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Nitrate Leaching Potential as Affected by the
Spatial Variability of Bt Horizon Morphology

presented by

Bruce Karl Johnson

has been accepted towards fulfillment
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Master of Science degree in Crop and Soil Sciences

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Major professor

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NITRATE LEACHING POTENTIAL AS AFFECTED BY THE SPATIAL VARIABILITY OF Bt HORIZON MORPHOLOGY

By

Bruce Karl Johnson

A THESIS

Submitted to
Michigan State University
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ABSTRACT

NITRATE LEACHING POTENTIAL AS AFFECTED BY THE SPATIAL VARIABILITY OF Bt HORIZON MORPHOLOGY

By

Bruce Karl Johnson

The main objective of this study was to relate estimated nitrate leaching to field-scale spatial variability of Bt-horizon morphology. The six-hectare site contained coarse-loamy and fine-loamy Typic Hapludalfs. The site was cropped to corn and alfalfa, and irrigated with water and dairy lagoon waste.

220 soil profiles were grid-sampled and described. The Bt-morphology data were analyzed using geostatistical procedures. Semivariograms for Bt1 clay content, Bt1 thickness, and 2Bt2 thickness displayed strong spatial dependence over ranges of 10-30 meters. Control-section clay content varied from 7-28 percent across the site.

Soil-water nitrate concentrations at a one-meter depth were sampled weekly using suction lysimeters. The suction-lysimeter data could not be directly correlated with Bt-horizon morphology. However, the CERES Maize computer model estimated nitrate fluxes under corn for the range of control-section clay contents. The model predicted consistently lower nitrate leaching with increasing clay content, and accurately predicted corn-grain yield and soil-water nitrate concentrations.

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INTRODUCTION

Nitrate contamination of groundwater is an environmental concern, and agricultural activities are a major source of nitrates. At the Kellogg Biological Station (KBS) in southwestern Michigan, a center-pivot irrigation system disposes dairy lagoon waste onto corn and alfalfa fields. Research scientists, KBS farm managers, and local residents were interested in estimating the degree of nitrate leaching from these fields. The purpose of this study was to estimate the nitrate flux under the KBS center-pivot system, to predict the effects of soil spatial variability on the nitrate flux, and to compare soil-water nitrate concentrations under corn, alfalfa, and hardwood forest. The goal was to provide information for farm-management decisions and to determine if the soil variability dictated special management practices for reducing field-wide nitrate leaching.

Many factors influence the extent of agricultural nitrate leaching to groundwater. Key management factors are N-fertilizer rates and timing, water management, cropping systems and tillage, all of which are essentially controlled by the farmer. Soil morphology can also be an important determinant of the rates and degrees of nitrate leaching. Any management strategies which address nitrate leaching must consider the inherent soil properties that interact with management variables.

Soil profiles with fine-textured horizons and/or textural discontinuities restrict water movement through the soil, thus increasing the potential for plant uptake or denitrification (Pratt, et al., 1972; Devitt, et al., 1976). Control-section texture has been significantly correlated with average soil nitrate concentrations below the root zone (Lund, et al., 1974). Control-section clay content alone accounted for 68 percent of the subsoil nitrate variation.

Profile drainage, and hence nitrate leaching, is probably governed by the least-permeable horizon in the profile (Nielsen, et al., 1973; Jones and Kiniry, 1986). For the Typic Hapludalfs of the KBS center-pivot field, the least-permeable horizons are the Bt horizons. A 1987 study at KBS demonstrated the spatial dependence of Bt-horizon morphology (J.R. Crum, 1989, unpublished data). Thus, it is the spatial variability of the Bt-horizon morphology which may control the degree of nitrate leaching under given management practices at KBS. By documenting the Bt-horizon spatial variability and modelling its effect on nitrate leaching, it can be determined whether soil variations are influential enough to warrant special management practices for areas more susceptible to nitrate leaching.

Hypothesis

Field-scale spatial variability of Bt-horizon morphology significantly affects nitrate leaching in the Typic Hapludalfs at KBS. Soil profiles which contain thinner and/or coarser-textured Bt horizons may contribute disproportionately to field-wide nitrate leaching.

Objectives

1) To characterize the spatial variability of Bt-horizon morphology for a portion of the KBS center-pivot field.

2) To examine the effects of soil variability and land-uses on soil-water nitrate concentrations.

3) To use actual soil-water nitrate concentrations and computer-modelled profile drainage to estimate the annual nitrate flux under corn, for a range of Bt-horizon variations.

4) To compare computer-modelled nitrate leaching estimates for rainfed and irrigated simulations, and to validate model outputs where possible.

LITERATURE REVIEW

I. THE NITRATE "PROBLEM"

Groundwater quality is a major environmental concern. One of the most ubiquitous contaminants in groundwater is nitrate (NO3-), an inorganic form of nitrogen. In Michigan, the incidence and severity of groundwater nitrate contamination has risen sharply in the last two decades, a trend which is mirrored nationally and internationally (D'Itri et al., 1985; Fairchild, 1987; Kittleson and Kruska, 1987). Many uncertainties exist about the significance, mechanisms, effects, future trends, and possible solutions associated with this problem.

Many natural and anthropogenic sources of nitrates occur in the environment. In nature, principal sources of inorganic nitrogen are mineralization (decomposition) of organic matter and inorganic nitrogen found within minerals/geologic deposits. Man-made sources of nitrates include industrial and automotive emissions, industrial discharge, urban sewage and runoff, agricultural N-fertilizers, livestock wastes, and rural septic systems (National Research Council, 1978). In rural areas, excessive nitrates in surface and groundwaters are strongly tied to agricultural activities and fertilizer use (NRC, 1978; Spalding and Exner, 1980; Hubbard et al., 1984; Loehr, 1984). Production agriculture may account for three-fourths of the nitrogen in US streams (Keeney, 1982). Nitrates, due to their high solubility and negative charge, migrate via soil-water movement in most temperate soils.

Excess agricultural nitrates affect both surface and ground-water systems. Small (<10 ppm) nitrate-level increases have resulted in "moderate" increases in biotic productivity which can alter stream/lake ecology (NRC, 1978). Nitrate is a limiting nutrient only in highly eutrophic lakes and streams with low nitrogen-to-phosphorous ratios (NRC, 1978). In most inland aquatic ecosystems, phosphorous is the limiting nutrient, and the eutrophication effects of nitrate increases are relatively small (NRC, 1978). Nitrate increases in groundwater generate concern primarily due to the degradation of drinking-water supplies.

The impact of nitrates on human health is not clearly understood. Nitrates are directly toxic only in massive doses, but nitrates can be converted in human digestive systems to nitrite (NO2-) and possibly N-nitroso compounds. In infants less than two years old, a potentially fatal condition known as methemoglobemia (cyanosis) can result from excessive nitrate ingestion and subsequent nitrite formation (NRC, 1978). Infants less than three months old are particularly susceptible to the condition, due to the presence of gastric bacteria which can readily oxidize nitrates to nitrites. In 1962 the EPA established an upper limit for drinking water of 10 ppm nitrogen in the nitrate form (10 ppm NO3--N). The incidence of methemoglobemia is rare when drinking water contains less than 10ppm NO3--N, but it measurably increases at higher levels (NRC, 1978). Methemoglobemia "is rarely fatal, is readily diagnosed, and is rapidly reversible with clinical treatment" (NRC, p.6). Milk and bottled water are safe alternatives for infant diets if tap-water quality is suspect. No case of methemoglobemia has been documented in an adult human (NRC, 1978).

A more serious health threat is represented by N-nitroso compounds, which are potential by-products of nitrate/nitrite ingestion. Nitrosamine derivatives are of particular concern. In laboratory animals, nitrosamines are carcinogenic for all vital tissue types and can induce tumors from a single dose given at infancy. Nitrosamine risk factors for humans cannot be accurately estimated; risk estimates vary by one or two orders of magnitude (NRC, 1978). Nitrosamines potentially metabolized from drinking water are minute compared to such sources as cured meats and cigarettes (NRC, 1978; Food Safety and Quality Service, 1978). The real health risks posed by typical nitrosamine exposure are believed small, but enough ambiguity exists for limiting exposure to these compounds and their precursors (NRC, 1978).

Limiting the ingestion of inorganic nitrogen depends on knowledge of the relative contribution from various sources. An "average" American ingests 80% of dietary nitrates from vegetables, and two liters per day of water at the EPA limit would contribute only 17 percent to total daily intake (data from White, 1975; re-calculated by author for 10ppm NO3--N water). Because ingested nitrates are significant due to their conversion to nitrite (NO2-), we must also consider direct nitrite ingestion. The largest source of ingested nitrite is saliva, but the slow rate of formation and ingestion probably produces minimal effect (NRC, 1978). Otherwise, cured meats represent the largest single-dose nitrite source. Cured meats are also a direct source of nitrosamine compounds (Food Safety and Quality Service, 1978). Health risks associated with nitrates, nitrites, and nitrosamines are controversial (NRC, 1978), but drinking water is not a major source of these compounds. Because typical nitrate ingestion from water is relatively minor, infant health and public policy enforcements are the prime reasons for maintaining the EPA standard (NRC, 1978).

Trends in groundwater data suggest that nitrate increases may persist for some time, regardless of current activities. With the rates of nitrate accumulation in groundwater largely unknown, and health effects still uncertain, a conservative approach toward nitrate-leaching management seems wise. Furthermore, nitrogen losses continue to represent sub-optimal yields for farmers, economic input losses, and inefficient recycling of nitrogen wastes.

The research emphasis on nitrates may seem questionable given the apparent seriousness of such problems as pesticide contamination of groundwater. But nitrates do provide an opportunity to study how a rather ubiquitous, mobile contaminant leaches through soils and enters groundwater systems. Nitrate-leaching research provides important clues for soil-to-aquifer transport processes and contaminant travel times. This knowledge is applicable to a wide range of groundwater contamination problems.

II. MANAGEMENT FACTORS AFFECTING FERTILIZER NITRATE MOVEMENT TO GROUNDWATER

Two conditions are essential for nitrate leaching to groundwater: 1) soil nitrates must be available for leaching, and 2) water must transport nitrates below the root zone (Smika, et al., 1977). These two conditions highlight the central roles played by nitrogen application and water management as primary management variables for limiting nitrate losses. However, crop uptake of N is dependent upon so many interrelated factors that the entire farming system must be geared toward maximizing N-use efficiency. As Keeney (1982, p.626) states, "The greatest need is to predict accurately the N dose-response relationship for a given crop on a given farm." There is no advantage in applying excess N if other factors are limiting production.

Nitrogen Fertilizer Rates

The environmental effects of nitrogen fertilizer rates are not due to the rates per se, but to the degree to which the crop can use the applied N (NRC, 1978). This fact has frustrated attempts to recommend simple, environmentally sound, fertilizer-rate guidelines. The difference between applied N and crop uptake represents a potentially leachable fraction, depending largely upon the degree of denitrification (Stanford, 1973). Given the variability in quantifying directly-measured N-leaching, the nitrogen mass balance remains a good overall indicator for estimating leaching potential at field scales (Pratt et al., 1972).

While total N uptake may increase with N-application rates, the percent recovery of N decreases (Gerwing, et al., 1979; Olson & Kurtz, 1982; Motavalli et al., 1989). Nightingale (1971) found a positive correlation between N-fertilizer rates, soil NO3--N concentrations below the root zone, and groundwater concentrations of NO3--N. The study included several crops and soil types, and emphasized that N-use efficiency was more deterministic of leaching than N-fertilizer rates themselves. Residual NO3--N after harvest is a major factor in leaching, and excess N may not appear in water wells for many years (Pratt et al., 1972). Smika et al. (1977) found a high negative correlation ($r=-0.99$) between nitrate leaching at 1.5 meters and total dry matter production for corn, suggesting a strong inverse relationship between N-leaching and N-use efficiency. Total residual-N in soil profiles is related to fertilization rates (Olsen et al., 1970; Chichester & Smith, 1978), and long-term overapplication can result in greater losses to subsurface water (Chichester & Smith, 1978).

Fertilizer Timing

If excess soil nitrate is limited throughout the growing season, the probability of a precipitation or irrigation event transporting nitrate is reduced. The theory behind timed N-applications is that fertilizer applications should be synchronized with crop demand, thereby placing nitrogen in the environment only when there is good probability of crop uptake (Stanford, 1973; Olson & Kurtz, 1982).

In Minnesota, single N-applications increased aquifer nitrate levels by 7 to 10 ppm under irrigated corn, but no nitrate increase resulted from the same rate split over four applications (Gerwing et al., 1979). Timmons and Dylla (1981) reported 12% greater NO_3^--N losses for one-time broadcast versus split fertilizer applications, but only under higher (5cm/application) irrigation rates. The Timmons study lacks treatment-specific yield data, however, leaving crop uptake differences as an uncontrolled variable. On a sandy Wisconsin soil, Saffigna et al. (1977) reduced seasonal nitrate leaching under potatoes from 200 to 120 kg

N/ha by decreasing N-fertilizer rates and increasing the frequency of split applications. Potato yields were the same for both the conventional and improved treatments.

Crop simulation models provide an interesting theoretical glimpse at benefits derived from timed applications. Alocilja and Ritchie (1989) used the CERES Maize model to schedule nitrogen applications, optimizing economic returns versus nitrate leaching. If the model is validated for a given geographic area and proper irrigation equipment is available, this approach may represent a state-of-the-art, dynamic management strategy for optimizing nitrogen use and environmental quality.

The practice of splitting applications is a farm management decision. Split applications for most farmers are limited to an initial broadcast and single sidedress, due to traffic considerations and operational costs (Keeney, 1982). Farmers cannot synchronize these early applications with the peak nitrogen demand by corn and other non-leguminous crops. For operations with irrigation systems, multiple split applications can maximize N-use efficiency and reduce nitrate losses (Keeney, 1982).

Water Management

Nitrogen application rates and methods are intimately related to water management in minimizing nitrate losses to groundwater. Water movement plays a critical role in nitrate leaching because: 1) nitrate is extremely water-soluble, and nitrates are not adsorbed by soils with net CEC; 2) insufficient moisture may result in poor N-uptake, leaving large amounts of leachable residual N, 3) intense precipitation events may drive nitrates below the root zone, and 4) hydraulic discontinuities or saturation may accelerate denitrification.

Owens (1960) directly related leaching losses to water movement in soils. Pratt et al. (1972) found excellent correlation between observed soil NO3--N amounts to 30 meters and flux estimates calculated by multiplying excess N/year estimates with water transit times. Limiting percolation below the root zone by varying sprinkler irrigation reduced nitrate losses in two studies (Saffigna, et al., 1977; Smika et al., 1977). Hergert (1986) demonstrated that even incrementally applied N can be leached if sandy soils are over-irrigated. In an extreme demonstration, Endelman et al. (1974) noted nitrate movement of 15-20 cm per day on a loamy sand under 2.5 centimeters of applied water per day. This finding underscores the high potential for nitrate leaching through coarse-textured soils.

Tillage and Cropping Effects

Several factors influence the effects of tillage practices on nitrate leaching. Tyler and Thomas (1977) found higher leaching rates for NO_3^--N and a chloride tracer under no-till versus conventional tillage. This was consistent with the generally-accepted view that, on average, no-till produces greater water infiltration. Kanwar et al. (1985) demonstrated an opposite effect, with far less nitrate leaching to 1.5 meters under no-till. Gilliam and Hoyt (1987) attributed the discrepancy to differences in nitrogen distribution within the soil matrix. Macropore flow accounts for proportionately greater solute transport when N is relatively unincorporated; displacement flow transports the N in the soil matrix (Tyler and Thomas, 1981). Most current theories regarding nitrogen dynamics and water infiltration/movement suggest a probable increase in NO_3^- leaching under no-till (Gilliam and Hoyt, 1987).

Cropping systems can affect seasonal nitrate leaching, but long-term effects are unclear. Crops which require high N inputs obviously engender some increased risk of N-loss. Olsen et al. (1970) related higher nitrate leaching levels to the frequency of corn in a corn-fallow rotation. Alfalfa can reduce soil profile NO_3^--N in rotations with non-leguminous crops (Stewart et al., 1967; Schertz & Miller, 1972), and the residual NO_3^--N can be removed down to several meters (Mathers, et al., 1975). The literature regarding magnitudes and rates of nitrogen release after legume plow-down is scarce and conflicting. Legume residues can contribute to higher leached-N levels than residues from N-fertilized non-legumes (Adams and Pattinson, 1985;

Groffman et al., 1987). Further research is needed regarding long-term nitrogen balances and redistribution of soil-N under crop rotations.

III. SOIL MORPHOLOGY FACTORS RELATED TO NITRATE CONTAMINATION OF GROUNDWATER

Effects of Soil Morphology

Soil morphology can strongly affect rates and degrees of nitrate leaching. Such factors as soil texture, structure, horizonization, and microtopography determine soil hydraulic behavior, which subsequently affects leaching rates and denitrification potentials (Nielsen, et al., 1973; Van De Pol et al., 1977; Cameron et al., 1979; Wagenet, 1984). Soil morphology and hydraulic characteristics are spatially variable and are, therefore, difficult to relate statistically to nitrate leaching (Nielsen et al., 1982)

Soil texture is a major determinant of nitrate leaching potential. Lund et al. (1974) related control-section texture to deep (1.8-8m) nitrate concentrations on Alfisol and Entisol soils; the regression explained 86% of the nitrate variability. Well-drained, coarse-textured profiles typically exhibit low denitrification potentials and high hydraulic conductivities (Devitt et al., 1976; Saffigna et al., 1977; NRC, 1978). These conditions favor nitrate persistence and transport below the root zone. Coarse-textured soils have low water-holding capacities and require frequent irrigation, thus increasing the potential for nitrate leaching (Smika et al., 1977). Many studies document the nitrate-leaching problems associated with coarse-textured soils (e.g. Devitt et al., 1976; Saffigna and Keeney, 1977; Hughes, 1983; Hergert, 1986).

Morphological properties which tend to restrict water movement reduce the probability of nitrate leaching. The combined effects of soil texture, structure, horizonization, and pore continuity strongly affect leaching processes (Bouma, 1983). Finer-textured layers may decrease percolation rates, increase probability of plant uptake, and promote denitrification (Pratt et al., 1972; Nielsen et al., 1973). However, well-structured fine layers can be rapidly permeable. Textural discontinuities between layers can suspend water and create saturated zones favorable for denitrification (Lund et al., 1974). The hydraulic characteristics of the least-permeable soil layer probably govern profile drainage and hence nitrate leaching (Nielsen, et al., 1973; Jones and Kiniry, 1986).

Solute transport is often modeled using displacement theory, which apparently fails to describe real flow in structured soils (Tyler and Thomas, 1981). McMahon and Thomas (1974) demonstrated faster solute movement in undisturbed soil cores versus disturbed soil cores. Many studies (Wild and Babiker, 1972; Quisenberry and Phillips, 1976; Tyler and Thomas, 1981; Richter and Jury, 1986; Priebe and Blackmer, 1989) implicate preferential flow via macropore channels as a major avenue for solute movement. Visual dye tracings in two studies confirmed water movement in continuous soil channels (Wild and Babiker, 1972; Tyler and Thomas, 1981). Macropore flow may occur more often where field microtopography produces ponded conditions (Cameron, et al., 1979).

The extent of macropore flow depends upon soil moisture conditions and precipitation intensity. Many macropore-flow studies employ water applications at or near soil saturation, and saturation is not representative of normal field conditions (Cameron et al., 1979). Quisenberry and Phillips (1976) found that applied water is less likely to flow through channels when the initial soil moisture is well below field capacity. At water inputs greater than one pore volume, structured soils can actually leach less solute than unstructured soils, due to non-mixing of percolating water with the soil matrix (Tyler and Thomas, 1981; Kanwar et al., 1985). Soil-structure effects depend upon such factors as the distribution of solute in the soil matrix, water infiltration rate, and initial soil-water content (Quisenberry and Phillips, 1976; Gilliam and Hoyt, 1987).

Variability of Nitrate Leaching Processes

Several reviews document the spatial variability of soil morphology (Beckett and Webster, 1971; Webster, 1977;

Wilding, 1984). The morphological factors which determine soil hydraulic properties often interact independently over variable scales (Trangmar, 1984). Therefore, it is not surprising that soil hydraulic properties typically display much greater variation than soil morphology properties. The spatial variability of hydraulic characteristics is further complicated by the high degree of temporal variability in soil-water content and distribution (Wagenet, 1984).

Accurate estimation of field-scale nitrate leaching requires data for both nitrate concentrations and profile drainage at specific points in time. These data sets often exhibit large spatial and temporal variability, and thus require intensive sampling schemes for reliable characterization. Typically, suction or block lysimeters collect samples for nitrate concentration measurements. Several methods, including lysimeters and water-balance calculations, estimate soil-water drainage volume. Biggar and Nielsen (1976) indicate that estimating solute flux as a product of average solute concentrations and average water drainage is theoretically unsound. A logical approach is to calculate a solute flux for each sampling date, using a mean field-wide solute concentration and estimates of water drainage below the root zone (B.G. Ellis, 1989, personal communication). Seasonal flux totals can then be calculated from the incremental flux calculations.

In summary, intrinsic soil properties are major determinants of nitrate leaching potential. These properties also affect leaching by influencing management requirements and practices (e.g. irrigation of sandy soils). Soil morphological properties affect nitrate leaching (Lund et al., 1974; Devitt et al., 1976) and also display spatial variability (Wilding and Drees, 1983). Soil surveys account for some morphology variation, but morphological variation within map units and fields can create differential leaching (Richter and Jury, 1986). Estimation of soil spatial variability is necessary for identifying extreme soil conditions which may contribute disproportionately to excessive nitrate leaching (Wagenet, 1984).

IV. SOIL SPATIAL VARIABILITY

Soil variability is a traditional problem in the agricultural sciences. As early as 1915, Harris remarked that soil variability could "profoundly" affect agronomic experiment results (Campbell, 1979). Classical "aggie statistics" were devoted to estimating means from crop-yield trials, which required the control of such experimental-error sources as soil changes (Gutjahr, 1984). In the 1920's R.A. Fisher developed randomization and blocking techniques to minimize the effects of soil variability on agronomic experiments, but without estimating its magnitude or structure (McBratney, 1984).

Soils vary systematically across landscapes, which is an essential paradigm for pedologists (Wilding and Drees, 1983). Soil variance is partitioned geographically by mapping soils into relatively homogeneous units, and taxonomically by separating soils into diagnostic classes (Webster, 1985). The basic objective is to enhance predictive capabilities of soil-property occurrence by minimizing within-unit variance and maximizing variance between units. The intended soil use often dictates the scale and nature of observation, which is tied to activities such as soil characterization, land-use planning, agronomic experiment design, and fertilization recommendations. Typical soil surveys do not map significant soil variation for many intensive uses, though there is little value in mapping soil at less than the minimum management capability (Beckett and Webster, 1971).

It was not until the 1970's that widespread interest emerged in the application of statistics to the degrees and patterns of soil variability (Wilding and Drees, 1983). The emergence of geostatistical methods, or statistical analyses which consider the spatial orientation of observations, was perhaps the most significant development (Webster, 1985). This accompanied more intensive land-uses and an increasing level of sophistication in soil management. Systematic pedogenic processes and landscape position determine soil occurrence, therefore random statistics are not easily applied to spatial variation. The systematic spatial variation of soil properties, if geostatistically quantified, can provide greater predictive capabilities than conventional statistics (McBratney and Webster, 1983).

Classical Statistics

Statistical procedures first require definition of a sample population. In soil science, the samples are usually drawn from a geographic volume (e.g. horizon, pedon, field) or from defined taxonomic units (e.g. series, map unit, sub-group) (Webster, 1985). A basic statistical characterization requires knowledge of the sample probability distribution, mean, and standard deviation (Warrick and Nielsen, 1980). Most soil properties are either normally or log-normally distributed (Wilding and Drees, 1983). A normal distribution is required for conventional statistics, so log-normal or complex distributions require transformation prior to statistical analysis.

The relationship between the sample mean and standard deviation is an indicator of sample variability. A commonly used statistic is the coefficient of variation (CV), which is the standard deviation as a percent of the sample mean (Wilding and Drees, 1978; Warrick and Nielsen, 1980). The CV is unitless and therefore allows comparisons of variability among data sets. It is a valid statistic only when there is a normal distribution, non-zero mean, and no covariance between the mean and standard deviation (Wilding and Drees, 1978). The mean and standard deviation can also indicate the number of samples required to estimate a soil property to a given level of precision; that is, place confidence limits on a randomly-drawn observation for a specified probability. As soil variation increases, the number of samples required can increase drastically (Wilding and Drees, 1983).

Soil properties exhibit some general trends in their degree of variation. Typically, soil morphological and physical properties are less variable than management-affected properties (Wilding and Drees, 1983). Cultivated fields tend to display greater nutrient spatial variability than uncultivated fields (Beckett and Webster, 1971). Soil hydraulic properties are among the most-variable properties, which have great implications for soil pedogenic processes and soil behavior (Bouma, 1983). Total sample variance increases with size of sample area, but contributions from various observation scales "follow no consistent pattern" (Wilding and Drees, 1983). Beckett and Webster (1971) indicated that any square meter of soil can account for up to half of the total within-field variance for many soil properties.

Systemic Versus "Random" Variation

Soil variability results from interactions of soil-forming factors, processes and soil management; long-range phenomena produce long-range variations, and short-range phenomena produce changes over small distances (Beckett and

Webster, 1971; Trangmar, 1984). Soil-forming factors and processes are themselves spatially-dependent, which results in spatially-dependent soil property variation (Burrough, 1983). However, these pedogenic and management factors interact stochastically (probabalistically) over many scales, which produces both systematic variation and apparent randomness in soil-property observations.

Systematic variation (i.e. "spatial correlation") has been observed for soil properties at virtually all scales of observation (Burrough, 1983). A given soil property, measured at different sample intervals, displays structure in the variance but shows different ranges of spatial dependence for different scales (Uehara et al., 1984). Soil properties can be considered as fractal quantities in which variation patterns are a function of observation scale. In fact, systematic versus random variation is entirely scale-dependent and increasingly-finer scales reveal structure to apparently random variations (Burrough, 1983). The quantification of soil variability is also dependent upon the soil property and sampling methodology, a crucial fact often ignored in such studies (Trangmar, 1984; Wagenet, 1984).

Nested Soil Variation and Observation Scale

Scale dependence reflects the "nested" nature of soil variation; that is, small-distance variations occur within the context of larger variations. Variances of soil properties do not increase constantly over increasing distances, but step-wise across new scales of variation. These abrupt changes in variance reflect the predominance of a new controlling factor or process (Webster, 1977).

When nested variation occurs, it is advantageous to identify abrupt changes in the mean for a property (Burrough (1983b). Nested sampling and analysis partitions variance between hierarchical sub-divisions of a population, which can be divided geographically or taxonomically (Youden and Mehlich, 1937). The variance contribution and scale differ with the sample population and property at a given observation scale. The total variance, of course, increases with increased sample area (Webster, 1985).

Nested analysis assumes that the variation has independent components of variation at each level (Webster, 1985). The complex interaction of soil-forming phenomena and the nested character of genetic factors make this a tenuous proposition. Geostatistical techniques do not require these assumptions, but only characterize the continuous nature of spatial variation. In doing so, they can often identify nested variation over several scales (Trangmar, et al., 1985).

V. GEOSTATISTICS

"Geostatistics" refers collectively to the procedures for sampling and estimating spatially-dependent variables (Trangmar, 1984). The techniques originated primarily within the South African gold-mining industry, where statistician D.G. Krige sought an empirical method for predicting gold ore placement. Georges Matheron generalized these empirical techniques into a rigorous mathematical theory during the 1950's and '60's (see Matheron, 1971). The foundation of Matheron's spatial statistics is the theory of regionalized variables. It not only accommodates the statistical analysis of spatially-related data, but provides theories for sampling variability and sample size, including a complete theory of estimation error. A major application is the optimal, unbiased interpolation of spatial data points, with an associated variance estimate (i.e. confidence) for each point (Trangmar, et al., 1985). Significantly, it allows an evaluation of sampling-scheme variance before sampling, provided a basic idea of the spatial variability is known (McBratney and Webster, 1983).

Several review papers summarize the development of geostatistics and its application to soil science. Among them are Burgess and Webster (1980a,b,&c), Trangmar et al., (1985), and Webster (1985). Simplified derivations of the underlying mathematical theories are given by Olea (1975), along with applications for exploration geology. The most complete and rigorous discussions are presented by Matheron (1971) and Journel and Huijbregts (1978), but they are difficult for most readers. This review begins with a discussion of regionalized variables and stationarity, concepts that provide theoretical justification for semivariance and kriging calculations. The semivariance is the major statistic for indicating spatial dependence, and kriging (after D.G. Krige) is the subsequent interpolation procedure.

The Theory of Regionalized Variables

Consider a data set of soil pH values collected from a farmer's field. Each value is a random variable which is part of an infinite set of sample pH values for that field. When a particular random variable is associated with the coordinate where it was sampled, the variable becomes a regionalized variable. That is, both the pH value and its position in space are relevant to the statistical analysis. If the infinite set of pH values were associated with their respective infinite sample points, it would generate a probability density function. This function is called the random function. The concepts of random variables, regionalized variables, and random functions constitute the core of regionalized-variable theory.

The concept of a "random function" may seem paradoxical in describing spatially-dependent phenomena. In fact, a random function may describe a highly-structured, spatially dependent set of data, or the converse. The random function does not imply necessary randomness, but simply indicates that any element within the probability distribution can theoretically associate with any given geographic point. This satisfies the requirements of statistical randomness and allows the application of some conventional statistical concepts to geostatistics (Olea, 1975). Gutjahr (1984) describes the random function as a "spatial stochastic process", a phrase that well-describes many soil property occurrences.

Regionalized data must exhibit a normal distribution or be transformable to a normal distribution (Trangmar, 1984). The regionalized variables possess several characteristics not usually shared by conventional data. The geometric support describes the sample size, shape, and orientation (Olea, 1975; Webster, 1985). It can be a critical consideration, as many measured soil properties (e.g. hydraulic conductivity) are highly dependent upon the sample's characteristics (Wagenet, 1984). The larger volume from which the samples are drawn is termed the geometric field. Spatial data may exhibit anisotropy, or differential variance according to sampling direction. Regionalized variables generally display continuity at most scales of observation (Olea, 1975).

The exact nature and determinants of the probability density (i.e. "random") function are usually unknown, as in conventional statistics. The essential assumptions required for geostatistics involve the concept of stationarity, which is analogous to the independence of observations and errors in classical statistics (Olea, 1975). The concepts of random functions and stationarity serve as the basis for statistical inferences regarding expected values and variances within a region.

Stationarity[1]

The random function, herein designated Z(x), is defined as the set of infinite random variables (of one property) which are associated with any location "x" in a specified region. Stationarity (i.e. statistical independence) requires that the random function be identical for all sample locations. Expressed in statistical terms, the expected value of a randomly-drawn sample is the mean of the random function:

$$E[Z(x)] = \mu = \text{mean}$$

It follows that two random samples separated by a vector "h" (termed the "lag") have the same expected value μ, and therefore the expected difference is zero:

---

1 For simplicity, statistical notations used herein are consistent with Trangmar (1985).

$$E[Z(x)-Z(x+h)] = 0$$

If the random function satisfies these two requirements, it exhibits first-order stationarity. It is "first order" in the sense that the mean estimate has a power of one. Variance statistics are squared terms ($\sigma 2$, $s2$) and are therefore "second-order" statistics. It is important to note that "h" is a vector quantity which contains both distance and directional components.

Whereas first-order stationarity implies regional stability of the distribution mean, second-order stationarity indicates constancy of the spatial covariance C(h):

$$C(h) = E[Z(x)-\mu][Z(x+h)-\mu]$$

If the spatial covariance is constant for each pair of observations separated by lag "h", regardless of pair location in the region, then there is second-order stationarity. The existence of second-order stationarity indicates that the sample variance s2 is finite and constant throughout the region.

Certain natural phenomena exhibit unlimited dispersion, and cannot be described correctly using a finite variance (Olea, 1975). Thus there is no strict second-order stationarity. In such cases, a weaker assumption of variance stability is used, which requires only a finite variance between observation pairs separated by lag "h". Once again, the statistic must be independent of location:

$$VAR[Z(x)-Z(x+h)] = E[Z(x)-Z(x+h)]2$$
$$= 2\tau(h)$$

This describes the variance of the difference between pairs of observations, which must be divided by two to yield a per-observation variance. This is why the resulting statistic $\tau(h)$ is known as the semivariance. For soil data, stationarity via the intrinsic hypothesis is usually realized for local neighborhoods within a region. This is sufficient for spatial analysis where the variance is relatively stable within some maximum lag radius, but may break down if strong local trends are present (Trangmar, et al., 1985; Webster, 1985).

The semivariance statistic possesses several advantages over similar techniques such as autocorrelation. Autocorrelation must have second-order stationarity, a condition frequently lacking in soil data. Soil change is systematic over landscapes, and soil properties do not typically exhibit spatial covariances which are independent of location (Yost et al., 1982). The semivariance reveals the nature of the property variation, and can also account for local trends (drift) in the data. Perhaps most importantly, the semivariance provides statistics for kriging techniques, which are used for unbiased, optimal interpolation between known data points and the efficient design of sampling schemes (Burgess and Webster, 1980a).

The Semivariance and Semivariogram

For spatially-related data, the semivariance statistic confirms what we know intuitively; that points closer together are generally more alike than those separated by greater distances. The semivariance is a measure of the average similarity between points a given vector apart (Burgess and Webster, 1980a). The spatial relationships among data points is represented by plotting the semivariance versus the lag distance "h", and the graph is known as the semivariogram or variogram. The semivariogram is the basic tool for understanding and modelling spatial variation.

If second-order stationarity applies, the semivariance can be defined by the total sample variance and the covariance for lag "h" (see Figure 1):

$$\tau(h) = s2 - C(h)$$

The intrinsic hypothesis is usually assumed instead, and the semivariance is estimated by the following equation:

$$\tau(h) = ½Nh\Sigma[Z(x)-Z(x+h)]2$$

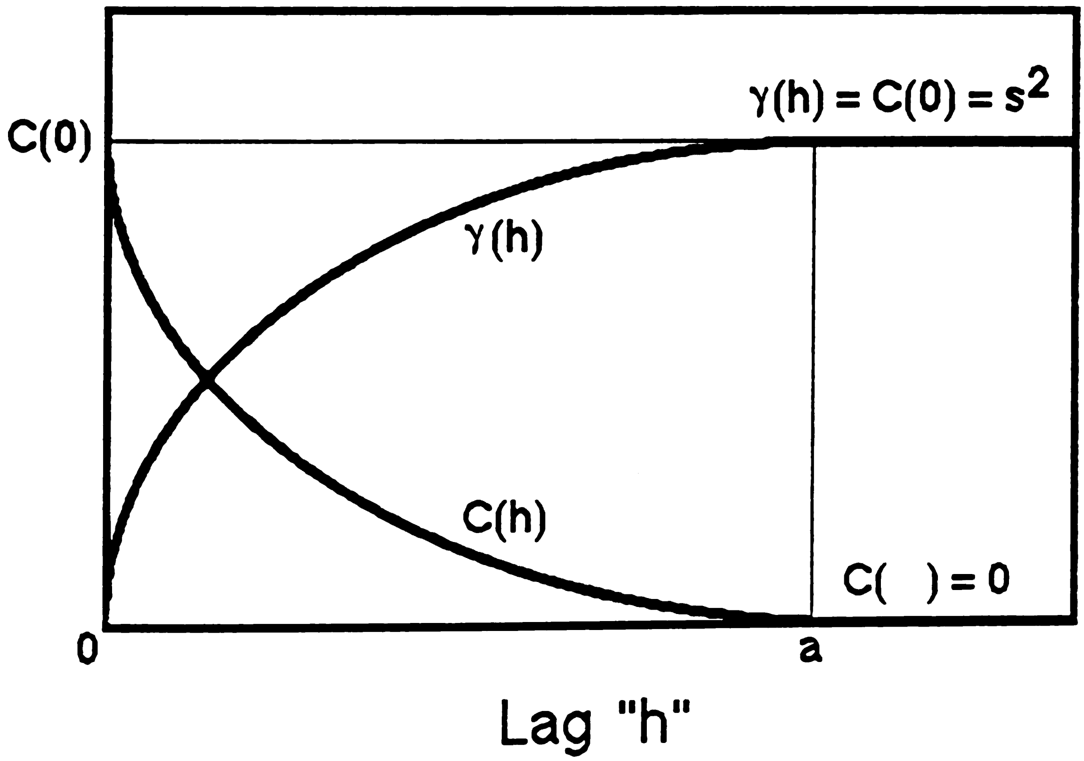

Figure 1. Relationship between covariance and semivariance.

where Nh is the number of sample observations (not pairs) separated by lag "h". This equation derives directly from the definition of the intrinsic hypothesis for the random function. The concept is quite analogous to the sum of squares for estimation variance (s2) in conventional statistics.

A schematic construction of an idealized semivariogram is depicted by Figures 2a and 2b. The sample points represent a portion of a square grid, and assume a general increase in property variance with increasing distance. The semivariogram has three basic components: the sill, range, and nugget variance. The sill is a region of relatively constant semivariance, and approximates the total sample variance (s2). It represents a lack of spatial dependence over the corresponding lag distances. Semivariograms which increase continuously do not define a sill or range; this indicates non-stationarity and the presence of trends, requiring some form of de-trending (Burgess and Webster, 1980c).

The range is defined by the lag value at which the curve reaches the sill; it is the geographic range over which the property exhibits spatial dependence. The nugget variance (or simply "nugget") is the y-intercept value of the semivariance. Theoretically, the semivariance should be zero at zero lag, but usually it is not. The nugget represents unexplained or "random" variance which cannot be characterized by the sampling scale or methodology

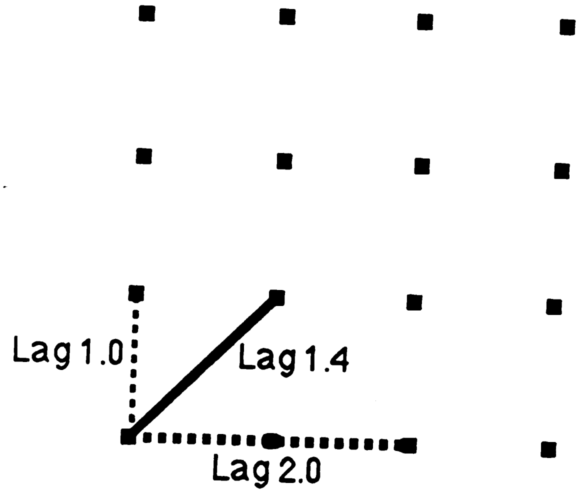

Figure 2a. Portion of hypothetical grid, illustrating semivariance computation for given lags.

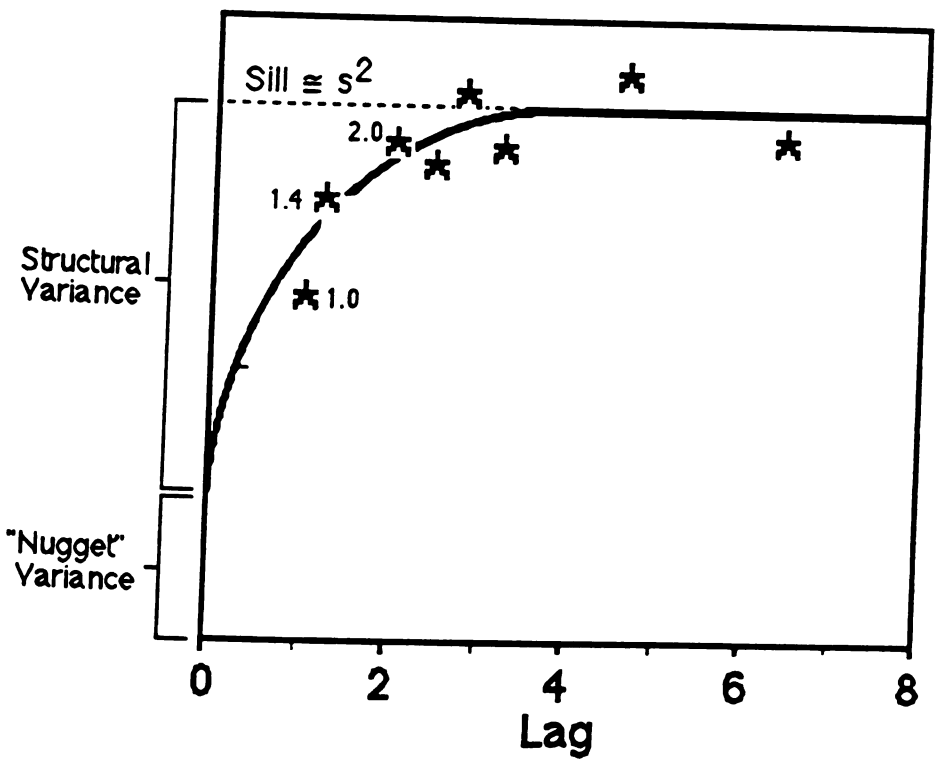

Figure 2b. Hypothetical semivariogram resulting from computations in Figure 2a. Labels indicate semivariogram features, numbers refer to lags.

(Trangmar, et al., 1985). The difference in value between the sill and the nugget variance is the "structural variance" due to both systematic and random variation with increasing lag (Wilding and Drees, 1983).

The lack of any recognizable pattern to the semivariogram indicates that there is either no spatial dependence for the measured property, or that the study methodology and sampling scheme were inappropriate for its characterization (Trangmar, et al., 1985). The observation scale and sampling interval are key considerations for detecting a given degree of spatial variation. The required precision of spatial characterization is a function of the investigation objectives. Determining an appropriate sampling scheme is often an iterative process of using preliminary transects to gauge variability, implementing a resulting sampling scheme, and sampling additional points where variance is large or where short-interval information is required (Burgess and Webster, 1980b). All of the considerations of nested soil variation, observation scale, etc., are essential to a well-designed study. These factors are tempered by practical constraints, such as the investigator's time and resources.

Semivariogram Models

Semivariogram construction requires fitting a mathematical model (i.e. a linear or non-linear function) to the plotted semivariance points. Soil variation is continuous at most observation scales, and semivariograms are likewise continuous functions (Webster, 1985). No general mathematical formula exists for fitting the variety of semivariogram patterns (Burgess and Webster, 1980a). Though models only approximate the true soil variation pattern, the model choice is critical. It is the model which ultimately generates statistics for kriging procedures, and model selection may be the largest source of ambiguity in kriging (Vieira et al., 1981).

Models are typically fitted to sample variograms by a least-squares approximation. Variogram points are weighted for fitting according to the number of sample pairs used in their calculation (Vieira et al., 1981; Trangmar, et al., 1985). The least-squares method is a reasonable compromise between model fit and the computational time required by more elaborate procedures (McBratney and Webster, 1986). Not just any model which appears to fit the semivariogram is valid (McBratney and Webster, 1986); models listed in Journel and Huijbregts (1978) are safe choices. Prediction equations include the linear, spherical, double spherical, and exponential models. The most commonly used models in soil science for stationary semivariograms are the exponential and spherical models (McBratney and Webster, 1986).

There is no definitive procedure for choosing an appropriate semivariogram model (Webster, 1985). Usually some combination of statistics, general semivariogram appearance, study objectives, and knowledge of soil variation is used for model selection (Vieira et al., 1981; Webster, 1985). The general statistical criteria which favor a particular model are a high r2 value, small nugget variance (relative to sill), and a large range. The statistical considerations are balanced against subjective factors such as model-fit within the range of spatial dependence, which is critical for kriging procedures.

One cautionary note involves the use of "linear-with-sill" models. The model fits some data sets well, and it is attractive due to its simplicity. However, McBratney and Webster (1986) indicate this model is theoretically sound only for one-dimensional semivariograms. It should not be used for two-dimensional semivariograms!

Kriging

Kriging (pronounced "KREEG-ing") is simply a set of techniques for interpolating values between known data points. Perhaps due to its relatively complex mathematics, some mystery surrounds the process. This is unfortunate because the basic concepts of kriging are simple to understand. All interpolation procedures use some method for weighting the surrounding data (sample) points, but most methods are empirical. In kriging, the weights are mathematically chosen to simultaneously provide a statistically unbiased estimate and a minimum local variance (Webster, 1985). Matheron (1971) performed the difficult theoretical derivations for kriging equations, and computers do the actual calculations. The only difference between kriging and other interpolation procedures is calculation of sample-point weights, but this has great implications for the quality of interpolation and its applications (Trangmar, et al., 1985).

Kriging is a weighted local averaging of the sample values in a neighborhood (Trangmar, et al., 1985; Webster, 1985). It provides a statistically unbiased estimate of the interpolated (or "kriged") value. This means that the expected value of the estimate equals the estimate itself, and the expected difference between the kriged point and its observed value is zero:

$$E[z'(xo)] = z(xo) \quad \text{and} \quad E[z'(xo)-z(xo)] = 0$$

where z'(xo) = kriged estimate, and z(xo) = observed value.

The result is that kriged values equal the original data values at sample locations, a condition frequently lacking with other procedures (Olea, 1975; Trangmar, et al., 1985). Kriging also provides an estimation variance for each predicted value. Hence the reliability is known for each interpolated value and statistical confidence limits can be set. Where spatial dependence is present, kriging provides an optimal, unbiased interpolated value of known variance. No other interpolation techniques can provide this.

All kriging techniques assume an underlying normal distribution and stationarity of sample data via the intrinsic hypothesis (Trangmar, et al., 1985). Kriging generally provides more reliable interpolation estimates because it considers local sample points and the variance only within that neighborhood. In contrast, classical statistics makes predictions based largely upon the total regional variance, which is usually larger than the local variance (Webster, 1985). The common endproduct of kriging, and other interpolation methods, is an isarithmic map of the observed property. An isarithm connects points of equal inferred (predicted) value for a property. The kriged map has the important advantage of known reliability, because estimation variances are provided for each interpolated value.

Punctual kriging interpolates point values which theoretically have a size, shape, and orientation identical to the sample. In many situations, estimations are desired over small areas surrounding the sample points. Block kriging is a procedure for making value and error estimates averaged over a defined area. Punctual and block kriging differ only by the computation of sample-point weights. The following discussion begins with punctual kriging concepts, which are later related to block kriging techniques.

Punctual Kriging Concepts

The calculation of sample-point weights is the principal computation for kriging procedures. The semivariogram model is the basis for determining the weights for each sample point, using the lag vector between the sample and kriged point. The semivariogram range defines the neighborhood radius within which sample values are considered; kriging is not useful beyond the range of spatial dependence (Webster, 1985).

Essentially, a distinct weight is calculated for each sample point based upon the semivariance between itself and the interpolated point. The sample-point weights must satisfy simultaneously the conditions that their sum equals one and the estimation variance be minimized (Burgess and Webster, 1980a). The actual weight calculations involve matrices, partial derivatives and Lagrangian multipliers and are beyond this review. Readers are referred to Journel and Huijbregts (1978) and Webster (1985) for further explanation. Once a unique weighting term is derived for a sample point, it is used to calculate both the interpolated value and its associated estimation variance.

The basic equation for interpolating points via kriging is simply the sum of each sample value multiplied by its corresponding weight, summed for the "n" sample points used:

$$z'(xo) = \Sigma Li \; z(xi)$$

where $z'(xo)$ = kriged estimate

$z(xi)$ = sample value

Li = weight applied to sample value $z(xi)$

n = number of sample points used for interpolation

Trangmar, et al., (1985) state, "The estimation variance is minimized by finding the unique combination of weights which minimize the sum of semivariances between the interpolated point and sample locations." The corresponding equation is:

$$\sigma 2 = \Sigma Li \tau(xi, xo) + \mu$$

where $\tau(xi,xo)$ = semivariance between sample and kriged point (from semivariogram model)

μ = Lagrangian multiplier associated with function minimization

Li = weight applied to semivariance $\tau(xi,xo)$

n = number of sample points used

In both equations, the sample value and its associated variance use the same weight for a given sample location (Burgess and Webster, 1980a).

Figure 3 shows actual weights calculated for a kriged point "P". The closest sample points are weighted heavily, which conforms to our intuitive notions for interpolation (Webster, 1985). Due to the large weights placed on the nearest points, semivariograms should ideally be well-estimated at the shortest lags within the neighborhood radius. In Figure 3 the kriged estimate for point "P" would be calculated by multiplying each sample value by its associated weight, and summing up the results for all sample locations. The estimation variance is similarly calculated, except the weight at each location is multiplied by the semivariance between the sample point and point "P", and the Lagrangian multiplier is added for minimization. In this figure, the weighting differs by both distance and direction, reflecting semivariance anisotropy.

The weights calculated for individual sample points depend upon several factors. Distance between the kriged point and sample point is often most determinant of weight. This is mediated by the sample-point geometry around the estimated value. Lone points tend to receive more weight than clustered points, and nearby points can "screen" more distant points lying in the same general direction. Thus the use of regular grids is efficient, and for irregularly-spaced sampling the addition of points in sparsely-sampled areas can greatly reduce local estimation variance (Webster, 1985). Estimation variances are always higher along the borders of sample areas, due to reduced number of neighboring data points (Trangmar, et al., 1985).

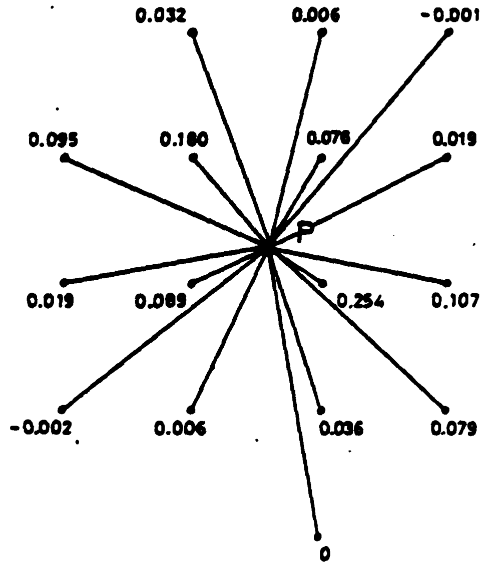

Figure 3. Example of sample-point weights generated by punctual kriging. Note the effects of distance, screening, and anisotopy on sample weights (from Webster, 1985).

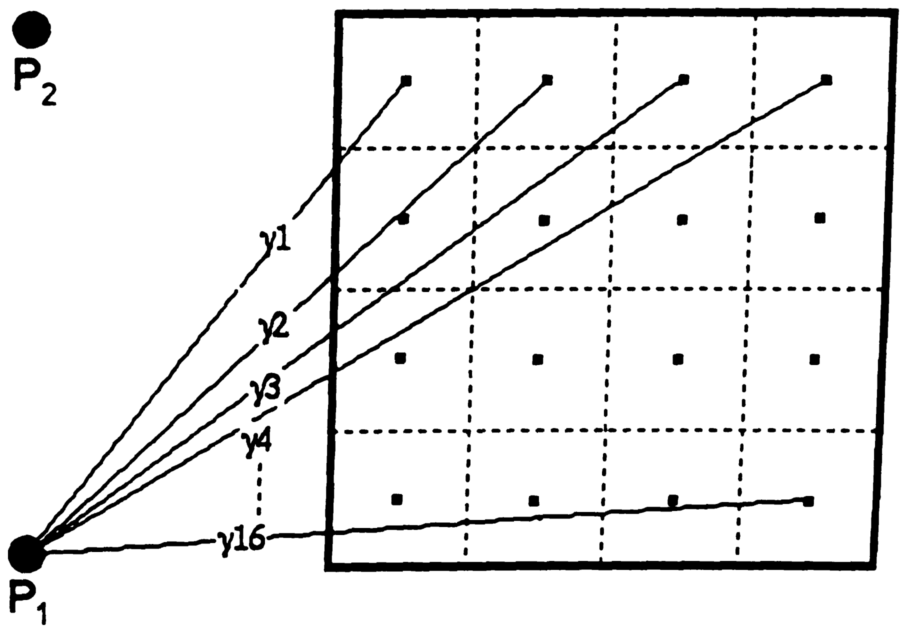

Figure 4. Illustration of sample-point weight calculation for block kriging. In this example, point P1 is weighted via an average of 16 point-to-block semivariances.

Block Kriging

Soil scientists are generally interested in average soil properties within localized areas. Even with punctually-kriged data, point estimates are usually considered to represent an area. Punctual kriging results in detailed maps, but generates isarithms having local discontinuities and rough patterns. These discontinuities can obscure longer-range trends which are more important to the study objective or soil uses (Trangmar, et al., 1985). Furthermore, isarithm discontinuities can shift if the map origin or orientation is shifted (Burgess and Webster, 1980b). Punctual kriging is therefore commonly used for locating additional sampling points which will significantly reduce large local variances. Block kriging, with its lower estimation variances and wider applicability, is generally preferred for characterization and mapping of soil properties.

Block kriging differs from punctual kriging only in the determination of the weights used for interpolation and estimation variance. The determination of weights for sample points is accomplished by calculating an average semivariance between a sample point and several points within the interpolated block (Fig. 4). The individual semivariances are calculated using the semivariogram and the lag between the sample point and the within-block point. As with punctual kriging, the combination of sample-point weights are chosen so the estimation variance is minimized (Trangmar, et al., 1985).

In block kriging, the variance estimate is partitioned into a within-block and between-block variance (Trangmar, et al., 1985). The additional variance term in block kriging is the within-block variance of classical statistics (Webster, 1985). Large nugget variances contribute excessively to the total estimation variance, and if partitioned out by blocking can greatly increase interpolation precision. The general concept for block kriging variance is:

Estimation variance = Total local variance - within-block variance

Since the estimation variance alone affects the interpolation precision of the block, interpolation variances are always smaller when a given data set is block kriged rather than punctually kriged (Burgess and Webster, 1980b).

For example, the kriging computer program BLOCK (Robertson, 1987) generates 16 points within each kriged block to calculate an average point-to-block semivariance. This average semivariance is then used to calculate the sample-point weight required for interpolation. In Figure 4, the sample-weight calculation for point "P1" is illustrated. Similar calculations would be performed for point "P2" and other neighbors, such that the sample weights sum to one. The within-block variance is also calculated from the 16 within-block points, again using the semivariogram model. The estimation variance for the block is the weight-averaged difference between the sum of all point-to-block variances and the within-block variance.

In practice, kriging is often performed using an isotropic variogram model, and hence the weights depend only upon their distance from the kriged point. If significant anisotropy exists, then an anisotropic semivariogram model should be used for determination of weights. This results in more accurate interpolation (Trangmar, et al., 1985). The number of sample points required to reasonably krige an estimate depends upon point geometry and the degree of anisotropy. Reported values range from seven (Vauclin et al., 1983) to 25 (Webster and Burgess, 1980a).

Geostatistical Applications to Leaching Studies

Geostatistical techniques can be applied to any soil property which may affect leaching. This application, however, is subject to the many sampling and methodological considerations referred to in Section IV (see also Wagenet, 1984). Recognition of spatial dependence relies largely upon the design of appropriate sampling schemes and experimental methodologies. Otherwise, spatial relationships may be obscured by experimental errors.

Soil-water properties and solute transport are particularly variable and difficult to characterize (Nielsen et al., 1973; Bouma, 1983; Wagenet, 1984). Many studies indicate large spatial variability in these properties, with short-ranges of spatial dependence. Kriging techniques have been used to estimate the efficiency of sampling schemes for water infiltration (Vieira et al., 1981), and to characterize variability of soil-water tension (Yeh et al., 1986). Co-kriging, which utilizes spatial correlation between a sampled property and a less-sampled covariate, has been used to estimate available water content based upon soil texture (Vauclin et al., 1983).

One study (Flaig et al., 1986) used semivariograms and kriging to directly estimate nitrate leaching under high-intensity irrigation. Nitrate movement was monitored using suction lysimeters arranged in two 35-meter transects, and one 10m by 10m grid. Sample spacing ranged from one meter to 0.25 meters. The results indicated spatial dependence of nitrate pulse velocity and total nitrate loss at lag distances of less than five meters. The nugget variance accounted for 50-70% of the total variance. Semivariogram generation and kriging estimates were constrained by low sample numbers, but some improvement was gained in areal leaching estimations.

As geostatistical applications to soil studies become more sophisticated, the potential increases for predicting leaching variability. The short-range spatial dependence of many soil-water properties may practically limit characterization of large areas, owing to large sample numbers. Co-kriging techniques may be useful where spatial variation of correlated properties is already known. For intensive land-uses (e.g. animal feedlots), a thorough spatial analysis may be feasible and reduce the impact of point-source contamination.

METHODS AND MATERIALS

Study Site Location

The study site is located at the W.K. Kellogg Biological Station (KBS), in the northeast corner of Kalamazoo County, Michigan (NE¼, NE¼, section 5, T.1 S., R.9 W; see Figure 5). The site is situated on a pitted outwash plain approximately one mile southwest of a recessional moraine. Elevation is 290 meters above sea level. The major soils at KBS are the Kalamazoo Loam (Fine-loamy, mixed, mesic, Typic Hapludalf) and Oshtemo Sandy Loam (Coarse-loamy, mixed, mesic, Typic Hapludalf). Small areas of Cohoctah (Coarse-loamy, mixed, mesic, Fluvaquentic Haplaquoll), Pella (Fine-silty, mixed, mesic, Typic Haplaquoll), Plainfield (mixed, mesic, Typic Udipsamment), and Spinks (Sandy, mixed, mesic Psammentic Hapludalf) soil series occur within the KBS boundaries (Whiteside, 1982).

The work reported here was done on a 6-hectare study site, located within a 60-hectare field (Figure 6). The eastern two-thirds of the field was cropped to continuous corn from 1984 to 1989. The western third was cropped to alfalfa from 1984 to May 1989, after which it was planted to no-till corn. The field has been under a center-pivot irrigation system since 1984, which is used to apply dairy lagoon waste, fertilizer, and irrigation water. In 1989 the dairy maintained 285 dairy cattle, 150 of which were adult

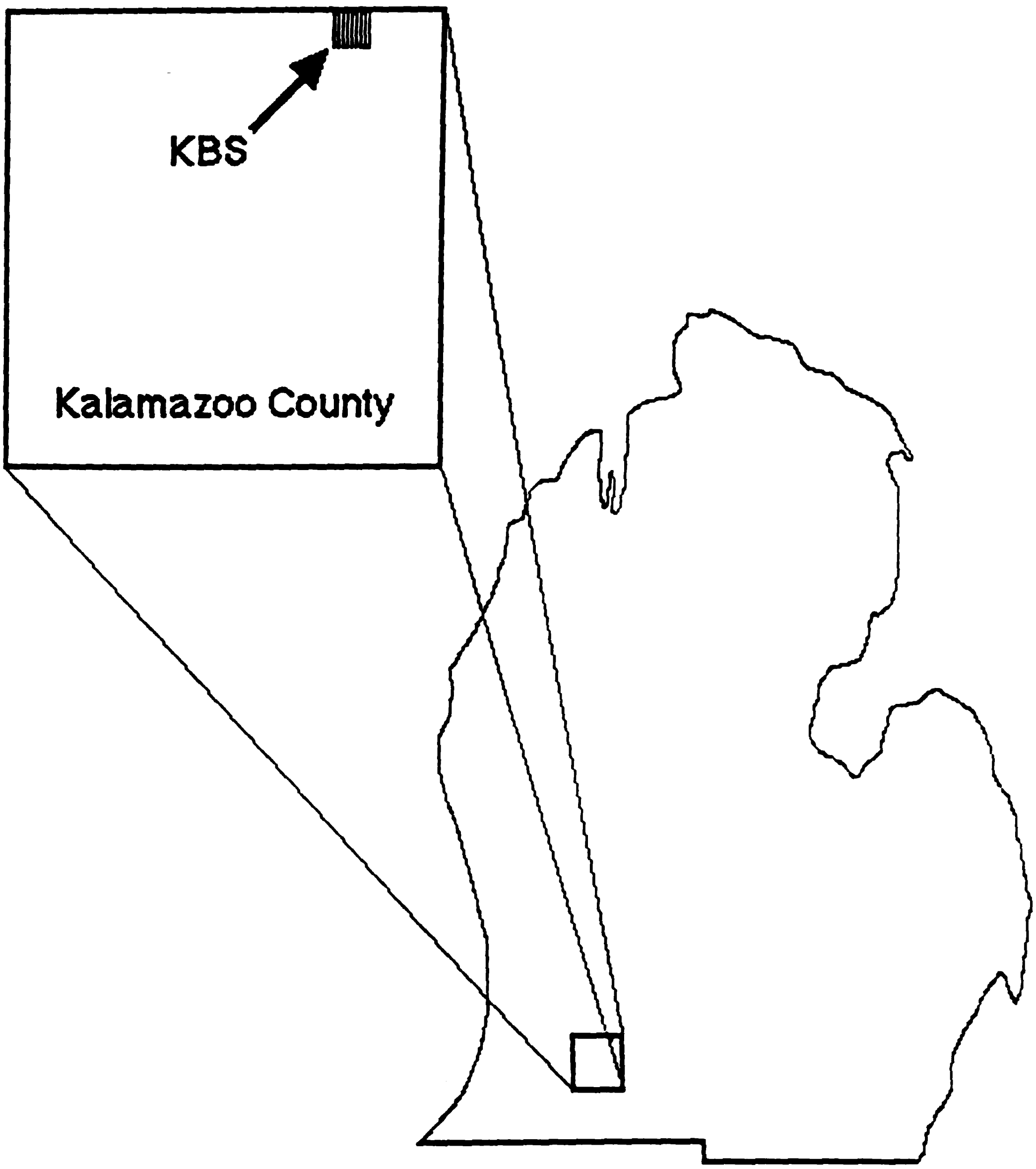

Figure 5. Location map of Kalamazoo County and Kellogg Biological Station (KBS).

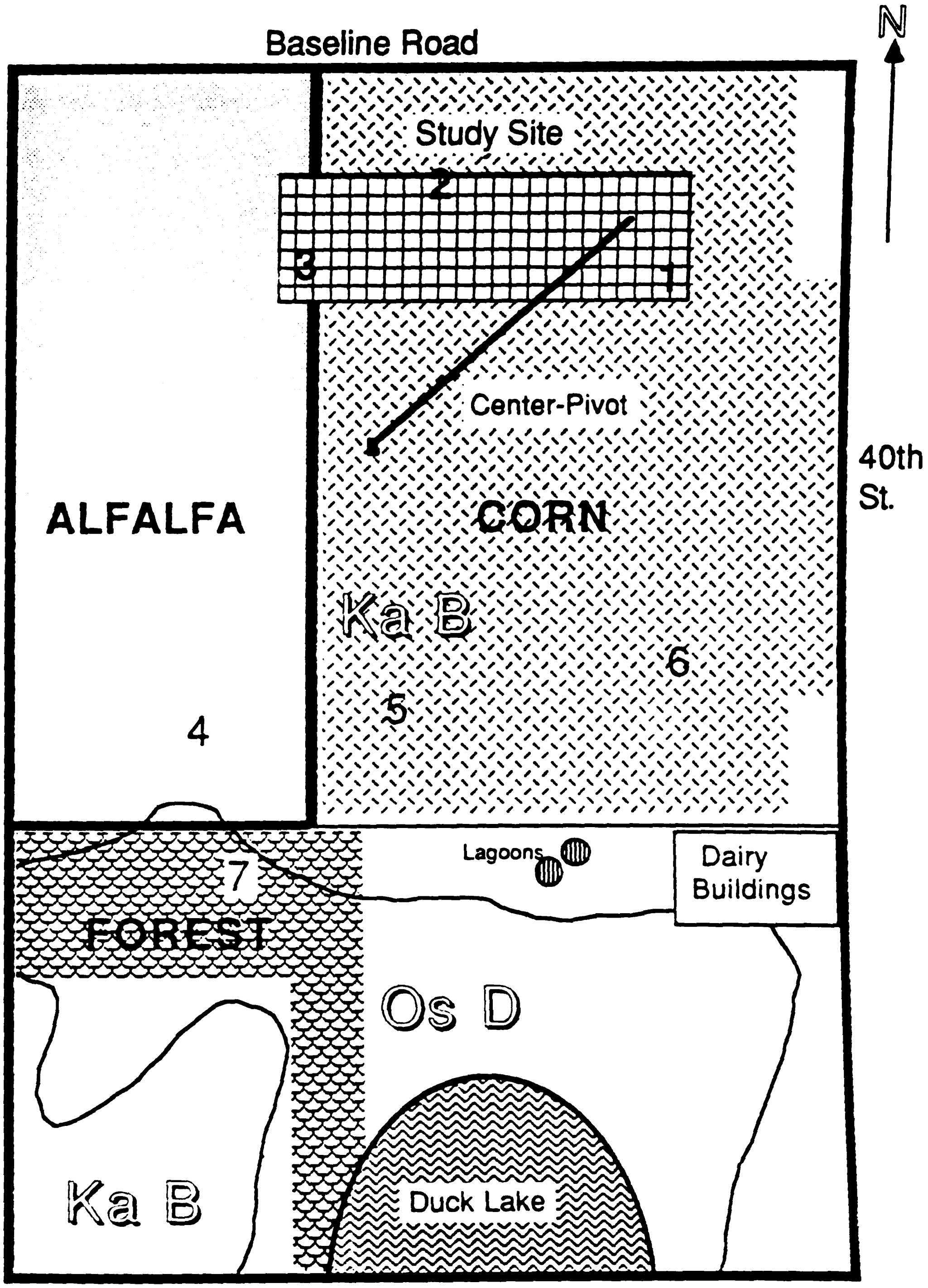

Figure 6. Schematic diagram of the study site within the KBS center-pivot field. Numbers refer to lysimeter clusters. Soil map unit boundaries from Austin (1979). Symbol KaB is Kalamazoo Loam, 0-2% slope; OsD is Oshtemo Sandy loam, 12-18% slope. Map scale

cows. Manure is washed into tanks and separated into liquid and solid fractions. The liquid fraction is temporarily stored in lagoons, while the solids are composted, re-used for bedding, and subsequently spread on fields.

Soil-water Nitrate Sampling

Suction lysimeters were installed in June 1987 to monitor soil-water nitrate levels underneath the center-pivot system. The lysimeter cups were installed immediately below the contact between the sandy-loam Bt horizon ("2Bt2") and the underlying banded sand/loamy-sand outwash material ("3C" horizon) (Figure 7). Depth of cup placement ranged from 0.8-1.6 meters. Horizon depths and thicknesses were recorded for each lysimeter installation. Seven clusters of four to six lysimeters were installed; four clusters in the corn, two in the alfalfa, and one in the adjacent hardwood forest (Figure 5). The lysimeters were arranged in a rough square shape approximately five meters to a side, and numbered as one (north), two (east), three (south) and four (west). Clusters one and two contained two additional shallow lysimeters (1.5 and 1.6; 2.2 and 2.5). The lysimeters were vacuum-pumped to a 0.7 bar tension and usually sampled on a weekly basis from June 1987 through June 1989. Samples were cooled to four degrees centigrade and analyzed at the earliest opportunity with a LACHAT flow-injection autoanalyzer (FIA) (cadmium-reduction method).

All colors are moist colors

Ap- 0 to 25 cm; dark grayish brown (10YR 3/2) loam; weak medium granular structure; friable; abrupt smooth boundary.

E- 25-30 cm; brown (7.5YR 5/4) loam; weak medium sub-angular blocky structure; friable; gradual wavy boundary.

Bt1- 30-70 cm; brown/dark brown (7.5YR 4/4) clay loam; moderate medium sub-angular blocky structure; firm; clear wavy boundary.

2Bt2- 70-120 cm; brown (7.5YR 5/4) sandy loam; weak medium sub-angular blocky structure; friable; gradual wavy boundary.

3C- 120-150 cm. brown (10YR 5/3) sand; single-grained; loose; dark brown (7.5YR 4/4) loamy sand to sandy loam bands; massive; very friable; bands 1-7cm thick and occur at 2-15 cm spacings. Lower boundary estimated at 200-300 cm depth.

300 - 500 cm. Interbedded calcareous sands and gravels.

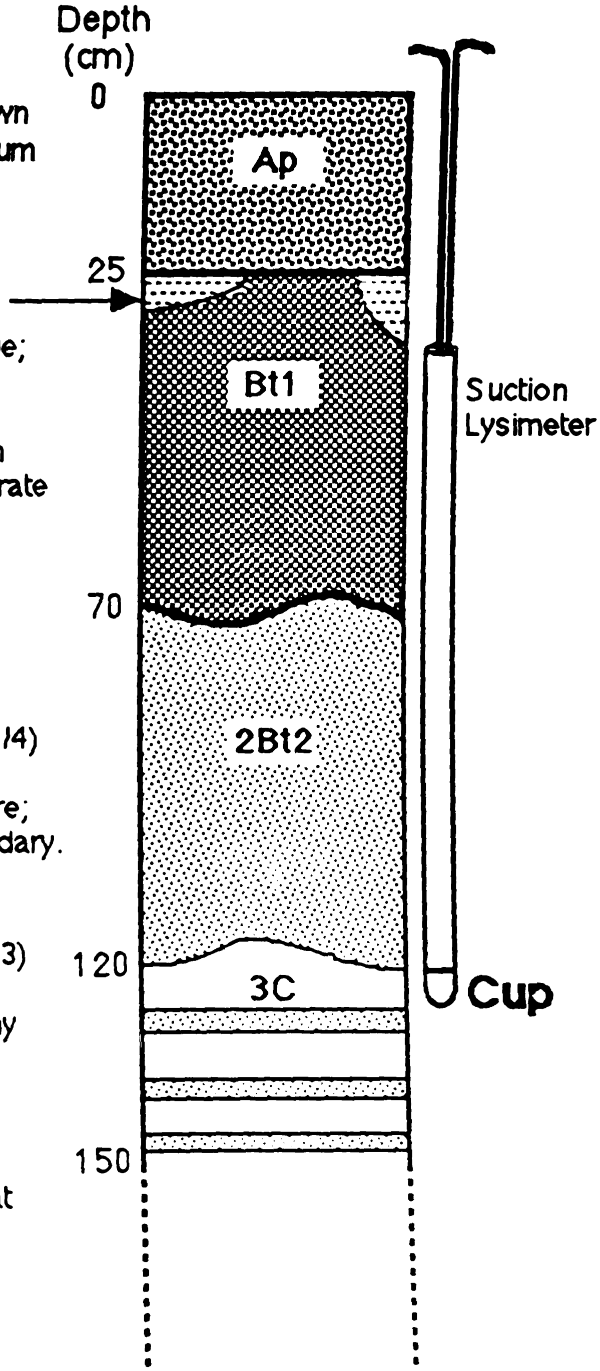

Figure 7. "Typical" Kalamazoo Loam pedon as observed at the study site. Lysimeter cups were placed at the 2Bt2-3C horizon boundary.

A deep soil core was taken at the center of each lysimeter cluster in December 1988. A 7.6cm-diameter bucket auger was used to take soil samples by horizon in the upper solum, and at 15-centimeter increments below the sandy-loam 2Bt2 lower boundary. Maximum core depth was dictated by the presence of gravel layers at 2.5-4.5 meters. Soil samples were cooled to four degrees centigrade, extracted with 1N KCl, and analyzed on the LACHAT.

An attempt was made to quantify the spatial variability of nitrogen applications via the center-pivot irrigation system. Collection bottles were placed on the same grid points used for soil profile sampling (222 bottles) on June 29, 1988, and liquid manure was applied. Due to a mechanical problem, only the southeast corner of the study site was irrigated, providing 40 samples. Insufficient points were available for geostatistical analysis, but limited data were provided on the variability of the liquid manure nitrogen contents during a field application. The effort was not repeated due to a lack of lagoon waste and time.

Soil Variability Sampling and Analysis

Sample points were located along a rectangular grid at 20-meter intervals. The interval was chosen based upon a soil variability study performed one mile from the current study site (J.R. Crum, 1989, unpublished data). The grid was situated to take advantage of three existing lysimeter clusters (two in corn, one in alfalfa). At each cluster, two right-angle transects were sampled for short-range soil variation, using intervals of 0.5, 1, 2, 4, 8, and 16 meters. The entire grid measured 440 by 140 meters, with the long axis oriented east-west. The grid enclosed an area of 6 hectares (15 acres) and contained 222 sample points (see Figure 5). The grid dimensions were ultimately chosen because they encompassed the three lysimeter clusters, did not exceed the resources of the study, and provided ample points for geostatistical analysis. Ultimately, 219 out of the possible 222 pedons were sampled; the three unsampled points were too close to existing lysimeters.

Grid points were located and flagged using a WILD Distomat and Theodolite (Total Station). Points were located to within a five-centimeter error, and elevations were recorded for topographic map production. The raw survey data were converted to coordinate data using the WILDSOFT computer program (Wild Heerbrug Instruments, Inc., 1987).

Soil sampling at each point was accomplished using a Giddings hydraulic probe mounted on a pickup truck. A 6.3cm-diameter sampling tube was used to take soil cores to a minimum depth of 1.5 meters. Horizon depths and thicknesses were measured and recorded in inches. Horizon descriptions were made and samples taken for all designated horizons greater than three inches (7.6 cm) thick. The main criterion for splitting sub-surface horizons was soil texture; other morphological criteria (e.g. color) were used for splitting only if judged relevant to water movement/leaching conditions. The goal was to minimize horizon numbers for each pedon, thus aiding statistical analysis and modelling, without compromising on relevant morphological characteristics. Roughly 300 grams of soil were taken for each horizon.

The soil samples were air-dried, crushed, and passed through a two-millimeter sieve. Percent coarse fragments were recorded for gross characterization. Particle-size analyses were performed on the fine-loamy and coarse-loamy Bt horizons using a modified hydrometer method (Grigal, 1973). Dispersed soil samples were first washed through a 53-micron (#270) sieve and the sands oven dried. Sands were sieved into the five USDA sand fractions and the weights for each class recorded. Silt was determined by difference.

Geostatistical Procedures

Semivariograms were calculated for argillic horizon thickness and clay content using the SEMIVAR program (Robertson, 1987). The semivariograms were first generated using the maximum available lag distance of 462 meters. The lag distance at which a clear sill became apparent was the maximum lag distance used for subsequent variogram generation and model fitting. Step sizes were chosen by observing the frequency distribution of couples and the visual smoothness of the curve. The selected semivariograms were run through SAS (SAS, 1988) and fitted with linear, spherical, exponential and gaussian models. Models were chosen based upon a combination of highest r-squared values, lowest nugget variances, and logical agreement with field observations of soil properties. The Akaike Information Criterion (AIC) was also used for model selection. The AIC ranks each model based upon model fit versus the number of model parameters (Webster and McBratney, 1989).

Each property was block-kriged with the statistics generated from the chosen semivariogram model by using the BLOCK computer program (Robertson, 1987). A width of four meters was chosen for the block size, which defined 3850 blocks within the study area. A maximum search radius of 462 meters was used, and the 32 nearest data points ("neighbors") were used for kriging.

Control-section[2] clay content was calculated for each block using the kriged values for Bt1 clay content, Bt1 thickness, and 2Bt2 thickness. The semivariogram for 2Bt2 clay content indicated virtually no spatial dependence, so the horizon sample-mean clay percentage was used in all calculations. The generated control-section data was gridded in SURFER (Golden Software, 1987) using the minimum-curvature grid method. The gridded estimates were used to produce an isarithmic map of control-section clay content,

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2 For the Typic Hapludalfs of this study, the control section for particle-size class is the upper 50cm of the argillic horizon(s), or the entire argillic horizon(s) if less than 50cm thick.

using 1% control-section classes (e.g. 14% clay, 15% clay, etc.) The isarithmic map, morphological data, and series definitions were used to map the soil series within the site. The land area occupied by each control-section class was also estimated by a SURFER area-of-surface routine.

Computer Modelling of Nitrate Leaching

The effects of soil variability on nitrate leaching were modelled using the CERES Maize computer program (Ritchie, et al., 1989; version 2.10). To model these effects, argillic-horizon variations were considered as treatment variables, while management inputs were held constant. The standard soil input file, SPROFILE.MZ2, contained 22 soil types. Each "soil" in the file represented a typical pedon for each 1% class of argillic-horizon clay content.

To generate the necessary silt and sand data for the kriged blocks, the silt sample data were block-kriged into 4m x 4m blocks using SURFER, which assumed a linear semivariogram. The silt data were used because the semivariogram displayed more predictable spatial variation than the sand data. The clay and silt percentages were summed for each block, and the sand percentage was determined by difference.

An "average" pedon was then constructed to represent each 1% class of control-section clay content. To do this, all blocks within a given 1% class were used to calculate a mean texture and thickness for the Bt1 and 2Bt2 horizons. For all 22 pedons, constant values for Ap and 3C texture and thickness were used. Mean thicknesses for the Ap and 3C horizons were calculated from morphological data, and horizon texture was estimated by hand-texturing. The result was 22 distinct pedons with the same Ap and 3C horizons, but with varying argillic-horizon textures and thicknesses.

The pedon data were input into the SOILW program, which estimated soil hydraulic properties for the CERES model from the morphological data (Ritchie and Crum, 1989). SOILW required data for horizon bulk densities and organic-matter content, and these were approximated using data from a nearby study site (D. Reinert and J.R. Crum, personal communication, 1989). The output from SOILW for each pedon was incorporated into the SPROFILE.MZ2 file, which was then in the proper format for running the CERES model. The pedons were all limited to a one-meter depth to allow leaching comparisons with the suction-lysimeter data.

All management factors were input according to available KBS farm records (Harold Webster, 1989, personal communication). Since no precise irrigation records exist, an available-water threshold of 55% was used for model irrigation scheduling. Where dairy lagoon waste was used as fertilizer, the model input choice was ammonium nitrate. This decision was based on a preliminary study which indicated rapid mineralization rates for the dairy waste at

25 degrees centigrade (B.G. Ellis and J.R. Crum, personal communication, 1989). The corn variety used in the model was Pioneer 3780, which had similar genetic characteristics to the variety planted at the study site (Great Lakes 582).

The model source code was modified to run on a planting-date to planting-date basis. This was done so that 1) the simulation would run beyond the harvest date, and 2) the modelled nitrogen leaching could be related to a complete cropping cycle. The weather file contained actual KBS weather data for the period January 1, 1987-November 30, 1989. The weather data were collected at the block-lysimeter weather station at KBS, supplemented when necessary with data from the KBS pond and/or Gull Lake weather stations. To complete the modelling of the 1989-90 year, data from December 1987-April 1988 were used. These data were chosen because they were close to the historical precipitation means for each month.

The model was run to provide leaching estimates for each control-section class, under both irrigated and rainfed conditions. The nitrogen-balance output file (OUT4) was modified to provide incremental and cumulative nitrate leaching for the April-to-April year. Output files were also generated for water balance, plant phenological development, and grain yield.

Figure 8 summarizes the methodology for creating the soil-profile input data which were used in the CERES Maize modelling.

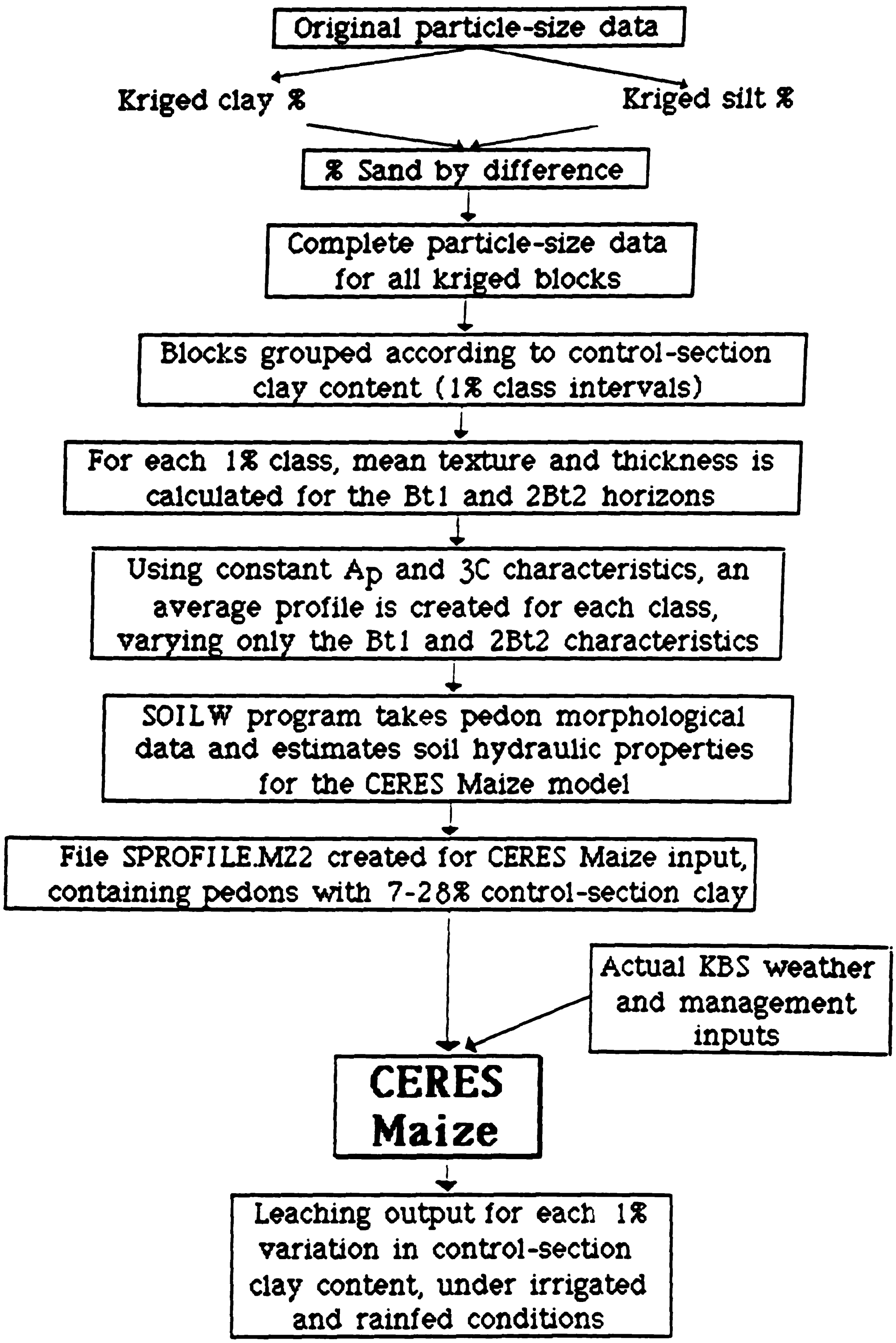

Figure 8. Flow diagram for CERES Maize modelling of Bt-horizon spatial variability.

RESULTS AND DISCUSSION

I. SOIL VARIABILITY

The basic soil morphology data is presented in Appendix I, which contains horizon thickness, control-section clay, soil-series classification, and grid coordinate data. The six horizon designations were sufficient to accurately describe all pedons in the field for the purposes of the study. In general, the sequence of horizons and their gross morphology (e.g. texture, structure, color) were remarkably similar across the field. This is reflected in the series classification of the 219 pedons: 148 (68%) classified as Kalamazoo, and 65 pedons (30%) as Oshtemo. The remaining six pedons were comprised of three Spinks (1%) and three Miami taxadjunct (1%) pedons. The major differences between pedons were related to the presence or absence of a fine-loamy Bt horizon over the underlying coarse-loamy and/or sandy materials. Where the fine-loamy Bt horizon was thicker and finer-textured, Kalamazoo or Miami pedons were found. Where the fine-loamy Bt was thinner, coarser-textured, or absent, the pedons classified as Oshtemo or Spinks.

All pedons were categorized as well-drained to moderately well-drained. The only indications of reducing conditions within the profiles were high-chroma mottles found in the lower Bt horizons of Miami profiles (2 pedons), and mottles or gleying found in fine-loamy inclusions of 12 other pedons. No significant mottling was observed above any of the fine-loamy inclusions.

Statistics for horizon-thickness data are presented in Tables 1 and 2. Conventional statistics were applied to Ap, Bt1, and 2Bt2 thicknesses and Bt1 and 2Bt2 clay contents, as these frequency distributions all approximated a normal distribution (Charles Cress, personal communication, 1989). The thickness data for E horizons and fine-loamy inclusions followed non-normal distributions, which were not amenable to simple transformations. Therefore, median, mode, and range were used to describe these distributions.

Table 1. Horizon-Thickness Statistics

	Mean (cm)	Std Dev (cm)	CV (%)	Max (cm)	Min (cm)
Ap Thickness	23.0	4.1	17.8	38	15
Bt1 Thickness	34.1	18.3	53.7	89	0
2Bt2 Thickness	43.1	28.1	65.9	142	0
Depth to 3C or inclusion	105.6	29.7	28.1	216	46

Table 2. Thickness Statistics for E Horizon and Inclusions

	Median (cm)	Mode (cm)	Max (cm)	Min (cm)
E Horizon	13	10	51	7
Fine-loamy Inclusions	50	40	134	15

Statistics for the Bt-horizon characteristics are presented in Table 3. The coefficients of variation (CV) indicate that Bt-horizon thicknesses were much more variable than clay contents for the sample population. The low CV for Bt1 clay content is noteworthy because the Bt1 clay content strongly influences the control-section clay content. Plots of Bt1 clay contents and thicknesses versus 2Bt2 characteristics revealed no relationships. Likewise, there was no relationship between Bt1 clay content versus Bt1 thickness, or 2Bt2 clay content versus 2Bt2 thickness. The matrix shown in table 4 demonstrates the absence of linear correlation for these properties.

Notes on Soil Horizons

The A horizons varied in texture from loam to sandy loam, with field-textured clay contents estimated between 10 and 18 percent. Estimates of sand content varied between 40 and 70 percent. Color was most commonly a 10YR 3/2 (moist) and 10YR 5/2 (dry). The major variation in the A horizon was thickness, which was a function of whether the sample point was located in a tillage row or between the row. The lower horizon boundary was abrupt and smooth.

An E horizon greater than or equal to seven centimeters was described in 87 of the 219 pedons (40%). In pedons with fine-loamy Bt1 horizons, the E horizon was loam textured, usually less than 15 centimeters thick, and had a color of

Table 3. Bt-horizon statistics.

	Mean (cm)	Std Dev (cm)	CV (%)	Max (cm)	Min (cm)
Bt1 Thickness (cm)	34.1	18.3	53.7	89	0
2Bt2 Thickness (cm)	43.1	28.1	65.9	142	0
Bt1 Clay (%)	25.6	4.5	17.6	37	11
2Bt2 Clay (%)	10.0	3.0	30.0	23	5
Control-section Clay (%)	20.4	6.0	29.7	35	5

Table 4. Simple correlation matrix for Bt properties

	Bt1 Clay	2Bt2 Clay	Bt1 Thick	2Bt2 Thick
Bt1 Clay	1			
2Bt2 Clay	0.07	1		
Bt1 Thick	0.19	0.06	1	
2Bt2 Thick	0.18	0.13	0.14	1

All values are "r" (simple correlation)

7.5YR 5/4 to 10YR 5/3. In many pedons, tongues of E horizon material penetrated into the Bt horizon. Where the E horizon occurred above coarse-loamy or sandy Bt horizons, the texture was sandy loam to sand, thicknesses were generally greater (15-51cm), and typical soil color was 10YR 5/2 or 5/3. The E-horizon lower boundary was gradual and wavy to the underlying Bt horizon.

The major difference between pedons, and their subsequent classification, was the presence, texture, and thickness of a fine-loamy textured Bt1 horizon. This Bt horizon displayed a characteristic moderate, medium sub-angular blocky structure and firm moist consistence. Clay skins were well-developed on ped faces, root channels, and coarse fragments. Color was quite constant across the field, usually a 7.5YR 4/4, with clay skins often a value darker. Mean coarse-fragment content was 4.5% by weight, and in many pedons the coarse fragments appeared to be concentrated near the lower horizon boundary. The lower boundary was clear and wavy to the next horizon.

The Bt horizon in the underlying material was most often designated 2Bt2, where it occurred below a fine-loamy Bt1. If no fine-loamy Bt1 was present, it was designated as a Bt1 horizon in the pedon description, but considered with the "2Bt2" horizons for statistical purposes. The texture was consistently sandy loam, and soil color ranged from 7.5YR 4/4 to 7.5YR 5/6. Structure was characterized as weak medium sub-angular blocky structure. Clay bridging was observed between sand grains, and occasional clay patches were noted. Mean coarse-fragment content was 10.9% by weight. The lower boundary to the 3C horizon was gradual and wavy. Where a fine-loamy inclusion was present, the lower boundary was clear and wavy.

A fine-loamy "inclusion" of till-like material occurred in 27 out of the 219 pedons, most often "within" the 2Bt2 or 3C horizons (labelled "BC" in Appendix I). The field texture was loam or clay loam and the structure was massive. The only pedogenic development appeared to be leaching of carbonates and development of color. Occasional clay patches were observed in the upper portion of some inclusions. High- and/or low- chroma mottles were observed in nine inclusions, while three exhibited dominantly gleyed colors. An increase in apparent soil moisture was often observed at the lower boundary, sometimes approaching saturation. Based upon mottled/gleyed soil colors and soil-moisture observations, saturated conditions could exist for denitrification. However, organic carbon at that depth is likely a limiting factor for denitrifiaction. A spatial analysis revealed no observable pattern to their distribution within the study site. The lower boundary was usually clear and wavy to the 3C horizon. In eight of the 219 pedons, the inclusion extended to the deepest sampling depth. In four of these pedons, it occurred too deeply to affect the classification. Two of the inclusions occurred beneath a 3C horizon.

The 3C horizon was the lowermost horizon described in all but ten pedons (eight pedons ended in a fine-loamy inclusion and two in 2Bt2). The 3C was easily recognized in the field by two distinct features, lamellae and an overall change in sand-size distribution. The lamellae were approximately one to seven centimeters thick, and occurred at 2-15 centimeter spacings. The coarser-textured bands were sand to loamy sand, 10YR 5/3 color, and the finer-textured lamellae were loamy sand to sandy loam, 7.5YR 4/4 in color. The contact between bands was most often abrupt, but the apparent eluviation/illuviation of clay sometimes produced clear sub-horizon boundaries. The sand fraction of the 3C contained a noticeably higher proportion of fine and very fine sand than the "2Bt2" horizon, but was still within a "medium" USDA sand textural class. This sand-fraction change was uniform across the site, and with the lamellae was considered diagnostic for the horizon designation.

Two major associated observations were made regarding the 3C horizon. Whether the 3C was overlain by fine-loamy or coarse-loamy material, increases in soil moisture were occasionally observed just above the 3C upper horizon boundary. This apparent hydraulic discontinuity justified the placement of the lysimeter cups, where regular soil water samples could be drawn reliably below the root zone of corn. Secondly, although the 2Bt2/3C boundary was only one meter deep on average, no corn roots were ever observed in a 3C horizon on the site. Minirhizotron images from another field at KBS reveal little root biomass in these banded sands (A.J.M. Smucker, J.T. Ritchie, personal communication, 1989). The complete lack of roots also justified the assumption that nitrates reaching the 3C layer are essentially unavailable for uptake by annual crops, and are likely to be leached.

Although the 219 pedons were sampled to a minimum depth of 1.5 meters, not one of these soil cores extended into unaltered outwash material. In December 1988, deep cores were taken for soil nitrogen analyses at the center of each lysimeter cluster. The cores were sampled with a bucket auger and depth of sampling was limited by layers of impassable gravel. Table 5 lists the main features encountered in the sub-sola. Cluster three, in the alfalfa field, displayed a much shallower solum and depth to gravel than clusters one and two.

Table 5. Selected Sub-sola Characteristics (depth in meters)

Lysimeter Cluster	Lower Boundary of 3C horizon	Depth to Carbonates	Depth to Impassable Gravel
	----------	meters	----------
1	3.0	3.0	5.0
2	2.9	3.5	5.2
3	1.9	2.0	2.9

Pedon Classification

The data presented in Appendices I and II support the field observation that the study site displayed the range of an Kalamazoo-Oshtemo series continuum. Figure 9 shows the frequency distribution of pedons as a function of control-section clay content. The criterion separating the two series is the 18% control-section clay content, which separates the coarse-loamy and fine-loamy particle-size classes. This 18% break is difficult to define in the field, especially where two Bt horizons define the control section. Based upon the pedon data, 25 percent of the study site was occupied by coarse-loamy soils and 75 percent by fine-loamy soils (Figure 9). Pedons which contained only sandy loam Bt horizons represented the Oshtemo endmember, and pedons with fine-loamy Bt horizons greater than 50 centimeters thick represented the Kalamazoo endmember.

The pedons classified as Spinks were distinguished by their sandy profiles and the presence of the 3C lamellae as a discontinuous argillic horizon. The lamellae did meet the Psammentic Hapludalf requirements of summing to six inches (15 cm), and the Spinks series criteria of occurring at less than 36 inches (91 cm) deep. Although the illuvial formation of the finer-textured lamellae is debatable, the soil is morphologically and interpretatively a Spinks. The two pedons classified as Miami taxadjuncts were fine-loamy throughout and were moderately well-drained. The pedons do not meet all the Miami series requirements, but the taxadjunct classification is interpretatively accurate.

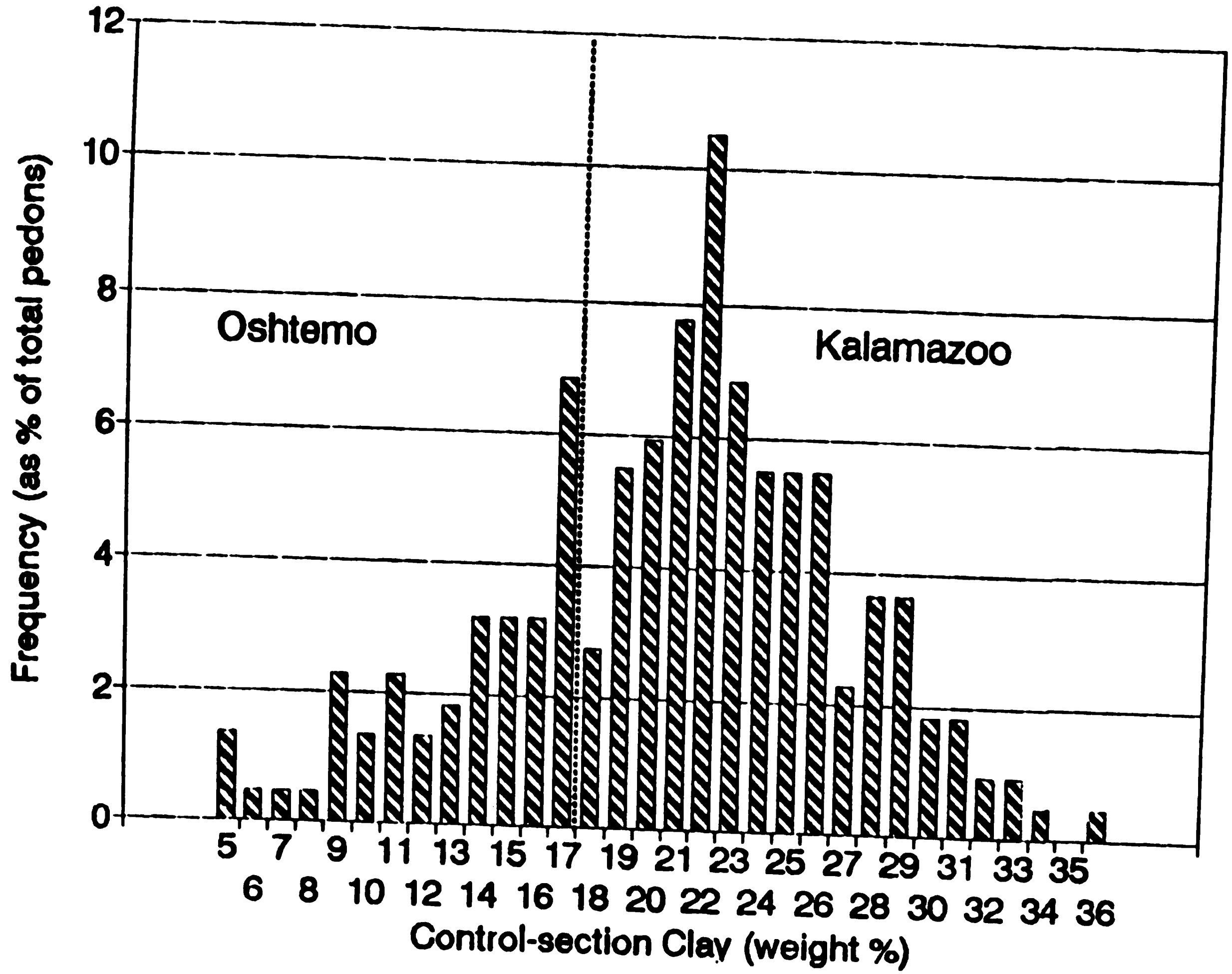

Figure 9. Pedon frequency distribution as percent of total pedons.

Semivariance Statistics

The argillic-horizon thickness and clay content data (Appendix II) provided ample couples for semivariance analysis. Semivariograms were originally generated using the maximum lag of 462 meters, and step sizes (lag class intervals) between 5 and 10 meters. After viewing the resulting couple distributions and the visual smoothness of the semivariogram output, a step size of 8 meters and a maximum lag of 90 meters was chosen for all final semivariograms. Table 6 shows the couple distribution for Bt1 and 2Bt2 thickness using these inputs. The semivariance calculations for clay content had fewer couples (approximately 4800), due to "missing" clay values when horizon thicknesses were zero.

The rectangular shape of the sampling grid did not allow enough couples for anisotropic semivariogram analysis. Isarithmic maps of the raw data did reveal some potential anisotropy, but it occurred over distances much greater than the isotropic semivariogram ranges. Therefore, isotropic models were fitted to the semivariograms, and were considered sufficient for kriging at less than 50-meter ranges.

The choice of a semivariogram model was relatively straightforward. For Bt1 clay content and thickness, and 2Bt2 thickness, the r^2 values were comparable for exponential, spherical, and gaussian models. However, the exponential model consistently provided a much lower nugget variance, which increased the precision of kriging interpolations. The exponential model also produced the lowest index for the Aikake Information Criterion (AIC), which essentially indicates it was the most parsimonious model tested (i.e. used a minimum of terms to fit a curve well).

Figures 10-13 display the semivariograms for each Bt property. The semivariograms all display linear or convex-upward shapes, indicating that drift was not serious and the intrinsic hypothesis was valid (Webster, 1985). Semivariograms for Bt1 clay content, Bt1 thickness, and 2Bt2 thickness all display a high degree of spatial dependence. The semivariogram for 2Bt2 clay content indicates virtually no spatial dependence at this scale of observation. As indicated by the low nugget variances for the three spatially-dependent properties, methodological errors are not a major factor in these semivariogram analyses.

Table 7 lists the principal semivariance statistics for the Bt properties. For the three Bt properties exhibiting spatial dependence, over 80% of the total variation was correlated with distance (i.e. "explained"); the nugget variance accounted for the "unexplained" variation. The sill values for the three properties closely approximated the sample variance of the conventional statistics. The reported range values in table 7 were calculated as 95 percent of the sill value (Journel and Huijbregts, 1978). The range values were sufficiently large to insure effective block kriging within the 20-meter-square grid cells.

Table 6. Semivariance couples, Bt1 and 2Bt2 thickness

Lag (m)	Number of Couples
1.6	75
7.4	102
16	116
21	436
29	439
40	427
45	694
56	405
62	919
72	619
81	852
88	724
Total	5808

Table 7: Semivariogram Statistics*

Property	r^2	Nugget Variance	Sill	% Variance "Explained"	Range (m)
Bt1 Clay (%)	0.82	3.7	19.0	80.5	22.9
2Bt2 Clay (%)	0.04	-	-	-	-
Bt1 Thick (cm)	0.73	0.0	315.9	100.0	11.7
2Bt2 Thick (cm)	0.90	125.6	837.2	85.0	27.5

* Exponential model used to fit all semivariograms.

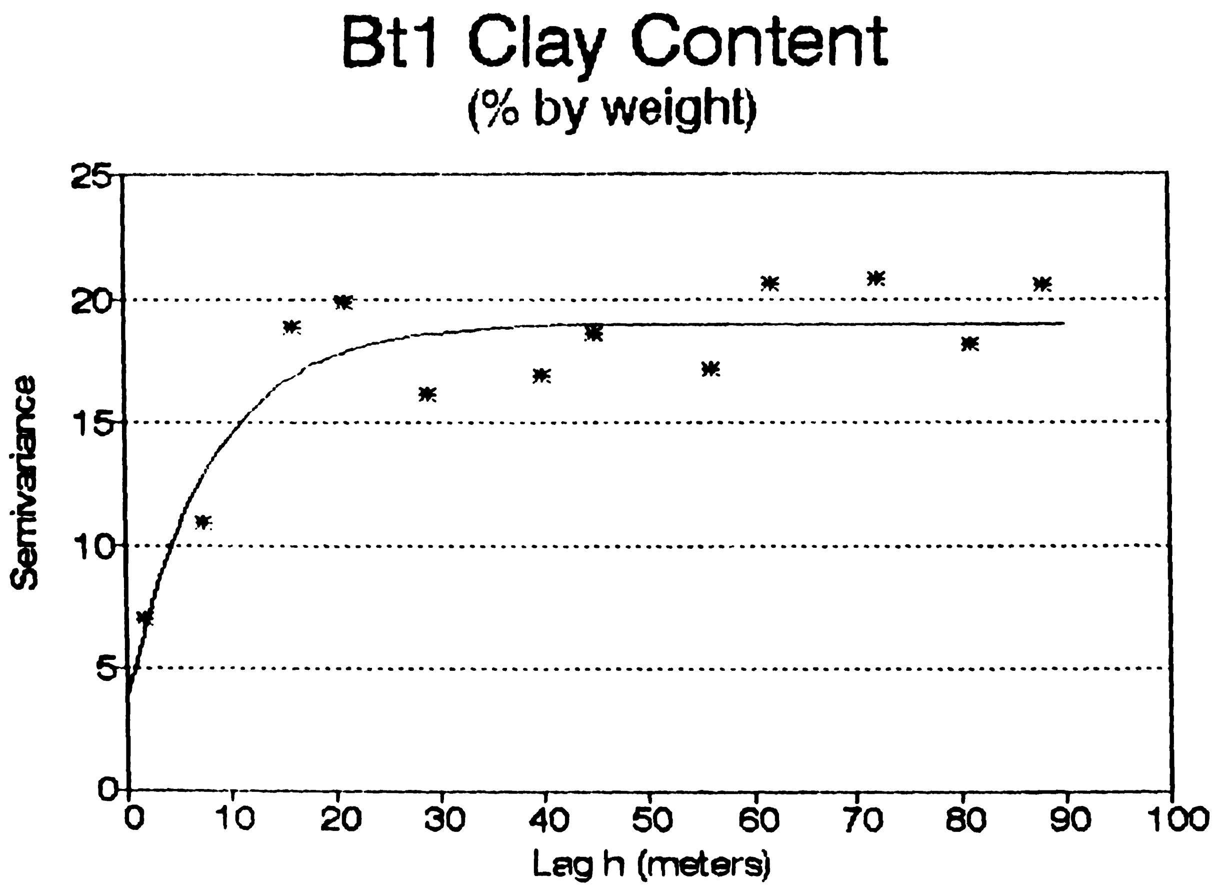

Figure 10. Semivariogram for Bt1 clay content.

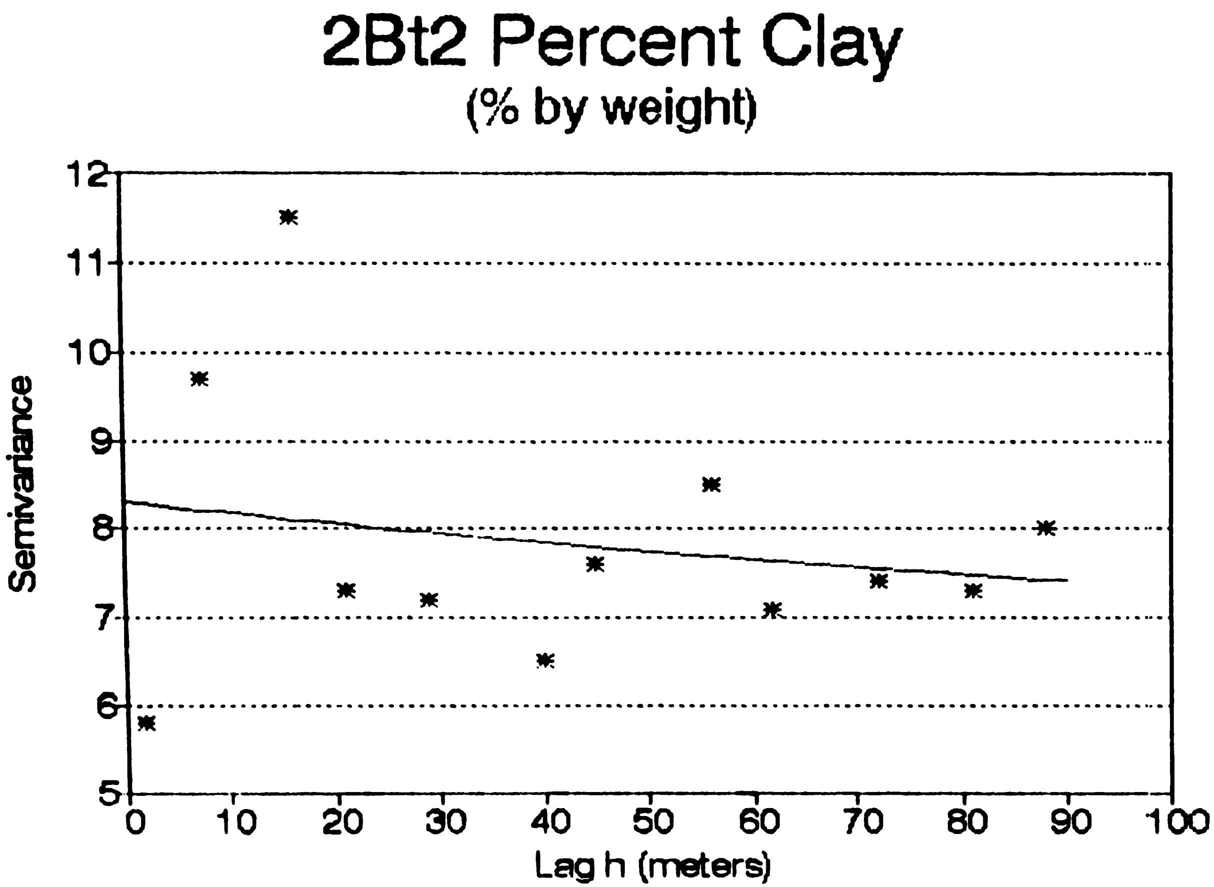

Figure 11. Semivariogram for 2Bt2 clay content.

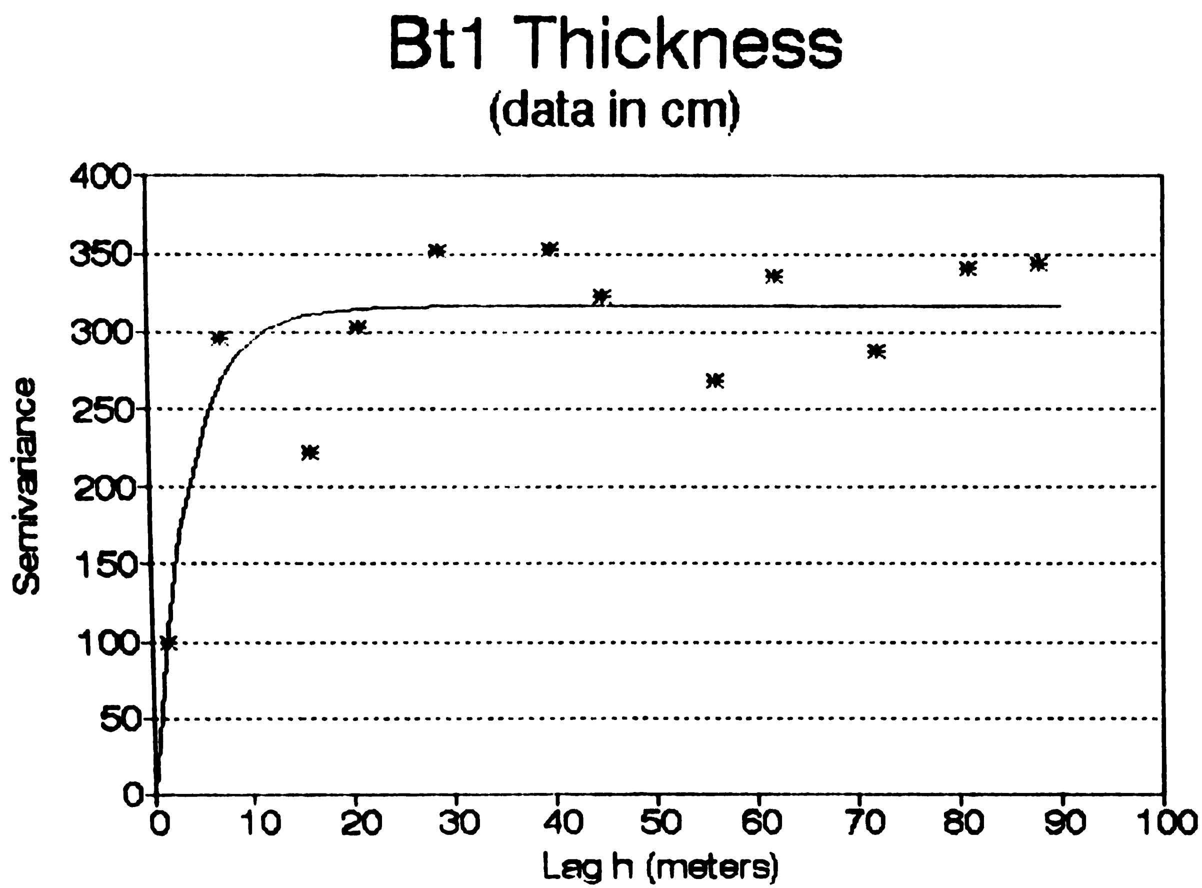

Figure 12. Semivariogram for Bt1 thickness.

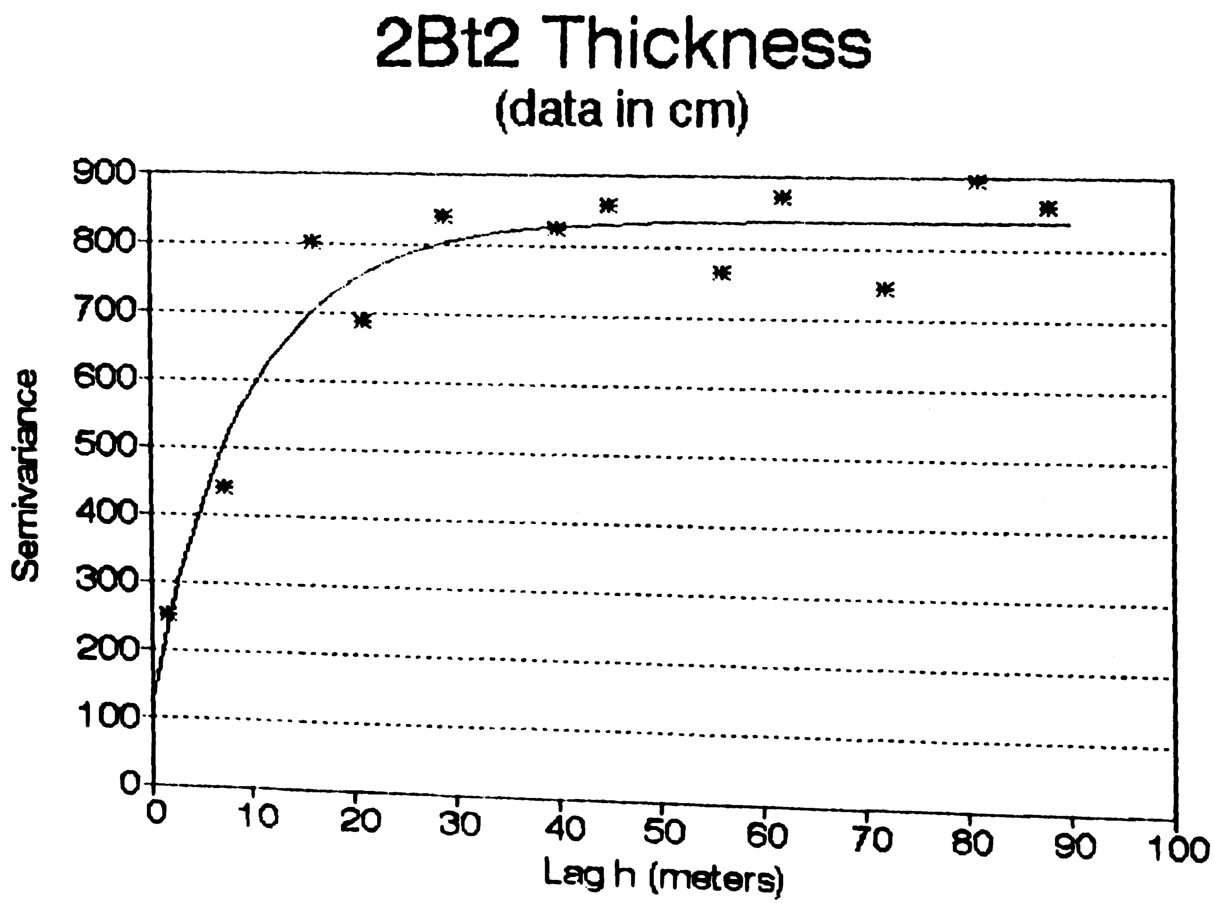

Figure 13. Semivariogram for 2Bt2 thickness.

Kriging Results

The block-kriging results are presented as an isarithmic map of control-section clay content, produced from estimates of Bt horizon properties (Figure 14). The kriged output resulted in a minimum control-section clay content of nine percent and a maximum of 26 percent. The map revealed an extensive, continuous area of coarse-loamy textured soil across the center of the study site. Figure 15 depicts the distribution of control-section classes as a percent of total land area. Oshtemo soils occupied 47 percent of the study area and Kalamazoo soils 53 percent. Nearly half of the area was occupied by soils with 16-20 percent control-section clay. Soils with less than 12 percent clay accounted for only three percent of the area, as did soils with greater than 24 percent clay.

A plot of the study-site topography is presented in Figure 16. The southeast grid corner (440,0) was designated as "0" meters elevation, and all elevations were relative to that point. A comparison of the block-kriged isarithmic map and a topographic contour plot revealed no consistent relationship between topography and control-section clay. This result confirmed a similar finding from a nearby field at KBS (J.R. Crum, personal communication, 1989).

Figure 17 displays a corresponding map of the morphological sample data, produced via inverse-distance interpolation (Golden Software, 1987). The inverse-distance

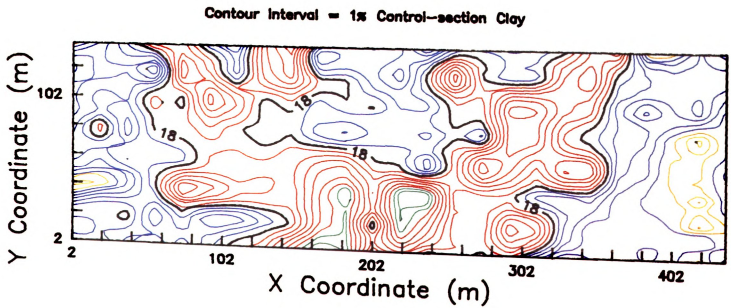

Figure 14. Block-kriged map of control-section clay content.

Key: green = <12%, red = 12-17.9%, blue = 18-23.9%, yellow = >24%.

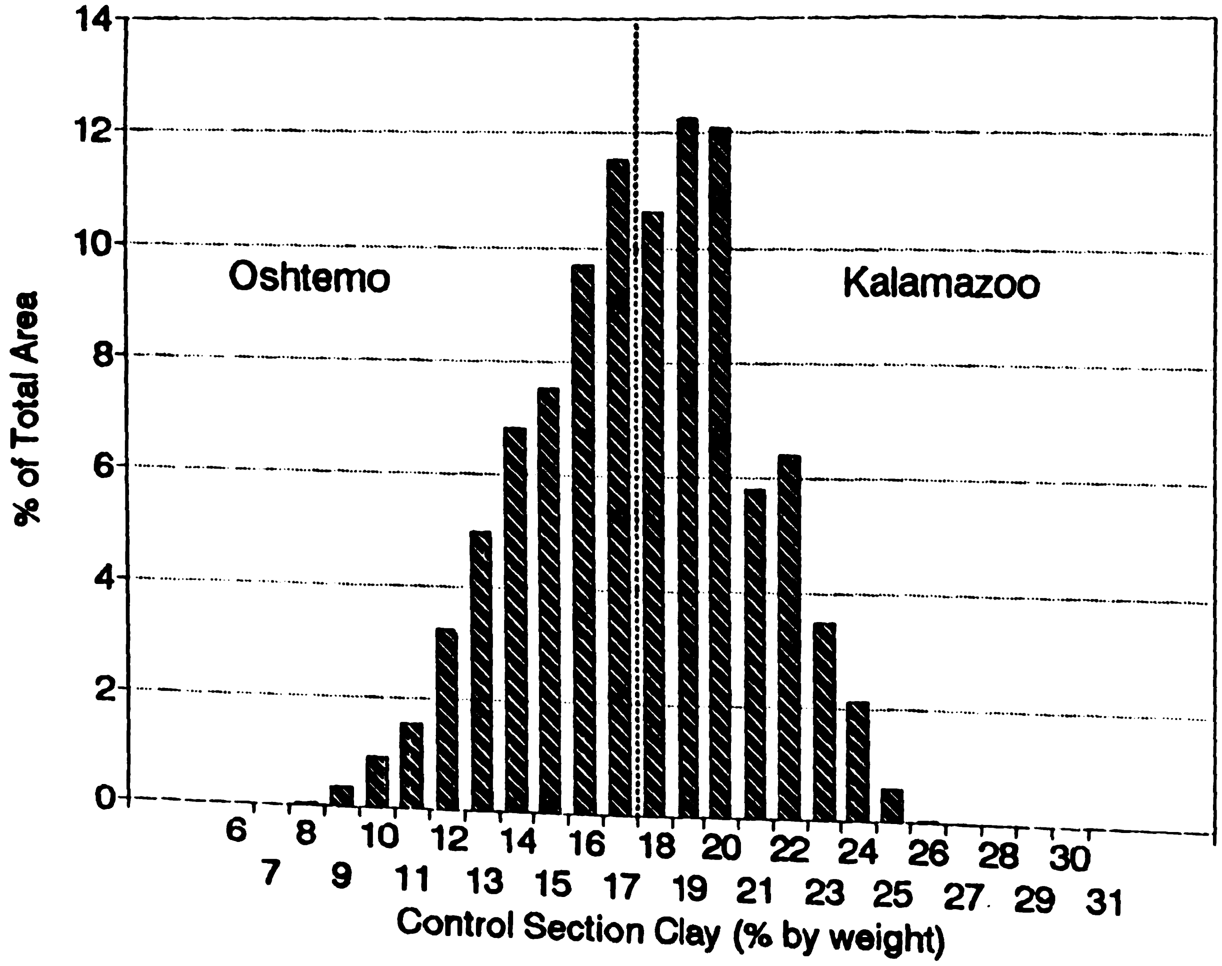

Figure 15. Area distribution of control-section classes, block-kriged map.

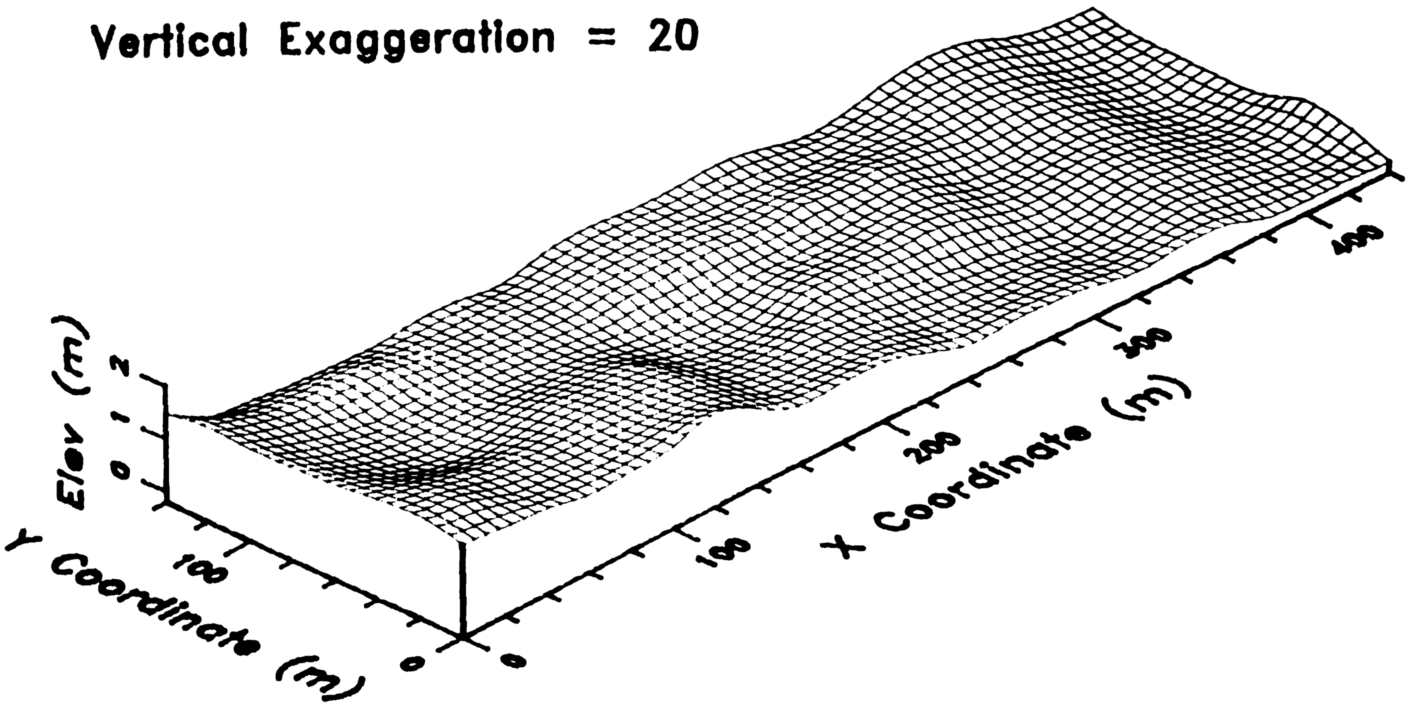

Figure 16. Topography of study site.

function weights neighboring sample points according to the general equation:

$$Z = \frac{\Sigma Z_i (1/d_i)^x}{\Sigma (1/d_i)^x}$$

where Z = interpolated value
Z_i = value of i^{th} neighbor (i = from 1 to "n" points)
d_i = distance from neighbor to interpolated value
x = exponential power assigned to function

The exponent "x" is often chosen arbitrarily, and usually given a value of two or three. The function is not an exact interpolator, as the sum of the weights does not necessarily equal one. The procedure is empirical and the estimation variance of interpolated values is unknown. Visually, Figure 17 displays greater local detail, but at the expense of obscuring more general trends. A comparison of Figures 14 and 17 reveals more extensive areas of extreme values in the inverse-distance map, which created a disjointed map appearance. The block-kriged data essentially averaged these extreme values via the block weighting procedure, which had the effect of smoothing the isarithms. The block-kriged map corroborated field observations that extreme clay-content values were basically point variations that are not mappable. The inverse-distance procedure gave much greater weight to these extreme values, which complicated the map appearance. Based upon field observations, practical soil management objectives, and theoretical interpolation

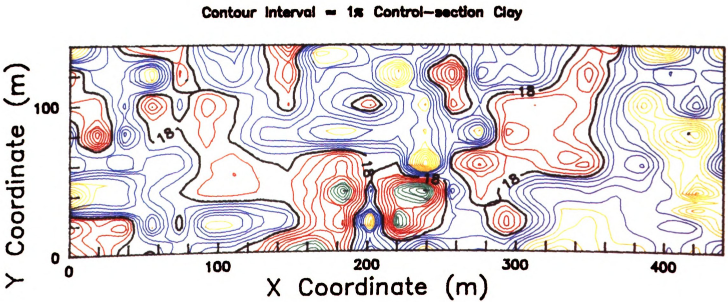

Figure 17. Inverse-distance map of control-section clay content.

Key: green = <12%, red = 12-17.9%, blue = 18-23.9%, yellow = >24%.

considerations, the block-kriged map is the best representation of study-site soil variability.

Whereas the block-kriged map estimated 47 percent Oshtemo and 53 percent Kalamazoo soil by area (Figure 15), the inverse distance map estimated 33 percent Oshtemo and 67 percent Kalamazoo (Figure 18). The inverse-distance method also produced a wider range of control-section values.

A key advantage of the kriging output is the interpolated values were statistically unbiased and each had an associated estimation variance. This allows statistical confidence limits to be placed on estimates of Bt properties. The semivariogram models produced low nugget variances, relatively high r^2 values, and sufficient ranges which increased estimation precision. For the kriged Bt properties, the pooled block variances were approximately one-third of the conventional sample variances (Table 8). The kriging estimation variances displayed a repetitive spatial pattern which is characteristic of grid sampling. Figure 19 depicts the estimation variances for Bt1 clay content. Lower estimation variances occurred near the lysimeter clusters due to increased sampling density. The pattern was similar for Bt1 and 2Bt2 thickness, but with different variance values.

The block-kriged output was used to determine the mean argillic-horizon properties for each 1% control-section class interval. The results are presented in Table 9. For the mean Bt1 textures, sand contents consistently decreased

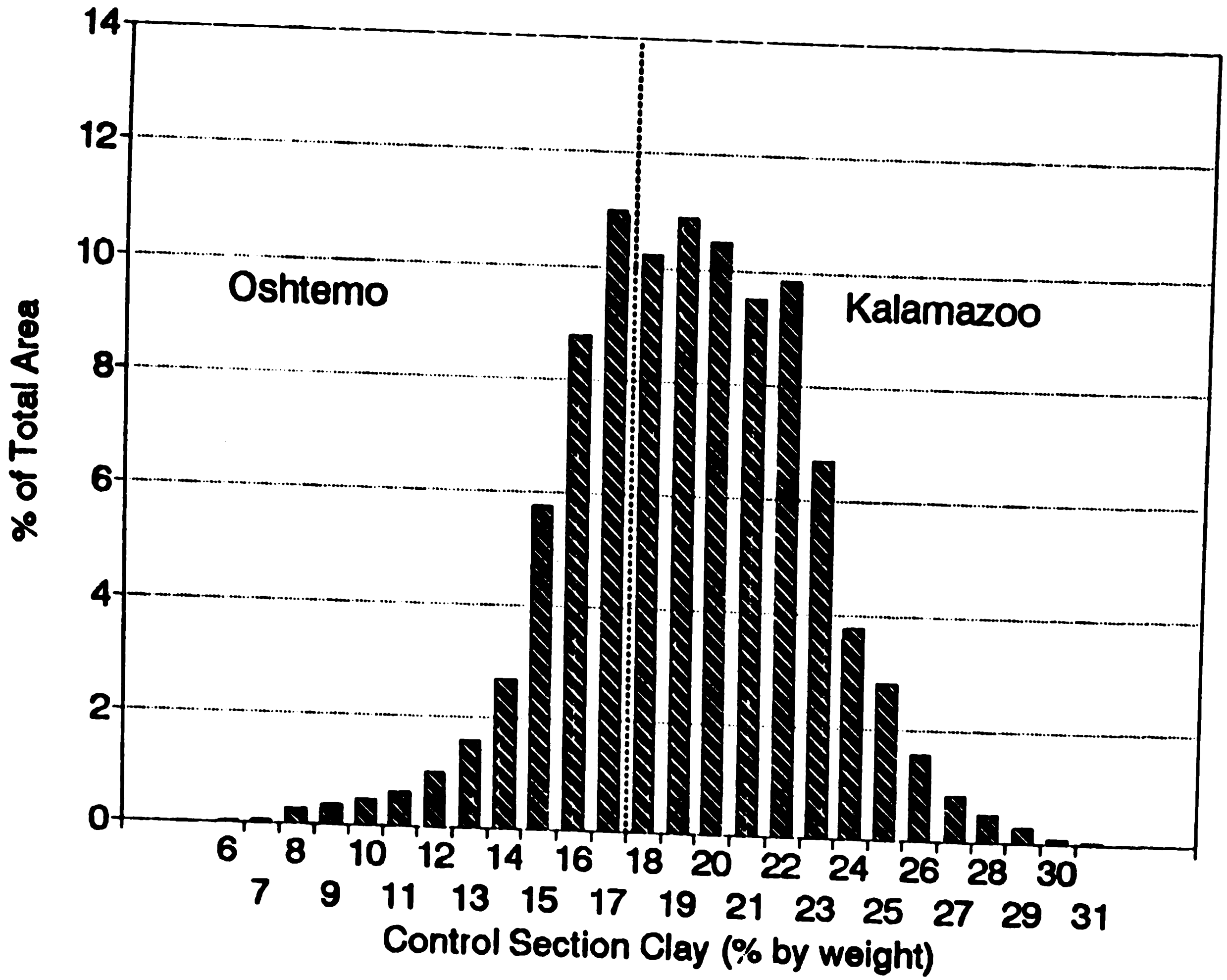

Figure 18. Area distribution of control-section classes, inverse distance map.

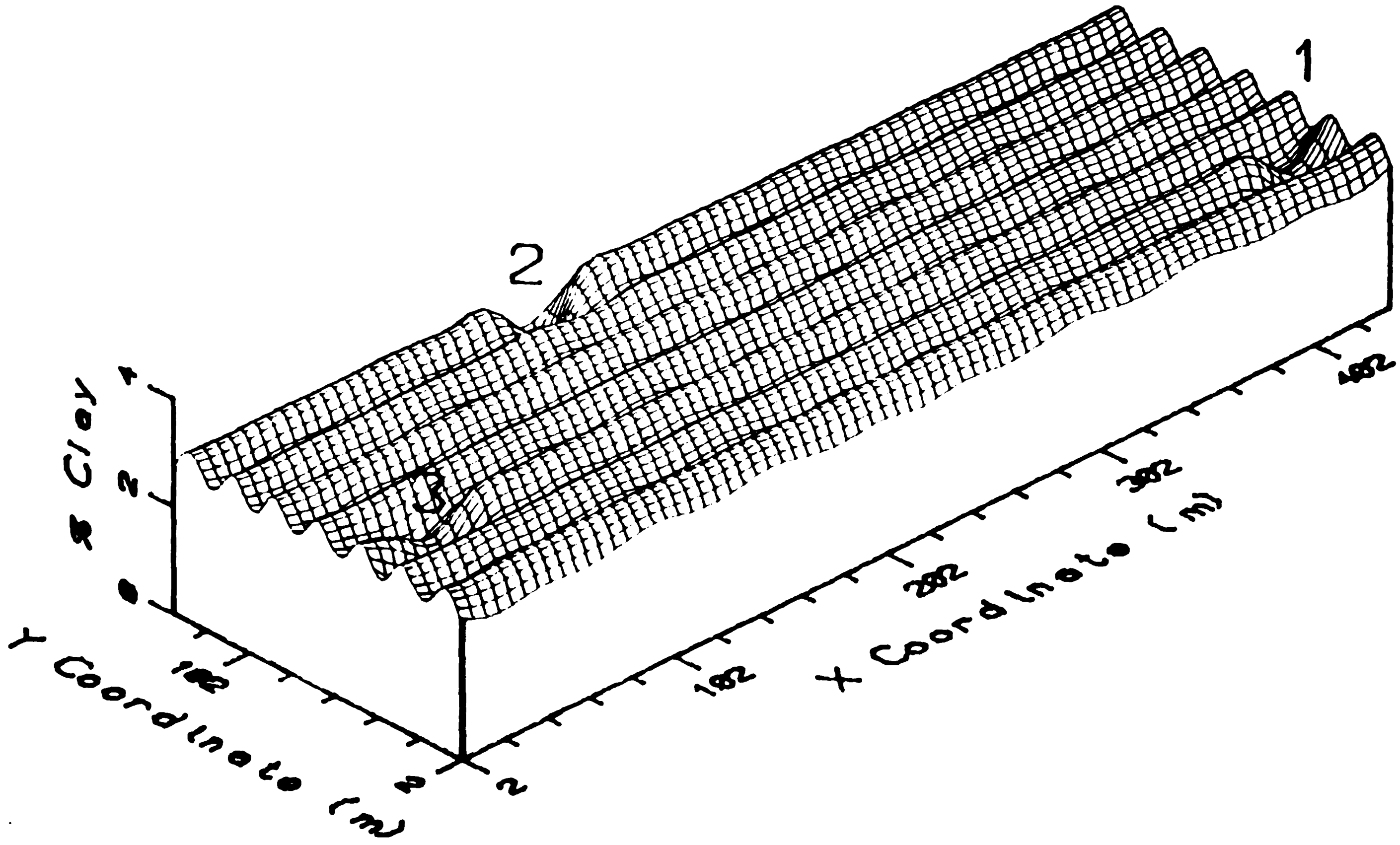

Figure 19. Estimation variance for block-kriged Bt1 clay content.

with increasing clay content. Mean Bt1 silt contents were somewhat variable for the Oshtemo profiles, but generally increased with increasing clay contents in Kalamazoo profiles. The 2Bt2 clay contents varied randomly at this observation scale, and were not considered a factor in systematic control-section clay variation. The sample means for 2Bt2 texture were therefore used in the table. The mean 2Bt2 sand and silt contents varied randomly within small ranges. The 2Bt2 thicknesses actually decreased slightly with increasing control-section clay. The data in Table 9 were used for modelling each control-section class (i.e. "soil type") with the CERES Maize model.

Table 8. Estimation Variance versus Sample Variance

Property	Estimation Variance	Sample Variance
Bt1 Clay (%)	7.0	20.4
Bt1 Thickness (cm)	121.1	333.7
2Bt2 Thickness (cm)	255.5	792.3

Table 9. Mean Bt properties by control-section class.

Control-section Class	# of blocks	Mean Bt1 Properties Clay (%)	Silt (%)	Sand (%)	Thick (cm)	Mean 2Bt2 Properties Clay (%)	Silt (%)	Sand (%)	Thick (cm)	Class Mean (%)
7	n=7	5.6	19.1	75.3	15	10.0	2.0	88.0	14	7.7
8	n=47	6.2	20.4	73.4	16	10.0	5.1	84.9	48	8.7
9	n=70	8.5	20.0	71.6	20	10.0	3.9	86.1	53	9.4
10	n=69	11.2	19.1	69.7	24	10.0	3.4	86.6	49	10.6
11	n=96	12.9	20.0	67.0	25	10.0	5.5	84.5	48	11.4
12	n=77	15.0	18.3	66.7	26	10.0	4.0	86.0	48	12.6
13	n=125	16.5	18.9	64.7	28	10.0	5.0	85.0	49	13.5
14	n=182	18.1	17.8	64.1	29	10.0	5.2	84.8	49	14.5
15	n=236	19.6	17.8	62.6	30	10.0	4.7	85.3	39	15.5
16	n=336	21.0	17.9	61.0	30	10.0	4.6	85.4	45	16.5
17	n=417	22.2	18.9	58.9	32	10.0	4.2	85.8	45	17.5
18	n=415	23.4	21.4	55.2	33	10.0	4.1	85.9	43	18.5
19	n=437	24.3	22.9	52.8	34	10.0	3.4	86.6	36	19.5
20	n=468	25.5	23.3	51.2	35	10.0	2.9	87.1	44	20.5
21	n=289	26.5	23.0	50.5	36	10.0	2.5	87.5	41	21.5
22	n=252	27.8	21.5	50.7	36	10.0	1.9	88.1	41	22.5
23	n=161	28.7	24.3	47.0	37	10.0	2.1	87.9	39	23.4
24	n=107	29.1	25.0	45.8	39	10.0	1.7	88.3	32	24.4
25	n=26	29.0	28.5	42.5	42	10.0	3.5	86.5	35	25.4
26	n=15	29.6	29.3	41.1	44	10.0	2.7	87.3	37	26.5
27	n=15	29.0	30.0	41.0	49	10.0	2.7	87.3	39	27.5
28	n=3	28.6	34.6	36.8	56	10.0	2.1	87.9	16	28.5

II. LYSIMETER RESULTS

Overview

The lysimeters were sampled on 72 dates during the two-year study period. The nitrate concentrations are summarized graphically in Appendix III for 27 lysimeters. Four shallow lysimeters (1.5, 1.6, 2.2, and 2.5) were not included because they were damaged by freeze-thaw during the first winter. The first reported data are for July 2, 1987 (day "0"), due to the anomalously high readings recorded during May and June 1987. These high readings were assumed to be the effects of lysimeter installation and equilibration, which was supported by the observation that such continuously high readings were not recorded again during the two-year study. Four lysimeters (1.4, 2.3, 4.3, and 5.4) apparently took slightly longer to equilibrate. The initial 80-ppm readings from these lysimeters were not included when calculating means and standard errors, as 80 ppm NO_3-N was also the upper detection limit for those particular analyses.

Lysimeters were not sampled during three extended periods: days 140-201, 410-442, and 536-575 (see Appendix III). For these periods, nothing could be definitively inferred about the pattern of nitrate concentrations. Other "missing" dates, especially for the alfalfa and forest lysimeters, indicate the lysimeter did not provide a sample on that date. The lysimeters usually retained a vacuum even if no sample was obtained, so inadequate soil moisture near the cup is postulated to explain "dry" samplings. Individual lysimeters did occasionally fail due to leaks in the rubber tubes, but these were isolated, random events.

Each land use was considered separately for statistical purposes. Statistical analyses of the lysimeter data were complicated by differences in the timing of nitrate concentration patterns. Maxima and minima between lysimeters often occurred several weeks apart, and particular time periods defined increasing trends for some lysimeters and decreasing trends for others. The statistical effect was to "dampen" the mean concentration patterns and cause fluctuations in the standard errors for those periods (Figures 21 and 22).

Due to low sample numbers (typically 10-15 in corn, 3-8 in alfalfa), a normal distribution had to be assumed for each sample date. Mean nitrate concentrations and standard errors were calculated on a per-sample-date basis (Figures 21 and 22). The means were considered to be reasonable estimates of the mean nitrate concentration which reached the 3C horizon on a given date, for each specified land use.

Experimental Control

The lysimeter data were collected under actual farm management conditions, which reduced experimental control. A major question was the variability of center-pivot nitrogen applications across the study site. In late June 1989, 222 bottles were placed along the soil-sampling grid to collect samples from a lagoon-waste application. Due to a mechanical failure of the center-pivot system, only 40 samples were obtained, all from the southeast corner of the grid. Table 10 lists the nitrogen analysis results for the applied lagoon waste.

Table 10. Nitrogen Analysis of Applied Lagoon Waste.

	Inorganic N (ppm as NH4, NO3)	Organic N (ppm)	Total N (ppm)
Mean	135.3	150.6	285.9
Std. Dev.	31.7	33.0	38.5
CV (%)	23.4	21.9	13.5

The low coefficient of variation (CV) for total Kjeldahl nitrogen (TKN) suggested that a relatively uniform nitrogen concentration reached the soil surface. The higher CV's for the inorganic and organic nitrogen simply indicated differences in the proportion of these fractions. The inorganic fraction was over 95 percent ammonium. A recent study indicates that the organic fraction could be mineralized within two weeks at 25 degrees centigrade (B.G. Ellis and J.R. Crum, personal communication, 1989). Therefore, the TKN values can be practically considered as the best indicator of nitrogen concentration variability which would affect the lysimeter measurements.

Reliable measurements of application-volume variability could not be made, as the center-pivot movement was halted during application. Thus for even a small portion of the grid, the total N application could not be accurately quantified. This essentially left site-wide application variability as an uncontrolled factor. The inability to define this variability was unfortunate, but realistically it would have characterized only a single event. Factors such as lagoon contents, wind speed and direction, corn height, temperature, etc. may have affected each irrigation event differently and influenced the spatial variability of nitrogen applications. Thus, establishing control under actual management conditions was practically unfeasible over a growing season.

It was not possible to reliably quantify the total nitrogen application over a growing season. When lagoon waste was applied as nitrogen fertilizer, nitrogen concentrations were assumed and liquid was applied to the nearest 2.5 millimeters. Applying a uniform, prescribed amount of nitrogen to the lysimeter clusters was unlikely, especially through a center-pivot system. Also, farm records were not detailed enough for precise quantification of nitrogen inputs. Therefore, no attempt was made to calculate a thorough nitrogen budget. A partial nitrogen budget was calculated for corn, considering only the recorded N-applications and corn yields (see "Corn" below).

Soil Water Balance

A soil water balance was calculated for a Kalamazoo Loam soil using Thornthwaite's method and actual 1987-89 precipitation and temperature data (Table 11; Figure 20). The water balance did not consider irrigation inputs, but served to indicate when rainfed leaching below a one-meter depth could be expected. The soil waster storage capacity was calculated from soil survey data (Austin, 1979) and KBS bulk density measurements (D.J. Reinert, personal communication, 1989). The calculated water capacity was 15.1 centimeters to a one-meter depth.

The calculated 1987-89 soil-water balances correlated with the relative 1987-89 corn-grain yields in Kalamazoo County. The 1987 and 1988 growing seasons were characterized by low soil-water storage values (Table 11), resulting in low corn-grain yields for both years (Rossman, et al., 1989). In 1989, soil-water storage values were high for the entire growing season, placing little water stress on corn crops. For Kalamazoo County, 1989 corn-grain yields were approximately double the 1987 and 1988 yields (Rossman, et al., 1990). Assuming similar management practices, the low yields in 1987 and 1988 would have left a larger amount of nitrogen in the soil profile than in 1989.

Table 11. Soil Water Balance, 1987-89 (Thornthwaite method).

Soil storage capacity = 15.10 cm of water in upper 1 meter.

Month	Mean Temp (°C)	Total Precip (cm)	Start Storage (cm)	Evapo-trans (cm)	Final Storage (cm)	Surplus (cm)
1987						
Jan	-3.1	2.96	10.00	0.00	12.96	0.00
Feb	-0.9	1.13	12.96	0.00	14.09	0.00
Mar	3.6	3.19	14.09	1.20	15.10	0.98
Apr	10.3	5.89	15.10	4.71	15.10	1.18
May	16.8	3.28	15.10	8.48	9.90	0.00
Jun	21.3	5.01	9.90	9.09	5.82	0.00
Jul	22.6	6.38	5.82	8.73	3.47	0.00
Aug	19.9	17.05	3.47	11.23	9.29	0.00
Sep	16.3	13.18	9.29	7.15	15.10	0.22
Oct	7.8	6.44	15.10	2.83	15.10	3.61
Nov	5.6	6.11	15.10	1.61	15.10	4.50
Dec	0.1	12.94	15.10	0.01	15.10	12.93
ANNUAL	10.0	83.56		55.04		23.42
1988						
Jan	-5.4	5.40	15.10	0.00	20.50	0.00
Feb	-5.5	4.10	20.50	0.00	24.60	0.00
Mar	2.1	6.00	24.60	0.64	15.10	14.86
Apr	9.0	7.01	15.10	4.05	15.10	2.96
May	15.9	3.18	15.10	8.07	10.21	0.00
Jun	20.2	3.61	10.21	8.06	5.76	0.00
Jul	23.2	10.66	5.76	12.00	4.42	0.00
Aug	22.3	12.25	4.42	12.44	4.23	0.00
Sep	16.3	16.37	4.23	7.19	13.41	0.00
Oct	7.0	12.71	13.41	2.51	15.10	8.50
Nov	4.7	14.32	15.10	1.33	15.10	12.99
Dec	-2.4	5.09	15.10	0.00	20.19	0.00
ANNUAL	9.0	100.70		56.29		39.32
1989						
Jan	0.1	3.60	20.19	0.02	15.10	0.00
Feb	-6.2	3.48	15.10	0.00	18.58	0.00
Mar	2.4	6.82	18.58	0.89	15.10	0.98
Apr	6.6	5.02	15.10	3.07	15.10	1.18
May	12.7	18.80	15.10	7.30	15.10	0.00
Jun	19.4	13.66	15.10	11.93	15.10	0.00
Jul	22.3	9.96	15.10	14.14	11.45	0.00
Aug	20.2	11.45	11.45	11.69	11.27	0.00
Sep	15.3	14.30	11.27	6.92	15.10	0.22
Oct	10.5	2.63	15.10	4.38	13.45	3.61
Nov	2.2	17.39	13.45	0.63	15.10	4.50
Dec	-2.4	5.09	15.10	0.00	20.19	12.93
ANNUAL	8.6	112.20		60.29		51.91

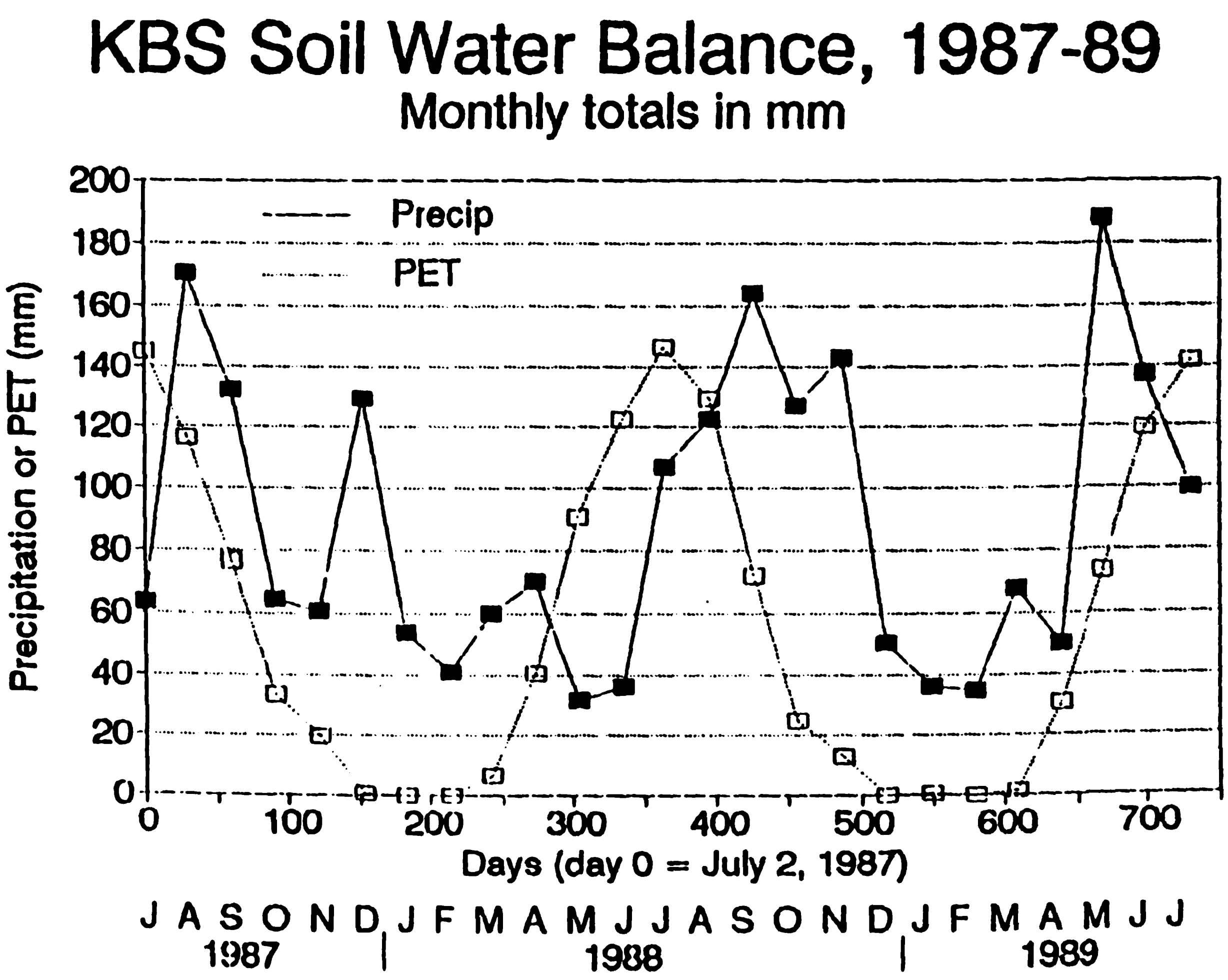

Figure 20. Soil-water balance for Kalamazoo Loam, 1987-89.

The surplus values (i.e. profile drainage) indicated drainage below one meter for the fall and spring months in each year. For years 1987 and 1988, 99-100 percent of soil-water drainage occurred between October 1 and April 30 of the following year. For 1989, 67 percent of the surplus soil water drained during the same months. Most of the predicted growing-season drainage in 1989 occurred during May. The soil-water balance for 1987-89 indicated that even with relatively wet growing seasons, the majority of soil-water drainage can be expected between October and April.

Comparative Land-Use Effects

There were several differences in lysimeter results according to land use. The average number of dates in which a lysimeter provided a sample was 62 under corn, 41 under alfalfa, and 13 under hardwood forest. Large differences in sample numbers were noted between clusters one and two (corn) and cluster three (alfalfa) even though soil profile differences were minimal. Although water management cannot be ruled out as a variable, differential water uptake above the 2Bt2/3C boundary according to vegetation type may have affected sample numbers. Both alfalfa and forest vegetation could extract stored soil water during May and June, when corn was still immature. The number of samplings may indicate the relative frequency of water movement into the

3C horizon, but nothing definitive can be said about the total volumes of percolating water.

The relative magnitude and temporal variability of nitrate concentrations also differed with land use. Seasonal peaks produced much higher maximum values under corn than alfalfa (Table 12). The minimum nitrate concentrations under corn were comparable to or higher than the maximum values under alfalfa. The maximum concentration peaks for the corn lysimeters appeared to be bi-modal, with the highest peaks occurring in July and slightly smaller peaks in November/December. The mean minimum concentrations under corn were typically 2-3 times higher than the mean minima under alfalfa. The maximum values under alfalfa were recorded during spring, when minimum values are recorded under corn. Nitrate concentrations under forest vegetation were consistently under two parts per million, with the exception of a single outlier in February 1988. Forest lysimeter samples were obtained principally between April and June 1988, November and December 1988, and April to June 1989. These periods were during or immediately following periods of predicted soil drainage via Thornthwaite's method (Table 11).

Corn

The cornfield lysimeters (clusters 1, 2, 5, and 6) displayed marked variation in the patterns and magnitudes of

Table 12. Maximum and minimum nitrate concentrations under corn and alfalfa Values in ppm N-NO3. Day number in parentheses (day "0" = 7/2/87)

CORN

Lysimeter	Maximum Fall '87	Minimum Spring '88	Maximum Summer '88	Maximum Fall '88	Minimum Spring '89
1.1	22 (113)	9 (288)	42 (376)	43 (442)	9 (651)
1.2	75 (125)	22 (323)	46 (383)	41 (491)	12 (630)
1.3	40 (110)	2 (288)	47 (376)	68 (491)	9 (651)
1.4	21 (140)	5 (259)	63 (369)	93 (450)	12 (728)
2.1	31 (201)	14 (295)	61 (354)	28 (484)	12 (630)
2.3	59 (110)	18 (295)	28 (354)	41 (529)	18 (630)
2.4	62 (140)	27 (288)	55 (383)	45 (536)	10 (630)
5.1	42 (118)	30 (281)	59 (376)	56 (529)	N/A
5.2	37 (140)	14 (281)	39 (383)	52 (536)	12 (651)
5.3	36 (125)	29 (281)	52 (376)	27 (491)	7 (651)
5.4	32 (208)	17 (309)	61 (383)	46 (529)	21 (651)
6.1	27 (140)	12 (281)	37 (376)	42 (491)	20 (651)
6.2	32 (118)	12 (295)	N/A	N/A	N/A
6.3	27 (140)	9 (288)	30 (362)	55 (491)	20 (651)
6.4	27 (140)	17 (301)	65 (383)	75 (442)	17 (651)

ALFALFA

Lysimeter	Maximum Summer '87	Maximum Spring '88	Maximum Spring '89
3.1	9 (71)	18 (267)	2 (582)
3.2	4 (64)	12 (274)	6 (575)
3.3	10 (50)	14 (267)	2 (575)
3.4	18 (85)	22 (267)	4 (582)
4.1	26 (85)	N/A	3 (575)
4.2	14 (85)	50 (242)	10 (575)
4.3	N/A	27 (295)	6 (575)
4.4	18 (99)	48 (259)	5 (582)

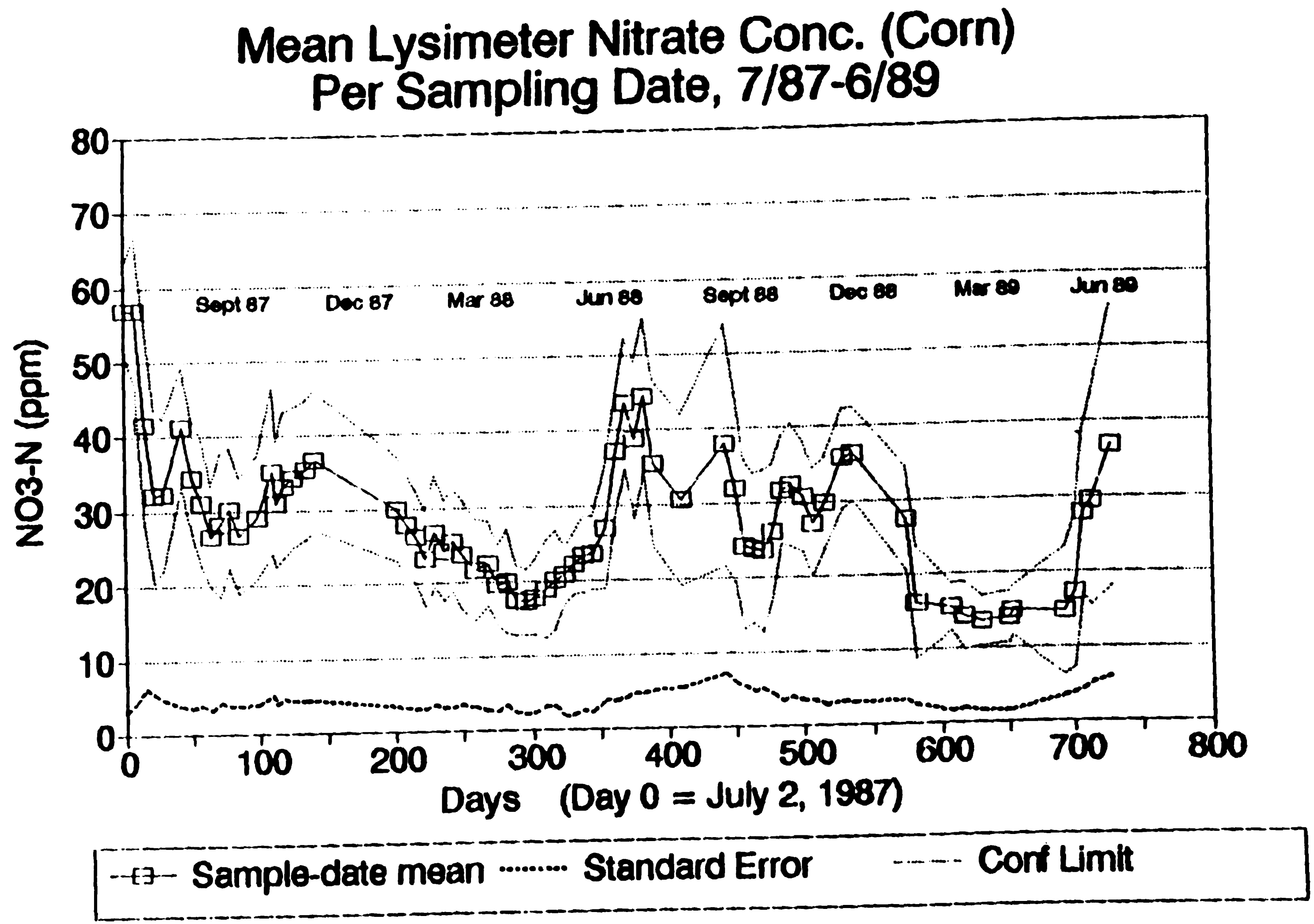

Figure 21. Mean lysimeter nitrate concentrations (corn), 1987-89.

nitrate concentrations. Although the temporal patterns were not synchronous between lysimeters, means and standard errors were calculated by sample date (Figure 21). Figure 21 reveals a consistent pattern in the nitrate concentrations over time: highest concentrations in mid-summer followed by a slight decrease in concentration; a second peak occurring in late fall/early winter, and a decline to a minimum in late spring. The relatively high initial values probably still reflected installation effects, but also represented an actual mid-summer peak. The data displayed the most "noise" during periods of maximum concentrations, when large differences occurred in the magnitude and timing of peaks. For most sample dates, the standard error was 10-15 percent of the sample mean, and the confidence interval was 50-70 percent of the mean. The standard error was highest during rapid rises in nitrate concentrations, largely due to differential timing of the increases.

On at least one occasion, a lysimeter cluster received an extra nitrogen input. Cluster one received up to 2.5 centimeters of lagoon waste on May 6, 1988 via a self-propelled irrigation pump ("traveller"). The volume and concentration were not quantified, so the amount of nitrogen applied was unknown. The data from cluster one were still used in field-wide statistics because the relative contribution to the seasonal N total was unknown, and applications to all clusters were only approximated.

Although the concentration peaks were highest in summer, the amount of soil-water drainage at that time was probably negligible. The soil-water balance (Table 11) indicated virtually no profile drainage from June-September in 1987 and 1988, and only five centimeters for June-September 1989. The lysimeters extracted samples under 0.07 MPa potential, so samples could have been obtained even without free drainage during summer. The fall readings, which occurred during a period of both high nitrate concentrations and drainage volumes, likely represented the greatest seasonal contribution to annual nitrate leaching. Other data from Michigan support the hypothesis that leaching between October and April accounts for the majority of annual leaching losses (Ellis, 1988).

The mean values in Figure 21 appeared to be quite consistent during the winter and spring months, when nitrate concentrations were decreasing at the 2Bt2/3C horizon boundary. The rate of decrease was much greater during the winter of 1988 (days 536-582), probably due to the intense precipitation and soil-water drainage that year (Table 11, Figure 20). The relatively stable readings during the winter may have resulted in part from sampling essentially the same soil-water pool. With a frozen soil surface, limited soil-water drainage would occur and the lysimeter would repeatedly sample a static water layer.

A comparison of 1989 nitrogen inputs and outputs were made for the center-pivot field. According to farm records, a total of 288 kg N/ha was applied during the growing season. The corn grain yield was 158 bu/acre without starter fertilizer and 173 bu/acre with starter. The recommended fertilizer rates for these yield goals are 210 kg N/ha and 230 kg N/ha, respectively (Warncke, et al., 1985). Thus, the total nitrogen applications in 1989 exceeded the recommended rates by 58-78 kg N/ha. These calculations did not account for nitrogen already contained in the soil profile; gaseous nitrogen losses were not considered either. It is clear, however, that nitrogen inputs exceeded yield-goal recommendations, and thus increased the potential for nitrate leaching. Of the total nitrogen applied in 1989, more than half was as inorganic fertilizer. Given the waste-disposal problem at the KBS dairy and the cost of inorganic nitrogen fertilizer, the lagoon waste should be thoroughly exploited as a nitrogen source before applying inorganic nitrogen.

Alfalfa

The lysimeter data for the alfalfa land-use are presented in Appendix III, lysimeter clusters three and four, and sample-date means are presented in Figure 22. Three immediate observations can be noted relative to the cornfield lysimeters: 1) the fewer number of samples, 2) the generally much lower nitrate concentrations, and 3) maximum values occurred in the spring months, when nitrate

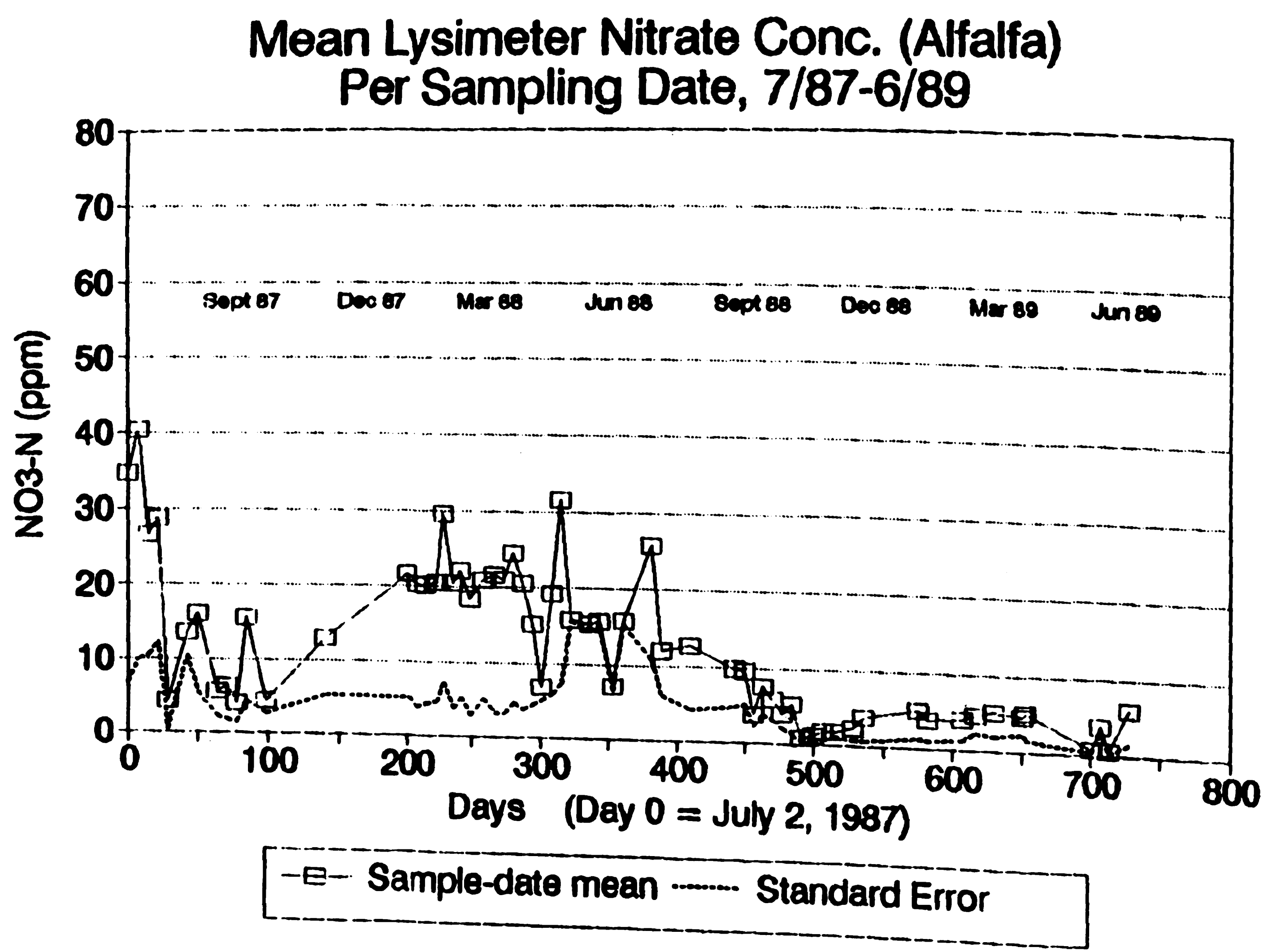

Figure 22. Mean lysimeter nitrate concentrations (alfalfa), 1987-89.

concentrations under corn were at a minimum. All the alfalfa lysimeters displayed a pronounced peak between days 200-300 (January-May 1988). A smaller peak occurred between days 550-650 (December 1988-April 1989). All lysimeters displayed a minimum trend between days 450 to 500. Lysimeter 4.1 was not operable between days 100 and 300.

The values for cluster four were consistently 2-3 times higher in early 1988 than those for cluster three (Appendix III; note: lysimeter 4.1 was inoperable). No data were available to directly explain these differences. The difference between clusters is hypothesized to be the result of differential lagoon-waste applications from the previous year. Farm records indicated that 2.5 centimeters of waste were applied during the summer of 1987, and 1.25 centimeters in mid-October 1987. In addition, lagoon waste was periodically fall-applied on alfalfa with a self-propelled "traveller" irrigation gun. The hypothesis is supported by the observation that these "traveller" applications were usually confined near the southern end of the alfalfa field, closer to cluster four than cluster three. Thus, cluster four probably received more nitrogen inputs during 1987. The fall-applied waste would mineralize and provide a nitrate source. The relatively constant lysimeter readings were probably due to the fact the soil surface was frozen from December through March and that the same soil-water pool was being repeatedly sampled. Nitrate concentrations eventually decreased in April 1988 except for lysimeter 4.4. The reason for its sustained pattern is not known.

No data existed to explain the large difference between the 1988 and 1989 peaks. The 1989 nitrate-concentration patterns were comparable between clusters. The difference was attributed to probable yield differences between the 1988 and 1989 alfalfa. The growing season was much wetter in 1989, and the higher yields would have removed more of the applied nitrogen. Even with irrigation, the 1988 crop was probably under enough water stress to reduce yields. This would have left more nitrogen in the soil for fall leaching. The hypothesis would also explain how the lysimeters were uniformly affected from 1988 to 1989. Unfortunately, alfalfa yield records were unavailable for 1988, so the hypothesis could not be tested.

Forest

The four forest lysimeters provided a total of only 53 samples during the two-year period. Although no particle-size data were available, the field description recorded during installation indicated that the pedons were within the Kalamazoo series. Thus the much lower sample numbers were not likely related to soil differences. The forest did not receive irrigation as did the crops, so less soil-water drainage was not surprizing. An additional explanation is that the forest vegetation depleted the soil-water storage to lower amounts during the early growing season, when annual crops are immature. This difference could remain into the fall recharge period. The forest lysimeters nearly always held a vacuum. The periods when samples were obtained coincide with times of high soil moisture and lack of freezing temperatures (Appendix III; Table 11).

The nitrate concentrations were all below two parts per million, with the exception of a single outlier. The outlier of 23 ppm on day 229 was the only lysimeter sample obtained for several weeks, and was considered inconsequential. The forest lysimeter data were consistent with a study in northwestern Michigan, where outwash-derived soils were planted to aspen, red pine, and white pine. The investigators sampled nitrate concentrations with suction lysimeters at a 1.2 meter depth, and detected no concentrations above two ppm NO_3-N over the three-year study period (Brockway and Urie, 1983). The data from these two studies suggest that nitrate leaching under well-drained forest sites in Michigan is negligible compared to agricultural nitrate leaching.

Nested Analysis and Required Sample Numbers

Because the cornfield contained the most lysimeter clusters under a single land-use, two separate analyses were run to characterize the nature of the lysimeter-measurement variability. The first was a nested analysis designed to partition the sample variance into within-cluster and between-cluster components (Table 13). The between-cluster variance component was significant on only 9 of 72 sampling dates at the 95 percent confidence level. This suggested that the clusters were generally ineffective for partitioning the total sample variance. Eight of the nine significant differences occurred during spring months when nitrate concentrations were low and relatively stable. However, some between-cluster component existed whenever the "F" test produced a value greater than one (41 of 72 dates). In terms of proportion, the within-cluster component accounted for at least half of the total variance (s^2) on 67 of 72 sample dates. The within-cluster variance often exceeded the total variance, due to random-error effects.

The within-cluster mean-square was often much greater than the between-cluster mean-square (Table 13). In practice, the within-cluster mean-square should not have greatly exceeded the between-cluster mean-square, because the between-cluster mean-square contains an additional error component. For dates where this occurred (mostly summer and fall), the clustering actually grouped the most dissimilar lysimeter measurements together. Three factors might account for this finding. One, soil differences such as the depth of the 2Bt/3C boundary were often as variable within clusters as between clusters. Two, the random variability of nitrate peak timing could account for large within-cluster variability. Finally, the lysimeter spacings within clusters

Table 13. Nested analysis of lysimeter data, by sample date.

Confidence interval = 50% of sample-date mean
Confidence level = 95%
* = significant at 95% level

DAY	COMPONENT Between Cluster MS1	Within Cluster MS2	Sample Variance s2	F test MS1/MS2	df		Proportion of s2 due to within-cluster MS2/s2
0	115.261	92.600	98.780	1.245	3,11		0.94
8	57.183	297.960	232.294	0.192	3,11		1.28
15	89.096	582.913	448.235	0.153	3,11		1.30
22	298.782	393.088	369.511	0.760	3,12		1.06
29	216.501	273.132	257.687	0.793	3,11		1.06
43	105.447	214.103	189.028	0.493	3,13		1.13
50	190.279	141.438	153.648	1.345	3,12		0.92
57	324.488	147.537	191.775	2.199	3,12		0.77
64	134.474	120.956	124.336	1.112	3,12		0.97
71	199.955	138.358	153.757	1.445	2,8		0.90
78	57.327	246.212	205.736	0.233	3,14		1.20
85	62.922	230.038	194.228	0.274	3,14		1.18
99	41.859	213.460	201.395	0.196	3,13		1.06
110	463.049	295.927	337.707	1.565	3,12		0.88
113	162.272	228.633	213.319	0.710	3,12		1.07
118	121.364	337.735	287.803	0.359	3,13		1.17
125	138.020	307.533	268.415	0.449	3,13		1.15
134	200.689	278.542	260.576	0.720	3,13		1.07
140	234.952	272.018	263.464	0.864	3,13		1.03
201	252.428	137.232	161.917	1.839	3,14		0.85
208	273.126	116.586	150.130	2.343	3,14		0.78
215	174.284	112.090	125.418	1.555	3,14		0.89
222	190.724	117.847	133.464	1.618	3,14		0.88
229	287.426	132.478	168.236	2.170	3,13		0.79
236	184.122	138.388	148.188	1.330	3,14		0.93
242	206.970	122.197	141.760	1.694	3,13		0.86
249	401.039	117.840	178.525	3.403	3,14	*	0.66
259	346.529	76.314	138.671	4.541	3,13	*	0.55
267	249.454	68.513	107.286	3.641	3,14	*	0.64
274	170.641	64.331	87.112	2.653	3,14		0.74
281	314.078	112.782	155.917	2.785	3,14		0.72
288	137.682	52.022	70.377	2.647	3,14		0.74

Table 13. Nested analysis of lysimeter data (con't).

295	118.585	18.719	61.620	6.335	3,14	*	0.30
301	104.468	57.807	69.472	1.807	3,12		0.83
309	193.126	40.928	91.661	4.719	3,9	*	0.45
316	214.008	98.160	124.894	2.180	3,13		0.79
323	66.007	41.598	46.828	1.587	3,14		0.89
330	53.156	56.645	55.897	0.938	3,14		1.01
337	28.916	99.334	78.209	0.291	3,10		1.27
344	52.451	79.499	73.257	0.660	3,13		1.09
354	403.785	136.878	198.472	2.950	3,13		0.69
362	133.213	214.008	196.694	0.622	3,14		1.09
369	152.087	263.214	237.569	0.578	3,13		1.11
376	1050.55	166.299	327.071	6.317	3,11	*	0.51
383	103.430	388.854	322.987	0.266	3,13		1.20
390	191.752	394.478	343.796	0.486	3,12		1.15
410	390.887	352.542	362.128	1.109	3,12		0.97
442	844.844	417.757	512.665	2.022	3,9		0.81
450	731.672	464.723	521.926	1.574	3,14		0.89
456	669.912	296.246	382.477	2.261	3,13		0.77
463	642.602	239.874	326.173	2.679	3,14		0.74
470	546.896	245.975	321.205	2.223	3,12		0.77
477	409.697	193.825	243.642	2.114	3,13		0.80
484	87.038	143.147	127.845	0.608	3,11		1.12
491	250.254	185.898	200.750	1.346	3,13		0.93
500	159.920	162.330	161.774	0.985	3,13		1.00
507	272.744	126.090	159.933	2.163	3,13		0.79
516	69.441	124.976	112.160	0.556	3,13		1.11
529	60.950	156.171	134.197	0.390	3,13		1.16
536	53.834	127.791	109.302	0.421	3,12		1.17
575	33.014	173.543	141.113	0.190	3,13		1.23
582	0.990	32.766	22.174	0.030	1,3		1.48
607	61.359	7.091	23.371	8.653	3,10	*	0.30
617	17.399	37.596	28.940	0.463	3,7		1.30
630	39.120	4.327	19.538	9.042	3,8	*	0.22
651	29.530	23.809	25.525	1.240	3,10		0.93
653	31.929	22.470	25.050	1.421	3,11		0.90
693	130.488	16.647	65.513	7.838	2,5	*	0.25
701	78.214	17.716	32.841	4.415	1,4		0.54
707	70.350	134.275	108.705	0.524	2,5		1.24
713	32.848	219.484	126.166	0.150	2,4		1.74
728	24.701	197.203	139.703	0.125	1,3		1.41

(5-10 meters) may have been larger than the spatial dependence of soil nitrate variability, although clustering may have reduced management variability. An interaction of these factors was likely, but the lack of such occurrences during January-June 1988 and March-June 1989 suggested that the variability associated with peak timing was the principal factor.

A second, unrelated analysis involved determining the number of lysimeters required to estimate the mean within a certain interval at a given confidence level. Stein's two-stage sample procedure was used, which estimates the total sample number "n" required after a preliminary sample has been characterized (Steel and Torrie, 1980). In this case, the variance estimate (s^2) for each sample date was used to estimate the lysimeter sample size required for a given degree of confidence. Stein's equation is:

$$n = \frac{t^2 s^2}{d^2}$$

where n = sample number required

t = Student's t value for the required confidence level and degrees of freedom

s = the sample standard deviation (in data units)

d = half-width of the desired confidence interval (in data units)

An "n" value had to be calculated for each sample date, because the nitrate concentration means were for each sample date. An arbitrary confidence interval of 50 percent of the sample-date mean was chosen (i.e. "d" equaled 25 percent of the mean). The confidence level was 95 percent ($\alpha = 0.05$). The results indicated that the true mean was within the given confidence interval, with 95 percent probability, on only 23 of 72 dates. Table 14 shows the number of dates which would have met the confidence criteria with a given range of sample numbers. If 20 samples were obtained on each date, the confidence criteria could have been met on nearly three-quarters of the sample dates. The 15 corn lysimeters most often provided between 12 and 14 samples.

Table 14. Lysimeter samples required for given precision, by number of sample dates.

Confidence interval = 50% of sample-date mean
Confidence level = 95% ($\alpha = 0.05$)

Number of samples needed	Number of dates
0- 5	1
6-10	14
11-15	15
16-20	23
21-25	6
26-30	7
31-35	2
36-40	1
41-45	2
46-50	1
Total Dates	72

This exercise demonstrated the difficulty in precisely estimating the mean nitrate concentration on any given date. Stein's equation was much more sensitive to changes in the confidence interval than the confidence level, because the magnitude of these changes affected "d" far more than the Student "t" values for the given degrees of freedom. Thus, the mean could not be estimated within narrow limits even at liberal confidence levels, unless a much larger number of lysimeters were used.

The use of lysimeter clusters in future experiments should be considered carefully. An estimate for the field-wide variance of the sample mean is given by the equation:

$$s^2_{\bar{y}} = \frac{\sigma^2_L}{CL} + \frac{\sigma^2_C}{C}$$

where $s^2_{\bar{y}}$ = variance estimate of sample mean

σ^2_L = variance component from individual lysimeters

σ^2_C = variance component from lysimeter clusters

C = number of clusters

L = number of lysimeters within clusters

Theoretically, the number of clusters should be maximized in order to minimize the field-wide sample variance. A "cluster" may even be a single lysimeter. In practical terms, the number of lysimeters in a cluster would depend upon how many were needed to provide a representative measurement. This is primarily a scientific consideration, dependent upon study objectives, criteria for lysimeter placement, etc. In this experiment, the clusters effectively partitioned the variance only during times when the field-wide variance was low. Thus, there was little advantage placing several lysimeters within a cluster. The suggestion would be to install 20-25 lysimeters for a given land-use, installed singly or in pairs to maximize "cluster" numbers. Lysimeters within a cluster should be separated by the minimum distance that precludes sampling the same soil water, in order to minimize soil and management variation. The lysimeters should be distributed field-wide if a field-wide estimate is needed.

Nitrogen Analysis of Deep Soil Cores

The deep soil cores (see Table 5) provided depth profiles of soil-nitrogen contents for December 16, 1988 (Figures 23, 24, and 26). All nitrogen values were expressed as kilograms of elemental nitrogen per 15 centimeters of soil. This was done because the upper soil profile was sampled by horizons of varying thicknesses, and the lower profile was sampled every 15 centimeters. This method of reporting allowed an equal-basis comparison of nitrogen-content values throughout the profile. For total nitrogen in the upper soil horizons, the values would be multiplied by the horizon thickness and then divided by 15 centimeters.

All cores displayed large soil-nitrogen concentrations for the Ap horizon, mostly as nitrate. Much of the Ap-horizon nitrogen was probably from lagoon waste applications made on October 8th and November 3rd. The applications totaled 2.5 centimeters of liquid, and assuming the mean concentration values in Table 10, applied 30 kg/ha of inorganic nitrogen to the soil (expressed as elemental N). An estimated 40 kg/ha of organic nitrogen was added with the applications, some of which may have been mineralized before December. The applications were made during a period of high soil-water content and precipitation, so there was a large potential for leaching to lower soil horizons.

The depth profiles under corn showed much higher values for nitrogen in cluster one than cluster two (Figures 23 and 24; Table 15). The data indicated the difference occurred primarily in the 1-2 meter depth, where a large peak occurred in the 3C horizon of the cluster one profile. It was hypothesized the extra nitrogen application to cluster one (in May) resulted in a much greater excess of post-harvest nitrogen which subsequently leached. A similar effect was reported by Saxton, et al. (1977) on an excessively fertilized cornfield in Iowa. To test this hypothesis, lysimeter means for clusters one and two were plotted over time (Figure 25). Nitrate concentrations at the 2Bt2/3C boundary were much higher in cluster one from August to December (Days 400-530). Assuming similar drainage

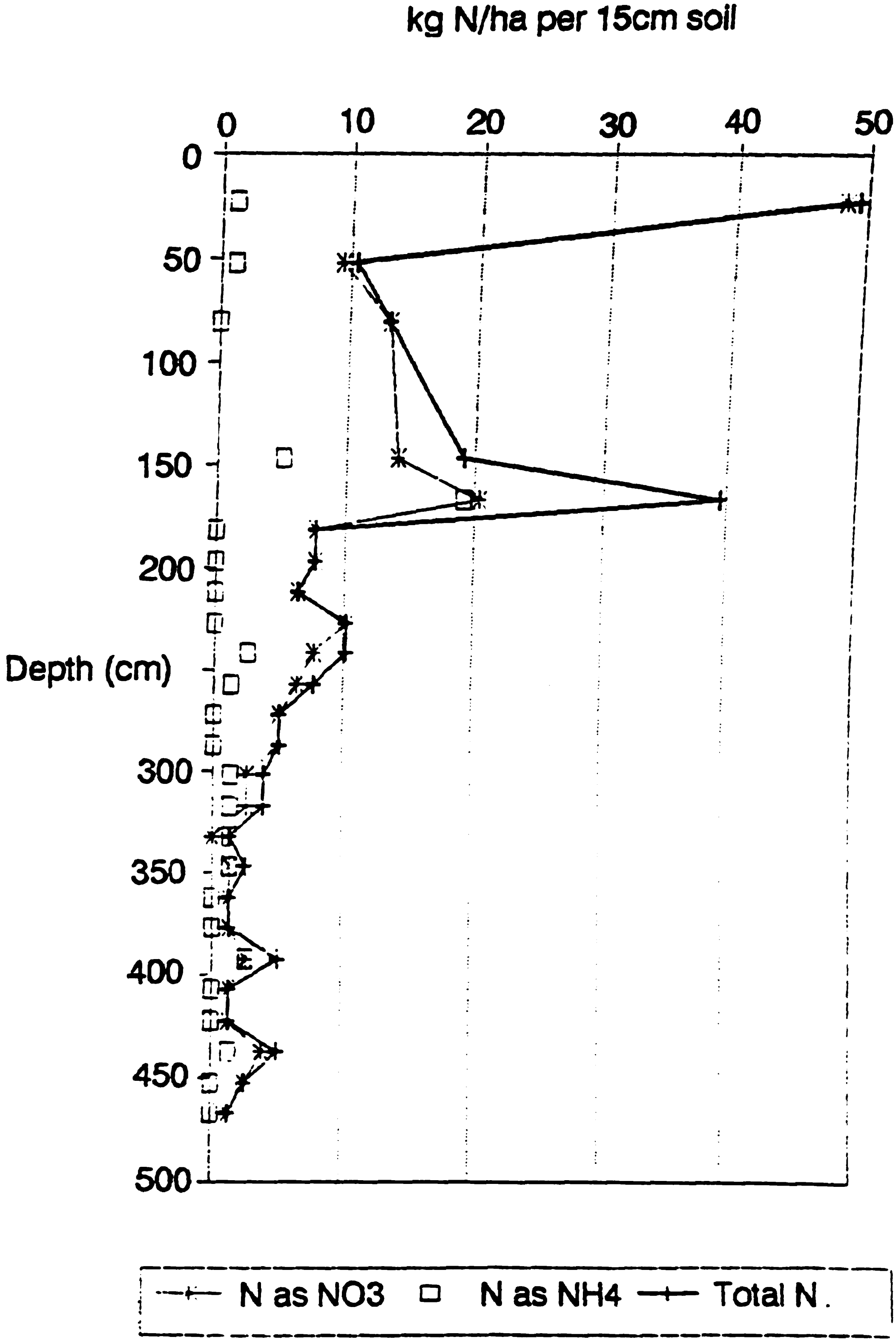

Figure 23. Nitrogen depth-profile for lysimeter cluster one, December 1988.

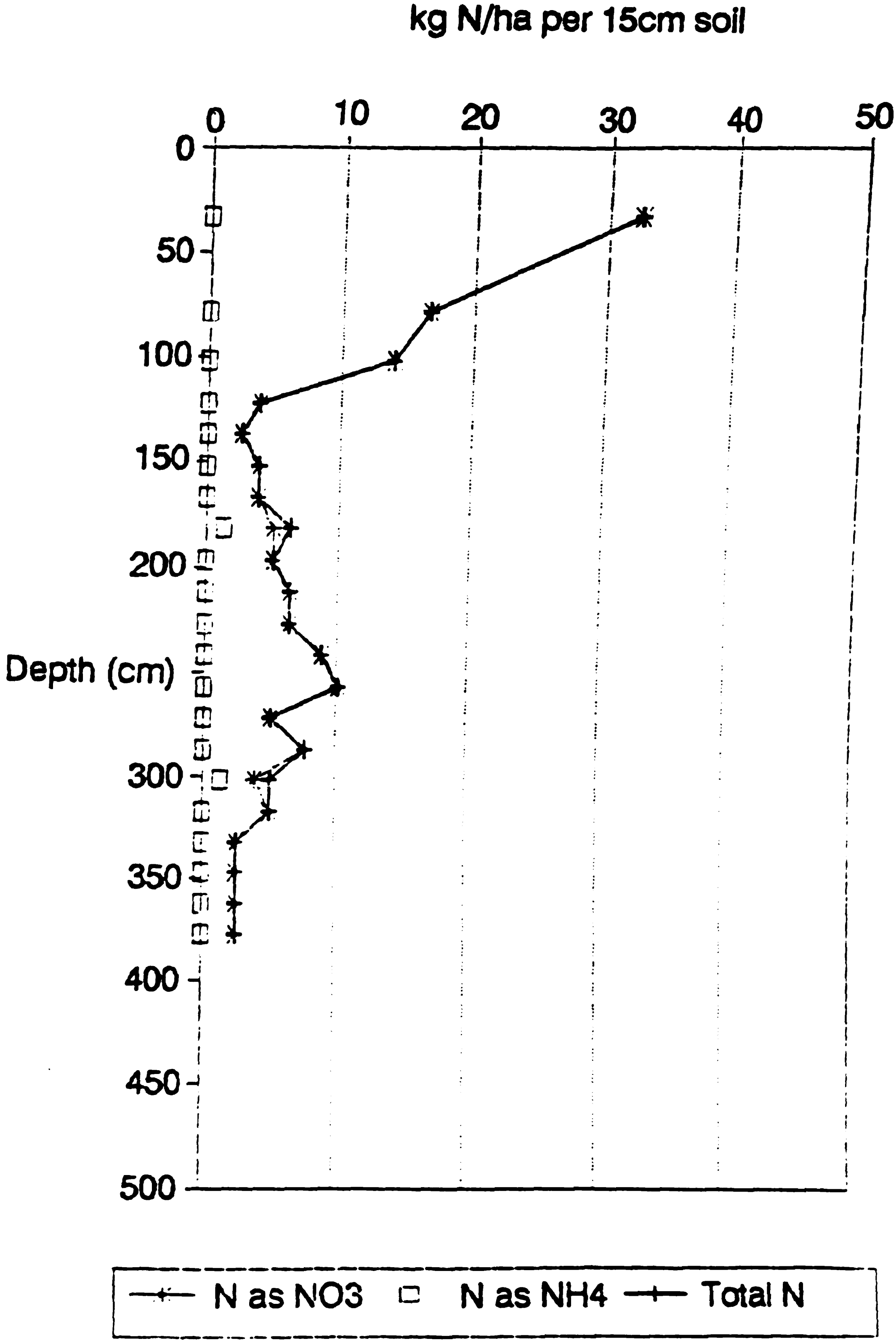

Figure 24. Nitrogen depth-profile for lysimeter cluster two, December 1988.

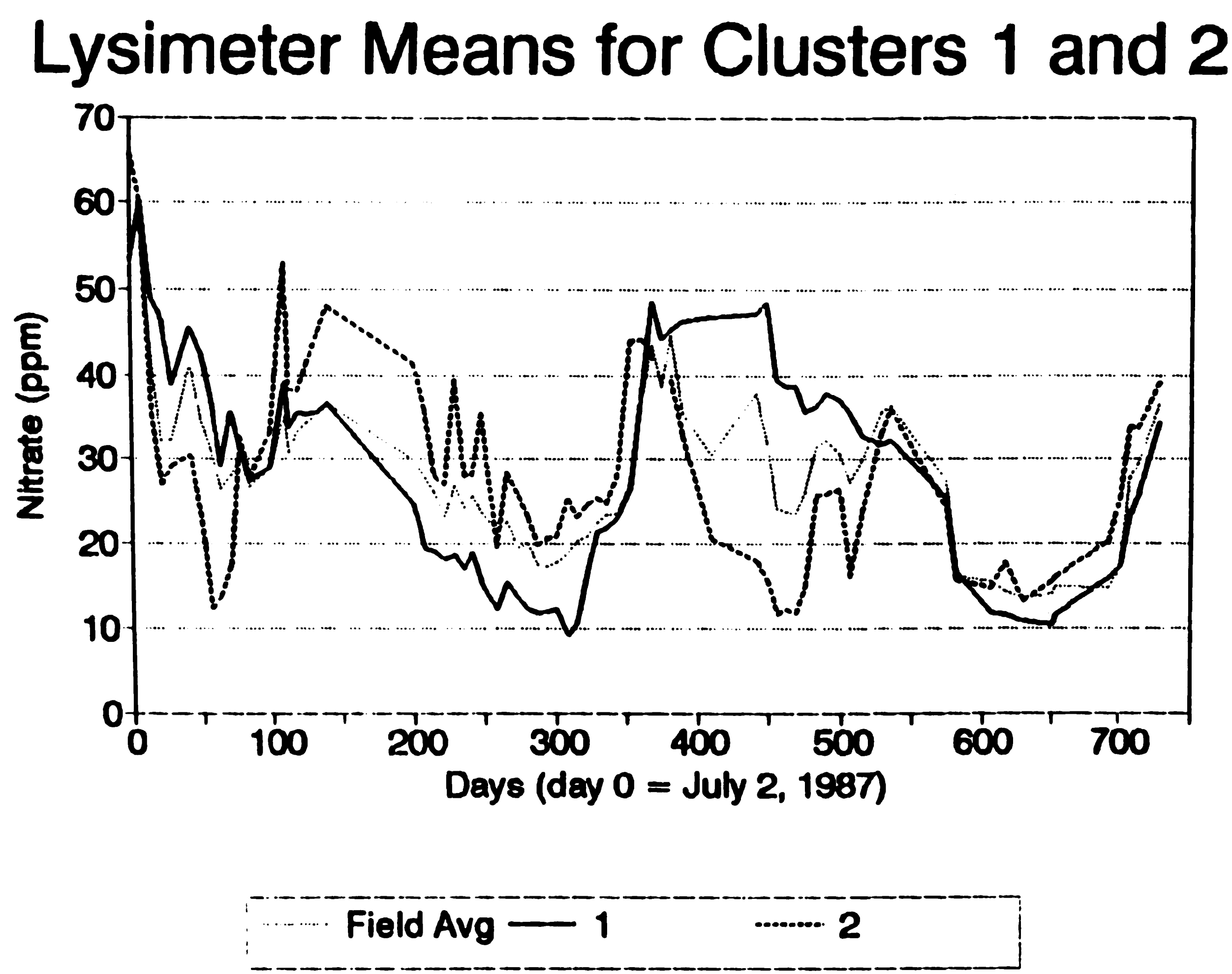

Figure 25. Lysimeter means for clusters one and two, 1987-89.

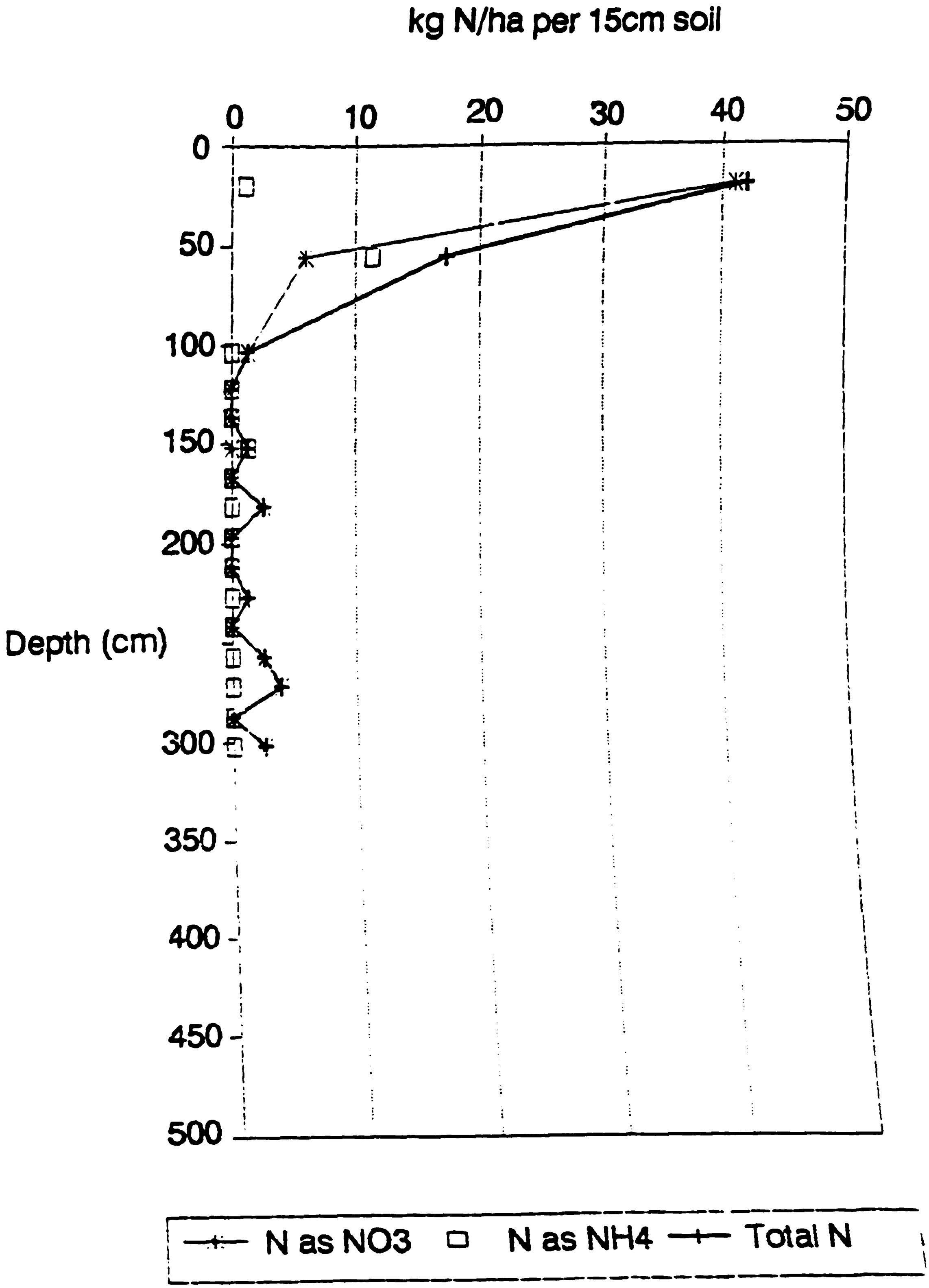

Figure 26. Nitrogen depth-profile for lysimeter cluster three, December 1988.

Table 15. Soil-Nitrogen Values for Deep Soil Cores.

Depth (m)	Cluster 1 kg N/ha			Cluster 2 kg N/ha			Cluster 3 kg N/ha		
	NO_3	NH_4	Total	NO_3	NH_4	Total	NO_3	NH_4	Total
0-1	135	11	146	145	0	145	73	29	102
1-2	86	42	128	26	1	27	3	1	4
2-3	43	5	48	49	1	50	10	0	10
3-4	11	6	17	15	0	15	-	-	-
4-4.5	9	1	10	-	-	-	-	-	-

volumes, cluster one leached 2-4 times as much nitrogen into the 3C horizon during the fall months.

Relatively high amounts of ammonium were found in the 2Bt2 and 3C horizons of the cluster one profile, while little ammonium was found in cluster two. The ammonium analyses for those horizons provided three consistent sub-sample analyses, so the value appeared reliable. The high ammonium values in cluster one may have been due to the May 1988 lagoon-waste application. The inorganic fraction of the waste was over 90 percent ammonium, and some may have percolated before it could be nitrified.

The nitrogen depth profile under alfalfa displayed high values only in the upper meter of soil (Figure 26). The Bt1 ammonium value in Figure 26 was adjusted due to an erroneously high-ammonium subsample. Of the three Bt1 sub-samples extracted, two sub-samples contained only one ppm ammonium, while the third contained nearly five ppm. The five ppm value may have been due to alfalfa root (nodule) material in the third sub-sample.

The profiles all displayed a general decrease in total nitrogen with depth, but with several periodic nitrogen peaks. Denitrification in the well-drained subsoil was unlikely. The soil-water balance (Table 11) predicted a surplus of 22 centimeters for October and November 1988. Given the 15 centimeter water-holding capacity of the upper meter of soil, and assuming the 3C banded sands had a water-holding capacity of 10 centimeters per meter of soil, miscible displacement would have moved a solute front 1.7 meters downward. Thus nitrate at the soil surface would leach to 1.7 meters, a depth which coincided with the nitrogen peak in cluster one. However, the nitrate was probably concentrated below the soil surface and should have theoretically leached more deeply. Because of cation adsorption, nitrification, and root uptake effects, the leaching of ammonium to 1.7 meters by displacement was considered unlikely. This would suggest that displacement was not the only nitrogen transport mechanism.

Wild (1972) found that nitrate leaching was slower than that predicted by displacement theory, and attributed the finding to water by-pass flow through large continuous pores. When soil is at high water contents, a large percentage of precipitation may percolate directly through the soil while displacing little of the existing soil water (Quisenberry and Phillips, 1976). This macropore flow may accelerate the transport of some solute, while retarding the transport of solute contained in smaller pores (Tyler and Thomas, 1981). This uneven transport can result in a breakthrough of solute well ahead of the major solute front (Wild and Babiker, 1976; Priebe and Blackmer, 1989). Many studies confirm a high degree of spatial and temporal variability in measuring solute transport rates and depths of solute fronts (Biggar and Nielsen, 1976; Richter and Jury, 1982; Priebe and Blackmer, 1989).

The patterns and depths of nitrogen distribution in these profiles were inconsistent with what can be explained by displacement theory alone. It is hypothesized that some of the solute which occurred at depth was due to macropore flow. This may explain the high ammonium content in the 3C horizon of cluster one and the occasional ammonium peaks at depth in all of the profiles. If macropore water was percolating during or immediately after a lagoon-waste application, the ammonium could be transported before being adsorbed or nitrified.

The occasional peaks in nitrogen contents at depth were attributed principally to soil hydraulic factors. Zones of high water content were occasionally observed during the profile sampling, where water perched above an apparent hydraulic discontinuity. Since most of the nitrogen was highly water-soluble nitrate, this would have effectively concentrated the nitrogen within those zones. Thus the nitrogen peaks really represented increased soil-water contents where the nitrates tended to reside.

Table 15 presents the same data expressed according to actual horizon thicknesses and summed for one-meter increments. All values refer to elemental nitrogen, with the total sub-divided into nitrate and ammonium contributions. Large differences were apparent in the total amount, distribution, and form of the soil nitrogen. Total nitrogen was twice as great in cluster one as cluster two, mostly due to the near absence of ammonium in the cluster-two profile.

The soil profile in cluster three had the lowest amount of total nitrogen for each of the upper three meters. All profiles contained only small amounts of total nitrogen at the deepest sampling depth.

Although the cores represented only three samples, it was clear that large amounts of nitrogen remained in the upper meter of soil. The fall lagoon-waste applications added large amounts of nitrogen, unfortunately confounding the attempt to monitor the movement of post-harvest residual soil nitrogen. The total nitrogen amounts suggested that as of mid-December 1988, not much nitrogen had moved below two-meter depth. It could be expected that internal soil drainage through winter-spring 1989 would further leach the nitrogen, to a point where subsequent corn crop recovery was unlikely.

Soil Variability and Nitrate Measurements

Several methodological problems confounded the research objective to relate soil variability and soil-nitrate measurements. The lysimeters were originally installed to monitor nitrate concentrations in "representative" field soils (Rice, et al., 1986). The lysimeters were then used for the present study under the false assumption that an unknown range of soil variants were included. Particle-size analyses were not performed when the lysimeters were installed, so the assumption was not directly negated. Table

16 lists the control-section clay estimates calculated from the block-kriged Bt1 clay contents, the 2Bt2 sample mean of 10 percent clay, and actual Bt thickness measurements. The estimated control-section clay contents varied over a range of only six percent, from 19 to 25 percent. Although the estimates certainly contained some error, it was clear that only a small portion of the study-site soil variability was included in lysimeter clusters one, two, and three.

Table 16. Control-section clay contents for study-site lysimeter clusters.

Lysimeter	Bt1 Clay (%)	Bt1 Thick. (cm)	2Bt2 Clay (%)	2Bt2 Thick. (cm)	Control-Section Clay (%)
1.1	25.8	40	10.0	28	22.6
1.2	25.7	47	10.0	15	24.8
1.3	26.0	32	10.0	14	20.2
1.4	26.9	38	10.0	64	22.8
2.1	26.9	35	10.0	21	21.8
2.3	25.1	36	10.0	23	20.9
2.4	25.4	30	10.0	10	19.2
3.1	26.0	28	10.0	42	19.0
3.2	25.9	41	10.0	42	23.0
3.3	26.8	32	10.0	25	20.8
3.4	27.3	32	10.0	26	21.1

Statistically relating soil variability to nitrate measurements was difficult. A major problem was to choose a nitrate measurement or statistic which was meaningful as an indicator of nitrate leaching. The lysimeter data reflected only nitrate concentrations, not fluxes. Thus, totals were meaningless. Seasonal nitrate concentration means were suspect due to temporal variability in peak timing and soil moisture. Finally it was decided to use the nitrate concentration maxima and minima, as they could be most reliably identified on a seasonal basis.

A series of multiple regression equations were performed to relate the maximum and minimum nitrate concentrations to soil factors at each lysimeter. The independent variables were Bt1 clay and thickness, 2Bt2 clay and thickness, combined Bt thickness, control-section clay content, and lysimeter cup depth. All *F* values were insignificant at the 0.1 confidence level except 2Bt2 thickness for the maximum fall 1988 values. In that case, the r-squared value was 0.52 with a positive slope. Upon examination, a single statistical outlier was revealed to be the source of the "significance". When removed from the regression, the *F* value was insignificant and the r-squared value was 0.02. It was concluded that maximum and minimum nitrate concentrations could not be related to Bt thicknesses or cup depth.

Several problems became apparent during the regression analysis. Given the demonstrated variability of the lysimeter measurements, it was improbable that nitrate concentrations could be related to such a limited range of Bt-horizon characteristics. Because regressions were done separately for corn and alfalfa, the sample numbers for each regression were limited to seven in corn and four in alfalfa. Clay contents were not available for clusters four, five, and six, which would have doubled the regression sample numbers. The dependent variables (nitrate maxima and minima) were unlikely indicators of nitrate leaching potential, and the range of Bt characteristics was limited. Ideally, the range of soil variants should have been regressed against seasonal nitrate flux totals. This was eventually accomplished only through computer modelling.

II. CERES Maize Modelling Results

Estimated Soil Hydraulic Characteristics

The morphological data for the 22 soil types (7-28% control-section clay) were input into the SOILW sub-routine, which estimated soil hydraulic characteristics (see Ritchie and Crum, 1989; also Methods). The Ap characteristics were held constant for all soil types. The argillic-horizon texture and thickness were input according to the results in Table 9. All 22 profiles were limited to a one-meter depth, so simulated leaching output could be compared against actual suction lysimeter data. The thickness of the 3C horizon was therefore dependent upon the thicknesses of the overlying horizons, so the one-meter limit could be maintained.

Table 17 lists the estimated hydraulic characteristics for each soil type. Definitions of the CERES model terms are as follows:

SWCON- soil-water drainage constant, the fraction of excess soil water drained per day (unitless). Excess water is the difference between the horizon saturated water content (SAT) and the drained upper limit (DUL).

SAT- saturated water content for the soil horizon, expressed as cm^3 water per cm^3 soil.

DUL- drained upper limit; soil-water content comparable to "field capacity" for the soil horizon. Expressed as cm^3 water per cm^3 soil. In Table 17, the only DUL values are for the Bt1 horizon, because the Ap, 2Bt2, and 3C values were constant for all soil types.

LL- lower limit of plant-extractable soil water for the horizon, in cm^3 water per cm^3 soil. Corresponds to a matric potential of approximately -2 MPa (Ritchie and Crum, 1989). As with DUL only the Bt1 LL values are reported in Table 17.

PESW- total plant-extractable soil water in the profile, comparable to water-holding capacity expressed in cm.

Table 17. CERES Soil Hydraulic Characteristics from Soil Morphology Data.

NOTE: Values in bold type are adjusted values (see text).

Control-Section Class (% Clay)	ESTIMATED SWCON	INPUT SWCON	Bt1 Horizon DUL	Bt1 Horizon LL	Profile PESW (cm)
			--(cm^3/cm^3)--		
7	.58	.68	.164	.044	13.5
8	.58	.62	.166	.045	13.3
9	.54	.57	.184	.064	14.0
10	.51	.53	.194	.075	14.3
11	.48	.49	.207	.088	14.3
12	.46	.46	.215	.097	14.4
13	.43	.43	.227	.109	14.4
14	.42	.42	.231	.114	14.5
15	.39	.39	.242	.125	14.5
16	.38	.38	.247	.130	14.5
17	.36	.36	.253	.136	14.5
18	.34	.34	.260	.143	14.6
19	.32	.32	.268	.150	14.6
20	.30	.30	.278	.160	14.7
21	.29	.29	.283	.165	14.7
22	.28	.28	.287	.169	14.7
23	.26	.26	.294	.176	14.7
24	.25	.25	.295	.177	14.8
25	.24	.24	.301	.181	15.0
26	.23	.23	.306	.186	15.1
27	.24	.24	.302	.182	15.3
28	.22	.22	.309	.187	15.6

In Table 17, the bold numbers indicate that the SWCON value was adjusted above the estimated value. This was done because the Ap horizons of the coarsest-textured profiles were coarser than average, and also because the 3C banded sands were weakly developed. The SWCON value is a drainage coefficient for the entire profile, and is intended to reflect the drainage rate of the profile's slowest-draining layer. The adjusted SWCON values were thought to be better reflections of profile drainage characteristics for those coarse-textured soil types. With increasing clay content, the estimated SWCON values decreased, and LL and DUL increased. The saturated value (SAT) equalled 0.337 for all Bt1 horizons, because the estimate is based upon a constant horizon bulk-density value. Except for the 27 percent control-section class, all estimates followed a consistent trend. The estimated hydraulic variables for the 27-percent class were similar to those for 25 percent control-section clay, except for a slightly higher plant-extractable soil water (PESW) (Table 17). The particular combination of soil-layer textures and thicknesses for the 27-percent class apparently resulted in slightly different hydraulic estimates.

The estimation of these values was critical for modelled leaching predictions. Not only do the values affect drainage conditions, but the soil-moisture values partly determine the modelled mineralization, nitrification, nitrogen uptake, and denitrification rates. Thus the hydraulic factors interact to affect both the simulated nitrogen availability and subsequent transport.

Irrigated Nitrate Leaching

The CERES model output for years 1987-89 predicted approximately the same amount of nitrogen losses for each year, despite large differences in precipitation (Figures 27-29). Annual nitrogen losses, tabulated from planting date to planting date, were between 120 and 145 kilograms of nitrogen per hectare. The graphs revealed three consistent trends with increasing control-section clay content: 1) the total nitrate leaching gradually decreased, 2) the proportion of nitrate leached prior to January decreased, and 3) the amount of denitrification increased. These effects were all consistent with the literature regarding soil texture and nitrogen losses (e.g. Lund, 1974; Devitt, 1976). The generally slower drainage of finer-textured profiles decreases the soil drainage rates and increases the potential for reduction/denitrification. In dry years, the finer-textured profiles can increase water availability and nitrogen uptake, thereby reducing residual soil nitrogen. These effects were all reflected in the CERES output (Figures 27-29; Table 18).

The effect of weather patterns, even under irrigation, was noticeable in the yield and nitrogen-loss data. Table 18 lists selected leaching-related outputs for the 18 percent control-section clay soil, which was representative of the majority of the study area. Although there was no major difference in the predicted water or nitrogen stress between

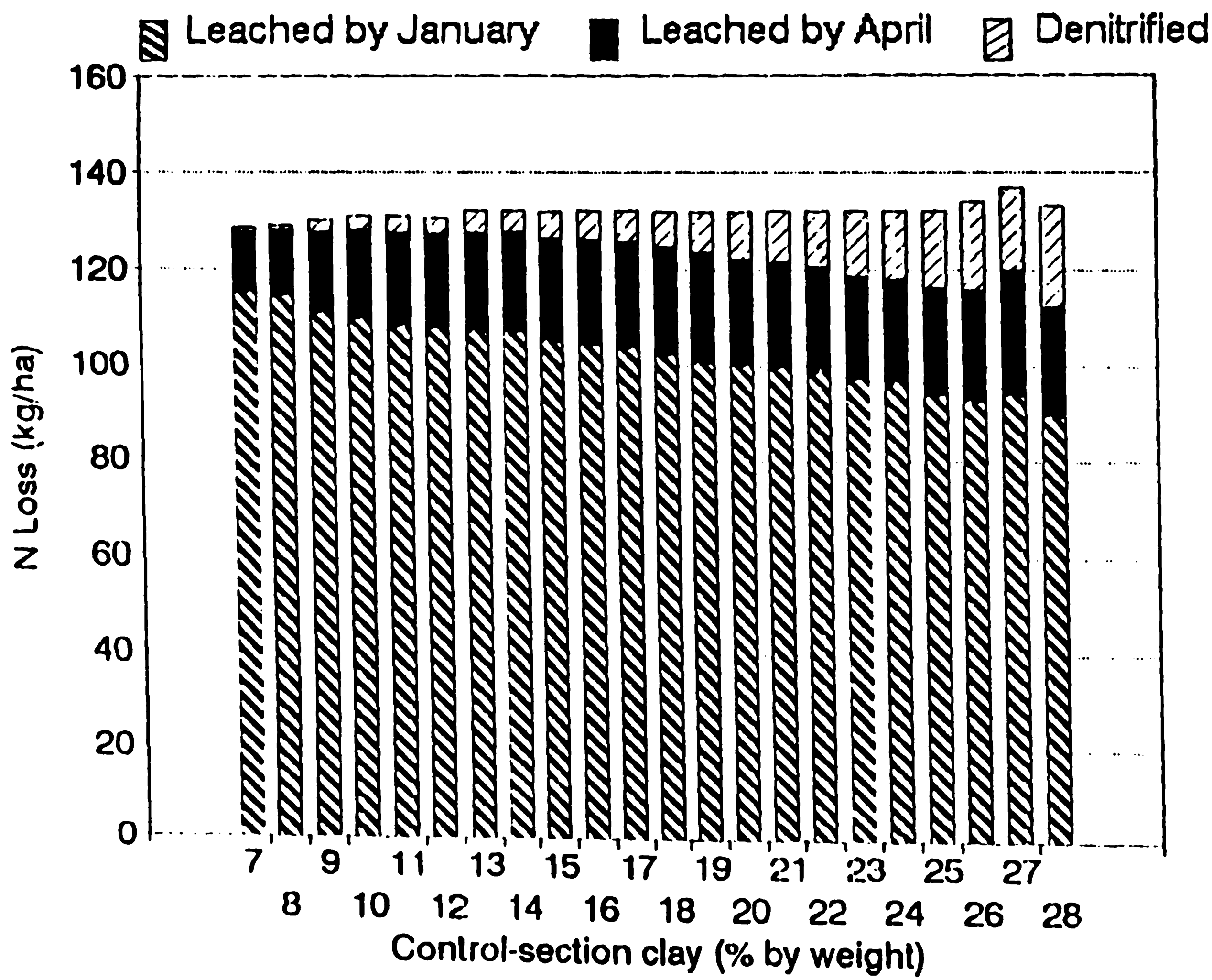

Figure 27. Nitrogen loss under irrigated conditions, 1987-88.

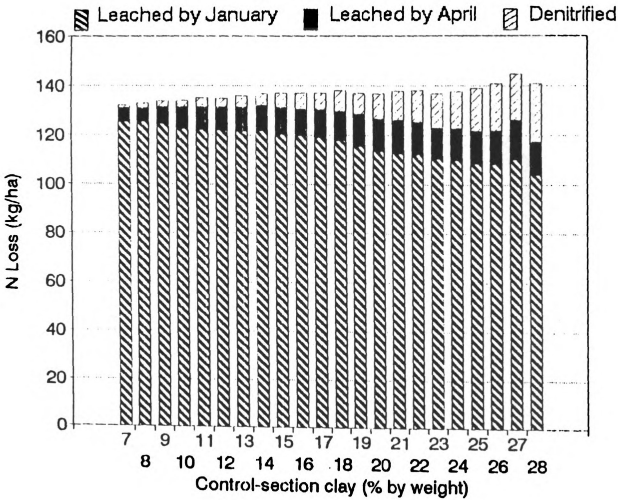

Figure 28. Nitrogen loss under irrigated conditions, 1988-89.

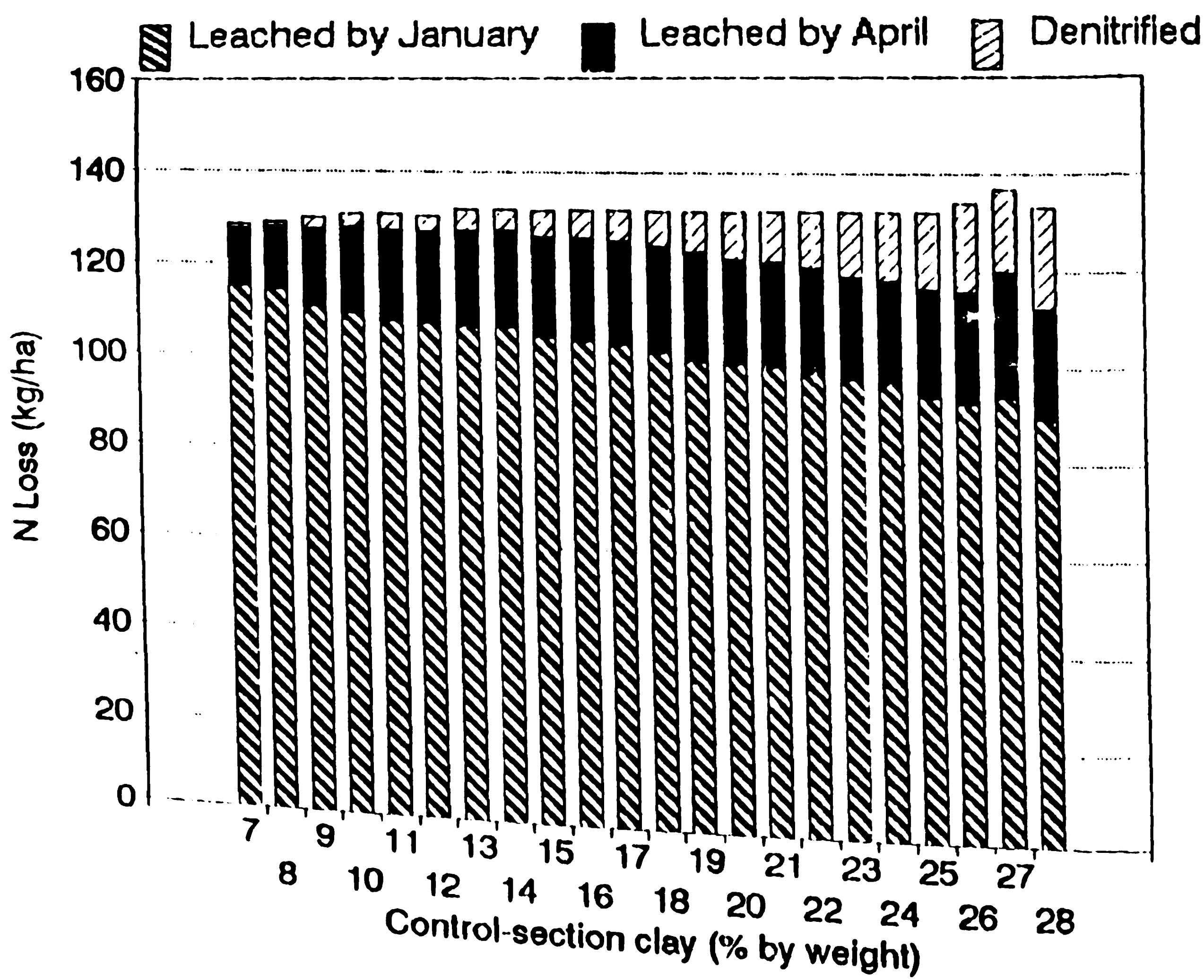

Figure 29. Nitrogen loss under irrigated conditions, 1989-90.

years, the predicted grain yield for 1988 was only 80 percent of the 1987 and 1989 yields. This was apparently due to the high temperatures in July and August 1988; the monthly mean for August 1988 was more than two degrees centigrade higher than in 1987 or 1989 (Table 11). The predicted result was a shortened grain-filling period and a kernel weight which was 80 percent of the 1987 and 1989 values. This kernel-weight variation accounted for the grain-yield differences. The predicted differences in mature biomass were also due to the abbreviated grain-filling stage, as evidenced by differential biomass additions during the modelled grain-filling growth stage.

Since the CERES fertilizer inputs were identical to the 1989 farm management practices, the predicted and actual yields for 1989 were compared. The model predicted 178 bushels per acre. The actual grain yields were 158 bu Ac^{-1} without starter fertilizer and 173 with starter. The results were sufficiently close to lend credibility to the model predictions, in terms of nitrogen uptake and residual soil nitrogen. It was unknown how well the modelled variety (Pioneer 3780) matched the phenological characteristics of the planted variety (Great Lakes 582), in terms of growth stages, required season length, etc.

The predicted leaching losses were inversely related to the amount of nitrogen uptake (Table 18). For 1987 and 1988, less than 10 percent of the predicted total nitrate leaching occurred before September 1st. In the relatively wet growing season of 1989, 30 percent of the total leaching occurred during the same period. Thus, the majority of the predicted annual nitrate leaching was strongly related to post-harvest soil-nitrogen contents. The estimated denitrification losses were nearly identical for the three model years (Table 18). The CERES model predicts denitrification based upon soil nitrogen concentrations, available carbon, and an excess of soil water above the drained upper limit (DUL). Because the first two factors varied little between runs, it appeared that soil moisture was the likely determinant in this case. The soil-moisture argument was consistent with the heavy post-harvest precipitation in 1988.

The leaching losses for the coarsest soil profiles (e.g. 7-10 percent clay) were expected to be relatively high due to the estimated hydraulic characteristics (Table 17). The model predicted slightly *less* total leaching for these profiles (compared to 11-13 percent clay) in 1987, and equivalent or slightly greater leaching in 1988 and 1989. The predicted nitrogen uptake was constant for all soil types within a given year, so the annual nitrogen inputs and outputs were the same. The leaching differences were not related to annual drainage volumes, nor to high-volume leaching events. The leaching output file (*OUTLCH*) revealed slight but consistent differences in the incremental nitrate leaching across soil types. Final residual nitrogen values in the soil profiles were unrelated to the total nitrate leaching.

A possible explanation for this was the nitrogen mineralization sub-routine was affected by the low soil-moisture in the coarse-textured profiles. The low DUL values and high SWCON values would drain a relatively large amount of excess water quite rapidly. The lack of soil moisture would slow mineralization and reduce the inputs to the soil inorganic nitrogen pool. This effect would not be observed in the standard CERES output files, but would explain slight differences that were calculated in the total nitrogen budgets for each soil type.

Rainfed Nitrate Leaching

Table 19 and Figures 30-32 summarize the rainfed leaching output. For the rainfed runs, a single broadcast of 125 kg N ha^{-1} was used, compared to the split applications totalling 288 kg N ha^{-1} for the irrigated runs. Although the rainfed simulations input less than one-third of the irrigated nitrogen fertilization, the rainfed runs for 1987 and 1988 leached between 75-90 percent of the corresponding irrigated runs. This was apparently due to the moisture stress which resulted in poor nitrogen uptake and yields under rainfed conditions. The difference between applied nitrogen and nitrogen uptake was similar between the rainfed and irrigated runs for 1987 and 1988. Hence the nitrate leaching totals were comparable. For 1989, the difference for the rainfed simulation was only one-fifth

Table 18. Selected model outputs for irrigated simulations. Soil input for 18 percent control-section clay.

Property	1987	1988	1989
Grain yield (bu Ac^{-1})	186	149	178
Mature biomass (kg ha^{-1})	20771	18567	19815
Nitrogen uptake "	246	215	234
Nitrate leaching "	121	130	125
Denitrification "	7	8	7

Table 19. Selected model outputs for rainfed simulations. Soil input for 18 percent control-section clay.

Property	1987	1988	1989
Grain yield (bu Ac^{-1})	58	55	161
Mature biomass (kg ha^{-1})	7387	5711	15280
Nitrogen uptake "	87	68	115
Nitrate leaching "	99	125	77
Denitrification "	4	6	5

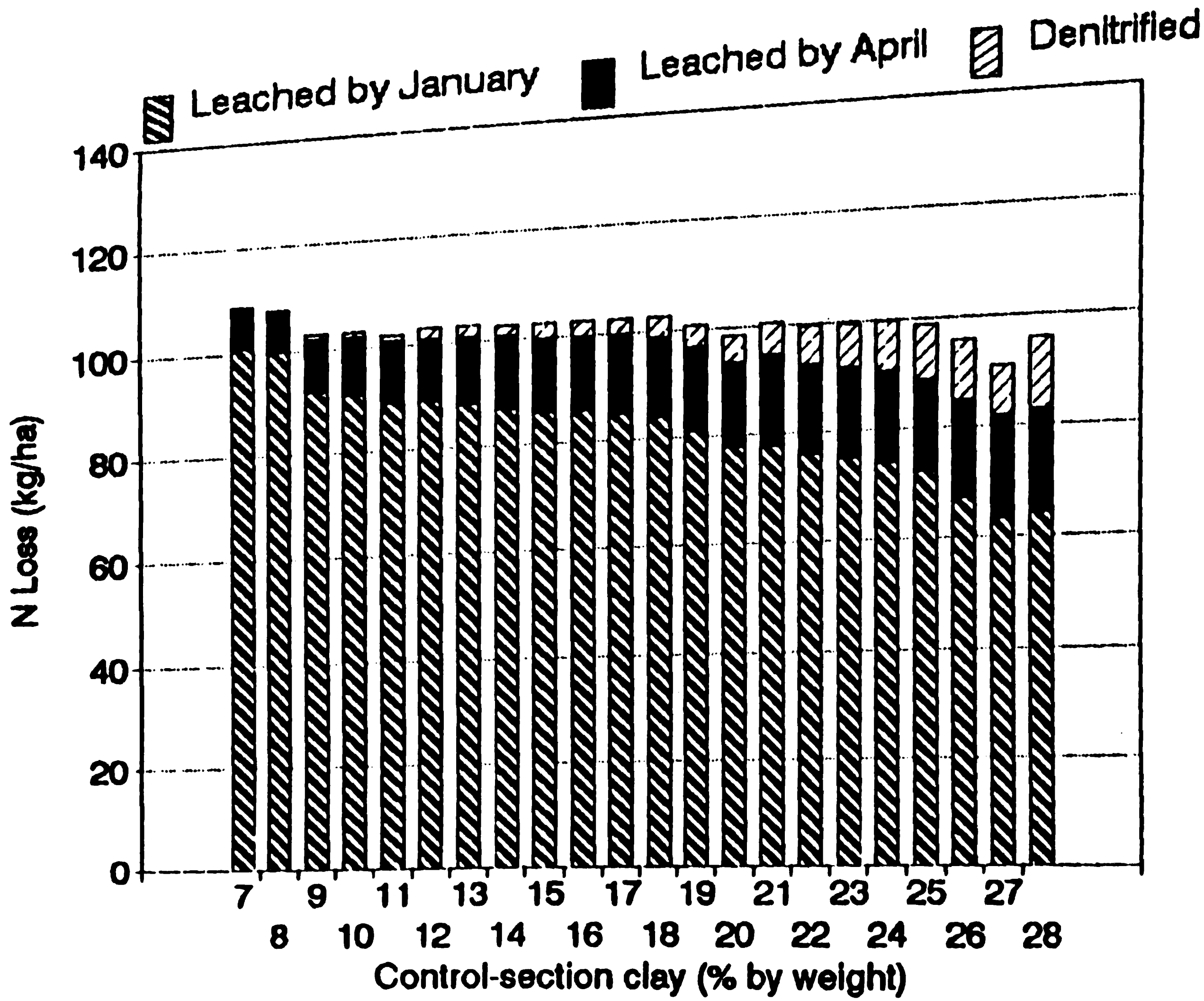

Figure 30. Nitrogen loss under rainfed conditions, 1987-88.

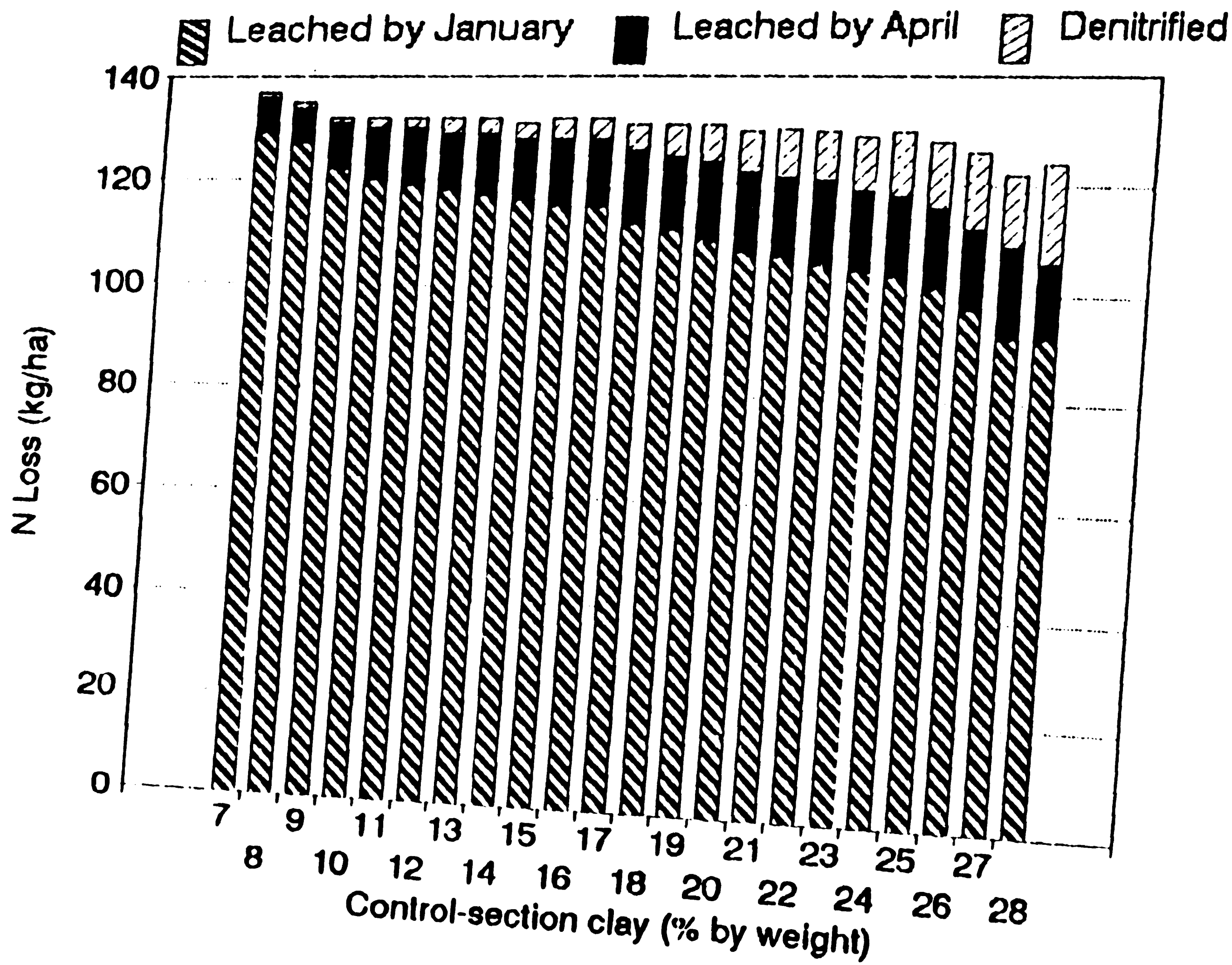

Figure 31. Nitrogen loss under rainfed conditions, 1988-89.

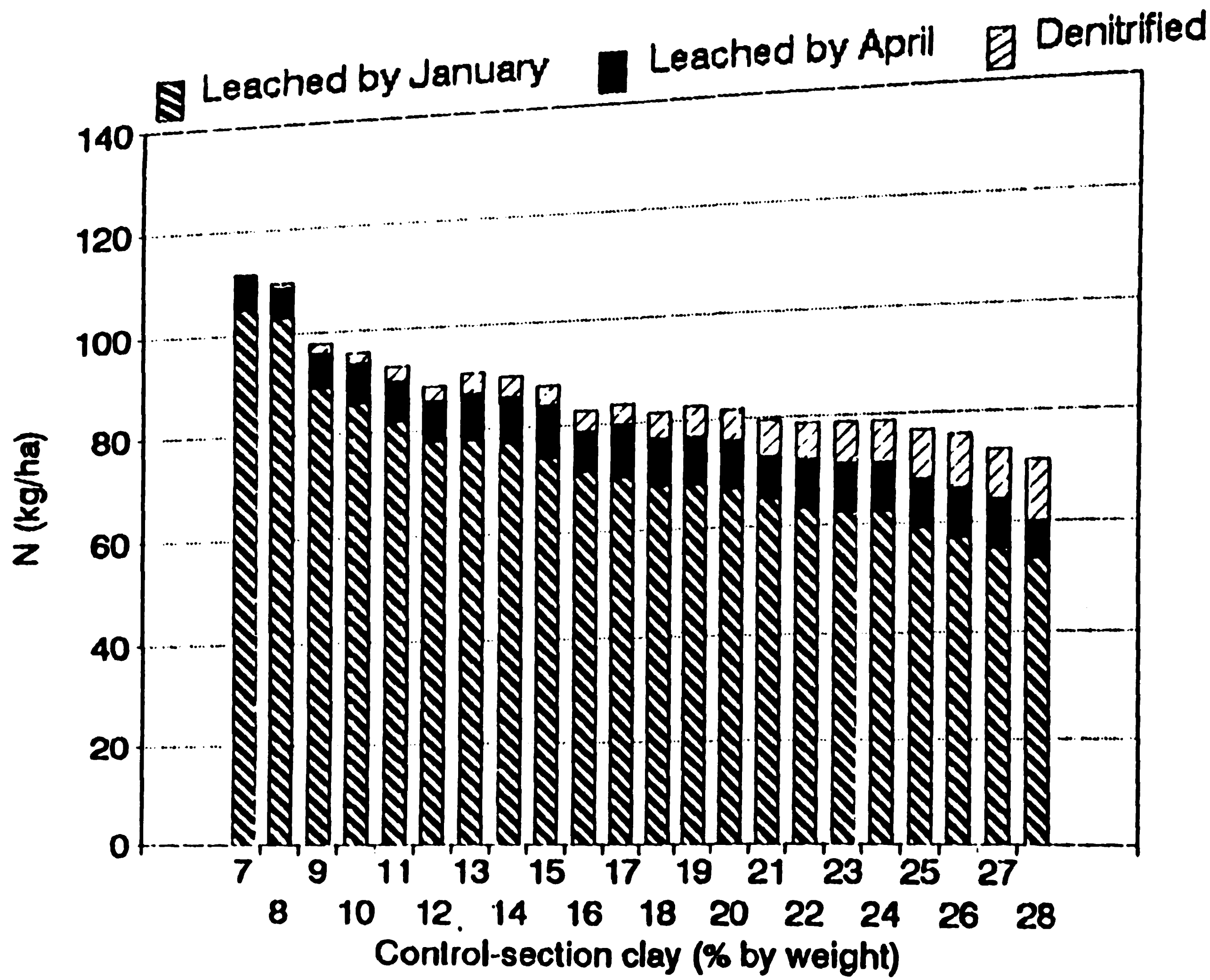

Figure 32. Nitrogen loss under rainfed conditions, 1989-90.

that of the irrigated run for most soil types, resulting in significantly lower predicted leaching.

The effect of soil type on predicted nitrate leaching was more pronounced under rainfed conditions for all three years. The effect was most obvious for the relatively wet 1989 growing season. Whereas the irrigated runs showed approximately a 10 percent difference in leaching across the range of soil types (relative to maximum leaching), the 1987 and 1988 rainfed output showed a 20-25 percent difference. For 1989, the rainfed output indicated nearly a 50 percent reduction in predicted nitrate leaching, going from 7 percent to 28 percent control-section clay.

The degree of rainfed leaching variation due to soil variation was again apparently due to predicted moisture stress and its effect upon nitrogen uptake. The range of rainfed nitrogen uptake across all soil types for 1987 was 78-98 kg N ha^{-1}; for 1988, 62-71 kg N ha^{-1}; and for 1989, 77-123 kg N ha^{-1}. Both the range and magnitude of nitrogen uptake values increased with decreasing moisture stress. When moisture stress was severe, the relative effects of soil hydraulic properties were minimal. But in years with adequate precipitation, the higher water-holding capacity of the finer-textured soil types resulted in lower moisture stress, higher nitrogen uptake, higher total biomass and grain yields, and large decreases in predicted nitrate leaching.

Estimates of Soil-water Nitrate Concentrations and Fluxes

The output contained in the OUTLCH files provided values for both drainage volume and nitrate flux. Thus it was possible to calculate the predicted soil-water nitrate concentration for each weekly increment. Based upon the estimated control-section clay contents of lysimeter clusters one and two, the modelled soil profile with 23 percent control-section clay was used for comparison. The results are presented in Figure 33, along with the lysimeter measurements for that time period (note: the days are not Julian calendar day numbers). The model closely predicted peak nitrate concentrations and the temporal pattern of soil-water nitrate variations. The predicted peaks were unimodal and described a rather regular temporal pattern. The actual lysimeter measurements were bi-modal and also displayed a well-defined pattern. In both 1987 and 1988, the modelled nitrate peak occurred between the measured bi-modal peaks. The modelled nitrate concentrations decreased earlier in time and to a greater degree than the field nitrate measurements.

The missing data points for the modelled concentrations were due to two factors. One, the model re-initialized the soil-profile initial conditions for each run, which lowered the initial soil-moisture and drainage from the end of previous runs. Two, when soil profile drainage did not occur, there was no way to calculate an estimate. For the

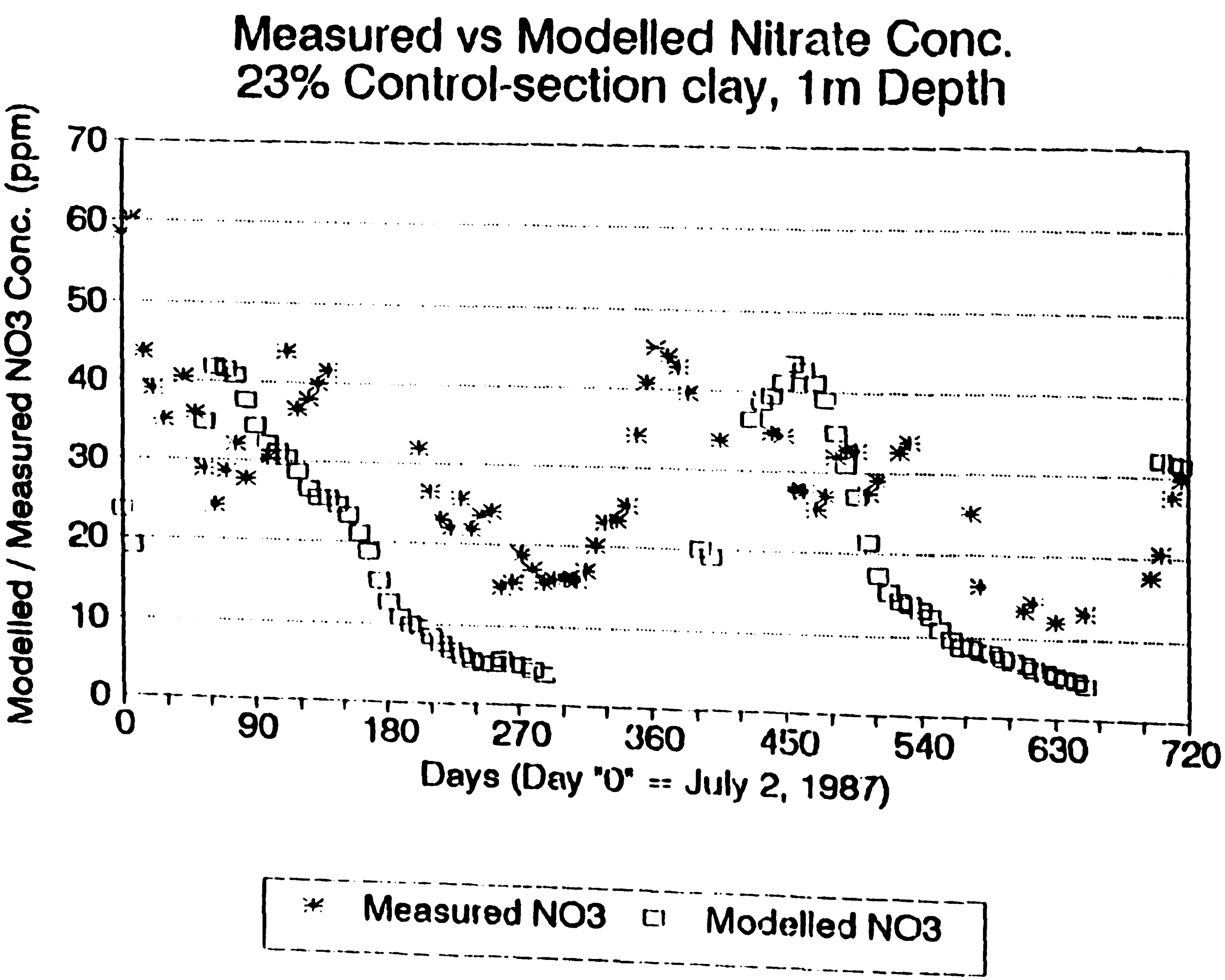

Figure 33. Measured versus modelled nitrate concentration, 23% control-section clay.

field-measured values, missing data points indicated that a sample was not obtained on that date.

A "valley" occurred between the measured nitrate peaks around days 60 (9/1/87) and 420 (8/26/88). These dates correspond roughly to the end of the corn grain-filling stage, and the temporarily depressed measurements were attributed to nitrogen uptake and a subsequent decrease in soil-nitrogen levels. After grain-filling, it was hypothesized that continued mineralization, decreased nitrogen demand and decreased plant water uptake could provide a temporary pulse of nitrate through the soil profile.

The minimum predicted values were approximately half of the measured minimum concentrations (days 300 and 660). This probably resulted from two fall lagoon-waste applications, which were not included in the modelling because they were unknown at the time. Also, the model does not account for a frozen soil surface, which restricts field infiltration and drainage during the winter months. However, the Thornthwaite water balance and the CERES drainage predict similar drainage totals between November and April of each run. With no incremental information for the Thornthwaite estimates, it is difficult to test the frozen-surface and drainage hypothesis.

For the sake of comparison, the incremental drainage volumes predicted by the CERES model were multiplied by the corresponding measured nitrate values for dates where both

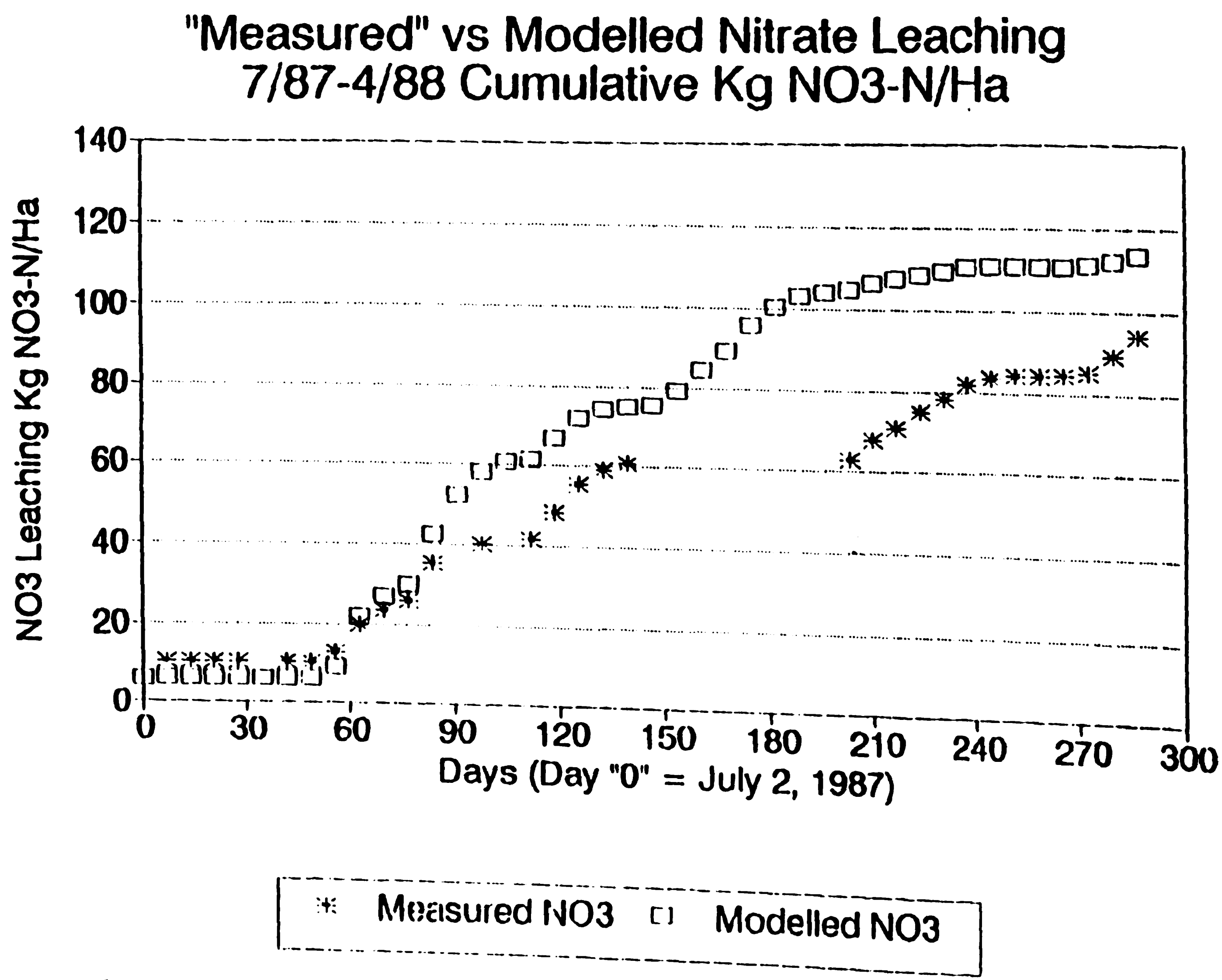

Figure 34. Predicted cumulative nitrate leaching, 1987-88.

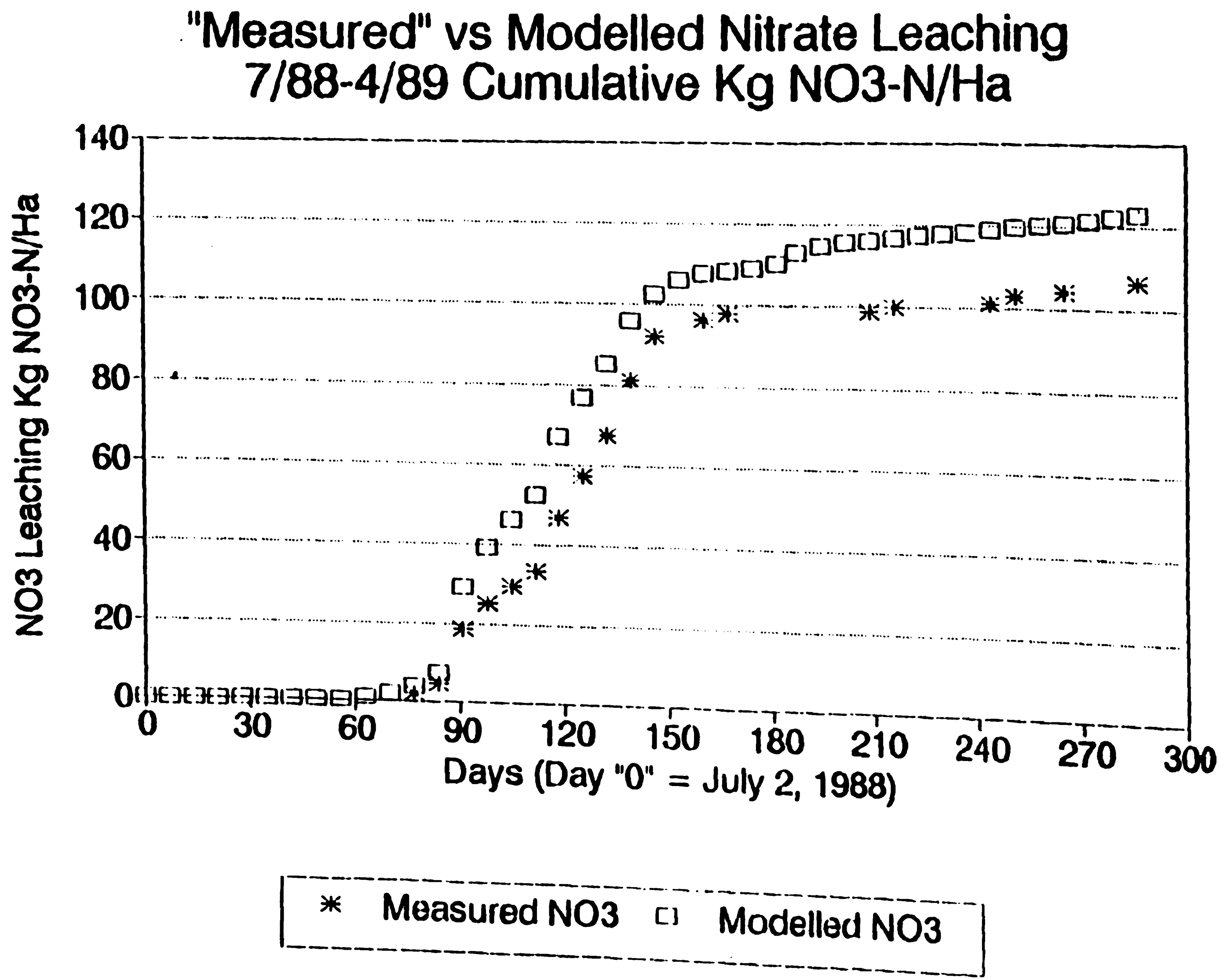

Figure 35. Predicted cumulative nitrate leaching, 1988-89.

data existed. The sample mean for clusters one and two was used for the nitrate value. The cumulative leaching was plotted for the 1987-88 and 1988-89 (April to April) years. Figures 34 and 35 display curves for the CERES leaching prediction and also for the calculated estimate using the measured nitrate mean. Despite the several missing dates for measured nitrate values, and hence no incremental estimate, the cumulative leaching estimates were quite close. The model does not account for two fall applications of lagoon waste each year, which were learned about after the modelling was completed. This would certainly raise the CERES leaching estimate. However, this omission was somewhat offset by the missing field data which certainly would have increased the calculated nitrate flux. It appeared the estimates were reliable based upon checks such as Figure 33 and the comparison with the Thornthwaite predictions.

Based upon the CERES modelling and the calculated leaching values, the best estimate for the nitrate flux at the KBS center-pivot field is:

1987-88 season : 95-115 kg N ha^{-1}

1988-89 season : 105-125 kg N ha^{-1}

CONCLUSIONS

1) Bt1 clay content, Bt1 thickness, and 2Bt2 thickness displayed a high degree of spatial dependence at the KBS study site. The range of spatial dependence varied between 10 and 30 meters. The 2Bt2 clay content displayed no spatial dependence at the scale of observation. Block kriging produced an isarithmic map of control-section clay contents, which varied between 7 and 28 percent clay.

2) Soil-water nitrate concentrations varied systematically over time and with land-use. Peak nitrate concentrations were higher under corn than under alfalfa. Under hardwood forest, the soil-water nitrate concentrations were consistently below 2 ppm nitrogen as nitrate.

3) Using actual soil-water nitrate concentrations and computer-modelled profile drainage estimates, nitrate flux estimates were calculated for the range of control-section clay contents at the study site. Under irrigated corn, an estimated 95-125 kg N ha^{-1} was leached below a one-meter depth during the 1987 and 1988 cropping seasons.

4) Nitrate leaching was computer-modelled for rainfed corn production, for the range of control-section clay contents at the study site. Predicted rainfed leaching losses were between 85 and 135 kg N ha^{-1} for the simulated 1987 and 1988 growing seasons.

5) The CERES Maize model predicted decreased nitrate leaching and increased denitrification losses with increasing control-section clay content, for study-site soils. This effect was most dramatic for the 1989 rainfed simulation, where predicted losses under the finest-textured profile were only 55 percent of those under the coarsest-textured profile.

6) The model accurately predicted corn-grain yields and peak soil-water nitrate concentrations. Close agreement was obtained between modelled nitrate leaching estimates and fluxes calculated from nitrate-concentration measurements and fluxes calculated from nitrate concentration measurements and predicted soil-water drainage.

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APPENDIX I

Horizon Depth and Thickness Data

Appendix I. Pedon Horizon-Depth Data
Note: See text for horizon descriptions

COORDINATE (m)			HORIZON DEPTHS (Centimeters)						SOIL SERIES DATA	
X	Y	Z	Ap	E	Bt1	2Bt2	BC	3C	CS Clay	Series
0.0	0.0	1.6	0-20	20-38	38-56	56-91		91-160	12.2	Oshtemo
0.0	20.0	1.8	0-25	25-41	41-56	56-114		114-160	11.9	Oshtemo
0.0	40.0	1.7	0-20	20-30	30-114		114-152	152-193	30.6	Kalamazoo
0.0	60.0	1.6	0-18	18-28	28-61	61-109		109-178	17.9	Oshtemo
0.0	80.0	1.6	0-20	20-33	33-74	74-140		140-160	21.3	Kalamazoo
0.0	100.0	1.6	0-18		18-43	43-91		91-152	16.8	Oshtemo
0.0	120.0	1.6	0-20	20-30	30-61	61-109		109-175	16.0	Oshtemo
0.0	140.0	1.5	0-20		20-86	86-130		130-180	29.6	Kalamazoo
20.0	0.0	1.5	0-20		20-36	36-69		69-175	14.8	Oshtemo
20.0	20.0	1.7	0-20		20-48	48-79		79-175	15.4	Oshtemo
20.0	40.0	1.6	0-18	18-46	46-107		107-142	142-175	22.6	Kalamazoo
20.0	60.0	1.3	0-15		15-48	48-104		104-178	19.1	Kalamazoo
20.0	80.0	1.2	0-20		20-41	41-160		160-175	10.3	Oshtemo
20.0	100.0	1.3	0-23		23-51	51-99		99-180	16.1	Oshtemo
20.0	120.0	1.3	0-23		23-58	58-89		89-160	19.8	Kalamazoo
20.0	140.0	1	0-20	20-36	36-114			114-160	21.6	Kalamazoo
40.0	0.0	1.4	0-20		20-53	53-81		81-157	19.4	Kalamazoo
40.0	20.0	1.4	0-23		23-48	48-124		124-152	12.4	Oshtemo
40.0	40.0	1.4	0-20		20-66	66-109		109-157	24.8	Kalamazoo
40.0	60.0	1	0-25	25-46	46-64	64-99		99-170	12.8	Oshtemo
40.0	80.0	1	0-33		33-76	76-147		147-178	25.1	Kalamazoo

Appendix I. Pedon Horizon-Depth Data
Note: See text for horizon descriptions

COORDINATE (m)			HORIZON DEPTHS (Centimeters)						SOIL SERIES DATA	
X	Y	Z	Ap	E	Bt1	2Bt2	BC	3C	CS Clay	Series
40.0	100.0	1	0-28		28-58	58-104		104-168	21.9	Kalamazoo
40.0	120.0	1.1	0-25	25-38	38-71	71-165		165-208	20.1	Kalamazoo
40.0	140.0	0.8	0-28	28-38	38-66	66-97		97-168	16.4	Oshtemo
60.0	0.0	1.3	0-20	20-38	38-58	58-79		79-163	17.0	Oshtemo
60.0	20.0	1.3	0-20		20-58	58-94		94-163	27.8	Kalamazoo
60.0	40.0	1.2	0-23		23-58	58-76		76-160	17.0	Oshtemo
60.0	60.0	0.9	0-23		23-61	61-102		102-168	21.3	Kalamazoo
60.0	80.0	0.9	0-20		20-41	41-61		61-160	16.2	Oshtemo
60.0	100.0	0.8	0-23	23-36	36-112	112-157		157-198	10.8	Oshtemo
60.0	120.0	1.1	0-20		20-91	91-142	142-170		30.4	Kalamazoo
60.0	140.0	0.7	0-20		20-41	41-69	135-175	69-135	13.3	Oshtemo
80.0	0.0	1.3	0-20	20-36	36-137			137-173	22.6	Kalamazoo
80.0	20.0	1.2	0-23	23-33	33-48	48-91		91-157	13.3	Oshtemo
80.0	40.0	1.2	0-28	28-41	41-155		155-178	178-216	16.6	Oshtemo
80.0	60.0	1	0-20		20-61	61-81		81-168	23.4	Kalamazoo
80.0	80.0	0.8	0-23		23-58	58-130	130-180	180-211	18.7	Kalamazoo
80.0	100.0	0.8	0-23		23-58	58-112		112-168	22.7	Kalamazoo
80.0	120.0	1	0-18	18-33	33-76			76-170	10.8	Oshtemo
80.0	140.0	0.7	0-23	23-36	36-64	64-130		130-170	14.8	Oshtemo
100.0	0.0	1.4	0-23	23-41	41-61	61-152			14.1	Oshtemo
100.0	20.0	1.2	0-23		23-69	69-94		94-168	35.2	Kalamazoo

Appendix I. Pedon Horizon-Depth Data
Note: See text for horizon descriptions

COORDINATE (m)			HORIZON DEPTHS (Centimeters)						SOIL SERIES DATA	
X	Y	Z	Ap	E	Bt1	2Bt2	BC	3C	CS Clay	Series
100.0	40.0	1.2	0-20	20-33	33-48	48-124	124-163	163-216	13.2	Oshtemo
100.0	60.0	1.1	0-15	15-28	28-41	41-69		69-168	14.3	Oshtemo
100.0	80.0	0.8	0-20	20-38	38-61	61-102		102-168	14.0	Oshtemo
100.0	100.0	0.8	0-30		30-46			46-175	8.8	Oshtemo
100.0	120.0	0.8	0-23	23-33	33-94		94-127	127-168	24.4	Kalamazoo
100.0	140.0	0.6	0-28		28-74	74-99		99-170	27.8	Kalamazoo
120.0	0.0	1.6	0-18		18-48	48-122		122-152	18.6	Kalamazoo
120.0	20.0	1.3	0-25		25-64	64-99		99-165	23.0	Kalamazoo
120.0	40.0	1.2	0-23		23-46	46-61		61-163	14.6	Oshtemo
120.0	60.0	1	0-25		25-53	53-99		99-178	16.9	Oshtemo
120.0	80.0	0.7	0-36		36-74	74-117		117-165	24.2	Kalamazoo
120.0	100.0	0.7	0-25	25-36	36-69	69-102		102-163	23.1	Kalamazoo
120.0	120.0	0.7	0-20		20-58	58-117		117-168	23.5	Kalamazoo
120.0	140.0	0.7	0-20		20-61	61-112		112-178	25.1	Kalamazoo
140.0	0.0	1.2	0-20	20-36	36-43	43-130		130-173	8.5	Oshtemo
140.0	20.0	1.2	0-30		30-69	69-89		89-168	24.8	Kalamazoo
140.0	40.0	1.1	0-23		23-56	56-91		91-173	17.4	Oshtemo
140.0	60.0	1	0-23		23-58	58-71		71-203	18.6	Kalamazoo
140.0	80.0	0.7	0-18	18-28	28-58			58-163	21.6	Kalamazoo
140.0	100.0	0.7	0-25		25-114	114-147		147-216	13.7	Oshtemo
140.0	120.0	0.7	0-25	25-71	71-168			168-216	11.7	Oshtemo

Appendix I. Pedon Horizon-Depth Data
Note: See text for horizon descriptions

COORDINATE (m)			HORIZON DEPTHS (Centimeters)						SOIL SERIES DATA	
X	Y	Z	Ap	E	Bt1	2Bt2	BC	3C	CS Clay	Series
140.0	140.0	0.6	0-23	23-69				69-168	5.0	Spinks
160.0	0.0	0.9	0-23	23-64	64-127			127-170	5.6	Oshtemo
160.0	20.0	0.8	0-25		25-56	56-94		94-170	16.1	Oshtemo
160.0	40.0	0.7	0-25		25-64	64-97		97-165	16.4	Oshtemo
160.0	60.0	0.6	0-25		25-66	66-163	163-216		15.7	Oshtemo
160.0	80.0	0.5	0-25		25-71	71-160		160-206	25.1	Kalamazoo
160.0	100.0	0.6	0-23		23-61	61-122		122-165	21.7	Kalamazoo
160.0	120.0	0.7	0-23		23-69	69-145	145-160	160-178	22.1	Kalamazoo
160.0	140.0	0.5	0-33	33-51	51-71	71-102		102-173	13.2	Oshtemo
180.0	0.0	0.9	0-23	23-36	36-69		69-203	203-246	15.2	Oshtemo
180.0	20.0	0.7	0-25	25-33	33-86			86-168	10.4	Oshtemo
180.0	40.0	0.6	0-23	23-74				74-163	5.0	Spinks
180.0	60.0	0.4	0-36		36-51	51-97		97-178	12.2	Oshtemo
180.0	80.0	0.4	0-23		23-69			69-160	26.0	Kalamazoo
180.0	100.0	0.7	0-20		20-43	43-71		71-163	18.3	Kalamazoo
180.0	120.0	0.7	0-23		23-48	48-69		69-155	18.1	Kalamazoo
180.0	140.0	0.7	0-20		20-61	61-86		86-160	21.5	Kalamazoo
200.0	0.0	0.9	0-20		20-61	61-130		130-163	24.1	Kalamazoo
200.0	20.0	0.7	0-28		28-107		107-185	185-211	28.2	Kalamazoo
200.0	40.0	0.7	0-18		18-51	51-142		142-211	20.6	Kalamazoo
200.0	60.0	0.4	0-20		20-46	46-91		91-163	18.6	Kalamazoo

Appendix I. Pedon Horizon-Depth Data
Note: See text for horizon descriptions

COORDINATE (m)			HORIZON DEPTHS (Centimeters)						SOIL SERIES DATA	
X	Y	Z	Ap	E	Bt1	2Bt2	BC	3C	CS Clay	Series
200.0	80.0	0.4	0-20		20-46	46-89		89-170	23.4	Kalamazoo
200.0	100.0	0.8	0-18	18-28	28-46	46-94		94-163	15.6	Oshtemo
200.0	120.0	0.8	0-20		20-58	58-71		71-178	21.8	Kalamazoo
200.0	140.0	0.8	0-23	23-30	30-58	58-104		104-163	20.6	Kalamazoo
220.0	0.0	0.7	0-23	23-30	30-48			48-170	19.5	Kalamazoo
220.0	20.0	0.7	0-18	18-38	38-132		132-170		7.5	Oshtemo
220.0	40.0	0.7	0-25		25-102			102-178	9.4	Oshtemo
220.0	60.0	0.7	0-20	20-28	28-51	51-112		112-168	17.8	Oshtemo
220.0	80.0	0.6	0-23		23-56	56-127		127-160	22.1	Kalamazoo
220.0	100.0	0.8	0-23		23-61	61-119		119-165	21.1	Kalamazoo
220.0	120.0	0.7	0-18		18-59			59-165	30.0	Kalamazoo
220.0	140.0	0.7	0-28		28-58	58-104		104-188	20.3	Kalamazoo
240.0	0.0	0.5	0-23	23-41	41-84	84-112		112-165	25.9	Kalamazoo
240.0	20.0	0.4	0-20	20-30	30-46	46-61		61-165	16.1	Oshtemo
240.0	40.0	0.6	0-25	25-46				46-208	5.0	Spinks
240.0	60.0	0.7	0-23		23-66	66-86		86-160	32.8	Kalamazoo
240.0	80.0	0.5	0-28	28-36	36-94		94-201		24.3	Kalamazoo
240.0	100.0	0.7	0-28	28-36	36-84	84-130		130-163	25.5	Kalamazoo
240.0	120.0	0.6	0-23	23-33	33-71			71-163	18.3	Kalamazoo
240.0	140.0	0.7	0-20		20-51	51-150		150-211	23.9	Kalamazoo
260.0	0.0	0.5	0-20	20-36	36-56			56-160	20.8	Kalamazoo

Appendix I. Pedon Horizon-Depth Data
Note: See text for horizon descriptions

COORDINATE (m)			HORIZON DEPTHS (Centimeters)						SOIL SERIES DATA	
X	Y	Z	Ap	E	Bt1	2Bt2	BC	3C	CS Clay	Series
260.0	20.0	0.4	0-30	30-38	38-66	66-114		114-170	19.3	Kalamazoo
260.0	40.0	0.5	0-25	25-33	33-61	61-74		74-170	22.7	Kalamazoo
260.0	60.0	0.7	0-20	20-28	28-51	51-84		84-170	16.5	Oshtemo
260.0	80.0	0.6	0-23	23-46	46-91	91-132	132-150	150-170	19.5	Kalamazoo
260.0	100.0	0.8	0-18		18-38	38-163		163-216	14.3	Oshtemo
260.0	120.0	0.6	0-20	20-30	30-114		114-173	173-218	9.8	Oshtemo
260.0	140.0	0.7	0-20	20-30	30-56	56-137		137-173	18.2	Kalamazoo
280.0	0.0	0.5	0-20	20-46	46-102	102-170		170-206	21.6	Kalamazoo
280.0	20.0	0.3	0-23		23-58	58-81		81-175	20.0	Kalamazoo
280.0	40.0	0.4	0-23		23-46	46-81		81-170	16.0	Oshtemo
280.0	60.0	0.7	0-23	23-48	48-173			173-198	9.5	Oshtemo
280.0	80.0	0.7	0-28	28-48	48-104	104-160		160-173	29.4	Kalamazoo
280.0	100.0	0.7	0-23		23-66	66-112		112-178	19.1	Kalamazoo
280.0	120.0	0.5	0-23		23-79	79-132		132-170	27.4	Kalamazoo
280.0	140.0	0.6	0-20		20-51	51-76		76-170	20.9	Kalamazoo
300.0	0.0	0.4	0-30	30-41	41-89	89-127	127-178		21.2	Miami
300.0	20.0	0.3	0-28	28-46	46-64			64-178	8.8	Oshtemo
300.0	40.0	0.2	0-25		25-58	58-81		81-170	20.4	Kalamazoo
300.0	60.0	0.6	0-23		23-64	64-145		145-170	18.7	Kalamazoo
300.0	80.0	0.7	0-20	20-33	33-56			56-160	8.3	Oshtemo
300.0	100.0	0.7	0-23	23-58	58-84			84-170	12.0	Oshtemo

Appendix I. Pedon Horizon-Depth Data
Note: See text for horizon descriptions

COORDINATE (m)			HORIZON DEPTHS (Centimeters)						SOIL SERIES DATA	
X	Y	Z	Ap	E	Bt1	2Bt2	BC	3C	CS Clay	Series
300.0	120.0	0.5	0-23	23-33	33-107		107-163	163-216	20.6	Kalamazoo
300.0	140.0	0.4	0-25	25-33	33-74	74-99		99-170	26.2	Kalamazoo
320.0	0.0	0.3	0-20		20-66	66-91		91-160	33.3	Kalamazoo
320.0	20.0	0.1	0-23		23-48	48-61		61-216	19.4	Kalamazoo
320.0	40.0	0.1	0-28		28-89	89-130		130-170	28.7	Kalamazoo
320.0	60.0	0.3	0-23		23-38	38-150	150-183	183-211	15.6	Oshtemo
320.0	80.0	0.3	0-20		20-51	51-132	132-157	157-211	18.6	Kalamazoo
320.0	100.0	0.6	0-23		23-51	51-140	140-155	155-173	14.6	Oshtemo
320.0	120.0	0.5	0-23		23-61	61-69		69-165	27.0	Kalamazoo
320.0	140.0	0.4	0-28		28-61	61-79		79-173	20.7	Kalamazoo
340.0	0.0	0.4	0-20		20-58	58-107		107-178	26.5	Kalamazoo
340.0	20.0	0.2	0-20	20-30	30-71	71-140		140-173	28.0	Kalamazoo
340.0	40.0	0.2	0-30		30-69	69-124		124-165	21.7	Kalamazoo
340.0	60.0	0.3	0-28	28-48	48-140		140-211	211-254	6.4	Oshtemo
340.0	80.0	0.3	0-30	30-48	48-69	69-142	142-191	191-241	17.4	Oshtemo
340.0	100.0	0.4	0-33	33-56	56-71	71-130	130-170		13.2	Oshtemo
340.0	120.0	0.6	0-23	23-43	43-71			71-175	8.8	Oshtemo
340.0	140.0	0.6	0-25	25-48	48-74	74-109		109-173	19.9	Kalamazoo
360.0	0.0	0.3	0-23		23-48	48-66		66-168	24.1	Kalamazoo
360.0	20.0	0.4	0-18	18-25	25-61	61-97		97-170	23.2	Kalamazoo
360.0	40.0	0.3	0-23		23-61	61-122		122-173	24.3	Kalamazoo

Appendix I. Pedon Horizon-Depth Data
Note: See text for horizon descriptions

COORDINATE (m)			HORIZON DEPTHS (Centimeters)						SOIL SERIES DATA	
X	Y	Z	Ap	E	Bt1	2Bt2	BC	3C	CS Clay	Series
360.0	60.0	0.4	0-18	18-25	25-61	61-122		122-173	21.5	Kalamazoo
360.0	80.0	0.3	0-20		20-53	53-99		99-170	22.0	Kalamazoo
360.0	100.0	0.5	0-23		23-53	53-71		71-173	20.6	Kalamazoo
360.0	120.0	0.6	0-25		25-48	48-71		71-173	19.1	Kalamazoo
360.0	140.0	0.7	0-23	23-30	30-127			127-173	10.2	Oshtemo
380.0	0.0	0.1	0-20		20-51	51-66		66-178	25.0	Kalamazoo
380.0	20.0	0.2	0-20	20-28	28-58	58-84		84-170	22.1	Kalamazoo
380.0	40.0	0.3	0-20		20-53	53-152		152-168	22.3	Kalamazoo
380.0	60.0	0.3	0-23	23-33	33-53	53-91		91-165	16.6	Oshtemo
380.0	80.0	0.3	0-23		23-53	53-81		81-165	22.5	Kalamazoo
380.0	100.0	0.4	0-23	23-33	33-79	79-97		97-170	30.1	Kalamazoo
380.0	120.0	0.4	0-23		23-64	64-81		81-165	20.6	Kalamazoo
380.0	140.0	0.6	0-18		18-58	58-104		104-170	28.5	Kalamazoo
400.0	0.0	0	0-25	25-61	61-91	91-147		147-178	21.3	Kalamazoo
400.0	20.0	0.1	0-23	23-30	30-64	64-107		107-165	21.4	Kalamazoo
400.0	40.0	0.1	0-23		23-53	53-102		102-163	21.4	Kalamazoo
400.0	60.0	0	0-20		20-51	51-74		74-165	24.0	Kalamazoo
400.0	80.0	0	0-20		20-56			56-165	28.8	Kalamazoo
400.0	100.0	0.1	0-23		23-56	56-76		76-170	22.4	Kalamazoo
400.0	120.0	0.1	0-18		18-43	43-97		97-180	18.8	Kalamazoo
400.0	140.0	0.3	0-15		15-61	61-127		127-170	32.6	Kalamazoo

Appendix I. Pedon Horizon-Depth Data
Note: See text for horizon descriptions

COORDINATE (m)			HORIZON DEPTHS (Centimeters)						SOIL SERIES DATA	
X	Y	Z	Ap	E	Bt1	2Bt2	BC	3C	CS Clay	Series
420.0	0.0	0.1	0-18		18-51	51-97		97-173	25.0	Kalamazoo
420.0	20.0	0	0-18	18-58	58-79	79-152		152-173	16.4	Oshtemo
420.0	40.0	0	0-25		25-76	76-127		127-168	32.0	Kalamazoo
420.0	60.0	-0.1	0-25		25-71	71-97		97-178	25.9	Kalamazoo
420.0	80.0	-0.2	0-30		30-84	84-135		135-170	31.6	Kalamazoo
420.0	100.0	-0.1	0-30		30-79	79-142		142-173	17.8	Oshtemo
420.0	120.0	-0.1	0-25		25-56	56-89		89-170	20.9	Kalamazoo
420.0	140.0	0.1	0-25		25-56	56-198		198-218	19.8	Kalamazoo
440.0	0.0	0	0-20	20-30	30-61	61-76		76-168	19.7	Kalamazoo
440.0	20.0	0.2	0-20		20-53	53-74		74-168	27.7	Kalamazoo
440.0	40.0	0.4	0-23	23-28	28-56		117-173	56-117	25.1	Kalamazoo
440.0	60.0	0.1	0-18		18-38	38-69		69-168	18.2	Kalamazoo
440.0	80.0	0	0-20		20-48	48-94		94-152	20.6	Kalamazoo
440.0	100.0	0	0-23		23-58	58-86		86-168	26.0	Kalamazoo
440.0	120.0	-0.1	0-18		18-46	46-86		86-173	20.5	Kalamazoo
440.0	140.0	0.1	0-20		20-58	58-135		135-165	27.3	Kalamazoo
LYSIMETER CLUSTER 1										
420.0	20.5	-	0-18	18-36	36-81	81-135		135-170	23.8	Kalamazoo
420.0	21.0	-	0-20		20-81			81-170	21.5	Kalamazoo

Appendix I. Pedon Horizon-Depth Data
Note: See text for horizon descriptions

COORDINATE (m)			HORIZON DEPTHS (Centimeters)						SOIL SERIES DATA	
X	Y	Z	Ap	E	Bt1	2Bt2	BC	3C	CS Clay	Series
420.0	22.0	-	0-23		23-84	84-130		130-170	26.5	Kalamazoo
420.0	24.0	-	0-23	23-36	36-97	97-127		127-170	24.5	Kalamazoo
420.0	28.0	-	0-23	23-33	33-79	79-102		102-170	30.7	Kalamazoo
420.0	36.0	-	0-23		23-64	64-91		91-170	22.4	Kalamazoo
404.0	20.0	-	0-20		20-58	58-86		86-170	21.1	Kalamazoo
412.0	20.0	-	0-23	23-30	30-89	89-127		127-173	28.5	Kalamazoo
418.0	20.0	-	0-23	23-36	36-79	79-119		119-163	23.9	Kalamazoo
419.0	20.0	-	0-18		18-79	79-99		99-170	28.5	Kalamazoo
419.5	20.0	-	0-20	20-46	46-79	79-112		112-170	16.2	Oshtemo

LYSIMETER CLUSTER 2

174.0	133.0	-	0-33		33-79	79-102		102-170	29.7	Kalamazoo
173.5	133.0	-	0-30		30-79	79-109		109-173	29.0	Kalamazoo
173.0	133.0	-	0-30		30-74	74-127		127-170	25.0	Kalamazoo
172.0	133.0	-	0-28	28-36	36-81	81-117		117-168	25.5	Kalamazoo
170.0	133.0	-	0-28	28-38	38-76	76-137		137-160	21.9	Kalamazoo
166.0	133.0	-	0-36	36-46	46-114	114-132		132-216	26.5	Miami
158.0	133.0	-	0-38		38-86	86-216			16.4	Oshtemo
174.0	132.5	-	0-30		30-69	69-104		104-168	27.8	Kalamazoo

Appendix I. Pedon Horizon-Depth Data
Note: See text for horizon descriptions

COORDINATE (m)			HORIZON DEPTHS (Centimeters)						SOIL SERIES DATA	
X	Y	Z	Ap	E	Bt1	2Bt2	BC	3C	CS Clay	Series
174.0	132.0	-	0-30		30-66	66-119		119-173	19.7	Kalamazoo
174.0	131.0	-	0-30		30-76	76-102		102-168	25.1	Kalamazoo
174.0	129.0	-	0-25		25-64	64-81		81-167	21.0	Kalamazoo
174.0	125.0	-	0-30	30-43	43-122		122-198	198-216	23.6	Kalamazoo
174.0	117.0	-	0-20		20-33	33-89		89-178	21.5	Kalamazoo
LYSIMETER CLUSTER 3										
32.0	43.0	-	0-20		20-56	56-104		104-191	22.3	Kalamazoo
31.5	43.0	-	0-20		20-56	56-99		99-160	21.0	Kalamazoo
31.0	43.0	-	0-23		23-61	61-97		97-160	23.1	Kalamazoo
30.0	43.0	-	0-20		20-56	56-104		104-168	23.0	Kalamazoo
24.0	43.0	-	0-25		25-109		109-173	173-216	28.2	Kalamazoo
32.0	43.5	-	0-18	18-25	25-61	61-91		91-170	21.5	Kalamazoo
32.0	44.0	-	0-23		23-64	64-91		91-170	25.5	Kalamazoo
32.0	45.0	-	0-20		20-76	76-107		107-170	23.4	Kalamazoo
32.0	47.0	-	0-20		20-76	76-102		102-170	27.3	Kalamazoo
32.0	51.0	-	0-20		20-69	69-112		112-170	22.2	Kalamazoo
32.0	59.0	-	0-18		18-53	53-91		91-170	21.6	Kalamazoo

APPENDIX II

Data Input for Semivariogram Calculations

Appendix 2. DATA INPUT FOR SEMIVARIOGRAM CALCULATIONS

Note: "-99.0" used for missing "% clay" when thickness is "0"

Coordinate (m)		Bt1 Data		2Bt2 Data		Control-Sec. Clay
X	Y	Clay (%)	Thickness (cm)	Clay (%)	Thickness (cm)	(%)
0.0	0.0	22.5	18	6.4	35	12.2
0.0	20.0	24.4	15	6.5	58	11.9
0.0	40.0	30.6	84	-99.0	0	30.6
0.0	60.0	23.6	33	6.9	48	17.9
0.0	80.0	24.5	41	7.0	66	21.3
0.0	100.0	26.6	25	6.9	46	16.8
0.0	120.0	21.6	31	7.0	48	16.0
0.0	140.0	29.6	66	7.0	44	29.6
20.0	0.0	25.6	16	9.5	33	14.8
20.0	20.0	22.5	28	6.4	31	15.4
20.0	40.0	22.6	61	-99.0	0	22.6
20.0	60.0	25.4	33	6.9	56	19.1
20.0	80.0	15.6	21	6.4	119	10.3
20.0	100.0	22.5	28	8.0	48	16.1
20.0	120.0	27.5	28	9.9	31	19.8
20.0	140.0	21.6	78	-99.0	0	21.6
40.0	0.0	26.4	33	5.9	28	19.4
40.0	20.0	17.7	25	7.0	76	12.4
40.0	40.0	26.4	46	6.5	43	24.8
40.0	60.0	20.6	18	8.4	35	12.8
40.0	80.0	27.5	43	10.3	71	25.1
40.0	100.0	27.5	30	13.4	46	21.9
40.0	120.0	26.4	33	7.9	84	20.1
40.0	140.0	23.4	28	7.4	31	16.4
60.0	0.0	24.5	20	9.9	21	17.0
60.0	20.0	32.4	38	13.4	36	27.8
60.0	40.0	20.5	35	8.9	18	17.0
60.0	60.0	25.4	38	8.5	41	21.3
60.0	80.0	23.4	21	6.6	20	16.2
60.0	100.0	10.8	76	6.6	45	10.8
60.0	120.0	30.4	71	9.1	51	30.4
60.0	140.0	15.7	21	11.5	28	13.3
80.0	0.0	22.6	101	-99.0	0	22.6

Appendix 2. DATA INPUT FOR SEMIVARIOGRAM CALCULATIONS

Note: "-99.0" used for missing "% clay" when thickness is "0"

Coordinate (m)		Bt1 Data		2Bt2 Data		Control-Sec. Clay
		Clay	Thickness	Clay	Thickness	
X	Y	(%)	(cm)	(%)	(cm)	(%)
80.0	20.0	23.4	15	9.0	43	13.3
80.0	40.0	-99.0	0	16.6	114	16.6
80.0	60.0	26.3	41	10.1	20	23.4
80.0	80.0	22.4	35	10.1	72	18.7
80.0	100.0	29.4	35	7.1	54	22.7
80.0	120.0	-99.0	0	10.8	43	10.8
80.0	140.0	18.5	28	10.1	66	14.8
100.0	0.0	24.6	20	7.1	91	14.1
100.0	20.0	37.5	46	9.0	25	35.2
100.0	40.0	20.5	15	10.1	76	13.2
100.0	60.0	20.4	13	11.5	28	14.3
100.0	80.0	17.5	23	11.0	41	14.0
100.0	100.0	-99.0	0	8.8	16	8.8
100.0	120.0	24.4	61	-99.0	0	24.4
100.0	140.0	29.3	46	10.4	25	27.8
120.0	0.0	24.4	30	10.0	64	18.6
120.0	20.0	26.4	39	10.9	35	23.0
120.0	40.0	17.5	23	10.1	15	14.6
120.0	60.0	22.4	28	9.9	46	16.9
120.0	80.0	28.4	38	11.0	43	24.2
120.0	100.0	30.4	33	9.0	33	23.1
120.0	120.0	28.2	38	8.5	59	23.5
120.0	140.0	28.8	41	8.1	51	25.1
140.0	0.0	20.5	7	6.5	87	8.5
140.0	20.0	29.4	39	8.6	20	24.8
140.0	40.0	22.5	33	7.5	35	17.4
140.0	60.0	22.5	35	8.0	13	18.6
140.0	80.0	21.6	30	-99.0	0	21.6
140.0	100.0	13.7	89	11.4	33	13.7
140.0	120.0	-99.0	0	11.7	97	11.7
140.0	140.0	-99.0	0	5.0	99	5.0
160.0	0.0	-99.0	0	5.6	63	5.6
160.0	20.0	21.4	31	7.5	38	16.1

Appendix 2. DATA INPUT FOR SEMIVARIOGRAM CALCULATIONS

Note: "-99.0" used for missing "% clay" when thickness is "0"

Coordinate (m)		Bt1 Data		2Bt2 Data		Control-Sec. Clay
		Clay	Thickness	Clay	Thickness	
X	Y	(%)	(cm)	(%)	(cm)	(%)
160.0	40.0	18.6	39	8.4	33	16.4
160.0	60.0	16.6	41	11.5	97	15.7
160.0	80.0	26.4	46	10.5	89	25.1
160.0	100.0	26.6	38	6.1	61	21.7
160.0	120.0	22.5	46	17.5	76	22.1
160.0	140.0	18.5	20	9.6	31	13.2
180.0	0.0	-99.0	0	15.2	33	15.2
180.0	20.0	-99.0	0	10.4	53	10.4
180.0	40.0	-99.0	0	5.0	89	5.0
180.0	60.0	16.2	15	10.5	46	12.2
180.0	80.0	26.0	46	-99.0	0	26.0
180.0	100.0	22.5	23	14.8	28	18.3
180.0	120.0	24.5	25	10.5	21	18.1
180.0	140.0	23.3	41	13.3	25	21.5
200.0	0.0	27.9	41	7.0	69	24.1
200.0	20.0	28.2	79	-99.0	0	28.2
200.0	40.0	27.1	33	8.0	91	20.6
200.0	60.0	26.0	26	10.5	45	18.6
200.0	80.0	29.0	26	17.4	43	23.4
200.0	100.0	21.0	18	12.5	48	15.6
200.0	120.0	24.1	38	14.6	13	21.8
200.0	140.0	27.0	28	12.5	46	20.6
220.0	0.0	19.5	18	-99.0	0	19.5
220.0	20.0	-99.0	0	7.5	94	7.5
220.0	40.0	-99.0	0	9.4	77	9.4
220.0	60.0	28.2	23	8.9	61	17.8
220.0	80.0	28.0	33	10.5	71	22.1
220.0	100.0	25.1	38	8.5	58	21.1
220.0	120.0	30.0	41	-99.0	0	30.0
220.0	140.0	26.9	30	10.4	46	20.3
240.0	0.0	29.0	43	7.0	28	25.9
240.0	20.0	19.2	16	12.8	15	16.1
240.0	40.0	-99.0	0	5.0	21	5.0

Appendix 2. DATA INPUT FOR SEMIVARIOGRAM CALCULATIONS

Note: "-99.0" used for missing "% clay" when thickness is "0"

Coordinate (m)		Bt1 Data		2Bt2 Data		Control-Sec. Clay
X	Y	Clay (%)	Thickness (cm)	Clay (%)	Thickness (cm)	(%)
240.0	60.0	36.1	43	12.9	20	32.8
240.0	80.0	24.3	58	-99.0	0	24.3
240.0	100.0	26.1	48	11.0	46	25.5
240.0	120.0	18.3	38	-99.0	0	18.3
240.0	140.0	33.0	31	9.0	99	23.9
260.0	0.0	20.8	20	-99.0	0	20.8
260.0	20.0	25.5	28	11.4	48	19.3
260.0	40.0	28.4	28	10.3	13	22.7
260.0	60.0	22.4	23	11.4	33	16.5
260.0	80.0	20.6	45	10.0	41	19.5
260.0	100.0	24.4	20	7.6	125	14.3
260.0	120.0	-99.0	0	9.8	84	9.8
260.0	140.0	28.4	26	7.1	81	18.2
280.0	0.0	21.6	56	8.6	68	21.6
280.0	20.0	24.6	35	9.4	23	20.0
280.0	40.0	25.4	23	8.0	35	16.0
280.0	60.0	-99.0	0	9.5	125	9.5
280.0	80.0	29.4	56	7.1	56	29.4
280.0	100.0	20.5	43	10.7	46	19.1
280.0	120.0	27.4	56	11.8	53	27.4
280.0	140.0	27.4	31	10.3	25	20.9
300.0	0.0	21.1	48	23.7	38	21.2
300.0	20.0	-99.0	0	8.8	18	8.8
300.0	40.0	25.4	33	10.7	23	20.4
300.0	60.0	20.6	41	10.2	81	18.7
300.0	80.0	-99.0	0	8.3	23	8.3
300.0	100.0	-99.0	0	12.0	26	12.0
300.0	120.0	20.6	74	-99.0	0	20.6
300.0	140.0	29.5	41	11.2	25	26.2
320.0	0.0	35.3	46	10.4	25	33.3
320.0	20.0	23.9	25	10.7	13	19.4
320.0	40.0	28.7	61	5.4	41	28.7
320.0	60.0	22.5	15	12.7	112	15.6

Appendix 2. DATA INPUT FOR SEMIVARIOGRAM CALCULATIONS

Note: "-99.0" used for missing "% clay" when thickness is "0"

Coordinate (m)		Bt1 Data		2Bt2 Data		Control-Sec. Clay
X	Y	Clay (%)	Thickness (cm)	Clay (%)	Thickness (cm)	(%)
320.0	80.0	22.5	31	12.2	81	18.6
320.0	100.0	19.5	28	8.3	89	14.6
320.0	120.0	30.4	38	10.8	8	27.0
320.0	140.0	25.6	33	11.2	18	20.7
340.0	0.0	32.7	38	6.8	49	26.5
340.0	20.0	32.0	41	9.7	69	28.0
340.0	40.0	25.4	39	8.8	55	21.7
340.0	60.0	-99.0	0	6.4	92	6.4
340.0	80.0	28.7	21	9.2	73	17.4
340.0	100.0	15.5	15	12.2	59	13.2
340.0	120.0	-99.0	0	8.8	28	8.8
340.0	140.0	28.9	26	10.2	35	19.9
360.0	0.0	28.8	25	17.6	18	24.1
360.0	20.0	28.8	36	8.9	36	23.2
360.0	40.0	28.7	33	10.4	61	24.3
360.0	60.0	27.2	36	7.0	61	21.5
360.0	80.0	28.7	33	9.0	46	22.0
360.0	100.0	28.5	30	7.5	18	20.6
360.0	120.0	30.2	23	8.0	23	19.1
360.0	140.0	-99.0	0	10.2	97	10.2
380.0	0.0	30.4	31	13.8	15	25.0
380.0	20.0	28.6	30	12.4	26	22.1
380.0	40.0	30.2	33	7.0	99	22.3
380.0	60.0	28.9	20	8.4	38	16.6
380.0	80.0	27.3	30	15.4	28	22.5
380.0	100.0	31.8	46	10.8	18	30.1
380.0	120.0	22.5	41	11.9	17	20.6
380.0	140.0	33.3	40	9.4	46	28.5
400.0	0.0	28.6	30	10.4	56	21.3
400.0	20.0	27.1	34	9.4	43	21.4
400.0	40.0	30.4	30	7.9	49	21.4
400.0	60.0	33.3	31	8.9	23	24.0
400.0	80.0	28.8	36	-99.0	0	28.8

Appendix 2. DATA INPUT FOR SEMIVARIOGRAM CALCULATIONS

Note: "-99.0" used for missing "% clay" when thickness is "0"

Coordinate (m)		Bt1 Data		2Bt2 Data		Control-Sec. Clay
X	Y	Clay (%)	Thickness (cm)	Clay (%)	Thickness (cm)	(%)
400.0	100.0	28.8	33	9.9	20	22.4
400.0	120.0	28.7	25	8.9	56	18.8
400.0	140.0	34.7	46	8.4	66	32.6
420.0	0.0	33.3	33	9.0	46	25.0
420.0	20.0	23.7	21	11.1	73	16.4
420.0	40.0	32.0	51	9.4	51	32.0
420.0	60.0	27.3	46	9.8	26	25.9
420.0	80.0	31.6	54	6.4	51	31.6
420.0	100.0	17.9	49	10.7	63	17.8
420.0	120.0	27.1	31	10.8	33	20.9
420.0	140.0	27.1	31	7.8	142	19.8
440.0	0.0	23.8	31	11.2	15	19.7
440.0	20.0	34.1	33	15.2	21	27.7
440.0	40.0	25.1	28	-99.0	0	25.1
440.0	60.0	28.8	20	11.2	31	18.2
440.0	80.0	28.7	28	10.3	46	20.6
440.0	100.0	32.3	35	11.3	28	26.0
440.0	120.0	27.3	28	11.9	40	20.5
440.0	140.0	32.1	38	11.9	77	27.3

LYSIMETER CLUSTER 1

420.0	20.5	25.6	45	7.8	54	23.8
420.0	21.0	21.5	61	-99.0	0	21.5
420.0	22.0	26.5	61	10.2	46	26.5
420.0	24.0	24.5	61	9.3	30	24.5
420.0	28.0	32.5	46	9.6	23	30.7
420.0	36.0	25.4	41	8.7	27	22.4
404.0	20.0	24.5	38	10.2	28	21.1
412.0	20.0	28.5	59	14.6	38	28.5
418.0	20.0	25.4	43	14.6	40	23.9
419.0	20.0	28.5	61	10.1	20	28.5
419.5	20.0	21.6	33	5.8	33	16.2

Appendix 2. DATA INPUT FOR SEMIVARIOGRAM CALCULATIONS

Note: "-99.0" used for missing "% clay" when thickness is "0"

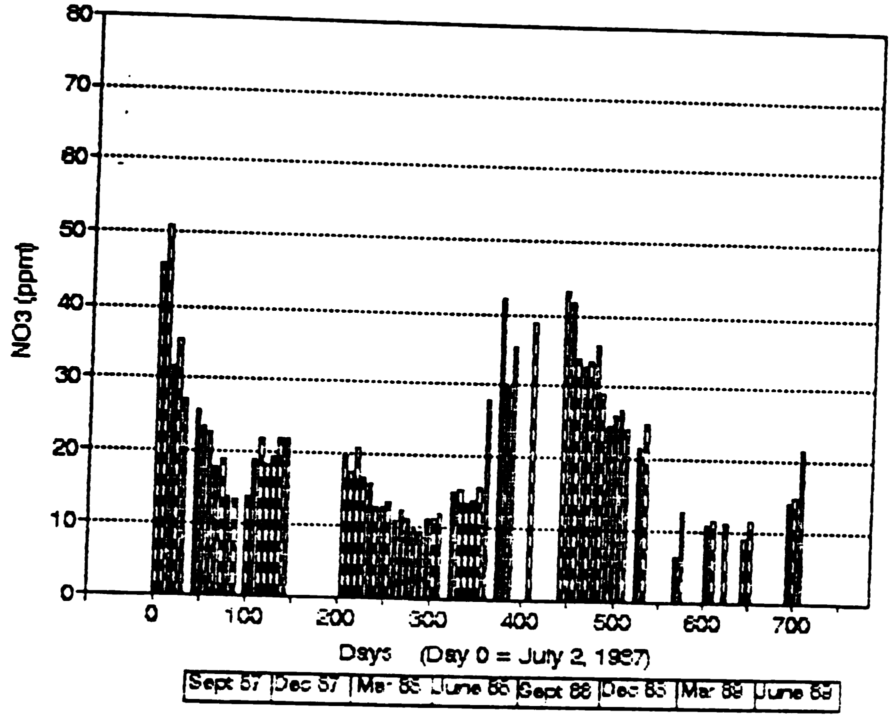
Coordinate (m)		Bt1 Data		2Bt2 Data		Control-Sec. Clay
X	Y	Clay (%)	Thickness (cm)	Clay (%)	Thickness (cm)	(%)
LYSIMETER CLUSTER 2						
174.0	133.0	31.0	46	15.2	23	29.7
173.5	133.0	29.4	49	8.0	30	29.0
173.0	133.0	26.5	44	13.9	53	25.0
172.0	133.0	26.6	45	15.5	36	25.5
170.0	133.0	24.6	38	13.5	61	21.9
166.0	133.0	26.5	68	18.5	18	26.5
158.0	133.0	16.6	48	12.5	130	16.4
174.0	132.5	32.6	39	10.6	35	27.8
174.0	132.0	22.9	36	11.5	53	19.7
174.0	131.0	26.4	46	9.6	26	25.1
174.0	129.0	24.4	39	9.0	17	21.0
174.0	125.0	23.6	79	-99.0	0	23.6
174.0	117.0	17.7	13	22.9	56	21.5
LYSIMETER CLUSTER 3						
32.0	43.0	27.1	36	9.9	48	22.3
31.5	43.0	25.5	36	9.5	43	21.0
31.0	43.0	26.5	38	12.4	36	23.1
30.0	43.0	28.4	36	9.1	48	23.0
24.0	43.0	28.2	84	-99.0	0	28.2
32.0	43.5	25.4	36	11.5	30	21.5
32.0	44.0	29.4	41	8.0	27	25.5
32.0	45.0	23.4	56	8.5	31	23.4
32.0	47.0	27.3	56	7.5	26	27.3
32.0	51.0	22.5	49	8.5	43	22.2
32.0	59.0	27.4	35	8.1	38	21.6

APPENDIX III

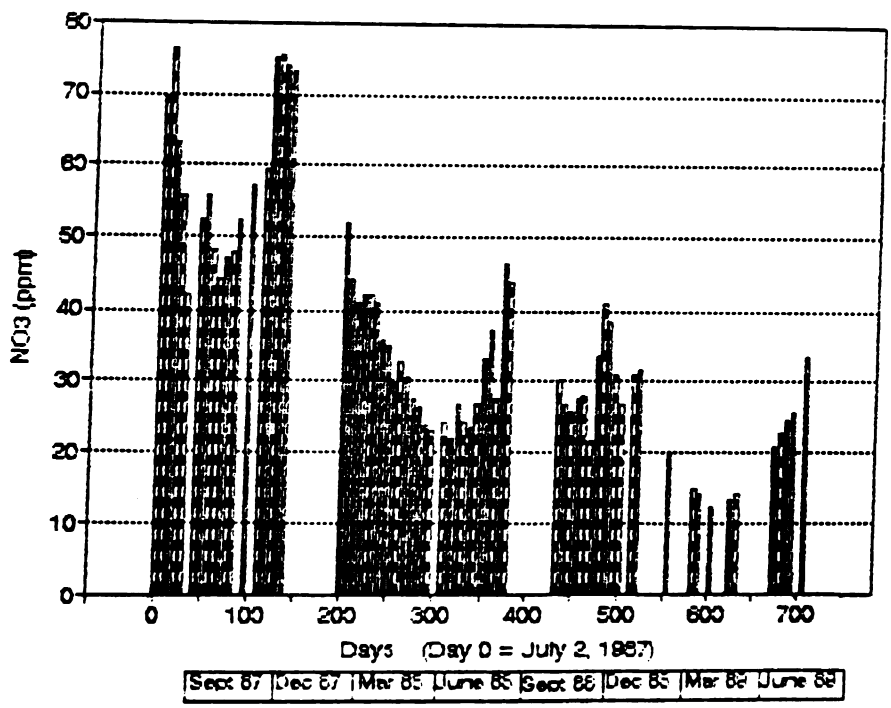
Graphs of Lysimeter Nitrate Concentrations, 1987-89

DAY #	DATE (yr/mo/day)	DAY #	DATE (yr/mo/day)
0	870702	323	880521
8	870710	330	880528
15	870717	337	880604
22	870724	344	880611
29	870731	354	880621
43	870814	362	880629
50	870821	369	880706
57	870828	376	880713
64	870904	383	880720
71	870911	390	880727
78	870918	410	880816
85	870925	442	880917
99	871009	450	880925
110	871020	456	881001
113	871023	463	881008
118	871028	470	881015
125	871104	477	881022
134	871113	484	881029
140	871119	491	881105
201	880119	500	881114
208	880126	507	881121
215	880202	516	881130
222	880209	529	881213
229	880216	536	881220
236	880223	575	890128
242	880301	582	890204
249	880308	607	890301
259	880318	617	890311
267	880326	630	890324
274	880402	651	890414
281	880409	653	890416
288	880416	693	890526
295	880423	701	890603
301	880429	707	890609
309	880507	713	890615
316	880514	728	890630

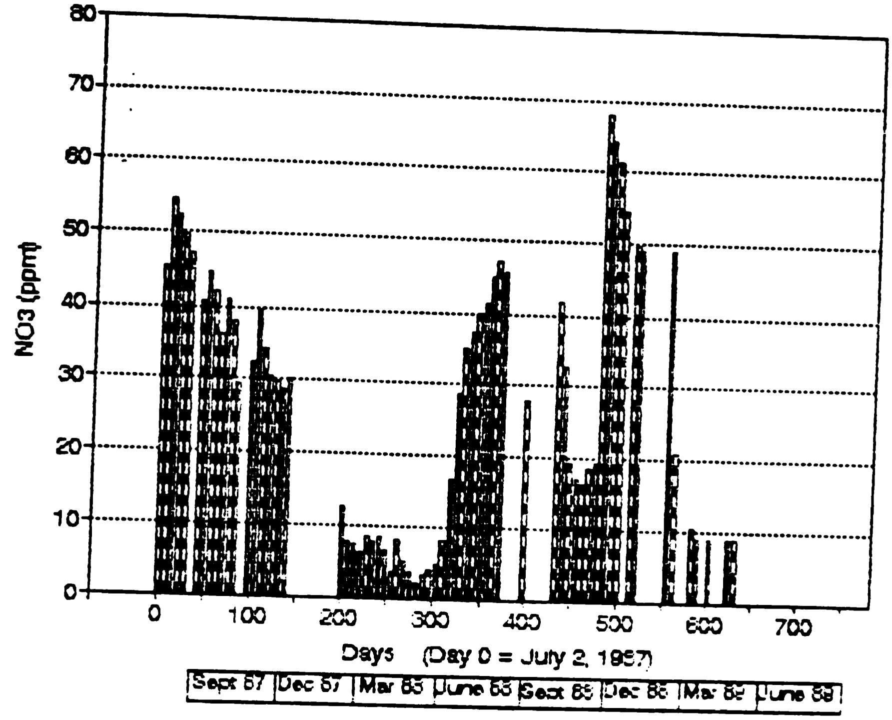
Lysimeter 1.1



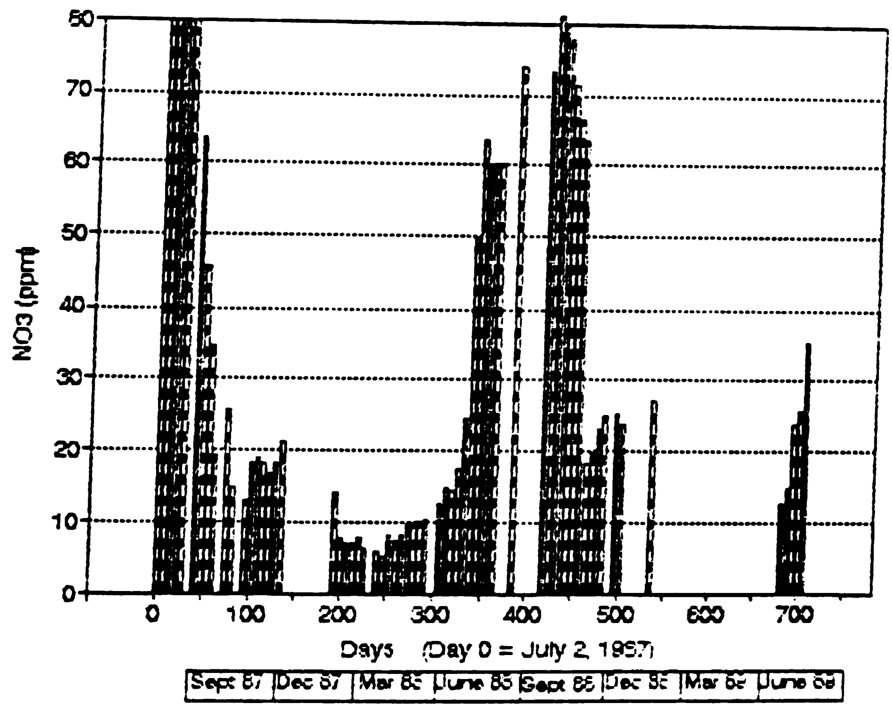
Lysimeter 1.2



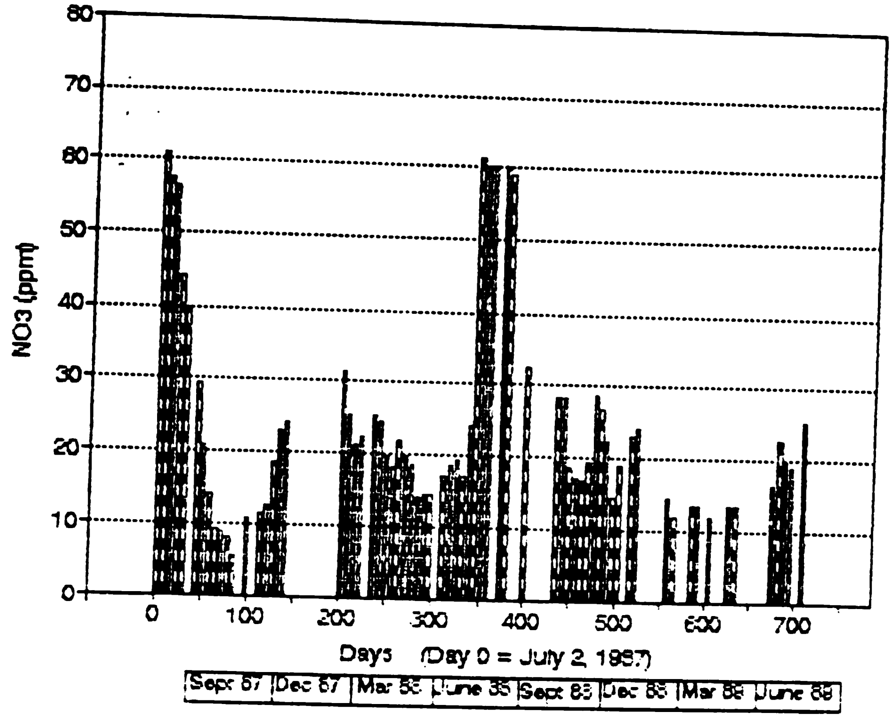
Lysimeter 1.3



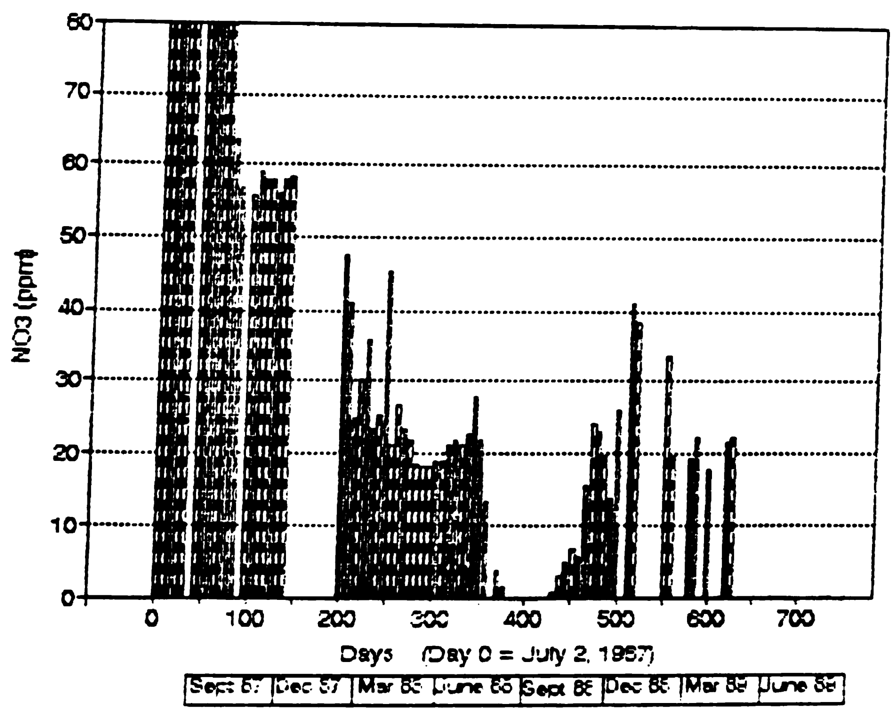
Lysimeter 1.4



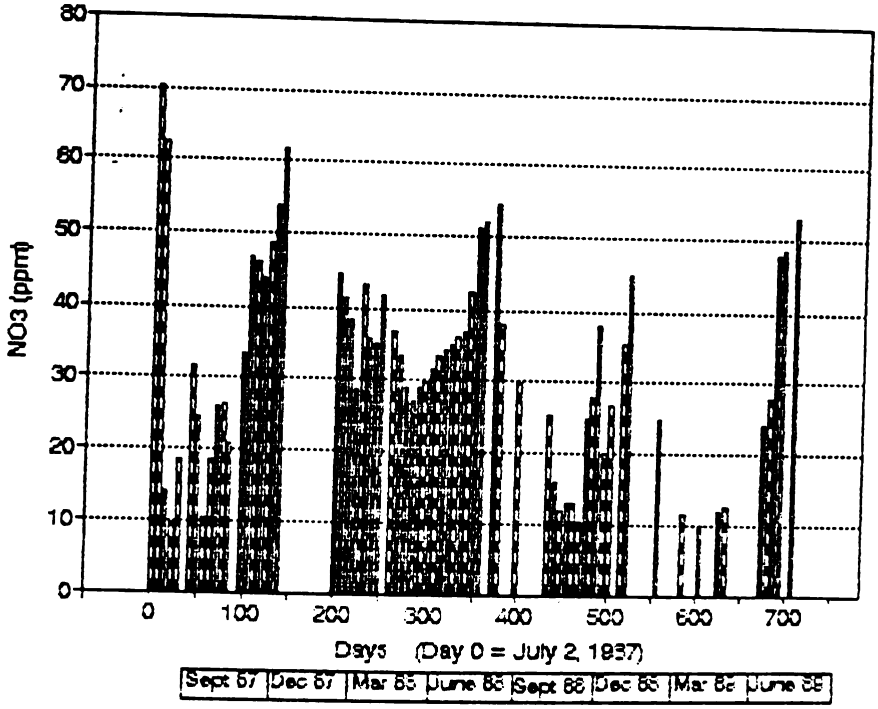
Lysimeter 2.1



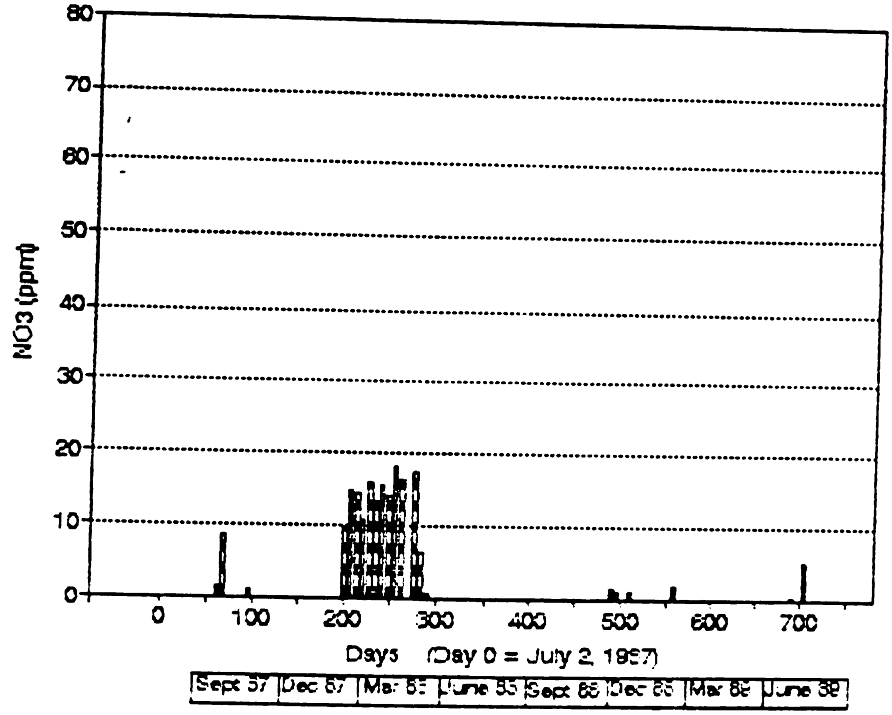
Lysimeter 2.3



Lysimeter 2.4



Lysimeter 3.1



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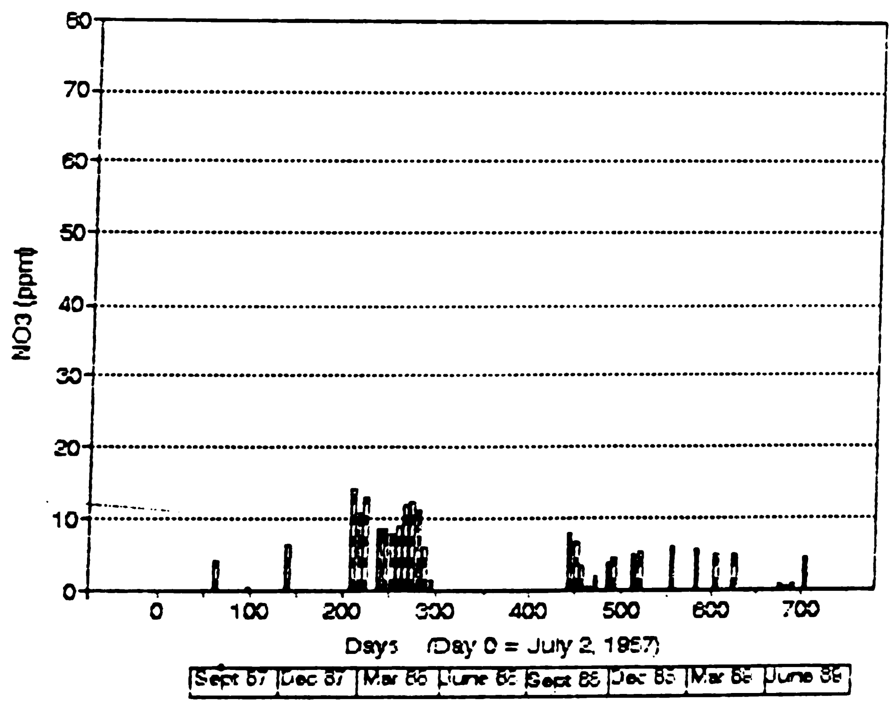

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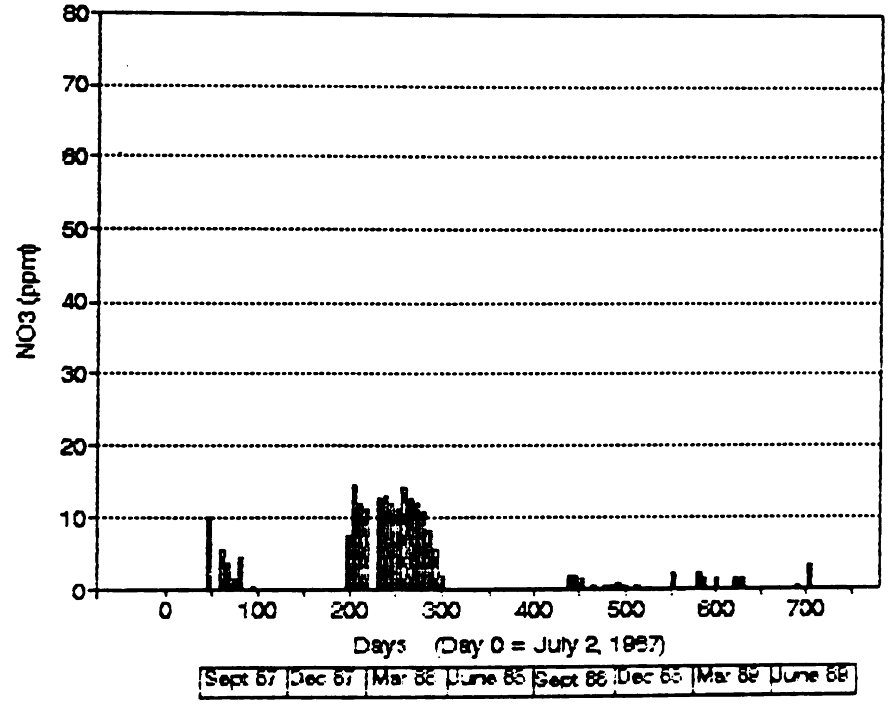

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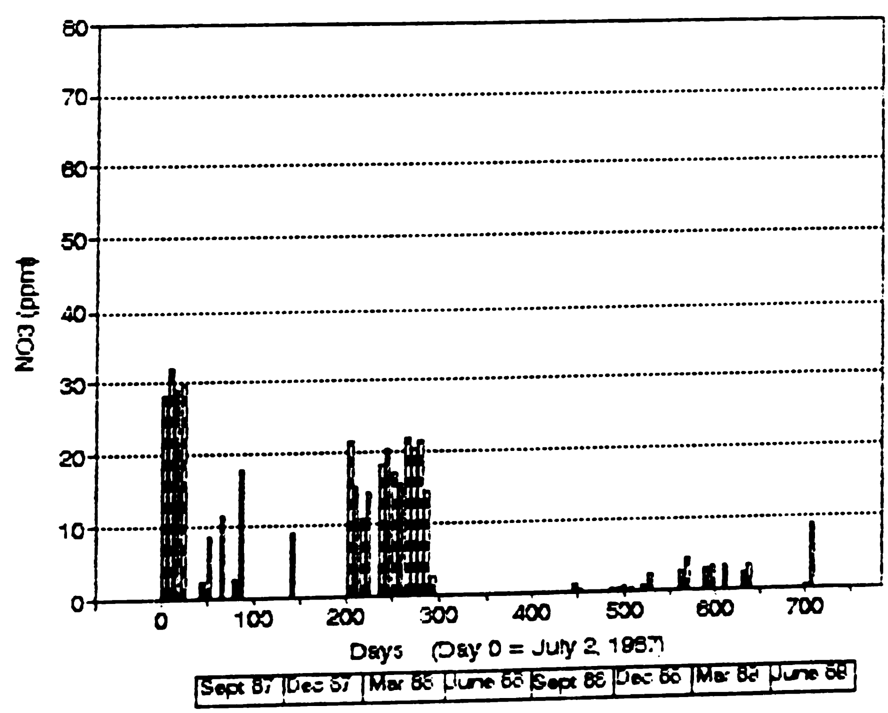

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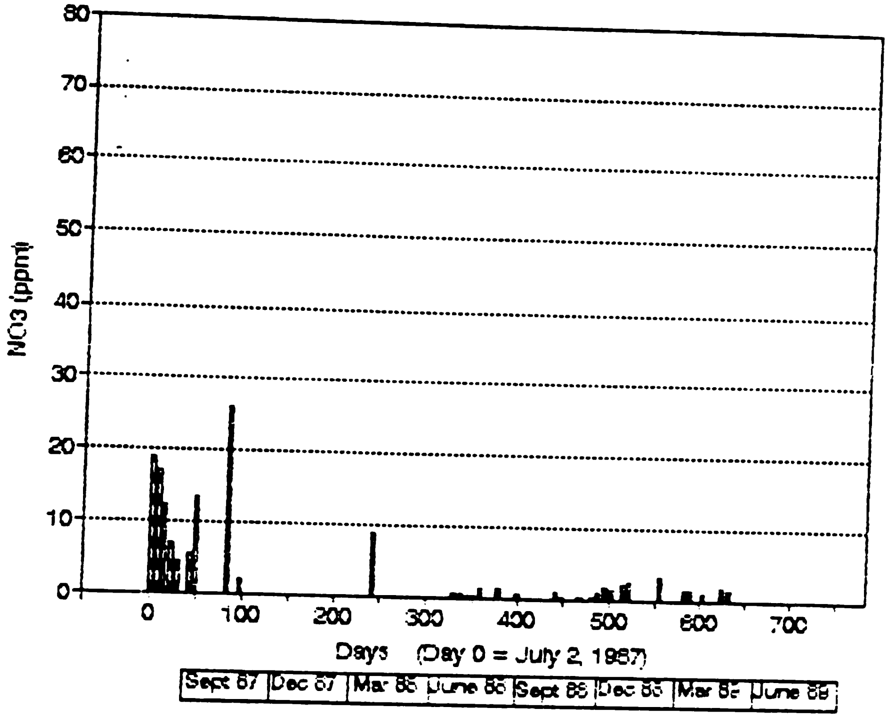

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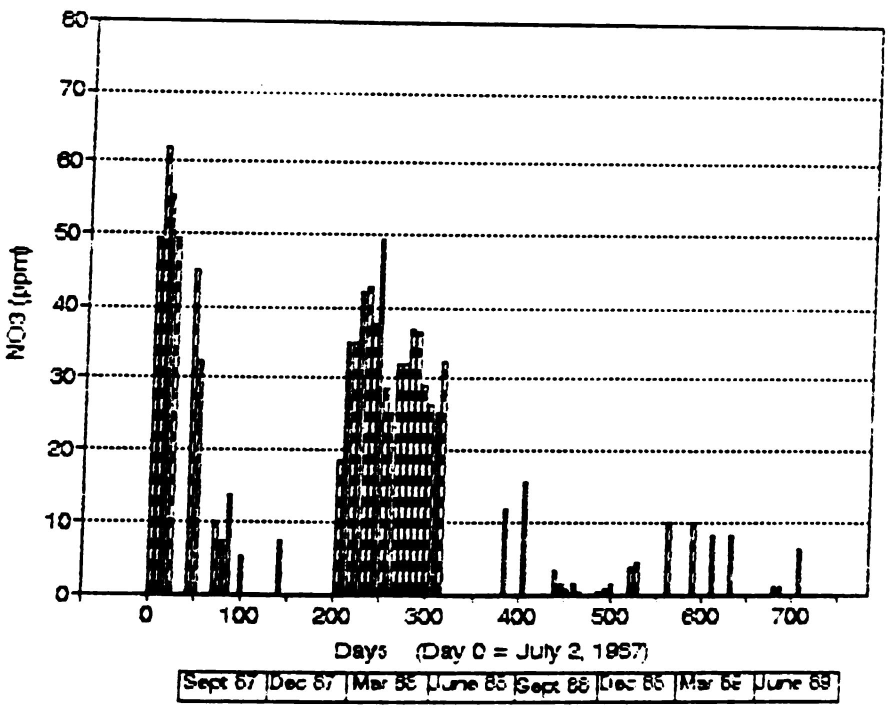

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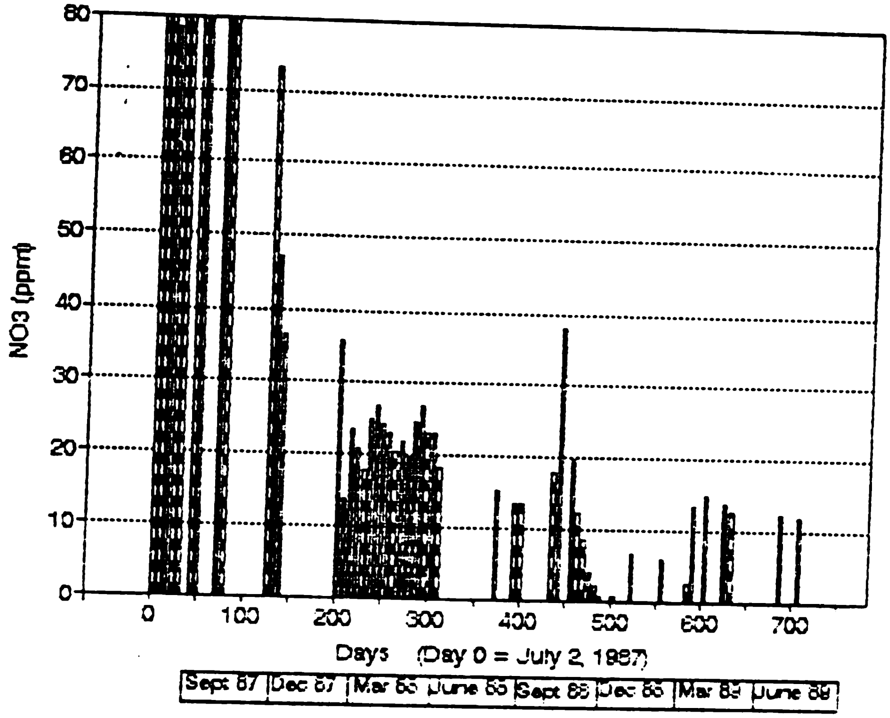

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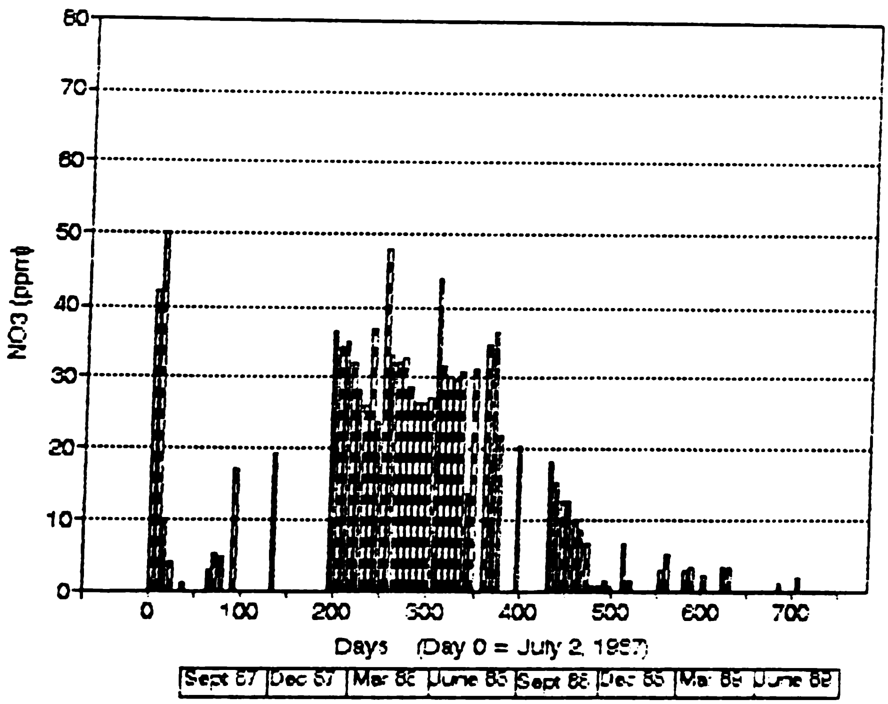
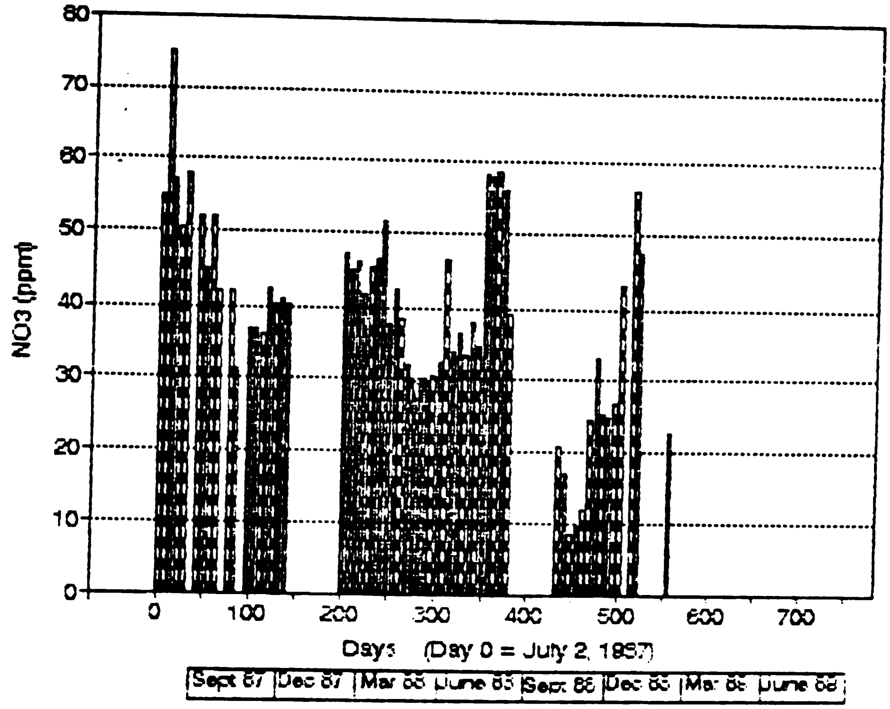


Lysimeter 5.1



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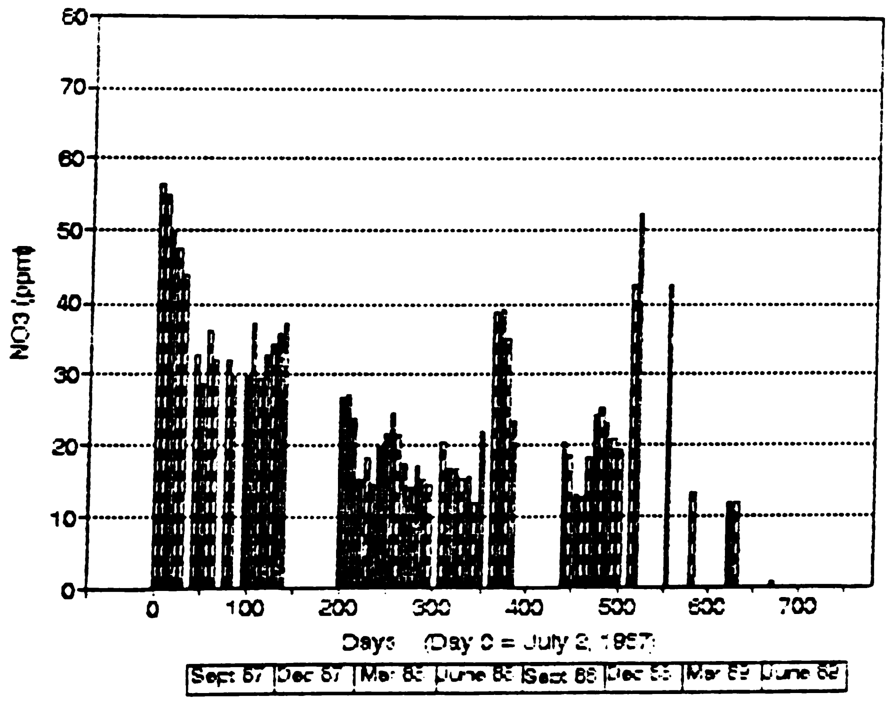

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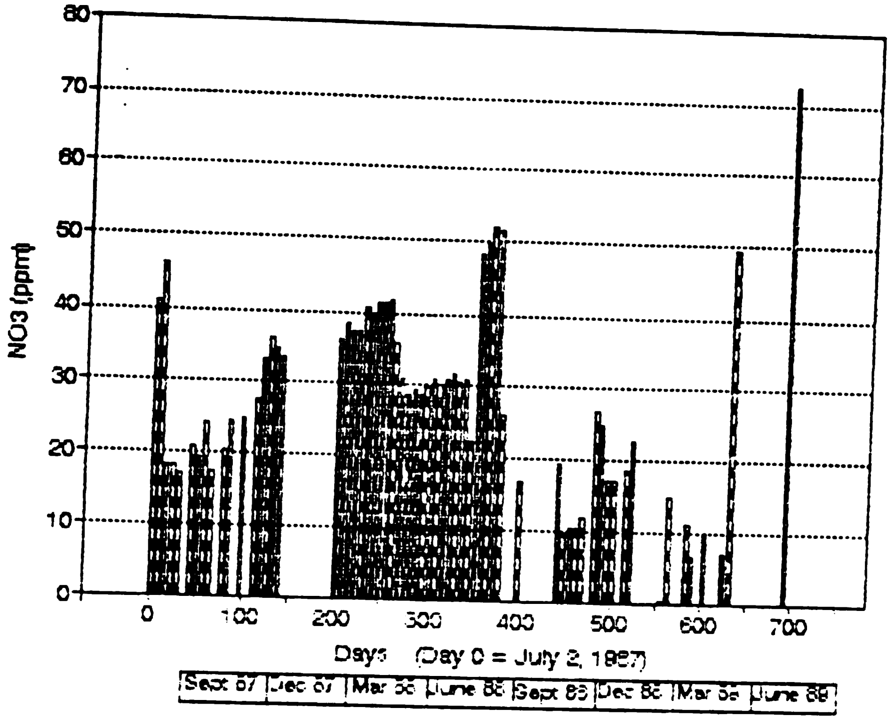

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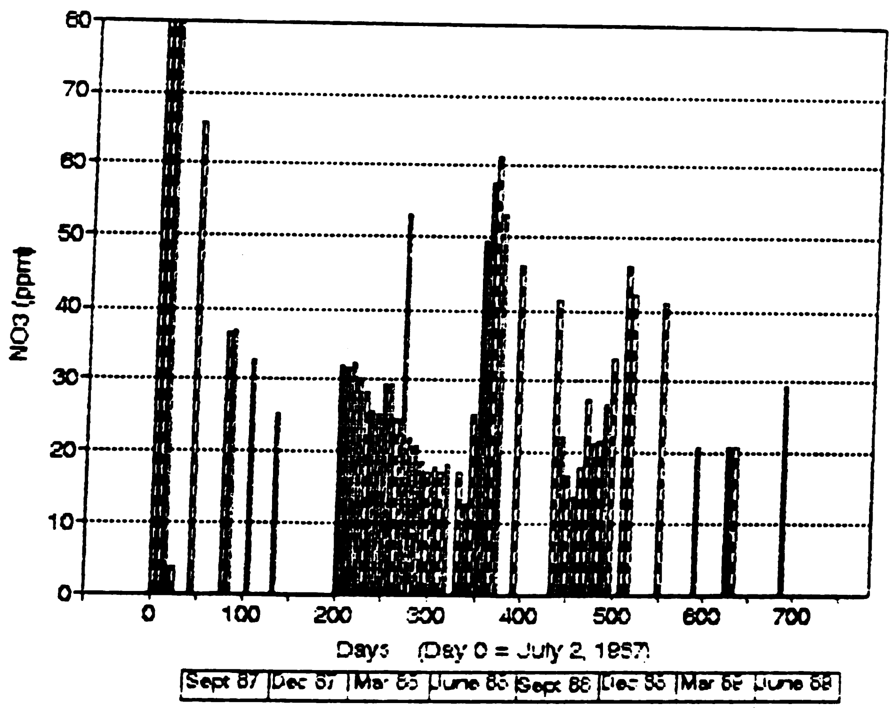
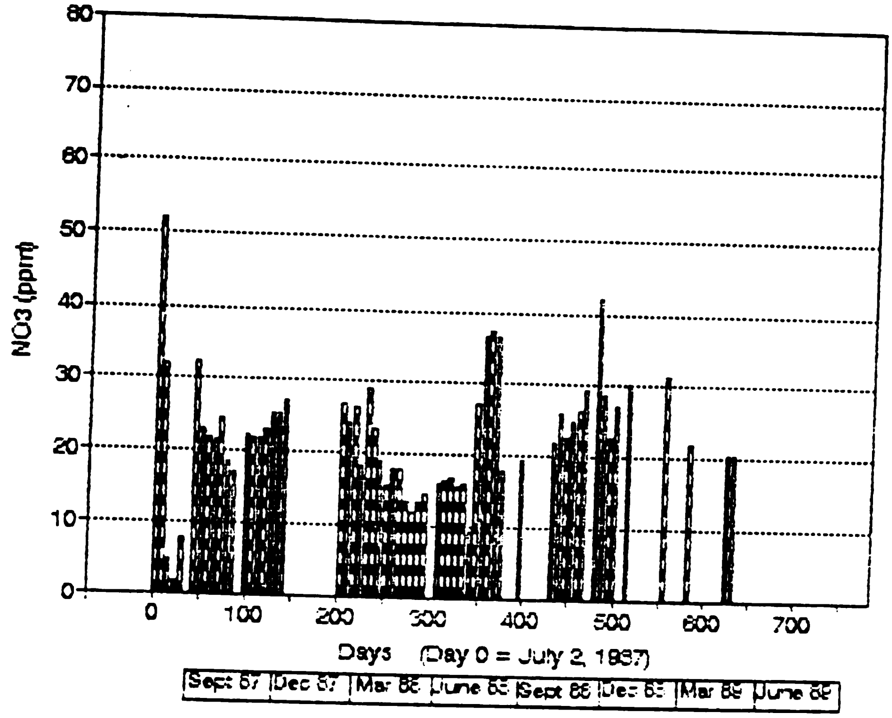


Lysimeter 6.1



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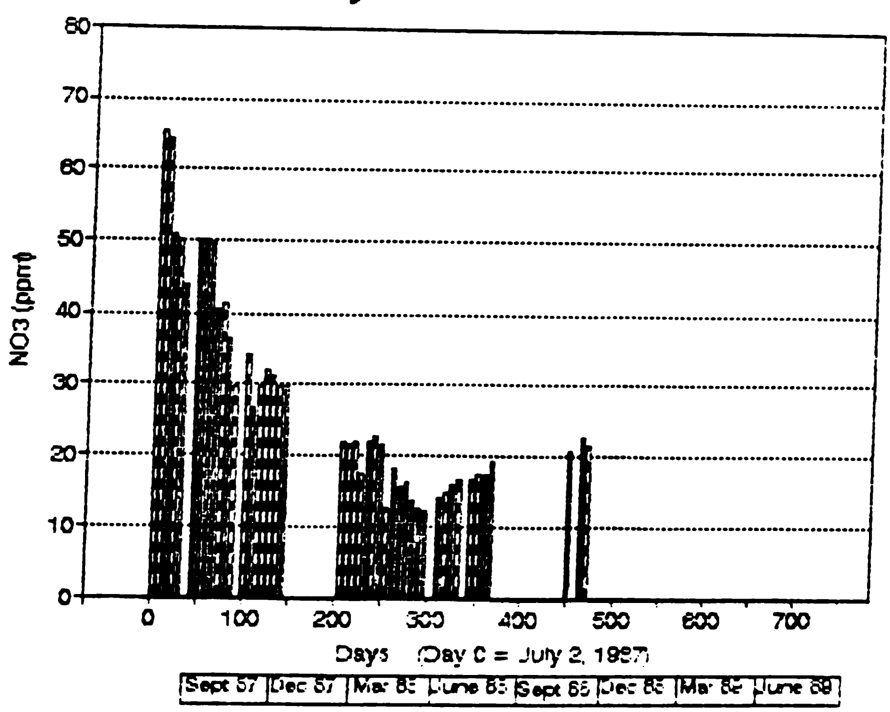

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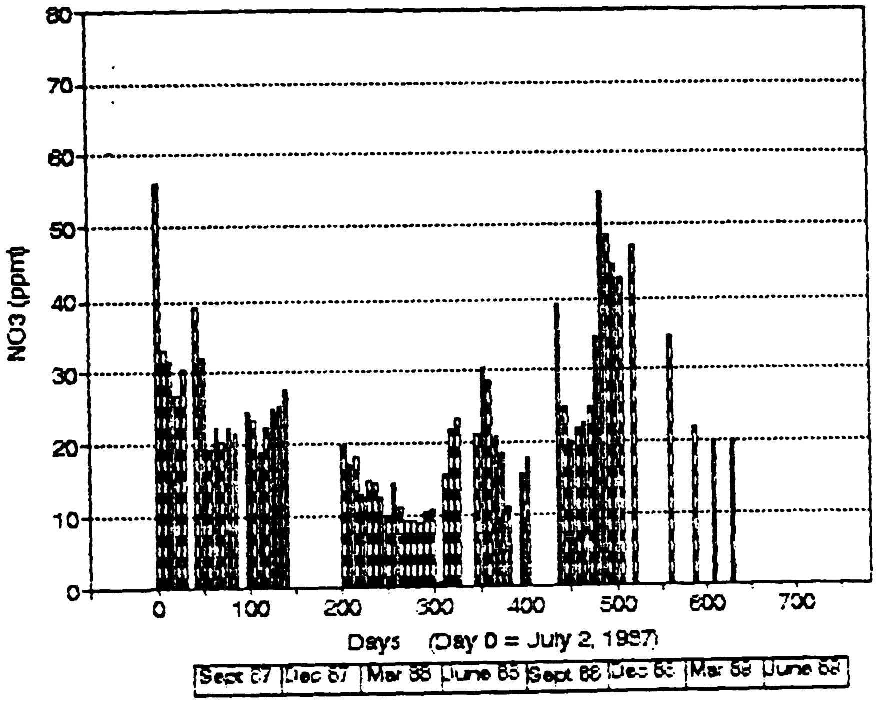

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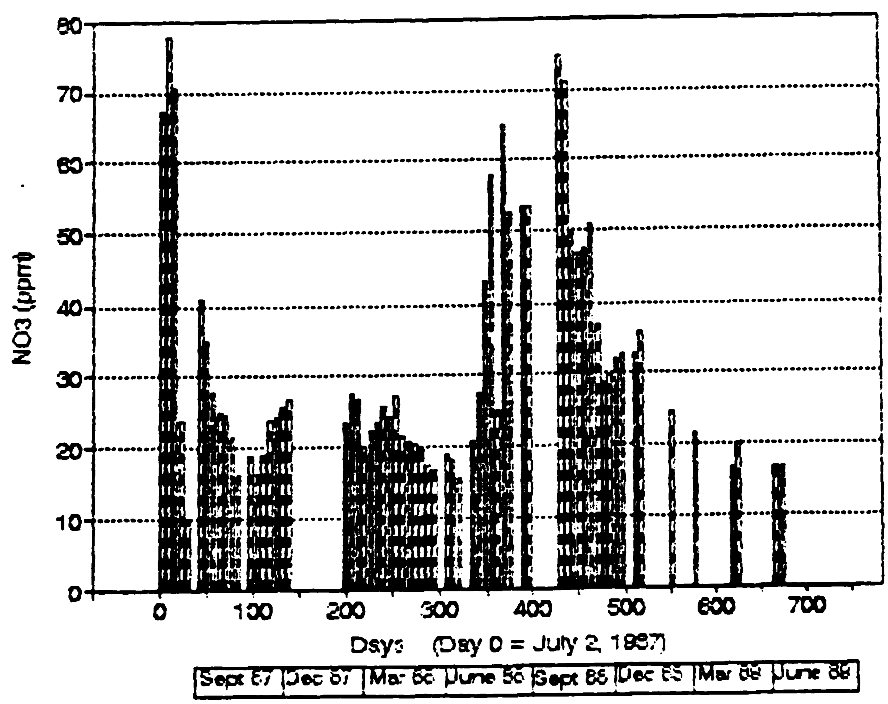
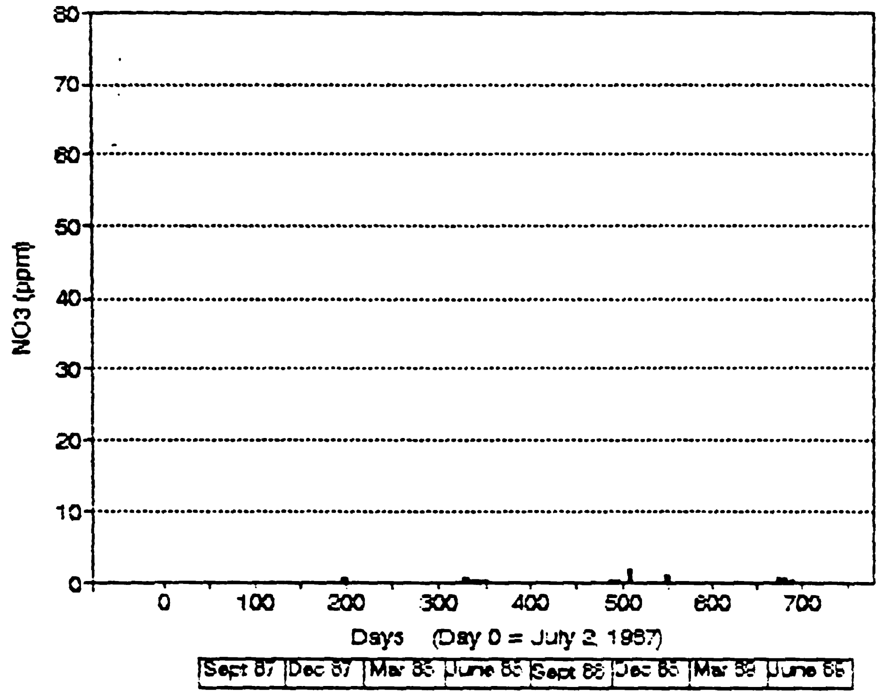


Lysimeter 7.1



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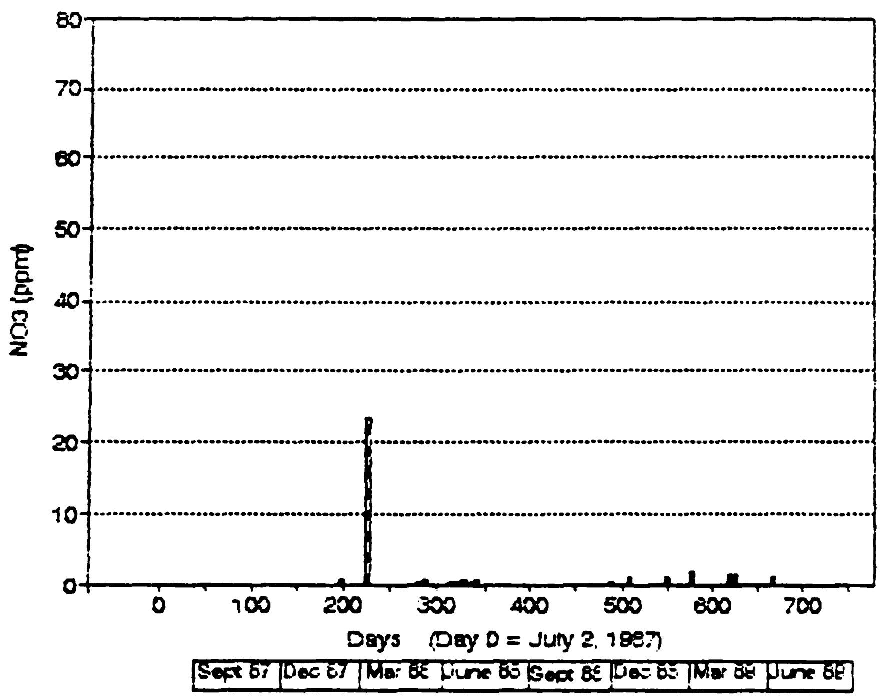

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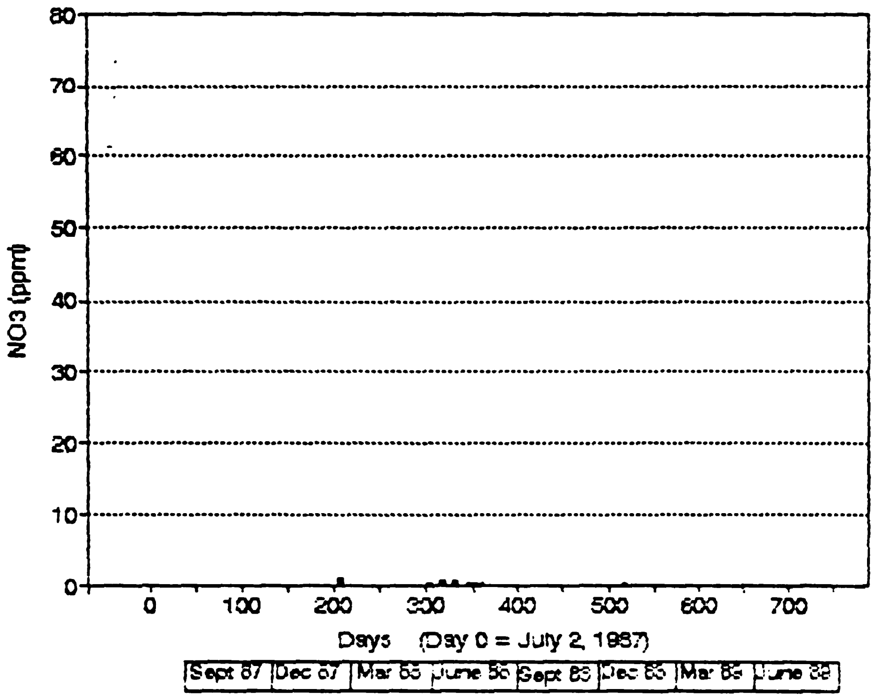

Lysimeter 7.4