlation (the closeness between the predicted and measured data) can be derived from the R^2 values. Regression equations were derived to show the trend in relationships between the model-predicted and field-measured (actual) values. The coefficient of regression (b_1) may indicate whether the rate of change of the model-predicted values corresponds to the rate of change of the field-measured data. After correcting for b_0 (i.e., after reducing b_0 to zero), b_1 may show clearly whether the model predicts correctly or tends to over- or underestimate the measured values. Such correction also is done in many biological and physical experiments, where generally the b_0 results from extrapolation. In our case, however, such correction is not possible since the b_0 values are real predicted values commensurate to field-measured data. Since most of the b_0 are non-zero values, it is difficult if not impossible to make a reliable evaluation of the model performance solely on the basis of the regression equations. Thus, t tests were used to further test the model performances. Using the appropriate degrees of freedom and a 90% confidence level, the models' ability to predict the total mass of N in the soil profile was tested. Whether the model predictions fall within the confidence intervals (especially with regard to N distribution in the soil, N in the grain and stover, stover and grain yields) was tested using the upper and lower confidence intervals. For the latter case, the precision of prediction was expressed in percentages, i.e., the number of times the predicted values fall within the intervals divided by the total number possible. The t tests were conducted for the upper (0 to 100 cm) and lower (100 to 200 cm) zones of the soil profile.

RESULTS AND DISCUSSION

I. Crop Yield and Nitrogen Recovery

A. Time and Source of N Application

Crop yield and N recovery in these systems are of particular interest since they directly relate to the potential for N to leach from the crop root zone. Any N that is not utilized by the crop may leach from the soil system.

1. Continuous-Corn Rotation

Yield and N uptake for corn grown on the Groseclose silt loam soil as influenced by time and source of N application were measured over three growing seasons (1986, 1987, and 1988) and two tillage management systems (no-till and conventional tillage). These data are presented in Tables 13 and 14. Analysis of variance showed that the main plot (tillage) and subplot (N) factors were significant for both yield and N uptake. The only significant interaction was the tillage by year interaction for N uptake. Where sewage sludge was employed to supply N to the crop, there was an increase in both total yield and total N uptake as compared with inorganic N applied either at planting or as a split application (Table 15). The difference in yield between treatments resulted from increased stover yields where sewage sludge was used as the N source. Similar results were noted for N uptake (Table 15). There was an increase in N uptake by the corn crop where sewage sludge was employed as the N source when compared to the inorganic N source applied as either preplant or split application. Much of this increase can be attributed to increased N content in the stover. There was no difference in yield and N recovery between N fertilizer applied at planting or by splitting the N application between two application dates. Tillage had a significant impact on both yield and N uptake (Table 16). Where no-till management was used, there was an increase in both yield (13%) and N uptake (6%) as compared with conventional tillage. With no-till management, yield and N uptake were increased for both the grain and stover components (Table 16). Yield and N uptake also varied among years (Table 17). Corn yields and N uptake were greater in 1988 than in 1986 or 1987. This reflects more favorable moisture conditions present during the 1988 growing season. Yield and N uptake were increased by 40% and 39% in 1988 as compared with the 1986 and 1987 growing seasons. The yield increase for 1988 resulted from increases in both the grain and fodder components while the increase in N uptake reflected increased N present in the grain.

For the continuous-corn rotation grown on the Groseclose soil, corn yields and N recoveries were increased where sewage sludge was used as the N source compared with the same rates of N applied as inorganic sources. There was no difference in yield or N uptake as a result of applying N at planting or by splitting the N application. Even though there was no difference in yield or N recovery with a split application of N, if all of the N is applied at planting the producer loses the flexibility of adjusting the N application rate later in the season to reflect changes in environmental conditions that could impact yield and thus influence N loss from the crop root zone. As expected, no-till resulted in increased yield as a result of increased moisture content. The increased moisture content where no-till management was employed for 1986, 1987, and 1988 is described in section III. A comprehensive description of the moisture content changes in the soil profile with both no-till and conventional-till management is given by Menelik (1990).

2. Corn-Wheat-Soybean Rotation

The yield and N uptake as influenced by time and source of 150 kg N ha^{-1} applied to conventional-till and no-till corn for two growing seasons (1986 and 1988) on the Suffolk sandy loam soil are shown in Tables 18 and 19. The analysis of variance showed that year and tillage were the primary sources of variation. It should be noted that corn suffered from moisture deficits as a result of inadequate precipitation during both the 1986 and 1988 growing seasons. Moisture stress conditions were accentuated in this coarse-textured soil because of the low water-holding capacity. There were no differences in yield or N uptake (Table 20) among the three fertilizer treatments (preplant, split, and sewage sludge). Silage yields ranged from 9,150 kg ha^{-1} for preplant application to 8,610 kg ha^{-1} where sewage sludge was utilized as the N source. The total N uptake for the three treatments varied little and averaged 123 kg N ha^{-1}.

Tillage management did not influence yield or N uptake where time and source of N application were studied (Table 21). Silage yields with conventional till averaged 8,610 kg ha^{-1} versus 9,280 kg ha^{-1} for no-till management. There was also no difference in N uptake between tillage management systems, with 124 and 121 kg N ha^{-1} being removed by the crop for conventional and no-till management systems. The reason no difference was present for no-till in this system might be the relatively small quantities of mulch present after the soil remained fallow following the soybean harvest; it may also have been affected by the low water-holding capacity of the soil.

Silage yield varied between years, while total N uptake was not different between years (Table 22). Yields were higher in the 1988 growing season (approximately 20%) than in the 1986 growing season. Further examination of these data show that stover yields increased by 79% in 1988 while grain yields were reduced by 55% when compared with 1986 data. The variation in stover and grain yield is a reflection of the total precipitation and the distribution of the precipitation throughout the growing season. The low grain yields in 1988 demonstrate the dramatic reduction in yield that can occur when severe moisture stress is present at the pollination and grain fill stages. Even though N uptake varied significantly between grain and stover components for the two growing seasons, there was no difference in total N uptake between the two years. Data collected in 1986 (Table 23) indicated that there were no differences between polymer- and lime-conditioned sewage sludges when applied at rates necessary to meet the N requirements of the crop.

With respect to source and time of N application, there was no difference in yield and N uptake between sewage sludge and inorganic N fertilizer as a N source. There was also no difference between the lime-conditioned and the polymer-conditioned sewage sludge as a N source. Even though we might expect a response to split application of N on this coarse-textured soil, this was not the case. Nitrogen use efficiency and N recovery were the same for preplant versus split N application. It should be noted, however, that during both the 1986 and 1988 growing seasons the corn was moisture stressed as a result of lower than normal rainfall. It should also be noted that if the N is applied preplant it removes the possibility for reducing the N application rate because of unsatisfactory growing conditions such as those experienced in this study. No-till management did not significantly increase yields in the corn-wheat-soybean rotation. The lack of a yield response to no-till probably reflects the smaller quantities of mulch present where corn is no-till planted into soybean stubble that has been present on the surface for approximately seven months longer than when corn is no-till planted into a mulch from a rye cover crop. The lack of a response to no-till also reflects the severe moisture stress conditions present in this soil during the study period.

B. Rate of Nitrogen Application

1. Continuous-Corn Rotation

The influence of N application rate, tillage, and growing season on corn yield and N uptake for the Groseclose soil are shown in Tables 24 and 25. The analysis of variance for these data showed that the main plot and subplot factors and the N by year and N by tillage interactions were significant for both yield and total N uptake.The relationship between yield and rate of N application for each of the three growing seasons can be described with quadratic functions (Figure 1 and Table 26). More than 90% of the variation in yield for all three years can be attributed to the rate of N application. The rate of increases in silage yield with increased N application (i.e., the linear component of the function) is higher in the 1988 growing season followed by the 1986 and 1987 growing seasons. The N rate that maximized yield varied between years. In 1986, the maximum yield was achieved at 142 kg N ha^{-1} while maximum yields were achieved at 160 and 210 kg N ha^{-1} rates in 1987 and 1988. The difference in yield between the three years is apparently related to the quantity and distribution of precipitation. In 1988 when moisture conditions were more favorable, corn yields and N recovery were higher than in 1986 and 1987. The increase in yields and N recovery reduces the quantities of N remaining in the soil that can potentially leach from the plant root zone. These data illustrate one of the most difficult management problems with respect to yield and N use in summer annuals: the inability to predict how much N to apply to the crop in any given year to maximize yield and minimize the potential for loss of N below the root zone, particularly for nonirrigated cropping systems.

The relationship between N uptake and N application rate among years could be described with a combination of linear and quadratic functions (Figure 2 and Table 26). As with yield, more than 90% of the observed variation in N uptake could be attributed to N application rate. The relationship between N uptake by the crop and N application rate in 1986 could be described with a quadratic equation. The N rate that maximized N uptake was 150 kg N ha^{-1}. In 1987 and 1988, N uptake and N application were linearly related. In 1987, the year with the lowest yields, only 0.30 kg of N was recovered for each kg of N applied. This lower N recovery again reflected reduced yields related to the moisture deficit conditions present during the growing season. In 1988, the highest yielding season, 0.62 kg of N was recovered for each kg of N applied. The large quantities of N removed from the 0 N treatment in 1986 (the first year of the study) indicates the need for a reliable N soil test, particularly in finer-textured soils where larger quantities of N are often present in the crop root zone following corn harvest. This is a particularly critical time with respect to N leaching because the months between corn harvest and corn planting are the time when the potential for N leaching is greatest. An effective soil test would allow for the reduction of the quantity of N applied for crop production by that quantity of plant-available N present in the root zone. Additional regression equations, describing the relationship between yield and N application rate and between N uptake and N application rate for the grain and stover components, are given in Table 26. Table 27 shows the difference between years when averaged over all N application rates for both yield and N uptake. The yield and N uptake data (Figures 1 and 2) demonstrate the difficulty in making N recommendations to increase the nitrogen recovery efficiency (NRE) and thus reduce the quantities of N that potentially will leach from the crop root zone. The data clearly show that the potential for N loss from the soil profile is greater following crops produced under moisture deficit conditions. To reduce the potential for leaching in any one year, it would be necessary to be able to assess the yield potential after planting and add the appropriate quantities of N at that time. Thus any mechanism available to control moisture availability, to predict N availability in the soil profile, and to predict yield would have a significant impact on yield, N recovery, and N loss from the root zone.

The relationship between the various yield components and N application for the two tillage management systems (no-till and conventional tillage) could be described with quadratic equations (Figure 3 and Table 28). Ninety-nine percent of the variation in yield (Figure 3) could be attributed to N application rates for both no-till and conventional-till management systems. The no-till system was clearly superior with respect to yield as compared to conventional tillage. Where no-till was employed, the maximum yield (14,770 kg ha^{-1}, Figure 3) was produced at 175 kg N ha^{-1} while the maximum yield for conventional tillage (12,400 kg ha^{-1}) was obtained at the 180 kg N ha^{-1} rate (Figure 3). At the 175 kg N ha^{-1} rate, no-till increased yields by 19% compared to the same N rate for conventional tillage. The increase in yield with no-till averaged over all treatments and all years (Table 29) was 14%. It is of interest to note that N application could be decreased by 10% from the rate calculated in Figure 1 to obtain maximum yield with a subsequent reduction in yield of less than 1%. The increase in yield with no-till compared with conventional tillage apparently resulted from moisture conservation where a mulch cover remained on the soil surface.

A quadratic function could be used to describe the relationship between total N recovery by the corn crop and N application rate for both no-till and conventional tillage (Figure 4). Most of the variation in N uptake in grain and stover components could be attributed to changes in N application rate for each of the tillage management systems (Table 28). Ninety-nine percent of the variation in total N uptake could be attributed to N application rate for both tillage systems. For both the no-till and conventional tillage management systems, maximum N uptake would occur at the highest N application rate. However, if the recommended N application rate for this particular cropping system is used (150 kg N ha^{-1}), 156 and 190 kg N ha^{-1} would be recovered in the crop for the conventional tillage and no-till treatments. A 10% reduction in N application would result in a 3 to 4% reduction in N uptake.

2. Corn-Wheat-Soybean Rotation

Total yields and N uptake for corn grown in 1986 and 1988 in the corn-wheat-soybean rotation on the Suffolk soil are shown in Tables 30 and 31. Analysis of variance showed that N application was significant for total yield and N uptake and that tillage, the tillage by year interaction, and the N rate by tillage interaction were also significant. Total yield for corn responded differently during the two growing seasons (Figure 5). There was no difference in yields during the 1986 growing season. This lack of response was attributed to the severe moisture stress that was present during this growing season. Yield data also indicated that enough N was initially present in the soil profile to meet the low plant N requirements under the moisture stress present during this growing season. In 1988, total yields were higher and the relationship between total yield and N uptake was described with a quadratic relationship. With this relationship, 86% of the observed variation in yield could be attributed to changes in the rate of N applied. According to this equation, maximum yield was produced at the 115 kg N ha^{-1} application rate. This rate is well below the recommended rate of 150 kg N ha^{-1}. These yields reflect the severe moisture stress that also was present in the 1988 growing season. Examination of the data in Table 32 shows that grain yields were adversely affected by moisture deficit conditions present at pollination and grain fill stages of growth for both years. Data in Table 30 indicate that grain yields were severely reduced at the higher N rates indicating that silking may have occurred earlier (collection of tissue at early silk indicated that this was the case) than for the other treatments and resulted in less pollination and thus less grain.

The relationship between N uptake and rate of N application could be described with a linear function in 1986 and a quadratic function in 1988 (Figure 6). In 1988, the NRE was extremely low as shown in the linear equation. There was only 0.14 kg of N recovered for each kg of N applied to this site. In 1988, the maximum N uptake was at the 180 kg N ha^{-1} rate. Thus, maximum N recovery was achieved at a N rate that was much higher than total yield, indicating that rate of N application increased the N content in the plant but not the yield. Again, this is an indicator that water and not N was the factor that limited yield in 1988. The estimated quantity of N recovered at the 180 kg N ha^{-1} rate was 125 kg N ha^{-1}. The values again show that the largest single factor that controlled nitrogen use efficiency and N recovery in this experiment was the available moisture present for crop growth. It also demonstrates the need for a mechanism to estimate more effectively the quantities of plant-available N present in the soil profile. The differences between years for yield and N uptake are given in Table 32.

No linear or quadratic relationships were found between yield and rate of N application for conventional tillage and no-till management systems (Figure 7). There was also no difference in total yield between tillage management systems (Table 33) although no-till did significantly increase grain yield. This increase in grain yield indicates that a higher moisture content was present at the critical pollination and grain fill stages where no-till was employed as the management system (see Section III, Soil Moisture Content). With conventional tillage, there was no change in yield with rate of N application. Where no-till was used, the 150 kg N ha^{-1} application rate increased yields when compared with the control treatment.

With respect to N uptake by the crop, no linear or quadratic function was found that described the relationship between N uptake and N application rate for conventional tillage (Figure 8). However, there was a linear relationship between N uptake and rate of N application where no-till management was employed. Nitrogen recoveries were higher at all N application rates than at the control, and the maximum N recovery was at the 150 kg N ha^{-1} application rate for conventional till. With no-till, 84% of the observed variation in N uptake could be attributed to variation in N application rate (Figure 8). Table 33 shows that there was a difference in yield components for tillage; no-till produced more grain and conventional tillage more stover.

II. Denitrification

Denitrification was determined by monitoring the N_2O flux and concentration distribution in the Groseclose soil profile on five separate occasions during the 1988 corn-growing season. Both conventional-till and no-till plots that received inorganic N at rates of 0, 150, and 225 kg N ha^{-1} and 150 kg of plant-available N from sewage sludge were monitored.

Cumulative seasonal denitrification losses are shown in Table 34. Nitrous oxide concentrations in the soil profile for the various sampling dates can be found in Menelik (1990). The soil profile N_2O concentrations were sampled in order to determine if Fick's law can be used to estimate the N_2O flux. This would then serve as an alternate to soil surface monitoring of N_2O flux.

Nitrous oxide flux from the conventional-till plots was 1.6 to 1.9 times higher than from the no-till plots. Even though the N_2O flux trended toward higher values where conventional tillage was used, there was no significant difference between the conventionally tilled and no-till plots. Denitrification is normally reported to be higher where no-till is employed, primarily due to the presence of more anoxic microsites in no-till soils (Linn and Doran 1984). The extremely dry growing season resulted in low denitrification rates in both the conventional-till and no-till plots. This reflects the limited number of anoxic microsites present in the field in the summer of 1988. Since denitrification occurs when facultative aerobic bacteria use the combined oxygen present in NO_3^- and NO_2^- as a terminal electron acceptor in place of O_2, large losses of N_2 and N_2O are not expected under the moisture deficit conditions present in the field. Groffman (1984) reached a similar conclusion.

Denitrification from conventional-till plots averaged 11.5 kg N ha^{-1} per season and 6.1 kg N ha^{-1} per season from the no-till plots. These values represent less than 2% of the applied N fertilizer. Differences among treatments are not statistically significant. Despite drought conditions during this growing season, denitrification loss is comparable with values reported in the literature for summer annuals. In a field study where N was applied as NH_4NO_3 and at the same level as in this experiment, N_2O-N accounted for 0.4 to 1.5% of the fertilizer added (Mosier et al. 1982). In dry regions with low rainfall activity, annual emission of 1 to 16 kg N_2O-N ha^{-1} was reported (McKeeney et al. 1980; Aulakh et al. 1982). But N_2O emission from N-fertilized and irrigated soils can be as high as 20 to 42 kg N ha^{-1} (Ryden and Lund 1980). The overall contribution of fertilizer N to N_2O emission is normally small in well drained soils. However, emissions tend to be higher for organic soils and heavily fertilized and irrigated crops (Hutchinson and Mosier 1979; Rice and Smith 1982; Aulakh et al. 1982; Mosier et al. 1983; Rolston et al. 1982). It is anticipated that if denitrification had been measured beginning at the time that N was applied and continued throughout the growing season that losses attributable to denitrification would have been higher. Also denitrification may have been higher in the no-till plots early in the growing season because of the higher moisture present in the upper part of the soil profile during this time.

Denitrification rates are expected to decrease as the growing season advances, primarily due to decreased N and moisture. This is demonstrated in Figure 9, although it is less obvious in Figure 10. All inorganic N treatments, without regard to tillage treatment, show highest denitrification in July and lowest in October. This is expected because the soil moisture content declines as the season progresses. The highest denitrification rate was 65 g N $ha^{-1}d^{-1}$ (control plots) and the lowest rate was 5 g N ha^{-1} d^{-1} (sludge plots). However, it should be remembered that these rates were not significantly different. Nitrous oxide concentration distribution in the soil profile for the five separate sampling dates is shown in Tables 35 - 39. From these results, it is not possible to compute and get reasonable results of N_2O flux using Fick's law. A probable cause for this response is the initial low N_2O concentration throughout the soil profile. Because sources of N and organic matter, as well as organisms capable of denitrification, are highly concentrated near the surface, denitrification will occur there at a higher rate when conditions are favorable. When N_2O forms at this point, it diffuses both upwards and downwards, due to N_2O concentration gradients, with almost equal intensity. Since transport by diffusion is slow, it may take longer to attain a reasonable N_2O concentration distribution throughout the soil profile than was allowable with the procedures employed. Thus, the N_2O flux reported here may not be the maximum flux possible, as can be verified from the N_2O gradients shown in Figures 11 and 12. However, they show an order of magnitude of the expected flux for such conditions. As in the N_2O flux reported above, N_2O concentration distribution differences in the profile are not statistically significant between tillage systems and among N treatments. Figures 11 and 12 confirm that moisture conditions were not optimal for denitrification. For example, on day 211 more denitrification was occurring below the 60-cm depth. Most studies indicate that denitrification decreases with depth and that low rates can be expected below the 60-cm depth. The absence of denitrification in the upper part of the soil profile indicates that few anaerobic microsites were present near the soil surface.

III. Soil Moisture Content

Mean moisture content data, determined at approximately monthly intervals from both the Groseclose and Suffolk soils, are shown in Tables 40-43. The moisture contents were measured, using a neutron moisture probe, at 30-cm (1-ft) intervals down to 150 cm (5 ft). A close inspection of the moisture content distribution with depth and time reflects the weather condition above the ground surface as well as the moisture extraction with depth by the roots. In 1986, there was initially an unusually severe drought with increased precipitation towards the end of the growing season. In 1987, precipitation was greater than normal before planting with severe moisture stress conditions developing within two months after planting because of abnormally low rainfall. In 1988, though precipitation was initially lower than in 1987, soil moisture content was, on average, either comparable to or slightly higher than in 1987. Soil moisture content was generally lower in the Suffolk soil in July and August of 1986 than in November of the same year for both till and no-till plots. The moisture content values indicate that in October 1986 the moisture content began to increase, which reflects the rainfall and evapotranspiration conditions present at this site. The increase in moisture content, however, did not extend below the upper 75 cm of the soil profile. Identical trends were also present for the Groseclose soil in 1986. The wetting front had penetrated deeper in the tilled than in the no-till plots in the Groseclose soil. In the Suffolk soil, there was no difference in penetration depth of the wetting front between tilled and no-till plots. The severity of the drought can be seen in the reduction in moisture content that took place even beyond the 165-cm depth.

Cumulative seasonal average moisture content to a depth of 165 cm shows that no-till retained higher moisture than conventional till for both the Suffolk and Groseclose soils. Examples of the cumulative moisture contents are shown in Figures 13 and 14.

IV. Nitrogen Retention in Soil

Construction of a N mass balance of the soil is utilized to determine N gains and losses in the system. Various studies pertaining to N mineralization and immobilization indicate that a steady state level of soil N exists in no-till and conventional till systems. This steady state assumption implies that only the adsorbed and dissolved N contents of the soil should be taken into consideration. Our approach was to consider the whole mass of soil, i.e., both the liquid and solid phases. Nitrogen additions and removals in the system were also considered (Tables 44-51).

A. Groseclose Silt Loam

The mass balance for conventional and no-till systems in 1986 shows a N gain in the soil profile under conventional tillage (Table 44) and a net loss where no-till management was employed (Table 45). Examination of the distribution of inorganic N throughout the soil profiles for the conventional-till and no-till systems (Figures 15 and 16) does not show any accumulation of N below the 1-m depth. There was, however, a large increase in inorganic N in the upper 50 cm of the soil profile under conventional-till management practices. The gain in inorganic N present in the upper part of the soil profile in the conventionally tilled plots may be due to mineralization of inorganic materials that were incorporated at the beginning of the experiment. The entire study area had been in no-till corn for several years prior to initiation of this study. Plowing the previously no-till corn land for the conventional-till plots incorporated large quantities of organic materials that had accumulated on the soil surface with no-till management into the soil and apparently resulted in a large increase in net N mineralization. This is consistent with literature indicating that converting from conservation to conventional tillage promotes mineralization (Gilliam and Hoyt 1987). The net loss from the no-till plots during the growing season does not appear to be a result of leaching because of the extremely dry conditions present. Since the UAN and sewage sludge were surface applied, these losses probably reflect a combination of NH_3 volatilization, net immobilization into the surface residue, and perhaps some additional denitrification above the values reported in the N balance. After the crop was harvested, here was, on average, 95 kg ha^{-1} more N remaining in the upper 1 m of the soil profile where conventional tillage was employed versus no-till management. This difference in N content between the no-till and conventional-till management can be readily seen in Figures 15 and 16. In the upper 80 cm of the soil profile, there were much larger quantities of inorganic N remaining in the plots where conventional till was employed as compared to no-till. The lower levels of N present in the upper 80 cm of the no-till system is also a reflection of the higher yields and higher N recoveries, while the higher N concentrations present in the conventionally tilled plots are attributed to enhanced mineralization.

During the winter months when precipitation exceeded evapotranspiration the large mass of N present at the 15- to 30-cm depths in the fall in the conventionally tilled plots (Figure 16) moved downward by approximately 40 cm to the 70-cm depth. Also, large decreases in N present in the soil profiles where 150 and 225 kg of inorganic N and the 150 kg of plant-available N from sewage sludge were observed during the winter months (Table 44 and Figure 17). It is believed that much of this N was lost as a result of leaching; however, there was no evidence of N accumulation below the 1-m depth to confirm this assumption. The other possibility would be enhanced denitrification of the N in the upper part of the soil profile. For the no-till plots the inorganic N peak moved from a depth of approximately 50 cm in the fall (Figure 16) to a depth of approximately 70 cm in the spring (Figure 18). Also, much smaller quantities of N were lost from the no-till plots when compared with the conventionally tilled plots. In fact, there was an increase in inorganic N content where sewage sludge was applied (Figures 16 and 18; Table 18), indicating that some mineralization of sewage sludge N may have occurred in late winter or early spring. Only the 225 kg N ha^{-1} treatment lost an appreciable quantity of N (71 kg). It should be remembered that this highest rate of inorganic N application is above the level that would normally be recommended for corn production under nonirrigated conditions. Although the no-till plots lost much less N than the conventionally tilled plots during the winter of 1987, the N distribution with depth for the no-till plots was similar to the conventionally tilled plots. In the no-till plots there was no indication that N had leached from the soil profile, as indicated by the absence of any N peaks between the 1- and 2-m depths. Menelik (1990) has analyzed these losses on a more comprehensive basis. We believe that the N lost from the upper 1 m of the soil profile leached through the 1- to 2-m depth (primarily weathered rock) by the process of macropore flow.

At the end of the 1987 growing season, the gain or loss of N did not follow a definite trend. The plots where lower N rates were applied tended to increase in N while plots receiving the highest rate of N application tended to have a net loss with respect to the N balance (Tables 46 and 47). Again there was no evidence that N had leached below the 1-m depth for either conventional or no-till management (Figures 19 and 20). The large increase in N that had accumulated at the end of the 1986 growing season with conventional tillage, which we attributed to mineralization, was not evident at the end of the 1987 growing season. In fact, N remaining in the upper 1 m of the soil profile at the end of the 1987 growing season averaged 172 kg ha^{-1} in the no-till plots and 175 kg ha^{-1} in the conventionally tilled plots (Tables 46 and 47). Figures 19 and 20 also show that the N remaining in both the no-till and the conventionally tilled treatments was distributed similarly at the end of the 1987 growing season. Both the conventionally tilled and no-till plots tended to have higher concentrations of inorganic N in the upper part of the soil profile, particularly at the higher rates of N application, and also at the 70- to 90-cm depths (Figures 21 and 22). Nitrogen loss from the soil profile during the winter and spring of 1988 was much lower than the losses observed for the winter of 1987. The greatest loss of N was 54 kg N ha^{-1} from the no-till plots that received 225 kg N ha^{-1}. During the winter of 1988, loss of N from the conventionally tilled plots was generally low and averaged 31 kg N ha^{-1} for the control and the inorganic N plots. The no-till plots averaged 22 kg N ha^{-1} for these same treatments.

At the end of the 1988 growing season, there were generally increases in the N balances for all treatments except the no-till 225 kg N ha^{-1} treatment (Tables 48 and 49). Also, there was little difference in N distribution throughout the soil profile (Figures 23 and 24). This was the highest yielding crop and thus more N was removed from the soil by the 1988 crop than by the 1986 and 1987 crops. These favorable environmental conditions for crop growth also may have resulted in enhanced net N mineralization; increases in N balances were noted during this growing season. These increases were primarily due to increased N uptake by the corn crop. Thus the N levels remaining in the soil profile at the end of the growing season were the lowest observed during the study. Only the 225 kg N ha^{-1} application rate to the no-till plots lost N from the soil profile. Since soil samples were not collected until June, and the rye was not killed until a much later date than normal, N leaching losses during the winter of 1989 may be underestimated.

There was a direct relationship between the N remaining in the upper 1 m of the soil profile at the end of the growing season and the quantity of N lost from the soil profile during the winter months (Figure 25) for both 1987 and 1988. This relationship could be described by a linear equation [N lost = -70.2 + 0.62 (N remaining)]. With this equation 87% of the observed variation in N loss from the soil profile could be attributed to N remaining in the soil profile at the end of the growing season.

This equation also indicates that there is a threshold value of approximately 113 kg N ha^{-1} in the upper 1 m of the soil profile. That is, only when inorganic N was present in the upper 1 m of the soil profile in concentrations greater than 113 kg ha^{-1} would N be expected to be lost from the soil profile. This threshold value is attributed to the resident NO_3^- present in soil solution in micropores that would be bypassed by macropore flow during the winter months. Even though the relationship between N remaining in the soil profile at the end of the growing season and N lost could be described by the same equation for 1987 and 1988, we would expect this threshold value to vary as a function of crop yield and growing season since the resident NO_3^- concentration in the micropores at the end of the growing season should vary. It is also possible that there may be some anion exchange capacity associated with the upper 1 m of the soil profile that could retard movement of NO_3^- through the soil profile.

B. Suffolk Sandy Loam

The N balance for corn grown on the Suffolk sandy loam soil during the 1986 growing season is shown in Table 50. Because yields were extremely low for both the conventionally tilled and no-till plots and there was little difference in the distribution of N through the soil profile (Figures 26 and 27), these data were pooled with respect to construction of a N balance. These data show (Table 50) that there was a relatively large quantity of N present in the upper 1 m of the soil profile before corn was planted in the spring of 1986. Because of the relatively large quantity of N initially present in the soil profile and the relatively low yields, there were large quantities of N remaining in the soil profile after the crop was harvested in the fall of 1986. These values ranged from 106 kg N ha^{-1} in the control plots to 193 kg N ha^{-1} at the 225 kg N ha^{-1} application rate. Figures 26 and 27 also show that some of the losses that occured during the 1986 growing season (Table 50) can be attributed to leaching below the crop root zone. The N distribution with depth (Figures 26 and 27) for both the no-till and conventionally tilled plots shows that N lost from both the 150 and 225 kg N ha^{-1} application rates is present in the soil profile between the 1- and 2-m depths.

Between October and February most of the N remaining in the soil at the end of the growing season had leached below the 1-m depth.This is evident from the N distribution shown in Figures 28 and 29. The only treatments with substantial N remaining in the soil profile at the end of February are the sewage sludge treatments. It should be remembered that sewage sludge was applied to the wheat plots in October 1986, after the soil samples were collected. These figures demonstrate that fall application of sewage sludges or for that matter N fertilizers may result in N leaching below the root zone by the end of February.This is in agreement with current recommendations from Virginia Polytechnic Institute and State University indicating that much of the N for wheat should be applied during the winter months and that efficiency will be increased if N application is split between dates during the winter wheat growing season. The rapidity with which N can leach below the rooting zone in the Suffolk soil is demonstrated by sampling of an accidental spill of N on Plot 1 (Figure 30). In less than a month after the spill had occurred, N had leached to a depth of 150 cm. This again indicates that much of the N remaining in the soil profile can be potentially leached from the root zone in these coarse-textured soils under environmental conditions that promote water flow through the soil.

The N distribution at the beginning of the 1988 growing season (Figures 31 and 32) showed that only small quantities of N were present at this time. The N distribution at the end of the 1988 growing season (Figsures 33 and 34) showed that only small quantities of N remained at this time (October 1988). There were, however, somewhat larger quantities of N remaining in the conventionally tilled plots where sewage sludge was applied. The N balance for the Suffolk soil (Table 51) shows that larger quantities of N were lost from the 225 kg N ha^{-1} application rate. It should be remembered that this N application rate is above the level normally recommended for corn on these nonirrigated coarse-textured soils. During the winter of 1989, substantial quantities of N were lost from the 225 kg N ha^{-1} rate and from the sewage sludge plots. It may be possible that sewage sludge mineralized at a more rapid rate in Years 2 and 3 than initially predicted.

There was also a direct relationship between N remaining in the upper 1 m of the soil profile at the end of the growing season and the quantity of N lost from the soil profile during the winter months (Figure 35) for the Suffolk soil for the winters of both 1987 and 1989. The relationship between N remaining in the soil profile and N lost during the winter months could be described by a linear equation [N lost = -37.9 + 0.99 (N remaining)]. This equation indicated that 99% of the variation in N lost from the soil profile during the winter months could be attributed to the quantity of N remaining in the soil profile at the end of the growing season. The relationship between N remaining in the upper 1 m of the soil profile and N lost indicated that there was a threshold value of approximately 38 kg N ha^{-1}. This means that in the years studied inorganic N in excess of 38 kg N ha^{-1} in the upper 1 m of the soil profile could be lost. This threshold value is attributed to the resident NO_3^- present in soil solution in micropores that would be bypassed by macropore flow. This threshold value is expected to be lower in years with more favorable moisture conditions. Data at this site indicated that N remaining in the soil profile at the end of the growing season was lost via leaching.

V. Fate of Nitrogen: Comparison of Models

The performance of the NTRM, CERES-Maize, and VT-MAIZE computer models was evaluated and compared with regard to corn grain and stover yield, total N uptake, total grain N contents, and the fate and distribution of N in soil for both the Blacksburg and Westmoreland County sites.

Measured as well as predicted corn stover yield for Groseclose and Suffolk soils for 1986, 1987, and 1988 are presented in Tables 52 and 53. The variation in measured stover yields on both soils reflects the prevailing weather condition at the time, which was characterized by drought and uneven distribution of rainfall. The measured stover yield from the Groseclose soil increased progressively with the years, with lowest yields in 1986 and highest yields in 1988 for both tillage systems. For conventional till, the NTRM model predicted highest stover yield for 1987 and lowest for 1986. For no-till, NTRM predicted the highest stover yield for 1988 and lowest for 1986, which was in agreement with the measured values. The CERES-Maize and VT-MAIZE models predicted for conventional till highest and lowest yields for 1988 and 1987, respectively. For no-till, both models predicted highest yield for 1988 but disagreed in the other two years. The models were not tested for the same number of treatments, since all N treatments were not compatible with each model. The NTRM model was tested on the greatest and the VT-MAIZE on the least number of N treatment levels. Table 54 shows the frequency of model predictions that were not significantly different from the observed values. These data show that the model performances varied with the type of tillage and soil. For the Groseclose soil, best estimates were made by the VT-MAIZE for conventional till (58%) and the NTRM for no-till (56%). VT-MAIZE did not perform as well for no-till; however, it should be remembered that it was not designed for use with a no-till management system. CERES-Maize always underestimated the stover yield, and it predicted an extremely low yield for 1987. This model gave fewer correct estimates than the others. When averaged over three years and the two tillage systems, the NTRM and VT-MAIZE models gave estimates that were the same as the field-measured values 47% and 46% of the time, respectively.

VT-MAIZE gave the best estimates for stover yields produced on the Suffolk soil in 1986 and 1988. It was within an acceptable range 75% and 88% of the time for conventional-till and no-till management systems, respectively. The NTRM model gave correct estimates for 25% of the stover yields. The above performances also may demonstrate that the VT-MAIZE functions best in sandy soils. Although VT-MAIZE performed the best for both tillage systems in both years, it is difficult at this stage to make conclusive statements. It is worth noting, however, that VT-MAIZE is also quite insensitive to fertilizer additions.

Both measured and predicted corn grain yields are presented in Tables 55 and 56. For the Groseclose soil, the NTRM and CERES-Maize models gave the best estimates of grain yields for conventional till and the NTRM for no-till. The performance levels were generally low. For conventional till, the performances for NTRM and CERES-Maize were 28% and 27%, respectively (Table 57). For no-till, the NTRM yielded 33% and the CERES-Maize only 20%. VT-MAIZE either under- or overestimated all measured values. The performance level for grain yields produced on the Suffolk soil was also low but slightly higher than values for the Groseclose soil. For conventional till, NTRM and CERES-Maize gave correct estimates 40% and 42% of the time, respectively. The best performance for no-till, 42%, was also attained with the NTRM model. For grain yield NTRM gave the best estimates for both soils, followed by CERES-Maize. A typical feature of these models was that they tended to underestimate grain yield on the Groseclose soil. Grain yields on the Suffolk soil were overestimated 100% of the time for both tillage systems by VT-MAIZE while NTRM and CERES-Maize over- and underestimated the grain yield 50% of the time.

The total N uptake for the Groseclose and Suffolk soils is shown in Tables 58 and 59, respectively. All three models generally underestimated N uptake by corn for both tillage systems on the Groseclose soil (Table 60). VT-MAIZE gave the best estimates of N uptake, but the performance level is very low (21%). For the Suffolk soil, NTRM gave the best estimates for both conventional tillage (75%) and no-till (50%). VT-MAIZE averaged 25% correct estimates while CERES-Maize gave the poorest performance. In conclusion, although all three models underestimated the grain yield for the Groseclose soil, the VT-MAIZE is the best choice even though the number of predictions that were not different from those measured is very low and it is insensitive to variation in N fertilizer inputs. For the Suffolk soil, the NTRM is the best choice. Here also, all three models underestimate yield to some extent but the VT-MAIZE overestimated yield 56% of the time.

The soil N distribution at corn planting and harvest was measured for all N treatment levels and tillage systems from both the Groseclose and Suffolk soils. The N values obtained were used both as initial input and for comparison and evaluation of model output at harvest. All three models were tested. Figures 36 and 37 show N distribution as measured and predicted by the three models for the control and the 225 kg N ha^{-1} treatment levels for conventional till on the Groseclose soil. In Figure 36, all three models predicted the N distribution in the upper 100 cm quite well. In the lower regions, however, all models overestimated the soil N content. In Figure 37, NTRM and CERES-Maize models predicted the soil N distribution reasonably well. The VT-MAIZE, however, overestimated the N content in the upper 70 cm.

A modified version of VT-MAIZE was developed, while this research was being conducted, for N distribution in soil and for crop yield. Figures 38 and 39 compare the modified version of VT-MAIZE with the other two models for N distribution through the Groseclose soil profile for the N control plots. Figures 40 and 41 also compare the same models for the 225 kg N ha^{-1} treatment for both tillage systems. The modified VT-MAIZE tends to underestimate the total mass of N.

Figures 36-41 provide schematic illustrations for visual comparison of the models' performance in predicting the N distribution in soil. The models were evaluated by using linear regression accompanied by coefficients of determination. Both the predicted total N mass in the upper and lower parts of the soil profile and the number of times the model predicts the N concentration were determined (Menelik 1990). In addition to the above statistical tests, the models' ability to predict the N distribution in the soil profile was evaluated at the 90% confidence level. Subsequently, the percentage of times the model predicts correctly was computed and is presented in Tables 61 and 62. Predictions of N in various soil segments by both NTRM and the CERES-Maize agreed very closely with the measured data. VT-MAIZE did not perform as well as the other two models, especially in the upper part of the soil profile. For the Groseclose soil, NTRM and the CERES-Maize did equally well for conventional till but the NTRM is slightly preferable for no-till. In the Suffolk soil, both NTRM and CERES-Maize performed very well. However, NTRM was slightly better. In the lower portion of the soil profile (between 1 and 2 m), all three models performed closely and equally well for both tillage management systems and sites.

The NTRM, CERES-Maize, and VT-MAIZE models are made up of different submodels from various sources for the various processes, and it is not to be expected that a given model would excel for each of the tillage practices at all N treatment levels for all years. As weather and soil moisture conditions varied both spatially and temporally, each submodel reacted either favorably or adversely, thus affecting the whole model performance in all its facets. In Table 63, the areas in which each model is deemed to be superior compared to the others are shown. This will help the model user choose the most appropriate model for the purpose intended. It should be noted, however, that the evaluations in Table 63 do not include the updated version of VT-MAIZE.

VI. Conclusions

A. Corn Yield and Nitrogen Recovery

1. Organic versus Inorganic N Sources

a. For the Groseclose soil, plant-available N (150 kg N ha^{-1} from sewage sludge) increased both total yield and N uptake when compared with N applied as UAN solution. There were also visual differences in the field. Corn in the conventionally tilled plots that received sewage sludge as the N source did not show the severe moisture stress symptoms that were present where inorganic N was applied.

b. On the coarse-textured Suffolk soil, there was no difference in yield and N recovery between N applied in the form of sewage sludge or N from inorganic sources.

c. There were no differences in yield and N uptake between the polymer- and lime-conditioned sewage sludges.

2. Split versus Preplant N Application

a. There was no difference in corn yield and N recovery between preplant and split N applications. It should be noted, however, that the corn was severely moisture stressed in 1986 and 1988 on the Suffolk soil and during 1986 and 1987 on the Groseclose soil and moderately stressed in 1988 on the Groseclose soil.

b. These data indicate that the producer can utilize split applications of N as a strategy for maximizing economic returns and simultaneously reducing the potential for loss of N below the root zone. Splitting the N application allows the producer to wait until sidedress N is applied before making a decision on the quantities of N to be applied to the corn crop. There are several advantages that can be realized by waiting until later in the growing season to make a decision with respect to level of N application. If an appropriate soil test were available it would enable the producer to take into consideration residual N, thus decreasing the total quantity of N applied and reducing the potential for leaching losses while also decreasing the cost of fertilizer N applied to the crop. (This concept will be developed in more detail later). Because there is a risk of leaching losses occurring earlier in the corn growing season when precipitation may still be present in excess of evapotranspiration, application of most of the N as a sidedress application would minimize the potential for N loss during the highly susceptible period at and immediately following planting. Employing sidedress N application as the principal time for N application would also enable the producer to adjust N application rate based on changes in weather conditions or the economy.

3. Rate of N Application

a. Tillage had a significant impact on both yield and N uptake for the Groseclose soil. Where no-till management was used, there was an increase in both yield and N uptake as compared with conventional tillage. No-till increased total yield by 19% at the maximum yield point compared with conventional till. Yield and N uptake for both conventional and no-till could be described with quadratic equations.

b. The increase in yield and N uptake with no-till on the Groseclose soil was attributed to increased soil moisture with no-till management.

c. Yields were low for both no-till and conventional till on the Suffolk soil and reflect the moisture stress conditions present. There was no difference in yield between tillage management systems on the Suffolk soil, although no-till tended to be higher.

d. Quadratic equations could be used to describe the relationship between yield and N recovery and N applied for each of the three years on the Groseclose soil.

e. Yield and N recovery by the crop was influenced by moisture to a very large extent. This can be demonstrated by comparing the data collected in 1987 and 1988 on the Groseclose soil. Yield was reduced by 34% and N recovery by 52% in 1987, a dry year, as compared with 1988, a more favorable year with respect to plant-available moisture. During seasons when yields of corn are reduced by moisture stress, more N will remain in the soil profile at the end of the growing season after the crop has been harvested. This higher amount of N greatly increases the potential for N to be leached from the soil profile during the winter and spring months when N is most susceptible to leaching losses. In areas of the state where corn is typically followed by wheat in the crop rotation, an appropriate soil test, if available, would make it possible to determine residual plant-available N present following corn harvest. Thus a more informed decision could be made with respect to need for fall application of N to the wheat crop. In areas where corn is not followed by a small grain crop, a winter cover crop should be grown to recover as much of the remaining soil N as possible.

f. Plots where no N was applied had relatively large crop yields and plant N uptake, indicating that residual N was present in large enough quantities to meet much of the N requirement of the corn crop, particularly for the first year of the study for both the Groseclose and Suffolk soils. This observation can be confirmed from data collected on the Groseclose soil experimental site. Corn had been grown on this site, under no-till management conditions, for several years prior to the initiation of this study. In Year 1 of this study, 84% of the silage yield and 36% of the N recovered by the corn crop could be achieved without addition of N fertilizer. For the last year of the study (Year 3), 56% of the silage yield and 27% of the total N recovered by the crop could be obtained without N application. These data clearly indicate the need for development of a procedure for N recommendations based on consideration of the residual plant-available N in the soil profile.

B. Denitrification

1. Denitrification losses during the middle and latter stages of the growing season were low and amounted to less than 2% of the applied-N fertilizer.

2. There was no difference in N loss via denitrification between conventional till and no-till during the middle and latter stages of the growing season.

3. Extremely dry conditions apparently resulted in few anoxic microsites in both tillage systems and thus accounted for the low rates of denitrification measured. This is not an unexpected observation under the moisture stress conditions present in the field.

C. Nitrogen Leaching

1. There was a direct relationship between N loss from the soil profile

during the winter months and N remaining at the end of the growing season.

2. There were threshold values below which N was not lost via leaching. For the Groseclose soil this value was 113 kg N ha^{-1}; for the Suffolk soil, it was 38 kg N ha^{-1}.

3. Much larger quantities of N were lost from the soil profile for conventional till on the Groseclose soil in the first year of the study. This was attributed to the larger quantities of N remaining at the end of the growing season as a result of enhanced mineralization where no-till corn land was converted to conventional till with the incorporation of large quantities of organic materials.

4. There appeared to be little if any N lost to leaching during the growing season for the Groseclose soil. However, there were losses during the growing season for the coarser-textured Suffolk soil.

5. There were also large losses of N from the Suffolk soil during the winter after the first growing season. This reflects the large quantity of carryover N that was present in the soil profile when the study was initiated.

6. Even though there was a larger quantity of moisture present in the no-till plots on the Groseclose soil (one could observe visually the difference between no-till and conventionally tilled corn), the additional moisture did not result in increased N leaching but was utilized by the crop to increase yield and N uptake.

7. On the Groseclose soil much larger quantities of N were lost as a result of leaching in the first year of the study from the conventionally tilled plots as compared to the no-till plots. This increased N loss was attributed to enhanced N mineralization in the conventionally tilled plots and to decreased N uptake as compared to the no-till plots.

D. Comparison of Models

1. The model performances varied from year to year and from one tillage practice to another. The models appear to be written for average (normal) soil and climatic conditions. They do not make satisfactory predictions for all of the varying conditions encountered while this research was being conducted.

2. The results indicate that none of these models can be considered superior in every aspect to the other models. However, each model has positive qualities that make it attractive for a specific purpose.

3. With regard to N distribution in soil, the NTRM and CERES-Maize made satisfactory predictions. For the Groseclose soil, the NTRM often underestimates while the CERES-Maize overestimates N present in the upper parts of the soil profile. Between the 1- and 2-m depths, NTRM

tends to overestimate while the CERES-Maize underestimates. For the Suffolk soil, both models tend to overestimate in the upper portion of the soil profile while in the lower soil portion they predict accurately. Generally, however, the NTRM makes better predictions.

4. All three models still require a great deal of improvement and debugging. The modified VT-MAIZE is very promising.

VII. Recommendations

Observations made during this study indicate the need to develop a management strategy that would eliminate or reduce the application of N in excess of that required for crop production, thus reducing the potential for N leaching losses from the root zone.

1. Data in this report indicate that the quantity of N leached below the root zone can be reduced by more closely matching the N requirement of the plant with the N available in the soil for plant uptake. N recommendations for crop production in Virginia currently do not utilize a soil test to assess the quantity of N present in the soil profile that is available for crop growth. Because residual N is not considered, Virginia's N recommendations may be in excess of the N needs of the corn crop during many years. During years when less than optimal growing conditions are present (e.g., limiting moisture), typical N application rates will be in excess of those needed for the yield obtained and will result in larger quantities of N present in the soil profile after the crop is harvested. This N may be lost from the soil profile via leaching.

2. Nitrogen recommendations currently being made by Virginia Polytechnic Institute and State University are based on the yield potential of the soil on which the crop is being grown and the N application rate that will maximize net income at that expected yield level. Because of the absence of an appropriate soil test for residual soil N, and the lack of information on the relationship between residual N contained throughout a soil profile and additional applied N needed to obtain a given yield, residual soil N is not given consideration in making N recommendations.

3. One method for reducing the potential for N leaching from the soil profile would be to develop a N soil test and its subsequent yield correlation for identifying fields that have relatively large quantities of N present in the soil profile. This would reduce the quantity of N applied for crop growth to reflect the contribution of residual soil N. Because of the seasonal variation in soil N levels and the need to collect soil samples for P and K analysis in the fall, development of a N soil test has not been actively pursued or was not highly successful. Recent research in several states has indicated that significant levels of residual NO_3^--N can carry over to the next growing season. The quantity of N carryover depends primarily on the N remaining in the soil profile after the crop is harvested, soil properties, winter precipitation, and the presence or

absence of a winter cover crop. The possibility of soil NO_3^--N testing was discussed extensively at a recent workshop conducted by TVA/NFDC (1989). The discussions presented at this workshop indicated that there is potential for development of a pre-sidedress soil NO_3^--N test (PSNT) for assisting in making N recommendations for corn production. Researchers from Vermont and Pennsylvania noted that where laboratory soil incubation procedures (mineralization indexes) were poor predictors of soil N supply, PSNT had been successful. They also reported that PSNT could be viewed as an in situ incubation test. Existing literature supports this concept, showing that the most rapid rate of N mineralization occurs within three weeks of application of organic material to the soil. If a small initial quantity of N is applied preplant, a sample collected pre-sidedress will also allow for correction of soil N levels with respect to immobilization of N by high C/N residues that might be present in the soil.

4. Recent research conducted in Pennsylvania and Vermont indicates that little or no additional fertilizer N is needed for sites testing above 25 mg NO_3-N kg^{-1} of soil. In Iowa research the critical level for separating responsive from nonresponsive sites was 21 mg NO_3^--N kg^{-1} of soil.

5. Data from other states indicate that a NO_3^--N soil test that samples the upper 30 cm of the soil profile may be suitable in soils such as the Groseclose silt loam, where NO_3^--N present in the surface and subsurface may be highly correlated because of macropore flow. Where piston flow is dominant, such as in the Suffolk sandy loam, it may be necessary to sample to deeper soil depths to adequately correlate soil NO_3^--N and plant-available N. Current information indicates that successful development and implementation of a N soil test could be one of the most successful methods for reducing the quantities of N applied to the corn crop and thus for decreasing the quantity of N present that might leach from the plant root zone.

6. Research needs to be conducted in contained systems to more adequately evaluate BMPs with respect to N losses from the soil profile. The most logical method for making these types of assessments would be to construct a facility that would accommodate large undisturbed soil monoliths. Since soil structure plays such a dominant role in loss of water and soluble components through the soil system, use of undisturbed soils would be essential.

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Figures

Figure 1.
Relationship between corn silage yields and N application for 1986, 1987, and 1988 in a Groseclose soil.

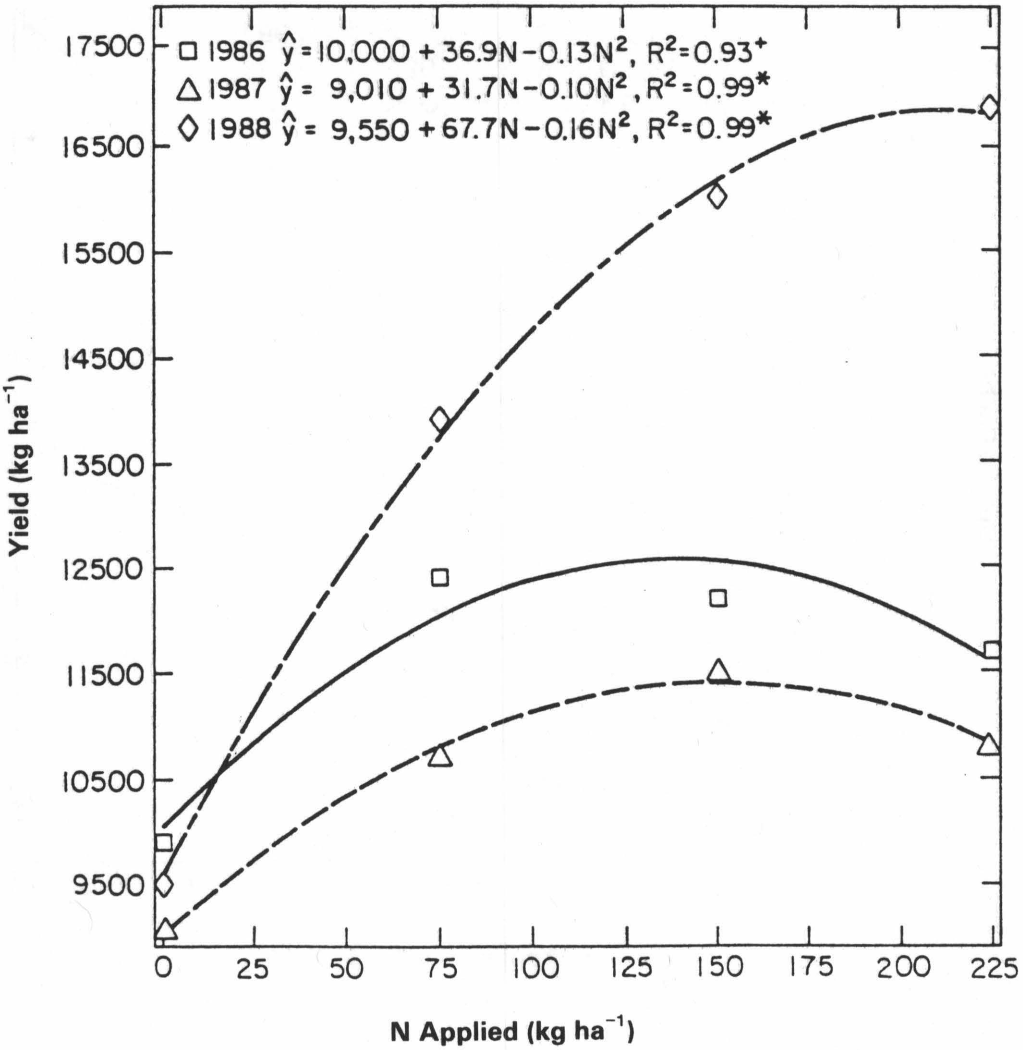


Figure 2.
Relationship between corn N uptake and N application for 1986, 1987, and 1988 in a Groseclose soil.

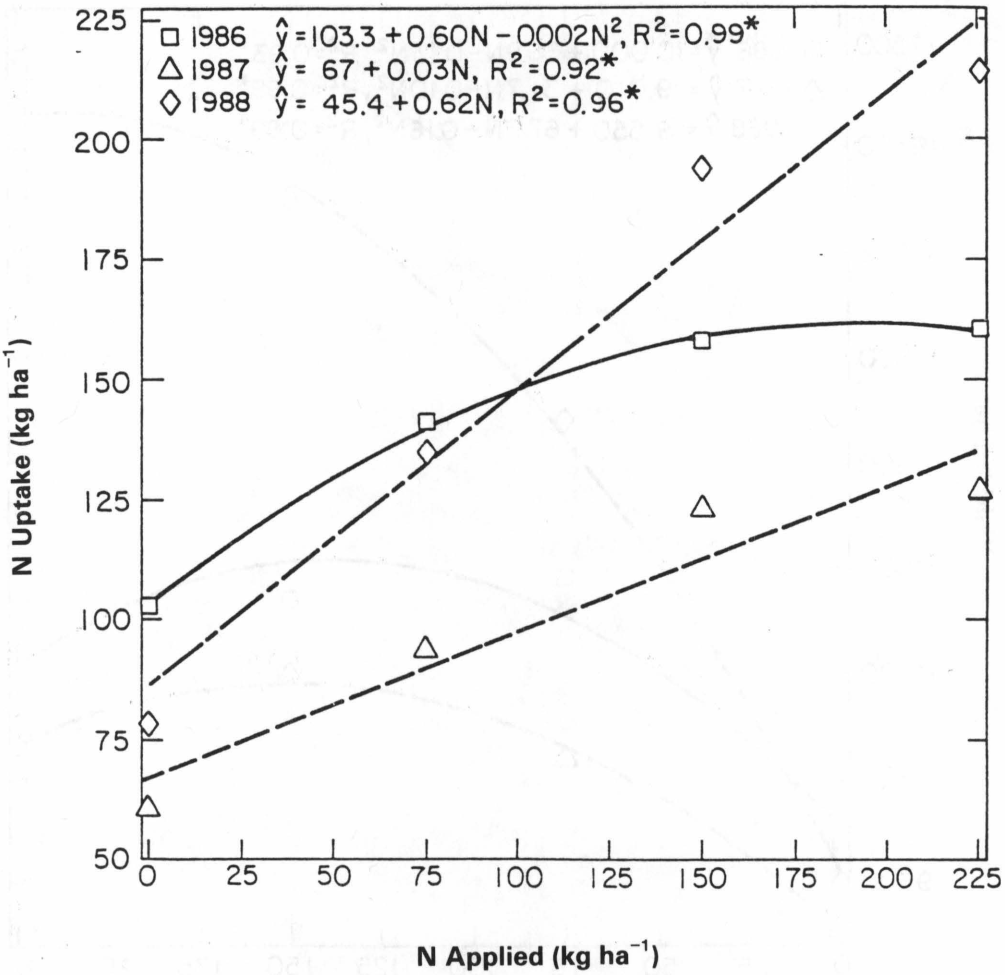


Figure 3.
Relationship between corn silage yield and N application for tillage systems in a Groseclose soil.

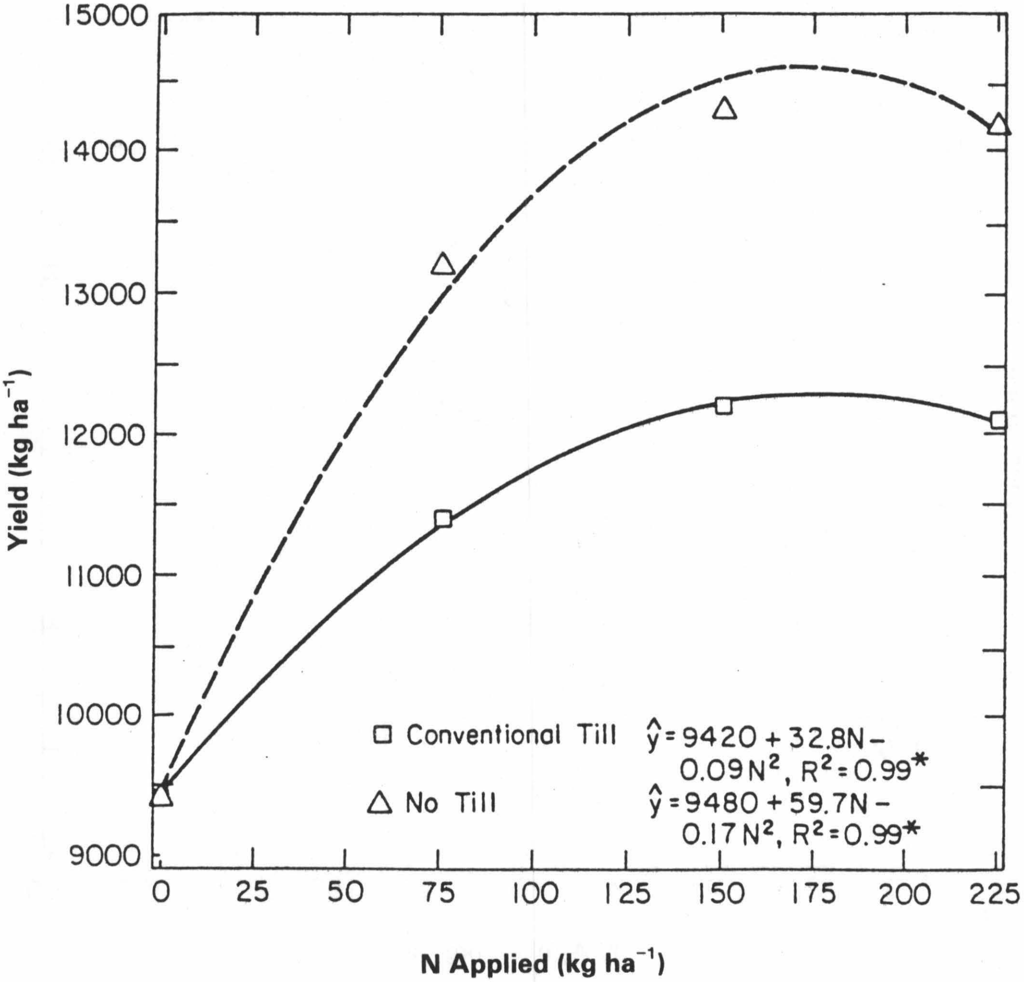


Figure 4.
Relationship between corn N uptake and N application for tillage systems in a Groseclose soil.

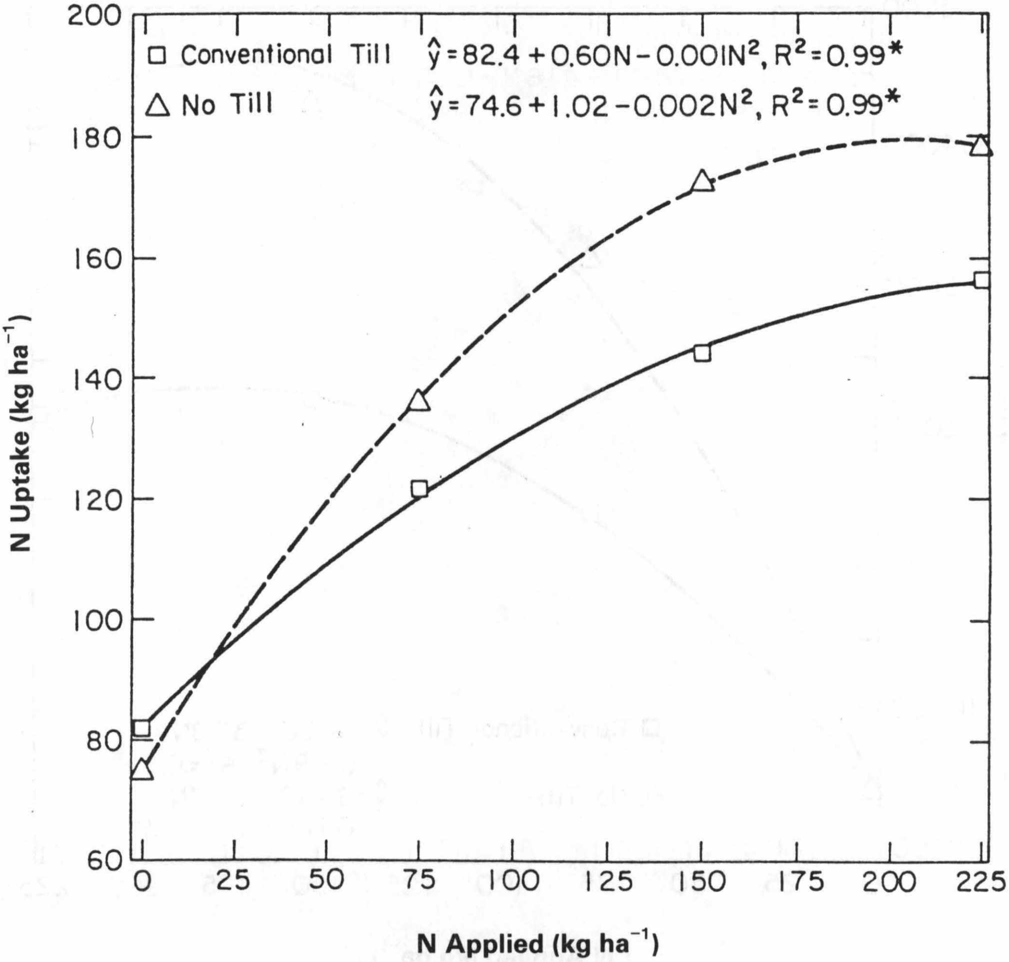


Figure 5.
Relationship between corn silage yield and N application for 1986 and 1988 in a Suffolk soil.

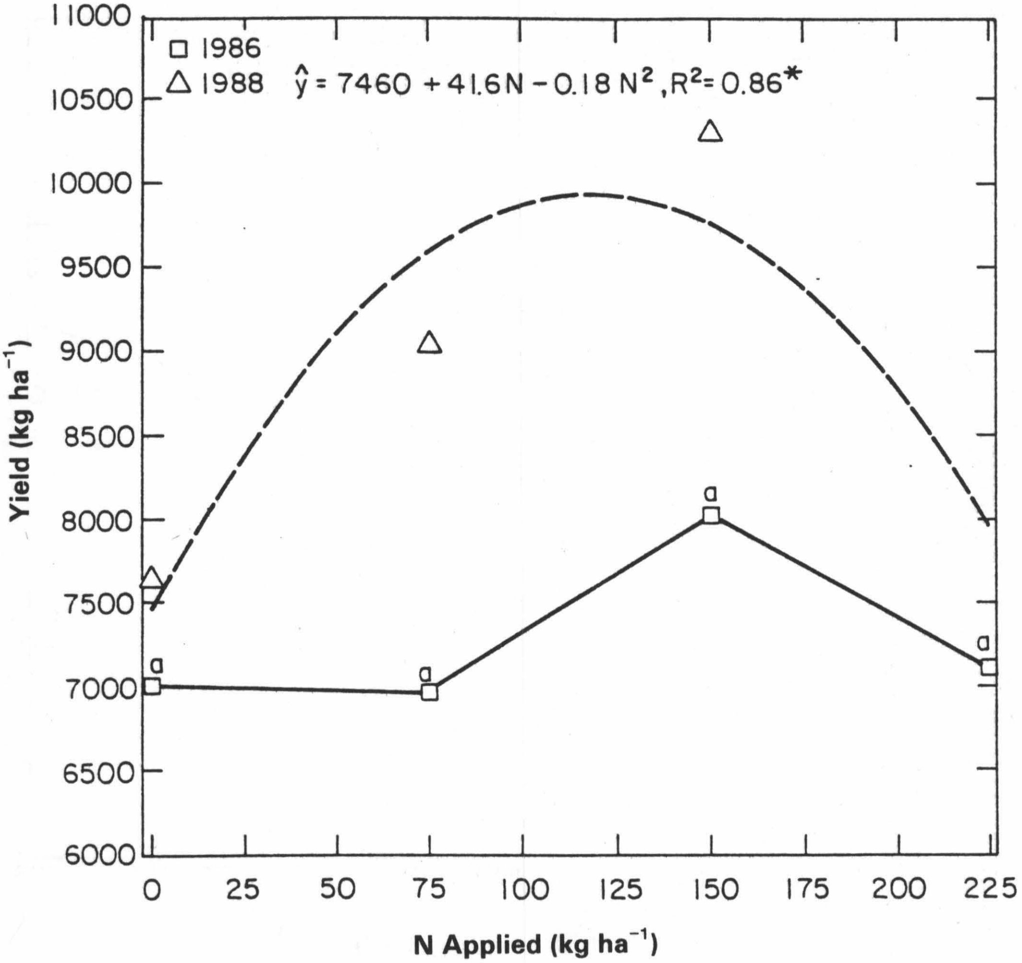


Figure 6.
Relationship between corn N uptake and N application for 1986 and 1988 in a Suffolk soil.

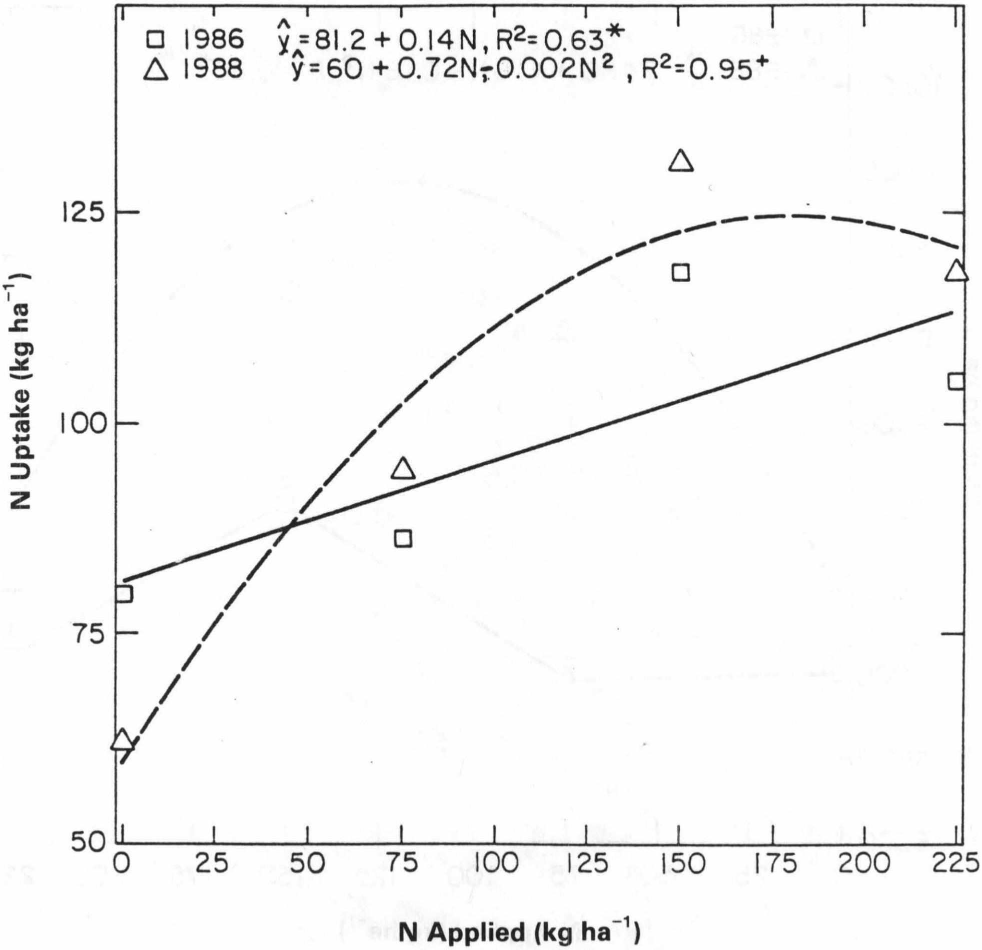


Figure 7.
Relationship between corn silage yield and N application for tillage systems in a Suffolk soil.

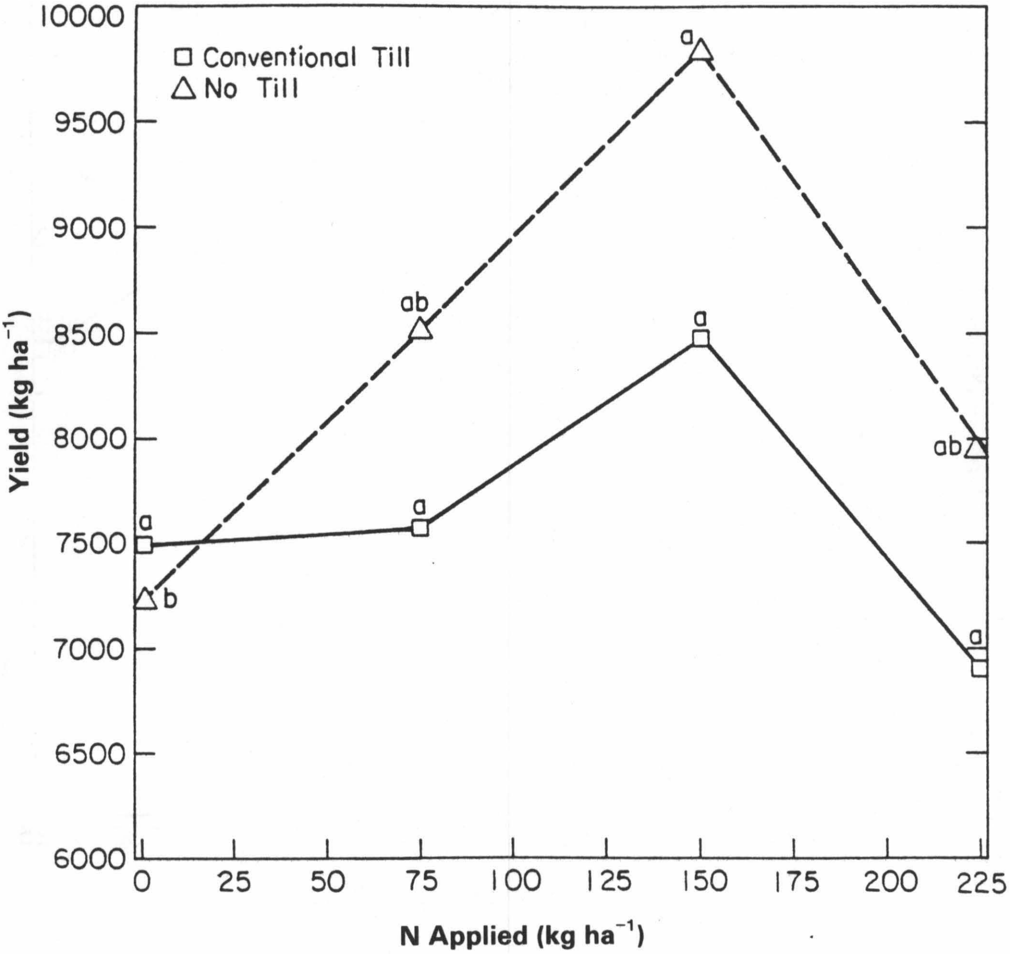


Figure 8.
Relationship between corn N uptake and N application for tillage systems in a Suffolk soil.

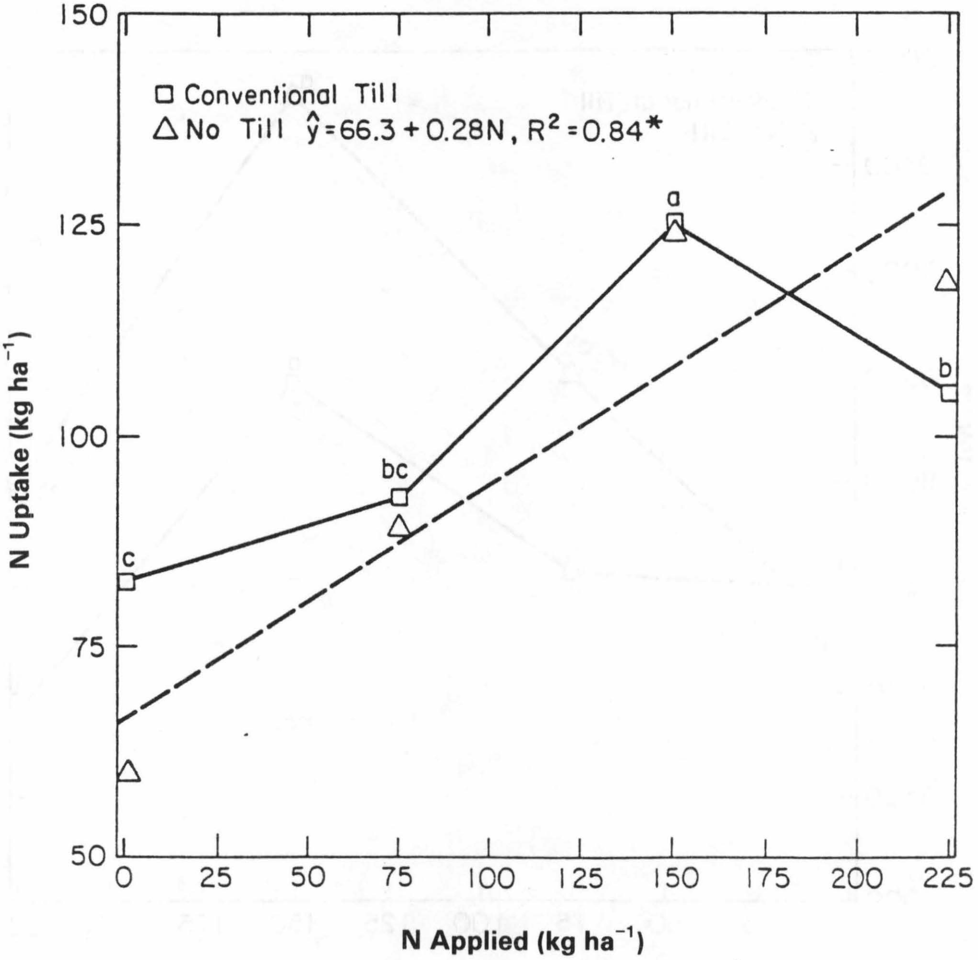


Figure 9.
Nitrous oxide -N flux distribution with time for conventional tillage.

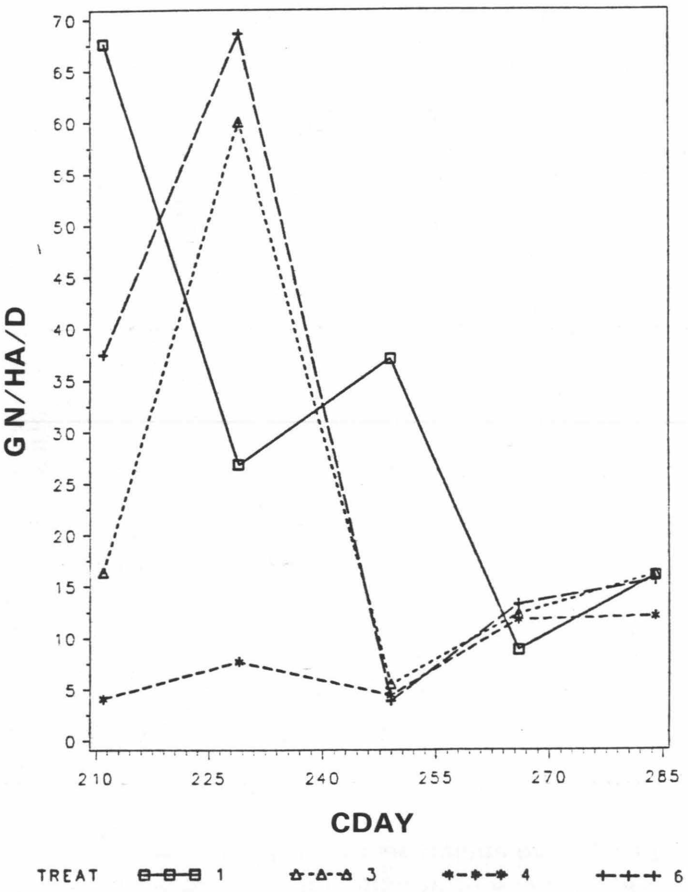


Figure 10.
Nitrous oxide -N flux distribution with time for no-till.

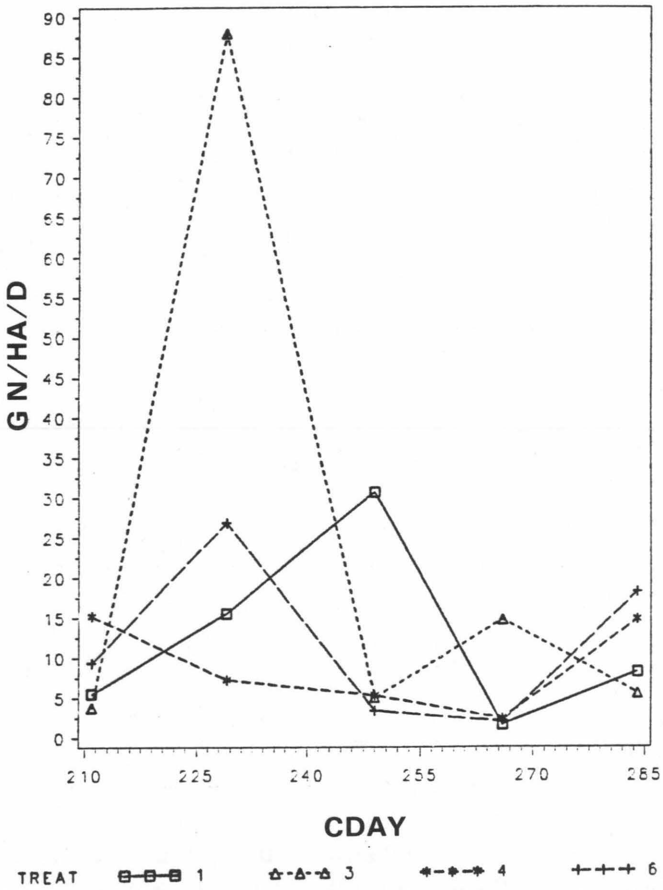


Figure 11.
Nitrous oxide -N flux distribution with depth for conventional till (with acetylene on day 211).

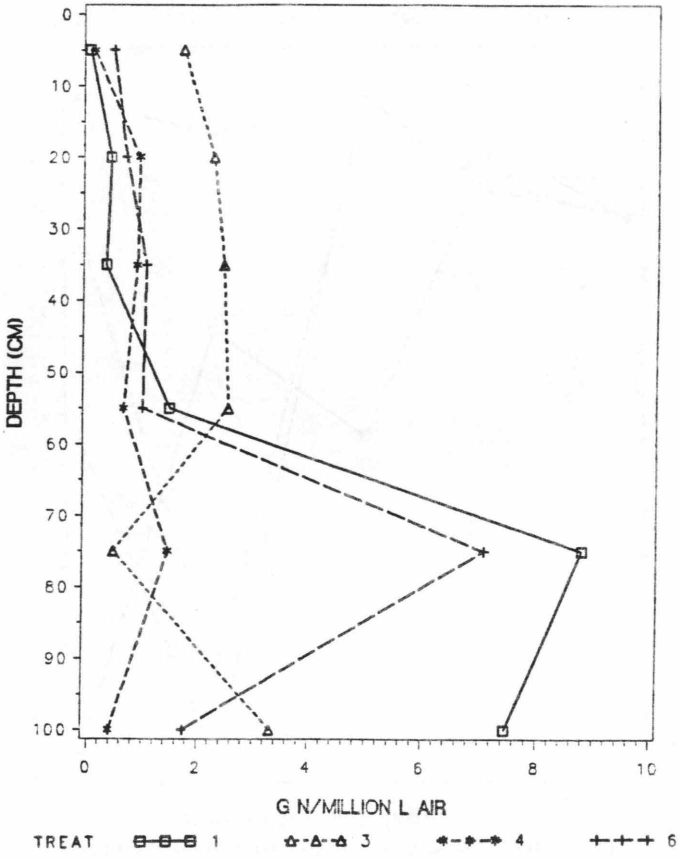


Figure 12.
Nitrous oxide -N flux distribution with depth for conventional till (with acetylene on day 284).

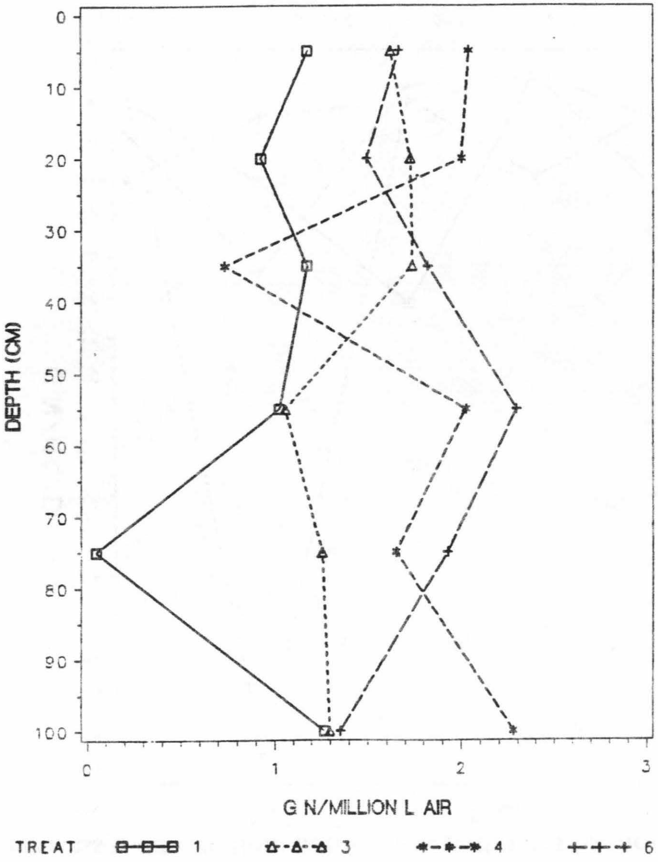


Figure 13.
Mean cumulative soil moisture content with depth in the Suffolk sandy loam soil in 1986.

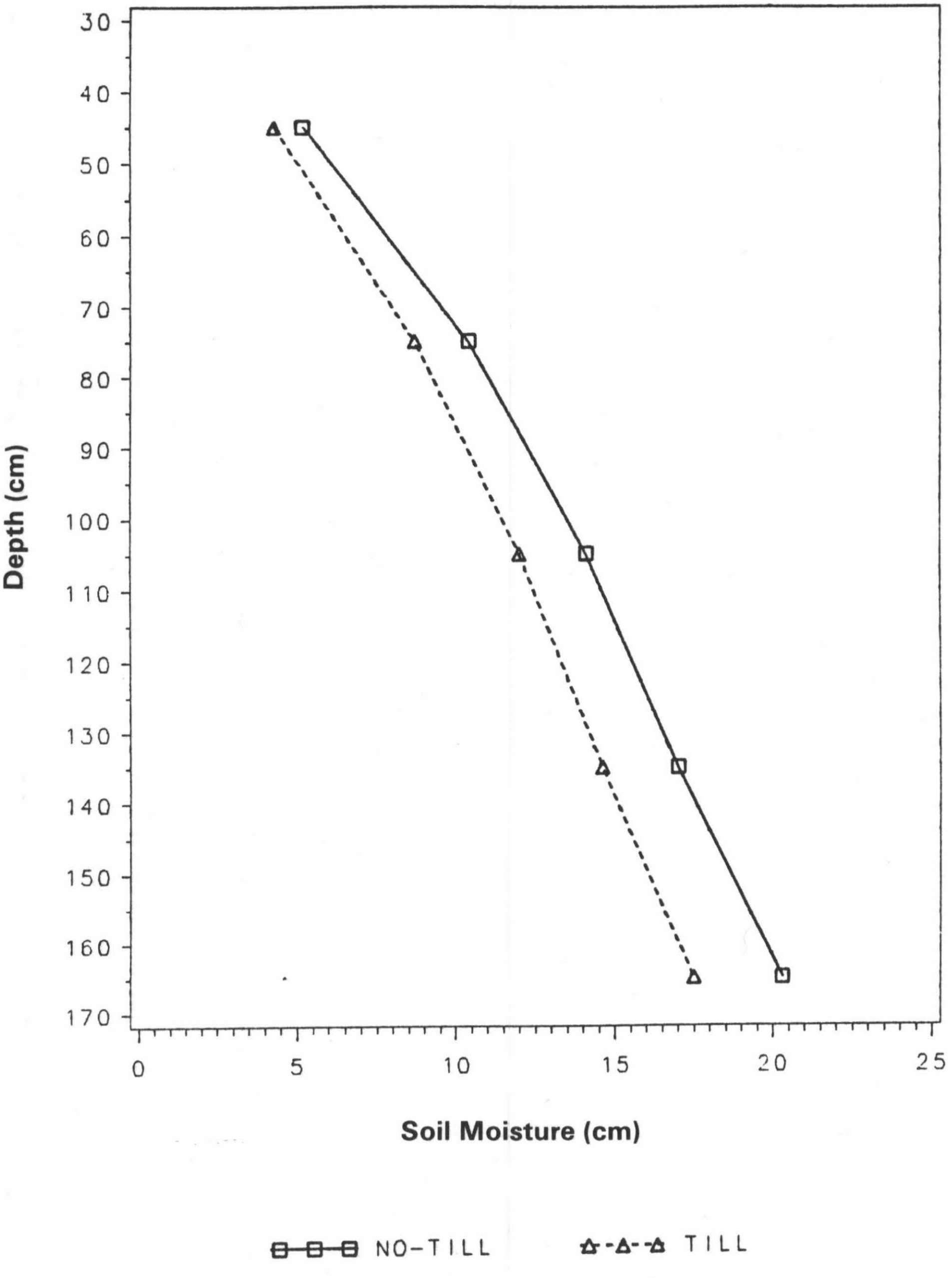


Figure 14.
Mean cumulative soil moisture content with depth in the Groseclose silt loam soil in 1986.

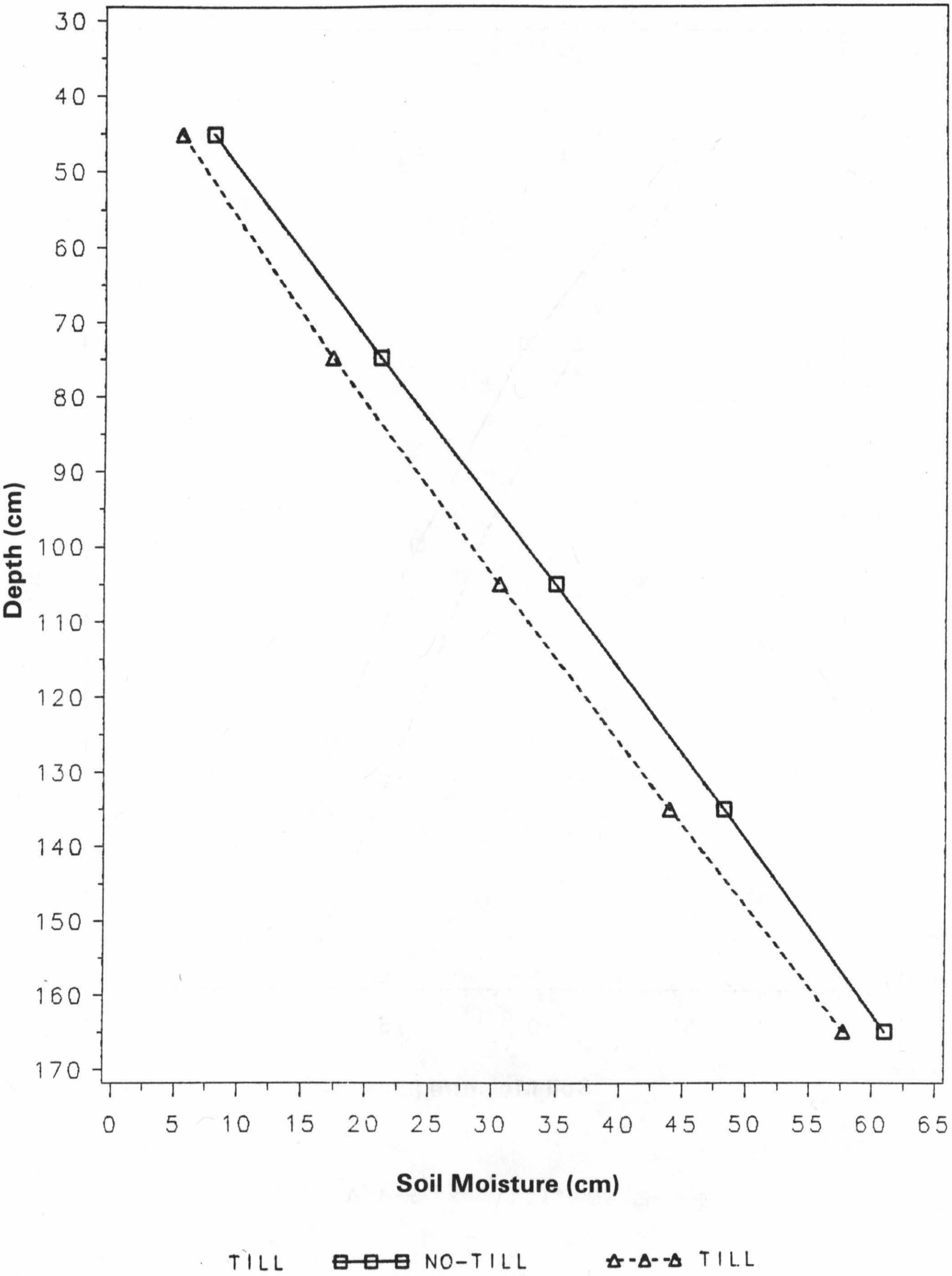


Figure 15.
Mean inorganic N distribution with depth (October 1986) in the no-till Groseclose soil.

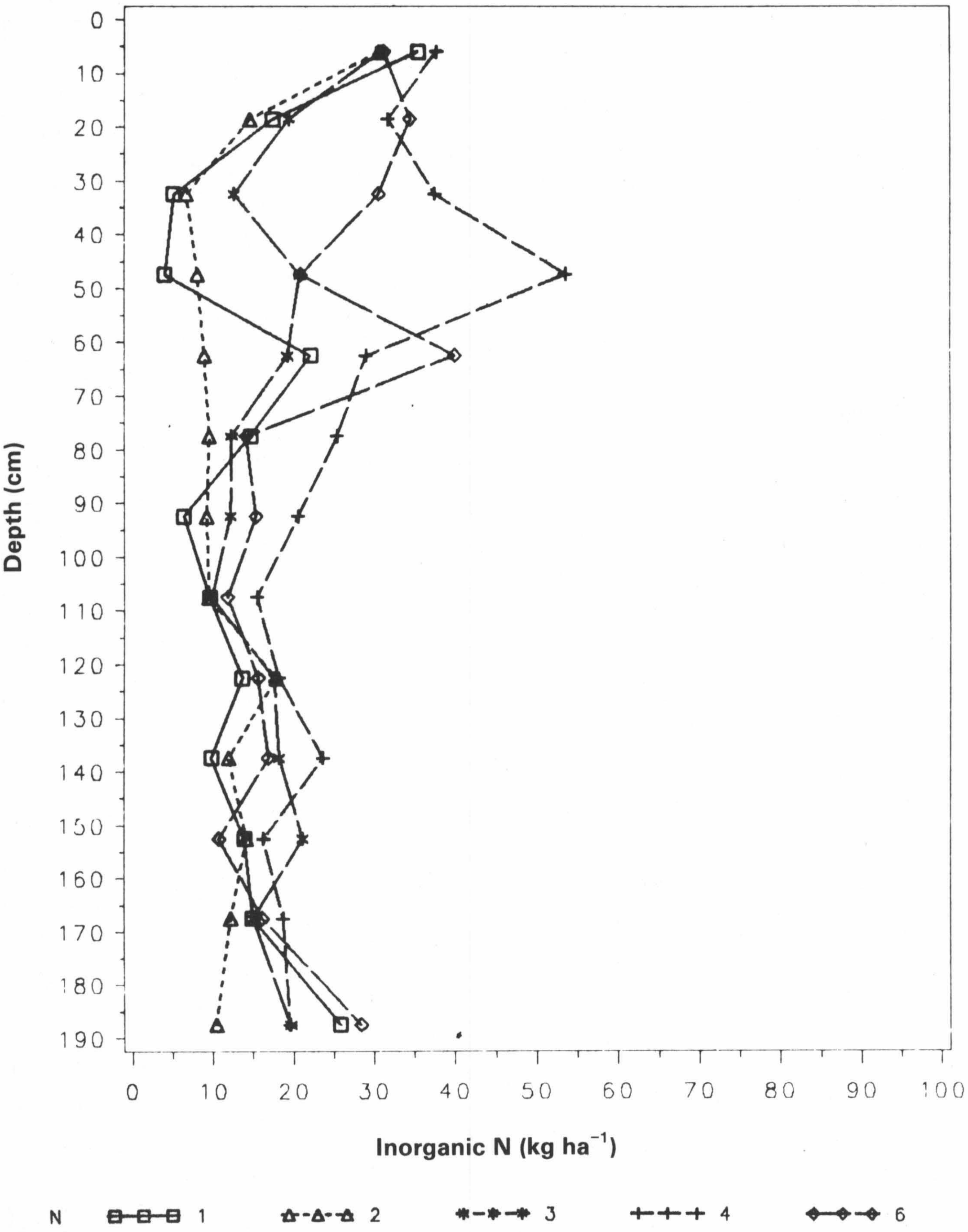


Figure 16.
Mean inorganic N distribution with depth (October 1986) in the conventionally tilled Groseclose soil.

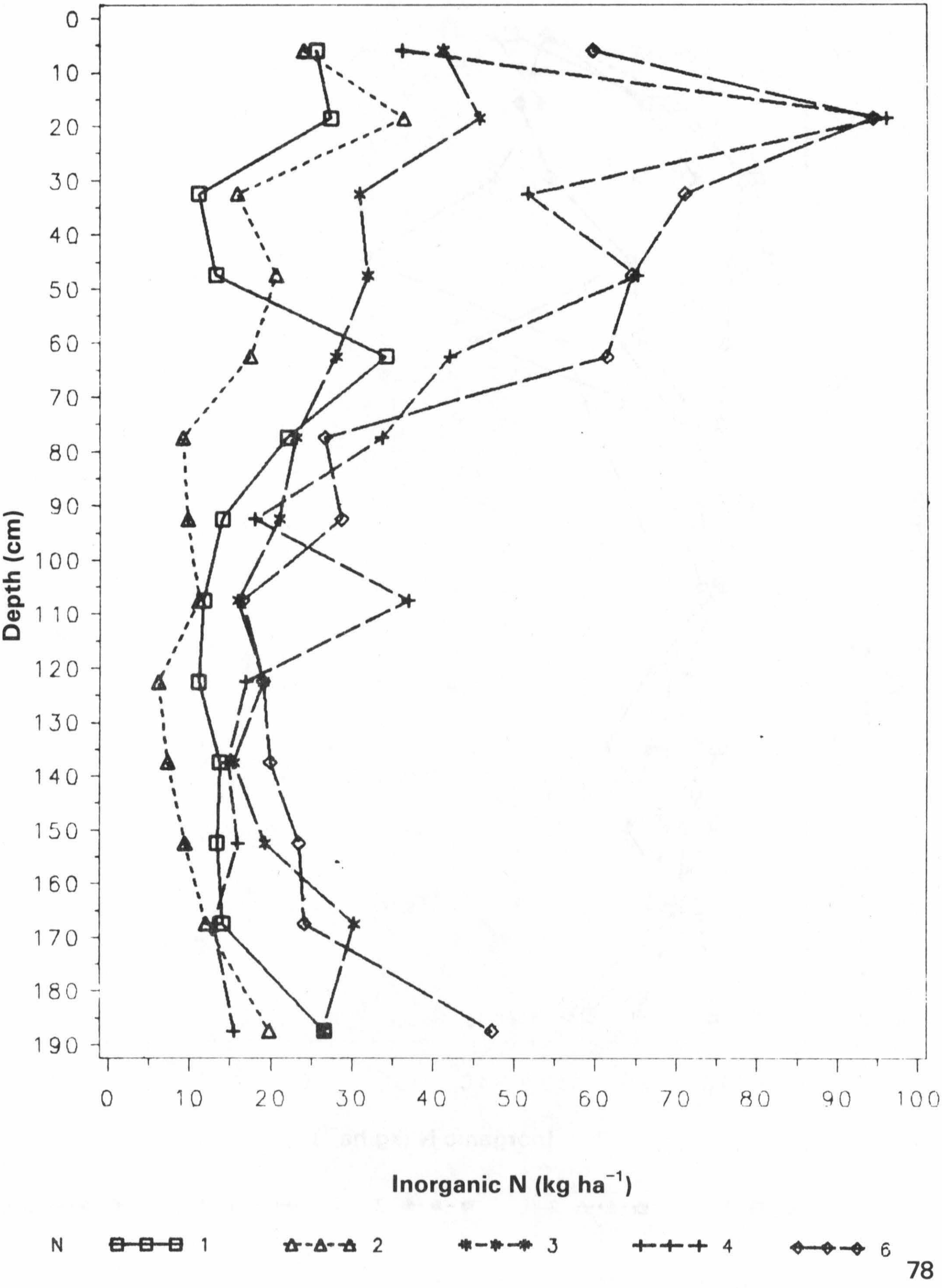


Figure 17.
Mean inorganic N distribution with depth (April 1987) in the no-till Groseclose soil.

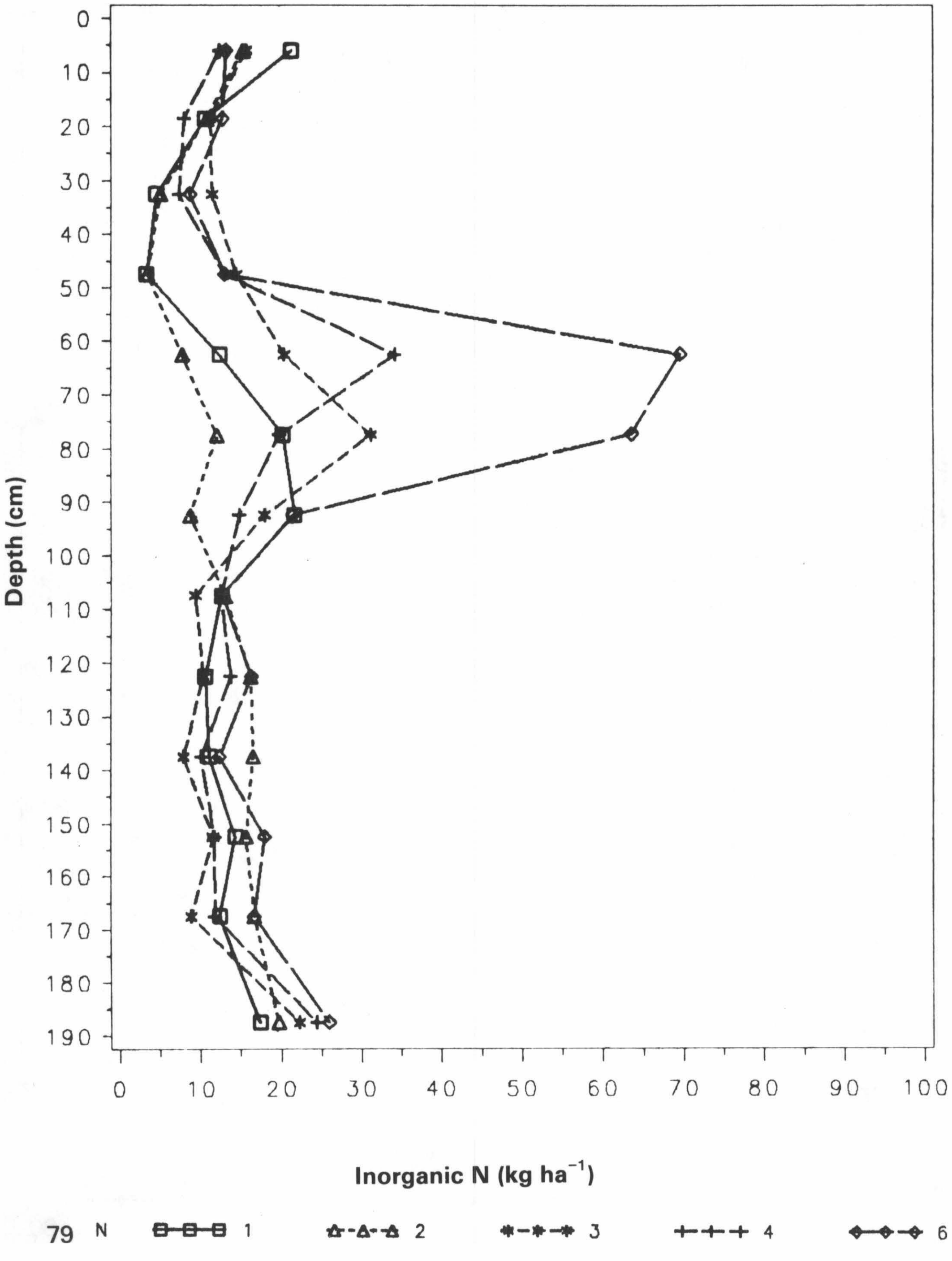


Figure 18.
Mean inorganic N distribution with depth (April 1987) in the conventionally tilled Groseclose soil.

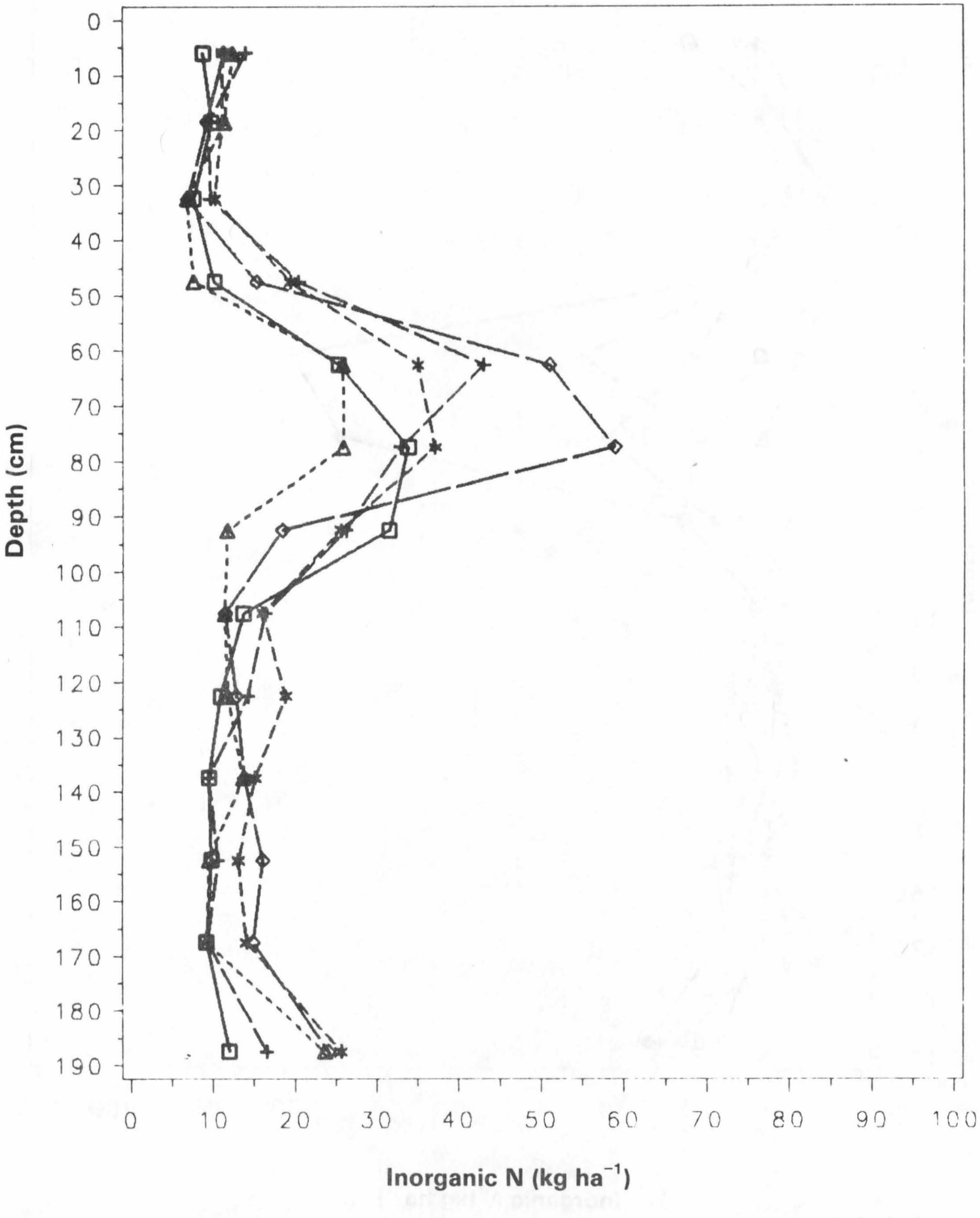


Figure 19.
Mean inorganic N distribution with depth (October 1987) in the no-till Groseclose soil.

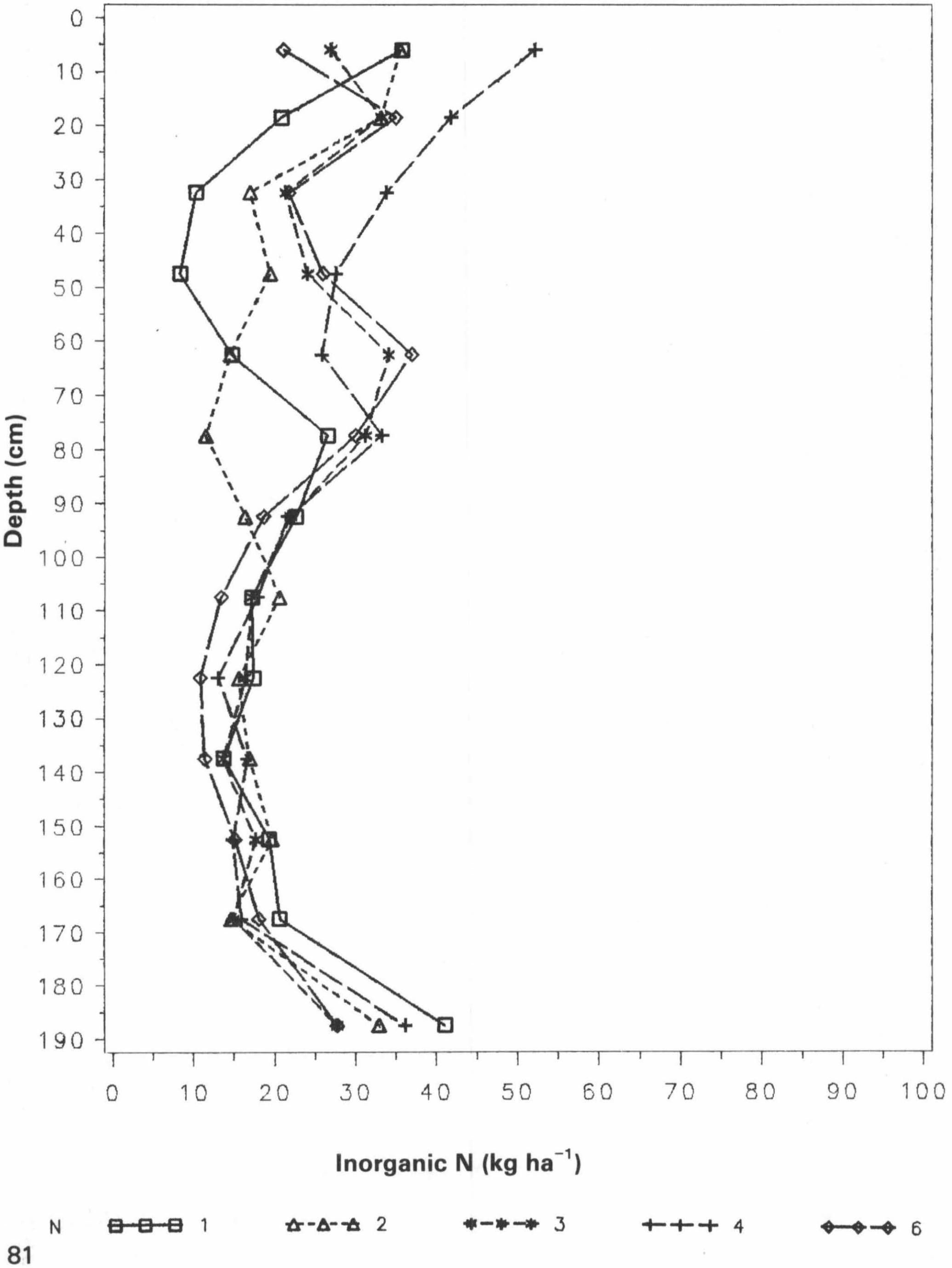


Figure 20.
Mean inorganic N distribution with depth (October 1987)
in the conventionally tilled Groseclose soil.

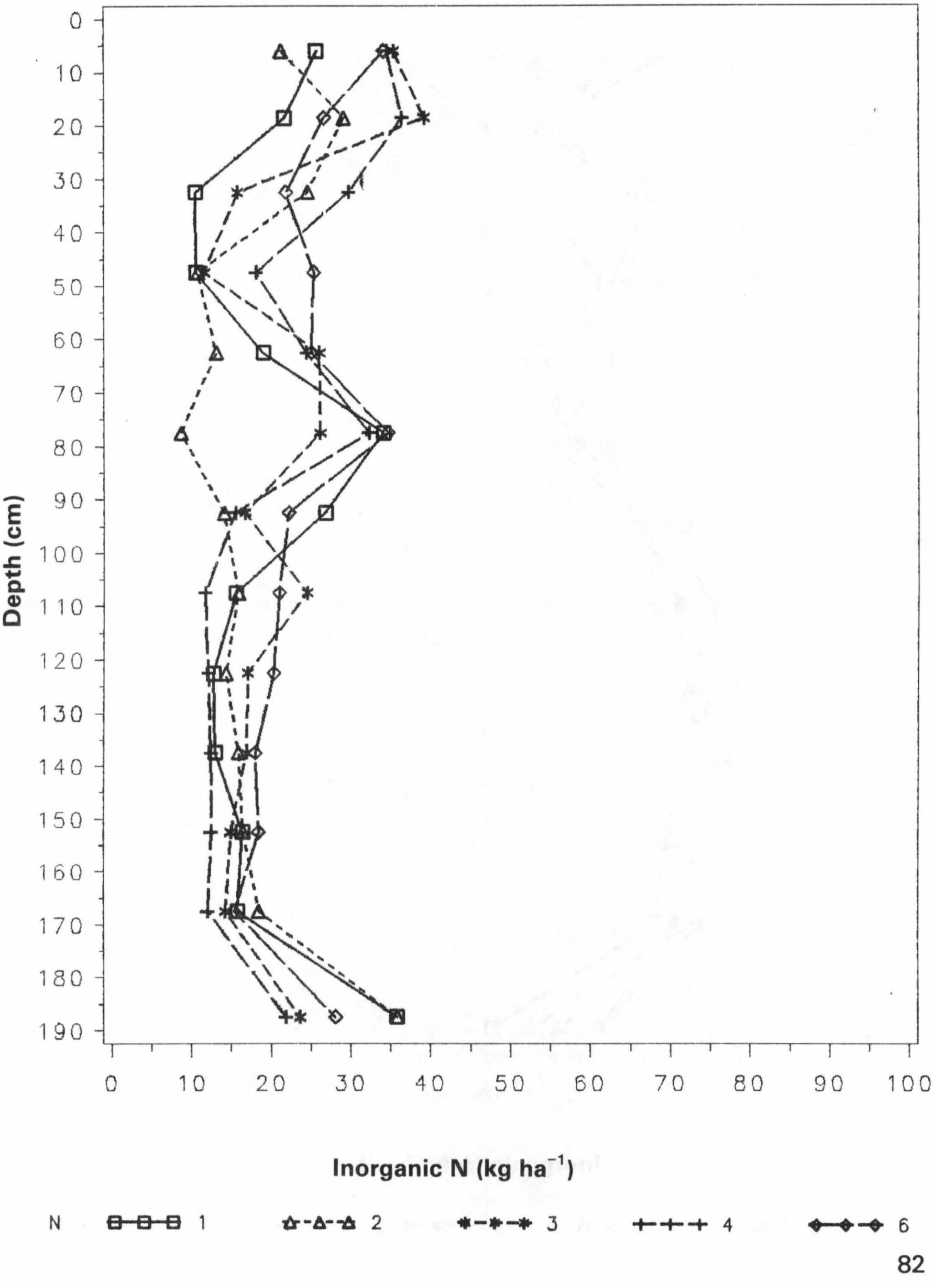


Figure 21.
Mean inorganic N distribution with depth (March 1988) in the conventionally tilled Groseclose soil.

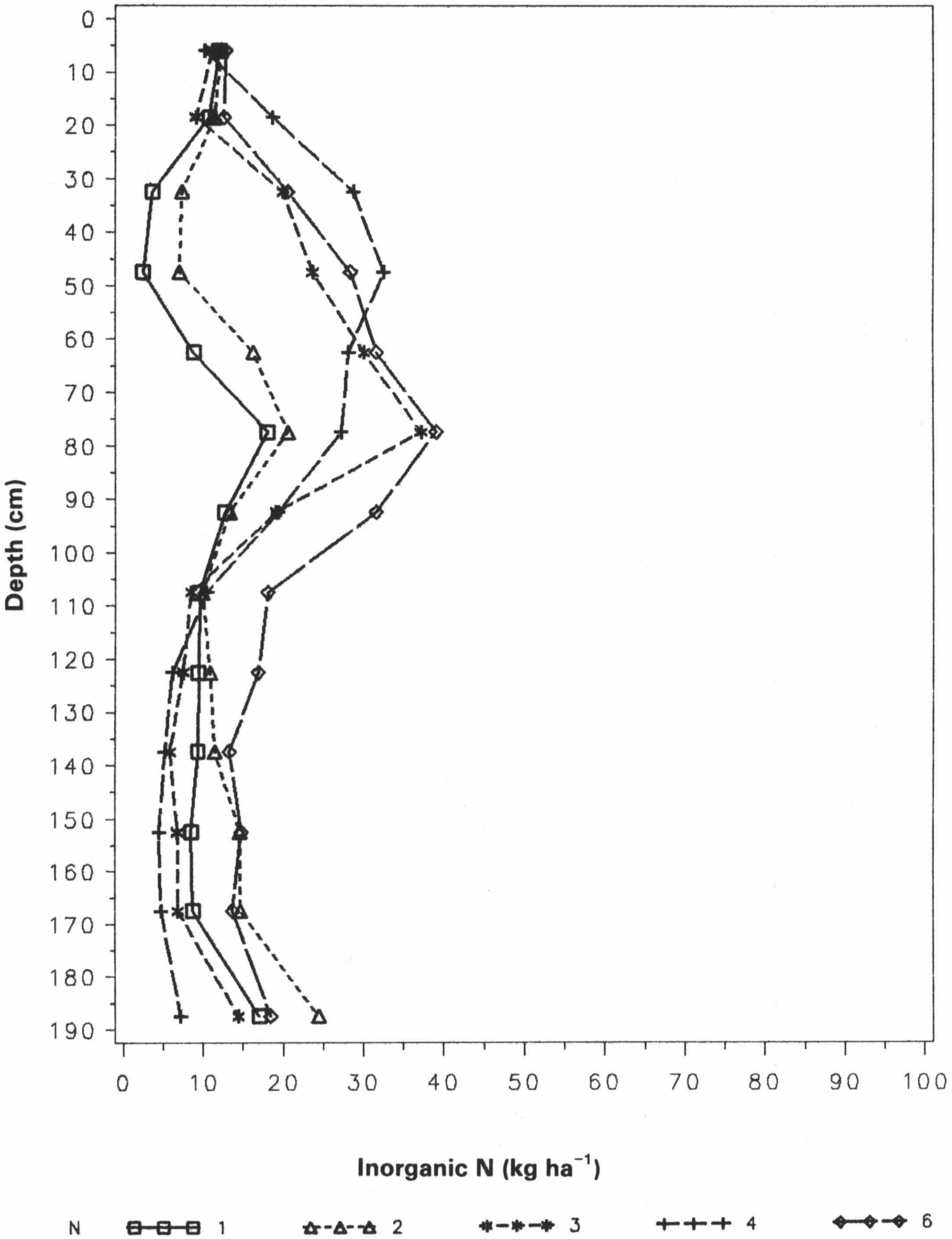


Figure 22.
Mean inorganic N distribution with depth (March 1988) in the no-till Groseclose soil.

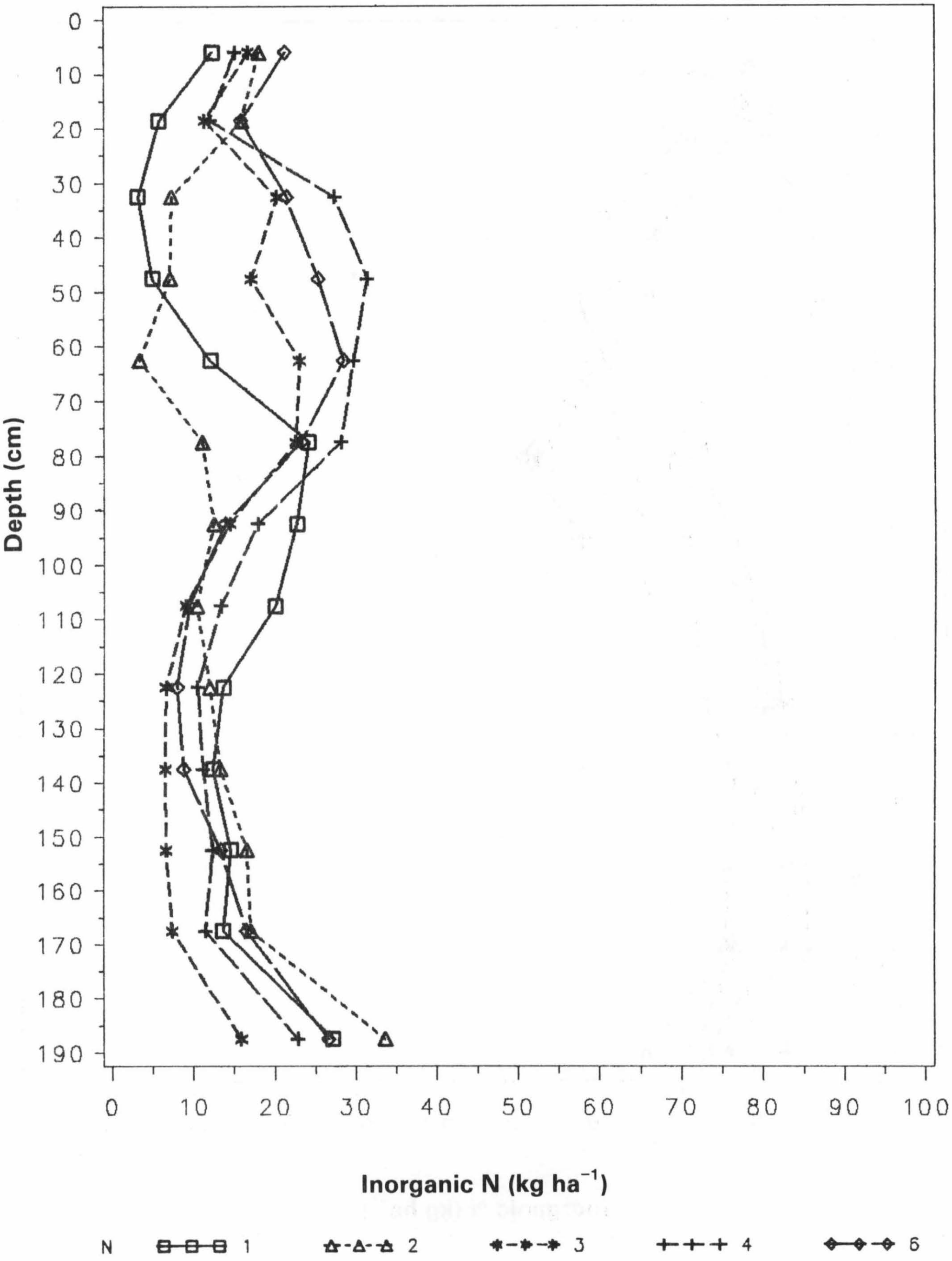


Figure 23.
Mean inorganic N distribution with depth (November 1988) in the conventionally tilled Groseclose soil.

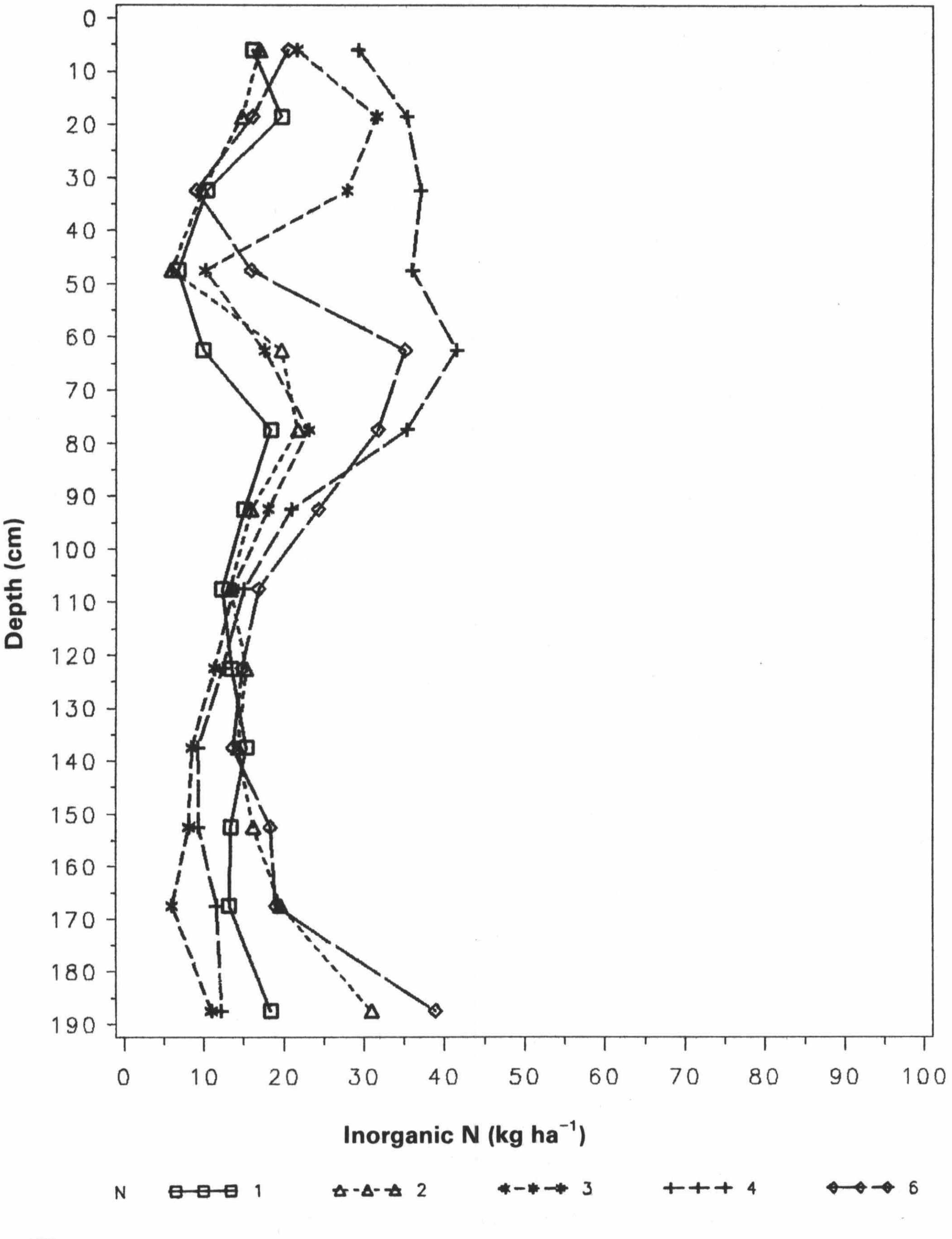


Figure 24.
Mean inorganic N distribution with depth (November 1988)
in the no-till Groseclose soil.

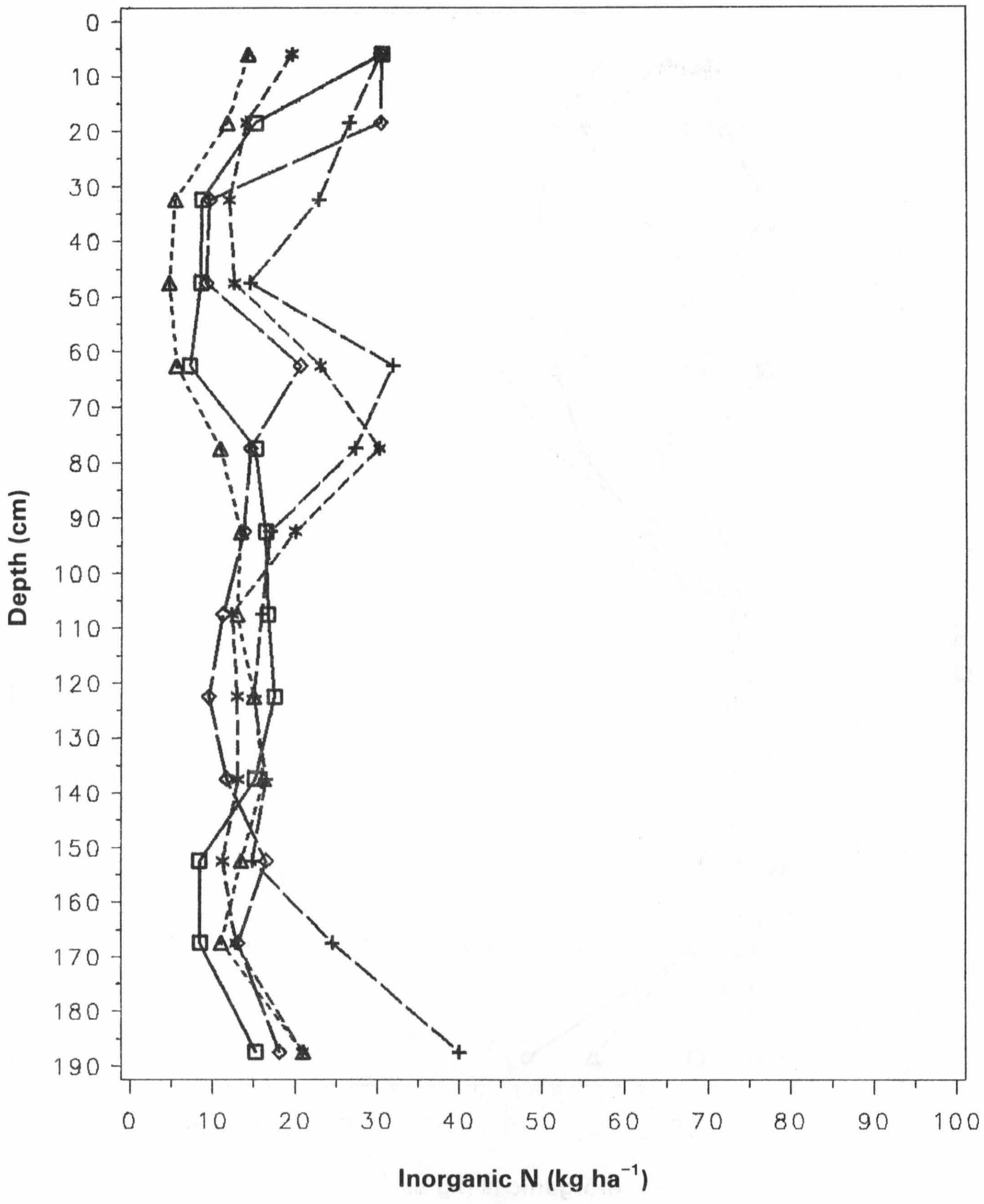


Figure 25.
Relationship between N remaining in soil profile and N lost during winter months for the Groseclose soil.

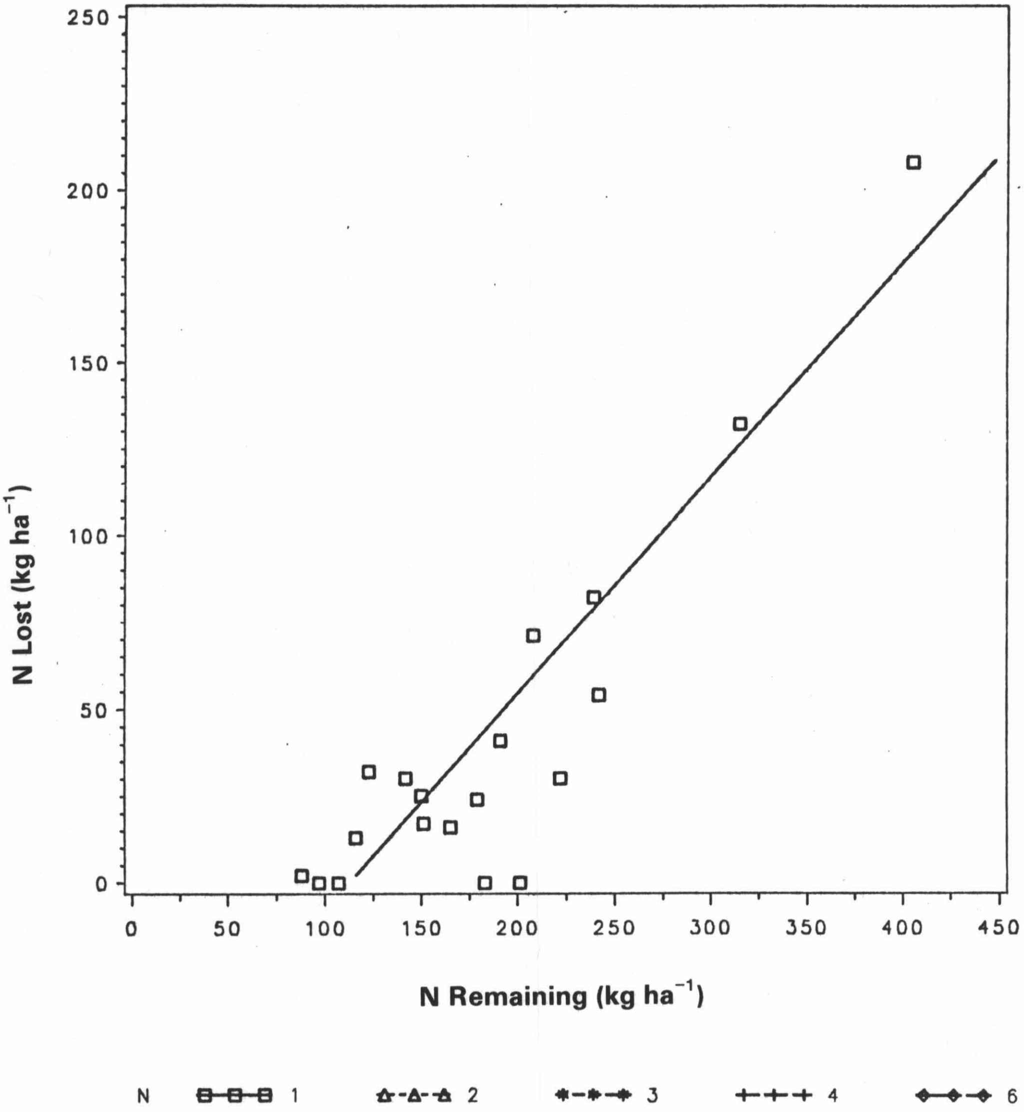


Figure 26.
Mean inorganic N distribution with depth (October 1986) in the no-till Suffolk soil.

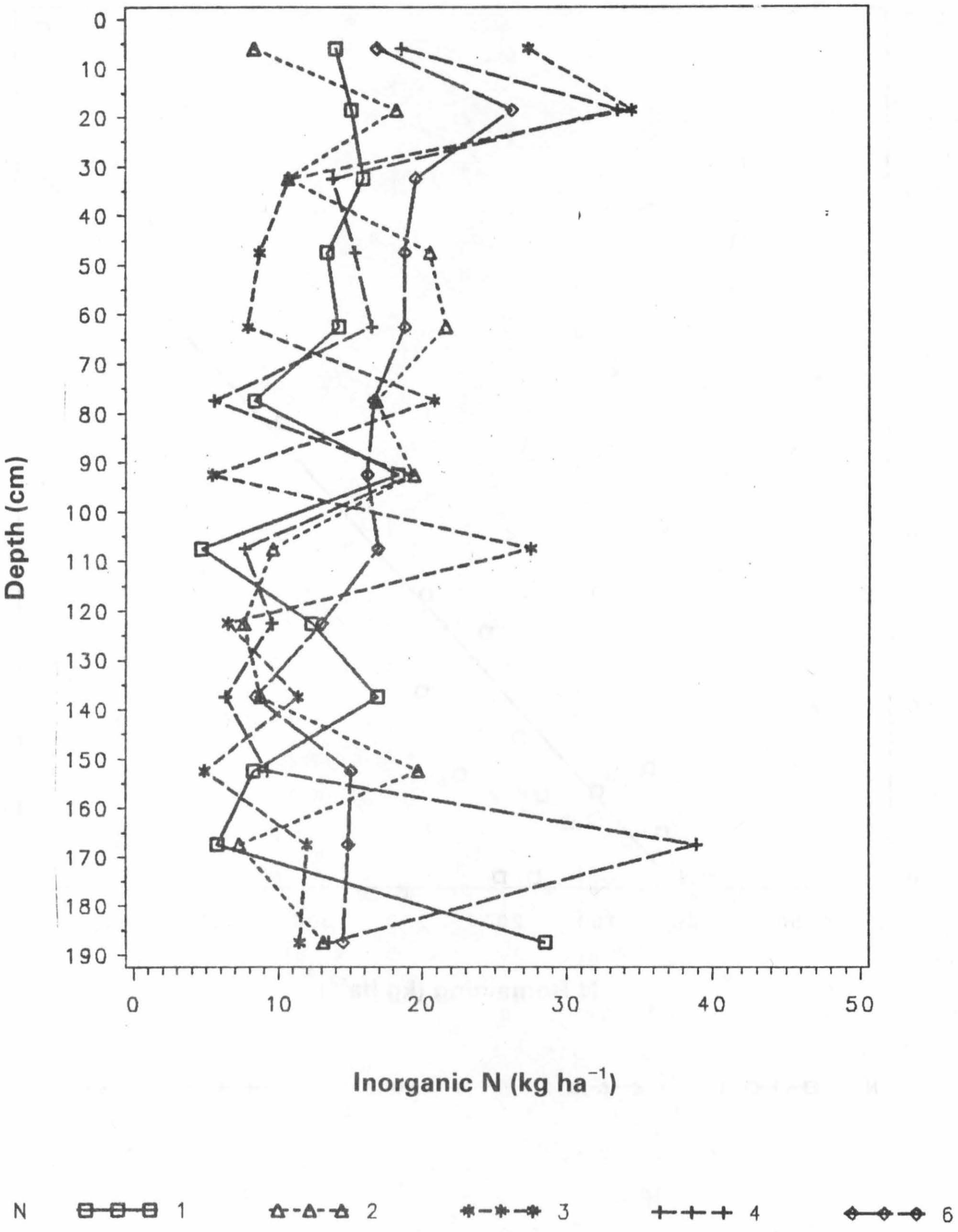


Figure 27.

Mean inorganic N distribution with depth (October 1986) in the conventionally tilled Suffolk soil.

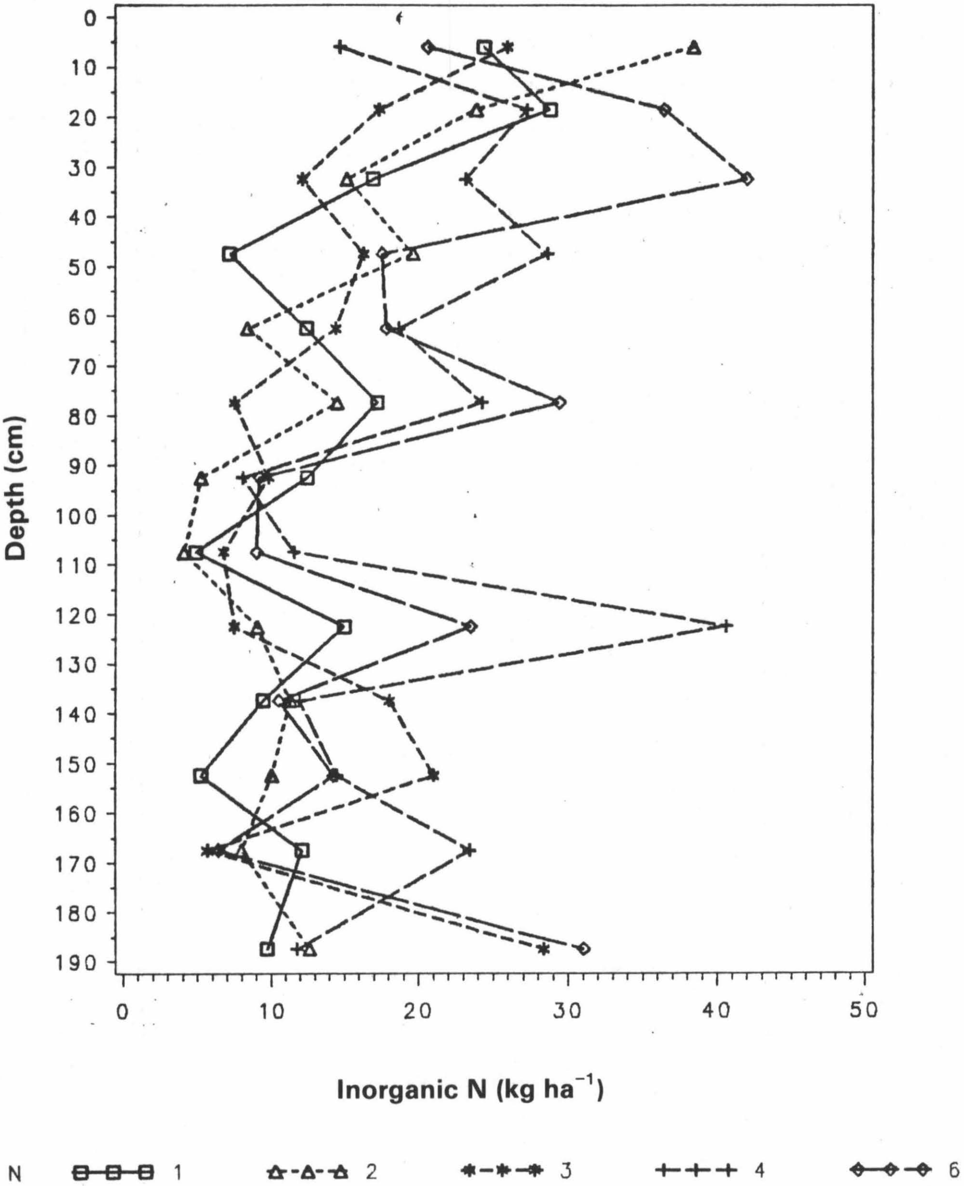


Figure 28.
Mean inorganic N distribution with depth (February 1987) in the no-till Suffolk soil.

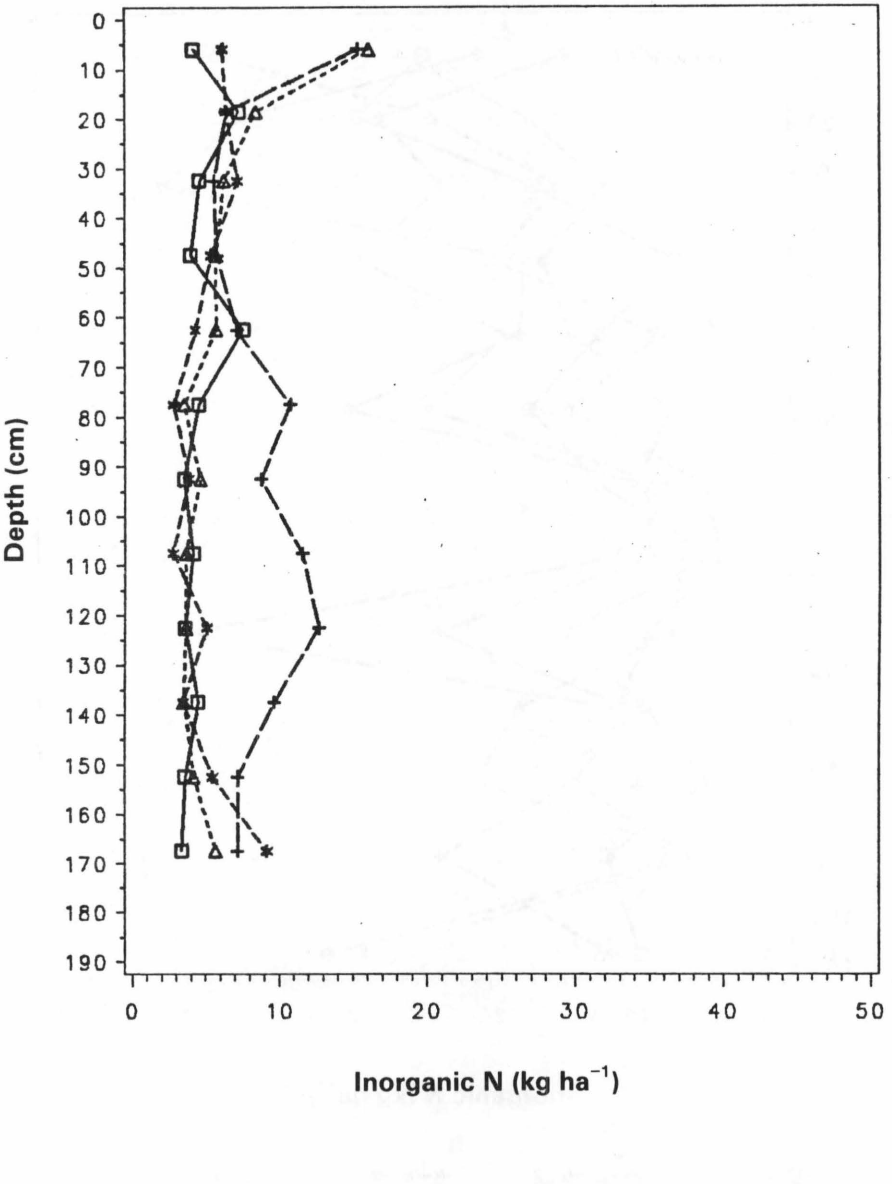


Figure 29.
Mean inorganic N distribution with depth (February 1987) in the conventionally tilled Suffolk soil.

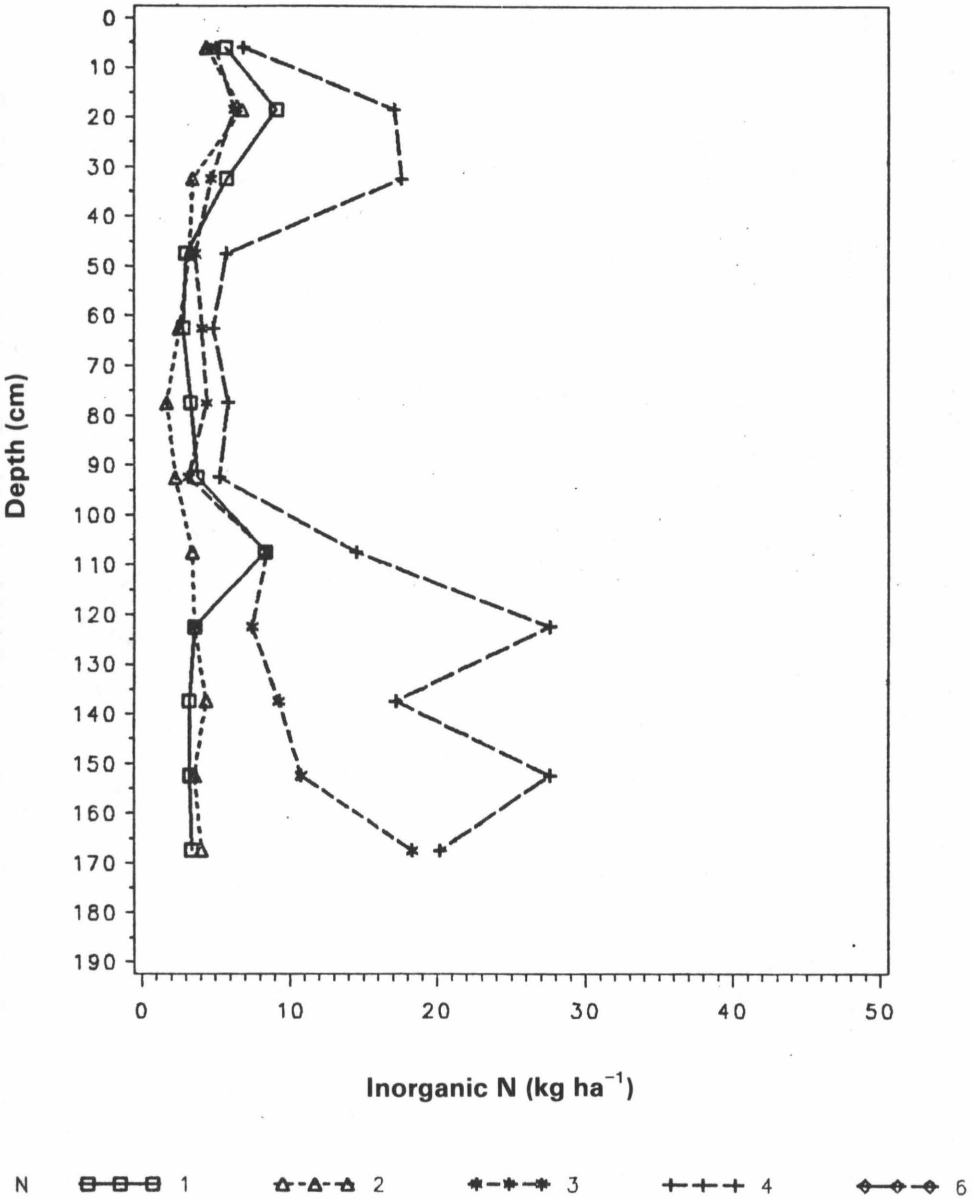


Figure 30.
Mean inorganic N distribution with depth in the Suffolk soil after a N spill on Plot 1.

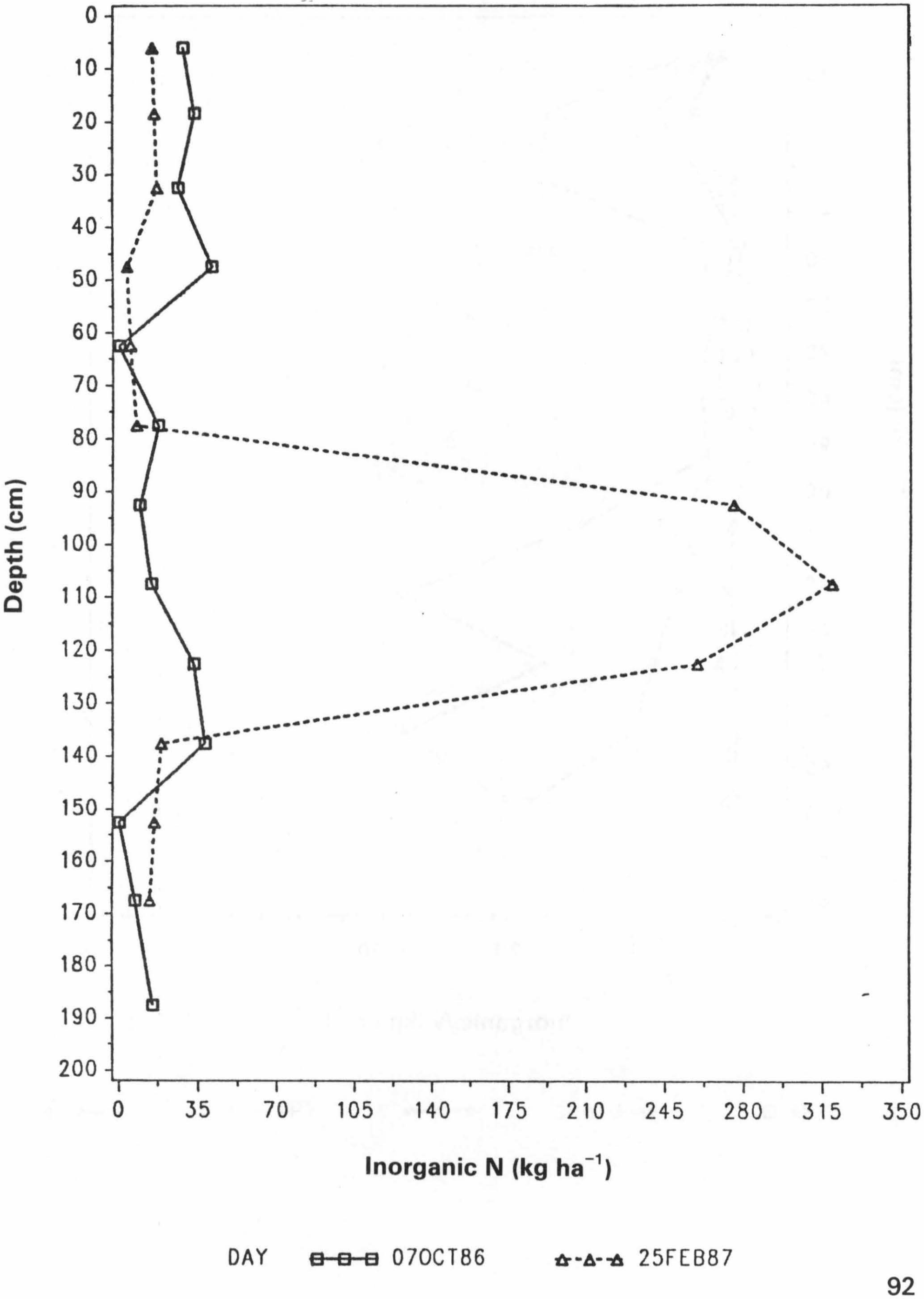


Figure 31.
Mean inorganic N distribution with depth (March 1988) in the conventionally tilled Suffolk soil.

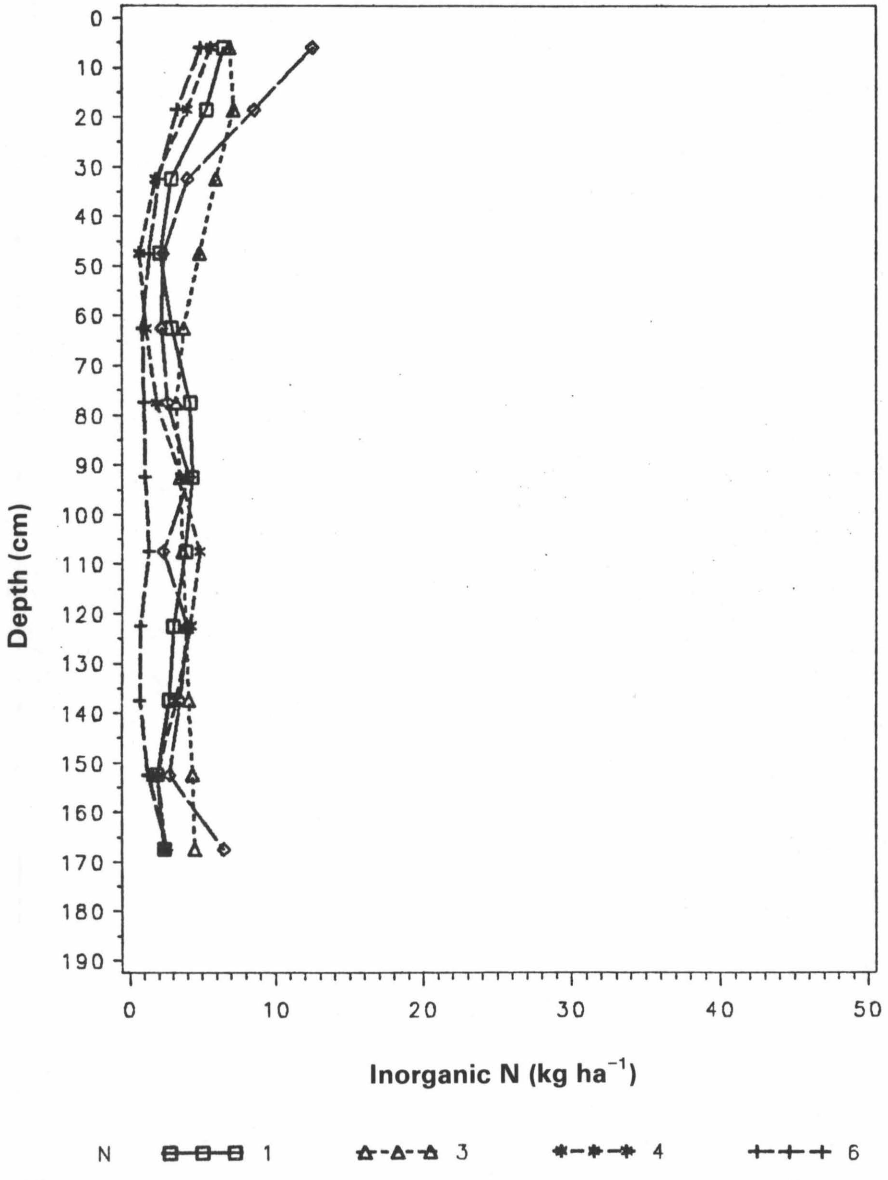


Figure 32.
Mean inorganic N distribution with depth (March 1988) in the no-till Suffolk soil.

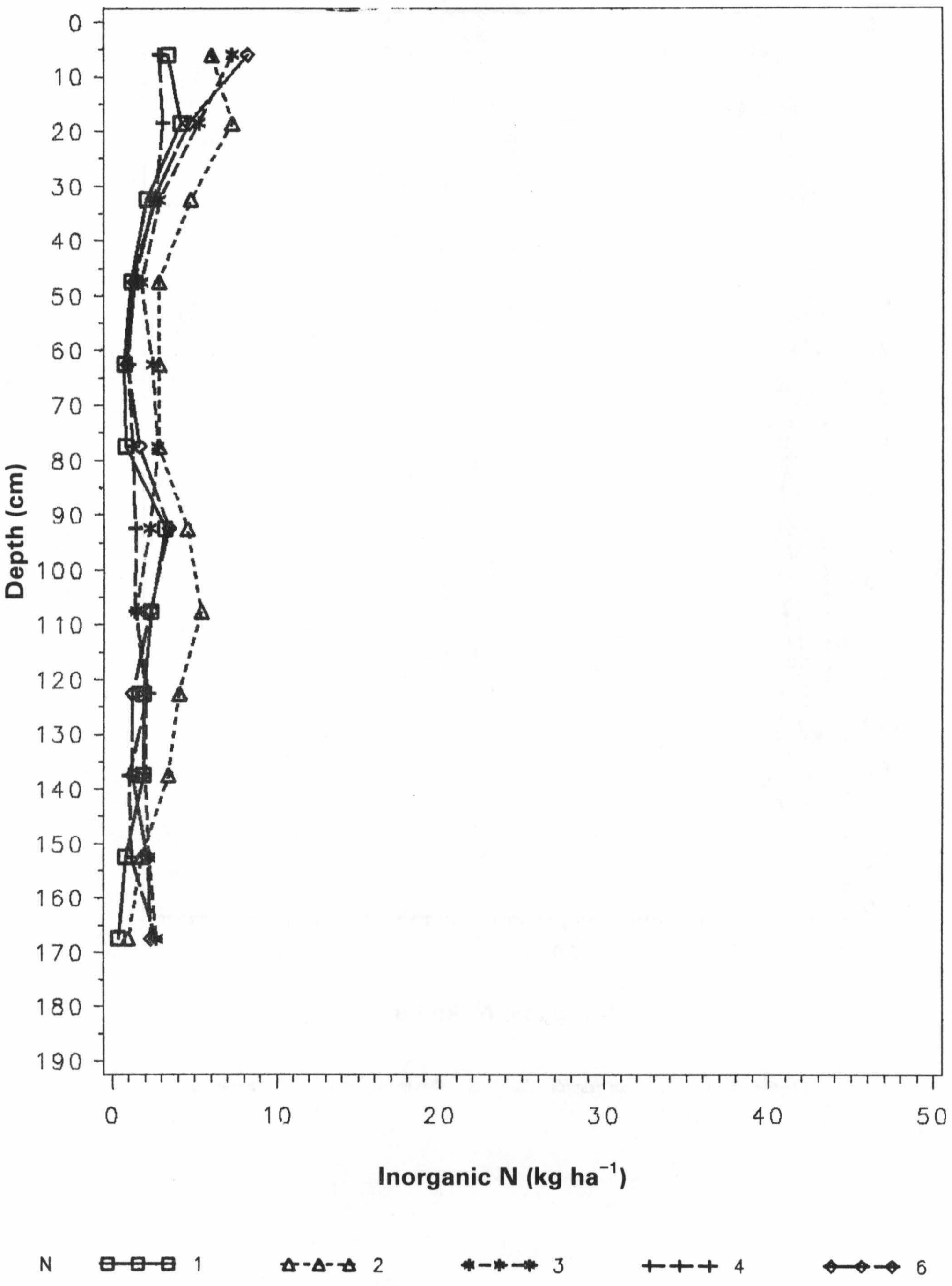


Figure 33.
Mean inorganic N distribution with depth (October 1988) in the conventionally tilled Suffolk soil.

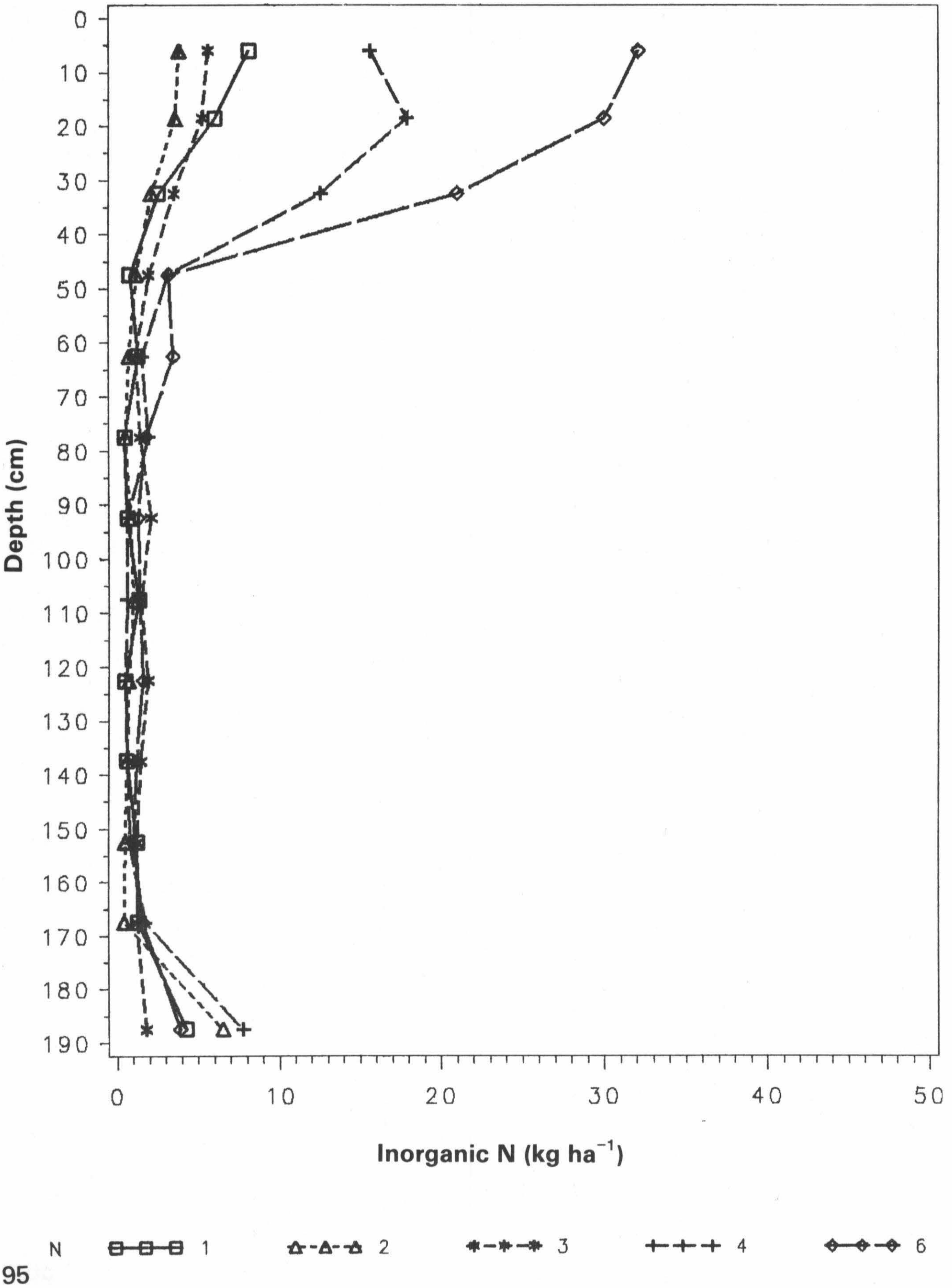


Figure 34.
Mean inorganic N distribution with depth (October 1988) in the no-till Suffolk soil;.

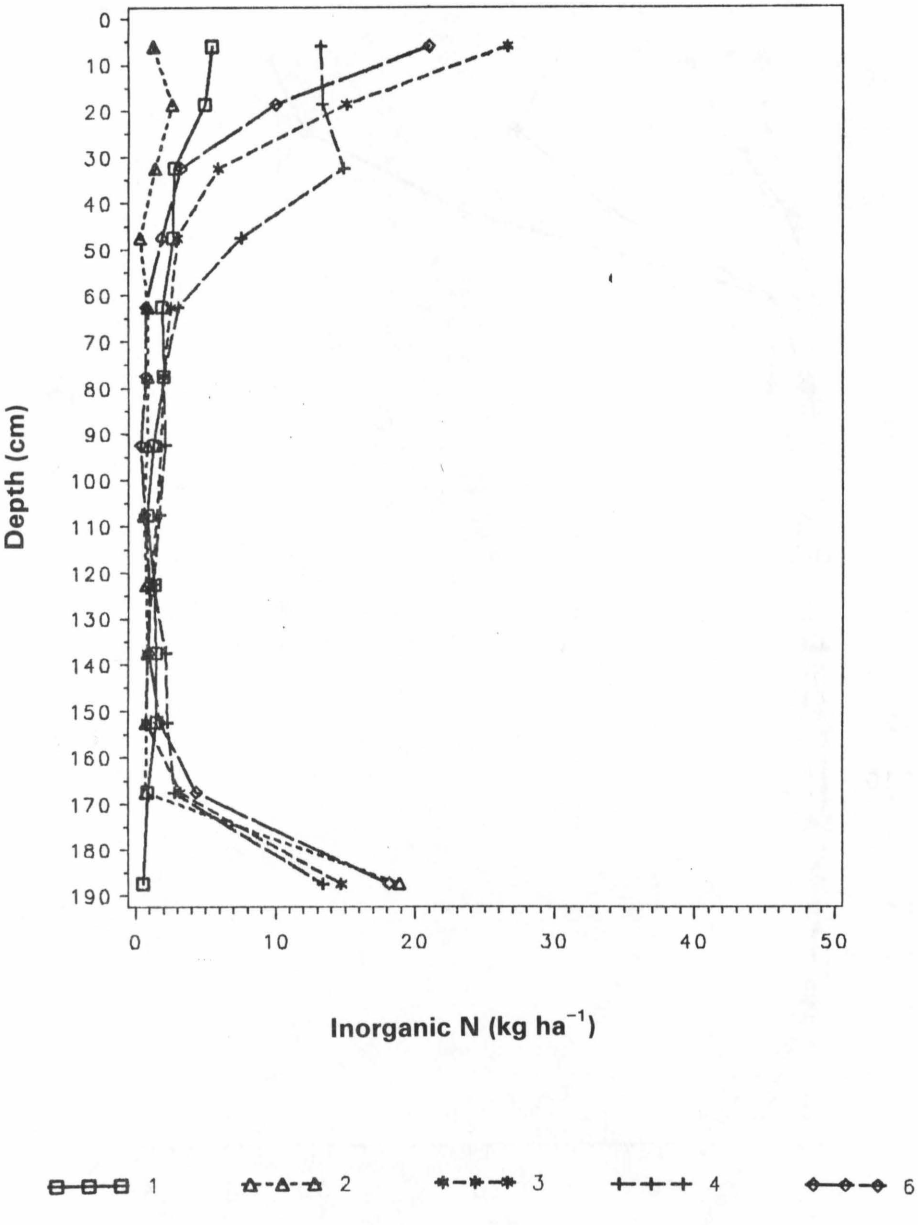


Figure 35.
Relationship between N remaining in the soil and N lost durig the winter months for the Suffolk soil.

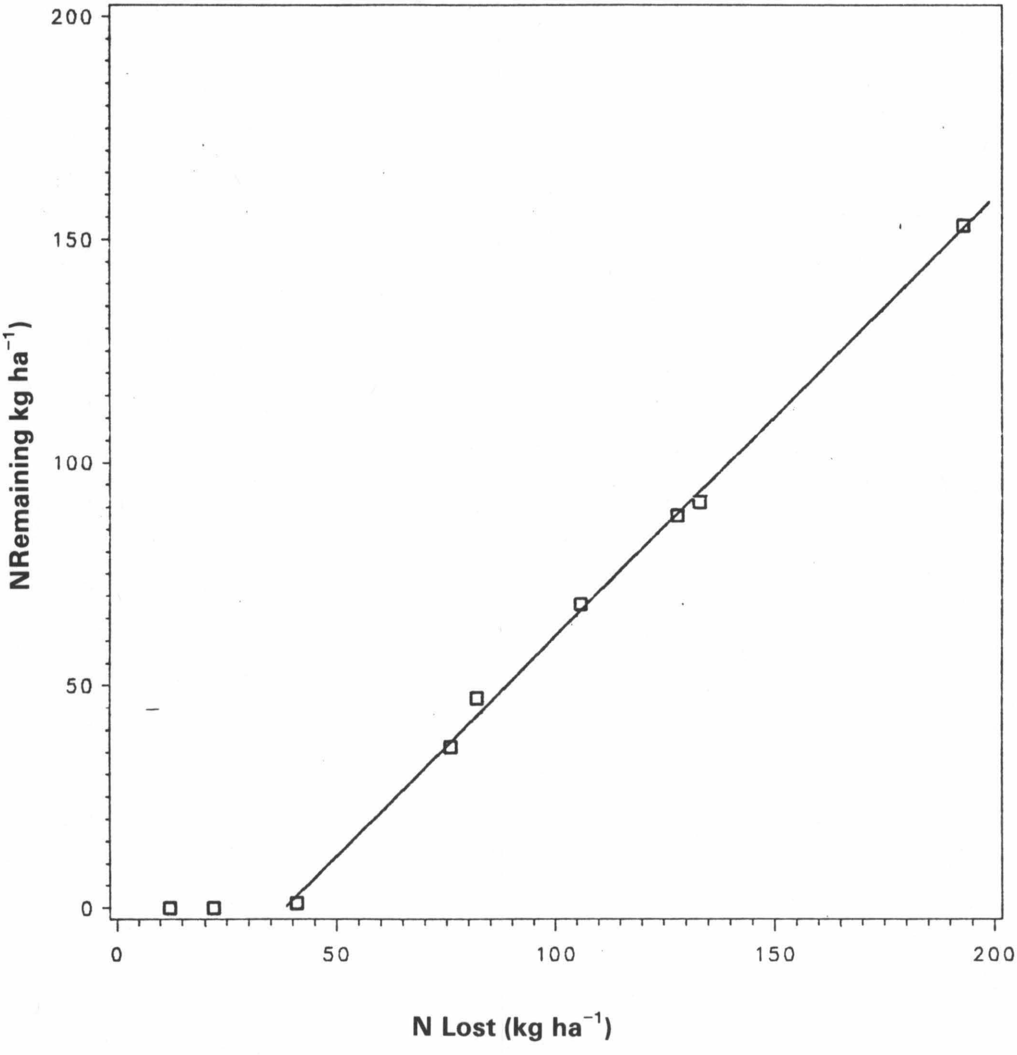


Figure 36.
Groseclose soil - mean soil N distribution as measured and predicted by three models for control conventional till.

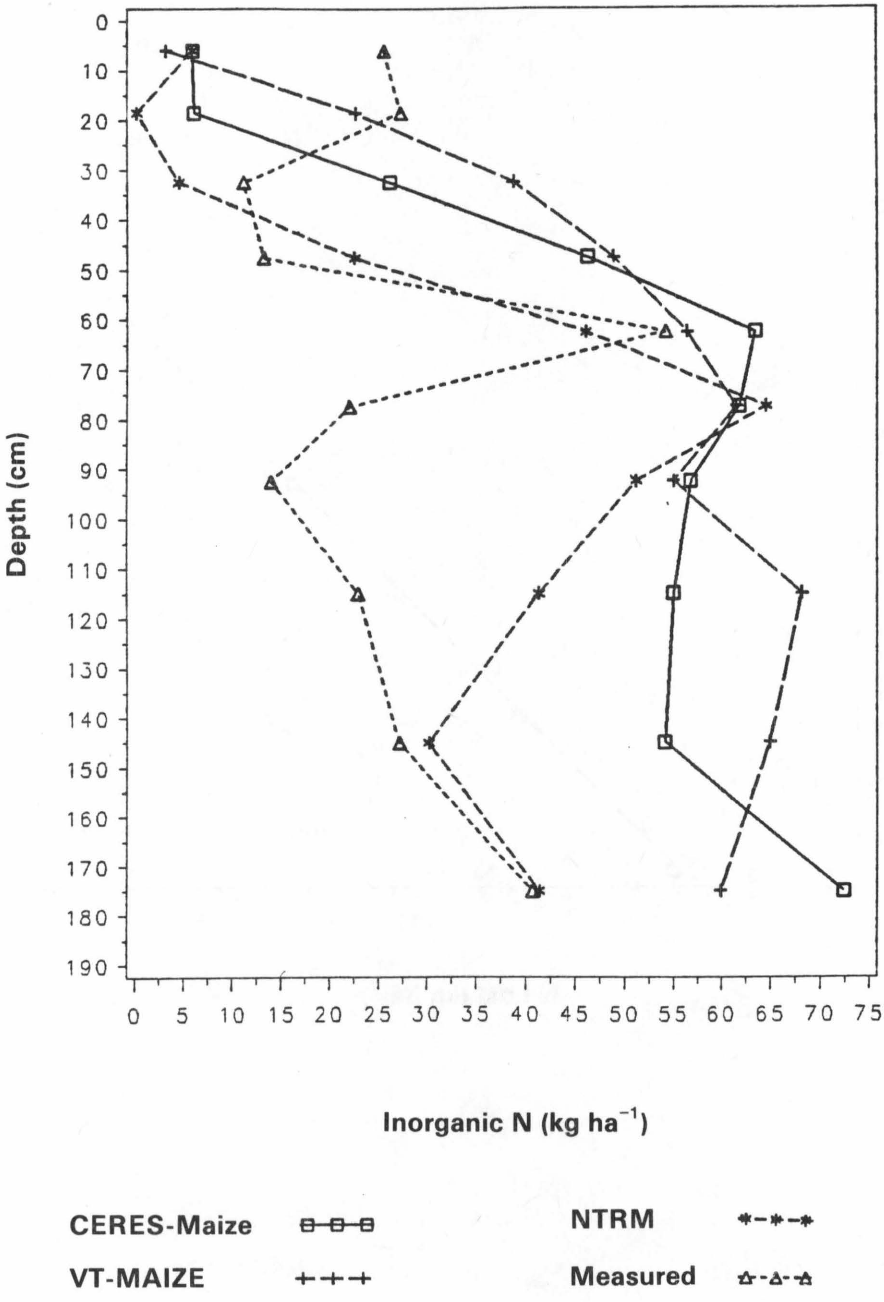


Figure 37.
Groseclose soil - mean soil N distribution as measured and predicted by the three models for 225 kg ha^{-1} treatment, conventional till.

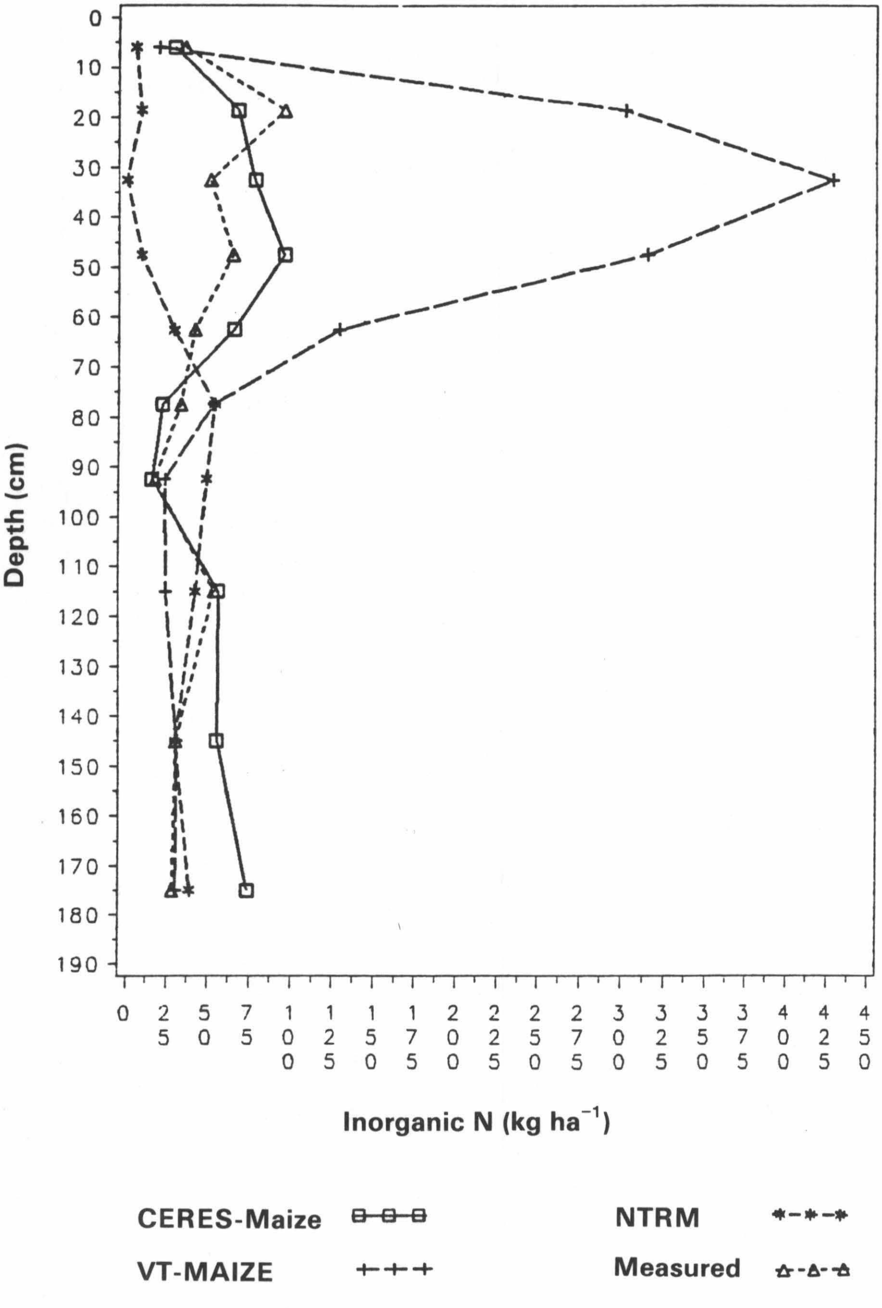


Figure 38.
Groseclose soil - a comparison of the modified VT-MAIZE with NTRM and CERES-Maize for control treatment, conventional till.

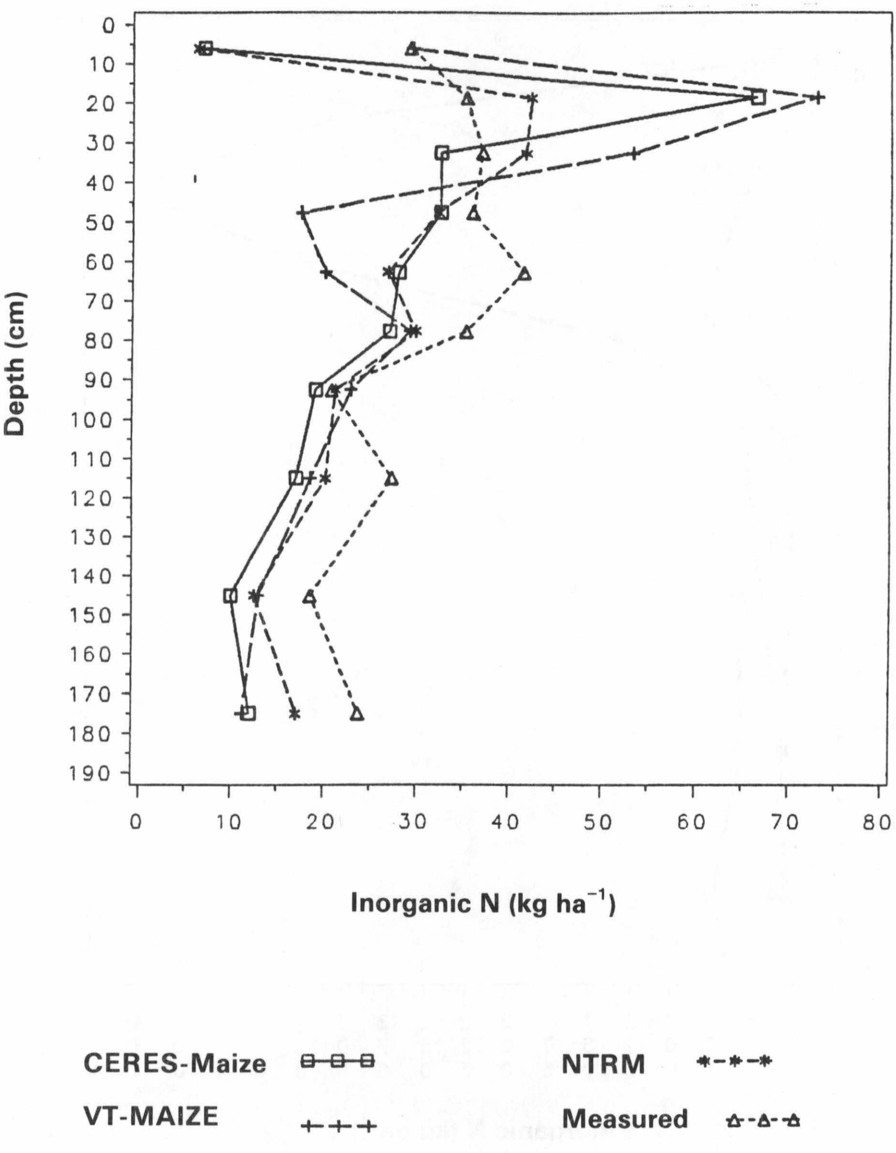


Figure 39.
Groseclose soil - a comparison of the modified VT-MAIZE with NTRM and CERES-Maize for control treatment, no-till.

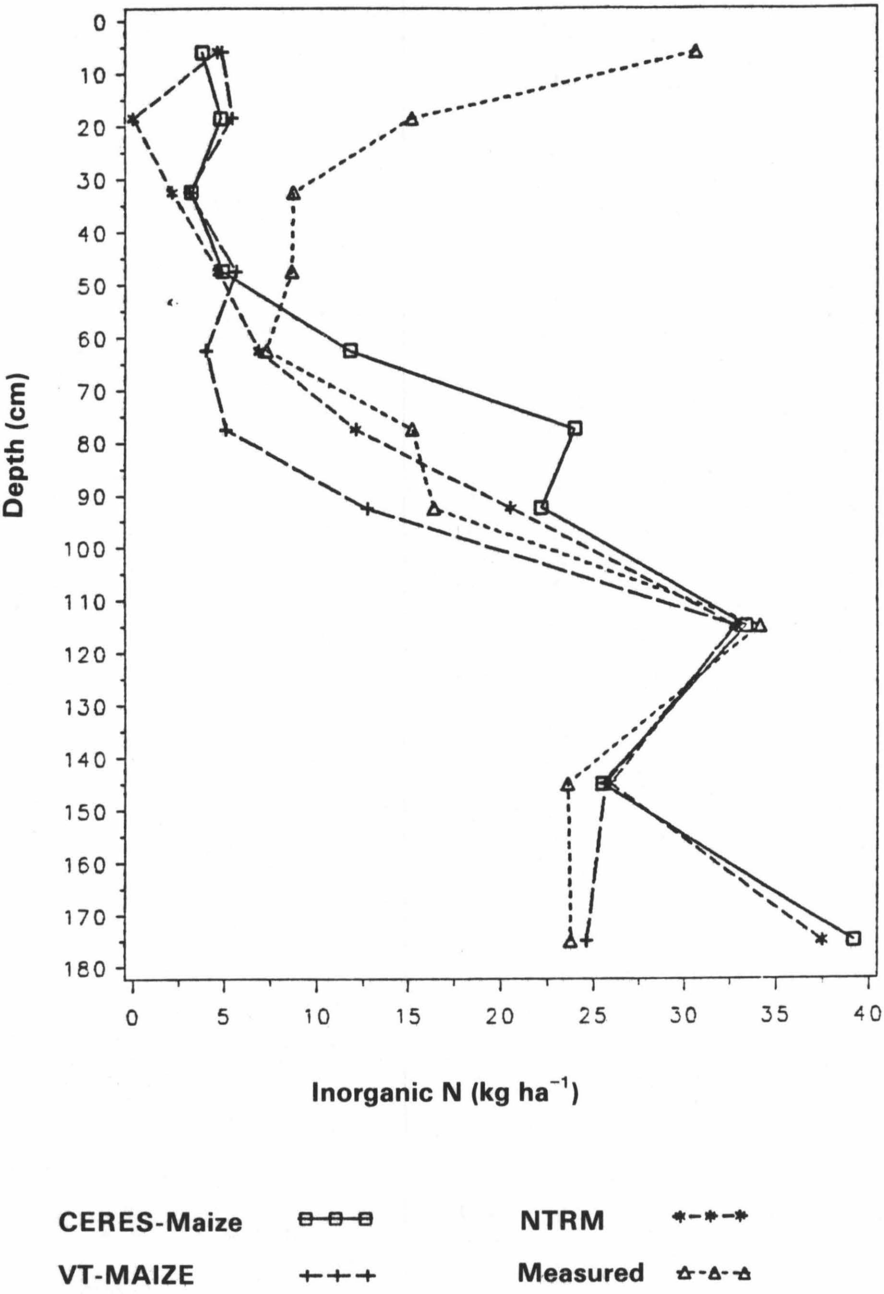


Figure 40.

Groseclose soil - a comparison of the modified VT-MAIZE with NTRM and CERES-Maize for 225 kg ha^{-1} treatment, conventional till.

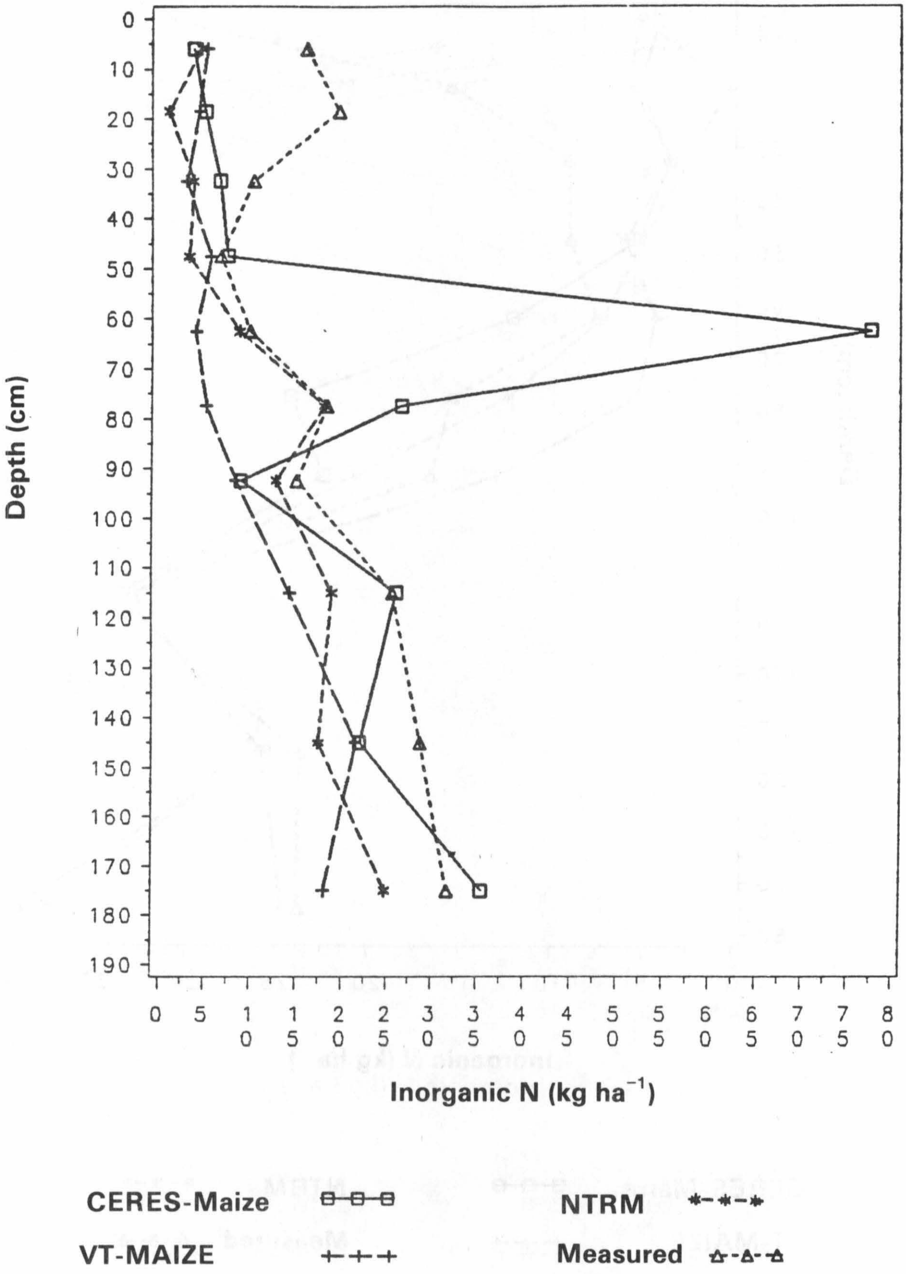
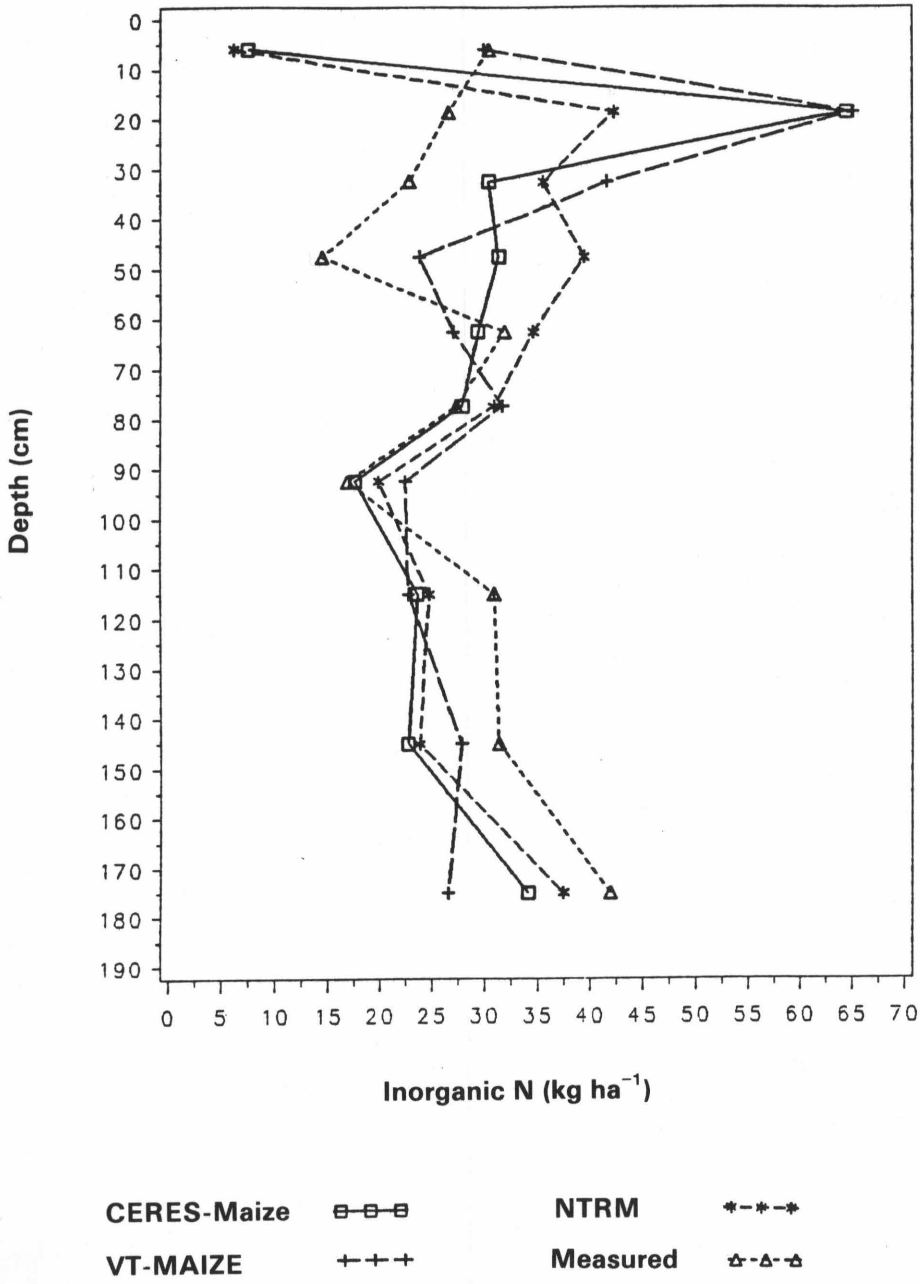


Figure 41.
Groseclose soil - a comparison of the modifed VT-MAIZE with NTRM and CERES-Maize for 225 kg ha^{-1} treatment, no-till.



Tables

Table 1
Particle size analysis for the Suffolk soil.

Depth (cm)	Sand %	Silt %	Clay %	Textural Class
0-12	75.5	16.0	8.5	Sandy loam
12-25	70.5	19.0	10.5	Sandy loam
25-40	59.0	21.5	19.5	Sandy loam
40-55	65.0	13.0	22.0	Sandy clay loam
55-70	66.0	12.0	22.0	Sandy clay loam
70-85	80.0	5.9	14.1	Sandy loam
85-100	83.2	3.8	13.0	Loamy sand
100-115	86.5	2.0	11.5	Loamy sand
115-130	88.5	2.0	9.5	Loamy sand
130-145	91.5	0.5	8.0	Sand
145-160	92.5	1.4	6.1	Sand
160-175	92.5	0.0	7.5	Sand
175-200	89.0	0.0	11.0	Loamy sand

Table 2
Particle size analysis for the Groseclose soil.

Depth (cm)	Sand %	Silt %	Clay %	Textural Class
0-10	25.6	61.4	13.0	Silt loam
10-20	26.3	59.7	14.0	Silt loam
20-30	23.5	51.5	25.0	Silt loam
30-45	16.4	28.6	55.0	Clay
45-60	12.3	18.7	69.0	Clay
60-75	11.1	23.9	65.0	Clay
75-90	21.4	28.6	50.0	Clay
90-105	23.7	32.3	44.0	Clay
105-120	28.4	32.6	39.0	Clay loam
120-135	21.3	28.7	50.0	Clay
135-150	19.1	39.9	41.0	Silty clay
150-165	23.4	43.6	33.0	Clay loam
165-180	21.4	46.6	32.0	Clay loam
180-200	22.1	39.9	38.0	Clay loam

Table 3
Selected soil chemical, physical, and hydraulic properties for the Suffolk soil.

Depth (cm)	Soil Properties										
	BDC	BDN	KsC	KsN	bC	bN	CEC	pH	Sat	Res	FC
0-12	1.2	1.5	823	449	6.8	4.5	4.3	5.7	48	11	30
12-25	1.2	1.5	609	407	6.0	4.5	3.4	5.0	47	12	24
25-40	1.3	1.6	396	365	5.2	5.0	2.3	5.0	45	15	27
40-55	1.3	1.5	588	502	11.7	11.6	2.2	4.9	44	13	23
55-70	1.3	1.5	814	239	5.3	7.2	3.1	5.0	46	10	21
70-85	1.4	1.5	518	254	4.7	4.2	3.6	4.7	49	10	26
85-100	1.4	1.6	951	558	3.5	6.1	2.1	4.8	51	12	22
100-130	1.5	1.5	1294	851	3.6	3.0	2.1	4.9	47	11	23
130-160	1.5	1.5	1300	1300	2.9	2.9	2.2	4.8	50	8	16
160-200	1.5	1.5	1300	1300	3.6	3.6	2.3	4.8	49	8	16

BDC = soil dry bulk density for conventional till (g ml^{-1})
BDN = soil dry bulk density for no-till (g ml^{-1})
KsC = saturated hydraulic conductivity for conventional till (cm day^{-1})
KsN = saturated hydraulic conductivity for no-till (cm day^{-1})
bC = Campbell b constant for conventional till
bN = Campbell b constant for no-till
CEC = cation exchange capacity (meq 100g^{-1} soil solid)
Sat = soil saturated moisture content (%)
Res = soil residual moisture content (%)
FC = soil moisture content at field capacity (%)

Table 4
Selected soil chemical, physical, and hydraulic properties for the Groseclose soil.

Depth (cm)	Soil Properties								
	BD	PD	Ksat	b	CEC	pH	Sat	Res	FC
0-12	1.22	2.26	430	11.3	7.4	5.5	51	18	35
12-25	1.40	2.37	100	18.0	4.9	5.2	49	20	37
25-40	1.44	2.48	300	24.4	4.5	5.3	46	21	42
40-55	1.35	2.48	207	30.3	5.7	5.4	55	28	42
55-70	1.32	2.46	1770	34.4	5.5	5.3	52	32	45
70-85	1.23	2.46	1000	34.0	4.5	5.0	53	32	45
85-100	1.18	2.46	1000	34.1	4.5	5.0	54	31	45
100-130	1.24	2.45	1000	34.2	3.4	5.1	54	30	44
130-160	1.25	2.45	--	--	2.4	5.0	60	32	40
160-200	1.24	2.45	--	--	3.5	5.0	60	31	40

BD = soil dry bulk density (g ml^{-1})
PD = soil particle density (g ml^{-1})
Ksat = saturated hydraulic conductivity (cm day^{-1})
b = Campbell constant

CEC = cation exchange capacity (meq 100g^{-1} soil solid)
Sat = soil saturated moisture content (%)
Res = soil residual moisture content (%)
FC = soil moisture content at field capacity (%)

Table 5
Mean soil moisture retention for conventional tillage in the Suffolk soil.

Suction (mbar)	Depth (cm)								
	20	30	50	60	80	90	100	110	120
	Moisture content (%)								
0	48.3	45.6	44.5	46.4	49.2	51.1	47.1	49.9	48.9
20	32.2	34.8	29.1	31.4	34.1	36.3	28.9	30.5	33.7
40	30.5	30.1	27.6	28.3	29.2	32.4	22.8	24.1	24.9
60	30.1	27.0	27.0	25.0	28.3	29.0	22.8	22.2	19.5
80	28.3	24.6	26.6	23.3	26.5	26.9	20.6	22.4	16.8
100	29.8	24.1	27.0	23.1	21.2	26.2	22.2	22.6	16.3
130	25.1	20.8	25.0	20.9	19.7	23.1	9.2	15.6	12.5
180	23.6	19.2	24.2	19.5	17.9	23.1	7.0	13.8	11.5
240	22.6	18.4	23.5	18.4	17.0	21.7	6.8	13.4	10.0
300	21.8	17.1	22.9	17.6	15.8	19.9	6.0	12.1	9.2
350	21.5	18.6	22.5	19.6	15.6	18.9	5.8	11.9	9.0
400	21.1	16.9	22.3	17.1	15.4	19.7	5.6	11.7	8.7
500	20.4	16.5	21.8	16.7	15.1	17.5	5.1	11.3	8.3
600	20.3	16.0	21.7	16.4	14.9	17.3	5.0	11.0	8.2
700	19.1	15.8	20.9	16.0	14.4	17.4	4.8	10.5	7.9
1000	18.2	14.4	20.6	15.1	13.9	17.2	4.3	10.1	7.4
4000	18.4	10.8	18.4	13.4	12.7	13.6	3.8	9.5	6.8
15000	14.0	12.8	18.0	15.0	12.1	14.1	2.8	8.5	2.9
b	6.8	5.2	11.7	5.8	4.7	5.4	1.6	3.6	2.9

b = Campbell constant

Table 6
Mean soil moisture retention for no-till in the Suffolk soil.

Suction (mbar)	Depth (cm)								
	20	30	50	60	80	90	100	110	120
	Moisture content (%)								
0	44.2	47.9	41.7	52.2	46.8	51.4	43.2	48.2	48.0
20	32.6	36.7	30.8	39.1	36.5	38.4	33.5	36.5	39.3
40	31.3	30.8	30.2	33.6	35.1	33.0	33.0	34.5	32.9
60	24.6	26.6	26.9	30.2	21.5	27.7	22.2	19.4	21.6
80	23.7	23.9	26.5	27.8	23.4	24.9	23.8	20.7	14.7
100	22.1	23.2	25.4	26.8	18.8	24.0	20.2	13.7	12.6
130	19.9	21.6	24.7	25.7	17.6	22.4	17.2	11.5	11.1
180	18.7	20.6	24.3	24.8	16.7	21.7	13.3	12.4	10.5
240	17.8	19.3	23.4	24.0	15.5	20.7	12.5	9.3	10.7
300	16.8	17.7	22.9	23.7	15.0	19.3	11.5	8.5	8.9
350	16.0	17.8	22.7	22.3	14.6	19.4	11.5	8.0	8.8
400	16.1	17.7	22.5	23.0	14.4	19.5	11.6	7.9	8.6
500	15.6	17.7	22.1	21.8	13.9	18.8	10.5	7.6	8.4
600	15.5	17.8	21.8	21.9	13.6	18.5	11.0	7.5	8.2
700	14.5	17.9	21.0	21.4	13.0	18.4	12.5	7.5	8.2
1000	13.9	16.4	20.9	20.3	12.6	17.7	12.0	6.8	7.7
4000	9.9	11.0	19.1	16.6	10.3	15.6	8.6	5.5	6.9
15000	10.2	13.2	16.8	16.5	11.3	15.0	8.8	5.5	6.7
b	4.5	5.0	11.6	7.2	4.2	6.1	3.1	2.4	3.0

b = Campbell constant

Table 7
Mean soil moisture retention for conventional tillage in the Groseclose soil.

Suction (mbar)	Depth (cm)				
	Ap	15	30	45	75
	Moisture content (%)				
0	55.6	46.9	52.1	60.3	68.4
20	48.4	43.4	42.1	49.4	61.2
40	44.7	42.0	40.8	47.4	59.2
60	40.4	41.1	39.5	46.0	58.4
80	39.1	39.6	39.0	45.2	57.5
100	37.6	39.7	38.4	45.1	57.7
130	35.8	38.9	37.6	44.3	57.2
180	35.2	38.1	37.2	43.9	56.7
240	35.3	37.1	36.9	43.3	56.1
300	34.7	35.5	36.3	42.3	55.4
350	32.9	35.2	36.1	42.4	55.4
400	32.8	35.2	36.3	42.5	55.4
500	31.8	35.1	35.8	42.4	55.2
600	31.4	34.7	35.7	42.1	55.0
700	31.1	34.8	35.1	42.0	55.0
1000	31.1	33.4	34.6	41.3	54.2
4000	25.8	28.4	31.3	39.3	51.2
15000	24.2	29.4	30.5	38.6	51.4
b	9.24	13.4	22.5	26.2	34.4

Ap = surface layer disturbed by cultivation
b = Campbell constant

Table 8
Mean soil moisture retention for no-till in the Groseclose soil.

Suction (mbar)	Depth (cm)				
	Ap	15	30	45	75
	Moisture content (%)				
0	51.6	56.3	52.1	60.3	68.4
20	41.1	47.5	42.1	49.4	61.2
40	39.4	45.7	40.8	47.4	59.2
60	37.8	44.5	39.5	46.0	58.4
80	37.0	44.0	39.0	45.2	57.5
100	36.0	43.6	38.4	45.1	57.7
130	34.9	42.9	37.6	44.3	57.2
180	34.3	42.4	37.2	43.9	56.7
240	33.7	42.4	36.9	43.3	56.1
300	32.8	42.1	36.3	42.3	55.4
350	32.2	41.9	36.1	42.4	55.4
400	33.3	41.9	36.3	42.5	55.4
500	31.7	41.6	35.8	42.4	55.2
600	31.3	41.5	35.7	42.1	55.0
700	31.0	41.2	35.1	42.0	55.0
1000	30.3	40.8	34.6	41.3	54.2
4000	23.0	37.0	31.3	39.3	51.2
15000	22.3	37.1	30.5	38.6	51.4
b	9.6	26.4	22.5	26.2	34.4

Ap = surface layer disturbed by cultivation
b = Campbell constant

Table 9
Sewage sludge and total nitrogen applied to the continuous-corn and corn-wheat-soybean rotations.

Treatment	Corn, 1986[1]		Wheat, 1986[2]		Corn, 1987[3]	
	Dry sludge	N	Dry sludge	N	Dry sludge	N
	mt ha^{-1}	kg ha^{-1}	mt ha^{-1}	kg ha^{-1}	mt ha^{-1}	kg ha^{-1}
Control	---	---	---	---	---	---
Low N	---	75	---	50	---	75
Medium N	---	150	---	80	---	150
High N	---	225	---	110	---	225
Split N	---	150	---	80	---	150
Sludge-polymer	8.2	540	4.2	200	9.6	540
Sludge-lime	20.3	670	13.3	620	---	---

[1] Rates applied to both the Suffolk and Groseclose soils

[2] Rates applied to winter wheat in the corn-wheat-soybean rotation grown on the Suffolk soil

[3] Rates applied to the second corn crop in the continuous corn rotation on the Groseclose soil

Table 10
Sewage sludge and total nitrogen applied to corn in 1988.

	Corn, 1988			
	Groseclose		Suffolk	
Treatment	Dry sludge	N	Dry sludge	N
	mt ha^{-1}	kg ha^{-1}	mt ha^{-1}	kg ha^{-1}
Control	---	---	---	---
Low N	---	75	---	75
Medium N	---	150	---	150
High N	---	225	---	225
Split N	---	150	---	150
Sludge-polymer	6.6	340	8.1	420
Sludge-lime	---	---	---	---

Table 11
Components of the anaerobically digested, lime- and polymer-conditioned sludges applied to corn and wheat in 1986.

	April 1986		October 1986	
Element	Lime	Polymer	Lime	Polymer
Solids (%)	18.2	14.6	22.2	14.3
Volatile Solids (%)	45.1	65.4	46.2	63.6
pH	10.1	7.3	11.2	7.2
Ca Carbonate Eq. (%)	37.8	1.4	38.9	2.9
Nitrogen (%)	3.3	6.0	4.6	4.7
NH_4-N (%)	0.3	0.6	0.7	1.2
Phosphorus (%)	2.3	2.6	2.0	2.0
Potassium (%)	0.1	0.1	0.1	0.1
Sulfur (%)	1.6	2.8	1.6	2.4
Calcium (%)	18.5	3.2	18.0	2.8
Magnesium (%)	0.5	0.3	0.6	0.3
Sodium (%)	0.1	0.1	0.1	0.1
Chloride (%)	0.9	0.5	1.2	1.3
Soluble Salts (%)	2.9	2.7	3.7	2.7
Copper (mg kg^{-1})	410.0	660.0	430.0	710.0
Zinc (mg kg^{-1})	2000.0	1800.0	1900.0	1900.0
Cadmium (mg kg^{-1})	3.0	7.0	3.5	7.5
Chromium (mg kg^{-1})	135.0	65.0	175.0	75.0
Nickel (mg kg^{-1})	30.0	35.0	45.0	35.0
Lead (mg kg^{-1})	105.0	60.0	80.0	70.0
Molybdenum (mg kg^{-1})	20.0	20.0	20.0	30.0
Boron (mg kg^{-1})	16.0	30.0	17.0	21.0

Table 12
Components of the anaerobically digested, polymer-conditioned sludge applied to corn in 1987 and 1988.

	April 1987	April 1988
Element	Polymer Sludge	Polymer Sludge
Solids (%)	17.8	16.6
pH	8.0	7.8
Ca Carbonate Eq. (%)	3.3	4.5
Nitrogen (%)	5.3	5.5
NH_4-N (%)	1.3	1.4
Phosphorus (%)	2.0	3.4
Potassium (%)	0.2	0.2
Sulfur (%)	0.3	3.3
Calcium (%)	2.6	2.4
Magnesium (%)	0.3	0.4
Sodium (%)	0.1	0.1
Chloride (%)	1.4	0.5
Soluble Salts (%)	1.8	2.3
Copper (mg kg^{-1})	420.0	550.0
Zinc (mg kg^{-1})	1020.0	900.0
Cadmium (mg kg^{-1})	8.0	4.0
Chromium (mg kg^{-1})	60.0	55.0
Nickel (mg kg^{-1})	40.0	15.0
Lead (mg kg^{-1})	65.0	80.0
Molybdenum (mg kg^{-1})	29.0	30.0
Boron (mg kg^{-1})	10.0	30.0

Table 13
Corn yield as influenced by time and source of N application and tillage in a Groseclose soil.

Treatment[1]	Year 1986 CT	1986 NT	1987 CT	1987 NT	1988 CT	1988 NT
	Grain Yield (kg ha^{-1})					
Preplant	5,350	6,390	3,120	4,470	7,060	8,010
Split	5,410	5,770	3,230	4,030	7,290	7,770
Sewage Sludge	5,000	6,020	3,880	4,440	7,680	8,240
	Stover Yield (kg ha^{-1})					
Preplant	6,160	6,530	7,250	8,220	7,730	9,180
Split	6,130	6,460	6.870	8,570	8,010	9,050
Sewage Sludge	6,540	6,740	7,550	8,330	9,280	9,680
	Silage Yield (kg ha^{-1})					
Preplant	11,500	12,900	10,400	12,700	14,800	17,200
Split	11,500	12,200	10,100	12,600	15,300	16,800
Sewage Sludge	11,500	12,800	11,400	12,800	17,000	17,900

[1] 150 kg N ha^{-1} was applied to both tillage management systems during 1986, 1987, and 1988
CT = conventional tillage
NT = no-till

Table 14
N uptake by corn as influenced by time and source of N application and tillage in a Groseclose soil.

Treatment[1]	Year					
	1986		1987		1988	
	CT	NT	CT	NT	CT	NT
	Grain N (kg ha^{-1})					
Preplant	91	128	55	81	123	137
Split	105	111	66	69	127	134
Sewage Sludge	97	117	73	82	137	147
	Stover N (kg ha^{-1})					
Preplant	51	44	49	60	62	64
Split	48	46	55	55	68	62
Sewage Sludge	73	48	76	52	77	72
	Total N (kg ha^{-1})					
Preplant	142	172	104	142	185	202
Split	153	157	121	124	195	196
Sewage Sludge	170	167	149	133	214	219

[1] 150 kg N ha^{-1} was applied to both tillage management systems during 1986, 1987, and 1988
CT = conventional tillage
NT = no-till

Table 15
Corn yield and N uptake as influenced by time and source of N applied to a Groseclose silt loam soil.[1]

	Yield (kg ha^{-1})			N uptake (kg ha^{-1})		
Treatment[2]	Grain	Stover	Silage	Grain	Stover	Silage
Preplant	5,730a*	7,510b	13.200b	103a	55b	158b
Split	5,580a	7,510b	13,100b	102a	56b	159b
Sewage Sludge	5,880a	8,020a	13,900a	109a	67a	176a

[1] Averaged over four replications, three years, and two tillage management systems

[2] N consisted of 150 kg N ha^{-1}

*Means with different letters differ at the 0.05 probability level by Duncan's New Multiple Range Test

Table 16
Corn yield and N uptake for two tillage management systems in a Groseclose silt loam soil.[1]

	Yield (kg ha^{-1})			N uptake (kg ha^{-1})		
Tillage	Grain	Stover	Silage	Grain	Stover	Silage
Conventional	5,330b*	7,280b	12,600b	97a	62a	159b
No-till	6,130a	8,080a	14,200a	112b	56a	169a

[1] Averaged over four replications, three 150 kg N ha^{-1} treatments, and three years

*Means with different letters differ at the 0.05 probability level by Duncan's New Multiple Range Test

Table 17
Corn yield and N uptake for three growing seasons in a Groseclose silt loam soil.[1]

	Yield (kg ha^{-1})			N uptake (kg ha^{-1})		
Year	Grain	Stover	Silage	Grain	Stover	Silage
1986	5,650b*	6,430c	12,100b	108b	52b	160b
1987	3,860c	7,800b	11,700b	71c	58ab	129c
1988	7,680a	8,820a	16,500a	134a	68a	202a

[1] Mean of four replications, three 150 kg N ha^{-1} treatments, and two tillage management systems

*Means with different letters differ at the 0.05 probability level by Duncan's New Multiple Range Test

Table 18
Corn yield as influenced by source and time of N application and tillage in a Suffolk soil.

	Year			
	1986		1988	
Treatment[1]	CT	NT	CT	NT
	Grain Yield (kg ha^{-1})			
Preplant	2,830	4,070	1,260	1,890
Split	3,160	4,480	1,380	2,100
Sewage Sludge (P)	3,020	3,780	1,390	1,550
Sewage Sludge (L)	3,710	3,720	-----	-----
	Stover Yield (kg ha^{-1})			
Preplant	4,890	4,220	7,960	9,490
Split	4,820	4,390	7,400	8,510
Sewage Sludge (P)	4,960	4,090	8,590	7,090
Sewage Sludge (L)	5,660	4,570	-----	-----
	Silage Yield (kg ha^{-1})			
Preplant	7,720	8,300	9,220	11,400
Split	7,990	8,870	8,780	10,600
Sewage Sludge (P)	7,980	7,870	9,990	8,640
Sewage Sludge (L)	9,400	8,300	-----	-----

[1]N consisted of 150 kg N ha^{-1}

P = anaerobically digested, polymer-conditioned sewage sludge from the James River plant

L = anaerobically digested, lime-conditioned sewage sludge from the Atlantic treatment plant

CT = conventional tillage

NT = no tillage

Table 19

N uptake by corn as influenced by source and time of N application and tillage in a Suffolk sandy loam soil.

Treatment[1]	Year			
	1986		1988	
	CT	NT	CT	NT
	Grain N (kg ha^{-1})			
Preplant	65	75	26	38
Split	73	86	29	42
Sewage Sludge (P)	63	77	29	32
Sewage Sludge (L)	86	73	--	--
	Stover N (kg ha^{-1})			
Preplant	62	35	97	100
Split	50	36	84	82
Sewage Sludge (P)	54	34	109	90
Sewage Sludge (L)	76	46	---	---
	Total N (kg ha^{-1})			
Preplant	126	110	123	117
Split	123	121	113	124
Sewage Sludge (P)	118	111	138	122
Sewage Sludge (L)	162	119	---	---

[1] N consisted of 150 kg N ha^{-1}

P = anaerobically digested, polymer-conditioned sewage sludge from the James River plant

L = anaerobically digested, lime-conditioned sewage sludge from the Atlantic treatment plant

CT = conventional tillage

NT = no tillage

Table 20
Corn yield and N uptake as influenced by time and source of N applied to a Suffolk sandy loam soil.[1]

	Yield (kg ha^{-1})			N uptake (kg ha^{-1})		
Treatment[2]	Grain	Stover	Silage	Grain	Stover	Silage
Preplant	2,510a*	6,640a	9,150a	51a	73a	124a
Split	2,780a	6,280a	9,060a	58a	63b	121a
Sewage Sludge	2,430a	6,180a	8.620a	51a	72a	123a

[1] Averaged over four replications, two years, and two tillage management systems

[2] Treatments consist of 150 kg N ha^{-1}

*Means with different letters differ at the 0.05 probability level by Duncan's New Multiple Range Test

Table 21
Corn yield and N uptake for two tillage management systems in a Suffolk sandy loam soil.[1]

	Yield (kg ha $^{-1}$)			N uptake (kg ha $^{-1}$)		
Tillage	Grain	Stover	Silage	Grain	Stover	Silage
Conventional	2,170b*	6,440a	8,610a	48a	76a	124a
No-till	2,980a	6,300a	9,280a	58b	63b	121a

[1] Averaged over four replications, three 150 kg N ha $^{-1}$ treatments, and two years (1986 and 1988)
*Means with different letters differ at the 0.05 probability level by Duncan's New Multiple Range Test

Table 22

Corn yield and N uptake for two growing seasons in a Suffolk sandy loam soil.[1]

	Yield (kg ha $^{-1}$)			N uptake (kg ha $^{-1}$)		
Year	Grain	Stover	Silage	Grain	Stover	Silage
1986	3,560a*	4,560b	8,120b	73a	45b	118a
1988	1,600b	8,170a	9,770a	33b	94a	127a

[1] Averaged over four replications, three 150 kg N ha^{-1} treatments

*Means with different letters differ at the 0.05 probability level by Duncan's New Multiple Range Test

Table 23

Corn yield and N uptake as influenced by time and source of N applied to a Suffolk sandy loam soil in 1986.[1]

	Yield (kg ha^{-1})			N uptake (kg ha^{-1})		
Treatment[2]	Grain	Stover	Silage	Grain	Stover	Silage
Preplant	3,450a*	4,560a	8,010a	70a	48a	118b
Split	3,820a	4,610a	8,430a	79a	43b	122a
Sewage sludge (P)	3,400a	4,530a	7,930a	70a	45a	115ab
Sewage sludge (L)	3,710a	5,030a	8,740a	79a	59a	138a

[1] Averaged over four replications and two tillage management systems

[2] Treatments consist of 150 kg N ha^{-1}

*Means with different letters differ at the 0.05 probability level by Duncan's New Multiple Range Test

P = polymer-conditioned sewage sludge

L = lime-conditioned sewage sludge

Table 24
Corn yield as influenced by N application and tillage system in a Groseclose soil.

Treatment[1]	Year					
	1986		1987		1988	
(kg ha^{-1})	CT	NT	CT	NT	CT	NT
	Grain Yield (kg ha^{-1})					
0	4,910	4,700	2,730	3,420	3,890	3,560
75	5,080	6,270	2,880	4,670	5,990	6,000
150	5,350	6,390	3,120	4,470	7,060	8,010
225	4,930	5,660	3,070	3,960	7,420	8,040
	Stover Yield (kg ha^{-1})					
0	5,210	4,870	5,970	5,950	5,670	5,810
75	6,040	7,390	7,020	6,860	7,150	8,610
150	6,160	6,530	7,250	8,220	7,730	9,180
225	5,970	6,930	6,380	8,180	8,380	9,860
	Silage Yield (kg ha^{-1})					
0	10,100	9,580	8,700	9,380	9,560	9,370
75	11,100	13,700	9,900	11,500	13,100	14,600
150	11,500	12,900	10,400	12,700	14,800	17,200
225	10,900	12,600	9,450	12,100	15,800	17,900

[1] N was applied at 0, 75, 150, and 225 kg ha^{-1} to both tillage management systems during three years

Table 25
N uptake by corn as influenced by N application and tillage system in a Groseclose soil.

Treatment[1]	Year					
	1986		1987		1988	
(kg ha $^{-1}$)	CT	NT	CT	NT	CT	NT
	Grain (kg ha $^{-1}$)					
0	81	72	38	40	53	45
75	95	105	47	74	90	83
150	91	128	55	81	123	137
225	105	111	59	76	132	150
	Stover (kg ha $^{-1}$)					
0	28	24	22	21	31	28
75	42	38	44	31	50	46
150	51	44	49	60	62	64
225	50	55	50	68	72	73
	Silage (kg ha $^{-1}$)					
0	109	96	60	61	84	73
75	137	146	91	105	141	129
150	142	172	104	142	185	202
225	155	166	109	144	204	223

[1] N was applied at 0, 75, 150, and 225 kg ha $^{-1}$ to both tillage management systems during three years

Table 26
Regression of N application on grain and stover yields and N uptake by year for corn grown in a Groseclose soil.[1]

Year	Regression Equation	R^2
	Grain yield (kg ha^{-1})	
1986	$y = 4{,}810 + 17.4\ N - 0.07\ N^2$	0.99*
1988	$y = 3{,}700 + 38.8\ N - 0.09\ N^2$	0.99*
	Stover yield (kg ha^{-1})	
1988	$y = 6{,}190 + 14.3\ N$	0.89*
	Grain N uptake (kg ha^{-1})	
1986	$y = 76.7 + 0.4\ N - 0.0001\ N^2$	0.99*
1987	$y = 39.6 + 0.34\ N - 0.001\ N^2$	0.99*
1988	$y = 53.7 + 0.42\ N$	0.95*
	Stover N uptake (kg ha^{-1})	
1986	$y = 26.5 + 0.20\ N - 0.0004\ N^2$	0.99*
1987	$y = 21.8 + 0.18\ N$	0.95*
1988	$y = 29.4 + 0.29\ N - 0.0004\ N^2$	0.99*

[1] Nitrogen was applied at 0, 75, 150, and 225 kg ha^{-1} to both tillage management systems
*Significance at the 0.05 probability level

Table 27

Corn yield and N uptake for three growing seasons in a Groseclose silt loam soil.[1]

	Yield (kg ha^{-1})			N uptake (kg ha^{-1})		
Year	Grain	Stover	Silage	Grain	Stover	Silage
1986	5,460b*	6,220b	11,700b	100a	43a	145a
1987	3.540c	6,980ab	10,500b	59b	42a	101b
1988	6,250a	7,800a	14,000a	101a	53a	155a

[1] Means over four replications, four N treatments (0, 75, 150, and 225 Kg ha^{-1}), and two tillage management systems

*Means with different letters differ at the 0.05 probability level by Duncan's New Multiple Range Test

Table 28
Regression of N application on grain and stover yields by tillage for corn grain in a Groseclose soil.[1]

Tillage	Regression Equation	R^2
	Grain yield (kg ha^{-1})	
CT	$y = 3{,}730 + 15.3\,N - 0.04\,N^2$	0.99**
NT	$y = 3{,}830 + 31.4\,N - 0.10\,N^2$	0.99***
	Stover yield (kg ha^{-1})	
CT	$y = 5{,}680 + 18.3\,N - 0.06\,N^2$	0.97*
NT	$y = 6{,}170 + 10.9\,N$	0.81*
	Grain N uptake (kg ha^{-1})	
1986	$y = 76.7 + 0.4\,N - 0.0001\,N^2$	0.99*
CT	$y = 55.2 + 0.31\,N - 0.0005\,N^2$	0.99***
NT	$y = 50.5 + 0.75\,N - 0.002\,N^2$	0.99**
	Stover N uptake (kg ha^{-1})	
CT	$y = 27.2 + 0.29\,N - 0.0007\,N^2$	0.99**
NT	$y = 24.1 + 0.27\,N - 0.0004\,N^2$	0.99***

[1] Nitrogen was applied at 0, 75, 150, and 225 kg ha^{-1} rates during the three growing seasons

CT = conventional tillage

NT = no-till

*, **, *** Significance at the 0.10, 0.05, and 0.01 probability levels, respectively

Table 29
The influence of tillage on yield and N uptake of corn grown in a Groseclose silt loam soil.[1]

	Yield (kg ha^{-1})			N uptake (kg ha^{-1})		
Tillage	Grain	Stover	Silage	Grain	Stover	Silage
Conventional	4,690b*	6,620b	11,300b	80b	46a	127b
No-till	5,440a	7,480a	12,900a	92a	46a	139a

[1] Means over four replications, four N rates, and two tillage management systems
*Means with different letters differ at the 0.05 probability level by Duncan's New Multiple Range Test

Table 30
Corn yield as influenced by N application rate and tillage for the 1986 and 1988 growing seasons in a Suffolk soil.

Treatment[1]	Year			
	1986		1988	
(kg ha^{-1})	CT	NT	CT	NT
	Grain Yield (kg ha^{-1})			
0	2,770	2,940	1,540	1,330
75	2,410	3,160	1,420	1,890
150	2,830	4,070	1,260	1,890
225	2,280	3,570	700	1,000
	Stover Yield (kg ha^{-1})			
0	4,600	3,800	6,040	6,380
75	4,650	3,750	6,530	8,230
150	4,890	4,220	7,960	9,490
225	4,360	4,000	6,420	7,370
	Silage Yield (kg ha^{-1})			
0	7,370	6,740	7,570	7,710
75	7,060	6,910	7,950	10,100
150	7,720	8,300	9,220	11,400
225	6,640	7,580	7,160	8,340

[1] Nitrogen applied as urea ammonium nitrate (UAN) solution
CT = conventional tillage
NT = no-till

Table 31

N uptake by corn as influenced by rate of N application and tillage for the 1986 and 1988 growing seasons in a Suffolk soil.

Treatment[1]	Year			
	1986		1988	
(kg ha^{-1})	CT	NT	CT	NT
	Grain (kg ha^{-1})			
0	63	46	26	21
75	50	59	28	34
150	65	75	26	30
225	49	75	16	22
	Stover (kg ha^{-1})			
0	39	17	42	36
75	43	22	65	62
150	62	35	97	88
225	51	35	94	104
	Total (kg ha^{-1})			
0	102	63	68	57
75	93	82	92	96
150	126	110	123	117
225	101	110	110	125

[1] Nitrogen applied as urea ammonium nitrate (UAN) solution

CT = conventional tillage

NT = no-till

Table 32

Yield and N uptake for corn grown in 1986 and 1988 in a Suffolk sandy loam soil.[1]

Year	Yield (kg ha^{-1})			N uptake (kg ha^{-1})		
	Grain	Stover	Silage	Grain	Stover	Silage
1986	3,030a*	4,260b	7,290a	61a	38b	99a
1988	1,320b	7,050a	8,370a	25b	73a	98a

[1] Means over four replicates, four N treatments (0, 75, 150, and 225 kg ha^{-1}), and two years

*Means with different letters differ at the 0.05 probability level by Duncan's New Multiple Range Test

Table 33
Yield and N uptake for corn grown with two tillage management systems in a Suffolk sandy loam soil.[1]

	Yield (kg ha^{-1})			N uptake (kg ha^{-1})		
Tillage	Grain	Stover	Silage	Grain	Stover	Silage
Conventional	1,860b*	5,750a	7,610a	39a	63a	102a
No-till	2,420a	5,660b	8,080a	45a	50b	95b

[1] Means over four replicates, four N treatments (0, 75, 150, and 225 kg ha^{-1}), and two years

*Means with different letters differ at the 0.05 probability level by Duncan's New Multiple Range Test

Table 34
Total seasonal denitrification in a Groseclose soil.

Treatment	Denitrification, kg N ha^{-1} season^{-1}			
	With Acetylene		Without Acetylene	
(kg ha^{-1})	Conventional	No-till	Conventional	No-till
0 (Control)	4.65	1.27	4.56	0.93
150	2.48	2.28	1.69	2.63
225	0.82	1.23	1.31	0.65
150 (sludge)	3.56	1.36	1.88	1.65
Total	11.51	6.14	9.44	5.86
Total N applied	525.00	525.00	525.00	525.00
% N loss	1.31	0.93	0.93	0.94

Table 35
Nitrous oxide-N concentration in g N per million L on calendar day 211 from a Groseclose soil.

Depth (cm)	Conventional till treatment (kg ha $^{-1}$)				No-till treatment (kg ha $^{-1}$)			
	0	75	225	SS	0	75	225	SS
5	0.00	1.70	0.09	0.43	0.06	0.07	0.33	0.11
20	0.39	2.25	0.91	0.67	0.81	0.46	0.23	0.30
35	0.31	2.45	0.88	1.04	0.05	0.36	0.30	0.61
55	1.48	2.54	0.65	0.99	0.11	0.19	0.34	0.63
75	8.80	0.47	1.46	7.09	1.24	0.75	1.03	1.55
100	7.46	3.32	0.41	1.75	0.07	0.97	2.33	0.42

SS = sewage sludge (150 kg plant-available N ha $^{-1}$)

Table 36
Nitrous oxide-N concentration in g N per million L on calendar day 229 from a Groseclose soil.

Depth	Conventional till				No-till			
	treatment (kg ha^{-1})				treatment (kg ha^{-1})			
(cm)	0	75	225	SS	0	75	225	SS
5	0.41	0.58	0.30	2.25	2.19	0.49	0.60	0.51
20	0.59	1.51	0.53	0.59	0.40	0.46	0.52	0.32
35	0.60	0.61	0.39	0.60	1.33	0.28	0.24	0.47
55	0.34	0.43	0.49	0.54	1.16	0.48	0.75	0.49
75	0.49	1.86	0.27	0.04	1.09	0.28	0.32	0.31
100	0.32	0.55	0.50	1.21	1.89	0.28	0.70	0.43

SS = sewage sludge (150 kg plant-available N ha^{-1})

Table 37
Nitrous oxide-N concentration in g N per million L on calendar day 249 from a Groseclose soil.

Depth	Conventional till				No-till			
	treatment (kg ha^{-1})				treatment (kg ha^{-1})			
(cm)	0	75	225	SS	0	75	225	SS
5	0.65	0.56	0.78	0.92	0.53	4.76	3.35	0.90
20	0.69	0.71	1.12	2.13	0.77	0.76	0.39	0.78
35	0.60	0.66	2.65	1.03	0.69	0.72	3.55	0.65
55	0.58	0.91	1.59	4.17	0.55	6.03	3.15	0.61
75	0.82	1.08	1.34	1.60	0.69	2.07	0.94	0.65
100	4.40	9.16	3.93	1.97	0.42	1.63	4.41	0.87

SS = sewage sludge (150 kg plant-available N ha^{-1})

Table 38
Nitrous oxide-N concentration in g N per million L on calendar day 266 from a Groseclose soil.

Depth	Conventional till treatment (kg ha^{-1})				No-till treatment (kg ha^{-1})			
(cm)	0	75	225	SS	0	75	225	SS
5	0.38	0.76	0.42	0.46	0.157	1.03	0.47	0.25
20	0.43	1.77	0.47	0.45	0.75	1.20	0.38	0.46
35	0.51	0.88	0.48	0.50	0.07	0.16	0.36	0.29
55	0.39	1.29	0.51	0.31	0.82	0.25	0.46	0.36
75	1.60	1.71	0.84	0.63	0.24	0.34	1.54	0.27
100	0.44	2.41	0.97	0.43	0.78	0.17	0.32	0.45

SS = sewage sludge (150 kg plant-available N ha^{-1})

Table 39
Nitrous oxide-N concentration in g N per million L on calendar day 284 from a Groseclose soil.

Depth	Conventional till treatment (kg ha^{-1})				No-till treatment (kg ha^{-1})			
(cm)	0	75	225	SS	0	75	225	SS
5	1.17	1.62	2.03	1.66	0.29	1.74	1.89	1.52
20	0.92	1.72	2.00	1.49	0.26	1.19	1.70	1.65
35	1.17	1.73	0.73	1.81	0.38	1.57	1.39	1.07
55	1.02	1.06	2.02	2.29	0.40	1.18	1.24	1.25
75	0.04	1.25	1.65	1.92	0.56	1.34	1.22	1.23
100	1.26	1.29	2.27	1.35	0.32	1.46	1.82	1.12

SS = sewage sludge (150 kg plant-available N ha^{-1})

Table 40
Suffolk soil, 1986 - mean monthly moisture content.[1]

Layer Depth (cm)	Conventional till			No-till		
	Dates					
	7/16	8/13	11/4	7/16	8/13	11/4
	Moisture Content (cm m^{-1})					
15-45	12.56	10.56	18.93	16.99	13.38	20.99
45-75	14.27	12.69	16.17	17.61	14.83	19.02
75-105	10.99	9.68	11.38	13.38	10.92	12.23
105-135	9.25	7.41	8.63	11.05	8.43	9.09
135-165	10.66	8.95	8.86	12.56	9.84	9.74

[1] Means averaged over 12 plots

Table 41
Groseclose soil, 1986 - mean monthly moisture content.[1]

Layer Depth (cm)	Till			No-till		
	Dates					
	7/9	8/11	10/23	7/9	8/11	10/23
	Moisture Content (cm m^{-1})					
15-45	16.40	14.10	23.29	29.85	21.98	27.22
45-75	40.34	36.08	39.36	45.92	40.67	42.31
75-105	45.92	41.66	42.64	47.23	44.61	43.95
105-135	44.28	43.62	43.95	44.94	43.62	42.64
135-165	46.93	44.61	44.61	43.30	41.33	41.33

[1] Means averaged over 12 plots

Table 42
Groseclose soil, 1987 - mean monthly moisture content.[1]

Layer Depth (cm)	Till					No-till				
	Dates									
	5/9	6/9	7/8	8/10	9/10	5/9	6/9	7/8	8/10	9/10
	Moisture Content (cm m^{-1})									
15-45	22.47	21.16	20.50	10.99	17.38	26.24	26.08	26.31	16.73	22.07
45-75	41.33	40.51	40.11	34.11	33.55	44.35	43.23	43.07	37.65	37.46
75-105	44.54	44.12	44.35	41.59	39.85	45.46	45.49	44.77	42.87	42.31
105-135	45.00	44.74	45.10	43.85	42.87	44.51	44.12	44.12	43.30	42.48
135-165	45.53	45.46	45.26	43.79	43.39	42.81	42.41	42.48	41.75	40.77

[1] Means averaged over 12 plots

Table 43
Groseclose soil, 1988 - mean monthly moisture content.[1]

Layer Depth (cm)	Till				No-till			
	Dates							
	7/5	8/8	8/25	9/19	7/5	8/8	8/25	9/19
	Moisture Content (cm m^{-1})							
15-45	15.22	13.45	12.89	17.32	20.43	18.37	17.38	21.98
45-75	37.98	35.36	34.83	36.01	41.72	38.31	38.15	38.80
75-105	43.07	41.72	41.43	40.90	44.87	43.30	42.97	42.71
105-135	43.43	43.39	43.20	42.97	43.46	42.97	42.48	41.75
135-165	44.18	43.95	43.79	43.39	41.49	40.90	40.57	40.57

[1] Means averaged over 12 plots

Table 44
Nitrogen balances for conventionally tilled corn grown in the Groseclose soil during 1986-87.

Mass balance components	Treatment (kg ha^{-1})				
	0	75	150	225	150(SS)
	Fall				
N applied					
Fertilizer	0	75	150	225	150
Rye	26	26	26	26	26
N in soil[1]	189	189	189	189	189
Total N	215	290	365	440	365
N recovered					
Corn crop	109	137	148	155	170
N in soil[2]	107	150	239	315	405
Denitrified	9	9	9	9	9
Total recovered	225	296	396	479	584
Gain (or loss)	1	(3)	48	56	210
	Winter				
N in soil[2]	107	150	239	315	405
N recovered					
Rye	24	24	26	27	26
N in soil[3]	98	101	131	156	171
Total recovered	122	125	157	183	197
Lost	0	25	82	132	208

SS = polymer-conditioned sewage sludge applied at a rate to provide 150 kg plant-available N ha^{-1}

[1] Inorganic N initially present in the soil profile (0-100 cm) in April 1986

[2] Inorganic N present in the soil profile (0-100 cm) in October 1986

[3] Inorganic N present in the soil profile (0-100 cm) in April 1987

Table 45
Nitrogen balances for no-till corn grown in the Groseclose soil during 1986-87.

Mass balance components	Treatment (kg ha^{-1})				
	0	75	150	225	150(SS)
	Fall				
N applied					
Fertilizer	0	75	150	225	150
Rye	26	26	26	26	26
N in soil[1]	189	189	189	189	189
Total N	215	290	365	440	365
N recovered					
Corn crop	96	146	165	172	167
N in soil[2]	88	97	165	208	183
Denitrified	9	9	9	9	9
Total recovered	193	252	339	389	359
Gain (or loss)	(22)	(36)	(24)	(51)	6
	Winter				
N in soil[2]	88	97	165	208	183
N recovered					
Rye	24	24	26	27	26
N in soil[3]	62	63	123	110	203
Total recovered	86	87	149	137	229
Lost	2	0	16	71	0

SS = polymer-conditioned sewage sludge applied at a rate to provide 150 kg plant-available N ha^{-1}

[1] Inorganic N initially present in the soil profile (0-100 cm) in April 1986

[2] Inorganic N present in the soil profile (0-100 cm) in October 1986

[3] Inorganic N present in the soil profile (0-100 cm) in April 1987

Table 46
Nitrogen balances for conventionally tilled corn grown in the Groseclose soil during 1987-88.

Mass balance components	Treatment (kg ha^{-1})				
	0	75	150	225	150(SS)
			Fall		
N applied					
Fertilizer	0	75	150	225	150
Rye	24	24	26	27	26
N in soil[1]	98	101	131	156	171
Total N	122	200	307	408	347
N recovered					
Corn crop	60	91	112	109	149
N in soil[2]	123	142	191	222	201
Denitrified	9	9	9	9	9
Total recovered	192	242	312	340	359
Gain (or loss)	70	42	5	(68)	12
			Winter		
N in soil[2]	123	142	191	222	201
N recovered					
Rye	24	24	26	27	26
N in soil[3]	67	88	124	165	176
Total recovered	91	112	150	192	202
Lost	32	30	41	30	0

SS = polymer-conditioned sewage sludge applied at a rate to provide 150 kg plant-available N ha^{-1}

[1] Inorganic N initially present in the soil profile (0-100 cm) in April 1987

[2] Inorganic N present in the soil profile (0-100 cm) in October 1987

[3] Inorganic N present in the soil profile (0-100 cm) in March 1988

Table 47
Nitrogen balances for no-till corn grown in the Groseclose soil during 1987-88.

Mass balance components	Treatment (kg ha^{-1})				
	0	75	150	225	150(SS)
	Fall				
N applied					
Fertilizer	0	75	150	225	150
Rye	24	24	26	27	26
N in soil[1]	62	63	123	155	203
Total N	86	237	299	407	379
N recovered					
Corn crop	61	105	133	144	133
N in soil[2]	116	151	179	242	176
Denitrified	9	9	9	9	9
Total recovered	186	265	321	395	318
Gain (or loss)	100	28	22	(12)	(61)
	Winter				
N in soil[2]	116	151	179	242	176
N recovered					
Rye	24	24	26	27	26
N in soil[3]	79	107	128	161	155
Total recovered	103	131	177	188	176
Lost	13	17	24	54	0

SS = polymer-conditioned sewage sludge applied at a rate to provide 150 kg plant-available N ha^{-1}

[1] Inorganic N initially present in the soil profile (0-100 cm) in April 1987

[2] Inorganic N present in the soil profile (0-100 cm) in October 1987

[3] Inorganic N present in the soil profile (0-100 cm) in March 1988

Table 48
Nitrogen balances for conventionally tilled corn grown in the Groseclose soil during 1988-89.

Mass balance components	Treatment (kg ha^{-1})				
	0	75	150	225	150(SS)
	Fall				
N applied					
Fertilizer	0	75	150	225	150
Rye	24	24	26	27	26
N in soil[1]	67	89	132	165	176
Total N	91	188	308	417	352
N recovered					
Corn crop	84	141	190	204	214
N in soil[2]	97	103	140	225	152
Total recovered	181	244	330	429	366
Gain or (loss)	99	56	22	12	14
	Winter				
N in soil[2]	97	103	140	225	152
N recovered					
Rye	54	40	63	73	93
N in soil[3]	113	118	151	168	182
Total recovered	167	158	214	241	273
Lost	0	0	0	0	0

SS = polymer-conditioned sewage sludge applied at a rate to provide 150 kg plant-available N ha^{-1}

[1] Inorganic N initially present in the soil profile (0-100 cm) in March 1988

[2] Inorganic N present in the soil profile (0-100 cm) in November 1988

[3] Inorganic N present in the soil profile (0-100 cm) in June 1989

Table 49
Nitrogen balances for no-till corn grown in the Groseclose soil during 1988-89.

Mass balance components	Treatment (kg ha^{-1})				
	0	75	150	225	150(SS)
			Fall		
N applied					
Fertilizer	0	75	150	225	150
Rye	24	24	26	27	26
N in soil[1]	79	75	129	161	150
Total N	103	174	305	413	326
N recovered					
Corn crop	73	129	200	223	219
N in soil[2]	92	75	131	170	140
Total recovered	165	204	331	393	359
Gain (or loss)	62	30	26	(20)	33
			Winter		
N in soil[2]	92	75	131	170	140
N recovered					
Rye	48	43	53	71	115
N in soil[3]	133	110	161	163	162
Total recovered	181	153	214	261	277
Lost	0	0	0	0	0

SS = polymer-conditioned sewage sludge applied at a rate to provide 150 kg plant-available N ha^{-1}

[1] Inorganic N initially present in the soil profile (0-100 cm) in March 1988

[2] Inorganic N present in the soil profile (0-100 cm) in November 1988

[3] Inorganic N present in the soil profile (0-100 cm) in June 1989

Table 50

Nitrogen balances for corn grown in the Suffolk soil during 1986-87.

Mass balance components	Treatment (kg ha^{-1})				
	0	75	150	225	150(SS)
	Fall				
N applied					
Fertilizer	0	75	150	225	150
N in soil^1	131	131	131	131	131
Total N	131	206	281	356	281
N recovered					
Corn crop	83	88	118	106	115
N in soil^2	106	128	133	193	162
Total recovered	189	216	251	299	277
Gain (or loss)	58	10	(30)	(57)	4
	Winter				
N in soil^2	106	128	133	193	162
N recovered					
N in soil^3	38	40	42	40	64
Total recovered	38	40	42	40	64
Lost	68	88	91	153	98

SS = polymer-conditioned sewage sludge applied at a rate to provide 150 kg plant-available N ha^{-1}

[1] Inorganic N initially present in the soil profile (0-100 cm) in April 1986

[2] Inorganic N present in the soil profile (0-100 cm) in October 1986

[3] Inorganic N present in the soil profile (0-100 cm) in February 1987

Table 51
Nitrogen balances for corn grown in the Suffolk soil during 1988-89.

Mass balance components	Treatment (kg ha^{-1}) 0	75	150	225	150(SS)
	Fall				
N applied					
Fertilizer	0	75	150	225	150
N in soil[1]	28	33	20	20	29
Total N	28	108	170	245	179
N recovered					
Corn crop	62	94	120	118	130
N in soil[2]	22	12	41	76	82
Total recovered	84	106	161	194	212
Gain (or loss)	56	(2)	(5)	(51)	33
	Winter				
N in soil[2]	22	12	41	76	82
N recovered					
N in soil[3]	40	40	40	40	35
Total recovered	40	40	40	40	35
Lost	0	0	1	36	47

SS = polymer-conditioned sewage sludge applied at a rate to provide 150 kg plant-available N ha^{-1}

[1] Inorganic N initially present in the soil profile (0-100 cm) in March 1988

[2] Inorganic N present in the soil profile (0-100 cm) in October 1988

[3] Inorganic N estimated by using the intercept data from 1987

Table 52
Groseclose soil - corn stover yield (measured vs. estimates by NTRM, CERES, and VT-MAIZE).

Treatment	Conventional till (kg ha^{-1})				No-till (kg ha^{-1})			
(kg ha^{-1})	Measur.	NTRM	CERES	VT-MA.	Measur.	NTRM	CERES	VT-MA.
	November 1986							
0	5210.0	7994.0	2160.4	5812.8	4870.0	5686.0	2218.3	447.6
75	6040.0	7456.0	2923.2	5812.8	7390.0	8008.0	2941.2	445.7
150	6160.0	5246.0	2943.7	5812.2	6530.0	5245.0	2943.7	399.7
225	5970.0	5799.0	2943.7	5811.7	6930.0	5805.0	2943.7	374.3
Split	6130.0	6717.0	2942.8		6460.0	6441.0	2942.5	
SS	6540.0	5602.0			6740.0	5602.0		
	November 1987							
0	5970.0	11430.0	177.4	5566.9	5950.0	13530.0	198.7	4308.1
75	7020.0	11410.0	206.3	5122.8	6860.0	10590.0	205.2	8228.3
150	7250.0	11270.0	208.2	5362.6	8220.0	9590.0	207.7	5790.9
225	6380.0	9471.0	208.2	5096.0	8180.0	8204.0	207.1	3772.5
Split	6870.0	11430.0	208.2		8570.0	7939.0	207.4	
SS	7550.0	7815.0			8330.0	11060.0		
	November 1988							
0	5670.0	5424.0	2218.2	8080.6	5810.0	6875.0	1281.9	7210.5
75	7150.0	8473.0	4857.0	7653.6	8610.0	11320.0	4819.1	8140.7
150	7730.0	8357.0	4943.0	8066.6	9180.0	8964.0	4916.2	8225.7
225	8380.0	10510.0	4963.0	8003.7	9860.0	11010.0	4937.6	7544.4
Split	8010.0	12240.0	4939.0		9050.0	11490.0	4955.0	
SS	9280.0	5578.0			9680.0	13380.0		

SS = sewage sludge
Split and sewage sludge are 150 kg N ha^{-1} each
Measur. is field-obtained data

Table 53
Suffolk soil - corn stover yield (measured vs. estimates by NTRM, CERES, and VT-MAIZE).

Treatment	Conventional till (kg ha^{-1})				No-till (kg ha^{-1})			
(kg ha^{-1})	Measur.	NTRM	CERES	VT-MA.	Measur.	NTRM	CERES	VT-MA.
	November 1986							
0	4600.0	12500.0	1627.1	4790.1	3800.0	60410.0	1448.8	3009.4
75	4650.0	11020.0	1662.4	4756.8	3750.0	71610.0	1633.6	2725.6
150	4890.0	10720.0	1664.8	4848.4	4220.0	68570.0	1652.7	2906.2
225	4360.0	10750.0	1665.7	4757.9	4000.0	67460.0	1661.9	2725.6
Split	4820.0	12100.0	1659.7		4390.0	79770.0	1628.2	
SS	4960.0	13530.0			4090.0	19900.0		
	November 1988							
0	6040.0	781.0	572.9	8184.0	6380.0	315.0	274.4	8457.6
75	6530.0	5521.0	3624.8	8184.0	8230.0	3774.0	3477.0	8457.6
150	7960.0	8892.0	3673.6	8184.0	9490.0	6631.0	3645.1	8457.6
225	6420.0	9047.0	3692.4	8184.0	7370.0	7004.0	3679.6	8457.6
Split	7400.0	8975.0	3740.7		8510.0	9035.0	3601.0	
SS	8590.0	1347.0			7090.0	438.0		

SS = sewage sludge
Split and sewage sludge are 150 kg N ha^{-1} each
Measur. is field-obtained data

Table 54
Model prediction performance for stover yield (% prediction).

	Models								
Tillage	NTRM			CERES			VT-MAIZE		
	Groseclose soil (%)								
	U	O	C	U	O	C	U	O	C
Till	6	55	39	100	0	0	25	17	58
No-till	0	44	56	93	0	7	67	0	33
Mean	3	50	47	97	0	3	46	8	46
	Suffolk soil (%)								
	U	O	C	U	O	C	U	O	C
Till	17	58	25	100	0	0	0	25	75
No-till	33	42	25	100	0	0	0	12	88
Mean	25	50	25	100	0	0	0	18	82

U, O, and C represent, respectively, % of under-, over-, or correct estimation of actual values

Table 55
Groseclose soil - corn grain yield
(measured vs. estimates by NTRM, CERES, and VT-MAIZE).

Treatment	Conventional till (kg ha^{-1})				No-till (kg ha^{-1})			
(kg ha^{-1})	Measur.	NTRM	CERES	VT-MA.	Measur.	NTRM	CERES	VT-MA.
	November 1986							
0	4910.0	4406.0	63.0	3931.0	4700.0	2822.0	66.0	0.0
75	5080.0	3674.0	78.0	3931.0	6270.0	3964.0	81.0	0.0
150	5350.0	2727.0	81.0	3930.0	6390.0	2727.0	81.0	0.0
225	4930.0	3197.0	81.0	3930.0	5660.0	3204.0	81.0	0.0
Split	5410.0	4006.0	81.0		5770.0	3816.0	81.0	
SS	5000.0	4290.0			6020.0	4290.0		
	November 1987							
0	2730.0	5292.0	17.0	8957.0	3420.0	6263.0	20.0	9947.0
75	2880.0	5296.0	22.0	8893.0	4670.0	4920.0	22.0	10709.0
150	3120.0	5238.0	22.0	8912.0	4470.0	4443.0	22.0	10196.0
225	3070.0	4388.0	22.0	8901.0	3960.0	3810.0	22.0	9987.0
Split	3230.0	5306.0	22.0		4030.0	3680.0	22.0	
SS	3880.0	3625.0			4440.0	5142.0		
	November 1988							
0	3890.0	3800.0	1012.0	0.0	3560.0	5264.0	331.0	0.0
75	5990.0	5417.0	5820.0	0.0	6000.0	7487.0	6034.0	0.0
150	7060.0	5298.0	7348.0	0.0	8010.0	6573.0	7356.0	0.0
225	7420.0	6783.0	7680.0	0.0	8040.0	6740.0	7714.0	0.0
Split	7290.0	8094.0	7473.0		7770.0	7215.0	7533.0	
SS	7680.0	4058.0			8240.0	10380.0		

SS = sewage sludge
Split and sewage sludge are 150 kg N ha^{-1} each
Measur. is field-obtained data

Table 56
Suffolk soil - corn grain yield (measured vs. estimates by NTRM, CERES, and VT-MAIZE).

Treatment	Conventional till (kg ha^{-1})				No-till (kg ha^{-1})			
(kg ha^{-1})	Measur.	NTRM	CERES	VT-MA.	Measur.	NTRM	CERES	VT-MA.
	November 1986							
0	2770.0	5989.0	886.0	7508.0	2940.0	2982.0	667.0	6675.0
75	2410.0	5951.0	928.0	7472.0	3160.0	3280.0	893.0	6522.0
150	2830.0	5537.0	931.0	7503.0	4070.0	29220.0	916.0	6657.0
225	2280.0	5371.0	932.0	7472.0	3570.0	29840.0	927.0	6522.0
Split	3160.0	6022.0	925.0		4480.0	36020.0	887.0	
SS	3020.0	5949.0			3780.0	10050.0		
	November 1988							
0	1540.0	592.0	8.0	7660.0	1330.0	267.0	0.0	7552.0
75	1420.0	3136.0	85.0	7660.0	1890.0	1848.0	85.0	7552.0
150	1260.0	1761.0	85.0	7660.0	1890.0	1258.0	84.0	7552.0
225	700.0	2165.0	83.0	7660.0	1000.0	1805.0	84.0	7552.0
Split	1380.0	1260.0	84.0		2100.0	1573.0	84.0	
SS	1390.0	929.0			1550.0	305.0		

SS = sewage sludge
Split and sewage sludge are 150 kg N ha^{-1} each
Measur. is field-obtained data

Table 57
Model prediction performance for grain yield (% prediction).

Tillage	NTRM			CERES			VT-MAIZE		
	Groseclose soil (%)								
	U	O	C	U	O	C	U	O	C
Till	44	28	28	73	0	27	67	33	0
No-till	44	23	33	80	0	20	67	33	0
Mean	44	25	31	77	0	23	67	33	0
	Suffolk soil (%)								
	U	O	C	U	O	C	U	O	C
Till	0	58	42	30	30	40	0	100	0
No-till	16	42	42	90	0	10	0	100	0
Mean	8	50	42	60	15	25	0	100	0

U, O, and C represent, respectively, % of under-, over-, or correct estimation of actual values

Table 58
Groseclose soil - total N uptake by corn (measured vs. estimates by NTRM, CERES, and VT-MAIZE).

Treatment	Conventional till (kg ha^{-1})				No-till (kg ha^{-1})			
(kg ha^{-1})	Measur.	NTRM	CERES	VT-MA.	Measur.	NTRM	CERES	VT-MA.
	November 1986							
0	109.0	79.4	27.8	32.3	96.0	87.1	27.2	27.5
75	137.0	78.6	43.5	112.1	146.0	75.3	43.2	29.4
150	142.0	83.1	45.2	113.4	172.0	82.2	45.3	26.5
225	155.0	82.7	45.2	138.2	166.0	84.2	45.4	26.3
Split	153.0	91.2	45.9		157.0	112.1	45.7	
SS	170.0	66.4			167.0	60.1		
	November 1987							
0	60.0	0.37	0.8	12.4	61.0	0.41	0.9	13.4
75	91.0	0.21	0.9	13.7	105.0	0.12	0.9	103.8
150	104.0	0.11	0.9	16.1	142.0	0.30	0.9	18.2
225	109.0	0.28	0.9	19.9	144.0	0.12	0.9	106.2
Split	121.0	0.22	0.9		124.0	0.20	0.9	
SS	149.0	0.29			133.0	0.95		
	November 1988							
0	84.0	21.77	14.4	25.7	73.0	24.49	8.1	94.4
75	141.0	47.49	76.7	69.3	129.0	61.69	82.5	142.4
150	185.0	48.32	115.4	76.8	202.0	48.95	116.3	158.8
225	204.0	48.32	137.3	96.4	223.0	64.57	138.3	187.3
Split	195.0	66.62	120.9		196.0	67.12	122.0	
SS	214.0	20.38			219.0	38.69		

SS = sewage sludge

Split and sewage sludge are 150 kg N ha^{-1} each

Measur. is field-obtained data

Table 59
Suffolk soil - total N uptake by corn (measured vs. estimates by NTRM, CERES, and VT-MAIZE).

Treatment (kg ha^{-1})	Conventional till (kg ha^{-1}) Measur.	NTRM	CERES	VT-MA.	No-till (kg ha^{-1}) Measur.	NTRM	CERES	VT-MA.
	November 1986							
0	102.0	117.1	19.6	102.1	63.0	43.4	15.4	115.8
75	93.0	114.5	2.4	149.2	82.0	68.6	19.8	125.8
150	126.0	123.9	20.5	197.6	110.0	86.3	20.2	195.7
225	101.0	116.3	20.5	250.8	110.0	86.9	20.4	232.2
Split	123.0	142.7	20.4		121.0	97.5	19.6	
SS	118.0	113.4			111.0	31.1		
	November 1988							
0	68.0	6.3	3.7	20.6	57.0	1.5	2.0	26.7
75	92.0	84.8	33.3	161.7	96.0	44.4	31.7	64.2
150	123.0	114.6	37.7	108.4	117.0	86.7	37.9	123.6
225	110.0	125.0	48.4	153.1	125.0	98.2	44.6	137.7
Split	113.0	127.8	44.7		124.0	128.5	39.3	
SS	138.0	13.1			122.0	2.4		

SS = sewage sludge
Split and sewage sludge are 150 kg N ha^{-1} each
Measur. is field-obtained data

Table 60

Model prediction performance for total N uptake (% prediction).

Tillage	Models								
	NTRM			CERES			VT-MAIZE		
	Groseclose soil (%)								
	U	O	C	U	O	C	U	O	C
Till	94	0	6	100	0	0	83	0	17
No-till	100	0	0	100	0	0	75	0	25
Mean	97	0	3	100	0	0	79	0	21
	Suffolk soil (%)								
	U	O	C	U	O	C	U	O	C
Till	17	8	75	100	0	0	13	62	25
No-till	50	0	50	100	0	0	25	50	25
Mean	34	4	62	100	0	0	19	56	25

U, O, and C represent, respectively, % of under-, over-, or correct estimation of actual values

Table 61

Groseclose soil - the number of times (%) a model correctly predicted the soil N concentration on soil segment basis.

Treat-ment	Till						No-Till					
	NTRM		CERES		VT-MAIZE		NTRM		CERES		VT-MAIZE	
	1986						1986					
Zones	U	L	U	L	U	L	U	L	U	L	U	L
0	67	50	67	50	67	50	67	75	33	75	33	50
75	67	25	50	0	17	25	50	75	33	25	0	25
150	83	100	100	100	33	100	17	100	33	75	17	75
225	83	100	100	100	17	100	50	100	67	75	33	100
Split	83	50	83	50			67	100	67	50		
SS	100	50					83	100				
	1987						1987					
Zones	U	L	U	L	U	L	U	L	U	L	U	L
0	50	50	50	75	50	75	33	50	50	75	33	75
75	50	100	83	100	33	100	83	100	83	100	17	100
150	17	25	50	25	33	25	50	100	50	100	33	100
225	50	100	67	50	33	50	50	75	83	75	50	50
Split	33	100	67	100			67	25	67	75		
SS	0	50					83	50				
	1988						1988					
Zones	U	L	U	L	U	L	U	L	U	L	U	L
0	83	100	50	100	50	100	50	75	33	75	67	75
75	67	100	67	100	50	100	67	100	100	100	33	100
150	50	100	67	100	17	100	67	75	67	75	17	75
225	67	100	67	75	17	75	50	100	67	100	33	75
Split	83	100	83	100			33	100	50	100		
SS	50	75					50	75				

SS = sewage sludge
Split and sewage sludge are 150 kg N ha^{-1} each
U and L represent, respectively, 0-90 and 90-200 cm of the soil profile

Table 62

Suffolk soil - the number of times (%) a model correctly predicted the soil N concentration on soil segment basis.

Treatment	Till						No-till					
	NTRM		CERES		VT-MAIZE		NTRM		CERES		VT-MAIZE	
	1986						1986					
Zones	U	L	U	L	U	L	U	L	U	L	U	L
0	67	100	33	100	50	0	83	100	67	100	50	50
75	67	100	50	100	17	25	67	50	67	50	33	0
150	83	100	17	100	0	75	83	100	67	50	33	25
225	83	100	83	75	17	25	50	100	50	75	33	50
Split	67	100	33	100			83	50	67	50		
SS	67	75					67	100				
	1988						1988					
Zones	U	L	U	L	U	L	U	L	U	L	U	L
0	50	50	67	50	17	50	100	100	67	75	33	0
75	50	0	50	0	25	0	0	33	0	67	17	0
150	83	100	50	100	33	75	17	50	100	100	17	0
225	67	75	67	75	33	0	83	100	67	100	0	50
Split	83	0	0	0			67	50	50	75		
SS	83	100					33	50				

SS = sewage sludge
Split and sewage sludge are 150 kg N ha^{-1} each
U and L represent, respectively, 0-90 and 90-200 cm of the soil profile

Table 63
Suitability of models for predicting selected soil- and crop-N aspects.

Soil and Plant Aspect	Groseclose soil		Suffolk soil	
	Conventional Till	No-till	Conventional Till	No-till
Stover yield	VT-MAIZE	NTRM	VT-MAIZE	VT-MAIZE
Grain yield	NTRM& CERES	NTRM	NTRM& CERES	NTRM
Tot. N uptake	VT-MAIZE	VT-MAIZE	NTRM	NTRM
Grain N [1]	CERES	CERES	VT-MAIZE	VT-MAIZE
Grain / ear[1]	CERES	CERES	VT&CERES	VT&CERES
Soil N	NTRM& CERES	NTRM& CERES	NTRM	NTRM

[1] NTRM has no provision

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