RENOVATION OF SIMULATED MUNICIPAL WASTEWATER THROUGH INTENSIVE IRRIGATION OF CORN GROWN ON A TILE DRAINED CONOVER LOAM

Thesis for the Degree of M. S.
MICHIGAN STATE UNIVERSITY
DOUGLAS LAWRENCE KARLEN
1975

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ABSTRACT

RENOVATION OF SIMULATED MUNICIPAL WASTEWATER THROUGH INTENSIVE IRRIGATION OF CORN GROWN ON A TILE DRAINED CONOVER LOAM

By

Douglas Lawrence Karlen

A field study to evaluate the effects of applying 25, 50, 100, and 200 cm of simulated municipal effluent to corn grown on a tile-drained loam soil was conducted. The renovation efficiency of the soil-crop system was evaluated by measuring nutrient losses through tile drainage, recoveries through plant uptake, and changes within the soil profile.

Nutrient losses were calculated by measuring the volume of tile flow after each irrigation or rainfall and measuring the nutrient concentration in the drainage water. Annual losses ranged from 0.1 to 18.0, 0.01 to 0.60, and 0.2 to 8.5 kg/ha N, P, and K, respectively. Losses increased with increasing rates of application.

The yield and nutrient uptake of seven corn hybrids were evaluated under four irrigation rates. Significant differences due to loading rate and hybrid were found. The treatment hybrid interactions were non-significant, which indicated that all hybrids responded similarly at all loading rates. Nutrient recovery through plant uptake

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accounted for more than 40, 80, and 130% of the applied N, P, and K, respectively, at the 25, 50, and 100 cm loading rates provided that the entire plant was harvested. Removal of only the grain substantially reduced nutrient recovery.

Analysis of soil profile samples indicated that the application of low K municipal effluents may result in a depletion of the exchangeable K unless supplemental fertilizer is applied. Sodium adsorption ratios and exchangeable sodium percentages indicated that there would be no problems due to excessive Na adsorption.

The soil water balances indicated substantial water losses through deep percolation, and therefore a potential for leaching large quantities of the unrecovered N from the soil profile. The Cl distribution in the soil profile following the application of 100 or 200 cm of simulated effluent confirmed the leaching potential, but the Cl/NO_3 ratios suggested that denitrification rather than leaching was the primary mechanism for the removal of unrecovered N.

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Douglas Lawrence Karlen

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Crop and Soil Science

1975

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Michigan State Unive

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Gratitude is expressed to Dr. R.J. Kunze for the many discussions and suggestions during this study.

I sincerely thank Dr. B.G. Ellis, and Professor E.H. Kidder for their assistance on my guidance committee.

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INTRODUCTION

The Federal Water Pollution Control Amendments of 1972 encouraged the development and utilization of land disposal techniques as alternatives to conventional and advanced wastewater treatment in the prevention of surface water pollution. Land disposal is not a new technique, since it was first practiced in Athens during the B.C. period. Large scale municipal wastewater renovation systems, which are currently being designed to renovate wastewater through crop irrigation on limited land resources, are in need of information regarding (a) the maximum and optimum loading rates for the various soil types and crops found within the United States, and (b) the renovation capacity of the soil and changes in the chemical and physical properties of the soil system which are influenced by these management practices (Pound and Crites, 1973a; Ramsey, Wetherhill, and Duffer, 1972).

The Dow Report (1972) recommends an annual application of 175 cm of municipal effluent on a loam soil with a permeability of 0.5 cm/hr. Ellis et al. (1972) concluded that applying more than 88 to 100 cm of effluent per year would overload this type of soil, causing the entire biosystem to lose its renovation capacity. Erickson (1972) concluded that the greatest research need in land treatment of effluents as it affects the physical changes in soils and crop yield is for field experiments with effluent application on medium to fine textured soils which have adequate artificial drainage.

The objectives of this research were: (1) to field test the hydraulic capacity of a medium-textured soil which has adequate artificial drainage in land disposal of municipal wastewater; (2) to determine the maximum hydraulic loading rate at which the biosystem would continue to function as a living filter, producing an economic crop yield, and making efficient use of the applied nutrients; and (3) to trace the fate of the applied N, P, and other nutrients in the effluent.

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LITERATURE REVIEW

History of Land Disposal

Land disposal of wastewater was first practiced in Athens during the B.C. period. Irrigation on farmland, which was the simplest method of waste treatment and disposal, was also practiced in Europe and England between the sixteenth and nineteenth centuries. Properly managed, these sewage farms were able to benefit from the nutrients without creating insect or odor problems (Metcalf and Eddy, 1972; DeTurk, 1935).

Land disposal in the United States began in the late nineteenth century. Wastewater was initially used only for irrigation; however, groundwater recharge projects were started in the early twentieth century in the semiarid regions of California and Utah. Wastewater irrigation in the East began to decline at this time because of rising populations and increased land value.

Today those crude sewage farms of the 1890's have been replaced by managed farms which utilize treated municipal wastewater for crop production and groundwater recharge (Pound and Crites, 1973b).

Current Status of Land Disposal

The Federal Water Pollution Control Act Amendments of 1972 created new interest in land disposal of wastewaters by implementing the national goal of eliminating the discharge of pollutants into navigable waters by 1985. Several points within the law encourage the utilization of land disposal techniques as alternatives to conventional and advanced wastewater treatment in the prevention of surface water pollution (Pound and Crites, 1973a).

Parizek, et al. (1967) carried out extensive studies at Pennsylvania State University to determine the degree of effluent renovation, the potential conservation of water, and the effect of municipal effluent on soils, crops, trees, and wildlife. They concluded that if properly managed, the soil system provides an effective method for effluent renovation and should be given consideration during the expansion of municipal waste treatment facilities.

Day, Tucker, and Vavich (1962) concluded that municipal effluent is a suitable source of irrigation water for the production of many small grains and forages in the semiarid southwest.

Sopper (1970) demonstrated that municipal effluents and sludges could be used to restore strip-mined soil banks to a more esthetic and productive state.

Pennypacker, Sopper, and Kardos (1967) reported that municipal effluents have been successfully disposed of by applying them to forest land. They concluded that land disposal of municipal effluent offers a solution to both water pollution and water supply problems which plague many areas of the country.

Current technology lacks sufficient information in many areas of wastewater disposal. Questions which remain unanswered include (a) the characteristics of municipal effluent, (b) the maximum and optimum loading rates for various soil types and crops found within the United States, and (c) the renovation capacity of the soil and the chemical and physical changes within the soil system which are influenced by land disposal of wastewater (Pound and Crites, 1973a; Ramsey, Wetherhill, and Duffer, 1972).

Characteristics of Municipal Effluent

Ellis, et al. (1972) reported that before the impact of wastewater disposal on a soil system can be evaluated, it is essential to know the characteristics of the effluent.

The characteristics of municipal effluents may be classified as physical, chemical, and biological. Pound and Crites (1973b) found that the constituents of raw sewage and the subsequent treatment plant effluents depend upon (1) the quality of the municipal water supply, (2) the industrial mix of the community, (3) the proportion of commercial to residential development, and (4) the nature of the residential community.

Physical Characteristics

Total dissolved solids (TDS) is the most important physical characteristic of wastewater. This includes floating, suspended, colloidal, and dissolved matter. The solids are important because they have a tendency to clog soil pores and coat the land surface. However, under proper management, these problems can be minimized (Pound and Crites, 1973b).

Other physical characteristics include temperature, odor, and color. The temperature of municipal effluent ranges between 50 and 70^{o}F which is not harmful to the soil or vegetation. Parizek, et al. (1967) found that during the winter the wastewater had a beneficial thawing effect on the soil and that it formed an insulating ice coat which protected crops from the cold air. Effluent color had no effect when applied to crops. Odors in wastewater are caused by the anaerobic decomposition of organic matter. Hydrogen sulfide is the primary cause, although other volatile compounds may be present (Pound and Crites, 1973b).

Chemical Characteristics

Pound and Crites (1973a) divided the chemical properties of wastewater into three categories: organic matter, inorganic matter, and gases.

Municipal water supplies rarely contain large quantities of organic matter. Therefore, almost all of the organic compounds found in effluents either entered during use or were formed during secondary treatment. Effluent organic matter is both soluble and particulate in nature (Hunter and Kotalik, 1973).

Principal organic compounds found in wastewater include proteins, carbohydrates, fats, and oils. These substances are usually found in small quantities and have no short term effects on the soil or vegetation. Long term effects have not been adequately determined (Pound and Crites, 1973b).

The primary inorganic constituents of wastewater include N, P, K, Ca, Mg, Na, and Cl. However, elements such as B, Cd, Cu, Ni, Pb, and Zn may be present in toxic quantities in some effluents.

Gases found in wastewater, with the exception of those causing odor problems, are relatively unimportant in land application. Dissolved oxygen in the wastewater is rapidly depleted soon after application; therefore atmospheric oxygen must be utilized to maintain aerobic soil conditions (Pound and Crites 1973b).

Biological Characteristics

The biological composition of municipal effluents originates in the sewage entering the treatment plant. Bacteria are the predominant microorganisms, although viruses, fungi, protozoa, nematodes, and other miscellaneous organisms have been found in secondary effluents.

Secondary treatment removes some bacteria and viruses by flocculation and secondary sedimentation. Disinfection using heat, ozone, bromine, iodine, or, most commonly, chlorine is the primary method of reducing the number of organisms in the effluent (Hunter and Kotalik, 1973; Pound and Crites, 1973b).

The biological composition of wastewater leads to some public apprehension about land disposal because of the potential for spreading pathogenic organisms. Foster and Engelbrecht (1973) found very little information on irrigation-caused epidemics when reviewing the microbial hazard of applying wastewater to soil. They concluded that wastewater should not be applied where underlying bedrock contains fractures or channels which would allow pathogens to move long distances, and that there should be at least two months between the last irrigation and the harvesting of edible crops.

Loading Capacity

Pound and Crites (1973a) found that the loading capacity of a land disposal system could be exceeded by excessive hydraulic, nitrogen, or organic loading rates.

The hydraulic capacity of a land disposal system is determined by the texture and structure of the soil, the depth to the existing water table, the crop, the climate, and the wastewater characteristics.

Hydraulic overloading will result in lower crop yields, anaerobic soil conditions, odors, and reduced renovation of the wastewater. If the soil filter ceases to function because of overloading, it may be rejuvenated by allowing it to drain and dry out. Usually after such a rest period, the soil filter will function adequately, provided the loading rates are reduced (Kunze, 1972).

The importance of not overloading the soil system was demonstrated by Shields, Ellis, Kunze, and Wolcott (1972, paper presented at the Annual ASA Meetings, Miami, Florida). The wastewater which was used for their study was spent $(NH_4)_2SO_3$ liquor from the Menasha Paper Company. The effluent contained about 1% solids which is much higher than normal secondary effluent; however, the problems which they observed in a 60-day study may be applicable to long term sewage disposal projects. The effluent was applied to a Spinks loamy sand and a Morley silty clay loam at rates of 0.25, 0.5, and 1.0 inches per day. Both soils accepted the maximum loading rate for 3 to 5 weeks. However, as the soil became overloaded surface slimes developed and the aggregates of the Morley soil were dispersed. The dispersion resulted in surface clogging, reduced infiltration rates, anaerobic conditions, and crop failure. Runoff approached 85% of the daily input toward the end of the experiment.

Pound and Crites (1973a) found that municipal effluents usually contain very small quantities of organic matter. Therefore, the problems associated with the disposal of paper mill waste probably will not be present for land disposal of municipal effluents, unless the soil system becomes hydraulically overloaded and anerobic conditions develop. Excessive organic loading can be prevented by following an intermittent application schedule and allowing time for the aerobic decomposition of organic matter.

Coarse textured soils tend to have greater infiltration and percolation rates. Therefore, N loading rather than hydraulic loading will limit wastewater disposal on these soils. Nitrogen loading has been defined as the pounds of applied N per acre per year. It has been calculated because of the potential build-up of nitrate in soils, drainage waters, and groundwater. This build-up can be minimized by limiting the pounds of total N applied to the amount removed by cover crops (Pound and Crites, 1973a).

Medium-and fine-textured soils have smaller hydraulic conductivities; however they also have a greater surface area. Therefore, the water has a longer residence time and the soils have a greater capacity to adsorb nutrients and filter wastes from the water (Kunze, 1972).

Various rates of effluent application have been reported. Pound and Crites (1973a) reported that loading rates for sprinkler irrigation of municipal wastewater ranged from 1.5 to 4.0 inches per week. Parizek et al. (1967)

applied effluent at rates of 1,2, and 4 inches per week on forest and agronomic land. An established gamelands area, having mixed hardwood vegetation, received rates of 2 and 4 inches per week throughout the summer and 6 inches per week during the winter.

Bauer and Matsche (1973) reported that the Muskegon Project was being designed for a 30 week irrigation season with an average loading of 3 inches per week, however maximum applications of 4 inches per week were anticipated. R.L. Cook (personal communication) observed that under these loading rates the corn crop suffered from a severe N deficiency. He suggested that this was probably due to a low nitrogen effluent (5 ppm) being applied at rates sufficient to leach the nitrate nitrogen from the profile before the plant could recover it.

Water Balance

The water balance in the soil profile influences the hydraulic loading capacity of the soil system. In its simplest form the soil water balance in a given volume of soil is merely the difference between water gains and losses (Hillel, 1971).

When water is applied to the land surface through rainfall or irrigation it may follow many paths. It may be intercepted by vegetation and returned to the atmosphere, infiltrate the soil surface, or run off along the ground surface (Carey, 1972).

Kunze (1972) defined infiltration as the movement of water into the soil. Water which enters the soil is then held in capillary pores or percolates through the profile and becomes a part of an existing water table. This water eventually flows into a nearby drain tile or ditch; however if no impermeable strata exist near the soil surface the water will eventually become a part of a deeper aquifer.

The rate of infiltration varies with soil, soil moisture, sprinkling intensity, and time. The infiltration rate decreases with time until the final infiltration capacity is reached. If this rate is exceeded, water will begin to pond on the surface or to trickle downslope as run off. The final infiltration rate will be profile-controlled if sprinkling intensity exceeds the infiltration capacity; however, if the intensity does not exceed this capacity, infiltration will be controlled by the supply rate (Kunze, 1972).

Carey (1972) defined percolation as the movement of water in soil beneath the ground surface but above the water table. Percolation may occur as either saturated or as unsaturated flow. Saturated flow is governed by the same parameters as groundwater flow, namely hydraulic conductivity and gradient. Unsaturated flow is essentially two-phase flow with both water and gas occupying the pores. The presence of air in the pores reduces the specific permeability by a factor between 0 and 1 depending upon the percent satur

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percent saturation of the soil. Experimental data has shown that 80% saturation was required before the unsaturated specific permeability reached 50% of the saturated value.

Both saturated and unsaturated flow are dependent upon permeability which is determined by pore size and soil structure. Therefore, soil type ultimately controls percolation.

In a heterogeneous medium such as glacial till, percolation is dependent upon the stratification of the various soil types. If a soil having a lower permeability underlies a more permeable material a recharge mound may develop. This will result in the development of radial gradients and the spreading of the percolate over a much larger area. Similarly, a layer with low permeability near the surface may result in surface ponding and runoff (Carey 1972).

Evaporation and transpiration are the primary processes through which water returns to the atmosphere. Evaporation occurs whenever the vapor pressure of a water mass exceeds the vapor pressure in the adjacent air. It is generally higher with increasing air and water temperatures, however only because of greater vapor pressure differences. Wind usually favors evaporation by removing saturated air and replacing it with air capable of taking up more water; however, it may reduce evaporation by hindering the transfer of the latent heat of vaporization (Carey, 1972).

Evaporation from moist soils requires more energy than evaporation from open water bodies due to the forces between the water and the soil particles. In an unsaturated soil, evaporation will cease when a thin layer of soil at the surface has lost its moisture. However, when the soil is saturated moisture migration under capillary forces continues to replace the water and evaporation continues as long as vapor pressure differences exist (Carey, 1972).

Transpiration is the same phenomena as evaporation except that the water escapes from moist pores and membranes in plants. Most transpiration occurs through leaves where it operates to bring nutrients and to maintain favorable leaf temperatures.

Shaw and Laing (1965) defined evapotranspiration as the water used by a crop. This consisted of both soil evaporation and plant transpiration. They found that the quantity of water used by a crop is dependant upon the amount of plant cover. Under a partial canopy, water use was usually much lower due to a reduction in the water available for surface evaporation.

Climatic factors such as temperature, solar radiation, and wind, along with the amount of available soil moisture ultimately determine the amount of water returned to the atmosphere.

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variations in topography greatly influence Michigan's climate. The climate at Lansing alternates between continental and semimarine. The average length of the growing season is 154 days. Precipitation is fairly well distributed throughout the year with an annual accumulation of about 31 inches. During the winter cloudiness prevails and the relative humidity remains rather high, however, during the summer sunshine is abundant and relative humidity is only moderate. Winds are predominantly southwesterly during the summer and west to northwesterly during the winter (Michigan Weather Service, 1971).

Renovation Capacity

The soil system is a complex treatment zone where many physical, chemical, and biological processes and interactions contribute to the renovation of the applied wastewater. The major renovation mechanisms include plant uptake, oxidation, reduction, adsorption, precipitation, ion exchange, and filtration (Pound and Crites, 1973a).

The solubility of various mineral phases in the soil ultimately controls the compositions of the soil solution; however, kinetic and thermodynamic factors must also be considered for many reactions which have sufficiently slow rates of precipitation and dissolution (Lindsey, 1973).

Particulate Matter

The filtration mechanism of the soil matrix separates the suspended organics from wastewater as it infiltrates the soil. McGauhey and Krone (1967) found the inert and organic particulate matter was effectively removed by the top 5 to 6 inches of soil. Bacterial oxidation then destroys the trapped particles, thus eliminating the biodegradable organics from the percolate (Pound and Crites, 1973a). Refractory organics such as phenols, fats, tannins, pesticides, and humic substances are broken down more slowly; however, physical entrapment and chemical adsorption of these compounds within the soil matrix should provide the necessary retention time for effective microbial degradation (Miller, 1973).

Bacteria and Viruses

Bacteria found in wastewater behave like other particulate matter and are removed by straining, sedimentation, entrapment, and adsorption. They are also subject to die-off when introduced into an unfavorable environment. Enteric pathogens, however, may survive and retain their virulence for about 2 months provided there is sufficient organic matter in the soil (McGauhey and Krone, 1967).

Viruses are removed by the soil matrix primarily by adsorption; however, the survival times of adsorbed viruses have not been explored (McGauhey and Krone, 1967).

Nitrogen

Ammonia and NH_4--N in wastewater are formed by the hydrolysis of urea and the biological decomposition of N containing organic compounds (Hunter and Kotalik, 1973).

When sewage effluent is applied in small amounts, the soil will remain predominantly aerobic and the NH_3 or NH^+_4 will be oxidized by microorganisms to NO^-_3. Under these conditions the fate of this N will be about the same as fertilizer N, i.e., about 50% taken up by plants, 25% lost through denitrification, and the remaining 25% lost through processes such as biological immobilization, NH_3 volatilization, or leaching (Bouwer and Chaney, 1974, unpublished manuscript).

The U.S. Department of Health, Education, and Welfare (1962) established a limit of 10 mg/l NO_3--N as the safe level for NO_3 in drinking water. Therefore, the efficiency of wastewater renovation with respect to N has been measured by determining the NO_3 concentration in the soil percolate.

Kardos and Sopper (1973a) used suction lysimeters to sample the soil solution. They reported that at hydraulic loading rates greater than 1 inch per week the NO_3 concentration 48 inches beneath a corn crop exceeded 10 mg/l.

Plants can recover substantial amounts of the applied nitrogen. Allison (1966) found recoveries in the crop varied widely with growth conditions and cropping systems. Recoveries in a single harvested crop, grown under optimum field conditions, usually will not exceed 50 to 70% of the applied N and are often below these values.

Sopper and Kardos (1973) reported that two corn hybrids recovered more than two times the amount of N applied at the 1 inch per week irrigation rate, and more

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than 100% of the applied N at the 2 inch per week rate. They also reported that reed canary grass, wheat, oats, alfalfa, and red clover could recover significant amounts of N provided that the loading rates were not much higher than the fertilizer requirements of the crop. This was also true for a mixed hardwood forest, plantations of red pine and white spruce, and an abandoned field with a vegetative cover of herbaceous annuals and perennials.

Denitrification is the most important process for the removal of N applied with the wastewater in excess of crop requirements (Lance, 1972). Losses may be higher where wastewater is more frequently applied than under normal agricultural practices. The higher soil moisture content inhibits diffusion of O_2 and organic C in the effluent may be used as an energy source by the denitrifying bacteria (Broadbent and Clark, 1965; Bouwer and Chaney, 1974, unpublished manuscript).

Denitrification requires the presence of NO_3 and organic C under anaerobic conditions. Therefore, since most N in wastewater is in the NH_3 form an aerobic phase in the soil is essential for the conversion of the N to NO_3. During this process, the organic C in the effluent will also be oxidized by hetertrophic aerobic bacteria.

Secondary municipal effluents usually contain relatively small amounts of C. This may limit denitrification when the wastewater moves into an anaerobic zone since approximately one milligram of organic C is required for each milligram of NO_3 that is denitrified. If organic C is limiting, it may be added by incorporating crop residues or adding C sources to the wastewater (Bouwer and Chaney, 1974, unpublished manuscript).

The effect of organic matter on denitrification is twofold. It serves as an energy source for the denitrifying bacteria, and its decomposition influences the O_2 demand within the soil. Root secretions by living plants also influence denitrification. The rhizosphere organisms which break down these secretions consume O_2 and the secretions themselves may serve as H_2 donors in denitrification (Broadbent and Clark, 1965).

The actual quantity of N lost through denitrification is difficult to determine. Allison (1966) reported that several lysimeter studies indicated losses of 15% of the fertilizer N; however, this included volatilization losses in addition to denitrification losses. Broadbent and Clark (1965) reported that denitrification losses in excess of 50% of the applied N have been encountered. Broadbent (1973) reported that in an uncropped column study using tagged $(NH_4)_2SO_4$ and applying 3 inches of water per week, more than 85% of the soluble N was unaccounted for. Therefore, he concluded that the N in the soil solution which is not intercepted by plant roots probably would not move into the water table, but would be denitrified.

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Nitrogen losses may also occur through NH_3 volatilization, or biological immobilization and incorporation into organic matter.

The amount of N which is lost through NH_3 volatilization is difficult to determine, however, Gardener (1965) reported that this loss has been found to be related to the loss of water through evaporation. The upward movement of water helps transport NH_3 to the soil surfaces, where the conditions which favor evaporation also favor the volatilization of NH_3.

The decomposition of plant materials usually results in changes in the quantity of organic N within the residue. Low N residues tend to increase in organic N content if N is available in excess of that contained in the residue; however, high N residues such as legumes may decline in organic N content (Bartholomew, 1965).

Corn stalks, cereal straws, and grasses are intermediate in N content, ranging between 0.5 and 1.5%. The organic N content of these materials usually increases during the early stages of decomposition. After a short period a residue containing organic N is formed. This organic N appears to be biologically stable since net mineralization is very slow. The magnitude of this immobilization can be estimated as follows. Corn stover and cereal straws may contain about 0.75% N or 15 pounds per ton of residue. During decomposition 20 to 25 pounds of N may be required to satisfy the needs of the microbes which effect the

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the decay. Therefore, this biological process results in a net tie-up of 5 to 10 pounds of the N which is added or becomes mineralized from the organic matter (Bartholomew, 1965).

Phosphorus

Municipal effluents usually contain about 10mg/l total P. Orthophosphate is the primary form found in wastewater. Condensed polyphosphates and organic forms are rapidly converted to this form during primary and secondary wastewater treatment or when applied to the soil (Murrman and Koutz, 1972).

Phosphorus renovation occurs primarily by adsorption, precipitation, or plant uptake. Soils should adsorb P until their adsorption capacity has been reached; however, Ellis and Erickson (1969, unpublished report to the Michigan Water Resource Commission) reported that the level of P in wastewater was not sufficient to utilize the entire adsorption capacity of many soils.

Precipitation mechanisms may control the amount of P in solution at both high and low pH values. Lindsey and Moreno (1960) utilized the solubility products of various P compounds to predict the formation and stability of various Ca, Fe, and Al phosphates that may form under various soil conditions. Iron and Al phosphates are precipitated in acid soils and therefore control P solubility at low pH, however, most wastewaters have pH values greater than 7.0 and therefore P solubility will probably be controlled by ca

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calcium phosphates such as dicalcium phosphate and octacalcium phosphate. Ellis (1973) reported that hydroxyapatite and fluorapatite form too slowly to have any effect on the precipitation of P from wastewaters.

Hook, Kardos, and Sopper (1973) and Sopper and Kardos (1973) reported that the amount of P taken up by cover crops accounts for a large part of the total P applied during irrigation with municipal effluents. They reported that when corn was used as a cover crop, annual P recoveries at the 1 in/wk loading rate ranged between 39 and 230% of the applied, while at the 2 in/wk loading rate recoveries ranged from between 21 and 143% of the applied. When reed canary grass was used as a cover crop it removed slightly more P than the agronomic crops; however, the recoveries accounted for only 24 to 63% of the applied P due to a greater hydraulic loading rate which increased the annual P application.

Kardos and Sopper (1973a) reported that below 6 inches, there was no significant increase in the P concentration of the soil profile. Soil water samples taken with suction lysimeters at the 48 inch depth showed that the P concentration had decreased 98.6 to 99.8% at the 1 in/wk loading rate and 98.1 to 99.6% at the 2 in/wk loading rate. This confirmed that the P in the wastewater was being removed through plant uptake, precipitation, or adsorption, and that it was not moving out of the soil profile into surface or ground waters.

Exchangeable Cations

The principal exchangeable cations in municipal effluents are Ca, Mg, K, and Na. These ions with the exception of Na are not expected to constitute any great hazards, since they are abundantly present under natural soil conditions. Various ion exchange reactions in the soil slow the downward movement of these ions; however, with continued leaching some will eventually enter the drainage water (Lindsey, 1973).

The recovery of these cations is not too important because of their natural abundance and their relatively unimportant role in the eutrophication of surface waters; however, Sopper and Kardos (1973) have computed the annual uptake of these ions by silage corn and reed canary grass. They found that at the 1 in/wk loading rate uptake in the corn crop accounted for 195 to 280% of the K, 25 to 38% of the Ca, 41 to 53% of the Mg, and 1 to 2% of the Na applied during the year. At the 2 in/wk loading rate uptake by the corn crop accounted for 114 to 130% of the K, 16% of the Ca, 28% of the Mg, and 1% of the Na applied during the year. Reed canary grass which received effluent at 2 in/wk throughout the year recovered 117% of the K, 9% of the Ca, 19% of the mg, and 1% of the Na applied during the year.

Potassium recoveries greater than 100% indicate a potential for the depletion of exchangeable and interlayer K. Therefore, since wastewater usually contains very little K,

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supplemental fertilization may be required to maintain optimum plant growth.

The level of salt in sewage effluent is not high enough to affect more than the most sensitive plants. Corn, bromegrass, reed canary grass, and other medium salt tolerant crops should encounter no salinity hazard from wastewater irrigation (Ellis, et al. 1972).

The physical properties of the soil may be susceptable to degradation due to excess adsorption of monovalent ions from the wastewater. The exchange of Na for Ca is particularly important in the irrigation of soils. If the cation exchange complex becomes sufficiently saturated with Na, dispersion of the soil will occur. This results in decreased infiltration rates and lower soil permeability (Ellis, et al. 1972).

Sodium adsorption ratios (SAR) have been used to evaluate the possible hazards of irrigation water, and can easily be applied to wastewaters used for irrigation. The ratio predicts the Na hazard by comparing the relative concentrations of Na, Ca, and Mg in the water. Continued irrigation with water having a high SAR value may lead to an accumulation of exchangeable Na and the formation of a soil having poor structure and low permeability (Richards, 1954).

Day, Stroehlein, and Tucker (1972) reported that 14 years of irrigating a Grabe silt loam with municipal wastewater resulted in a slight reduction in infiltration, and ar

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an accumulation of soluble salts, NO_3, and PO_4; however, the yields of various small grains were not reduced and minor changes in field crop culture were sufficient to correct any problems.

The exchangeable sodium percentage (ESP) is an estimate of the exchangeable Na when a soil and a wastewater have reached a steady state. Exchangeable Na percentages greater than 15 would be considered very serious; however, even lower values may seriously impede infiltration and percolation in fine textured soils (Ellis, 1973).

Henery, et al. (1954) reported that in a three year study, municipal effluent containing 680 ppm Na increased the exchangeable Na to 2.37 meq per 100 grams of soil. Exchangeable Ca and Mg decreased significantly, however, exchangeable K remained unchanged. Reduced infiltration rates were not mentioned despite the high exchangeable Na content.

Kardos and Sopper (1973b) reported a significant increase in exchangeable Mg and Na when wastewater was applied to a corn rotation. Exchangeable K and Ca showed no significant increases. Increases in exchangeable Mg, Na, and Ca were found in the forested areas, however, the effects of wastewater on exchangeable K were small and non-significant.

<u>Chloride</u>

The Cl concentration of municipal effluent is sufficient to result in excessive annual applications.

Kardos and Sopper (1973b) reported that the Cl concentration in the soil solution was almost five times higher in the wastewater treated area than in the control area.

Soils do not adsorb Cl to any extent. Ellis, et al. (1972) suggested that a minimum hydraulic loading rate of 1 in/wk would be sufficient for leaching the Cl from the profile.

Chloride is also removed by plant uptake. Sopper and Kardos (1973) reported that corn recovered 20 to 26% of the Cl at the 1 in/wk loading rate and 11 to 14% at the 2 in/wk loading rate. Reed canary grass removed 20% of the applied chloride.

Nutrient Content of Drainage Water

The quantity of nutrients found in the drainage water can be used to measure the renovation efficiency of land disposal systems. The N and P concentrations are of major concern from the standpoint of pollution. Nitrogen is important because it is a potential health hazard if large amounts of NO_3 enter potable water supplies. Phosphorus is important because of its influence on algal growth at concentrations as low as 10 ppb (Ellis, 1971).

Ellis and Erickson (1971) found that very small amounts of K leach despite its relatively high solubility. The quantities of Ca and Mg which are leached are primarily due to the weathering of limestone.

Ellis and Erickson (1971) and Johnston, et al. (1965) reported that NO_3--N accounted for the largest amounts of N found in drainage water; however, N losses also occurred in the NH_3 form, as NO_2, and organic N.

The amount of NO_3 reaching the drainage tile is a product of three different processes: (a) the production of NO_3 in the soil, (b) the utilization of NO_3 by the plant or other microorganisms, and (c) the movement of the NO_3 through the soil by percolating water. Ellis and Erickson (1971) found a greater fluctuation in the quantity of N leached, than in the concentration of N in the drainage water. They concluded that this could be attributed to the variability in the amount of drainage water.

Thomas and Barfield (1974) reported that the NO_3--N concentrations found in tile effluent may be an unreliable estimate of N losses from soils if the volume of tile flow does not account for the largest proportion of the total water flow. Using a mass N balance to determine the NO_3 concentration in seepage water compared to the concentration in the tile effluent, they concluded that the NO_3 concentration in the nontile drainage was much lower than in the tile effluent. The results of their study suggested that there was an oxidized zone close to the tile lines which protected the NO_3 from denitrification. In the water that did not flow through the tiles the NO_3 concentration was apparently lower initially, or else it was reduced through denitrification as the water flowed through the soil.

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Gast, Nelson, and MacGregor (1974) reported that denitrification rather than leaching or tile drainage was the primary mechanism responsible for the disappearance of unused fertilizer nitrogen.

Johnston, et al. (1965) concluded that the quantity of N and P discharged was related to the amount of applied fertilizer and the quantity of tile flow.

Ellis and Erickson (1971) reported the level of P in drainage water was very low. They concluded that when soils were fertilized at recommended rates, nutrient losses through tile drainage would be very small.

METHODS AND MATERIALS

Description of Experimental Site

The study was conducted on a Conover loam at the Michigan State University Soils Research Farm at East Lansing. This soil which developed from loamy, calcareous till is nearly level with slopes of 0 to 2%, has slow surface runoff, has moderate to moderately slow permeability, and is somewhat poorly drained with water table fluctuations between 60 and 300 cm. The site had been tiled in 1970 at a depth of 105 cm and at spacings of 15m.

Secondary municipal effluent was not available for this study. Therefore, a simulated effluent was prepared by injecting a solution of NaCl and 12-6-6 liquid fertilizer into irrigation water.

Four rates of effluent irrigation (25, 50, 100, and 200 cm per year) and six corn hybrids (Michigan (M) 396, M402, or Pioneer 3780, M500, M511, M572, and Funks 4444) were replicated three times in a split-plot design. The treatments were established over three adjacent tile lines to compensate for possible lateral flow. Each tile line and its drainage area of 557 square meters was then treated as a replicate.

Effluent was applied at 0.78 cm/hour through a solid set irrigation system. Risers were placed every 9 meters

along the laterals which were placed in the center of each replicate directly above the tile lines. Therefore, sprinkler spacings were approximately 9 x 15 meters.

Two types of Rainbird sprinklers were used to give a uniform distribution over the entire plot. The three central sprinklers were full-circle heads with 9/64 inch nozzles while the end sprinklers were semi-circle heads with 3/32 inch nozzles.

In 1973, a preplant mixture of paraquat and atrazine was applied to kill the bromegrass sod. To maintain optimum soil structure, the corn was no-till planted in 28 inch rows on May 14. Plant populations for the various hybrids are given in Appendix Table 22. A 16-16-16 starter fertilizer was applied at 280 kg/ha. This supplied the crop with 45 kg/ha N, P_2O_5, and K_2O. All additional nutrients were supplied by the simulated effluent.

Winter rye was planted following the harvest of silage corn. The rye which provided a nutrient sink for the fall and spring irrigations was mowed and plowed down as green manure in May of 1974. The field was disced, harrowed, and planted to corn on May 23. A 12-12-12 starter fertilizer was applied at 375 kg/ha and a pre-emergence mixture of atrazine and alachlor was applied for weed control.

Soil Water Balance

A soil water balance was determined by measuring water gains and losses throughout the growing season.

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Water gains included rainfall and the quantity of effluent an area received, while water losses included evapotranspiration (ET), tile drainage, deep percolation and water storage.

Rainfall was measured with a standard U.S. Weather Bureau rain gauge. The quantity of effluent which was applied was determined by the number of hours of irrigation.

Evapotranspiration losses were estimated from Class A open pan evaporation according to the procedures developed by Shaw and Laing (1965).

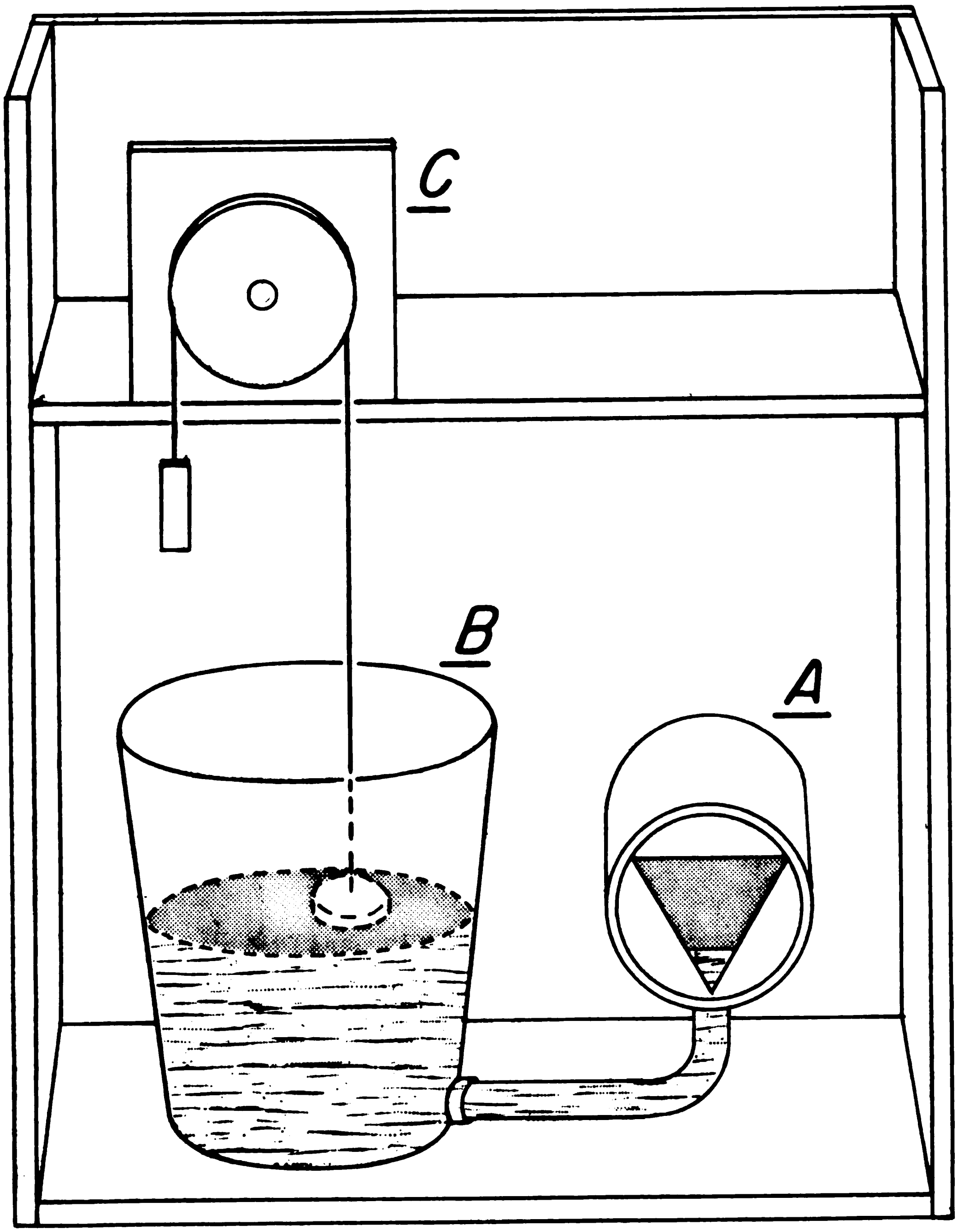
The volume of tile drainage was measured by replacing a clay tile with a plastic tube equipped with a 60° V-notch weir. This tube was connected to a plastic pail which functioned as a still well for a Stevens Water Stage Recorder (Figure 1). A calibration curve developed for each weir was used to convert the change in head to the volume of flow.

Water Sampling and Analysis

The tile drainage water was sampled several times throughout each flow period. These samples were analyzed for NO_3-N, P, K, Ca, Mg, Na, and Cl.

The NO_3 concentrations were measured with an Orion specific ion electrode during 1973 and early 1974. However, when the Technicon Auto-Analyser became available, NO_3 was measured colorimetrically using the cadmium reduction method

Figure 1. Cross-section of the tile flow monitoring system.



A Plastic Tile with 60° V-Notch Weir

B Plastic Pail fx, as Still Well

C Stevens Water Stage Recorder

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of Henriksen and Selmer-Olsen (1970). This method was more desirable since it was more sensitive and it eliminated any potential Cl interference.

The P concentration was measured colormetrically using ammonium molybdate and ascorbic acid for color development (Watanabe and Olsen, 1965).

The K and Na concentrations were determined photometrically using a Coleman flame photometer while Ca and Mg concentrations were determined by atomic absorption using a Perkin-Elmer 303 spectophotometer.

The Cl concentration was determined by using an Orion Cl specific electrode.

Plant Sampling and Analysis

Ear leaf samples were taken at first silking to measure the nutritional status of the actively growing plant according to the sufficiency guidelines published by Jones (1973).

Corn silage yields were determined by chopping a 15 meter row of each hybrid, and grain yields were determined by picking and shelling two 15 meter rows.

Winter rye yields were determined by chopping a 7.5 meter strip on each side of the irrigation line.

Samples were oven dried for moisture determination, and then ground to pass a 40-mesh sieve for laboratory analysis.

Total N was determined by semimicro Kjeldahl analysis (Bremner, 1956b).

The silage samples from 1973 and the winter rye samples were analyzed for P, Ca, Mg, Na, and K following a wet oxidation with nitric and perchloric acid (Jackson, 1958).

The P concentration was determined colorimetrically utilizing ammonium molybdate and ascorbic acid for color development (Watanabe and Olsen, 1965).

The K and Na concentrations were determined photometrically using a Coleman flame photometer, while Ca and Mg concentrations were determined by atomic absorption using a Perkin-Elmer 303 spectophotometer.

Soluble Cl was determined by potentiometric titration with $AgNO_3$ (La Croix, et al. 1970).

The ear leaf samples, grain samples, and the silage samples from 1974 were sent to the International Minerals and Chemical Corporation where they were analyzed spectographically for P, K, Ca, Mg, Na, Cu, Fe, Zn, B, Mn, Al, and Ba.

Soil Sampling and Analysis

Soil samples were taken in April and November of each year. Two cores per plot were taken to a depth of 270 cm and divided into the following increments for analysis (0-15, 15-30, 30-60, 60-90, 90-120, 120-150, 150-210, and 210-270 cm).

The samples were air dried, sieved through a 10 mesh screen, and analyzed for NH_4-N, NO_3 + NO_2 - N, extractable P, exchangeable Na, K, Ca, and Mg, and soluble Cl.

The NH_4-N and NO_3 + NO_2-N concentrations were determined by direct steam distillation (Bremner, 1965a).

Extractable P was measured colorimetrically with a Technicon Auto-Analyser II. The samples were extracted with 0.025 N NH_4F-HCl as outlined by Bray and Kurtz (1945). However, the procedure was modified by using a 1:4 soil-solution ratio and by shaking for 5 minutes. Color development was accomplished by using ammonium molybdate and 1,2, 4-aminonaphthosulfonic acid (Jackson, 1958).

Exchangeable K, Na, Ca, and Mg were extracted with 1N NH_4OAc. The K and Na concentrations were determined photometrically using a Coleman flame photometer, while Ca and Mg concentrations were determined by atomic absorption using a Perkin-Elmer 303 spectrophotometer.

Soluble Cl was measured by shaking the samples with saturated $CaSO_4$ for 30 minutes, and then measuring the conductivity with an Orion Cl specific electrode.

Statistical Analyses

All statistical analyses were performed on an CDC 6500 computer at the Michigan State Computer laboratory. The least significant differences (LSD) were calculated according to the procedures given by Steel and Torrie (1960).

RESULTS AND DISCUSSION

Effluent Characteristics

The simulated municipal effluent had approximately the same inorganic nutrient composition as the secondary effluent produced at East Lansing's municipal waste treatment plant (Table 1). The concentration of heavy metals, organic and total carbon, and suspended solids in the secondary effluent was sufficiently low so that no attempt was made to simulate the potential effects of these constituents. The annual application rates of N, P, K, Na, and Cl are given in Table 2.

Site Characteristics

The experiment was established on one of the most uniform sites available, but measurements with piziometer tubes indicated large variations in the drainage characteristics of the soil profile. These variations can probably be accounted for by the natural heterogeneity of soils developed from glacial till and the very non-uniform drainage patterns which often result.

Hydrologic Balances

Hydrologic balances were determined to trace the fate of the applied effluent at the various annual loading rates (Tables 3 to 6).

TABLE 1. Effluent composition.

Constituent	East Lansing's Secondary[a]	Simulated
	mg/l	
Total N	15.2	15.0
Nitrate N	3.1	3.5
Total P	4.9	3.3
Soluble P	1.1	2.2
K	8.6	6.2
Na	130	130[b]
Ca	100	200
Mg	25	62
Cl	260	200[bc]

[a] D'itri, F.M. (1973).

[b] In 1973 the simulated effluent contained 210 ppm Na and 324 ppm Cl.

[c] This was the amount of Cl added. The irrigation water had an additional 25 ppm Cl from natural sources.

TABLE 2. Annual application of N, P, K, Na, and Cl as influenced by the loading rate of simulated municipal effluent.

Treatment	N[a]	P[a]	K[a]	Na[b]	Cl[bc]
	kg/ha				
25 cm	83	28	53	330	507
50 cm	121	36	69	660	1014
100 cm	197	52	100	1320	2029
200 cm	349	85	163	2640	4058

[a] Includes 45 kg/ha N, P_2O_5, K_2O starter fertilizer.

[b] In 1973 the Na applications were 319, 909, 1780, 3343 kg/ha, and the Cl applications were 492, 1401, 2744, and 5154 kg/ha at the 25, 50, 100, and 200 cm loading rates, respectively.

[c] Based on the amount of Cl added.

TABLE 1. Soil water balance for an annual loading of 25 cm of simulated municipal effluent on corn.[a]

TABLE 3. Soil water balance for an annual loading of 25 cm of simulated municipal effluent on corn.[a]

Week	Rainfall	Irrigation[b]	ET	Tile Flow	Δ Storage	Deep Percolation
	cm					
1	0.00	0.00	1.62	0.00	-1.62	0.00
2	0.56	1.56	2.25	0.00	-1.75	0.00
3	2.44	0.78	1.67	0.00	-0.20	0.00
4	6.02	0.00	1.68	0.85[c]	0.00	3.29
5	0.00	0.00	1.62	0.00	-1.62	0.00
6	1.96	1.56	0.92	0.00	0.00	0.98
7	1.35	0.78	1.35	0.00	0.00	0.78
8	0.53	0.78	1.38	0.00	-0.07	0.00
9	0.81	1.56	1.17	0.00	0.00	1.13
10	0.00	1.56	1.96	0.00	-0.40	0.00
11	2.97	1.56	2.78	0.00	0.00	1.35
12	0.89	1.56	2.98	0.00	-0.53	0.00
13	0.00	1.56	4.21	0.00	-3.18	0.00
14	0.53	1.56	2.58	0.00	-3.67	0.00
15	1.47	1.56	3.90	0.00	-4.54	0.00
16	0.41	1.56	2.74	0.00	-5.31	0.00
17	3.78	1.56	2.82	0.00	-2.79	0.00
18	0.08	1.56	3.56	0.00	-4.71	0.00
19	3.28	1.56	2.95	0.00	-2.82	0.00
20	1.78	0.78	1.63	0.00	-1.89	0.00
21	1.78	0.78	1.65	0.00	-0.98	0.00
22	0.00	0.78	1.59	0.00	-1.79	0.00
23	1.17	0.00	1.69	0.00	-2.31	0.00
24	2.24	0.00	0.84	0.00	-0.91	0.00
25	0.23	0.00	0.75	0.00	-1.43	0.00
Total	34.28	24.96	52.29	0.85		7.53

[a]Measurements made between April 21 and October 12, 1974.

[b]Assuming 100% irrigation efficiency.

[c]Estimated due to system failure.

TABLE 4. Soil water balance for an annual loading of 50 cm of simulated municipal effluent on corn.[a]

TABLE 4. Soil water balance for an annual loading of 50 cm of simulated municipal effluent on corn.[a]

Week	Rainfall	Irrigation[b]	ET	Tile Flow	Δ Storage	Deep Percolation
	cm					
1	0.00	0.00	1.62	0.00	-1.62	0.00
2	0.56	2.34	2.25	0.01	-0.98	0.00
3	2.44	2.34	1.67	0.01	0.00	2.12
4	6.02	0.00	1.68	0.85[c]	0.00	3.49
5	0.00	0.00	1.62	0.00	-1.62	0.00
6	1.96	1.56	0.92	0.00	0.00	0.98
7	1.35	1.56	1.35	0.00	0.00	1.56
8	0.53	1.56	1.38	0.00	0.00	0.71
9	0.81	2.34	1.17	0.01	0.00	1.97
10	0.00	3.12	1.96	0.00	0.00	1.16
11	2.97	3.12	2.78	0.06	0.00	3.25
12	0.89	3.12	2.98	0.13	0.00	0.90
13	0.00	3.12	4.21	0.01	-1.10	0.00
14	0.53	3.90	2.58	0.04	0.00	0.71
15	1.47	3.90	3.90	0.01	0.00	1.46
16	0.41	3.90	2.74	0.08	0.00	1.49
17	3.78	3.12	2.82	2.01	0.00	2.07
18	0.08	3.12	3.56	0.02	-0.38	0.00
19	3.28	3.12	2.95	0.98	0.00	2.09
20	1.78	1.56	1.63	0.04	0.00	1.67
21	1.78	1.56	1.65	0.01	0.00	1.68
22	0.00	1.56	1.59	0.01	-0.04	0.00
23	1.17	0.00	1.69	0.00	-0.56	0.00
24	2.24	0.78	0.84	0.01	0.00	1.61
25	0.23	0.78	0.75	0.00	0.00	0.26
Total	34.28	51.48	52.29	4.29		29.18

[a]Measurements made between April 21 and October 12, 1974.
[b]Assuming 100% irrigation efficiency.
[c]Estimated due to system failure.

TABLE 5. Soil water balance for an annual loading of 100 cm of simulated municipal effluent on corn.[a]

Week	Rainfall	Irrigation[b]	ET	Tile Flow	Δ Storage	Deep Percolation
	cm					
1	0.00	2.34	1.62	0.00	0.00	0.72
2	0.56	3.12	2.25	0.01	0.00	1.42
3	2.44	3.12	1.67	0.12	0.00	3.77
4	6.02	0.00	1.68	0.85[c]	0.00	3.49
5	0.00	0.00	1.62	0.00	-1.62	0.00
6	1.96	1.56	0.92	0.02	0.00	0.96
7	1.35	2.34	1.35	0.00	0.00	2.34
8	0.53	3.12	1.38	0.11	0.00	2.16
9	0.81	3.90	1.17	0.02	0.00	3.52
10	0.00	5.45	1.96	0.20	0.00	3.29
11	2.97	6.23	2.78	1.19	0.00	5.23
12	0.89	7.01	2.98	0.84	0.00	4.08
13	0.00	7.01	4.21	0.43	0.00	2.37
14	0.53	7.01	2.58	0.91	0.00	4.05
15	1.47	7.01	3.90	1.16	0.00	3.42
16	0.41	7.01	2.74	1.17	0.00	3.51
17	3.78	7.01	2.82	4.24	0.00	3.73
18	0.08	7.01	3.56	1.49	0.00	2.04
19	3.28	6.23	2.95	3.20	0.00	3.36
20	1.78	3.12	1.63	1.20	0.00	2.07
21	1.78	3.12	1.65	0.13	0.00	3.12
22	0.00	3.12	1.59	0.08	0.00	1.45
23	1.17	1.56	1.69	0.02	0.00	1.02
24	2.24	1.56	0.84	0.78	0.00	2.18
25	0.23	3.12	0.75	0.07	0.00	2.53
Total	34.28	102.08	52.29	18.24		65.83

[a]Measurements made between April 21 and October 12, 1974

[b]Assuming 100% irrigation efficiency

[c]Estimated due to system failure.

TABLE 6. Soil water balance for an annual loading of 200 cm of simulated municipal

TABLE 6. Soil water balance for an annual loading of 200 cm of simulated municipal effluent on corn.[a]

Week	Rainfall	Irrigation[b]	ET	Tile Flow	Δ Storage	Deep Percolation
	----	----	---- cm ----	----	----	----
1	0.00	4.67	1.62	0.00	0.00	3.05
2	0.56	7.01	2.25	0.08	0.00	5.24
3	2.44	7.01	1.67	0.30	0.00	7.48
4	6.02	0.00	1.68	0.85[c]	0.00	3.49
5	0.00	0.00	1.62	0.00	-1.62	0.00
6	1.96	1.56	0.92	0.01	0.00	0.97
7	1.35	3.12	1.35	0.02	0.00	3.10
8	0.53	4.67	1.38	0.03	0.00	3.79
9	0.81	6.23	1.17	0.18	0.00	5.69
10	0.00	10.13	1.96	0.17	0.00	8.00
11	2.97	8.57	2.78	0.48	0.00	8.28
12	0.89	14.02	2.98	1.34	0.00	10.59
13	0.00	14.02	4.21	1.19	0.00	8.62
14	0.53	14.02	2.58	1.59	0.00	10.38
15	1.47	14.02	3.90	1.81	0.00	9.78
16	0.41	14.02	2.74	1.59	0.00	10.10
17	3.78	14.02	2.82	3.18	0.00	11.80
18	0.08	14.02	3.56	1.71	0.00	8.83
19	3.28	14.02	2.95	3.16	0.00	11.19
20	1.78	8.57	1.63	1.14	0.00	7.58
21	1.78	7.01	1.65	0.12	0.00	7.02
22	0.00	7.01	1.59	0.06	0.00	5.36
23	1.17	2.34	1.69	0.01	0.00	1.81
24	2.24	4.67	0.84	0.16	0.00	5.91
25	0.23	8.57	0.75	0.23	0.00	7.82
Total	34.28	203.30	52.29	19.41		165.88

[a]Measurements made between April 21 and October 12, 1974.

[b]Assuming 100% irrigation efficiency.

[c]Actual measurement.

The soil water balances for the 25 and 50 cm loading rates show that evapotranspiration (ET) losses accounted for 88 and 61% of the rainfall and applied effluent during the growing season. Tile flow accounted for 1 and 5% of the water losses, while deep percolation accounted for the remaining 11 and 34%, respectively.

The weekly water balances show that at the 25 cm loading rate losses were often greater than gains. This indicates that at this loading rate crop growth may have been limited due to a lack of water. At the 50 cm loading rate the water gains were almost always greater than losses, which suggests that the crop had sufficient water for maximum growth and nutrient uptake.

The soil water balances for the 100 and 200 cm loading rates show that only 38 and 22% of the water gains could be accounted for through ET losses. The volume of tile flow increased substantially at these loading rates, but it accounted for only 13 and 8% of the water losses, respectively. The remaining 48 and 70% of the water gains were attributed to deep percolation losses since surface runoff was negligible.

The natural heterogeneity of the soil and the non-uniform drainage patterns due to the distribution of sand smears and clay lenses throughout the profile probably accounted for the large quantity of water loss through deep percolation at these loading rates.

The weekly water gains at the 100 and 200 cm loading rates exceeded the requirements for maximum plant growth, and may have actually limited it by restricting root penetration due to an O_2 deficiency in the lower horizons.

Drainage Water Volume and Nutrient Concentration

The volume of tile flow (Appendix Table 23) showed a large fluctuation between weeks. This can be accounted for by the varying amounts of rainfall, applied effluent, and evaporative demand.

The NH_4^+ and NO_2^- concentrations in the drainage water were negligible, but substantial NO_3^- concentrations were found throughout most of the growing season (Figure 2).

During the first three weeks while the effluent was being applied to the winter rye, the NO_3 concentration and therefore N losses (Figure 3) in the drainage water were very low. After the corn was planted the NO_3 concentration rose substantially. This increase may have been due to leaching of N from the starter fertilizer, or N from the decomposing winter rye. During this time the weekly loading rates were not sufficient to cause a large volume of tile flow, and although the NO_3 concentration was quite high, the actual N losses remained small.

The NO_3 concentration in the drainage water continued to fluctuate above 10 mg/l through the 15th week. Nitrogen losses during this time were between 1 and 2 kg/ha/week. After the 15th week, when the corn crop began to grow at its maximum rate, the NO_3 concentration in the drainage water dropped below 10 mg/1, but N losses continued to be between 1 and 3 kg/ha/week. This indicates that although the corn was taking up large amounts of N, the weekly irrigation rates were sufficient to leach some of the applied N into the drainage water and possibly below the root zone of the corn.

The P concentration in the initial drainage water was always much higher than the concentration after several hours of tile flow (Figure 4) . This was probably due to the rapid infiltration and percolation of some of the applied effluent through sand smears and directly into the tile lines. As the number of hours of tile flow increased, a larger portion of the drainage water which entered the tile had its P load removed through adsorption, thus diluting the concentration of the effluent which was moving directly into the tile. The peak which occurred at the 48th flow hour coincides with the beginning of an irrigation and tends to support this theory.

The effects of this short circuiting on the N concentrations in the drainage water were not noticeable, due to the natural movement of NO_3 with the soil solution.

The short circuiting effect through the sand smears caused the mean weekly P concentrations in the drainage water (Figure 5) to be somewhat higher than the levels reported by Ellis and Erickson (1971). The P losses in the

Figure 2. Concentration of NO_3-N in drainage water (1974).

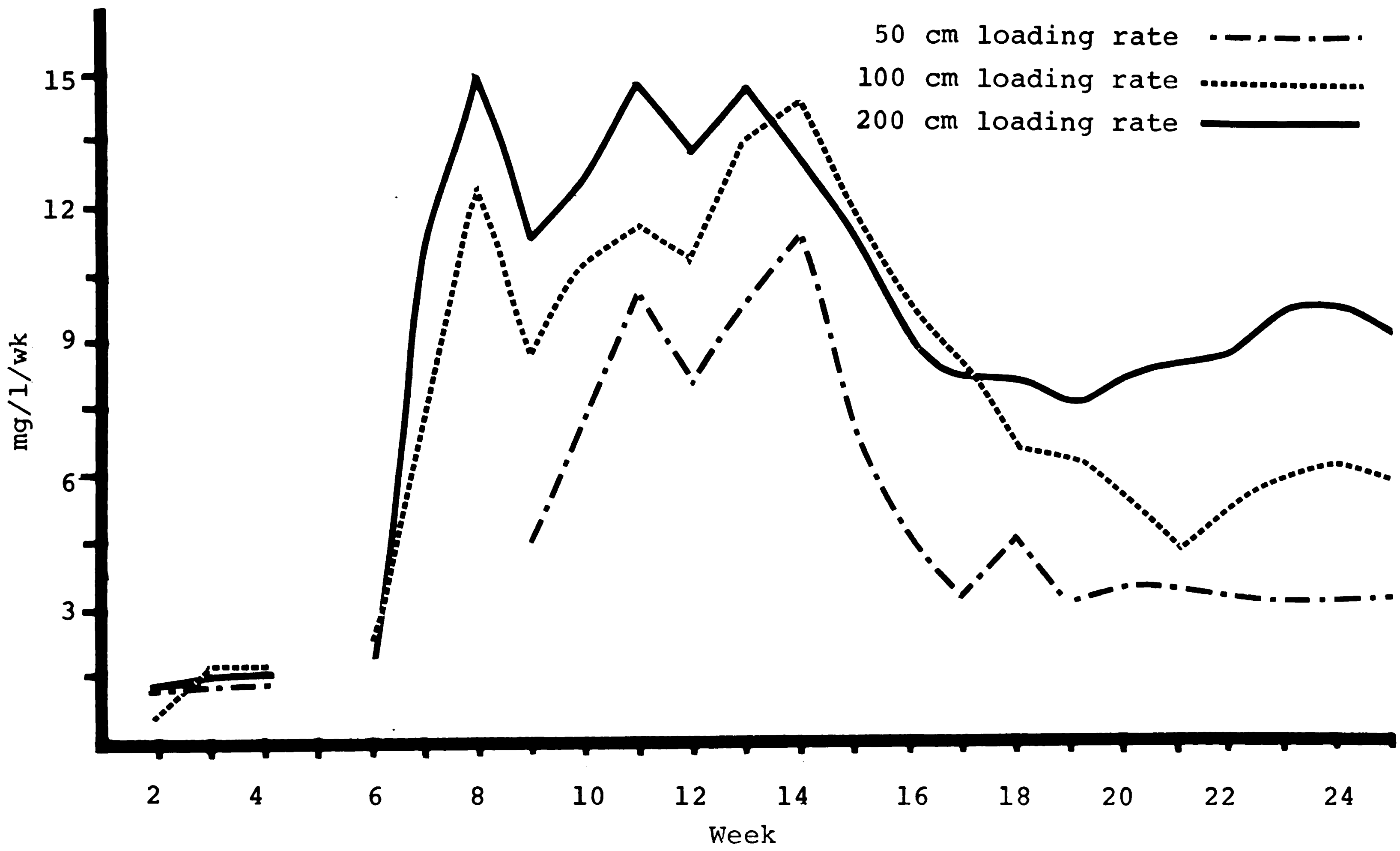
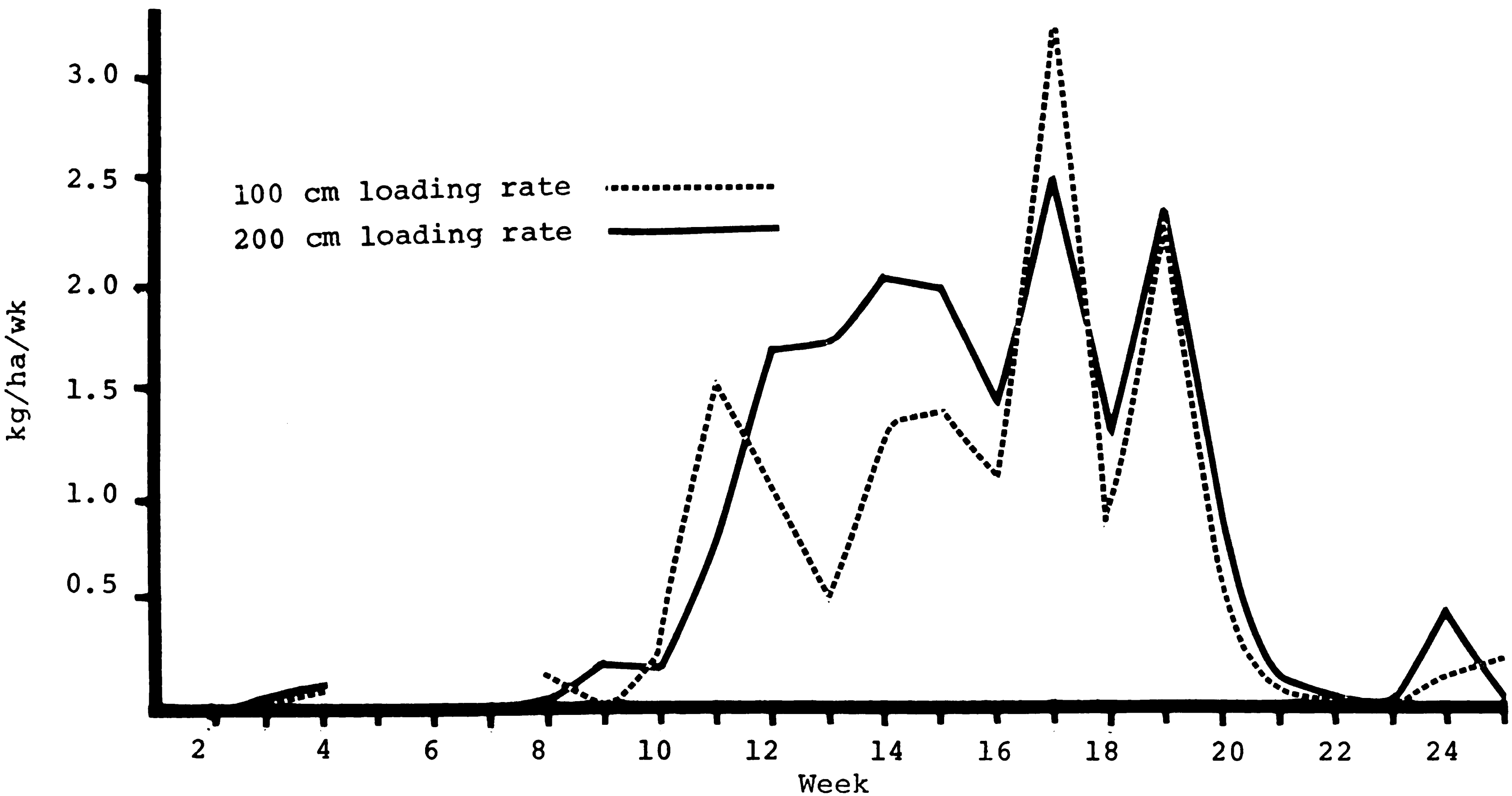


Figure 3. Nitrogen loss through drainage water (1974).



drainage water (Figure 6) reflect the higher concentrations, but appear to have been influenced more by the volume of tile flow.

The NO_3 concentrations in the drainage water in 1973 (Appendix Figure 12) were similar to the concentrations found in 1974. Rapid leaching of mineralized N with the first few irrigations probably accounted for the high concentrations in the initial drainage water samples.

Fluctuations in the P concentration were of the same magnitude in 1973 as in 1974. These fluctuations can probably be accounted for by the short circuiting effects of the sand smears (Appendix Figure 13).

The N and P losses were not computed for 1973, since it was not possible to measure the volume of tile flow at that time.

The K concentration in the drainage water was much higher in 1973 than in 1974 (Table 7). This was due to the replacement of some of the exchangeable K by the Na in the effluent. As the level of exchangeable K declined, less of it was replaced and therefore the concentration in the drainage water declined in 1974.

The K concentration in the drainage water was relatively stable throughout the growing season. The mean weekly concentrations were approximately 3 and 5 ppm at the 100 and 200 cm loading rates, respectively. This indicates that weekly K losses (Figure 7) were influenced more by the

Figure 4. Hourly concentration of P in tile drainage water (1974).

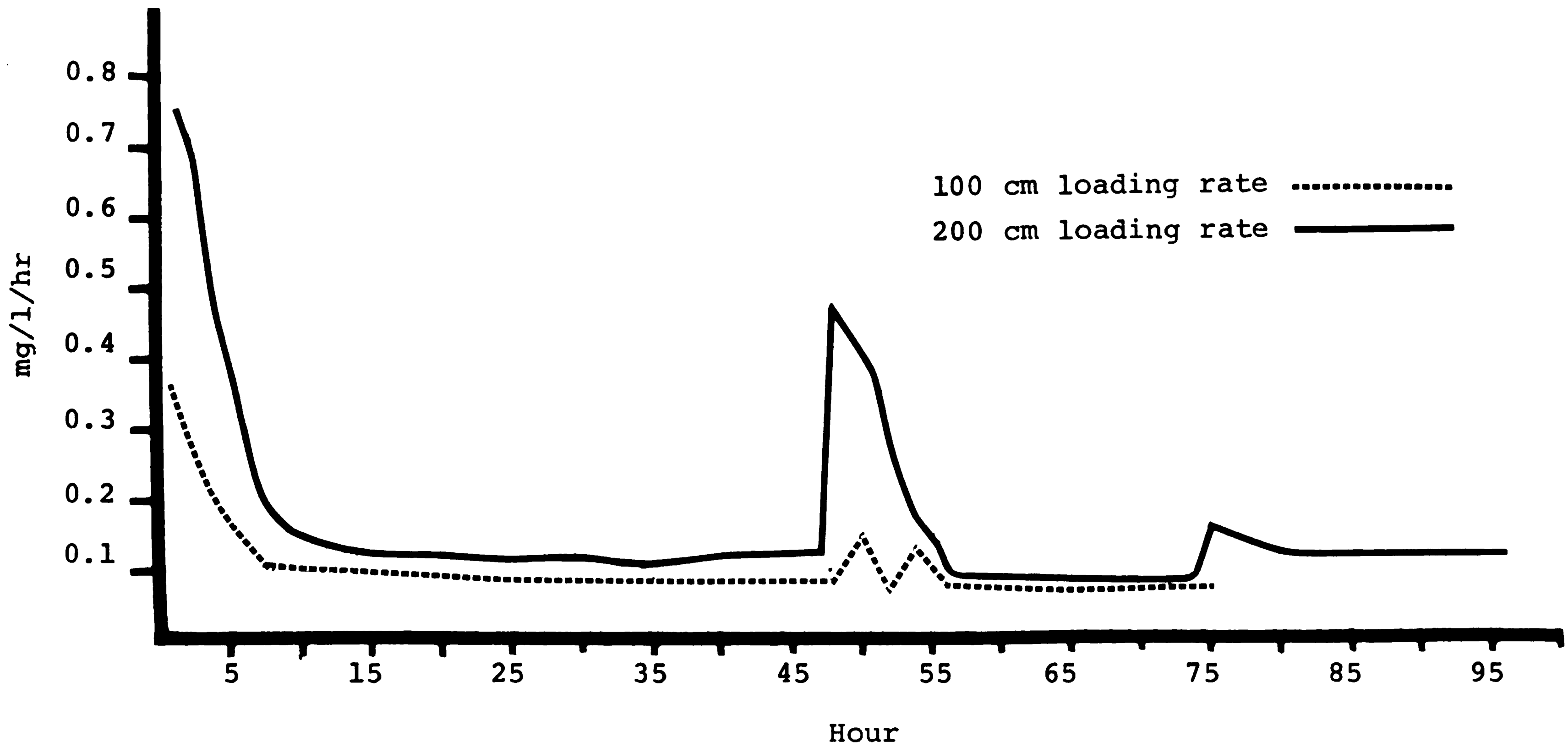


Figure 5. Weekly concentration of P in tile drainage water (1974).

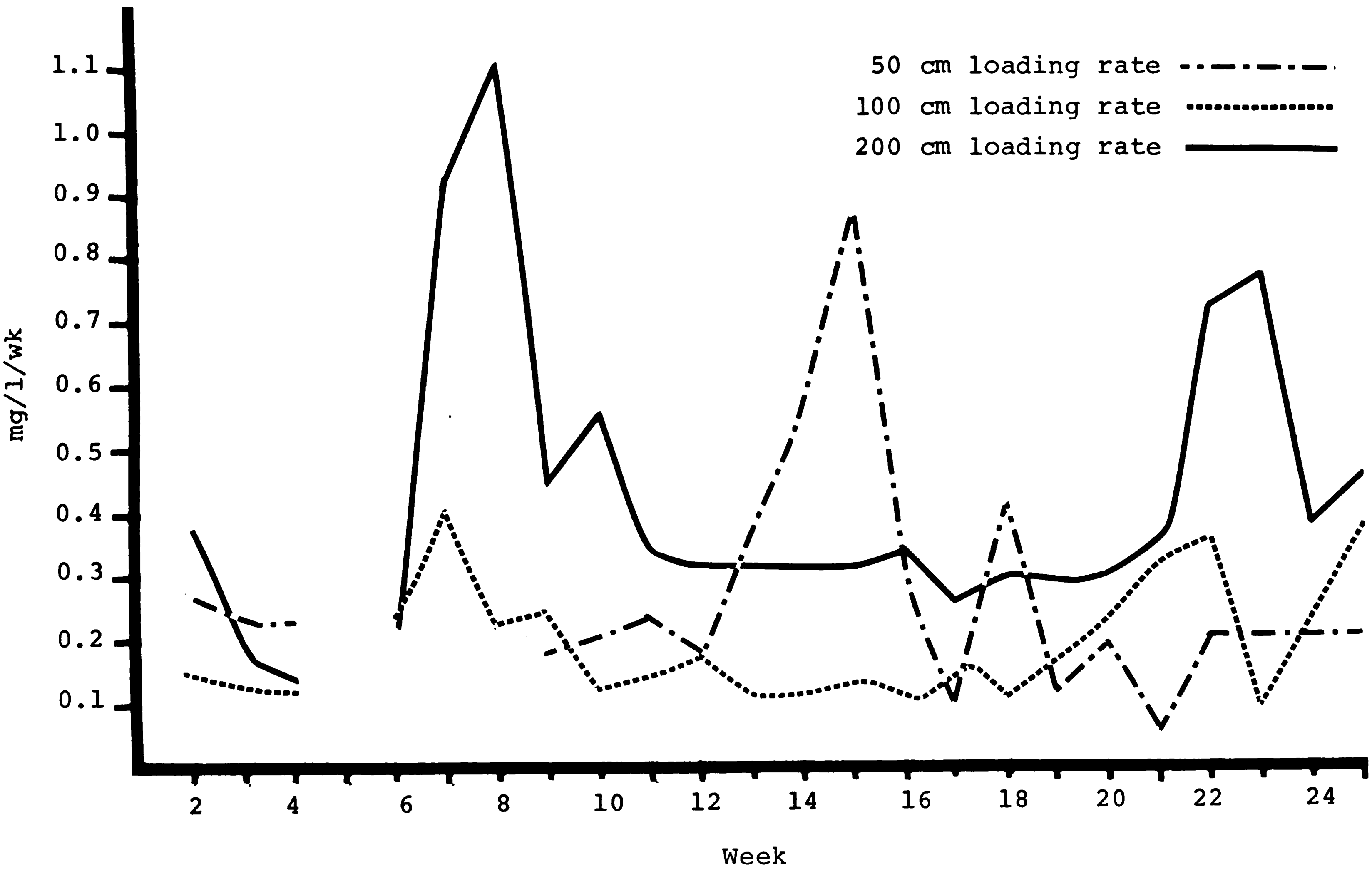
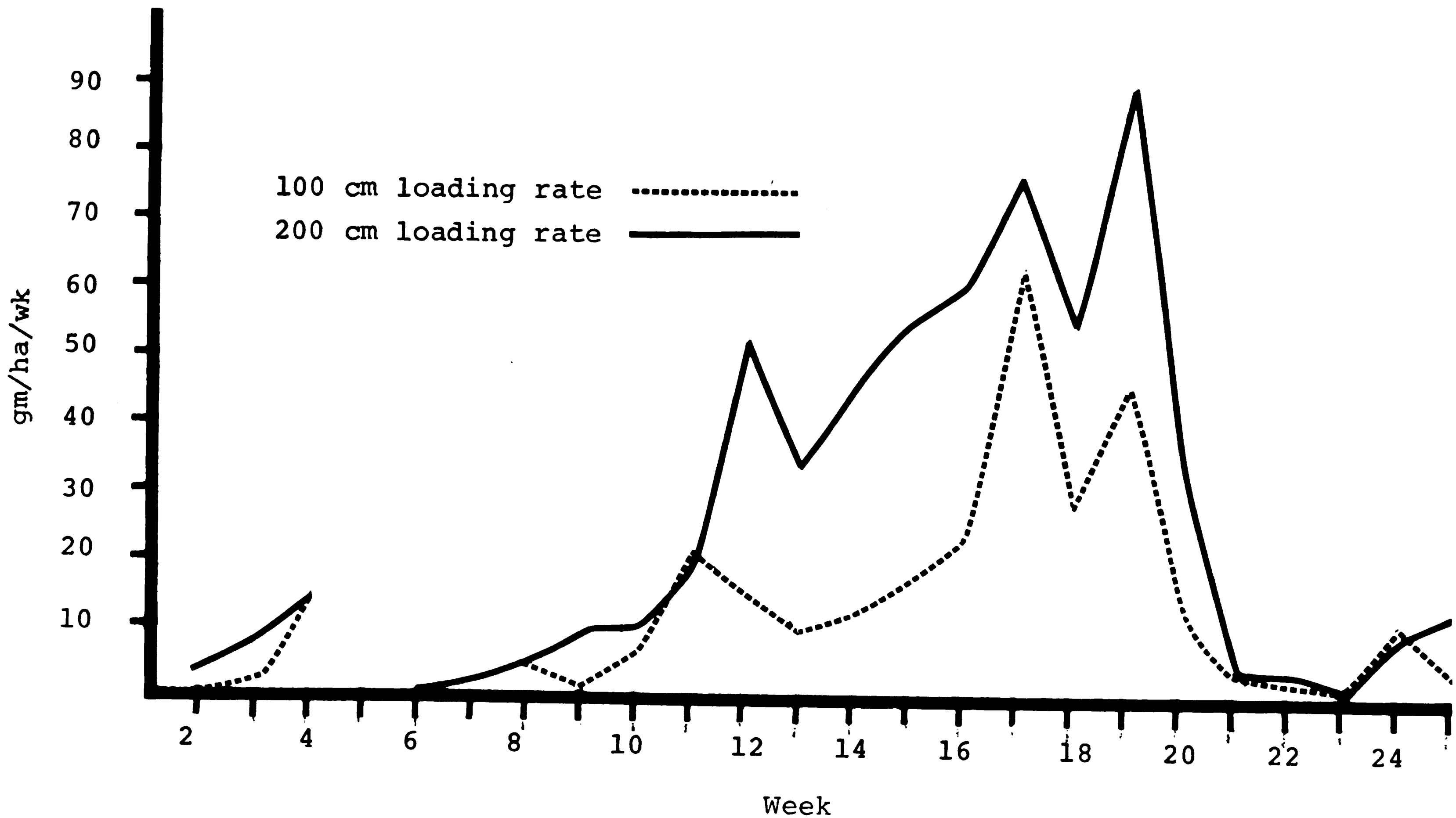


Figure 6. Weekly P losses in tile drainage water (1974).



volume of tile flow than variations in concentration.

Severe structural problems may result if the exchangeable sodium percentage (ESP) is greater than 15 (Richards, 1954). The sodium adsorption ratio (SAR) of the simulated municipal effluent was approximately 3.0, which indicated that this water would have a very low sodium hazard. The SAR values of the drainage water support this, indicating that after two years of irrigation with this effluent the maximum ESP was only 3.4 (Table 8). These values may increase slightly after more years of irrigation, however infiltration and percolation of rainfall and snow melt should insure that no structural problems will develop due to excessive sodium adsorption.

Nutrient Loss Through Drainage Water

Nutrient loss through the tile drainage water accounted for only a small amount of the applied N, P, and K (Table 9). Since tile flow accounted for only 1, 5, 13, and 8% of the rainfall and applied effluent at the 25, 50, 100, and 200 cm loading rates, respectively, there may have been a substantial nutrient loss through deep percolation. An estimate of this potential loss can be made by assuming (a) a uniform nutrient concentration in all of the soil water, (b) an irrigation efficiency of 100%, and (c) a uniform soil moisture content before and after the irrigation season. Therefore, deep percolation losses accounted for 13, 34, 48, and 70% of the rainfall and applied effluent at the 25, 50, 100, and 200 cm loading rates,

TABLE 7. Potassium concentrations in drainage water as influenced by the loading rate of simulated municipal effluent.

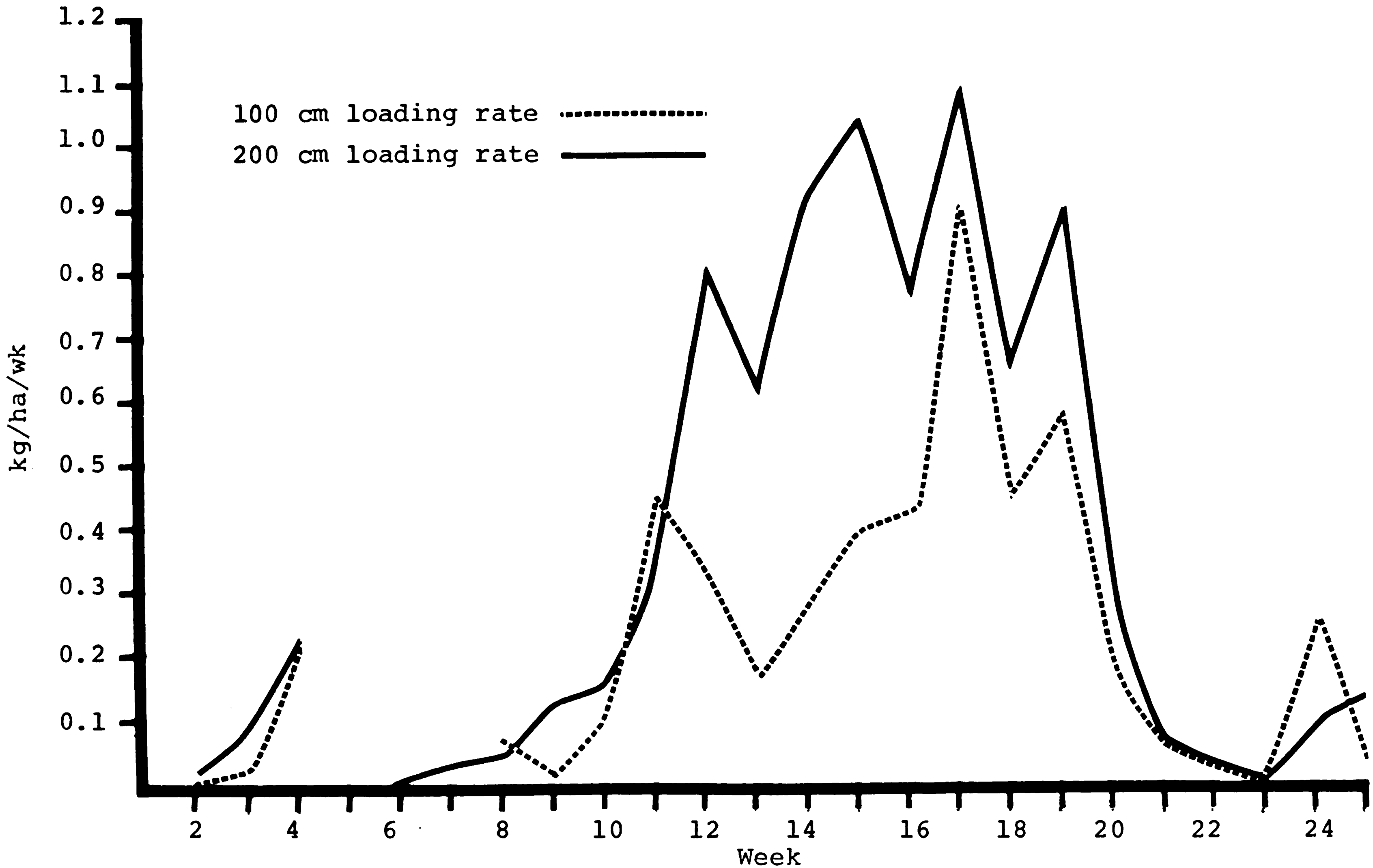
Treatment	1973	1974
	mg/l	
50 cm	12.7	10.3
100 cm	5.7	2.4
200 cm	9.8	4.3

TABLE 8. SAR of drainage water and corresponding ESP as influenced by loading rate of simulated municipal effluent.

Treatment	SAR	ESP[a]
50 cm	1.4	0.8
100 cm	2.4	2.3
200 cm	3.2	3.4

[a]Estimated from SAR values using Figure 22, USDA Handbook No. 60.

Figure 7. Weekly K loss in tile drainage water (1974).



respectively. By using the measured nutrient loss in the tile drainage, an estimate of the potential loss through deep percolation can be made (Table 10).

These estimates may be much greater than the real leaching losses. Mechanisms such as biological immobilization and denitrification often reduce NO_3 concentrations in the percolate to a much lower concentration than is found in the tile drainage. The findings of Thomas and Barfield (1974) indicated that unless the overall picture of drainage is known, estimating N loss in this manner may be very unreliable. Estimates of P loss may also be significantly higher due to the short circuiting of some effluent into the tile lines and therefore a much higher mean P concentration in the drainage water than in the soil percolate.

Irrigation efficiencies are rarely 100% due to losses through drift and evaporation. If these losses substantially reduced the amount of water applied, i.e. 70 to 80% efficiency, less water would have been attributed to deep percolation. Therefore, the nutrient losses through leaching would also be reduced.

Nutrient Composition and Recovery Through Plant Uptake

The 1973 ear leaf analyses (Table 11) indicated that the corn hybrids were slightly deficient in K, within the normal range for N, Ca, Mg, Zn, B, and Mn, and slightly above the sufficiency range in P according to the guidelines

TABLE 9. Nutrient loss through tile drainage water as influenced by annual loading rate of simulated municipal effluent.

Treatment	N	P	K
	kg/ha		
25 cm	0.1	0.01	0.2
50 cm	1.3	0.05	2.9
100 cm	14.8	0.28	4.9
200 cm	18.0	0.60	8.5

TABLE 10. Potential nutrient losses through deep percolation as influenced by annual loading rate of simulated municipal effluent.

Treatment	N	P	K
	kg/ha		
25 cm	1.3	0.13	2.5
50 cm	8.8	0.34	19.7
100 cm	101.	1.90	33.3
200 cm	153.	5.10	72.2

published by Jones (1973). The 1974 analyses indicated that the hybrids were deficient in both N and K, within the normal range for Ca, Mg, Zn, B, and Mn, and above the sufficiency range in P.

The nutrient concentrations in the ear leaves showed significant treatment responses (Table 12). The N, P, Ca, Na, Zn, B, and Mn concentrations increased with increasing rates of simulated effluent, while K concentrations decreased and Mg concentrations remained constant.

In 1973 N, Ca, Mg, Zn, B, and Mn concentrations were within the sufficiency range at all loading rates. The P levels were above the sufficiency range, while K levels were deficient at all rates of application. In 1974 N was deficient at all loading rates, but K was deficient only at the 100 and 200 cm rates. The P concentrations were within the normal range at the 25 and 50 cm loading rates, but slightly above at the 100 and 200 cm rates. The Ca, Mg, Zn, B, and Mn concentrations were within their sufficiency ranges at all loading rates.

The treatment x hybrid interactions showed no significant differences.

Corn silage yields (Table 13) showed significant treatment differences in both 1973 and 1974. Yields were maximized at the 50 cm loading rate, with only a slight reduction at the 200 cm rate of application. The 100 cm loading rate resulted in a significant yield reduction in

TABLE 11. Nutrient concentration in corn ear leaf samples as influenced by hybrid.[a]

Hybrid	N	P	K	Ca	Mg	Na	Zn	B	Mn
1973	%						ppm		
M 396[b]	2.92	0.59	1.47	0.70	0.26	0.19	28	14	47
M 402	3.06	0.64	1.43	0.77	0.26	0.19	34	12	43
M 500	2.70	0.57	1.43	0.71	0.24	0.20	38	12	36
M 511	2.66	0.58	1.45	0.69	0.26	0.20	29	12	36
M 572	2.88	0.56	1.45	0.72	0.27	0.20	29	13	43
F 4444[c]	2.64	0.55	1.50	0.72	0.28	0.23	27	12	33
LSD (.05)	0.15	0.05	NS	0.04	0.02	0.03	4	NS	7
1974									
M 396	1.64	0.52	1.68	0.66	0.28	0.14	26	14	44
P 3780[d]	1.74	0.52	1.59	0.65	0.30	0.14	35	15	40
M 500	1.72	0.56	1.64	0.74	0.27	0.13	38	17	48
M 511	1.68	0.52	1.72	0.67	0.28	0.15	29	14	40
M 572	1.71	0.47	1.61	0.68	0.28	0.14	26	12	36
F 4444	1.70	0.52	1.66	0.68	0.32	0.16	30	15	39
LSD (.05)	NS	0.05	NS	0.04	0.02	NS	3	3	5

[a]Averaged across all treatments.

[b]M--Michigan Certified Seed Company

[c]F--Funks Seed Company.

[d]P--Pioneer Seed Company.

TABLE 12. Nutrient concentrations in corn ear leaf samples as influenced by annual loading rate.[a]

Treatment	N	P	K	Ca	Mg	Na	Zn	B	Mn
1973	----------	----------	----------	%	----------	----------	------	ppm	------
25 cm	2.73	0.45	1.70	0.68	0.27	0.14	27	9	31
50 cm	2.84	0.54	1.36	0.68	0.23	0.18	31	10	33
100 cm	2.77	0.56	1.51	0.67	0.26	0.20	32	13	43
200 cm	2.91	0.78	1.26	0.85	0.28	0.28	34	17	52
LSD (.05)	NS	0.04	0.06	0.03	0.03	0.03	4	4	7
1974									
25 cm	1.50	0.29	1.88	0.68	0.30	0.06	26	8	34
50 cm	1.62	0.39	1.73	0.62	0.26	0.12	30	9	34
100 cm	1.80	0.58	1.59	0.66	0.28	0.16	32	16	44
200 cm	1.86	0.81	1.39	0.76	0.30	0.22	35	25	53
LSD (.05)	0.16	0.07	0.16	0.08	0.03	0.05	4	3	10

[a]Averaged across all hybrids.

1973, but no reduction in 1974. Corn hybrids showed significant differences in silage yield in both 1973 and 1974 (Table 14). It was not possible to determine which hybrids would be superior under these management practices because the data represents only two years of study. Treatment x hybrid interactions were non-significant indicating that all hybrids reacted similarly for all treatments.

Total nutrient uptake in the silage (Table 15) increased with increasing rates of simulated effluent, however the percent recovery of applied nutrients decreased.

Nitrogen uptake in the corn silage exceeded 40% of the applied at the 25, 50, and 100 cm loading rates in both 1973 and 1974. At the 200 cm loading rate recovery through plant uptake accounted for only 29 and 26% of the applied N, respectively. The N recoveries found under these management practices were within the range reported by Allison (1966), but much less than the levels reported by Sopper and Kardos (1973).

The amount of P taken up at the 25 and 50 cm loading rates exceeded the amount applied. Uptake at the 100 and 200 cm loading rates was less than the applied, which indicated a possible build-up of P at these loading rates. The P recoveries found in this study were approximately the same as those reported by Hook, et al. (1973) and Sopper and Kardos (1973).

TABLE 13. Corn silage yields as influenced by annual loading rate.[a]

Treatment	1973	1974
	metric tons/ha at 70% moisture	
25 cm	34	35
50 cm	37	42
100 cm	32	42
200 cm	36	39
LSD (.05)	3	5

[a]Averaged across all hybrids.

TABLE 14. Corn silage yields as influenced by hybrid.[a]

Hybrid	1973	1974
	metric tons/ha at 70% moisture	
M 396[b]	34	39
M 402	28	--
P 3780[c]	--	45
M 500	36	34
M 511	32	34
M 572	33	42
F 4444[d]	34	43
LSD (.05)	5	4

[a]Averaged across all treatments.
[b]M--Michigan Certified Seed Company.
[c]P--Pioneer Seed Company.
[d]F--Funks Seed Company.

TABLE 15. Nutrient uptake and recovery in corn silage as influenced by annual loading rate.[a]

Treatment	N		P		K	
1973	kg/ha	%[b]	kg/ha	%[b]	kg/ha	%[b]
25 cm	78	94	36	129	140	264
50 cm	89	74	36	100	126	183
100 cm	84	43	46	88	132	132
200 cm	100	29	48	56	142	87
LSD (.05)	14		8		NS	
1974						
25 cm	59	71	30	107	132	249
50 cm	72	60	38	106	160	232
100 cm	85	43	44	85	170	170
200 cm	90	26	52	61	148	91
LSD (.05)	20		8		NS	

[a]Averaged across all hybrids.

[b]Percent recovery based on the annual application through starter fertilizer and simulated effluent.

The annual uptake of K in the corn silage exceeded the application rate at the 25, 50, and 100 cm loading rates, and accounted for approximately 90% of the applied K at the 200 cm loading rate. This indicates that since secondary municipal effluents are usually relatively low in K, supplemental K fertilizer will have to be applied to insure maximum crop growth.

Appendix Tables 24 and 25 show the nutrient concentration in corn silage as influenced by the annual loading rate of simulated municipal effluent and as influenced by the corn hybrid, respectively.

The correlations between silage yield and nutrient concentration were not significant at the 5% level. Simple correlations between the nutrients are given in Appendix Table 26.

Corn grain yields showed significant treatment differences (Table 16) and significant differences between the hybrids (Table 17). In 1973 the grain yields were maximized at the 200 cm loading rate, however in 1974 they decreased slightly at this rate. The grain yields in 1974 were much lower than in 1973, apparently due to later planting and an early frost which killed the crop before it was physiologically mature. Also, insufficient amounts of N and K as indicated by leaf analysis may have reduced the grain yield.

It was not possible to determine which of the corn hybrids would always be superior under these management

TABLE 16. Corn grain yields as influenced by annual loading rate.[a]

Treatment	1973	1974
	quintals/ha at 15.5% moisture	
25 cm	69.0	51.5
50 cm	78.5	60.9
100 cm	81.0	65.3
200 cm	83.5	62.2
LSD (.05)	12.9	6.8

[a]Averaged over all hybrids.

TABLE 17. Corn grain yields as influenced by hybrid.

Hybrid	1973	1974
	quintals/ha at 15.5% moisture	
M 396[b]	76.0	57.1
M 402	65.3	--
P 3780[c]	--	72.2
M 500	74.1	53.4
M 511	75.3	44.6
M 572	79.7	62.8
F 4444[d]	94.2	69.7
LSD (.05)	12.9	5.2

[a]Averaged across all treatments.

[b]M--Michigan Certified Seed Company.

[c]P--Pioneer Seed Company.

[d]F--Funks Seed Company.

practices since the data represents only two years of study. The treatment x hybrid interactions were non-significant at the 5% level indicating that hybrids responded similarly at all loading rates.

Nutrient uptake in the corn grain was maximized at the 100 cm loading rate (Table 18). In 1973 N uptake was greater than 50% of the applied at the 25, 50, and 100 cm loading rates. In 1974 the best N uptake was 43% of the applied N. The P uptake by the corn grain was usually less than the applied. This indicates that if only grain is removed, there will be a build-up of P in the soil at these loading rates.

The amounts of N taken up in the corn grain in this study were somewhat lower than those reported by Parizek et al. (1967), but the levels of P and K taken up were approximately the same.

Appendix Tables 27 and 28 show the nutrient concentrations in the corn grain as influenced by the annual loading rate of simulated municipal effluent and as influenced by the corn hybrid, respectively.

The correlations between grain yield and nutrient concentration were non-significant at the 5% level. Simple correlations between the nutrients are given in Appendix Table 29.

The winter rye which was planted as a cover crop and later used as green manure showed a positive but non-significant yield response to increasing rates of simulated effluent. The nutrient concentrations in the rye increased significantly as loading rates increased (Table 19).

Soil Analysis

The distribution of NH_4, NO_3, Cl, P, K, Na, Ca, and Mg in the soil profile as influenced by the annual loading rate of simulated municipal effluent, year, season, and depth are given in Appendix Tables 30 to 37, respectively.

The mean NH_4 and NO_3 concentrations in the soil profile showed no significant changes due to the annual loading rate of effluent. There were significant differences between years, seasons, and as expected between depth increments.

The differences found between years and seasons can be accounted for by the high concentrations of NH_4 and NO_3 found in the surface 30 cm in the spring of 1974 (Tables 20 and 21). These high levels were probably due to the mineralization of organic N from the silage residue which had inadvertantly been returned to the experimental area after sampling.

The fate of the applied N which was not taken up by the plant or lost through tile drainage is uncertain. Gast, Nelson, and MacGregor (1974) and Endelman et al. (1974) have shown that NO_3 and Cl ions move at similar rates with the soil water. Since Cl is not lost through volitilization,

TABLE 18. Nutrient uptake and recovery in corn grain as influenced by annual loading rate.[a]

Treatment	N		P		K	
1973	kg/ha	%[b]	kg/ha	%[b]	kg/ha	%[b]
25 cm	84	101	29	104	19	36
50 cm	88	73	31	86	25	36
100 cm	104	53	35	67	26	26
200 cm	100	29	34	40	25	15
LSD (.05)	NS		NS		NS	
1974						
25 cm	36	43	15	54	17	32
50 cm	45	37	18	50	22	32
100 cm	52	26	19	36	24	24
200 cm	51	15	20	24	24	15
LSD (.05)	7		2		3	

[a]Averaged across all hybrids.

[b]Percent recovery based on the annual application through starter fertilizer and simulated effluent.

TABLE 19. Yield of and nutrient concentrations in winter rye as influenced by annual loading rate.

Treatment	Yield	N	P	K	Ca	Mg	Na	Cl
	metric tons/ha at 70% moisture	--------	%	-------	-------	-------	-------	-------
25 cm.	11.0	1.14	0.34	2.20	0.27	0.15	0.03	0.91
50 cm	11.0	1.24	0.36	2.28	0.30	0.15	0.04	0.99
100 cm	11.8	1.22	0.36	2.31	0.31	0.17	0.05	1.13
200 cm	12.8	1.43	0.38	2.40	0.36	0.18	0.06	1.33
LSD (.05)	NS	0.18	0.03	NS	0.07	0.02	0.02	0.18

the distribution of NO_3 and Cl in the soil profile may indicate the fate of the unrecovered N.

Kimble, et al. (1972) pointed out that Cl/NO_3 ratios can be used to varify the mechanism that would probably account for the unreoovered N, i.e., denitrification or leaching. They found that if denitrification occurs only in the upper part of the soil profile, the Cl/NO_3 ratios would remain constant below the zone of denitrification. If there was denitrification in the lower part of the profile, these ratios would increase.

Figures 8 and 9 show that at the 25 and 50 cm loading rates Cl accumulated in a zone between 30 and 120 cm, but at the 100 and 200 cm loading rates there was Cl movement throughout the entire profile. This confirms the soil water balances which indicated that at the 25 and 50 cm loading rates there was not a substantial movement of water out of the profile, while at the 100 and 200 cm loading rates deep percolation losses accounted for a large volume of the water.

The movement of Cl through the profile confirms that there was a potential for leaching of the unrecovered NO_3-N at the 100 and 200 cm loading rates, but the Cl/NO_3 ratios (Figure 10) increased with depth. This suggests that denitrification and not leaching was the primary mechanism for the removal of any unrecovered N.

These results substantiate the predictions made by Lance (1972) where he indicated that denitrification would be the most important mechanism for the removal of N which

TABLE 20. Distribution of NH_4--N in the soil profile as influenced by year, season, and depth.

Depth	1973		1974	
	Spring	Fall	Spring	Fall
(cm)	-------------	ug/gm	--------------	
0-15	8.77	6.31	21.35	7.75
15-30	7.60	5.16	20.74	6.89
30-60	4.02	2.74	8.30	5.07
60-90	2.94	2.17	6.58	3.56
90-120	2.54	1.45	4.36	3.86
120-150	2.33	2.22	2.78	3.46
150-210	2.58	2.13	6.24	3.09
210-270	1.97	1.24	2.46	2.92

TABLE 21. Distribution of NO_3--N in the soil profile as influenced by year, season, and depth.

Depth	1973		1974	
	Spring	Fall	Spring	Fall
(cm)	-------------	ug/gm	--------------	
0-15	4.70	4.75	12.57	8.08
15-30	4.30	3.32	11.63	6.38
30-60	1.94	1.58	2.42	4.83
60-90	1.10	1.36	2.15	3.58
90-120	0.77	0.91	2.64	2.11
120-150	0.75	1.27	1.09	2.23
150-210	1.23	1.51	1.61	2.15
210-270	1.46	0.41	1.99	1.80

was not recovered by the crop. They are also in agreement with the findings of Broadbent and Clark (1965); Broadbent (1973); Gast et al. (1974); Thomas and Barfield (1974).

Losses through adsorption, volatilization, or leaching of NH_4-N may have accounted for some of the applied N, but these mechanisms of N removal are usually very small in comparison to plant uptake, denitrification, biological immobilization, or leaching of NO_3-N.

The mean P levels found in the 0-15 and 15-30 cm increments showed a large variation between samplings (Table 33). These differences were found to be due to the natural soil variability rather than to the application of the various rates of simulated municipal effluent.

The P levels below 30 cm decreased very rapidly and remained constant between 60 and 270 cm. This indicates that other than the small amount of P which was short circuited into the tile and lost through the drainage waters, there was no P movement through the soil profile. These findings are in agreement with the Penn State Studies reported by Sopper and Kardos (1973a).

The annual application of 200 cm of simulated municipal effluent resulted in a substantial increase in exchangeable Na and a corresponding decrease in exchangeable K (Figure 11). The decrease in exchangeable K was progressive over the two years. The exchangeable Na concentration was approximately the same after each irrigation season, even though the infiltration and percolation of rainwater and

Figure 8. Distribution of NO_3 and Cl following the application of 25 and 50 cm of simulated municipal effluent in 1974.

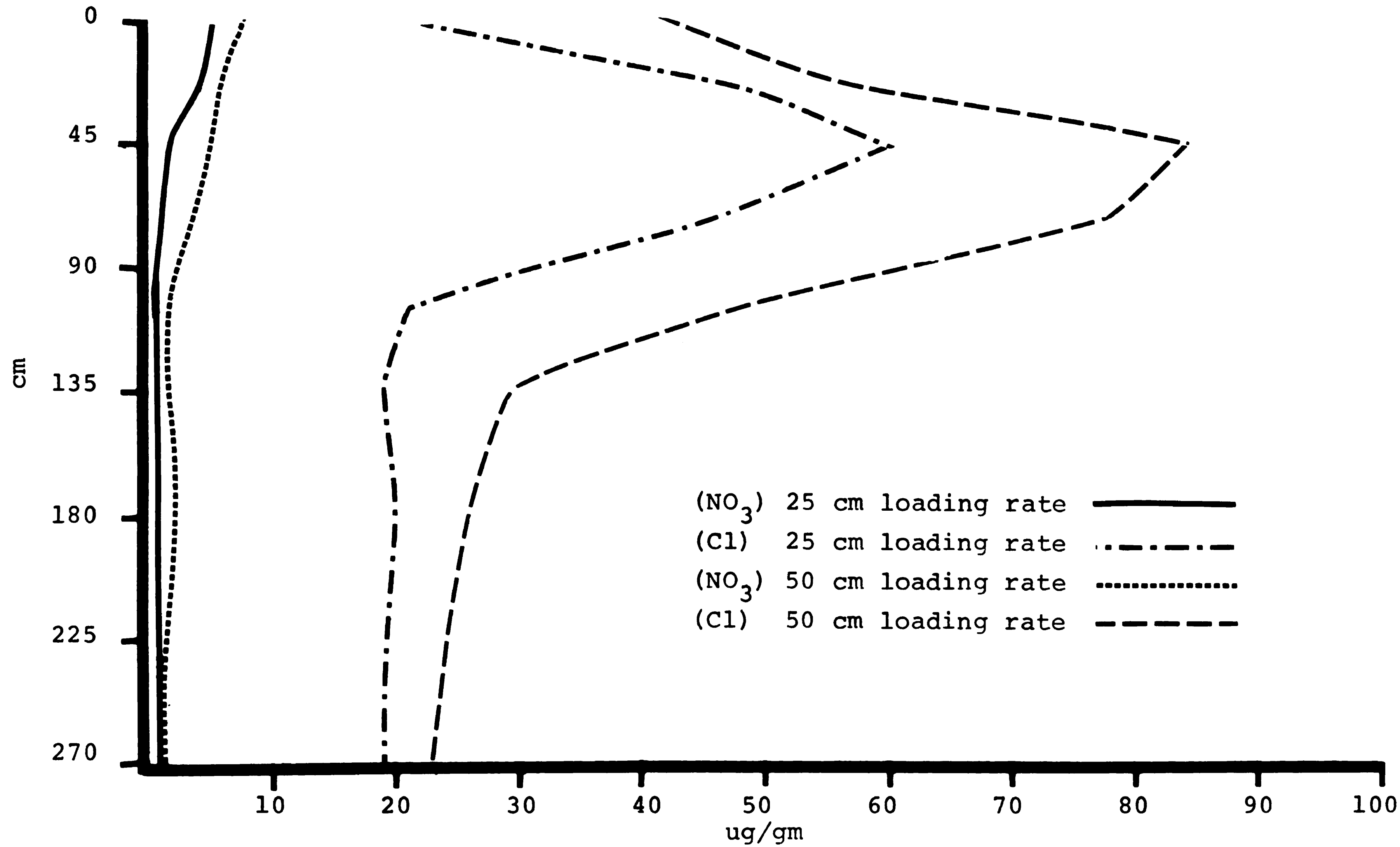


Figure 9. Distribution of NO_3 and Cl following the application of 100 and 200 cm of simulated municipal effluent in 1974.

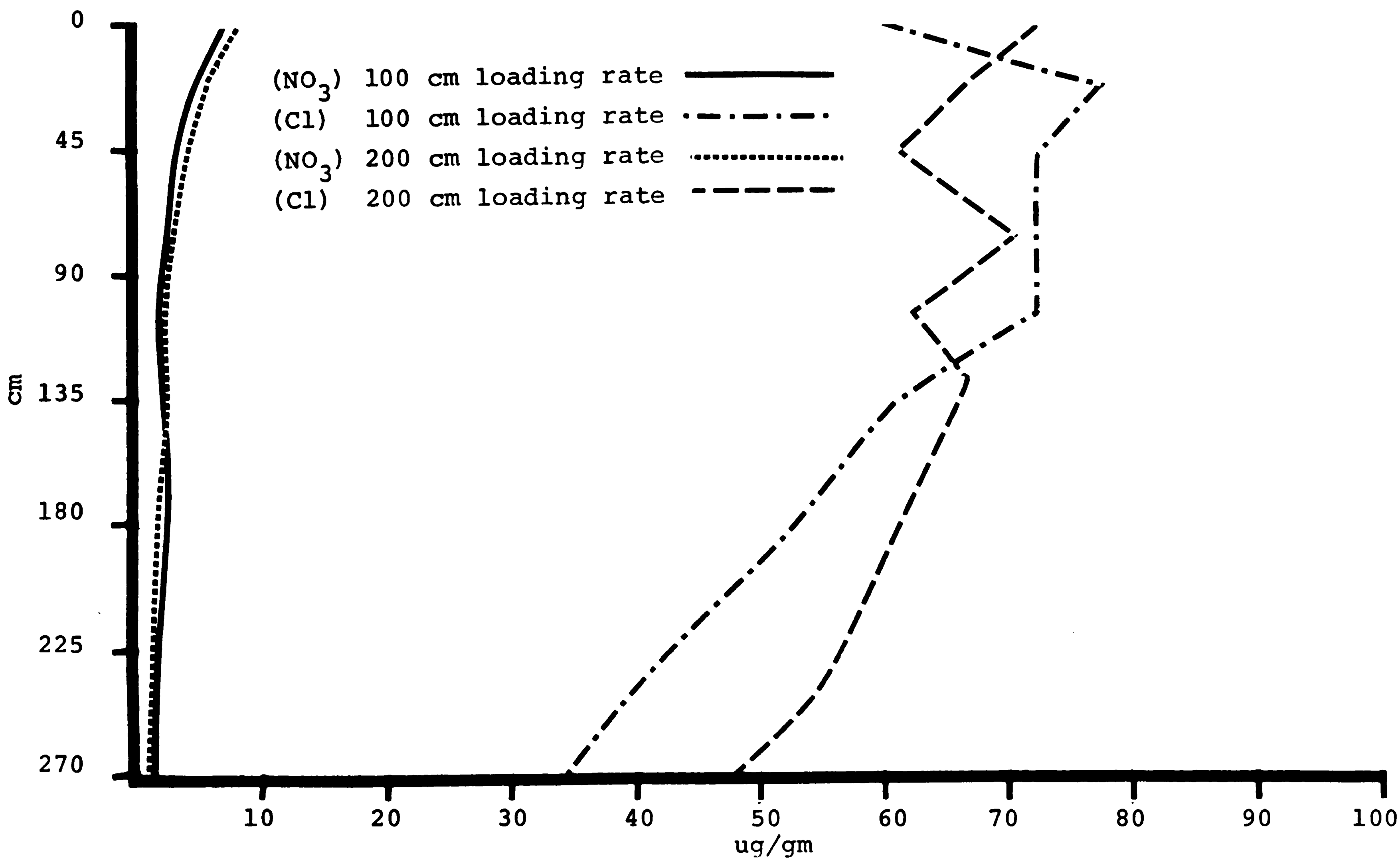


Figure 10. Cl/NO_3 ratio in soil profile following the application of 100 and 200 cm of simulated municipal effluent in 1974.

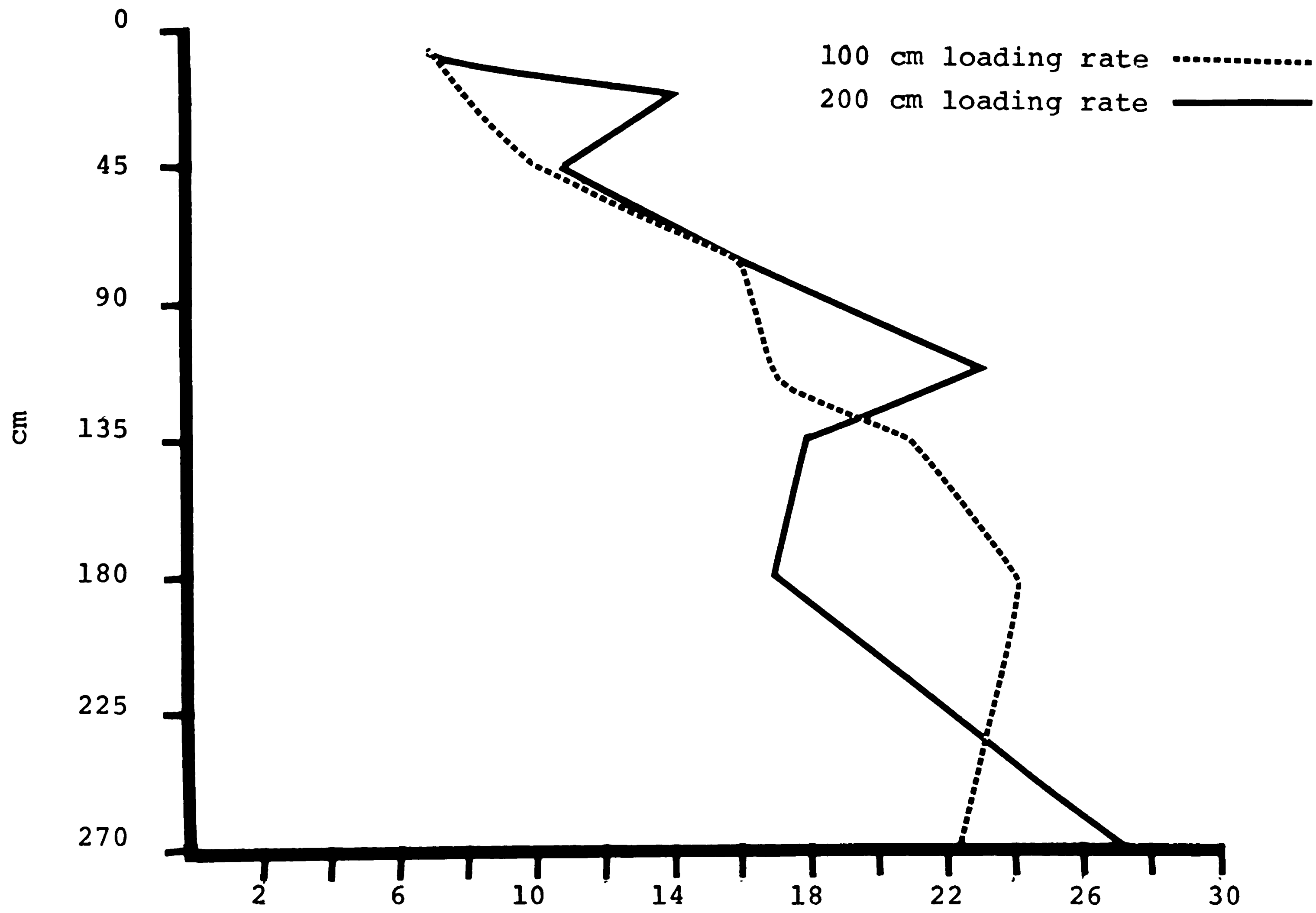
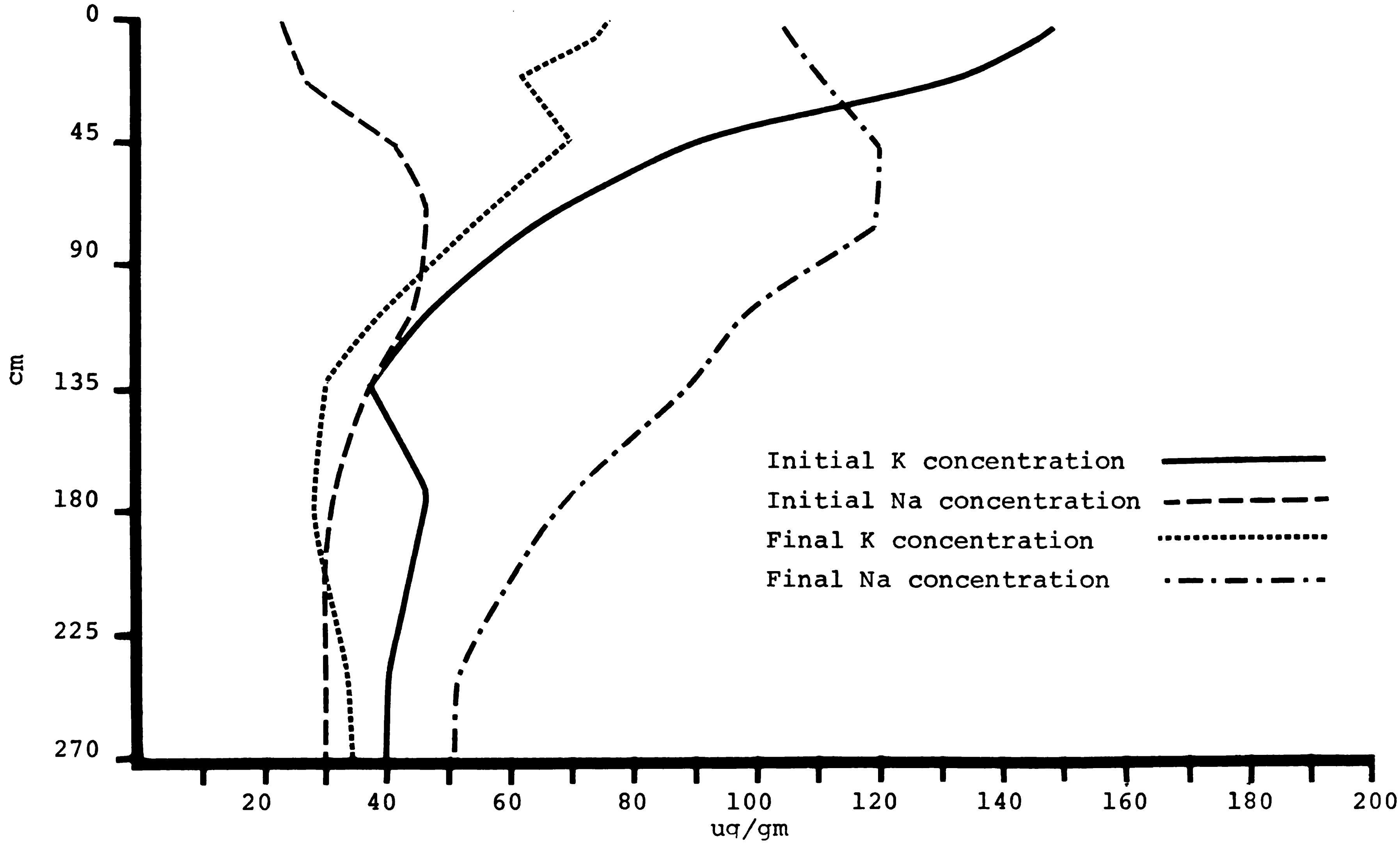


Figure 11. Distribution of K and Na in the soil profile before and after two years of irrigation with simulated municipal effluent at 200 cm per year.



snow melt had reduced it during the winter months. This indicates that the soil system had reached an equilibrium with the applied effluent, and that as the SAR had indicated there probably would not be any structural problems due to sodium.

The progressive decline in exchangeable K indicates that if municipal effluents which are usually low in K are to be renovated through land disposal, supplemental K must be applied to maintain optimum plant growth and nutrient uptake.

SUMMARY AND CONCLUSIONS

A field study was conducted to determine the possible effects of renovating municipal effluents through intensive irrigation of corn grown on a tile drained loam soil. Municipal effluent was not available at the experimental site, therefore a simulated effluent having an inorganic nutrient composition similar to that of East Lansing's municipal effluent was used. The effluent was applied at graduated weekly rates so that the total application would be 25, 50, 100, or 200 cm per year. Seven corn hybrids were evaluated for silage and grain yield, and for nutrient uptake under these management practices. From the results of this study the following conclusions can be made.

1. To insure efficient utilization of the applied nutrients through plant uptake, the annual loading rates should not exceed 100 cm of supplemental effluent. If the entire corn plant was harvested, uptake accounted for at least 40, 80, and 130% of the applied N,P, and K, respectively, at the 25, 50, and 100 cm loading rates.

2. The renovation of municipal effluents applied to soils formed from glacial till may be complicated by the natural variability of these soils and the non-uniform drainage patterns which often results.A short circuiting of the effluent through the sand smears may result in substantial

nutrient loss through the drainage water.

3. The annual nutrient recoveries were increased significantly if the entire corn plant was harvested.

4. Although significant differences were found among the hybrids, the treatment x hybrid interaction was not significant indicating that all hybrids responded similarly across all treatments.

5. For accurate monitoring of the nutrient loss through the drainage water from a land disposal system, both nutrient concentration and flow volume must be measured continuously.

6. The application of low K effluents may result in a depletion of the exchangeable K unless supplemental K fertilizers are applied.

7. The application of an effluent whose SAR is less than 5 is not likely to cause structural problems due to excess Na adsorption.

8. Although Cl/NO_3 ratios indicate that the unrecovered N was being lost through denitrification, a series of shallow wells should be monitored to determine if N is being lost by denitrification or through deep percolation.

9. Land disposal of secondary municipal effluent is a viable alternative to tertiary chemical treatment if the system is managed for maximum yield and nutrient recovery through plant uptake.

APPENDIX

Figure 12. Weekly concentration of NO_3-N in drainage water (1973).

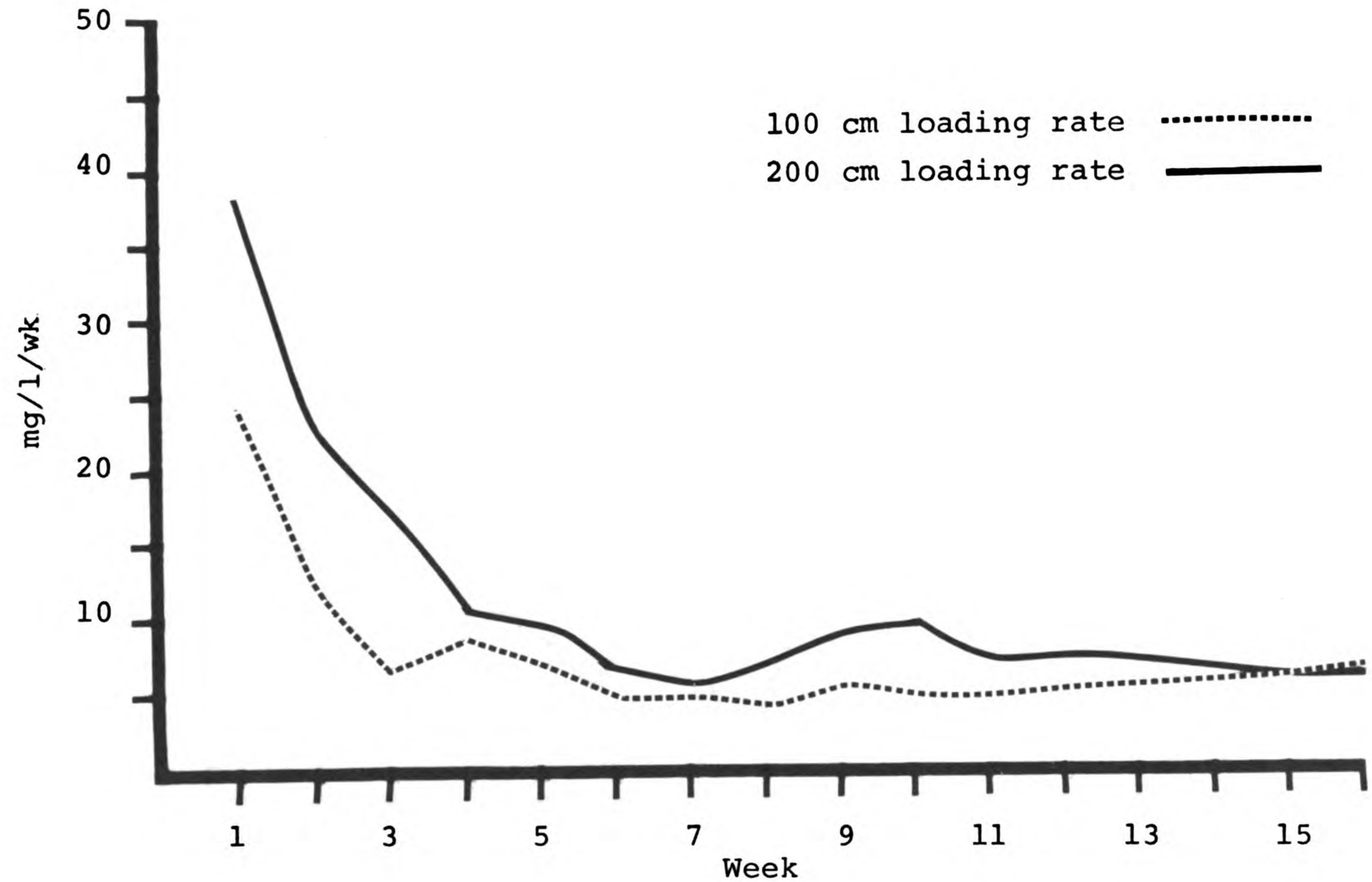


Figure 13. Weekly concentration of P in drainage water (1973).

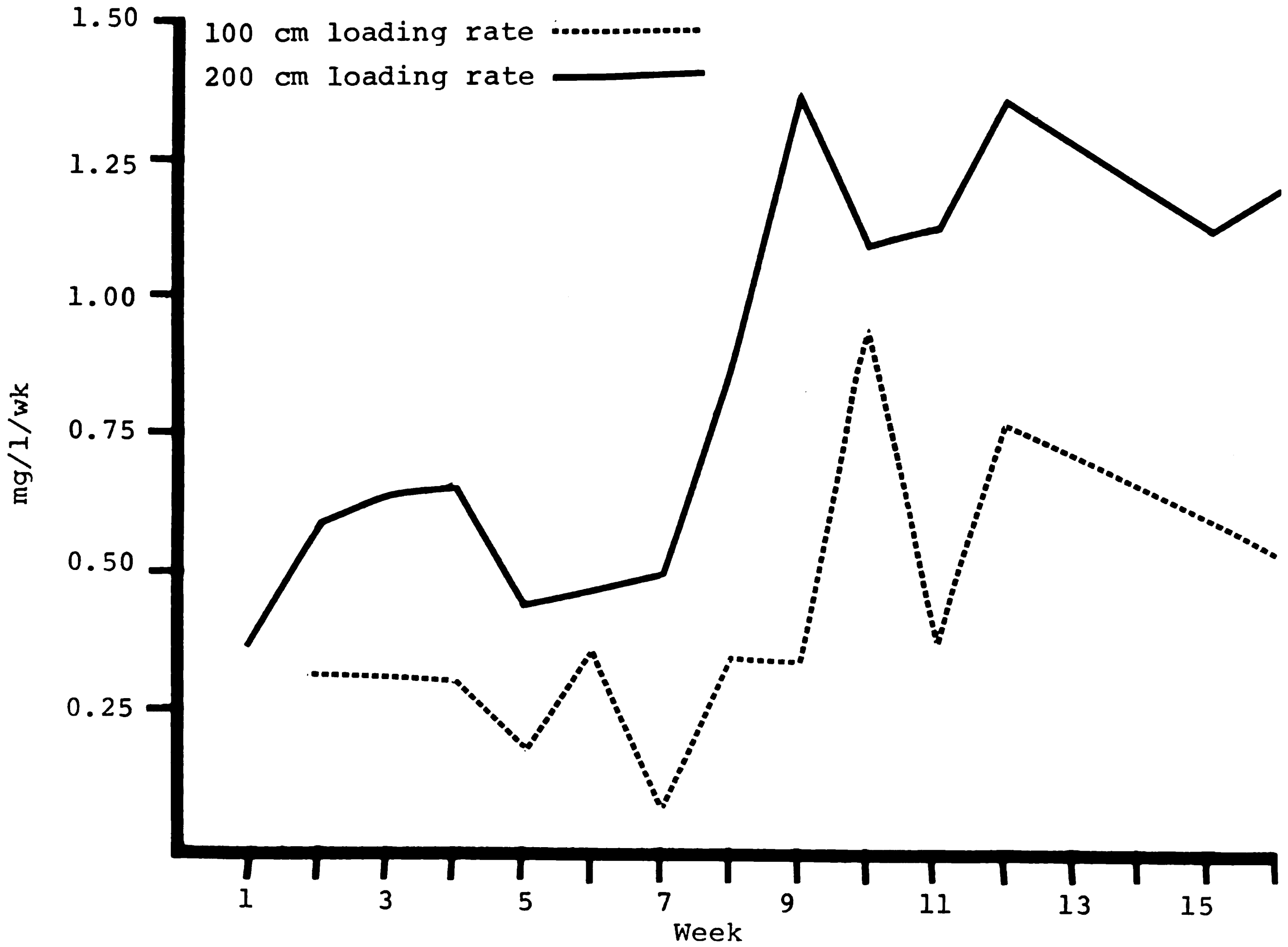


TABLE 22. Mean plant population of the corn hybrids.[a]

Hybrid	1973	1974
	------ plants/ha	--------
M 396[b]	20,950	27,800
M 402	18,150	------
P 3780[c]	------	26,050
M 500	27,100	23,250
M 511	23,650	24,750
M 572	22,450	26,300
F 4444[d]	30,750	27,150

[a]Averaged across all treatments.
[b]M--Michigan Certified Seed Company.
[c]P--Pioneer Seed Company.
[d]F--Funks Seed Company.

TABLE 23. Weekly volumes of tile drainage as influenced by annual loading rate.

Week	50 cm	100 cm	200 cm
	-----------	liters	-----------
1			
2	63	158	1398
3	102	1961	5111
4	14277[a]	14277[a]	14277[b]
5			
6		314	103
7			354
8		1872	556
9	140	415	3093
10		3410	2887
11	919	20056	8013
12	2137	14072	22470
13	43	7220	19985
14	656	15318	26680
15	167	19502	30448
16	1326	19655	26724
17	33736	71285	53415
18	274	25094	28717
19	16445	53770	53117
20	571	20224	19086
21	65	2184	2073
22	130	1275	945
23		399	211
24	84	13131	2746
25		1214	3807

[a]Estimated flow

[b]Measured flow

TABLE 24. Nutrient concentrations in corn silage as influenced by annual loading rate.[a]

Treatment	N	P	K	Ca	Mg	Na	Cl	Zn	B	Mn
1973	%							ppm		
25 cm	.75	.35	1.35	.28	.24	.06	.70			
50 cm	.81	.33	1.14	.32	.25	.13	.83			
100 cm	.88	.49	1.36	.37	.25	.15	.87			
200 cm	.92	.45	1.33	.47	.25	.23	.93			
LSD (.05)	.06	.04	.14	.04	NS	.01	.07			
1974										
25 cm	.56	.28	1.23	.26	.23	.03	.66	23	5	19
50 cm	.56	.30	1.27	.25	.20	.06	.69	15	5	16
100 cm	.69	.34	1.36	.28	.21	.08	.78	15	6	23
200 cm	.76	.44	1.30	.37	.23	.11	.72	17	10	29
LSD (.05)	.11	.04	NS	.03	.02	.02	.09	3	1	4

[a]Average concentrations over all corn hybrids.

TABLE 25. Nutrient concentrations in corn silage as influenced by hybrid.[a]

Hybrid	N	P	K	Ca	Mg	Na	Cl	Zn	B	Mn
1973	%							ppm		
M396[b]	.85	.40	1.31	.34	.24	.12	.85			
M402	.94	.46	1.34	.37	.26	.13	.73			
M500	.84	.38	1.26	.38	.25	.16	.76			
M511	.76	.40	1.34	.35	.25	.14	.89			
M572	.86	.44	1.25	.35	.24	.13	.91			
F4444[c]	.80	.36	1.26	.36	.24	.16	.86			
LSD (.05)	.10	.06	NS	NS	NS	NS	.13			
1974										
M396	.62	.38	1.30	.28	.22	.06	.72	19	6	21
P3780[d]	.64	.33	1.13	.26	.22	.05	.76	19	6	22
M500	.64	.31	1.26	.33	.21	.08	.71	16	7	25
M511	.68	.34	1.25	.30	.22	.07	.72	16	6	21
M572	.64	.36	1.31	.29	.22	.07	.71	18	6	19
F4444	.64	.33	1.44	.29	.22	.08	.66	17	7	23
LSD (.05)	NS	.03	.14	.03	NS	.03	.08	2	NS	4

[a]Average concentrations over all treatments.

[b]M--Michigan Certified Seed Company.

[c]F--Funks Seed Company.

[d]P--Pioneer Seed Company.

TABLE 26 . Simple correlations between nutrient concentrations found in corn silage.

1973	N	P	K	Ca	Mg	Na	Cl	Zn	Mn	B
N	1.000									
P	.507**	1.000								
K	NS	.276*	1.000							
Ca	.407**	.504**	NS	1.000						
Mg	NS	.251*	NS	.356**	1.000					
Na	.455**	.386**	NS	.898**	NS	1.000				
Cl	NS	NS	.353**	.506**	NS	.609**	1.000			
1974										
N	1.000									
P	.682**	1.000								
K	NS	NS	1.000							
Ca	.589**	.679**	NS	1.000						
Mg	NS	.369**	NS	.527**	1.000					
Na	.674**	.677**	NS	.757**	NS	1.000				
Cl	NS	NS	.826**	NS	NS	.328**	1.000			
Zn	.581**	.616**	NS	.828**	.492**	.663**	NS	1.000		
Mn	NS	NS	NS	NS	.409**	-.399**	-.272*	NS	1.000	
B	.669**	.761**	NS	.874**	.435**	.696**	NS	.881**	NS	1.000

* (.05) = .230 ** (.01) = .300

TABLE 27. Nutrient concentrations in corn grain as influenced by annual loading rate.[a]

Treatment	N	P	K	Mg	Zn
1973	----------%----------				ppm
25 cm	1.43	.49	.32	.19	35
50 cm	1.32	.47	.38	.18	33
100 cm	1.51	.51	.38	.20	32
200 cm	1.46	.50	.37	.20	34
LSD (.05)	.05	NS	.03	NS	NS
1974					
25 cm	.84	.34	.40	.13	19
50 cm	.87	.35	.43	.12	20
100 cm	.93	.35	.44	.13	17
200 cm	.99	.37	.46	.14	18
LSD (.05)	.06	.02	.02	.01	NS

[a]Averaged over all hybrids.

TABLE 28. Nutrient concentrations in corn grain as influenced by hybrid.[a]

Hybrid	N	P	K	Mg	Zn
1973	------------%	------------			ppm
M396[b]	1.39	.47	.34	.20	32
M402	1.37	.48	.35	.19	32
M500	1.45	.49	.36	.18	35
M511	1.39	.46	.32	.18	31
M572	1.51	.55	.43	.21	35
F4444[c]	1.47	.52	.36	.19	35
LSD (.05)	.08	NS	.07	NS	NS
1974					
M396	.91	.36	.45	.12	20
P3780[d]	.92	.36	.44	.14	18
M500	.88	.32	.38	.12	15
M511	.94	.34	.45	.12	19
M572	.93	.36	.47	.13	20
F4444	.85	.36	.40	.14	18
LSD (.05)	.05	.01	.02	.01	NS

[a]Averaged over all treatments.

[b]M--Michigan Certified Seed Company.

[c]F--Funks Seed Company.

[d]P--Pioneer Seed Company.

TABLE 29. Simple correlations between nutrient concentrations and corn grain yield.

1973	Yield	N	P	K	Mg
Yield	1.000				
N	NS	1.000			
P	.340*	.686**	1.000		
K	NS	.408**	.638**	1.000	
Mg	NS	.561**	.774**	.413**	1.000
	* (.05) = .282		** (.01) = .365		
1974					
Yield	1.000				
N	NS	1.000			
P	.350**	.457**	1.000		
K	NS	.519**	.555**	1.000	
Mg	.436**	.273**	.692**	NS	1.000
	* (.05) = .230		** (.01) = .300		

TABLE 30. Distribution of NH_4 in soil profile as influenced by treatment, year, season, and depth.

Depth	25 cm		50 cm		100 cm		200 cm	
	Spring	Fall	Spring	Fall	Spring	Fall	Spring	Fall
(cm) 1973	ug/gm							
0-15	6.14	8.46	7.91	7.10	10.55	7.18	10.48	2.51
15-30	6.56	5.95	7.07	6.60	8.57	5.52	8.22	2.58
30-60	4.11	3.08	4.38	3.94	5.38	1.29	2.22	2.65
60-90	3.26	1.36	1.79	4.30	3.77	1.22	2.94	1.79
90-120	1.75	0.72	1.50	1.94	3.77	1.00	3.15	2.15
120-150	1.68	2.51	2.37	1.79	2.15	3.30	3.12	1.29
150-210	2.18	1.43	2.01	2.58	2.44	2.08	3.70	2.44
210-270	2.15	0.36	1.61	1.65	2.22	1.50	1.89	1.47
1974								
0-15	18.54	6.89	18.15	9.63	25.33	7.36	23.39	7.12
15-30	18.15	4.70	14.56	8.06	18.80	7.83	31.43	6.97
30-60	4.95	2.66	4.52	8.06	12.34	7.67	11.41	1.88
60-90	3.08	2.74	6.31	3.45	8.46	5.17	8.46	2.90
90-120	2.01	2.66	3.01	4.23	9.97	3.29	2.44	5.25
120-150	3.16	2.35	1.86	4.70	4.02	2.82	2.08	3.99
150-210	4.23	1.96	4.02	3.44	12.98	2.98	3.73	3.98
210-270	2.73	1.18	1.86	3.05	3.01	2.74	2.22	4.70

TABLE 31. Distribution of NO_3 in soil profile as influenced by treatment, year, season, and depth.

Depth.	25 cm		50 cm		100 cm		200 cm	
	Spring	Fall	Spring	Fall	Spring	Fall	Spring	Fall
(cm) 1973	ug/gm							
0-15	3.98	5.17	4.22	4.45	4.38	4.66	6.24	4.73
15-30	3.41	4.16	4.34	3.52	4.84	3.95	4.63	1.68
30-60	1.83	1.36	1.58	2.44	2.83	1.00	1.50	1.50
60-90	1.11	0.93	0.90	2.30	0.93	1.15	1.47	1.08
90-120	0.00	0.43	0.72	1.15	1.29	1.08	1.08	1.00
120-150	0.14	0.79	0.82	0.50	0.43	1.65	1.61	2.15
150-210	0.86	0.57	0.64	2.73	1.36	1.51	2.08	1.22
210-270	1.86	0.57	1.29	0.00	1.36	0.93	1.32	0.14
1974								
0-15	11.19	5.09	8.90	10.96	17.65	7.12	12.56	9.16
15-30	11.41	5.09	10.14	8.46	6.38	5.01	18.58	6.97
30-60	1.58	1.80	0.29	7.59	4.38	4.85	3.44	5.09
60-90	0.64	1.25	2.01	5.32	2.15	3.76	3.80	3.99
90-120	0.43	1.02	4.34	1.96	3.88	2.58	1.86	2.90
120-150	1.00	0.78	1.22	2.74	0.29	2.82	1.86	2.58
150-210	1.15	0.71	1.36	3.06	1.43	2.90	2.51	1.96
210-270	1.86	1.41	3.88	1.72	1.00	1.96	1.22	2.11

TABLE 32. Distribution of Cl in soil profile as influenced by treatment, year, season, and depth.

Depth.	25 cm		50 cm		100 cm		200 cm	
(cm) 1973	Spring	Fall	Spring	Fall	Spring	Fall	Spring	Fall
	ug/gm							
0-15	21	22	16	54	16	68	20	82
15-30	18	35	15	71	13	84	17	80
30-60	16	69	10	108	8	91	15	69
60-90	15	52	10	97	11	88	11	77
90-120	13	19	10	59	8	84	12	71
120-150	10	14	11	25	8	71	13	78
150-210	14	13	12	21	12	49	16	72
210-270	16	12	13	20	11	33	15	60
1974								
0-15	16	22	26	31	28	52	36	63
15-30	10	61	24	41	18	70	30	53
30-60	10	52	36	61	20	54	22	53
60-90	21	35	58	59	32	55	34	63
90-120	28	24	62	38	31	60	34	54
120-150	19	22	39	34	38	52	33	54
150-210	17	28	27	30	41	48	48	51
210-270	14	26	20	28	36	45	54	48

TABLE 33. Distribution of P in soil profile as influenced by treatment, year, season, and depth.

Depth.	25 cm		50 cm		100 cm		200 cm	
	Spring	Fall	Spring	Fall	Spring	Fall	Spring	Fall
(cm.) 1973								
0-15	58.8	61.0	56.8	70.8	77.3	70.6	67.1	92.5
15-30	48.3	41.4	52.8	30.8	57.0	58.5	58.8	48.4
30-60	4.2	4.6	4.8	6.1	10.0	4.1	4.6	6.8
60-90	2.4	4.0	3.2	4.1	3.8	3.3	2.8	4.6
90-120	4.1	3.1	2.3	4.0	2.5	3.5	2.9	2.4
120-150	1.9	2.9	2.2	3.6	2.1	3.0	2.0	2.0
150-210	1.9	3.4	2.4	2.8	2.4	2.5	0.9	2.0
210-270	1.4	2.5	2.3	2.4	1.9	1.9	1.0	2.0
1974								
0-15	56.4	48.5	60.3	48.0	65.9	48.2	86.2	51.5
15-30	29.7	13.8	25.3	24.3	28.4	28.8	50.0	37.4
30-60	2.6	2.9	3.8	3.8	3.0	13.3	5.2	10.5
60-90	3.0	3.8	3.5	3.7	3.2	3.2	3.6	4.3
90-120	3.8	3.0	3.6	3.9	2.3	3.1	3.2	4.1
120-150	3.0	3.1	3.0	3.8	3.0	2.7	2.9	4.0
150-210	3.2	3.2	3.0	3.5	2.5	2.9	2.8	3.7
210-270	2.8	3.2	3.7	3.2	2.3	2.5	2.9	3.3

TABLE 34. Distribution of K in soil profile as influenced by treatment, year, season, and depth.

Depth.	25 cm		50		100 cm		200 cm	
	Spring	Fall	Spring	Fall	Spring	Fall	Spring	Fall
(cm) 1973	ug/gm							
0-15	95	179	120	114	108	156	145	110
15-30	95	94	136	80	97	118	133	88
30-60	61	68	89	66	85	72	89	68
60-90	48	62	69	48	66	47	63	54
90-120	34	49	59	42	47	31	43	41
120-150	25	41	42	28	38	32	37	29
150-210	29	36	42	31	38	41	46	27
210-270	38	45	42	40	36	35	40	40
1974								
0-15	120	110	129	98	120	87	88	74
15-30	74	74	79	76	89	88	69	62
30-60	59	62	60	50	71	64	63	69
60-90	51	47	55	39	46	44	49	53
90-120	47	37	41	30	30	32	35	37
120-150	33	30	30	28	30	29	32	30
150-210	30	25	34	30	39	37	31	28
210-270	40	33	38	39	37	36	45	44

TABLE 35. Distribution of Na in soil profile as influenced by treatment, year, season, and depth.

Depth.	25 cm		50 cm		100 cm		200 cm	
	Spring	Fall	Spring	Fall	Spring	Fall	Spring	Fall
	ug/gm							
(cm) 1973								
0-15	35	53	26	106	29	108	24	121
15-30	34	68	25	124	28	113	25	122
30-60	46	37	32	105	32	95	42	113
60-90	53	43	42	70	45	69	46	114
90-120	44	40	45	58	39	54	44	88
120-150	43	39	49	56	46	43	37	83
150-210	41	33	33	46	45	43	30	62
210-270	44	32	30	46	39	36	31	72
1974								
0-15	29	82	45	70	74	102	77	106
15-30	36	59	60	95	88	118	79	110
30-60	30	57	65	95	99	120	118	129
60-90	34	46	61	72	77	93	112	130
90-120	32	33	46	41	41	74	67	96
120-150	23	24	29	30	36	55	53	79
150-210	26	25	26	24	40	38	54	66
210-270	25	26	28	21	32	27	51	51

TABLE 36. Distribution of Ca in soil profile as influenced by treatment, year, season, and depth.

Depth.	25 cm		50 cm		100 cm		200 cm	
	Spring	Fall	Spring	Fall	Spring	Fall	Spring	Fall
	ug/gm							
(cm) 1973								
0-15	1268	1362	1540	1328	1129	1470	1412	1215
15-30	1298	1248	1311	1366	1041	1295	1355	1151
30-60	1520	1067	1209	1739	1192	1504	1404	1199
60-90	2078	1591	1444	1969	1670	1540	1660	1152
90-120	2061	2154	2134	2367	1715	1521	1847	1514
120-150	2087	1914	2296	2210	1534	1644	1758	1624
150-210	2116	1929	2265	2290	1957	2101	2111	1952
210-270	2299	2393	2389	2404	2251	2324	2125	2458
1974								
0-15	1289	1308	1381	1511	1364	1458	1128	1346
15-30	1121	1158	1451	1445	1123	1306	994	1110
30-60	1096	1203	1574	1660	1413	1290	1097	1187
60-90	1619	1524	1854	1774	1565	1337	1441	1314
90-120	1818	1383	1789	1687	1358	1317	1165	1203
120-150	1880	1370	1582	1529	1276	1328	1108	1233
150-210	1560	1524	1577	1560	1430	1472	1363	1494
210-270	1600	1672	1622	1763	1511	1500	1641	1674

TABLE 37. Distribution of Mg in soil profile as influenced by treatment, year, season, and depth.

Depth.	25 cm		50 cm		100 cm		200 cm	
	Spring	Fall	Spring	Fall	Spring	Fall	Spring	Fall
	ug/gm							
(cm) 1973								
0-15	167	182	169	224	151	234	188	198
15-30	203	163	172	215	150	190	199	194
30-60	286	197	187	354	235	269	282	248
60-90	309	337	238	381	323	290	310	238
90-120	218	294	279	254	275	198	216	261
120-150	163	201	204	172	269	221	167	216
150-210	147	168	182	175	198	229	204	211
210-270	170	191	178	192	173	202	173	230
1974								
0-15	179	179	192	178	224	206	222	188
15-30	156	168	218	186	194	191	178	184
30-60	224	210	296	264	330	238	239	227
60-90	354	291	385	291	246	241	292	266
90-120	264	224	255	203	146	213	200	230
120-150	219	163	171	153	150	211	140	202
150-210	142	162	158	172	188	219	173	174
210-270	134	174	155	194	149	203	178	191

LIST OF REFERENCES

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Allison, F.E. 1966. The Fate of Nitrogen Applied to Soils. Advances in Agronomy, Vol. 18, pp. 219-258.

Bartholomew, W.V. 1965. Mineralization and Immobilization of Nitrogen in the Decomposition of Plant and Animal Residues. In: Soil Nitrogen. W.V, Bartholomew and F.E. Clark, Eds. American Society of Agronomy, Inc., Madison, Wis.

Bauer, W.J. and D.E. Matsche. 1973. Large Wastewater Irrigation Systems: Muskegon County, Michigan, and Chicago Metropolitan Region. In: Recycling Treated Municipal Wastewater and Sludge Through Forest and Cropland. W.E. Sopper and L.T. Kardos Eds. The Pennsylvania State University Press, University Park, Pennsylvania.

Bray, R.H. and L.T. Kurtz. 1945. Determination of Total, Organic, and Available Forms of Phosphorus in Soils. Soil Science 59:39-45.

Bremner, J.M. 1965a. Inorganic Forms of Nitrogen. pp. 1191-1206. In: Agronomy No. 9, Methods of Soil Analysis--Part 2. C.A. Black, Editor in Chief, American Society of Agronomy Inc., Madison, Wisconsin.

Bremner, J.M. 1965b. Total Nitrogen. pp. 1149-1178. In: Agronomy No. 9, Methods of Soil Analysis--Part 2. C.A. Black Editor in Chief, American Society of Agronomy Inc., Madison, Wisconsin.

Broadbent, F.E. and F. Clark. 1965. Denitrification. In: Soil Nitrogen. W.V. Bartholomew and F.E. Clark, Eds. American Society of Agronomy, Inc., Madison, Wis.

Broadbent, F.E. 1973. Factors Affecting Nitrification--Denitrification in Soils. In: Recycling Treated Municipal Wastewater and Sludge Through Forest and Cropland. W.E. Sopper and L.T. Kardos Eds. The Pennsylvania State University Press, University Park, Pennsylvania.

Carey, K.L. 1972. Hydrologic Aspects of Wastewater Disposal on Land. In: Wastewater Management by Disposal on Land. Corps of Engineers. U.S. Army, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Day, A.D., J.L. Stroehlein, and T.C. Tucker. 1972. Effects of Treatment Plant Effluent on Soil Properties. Journal of the Water Pollution Control Federation 44: 372-375.

Day, A.D., T.C. Tucker, and M.G. Vavich. 1962. Effect of City Sewage Effluent on Yield and Quality of Grain from Barley, Oats, and Wheat. Agronomy Journal 54: 133-135.

DeTurk, E.E. 1935. Adaptability of Sewage Sludge as a Fertilizer. Sewage Works Journal 7:4:597-610.

D'Itri, F.M. 1973. Water Quality Management--preliminary and background chemical data. Technical Report No. 31.2 Institute of Water Research, Michigan State University.

Dow Engineering Inc. 1972. Irrigation and Collection Facilities for Southeastern Michigan Wastewater Management Program. Preliminary Report for U.S. Army Corps of Engineers, Detroit District.

Ellis, B.G. 1971. Nutrient Cycling in Agricultural Systems. Published as Journal Article No. 5560 of the Michigan State Agricultural Experiment Station. MSU, East Lansing, Mich.

Ellis, B.G. and Erickson, A.E. 1971. The Nutrient Content of Drainage Water from Agricultural Land. Research Bulletin No. 31. Michigan State Agricultural Experiment Station, MSU, East Lansing, Mich.

Ellis, B.G., A.E. Erickson, B.D. Knezek, and A.R. Wolcot. 1972. Impact of Wastewater on Soils. Technical Report No. 30. Institute of Water Research, Michigan State University, East Lansing, Michigan.

Ellis, B.G. 1973. The Soil as a Chemical Filter. In: Recycling Treated Municipal Wastewater and Sludge Through Forest and Cropland. W.E. Sopper and L.T. Kardos, Eds. The Pennsylvania State University Press, University Park, Pennsylvania.

Endelman, F.J., D.R. Keeney, J.T. Gilmour, and P.G. Saffigna. 1974. Nitrate and Chloride Movement in the Plainfield Loamy Sand Under Intensive Irrigation. Journal of Environmental Quality 3:3:295-298.

Erickson, A.E. 1973. Physical Changes to Soils Used for Land Application of Municipal Waste--What Do We Know? What Do We Need to Know? In: Proceedings of the Joint Conference on Recycling Municipal Sludges and Effluents on Land. Champaign, Illinois.

Foster, D.H. and R.S. Engelbrecht. 1973. Microbial hazards of Disposing of Wastewater on Soil. In: Recycling Treated Municipal Wastewater and Sludge Through Forest and Cropland. W.E. Sopper and L.T. Kardos, Eds. The Pennsylvania State University Press, University Park, Pennsylvania.

Gardner, W.R. 1965. Movement of Nitrogen in Soil. In: Soil Nitrogen. W.V. Bartholomew and F.E. Clark, Eds. American Society of Agronomy, Inc., Madison, Wis.

Gast, R.G., W.W. Nelson, and J.M. MacGregor. 1974. Nitrate and Chloride Accumulation and Distribution in Fertilized Tile-Drained Soils. Journal of Environmental Quality 3:3:209-213.

Henery, C.D., R.E. Moldenhauer, L.E. Engelbert, and E. Truog. 1954. Sewage Effluent Disposal Through Crop Irrigation. Sewage and Industrial Wastes 26:123-133.

Henriksen, A. and A.R. Selmer-Olsen. 1970. Automatic Methods for Determining Nitrate and Nitrite in Water and Soil Extracts. Analyst 95:514-518.

Hillel, D. 1971. Soil and Water--physical principals and processes. Academic Press, Inc., New York, New York.

Hook, J.E., L.T. Kardos, and W.E. Sopper. 1973. Effect of Land Disposal of Wastewaters on Soil Phosphorous Relations. In: Recycling Treated Municipal Wastewater and Sludge Through Forest and Cropland. W.E. Sopper and L.T. Kardos, Eds. The Pennsylvania State University Press, University Park, Pennsylvania.

Hunter, J.V., and T.A. Kotalik. 1973. Chemical and Biological Quality of Treated Sewage Effluents. In: Recycling Treated Municipal Wastewater and Sludge Through Forest and Cropland. W.E. Sopper and L.T. Kardos, Eds. The Pennsylvania State University Press, University Park, Pennsylvania.

Jackson, M.L. 1958. Soil Chemical Analysis. Prentice-Hall Inc., Englewood Cliffs, New Jersey.

Johnston, W.R., F. Ittihadieh, R.M. Daum, and A.F. Pillsbury. 1965. Nitrogen and Phosphorus in Tile Drainage Effluent. Soil Science Society of America Proceedings. 29:287-289.

Jones, J.B. Jr. 1973. Plant Analysis as an Aid in Fertilizing Corn and Grain Sorghum. In: Soil Testing and Plant Analysis. L.M. Walsh and J.D. Beaton, Eds. American Society of Agronomy, Inc., Madison, Wisconsin.

Kardos, L.T. and W.E. Sopper. 1973a. Renovation of Municipal Wastewater Through Land Disposal By Spray Irrigation. In: Recycling Treated Municipal Wastewater and Sludge Through Forest and Cropland. W.E. Sopper and L.T. Kardos, Eds. The Pennsylvania State University Press, University Park, Pennsylvania.

Kardos, L.T. and W.E. Sopper. 1973b. Effects of Land Disposal of Wastewater on Exchangeable Cations and Other Chemical Elements in the Soil. In: Recycling Treated Municipal Wastewater and Sludge Through Forest and Cropland. W.E. Sopper and L.T. Kardos, Eds. The Pennsylvania State University Press, University Park, Pennsylvania.

Kimble, J.M., R.J. Bartlett, J.L. McIntosh, and K.E. Varney. 1972. Fate of Nitrate from Manure and Inorganic Nitrogen in a Clay Soil Cropped to Continuous Corn. Journal of Environmental Quality 1:4:413-415.

Kunze, R.J. 1972. Irrigation Management and Wastewater Disposal. In: Conference Proceedings Land Disposal of Wastewater. Michigan State University, East Lansing, Michigan.

LaCroix, R.L., D.R. Keeney, and L.M. Walsh. 1970. Potentiometric Titration of Chloride in Plant Tissue Extracts Using the Chloride Ion Electrode. Communications in Soil Science and Plant Analysis 1:1:1-6.

Lance, J.C. 1972. Nitrogen Removal by Soil Mechanisms. Journal of Water Pollution Control Federation. 44: 1352-1361.

Lindsey, W.L. 1973. Inorganic Reactions of Sewage Wastes With Soils. In: Proceedings of the Joint Conference on Recycling Municipal Sludges and Effluents on Land. Champaign, Illinois.

Lindsey, W.L. and E.C. Moreno. 1960. Phosphate Phase Equilibria in Soils. Soil Science Society of America Proceedings 24:177-182.

McGauhey, P.H. and R.B. Krone. 1967. Soil Mantle as a Wastewater Treatment System. SERL Report No. 67-11, University of California, Berkeley.

Metcalf and Eddy, Inc. 1972. Wastewater Engineering. McGraw-Hill Book Company, New York, New York.

Michigan Weather Service. 1971. Climate of Michigan by Stations. Michigan Department of Agriculture-Michigan Weather Service, East Lansing, Michigan.

Miller, R.H. 1973. The Soil as a Biological Filter. In: Recycling Treated Municipal Wastewater and Sludge Through Forest and Cropland. W.E. Sopper and L.T. Kardos, Eds. The Pennsylvania State University Press, University Park, Pennsylvania.

Murrman, R.P. and F.R. Koutz. 1972. Role of Soil Chemical Processes in Reclamation of Wastewater Applied to the Land. In: Wastewater Management by Disposal on the Land. Corps of Engineers. U.S. Army, Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Parizek, R.R., L.T. Kardos, W.E. Sopper, E.A. Myers, D.E. Davis, M.A. Farrel, and J.B. Nesbitt. 1967. Wastewater Renovation and Conservation. Pennsylvania State University Studies No. 23.

Pennypacker, S.P., W.E. Sopper, and L.T. Kardos. 1967. Renovation of Wastewater Effluent by Irrigation of Forest Land. Journal of the Water Pollution Control Federation 39:2:285-296.

Pound, C.E. and R.W. Crites. 1973a. Wastewater Treatment and Reuse by Land Application, Vols. 1 and 2. Environmental Protection Technology Series, Nos. EPA-660/2-73-006a, and EPA-660/2-73-006b.

Pound, C.E. and R.W. Crites. 1973b. Characteristics of Municipal Effluents. In: Proceedings of the Joint Conference on Recycling Municipal Sludges and Effluents on Land. Champaign, Illinois.

Ramsey, R.H., C.R. Wetherhill, and H.C. Duffer. 1972. Soil Systems for Municipal Effluents--A Workshop and Selected References. Water Pollution Control Research Series No. 16080 GWF 02/72.

Richards, L.A. 1954. Diagnosis and Improvement of Saline and Alkali Soils. Agricultural Handbook No. 60, U.S. Department of Agriculture.

Shaw, R.H. and D.R. Laing. 1965. Moisture Stress and Plant Response. In: Plant Environment and Efficient Water Use. W.H. Pierre, D. Kirkham, J. Pesek, and R. Shaw, Eds. American Society of Agronomy, Inc., Madison, Wis.

Sopper, W.E. 1970. Revegetation of Strip Mine Spoil Banks Through Irrigation with Municipal Sewage Effluent and Sludge. Compost Science 6-11.

Sopper, W.E. and L.T. Kardos. 1973. Vegetation Responses to Irrigation with Treated Municipal Wastewater. In: Recycling Treated Municipal Wastewater and Sludge Through Forest and Cropland. W.E. Sopper and L.T. Kardos, Eds. The Pennsylvania State University Press, University Park, Pennsylvania.

Steel, R.G.D. and J.H. Torrie. 1960. Principles and Procedures of Statistics. McGraw-Hill Book Company, Inc., New York, New York.

Thomas, G.W. and B.J. Barfield. 1974. The Unreliability of Tile Effluent for Monitoring Subsurface Nitrate-Nitrogen Losses from Soils. Journal of Environmental Quality 3:2:183-185.

U.S. Department of Health, Education, and Welfare. 1962. Public Health Service Drinking Water Standards. U.S. Department of Health, Education, and Welfare Publication No. 956.

Watanabe, F.S. and S.R. Olsen. 1965. Test of an Ascorbic Acid Method for Determining Phosphorus in Water and $NaHCO_3$ Extracts from Soil. Soil Science Society of America Proceedings 29:677-678.