AGRICULTURAL BENEFITS AND ENVIRONMENTAL CHANGES RESULTING FROM THE USE OF DIGESTED SEWAGE SLUDGE ON FIELD CROPS

An Interim Report on a Solid Waste Demonstration Project

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FOREWORD

In April 1967 the Federal solid waste management program together with the Metropolitan Sanitary District of Greater Chicago initiated a project to demonstrate the possible agricultural benefits and environmental changes that would result from applying digested sewage sludge to field crops. In addition, criteria are to be developed that can be used in selecting sites for this method of sludge disposal. This publication reports on the progress made after three year's work on this project.

Since agronomic field studies require a minimum of three years to integrate seasonal effects with measured parameters, the longer the duration of a field study, the greater the confidence level of the results. Construction and instrumentation of the lysimeter facility used for the present project was completed in Spring 1969. Therefore, one year of data--detailed climatic measurements, runoff and drain water analyses, and sludge applications--have been collected from the facility.

The statements made herein are thus based on data that have not yet been analyzed statistically, so that conclusions must be considered as tentative. We expect, nevertheless, that publication of this report will be useful in the interim period required until a thorough evaluation and interpretation of data are completed.

PREFACE

While the new lysimeter facility at the Northeast Agronomy Research Center of the University of Illinois was being established, peripheral experiments were conducted on existing small drum-type lysimeters. These preliminary experiments included high sludge loading rates, analyses of percolated water, fecal coliform analyses of soil surfaces, and various crop tolerances to sludge applications. A continuation of these experiments will permit: (1) continued study of increased sludge accumulations; (2) an increase in the confidence with which predictions of deleterious effects on agronomic crops, if any, might be expected under practical field conditions; (3) study of weathering rate of sludge residues; (4) study of the chemical regime in percolated water.

The Northeast Agronomy Research Center lysimeter facility, now in operation only one year, is uniquely suited to evaluate the feasibility of disposing of digested sludge on agricultural land. The following parameters can be studied:

1. Factors relevant to the bacteriological contamination of water and soils.

   a. The total counts of fecal coliforms in surface runoff water from field lysimeter plots as a function of number added by a digested sludge application, time after a sludge application, rainstorm intensity and duration, total runoff, and environmental conditions such as radiation, temperature, ground cover, etc.

   b. The total fecal coliform counts in drainage water from lysimeter plots as a function of all of the factors stated in "a" except for rainstorm intensity and duration.

c. Whether or not an equilibrium condition between rate of renewal and rate of die away is established at some depth in a soil profile. If such a zone is found to exist, determine factors that may influence the depth at which it is established.

d. The total fecal coliform counts in runoff water as a function of distance from point of sludge application for several ground cover conditions and rates of travel (or flow rates of runoff water) during the several seasons of the year.

2. Factors relevant to the chemical contamination of water and soils.

a. The concentrations of the various forms of nitrogen and total phosphorus in drainage water from the field lysimeter plots as a function of total concentrations added by sludge applications, time, effluent volumes, soil cover and other soil environmental conditions.

b. The concentrations of heavy metals (of major significance for one reason or another) in drainage waters as a function of the factors discussed under "a" immediately above.

c. The concentrations of nutrient elements, and important heavy metals in the solution and sediment phases of runoff water from the lysimeter plots, as a function of sludge loading rates, time, total runoff, rainstorm intensity and duration, and ground cover and other environmental conditions.

d. The conductivities, pH, and Eh of both drainage and runoff water from the lysimeter plots as a function of the variables noted respectively in "a" and "c" immediately above.

e. The total soil organic carbon contents with time as a function of sludge loading rates and soil type.

f. The total concentrations of heavy metals, pH, and conductivities at three depths in lysimeter soil profiles as a function of time and sludge loading rates.

g. The concentrations of N, P, K and heavy metals in plant tissue samples twice during a growing season as a function of sludge loading rates and soil type.

h. Characterize sludge organic matter fractions immediately after application and at least annually thereafter.

3. Physical changes in soils that may be attributed to sludge applications. Determine soil infiltration and aeration capacities as a function of time, sludge, loading rates, and soil types.
4. Responses of agronomic crops to sludge applications. Determine yields and composition of crops as a function of time, sludge loading rates, and soil types.

The preliminary studies indicate that weed control is a major problem when sludge is applied to agricultural land. Application of sludge dictates the use of herbicides and insecticides for effective weed and insect control. As the organic matter content of soil changes with time, the effectiveness and fate of pesticides will surely change. Thus, a natural extension of this project is an investigation of factors such as:

1. The concentration of pesticides in runoff and drainage water from the lysimeter plots as a function of time, effluent volumes, sludge loading rates, soil type, etc.
2. The persistence of pesticides in sludge-amended soils.

The data collected during the 1969 cropping season will only become significant if supported by another two or three year's results. The influence of climate on sludge applications to agricultural lands must be measured for several years before the results can be correlated with existing long-term weather data. Similarly, the gradual changes in soil properties resulting from sludge applications are accumulative and may take several years to become apparent. It is important, therefore, that the study be continued until such changes, especially if deleterious, become evident.

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INTRODUCTION

The disposal of liquid digested sludge on land is a practice extensively used. It has recently received more attention in the U. S. because of the high cost of alternate means (drying processes) of disposal and their effect on air quality. Land disposal has the additional advantage of returning the materials to a natural cycle which could be agriculturally beneficial. Before initiating such a land disposal operation, laboratory, greenhouse, and field investigations were initiated to determine, 1) the most practical amount, frequency, economical method, and time for applying digested sludge on crop land; 2) the probability of contaminating surface water and groundwater aquifers with pathogens and molecular organic and inorganic ions; 3) the changes in the soil related such physical and chemical characteristics that might be expected from frequent heavy applications of digested sludge; and 4) the crops and cropping systems that will provide maximum absorption of certain essential and non-essential elements supplied to the soil by digested sludge applications.

To that end, a field installation was planned which would allow us to evaluate the long-term effects on the soil-water-crop ecosystem of sludge disposal on land.

An experimental facility was established on the Northeast Agronomy Research Center (NEARC) near Elwood, Illinois. A large installation of 44, 50 x 10 foot experimental plots complete with equipment to collect, record, and sample, on a proportional volume basis, the runoff and drain water was completed on the site.

When the project was initiated in April 1967, it was known that the field facility could not be functional for the 1967 cropping season. Thus, an existing lysimeter facility on the Agronomy South Farm at the University of Illinois, U-C, was used to begin the investigation.

The following report contains preliminary data collected from all facilities and supplemental laboratory and greenhouse investigations.

PROPERTIES OF LIQUID DIGESTED SLUDGE WITH RESPECT TO LAND DISPOSAL

Chemistry of Liquid Digested Sludge

Liquid digested sludge is characterized as a 2-5% suspension of heterogenous solid matter in a dilute aqueous salt solution. The material is a black slurry which may be transported by pumping.

Ammonium-N, sodium, and potassium are found in the liquid phase and heavy metals and organic residues are usually found in the solid phase of digested sludge. Table 1 gives an average chemical composition of digested sludge samples taken from the Calumet Plant of the Metropolitan Sanitary District (MSD).

Seed Germination in Liquid Digested Sludge

Occasional reports of seed germination inhibition, following the application of liquid digested sludge on soils, are found in the literature. Although a salt effect is cited as the origin of this inhibition, there is no good evidence to support this hypothesis. Experiments were started to investigate the true nature of this inhibition. The seeds were first immersed in the digested sludge for 6 hours. They were then incubated in a petri-dish on 2 layers of filter paper (Whatman No. 1) soaked with 5 to 6 ml of digested sludge.

The inhibitory action of the digested sludge from the Calumet Plant, MSD on seed germination is indicated by the data in Table 2. The toxic properties were localized in the sludge supernatant; the ashes from the sludge supernatant were not toxic. The partial inhibition by the total sludge ashes indicates the possibility of some salts of toxic metal effects.

The incubation of the seeds, particularly of soybeans, with the digested sludge inside a petri-dish induced a microbial fermentation which may have caused

Table 1. Composition of digested sludge from the Calumet Treatment Plant, Metropolitan Sanitary District.

Component	Concentration, ppm
Total N	1000 - 3500
Ammoniun-N	500 - 2000
P	700 - 1550
K	150 - 175
Cr	10 - 50
Cd	10 - 35
Cu	30 - 45
Pb	15 - 33
Mn	7 - 15
Ni	1 - 3
Zn	72 - 292
In solids	----
C	22 - 27%
H	3 - 4%
N	3 - 3.5%

Table 2. Inhibitory effect of digested sludge on seed germination.

	Percentage Germination	
	corn	soybean
Control *	100	100
Sludge	19	0
Sludge supernatant	0	0
Ashes from total sludge	50	66
Ashes from sludge supernatant	100	100

*Seed germination in 10^{-4} M $CaCl_2$ aqueous solution.

the inhibition. However, when the assay was performed aseptically with autoclaved sludge, or with the sludge supernatant sterilized by filtration, the microbial fermentation was avoided but the inhibition persisted. Thus, microbial fermentation apparently did not cause the inhibition.

Confirmation of the fresh sludge toxicity toward seed germination was obtained in a greenhouse experiment with corn seeds planted 1 inch deep in sand. It was found that the equivalent addition of 1 inch of fresh digested sludge totally prevented seed germination, while the application of 2 inches of old digested sludge (aerated for 1 week) did not interfere with the germination.

The toxicity was removed by boiling of the sludge for a few minutes. Aeration of the liquid digested sludge by bubbling air through it for 5 days was sufficient to remove the toxicity.

Aging of the sludge in equilibrium with the atmosphere also reduced the toxicity. Although aeration was more efficient in reducing toxicity, it was not necessary. Indeed, Lunt (1) observed that soils amended with lagooned digested sludge were better for seed germination than those amended with fresh digested sludge.

Volatilization of Ammonia from Liquid Digested Sludge

Investigations conducted by Dr. R. I. Dick and assistants, Department of Civil Engineering.

In view of the probable limitations imposed by water pollutional characteristics of nitrogen in sludge, studies of possible inoffensive losses of nitrogen are pertinent. A loss which has been poorly quantitied is the escape of ammonia from liquid sludge by gas transfer. Such losses could occur in digested sludge storage facilities, during application, and following application.

A laboratory investigation of ammonia volatilization from liquid digested sludge was conducted using 8 in. diameter plexiglas columns. The gas evolved from each column was collected and bubbled through standard sulfuric acid to determine the amount of ammonia given off; and liquid samples were taken from various depths in the columns to construct an ammonium profile through the sludge. Results indicated that, at a temperature of 25°C and pH of approximately 7.5, the rate of deamination of organic nitrogen in the sludge exceeds the rate of ammonia movement to the surface and transfer to the atmosphere. Loss of gaseous ammonia at the surface of the sludge was nearly linear with time. A mathematical model of NH_3 volatilization from liquid digested sludge based on diffusion theory and an approximation of the deamination process has been developed and programmed for digital computer analysis. Use of the model permits prediction of the influence of variables such as depth, pH, and mixing on nitrogen loss.

Effect of Digested Sludge Application on Soil Atmosphere, Nitrification and Denitrification

Investigations conducted by Dr. R. I. Dick and assistants, Department of Civil Engineering.

The fate of nitrogen in sludge which is added to soil is highly dependent on the level of dissolved oxygen in the soil water. With normal soil conditions, ammonia is oxidized to the mobile nitrate form which may be lost by leaching. If anaerobic conditions are created in soil containing nitrates, denitrification occurs with the usual evolution of nitrogen gas to atmosphere.

A preliminary laboratory study was conducted to evaluate the effect of sludge application on oxygen concentrations in soil. Rates of denitrification of nitrates added to sludge-soil mixtures were also evaluated.

Experiments were conducted in laboratory lysimeters containing 5.5 ft. of Plainfield sand. A free water surface was maintained at the bottom of the lysimeters. Liquid digested sludge was added each week to the top of the lysimeters without mixing. Four lysimeters were used and rates of application were 0.25, 0.5, 0.75, and 1 in./wk. In addition, 0.5 in. of water was added to each of the columns weekly to simulate rainfall.

Samples collected at a depth of 2 in. below the surface of the soil following sludge applications indicated that total anaerobic conditions were not created during the first several hours following sludge applications of up to 0.75 in. In the column receiving 1 in./wk of sludge, soil pores at the 2 in. level were filled with moisture and hence anaerobic conditions would be expected near the surface of that column.

In all of the lysimeters, oxygen concentrations in the air within the soil decreased with depth and the abundance of carbon dioxide increased with depth. During the first day following sludge application, the carbon dioxide level was highest in the columns receiving the largest amount of sludge. However, with time, the carbon dioxide level decreased in the heavily dosed columns to levels below those in the columns receiving less sludge. After a week, the depletion of oxygen in the soil was greatest in the lysimeter receiving the least amount of sludge.

Nitrate profiles in the soil columns receiving varying amounts of sludge were obtained after varying lengths of time. Nitrates were first detected in the lysimeter leachate after 3 weeks of operation. Differences in the nitrate concentration of the soil moisture in the four lysimeters were not proportional to the differences in the amount of sludge which the columns received. After 5 weeks, soil moisture nitrate concentrations had reached maximum levels of from 300 to 800 mg/l although high levels had not yet been detected in the leachate.

It is of interest to know whether nitrate formed in the soil could be evolved as gas through creation of controlled anaerobic conditions. In separate laboratory studies, nitrates were added to digested sludge to assess the probable maximum rate at which denitrification might be expected to occur. The rate of denitrification of nitrates in sludge was found to be independent of the nitrate concentration until the nitrate level reached 1 or 2 mg/l. The maximum rate of the zero order reaction observed was about 10 mg/l of nitrate per hour at room temperature, although the rate depended on the characteristics of the digested sludge.

The rate of denitrification of nitrate added to a mixture of sludge and soil was compared to denitrification in sludge alone. In the sludge-soil mixture, the rate of denitrification continued to be independent of nitrate concentration, but denitrification proceeded at a slower rate than in sludge alone.

Digested Sludge Dewatering on Soils

The rate at which digested sludge dewaters after application on crop land is one parameter which is needed to determine possible application frequencies and loading rates.

The rate of digested sludge drying as a function of convective and radiative heat transfer has been reported by Quon and Ward (2) and Quon and Tamblyn (3). By varying temperatures, humidity differences and flow rates of air over a broad range of values, it was found that when sludge temperatures were low and the air humidity was high, the rate at which digested sludge dried by convective heat transfer was only about one-half the rate of evaporation from a free water surface. However, when sludge temperatures were high and air humidity was low, the rate of convective drying of digested sludge approached the rate of evaporation from a free water surface.

When evaporation was produced as a result of only radiant energy incident on the surface, the rate of evaporation from a digested-sludge surface and a free-water surface were found to be essentially equal. At an intensity of 1.0 cal per sq. cm per min., the evaporation rate was 0.9 x 10^{-3} gm per sq. cm per min. One-half of the incident energy on the sludge surface was expended as latent heat of vaporization. When drainage or infiltration of digested sludge water into sand contributed to the sludge dewatering process, the evaporation rate from the sludge surface as a result of radiative heat transfer was depressed by 22 percent.

It was found that digested sludge dried at a constant rate until its moisture content approached 75 to 90 and 66 to 84 percent by convective and radiative heat transfer respectively. Thus, at moisture contents of 70 to 90 percent, the rate of evaporation decreases and is referred to as a critical moisture content for sludge dewatering.

Factors determining the dewatering rate of digested sludge on soils were investigated under laboratory and field conditions. Soil columns of Blount silt loam and Plainfield sand were used in laboratory sludge dewatering studies. Metal infiltration rings were used for field studies.

Nitrate concentrations, electrical conductivity, pH, and Eh values of effluent and soil water samples were determined. Effluent from soil columns and soil solution samples were collected throughout the period in which the factors influencing the dewatering of sludge on soils was investigated.

It was found that when sludge is first applied on soils, dewatering of the sludge is fairly constant and the rate depends on infiltration of water into soils and water losses by evaporation. When the water content of sludge has been reduced to about 80 percent by weight, further drying of the sludge is by evaporation alone. Under laboratory conditions, evaporative losses of water from digested sludge were not detected when the moisture content of sludge was reduced to about 8 to 10 percent of the dry weight. On Blount silt loam soil, after the sludge moisture content was reduced to about 80 percent, the rate of drying of the sludge was less than the rate at which water was being evaporated from the surface of soil columns under laboratory conditions. Apparently, water which first infiltrated the soil surface was later transmitted back to the sludge solids on the soil surface to replace evaporative losses of water.

Initially, the infiltration rate of sludge liquid into sand is greater than into silt loam soils. After a few days of successive applications of sludge in the absence of complete drying, the rate varies between .06 and .006 cm/hr regardless of soil type. It appears that after a period of time, the infiltration rate is determined by the sludge cake and not by the soil surface. The soils are unsaturated with respect to moisture and their capacity to transmit moisture is always greater than the infiltration rate determined or controlled by the sludge cake.

The rate of infiltration of sludge liquid depends on the initial soil moisture content and solids content of the sludge. The higher the soil moisture and sludge solids contents, the lower is the rate of infiltration. However, antecedent moisture conditions affect the rate of sludge infiltration less on sandy than on fine textured soils.

When successive sludge applications are made at time intervals such that the sludge cake is not allowed to dry, infiltration rates decrease to very low levels. But, if the sludge cake is allowed to dry, the initial infiltration capacity is recovered.

The changes in soil pH and redox potentials were small following various rates and frequencies of sludge applications.

Nitrate nitrogen concentrations continued to increase in the soil with successive sludge applications both in laboratory and field studies. Soil solution nitrate concentrations ranged between 100 and 300 ppm where a total of 50 cm of sludge was applied in 70 days during field studies.

From nitrate concentrations and redox potential measurements, it appears that anaerobic conditions were seldom, if ever, produced in the soil by exceedingly high sludge loading rates.

Soil conductivity values were increased from an average value of about 1 millimho where only water applications were made to about 2.5 millimhos where a total of 50 cm of sludge was applied in 70 days. It appears from limited data that salts will be leached to deeper soil depths in a humid region. The salt buildup in the surface of a soil like Blount silt loam with continuous periodic sludge applications will not likely exceed that which was found with the total 50 cm application.

GREENHOUSE STUDIES

Greenhouse Studies on Nutrient Uptake and Growth of Corn on Sludge-Treated Soils

These investigations were carried out by J. B. Cropper* under the direction of Dr. L. F. Welch** in partial fulfillment of the M.S. degree. The following is from the summary of Mr. Cropper's thesis (4).

Four studies were conducted to determine what effect the sludge and its constituents might have on the germination and growth of corn and the soils upon which the corn was growing. The first experiment sought to determine what effects heavy metals contained in sludge would have on corn growth if they were allowed to build up in the soil over a period of several years. Pb, Cu, Cr, Zn, and Ni were added as chemical salts in amounts that would be equivalent to those concentrations that would theoretically build up in a soil after 6 acre-inch additions of sludge had been added for 0, 5, 10, 15, and 20 years. The second experiment was a study on the effects of leaching two soils, a sandy soil and a silt loam, with sludge. The third experiment was set up to observe the effects of heavy applications of dried digested sludge and lime additions had on nutrient uptake and especially on heavy metal uptake. The fourth experiment was a sludge irrigation experiment which sought to find out which weekly rate would be best. It was also designed to find out if extra nitrogen, phosphorus, or potassium was needed. It also included a germination study. Three types of sludge were compared on their effect on germination. These three types were: regular digested, fermented digested, and boiled digested.

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* Former Research Assistant, Department of Agronomy, University of Illinois.
** Professor of Soil Fertility, Department of Agronomy, University of Illinois of Urbana-Champaign.

The following points are of major interest when utilizing sludge for irrigation or other agricultural purposes to be cropped with corn and possibly other crops.

1. Sludge will provide adequate amounts of nitrogen, phosphorus, and potassium at the rate of 0.5 acre-inch per week during the growing season.

2. Sludge at the rate of 6 inches annually perhaps adds too much nitrogen.

3. Application of liquid digested sludge immediately after planting should probably be avoided unless not more than 0.5 acre-inches is applied.

4. Zinc and copper concentrations in corn are increased substantially by sludge fertilization. These metals could build up to toxic levels in the soils if sludge is applied at high rates for many years.

5. Sludge does not seem to have much effect of soil pH on a short-term basis.

6. Cation exchange capacity and buffering capacity of sandy soils is increased considerably by sludge applications.

7. Liming of sludge treated acid soils would be desirable for many reasons. It would tend to keep the heavy metals less soluble. Manganese, in particular, would be reoxidized by the increased pH of the soil so that it would not leach from the upper profile of the soil. Lime would promote more rapid nitrification of the tremendous amounts of ammonium nitrogen present in the soils after sludge additions.

SOUTH FARM LYSIMETER RESEARCH

Field study of the efects of disposal of digested sewage sludge (hereafter referred to as sludge) on land was begun in the spring of 1967. Existing lysimeters, each three feet in diameter and four feet deep were utilized. The lysimeter surfaces were at the same elevation as the surrounding soil, and underground pipes allowed collection of drain water. Eight soil types were represented (Brooklyn, Cisne, Cowden, Elliott, Saybrook, Herrick, Muscatine, and Tama) and replicated three times. All soils were silt loams with differences in internal drainage and permeability.

Sludge used on the lysimeters was obtained from the Calumet Treatment Plant of the Metropolitan Sanitary District of Greater Chicago. The sludge was applied as received from the digesters, i.e. as a liquid with ca. 3% solids. Table 1 lists the nutrient and metal concentrations found in sludge.

Sludge treatments were chosen on an estimation of the maximum liquid volume which could be accommodated. In 1967, rates of one inch and one-half inch per eight days were chosen, and totals of ten and five inches were realized. In 1968 and 1969, rates of one inch and one-half inch per week were adopted, and the maximum totals were ten and seven inches, respectively. Commercial fertilizer, at the rate of 200 lb/A nitrogen, 100 lb/A phosphorus, and 100 lb/A potassium, was used on the control plots in 1968 and 1969. Where necessary, plots were irrigated with water to equal the liquid volume of the maximum sludge rate.

Yields

Soybeans were planted in 1967. In 1968, grain sorghum and Reed canary grass were grown, and in 1969 corn and Reed canary grass were grown.

Whole soybean plants were harvested when the lower leaves began to yellow with maturity. There appeared to be a toxic condition, especially in the control lysimeters. The toxicity probably arose from a high Zn content in the soil (see Table 15) that apparently resulted from the galvanized construction of the lysimeters.

The yield data for soybeans are shown in Table 3. Sludge-treated plots produced significantly better grain and total plant yields than did the controls. Sludge additions ameliorated the toxic condition that was apparent in the controls.

Reed canary grass yields are listed in Table 4. Sludge treated plots yielded significantly more than control plants from the first cutting in each year. Second cutting yields from sludge-treated and control plots were similar in both years. Better physical condition of the soil and/or availability of residual nutrients in sludge-treated plots probably accounted for the higher first cutting yields on sludge-treated plots.

Means for sorghum grain yields were 430.4, 284.9, and 354.8 g for the maximum, 1/2 maximum, and control, respectively. Although the maximum sludge application produced the highest yield, the differences were not statistically significant at the 5% level (see Table 5). Sludge-treated plants matured a few days earlier than control plants.

Average corn yields (Table 5) were 110.61, 260.93 and 349.18 g per lysimeter for maximum, 1/2 maximum, and control rates, respectively. Unfortunately, leaf blight deleteriously affected the yield. Yields from sludge-treated plots were more severely reduced because the disease affected those plants sooner than the controls. Leaf samples for chemical analysis were collected before the corn disease symptoms appeared.

Table 3. Soybean yield means in grams dry weight from South Farm lysimeters, 1967.

Treatment	Whole Plant	Grain	Dry wt/plant
Maximum sludge	288.8**	88.3	14.4**
1/2 Maximum sludge	253.9**	83.0	12.0**
Control	78.2	24.4	4.3

**Significantly different from the control at the 1% level

Table 4. Reed canary grass yield means; South Farm lysimeters

Treatment	Dry weight in grams			
	7/19/68	9/9/68	5/26/69	9/18/69
Maximum sludge	190.3**	165.5	239.1	106.3
1/2 Maximum sludge	132.5**	140.1	231.6	91.4
Control	73.5	143.2	78.3	108.8

**Significantly different from the control at 1% level

Table 5. Sorghum (1968) and corn (1969) grain yield means; South Farm lysimeters

Treatment	Sorghum dry wt g	Corn 5% moisture g
Maximum sludge	430.4	180.61
1/2 Maximum sludge	284.9	260.93
Control	354.8	349.18

Table 6. Mean nitrogen content of soybean plants in percent dry weight

Treatment	Leaves	Grain
Maximum sludge	4.45	4.87
1/2 Maximum sludge	3.75	4.61
Control	3.42	3.94

Plant Chemistry

Addition of one inch of sludge to an acre provides about 330 lbs. of nitrogen approximately half of which is in the ammonium form. Therefore, during each of the first two seasons, the equivalent of over 3,000 lbs. of nitrogen per acre was added. Plants were analyzed for total nitrogen to determine what effect this high rate of application had.

Nitrogen content for soybean leaves and grain are presented in Table 6. Leaf values were 3.42, 3.75, and 4.45% for the three rates in ascending order. Nitrogen contents of the grain were 3.94, 4.61, and 4.87% with increasing application rates. The leaf nitrogen increased as expected with increasing applications of nitrogen from the sludge.

Total nitrogen content means for the two cuttings of Reed canary grass in 1968 are listed in Table 7. For the first cutting, nitrogen values were 4.10, 4.21, and 4.17% for the three increasing application rates. Concentrations for the second cutting were 2.84, 3.57, and 3.91% with increasing application rates. The relatively large reduction in nitrogen in the control sample (second cutting) probably occurred as only one fertilizer application was made in the spring.

Concentrations of total nitrogen in grain sorghum leaves are listed in Table 7. They are 1.48, 2.37, and 2.49% with increasing application rates.

The nitrogen contents of the crops even at the abnormally high fertility levels employed with sludge irrigation were not very different from those published and accumulated in a state-wide plant nutrient survey (5). Thus, it appears that these very high nitrogen rates from sludge had no deleterious effect on plant nitrogen composition.

Table 7. Total nitrogen content means for Reed canary grass and sorghum leaves from South Farm lysimeters

Treatment	R. C. G. Percent dry weight 7/19/68	R. C. G. Percent dry weight 9/9/68	Sorghum 1968
Maximum sludge	4.27	3.91	2.49**
1/2 Maximum sludge	4.21	3.57	2.37**
Control	4.10	2.84	1.48

**Significantly different from the control at the 1% level

Table 8. Micronutrient concentration means for soybean plants from the South Farm lysimeters.

Treatment	Concentration in ppm			
	Cu	Mn	Ni	Zn
<u>Leaves</u>				
Maximum sludge	29	145**	7.2	1186
1/2 Maximum sludge	29	129**	7.2	1251
Control	32	62	5.2	827
<u>Grain</u>				
Maximum sludge	45	38	7.6	276
1/2 Maximum sludge	43	58	7.3	295
Control	47	42	11.0	271

**Significantly different from the control at the 1% level

Reference to Table 1 will show that digested sludge has a rather high complement of heavy metals -- Cu, Zn, and Mn are essential in small quantities to plants whereas Cd, Pb, and Cr are nonessential. Heavy metals are usually toxic to plants at relatively low available soil concentrations. Because they are polyvalent, they are held rather tightly by the soil colloids which reduces their availability to plants. In the case of sludge, they are present as hydroxide (6) or other precipitated form in the solid phase. As long as the soil pH remains neutral, or above, heavy metals should not become very available to plants (1) from a sludge source. Potential hazard of toxicity from extended application of sludge to cropped land is a distinct possibility (7).

Soybeans. Cu, Mn, Ni, and Zn concentrations found in soybeans are listed in Table 8. Pb and Cr were not detected. Values for Cu were slightly higher, 43-47 ppm in the grain, than in the leaves, 29-32 ppm. Concentrations measured in this study were rather high, but differences due to sludge treatment were not sifnificant.

Mn concentrations in leaves were significantly different for sludge treatments while Mn levels in the grain were not. It is easier to influence the leaf composition than it is the grain. Concentrations ranged from 62-145 ppm for the control and maximum rate respectively.

Zn concentrations in leaves and grain of sludge-treated and control plants were unusually high. Since the control plants were also high in Zn, it was obvious that much of the Zn found in the plant samples came from the soil and not the sludge. Zn levels in all plants, including controls, were sufficiently high to be considered in the toxic range.

Sludge treated plants contained higher concentrations of Zn than the controls, yet the treated plants showed less toxicity. These results support the theory that Zn and phosphorus interact (4) and since the sludge added the equivalent of several hundred pounds per acre phosphorus, it may have restored a more normal ratio between the elements, thereby reducing the toxicity symptoms. Differences in Zn content of the grain were not significant relative to treatment.

Ni concentrations in leaves and grain were approximately the same, and differences due to sludge treatment were not significant.

Reed canary grass. Mn, Mg, Cu, and Zn concentrations in Reed canary grass leaves for the cuttings are presented in Tables 9 and 10. Cd and Cr were not detected. Mn concentrations in the first and second cuttings increased with increasing sludge rates and all sludge treatments were higher than the controls.

Mg concentrations in general do not significantly reflect treatment.

Grain sorghum. Concentrations of micronutrients in sorghum leaves and grain are shown in Table 11. Ca, Mg, and Cu contents did not vary significantly with sludge treatment. Like soybeans, micronutrient content of the grain was much lower than that of the leaves. This phenomenon could be useful if sludge application induces higher than normal heavy metal uptake, particularly where the edible plant part is the grain.

Zn and Mn concentrations in leaves and grain and Fe concentrations in grain showed highly significant increases with sludge application. Ni, Cr, and Pb were not detected in leaves or grain.

Corn. Table 12 lists the micronutrient concentrations found in corn leaves. Only Mn concentration showed significant response to sludge treatment. Pb was detectable in a few samples, but no Cr or Cd was detected in any.

Table 9. Micronutrient content means of Reed canary grass from South Farm lysimeters, 1968.

Treatment	Mn 7/19 ppm	Mn 9/9 ppm	Mg 7/19 %	Mg 9/9 %	Cu 7/19 ppm	Cu 9/9 ppm	Zn 7/19 ppm	Zn 9/9 ppm
Maximum sludge	104**	154	.226	.198	33*	32	345	823**
1/2 Maximum sludge	49**	96	.223	.350	25*	40	895	976**
Control	31	30	.292	.300	18	40	1168	635

*Significantly different from the control at the 5% level
**Significantly different from the control at the 1% level

Table 10. Micronutrient content means for Reed canary grass from South Farm lysimeters, 1969.

Treatment	Ca %	Mg %	Cu ppm	Fe ppm	Ni ppm	Zn ppm	Mn ppm
			5/26/69				
Maximum sludge	.259	.194	17	156**	5.1	595	114**
1/2 Maximum sludge	.229	.196	12	142**	4.3	585	62**
Control	.197	.112	9	125	4.0	550	32**
			9/18/69				
Maximum sludge	.412		5.0	76	4.6	1225	193
1/2 Maximum sludge	.386		5.1	71	3.0	1070	94
Control	.174		7.8	63	1.4	1030	36

**Significantly different from the control at the 1% level

Table 11. Micronutrient content means for sorghum leaves and grain from South Farm lysimeters, 1968.

Treatment	Ca ppm	Mg %	Cu ppm	Fe ppm	Zn ppm	Mn ppm
			Leaves			
Maximum sludge	-	.414	32	-	717**	173**
1/2 Maximum sludge	-	.422	41	-	589**	76**
Control	-	.220	38	-	252	16
			Grain			
Maximum sludge	62	.162	3.25	56**	60**	14**
1/2 Maximum sludge	75	.161	3.44	57**	58**	11**
Control	67	.137	2.86	32	30	5.8

**Significantly different from the control at the 1% level.

Table 12. Micronutrient content means for corn leaves from South Farm lysimeters, 1969.

Treatment	Ca %	Mg %	Cu ppm	Fe ppm	Ni ppm	Zn ppm	Mn ppm
Maximum sludge	0.761	0.593	12	215	1.0	1120	153**
1/2 Masimum sludge	0.797	0.869	13	147	1.1	1031	45**
Control	0.755	0.674	17	181	1.1	881	28

**Significantly different from the control at the 1% level.

The sludge-treated plants generally exhibited enhanced Zn, Mn, and Fe uptake. This enhanced uptake may be partly a function of addition of the elements in sludge, but there is good evidence that some of it may be an indirect effect of sludge addition. In no case has there been evidence of toxicities resulting from sludge addition in two years of this lysimeter study.

Soils

Soil test values for pH, available P and K of the soil from the lysimeter plots are shown in Table 13. The 1967 values preceded planting and sludge application. Soil pH, available phosphorus and potassium increased with sludge treatment.

Concentrations of organic carbon are given in Table 14. Organic C content increased with sludge application rates while the controls remained relatively constant.

Heavy metal concentrations, as determined by 0.1 N HCl (8) are given in Table 15. All of the heavy metals increased relative to the controls in sludge amended plots.

Leachates

Nitrate-N analyses of leachates (drain water) from the lysimeters are given in Figures 1 and 2. Concentrations from sludge-treated plots were significantly higher than those in the controls.

First leachates usually collected in November contained the highest nitrate concentrations, while the lowest concentrations occurred at the end of the collection period. Essentially no leachate was produced during the summer months. Nitrate-N concentrations in the control plots were uniformly low for all periods of the year.

Table 13. Means for pH, P_1 (available phosphorus), and potassium from South Farm lysimeter soils.

Treatment	pH	P_1 lb/A.	K lb/A.
	1967		
Maximum sludge	5.7	176	357
1/2 Maximum sludge	5.8	187	444
Control	5.8	182	390
	1968		
Maximum sludge	5.8	450**	644**
1/2 Maximum sludge	5.6	406**	551**
Control	5.7	183	299
	1969		
Maximum sludge	6.2*	226**	718**
1/2 Maximum sludge	5.9*	198**	507**
Control	5.6	146	516

**Significantly different from the control at the 1% level.
*Significantly different from the control at the 5% level.

Table 14. Organic carbon content means for South Farm lysimeter soils, percent dry weight.

Treatment	Pre-treated	8/21/67	10/20/67	5/12/68
Maximum sludge	1.90	2.51**	3.41**	5.98**
1/2 Masimum sludge	1.98	2.19**	2.95**	3.37**
Control	1.91	1.90	1.78	1.82

**Significantly different from the control at the 1% level.

Table 15. Heavy metal content means of South Farm lysimeter soils sampled 5/2/69.

Treatment	Parts per Million						
	Cd	Cr	Cu	Mn	Ni	Pb	Zn
Maximum sludge	36	45	352	306	18	209	2175
1/2 Maximum sludge	18	27	138	279	9.1	162	1205
Control	n.d.	n.d.	17	122	0.75	12	459

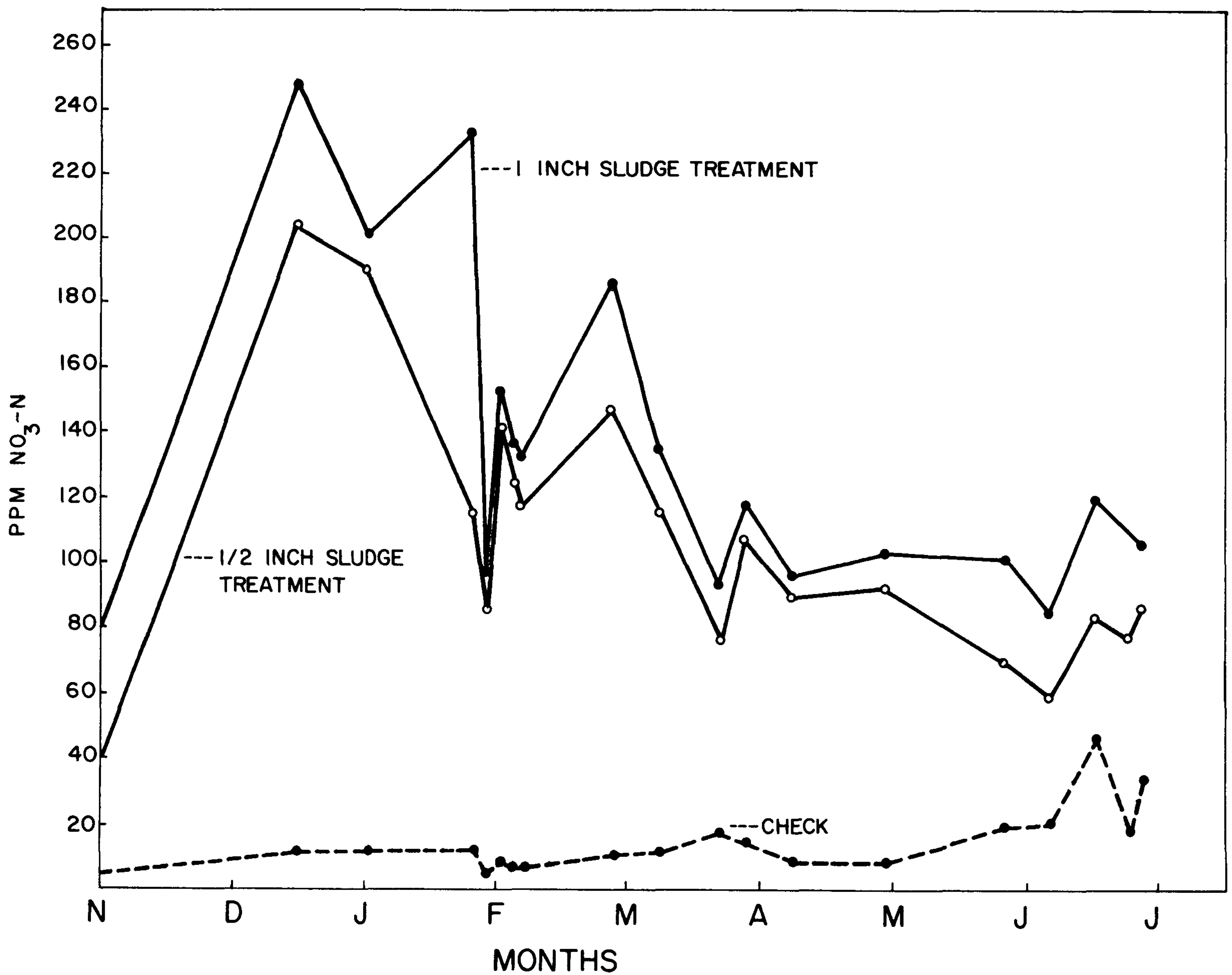

FIGURE 1. NITRATE-NITROGEN CONCENTRATIONS IN SOUTH FARM LYSIMETER LEACHATE NOVEMBER 1967 - JUNE 1968.

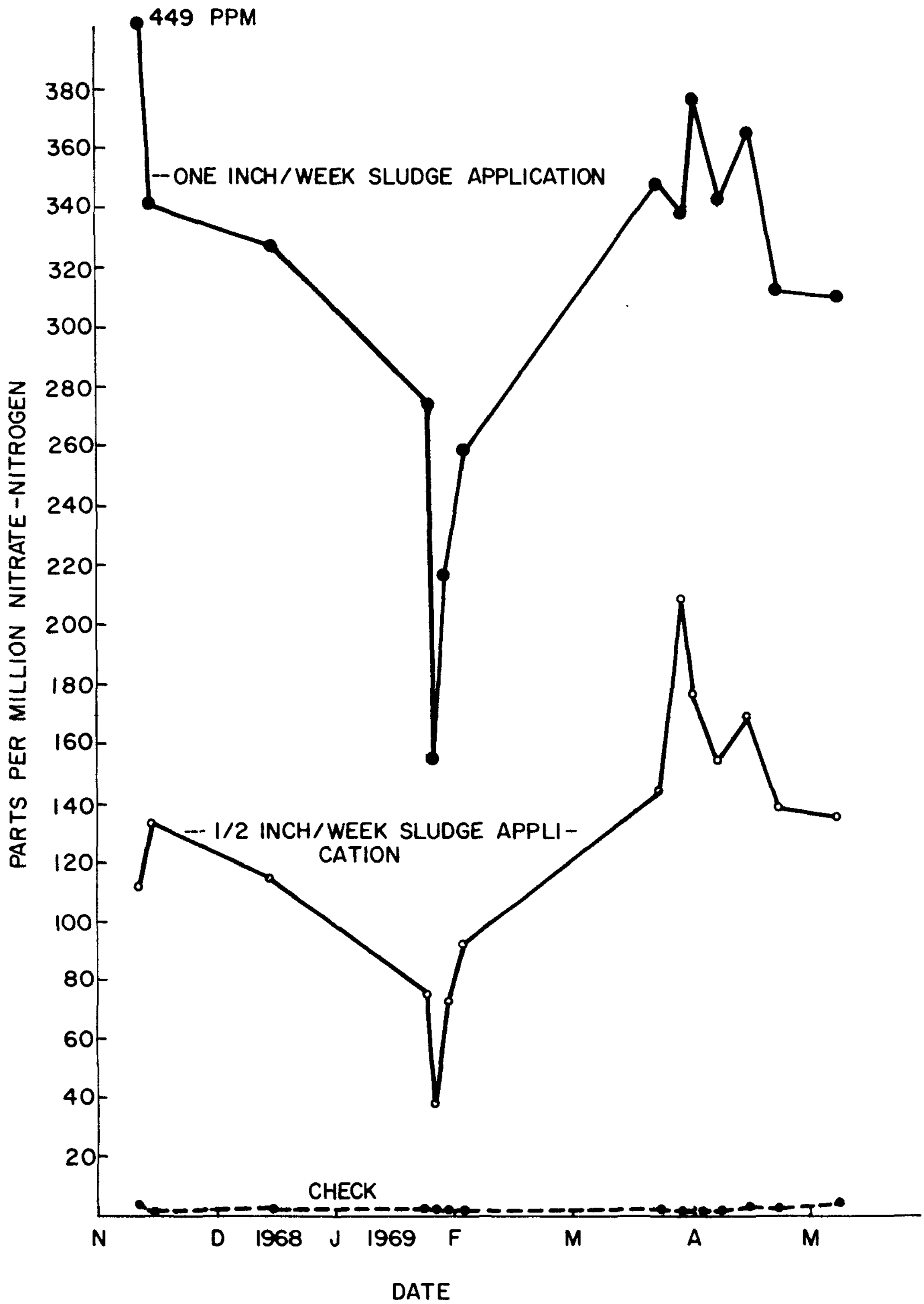

FIGURE 2. NITRATE-N CONCENTRATIONS IN SOUTH FARM LEACHATE 11/68 - 5/69

Figures 3 and 4 show the accumulated losses of nitrogen as nitrate in leachate. Total nitrogen losses reflected the sludge treatment.

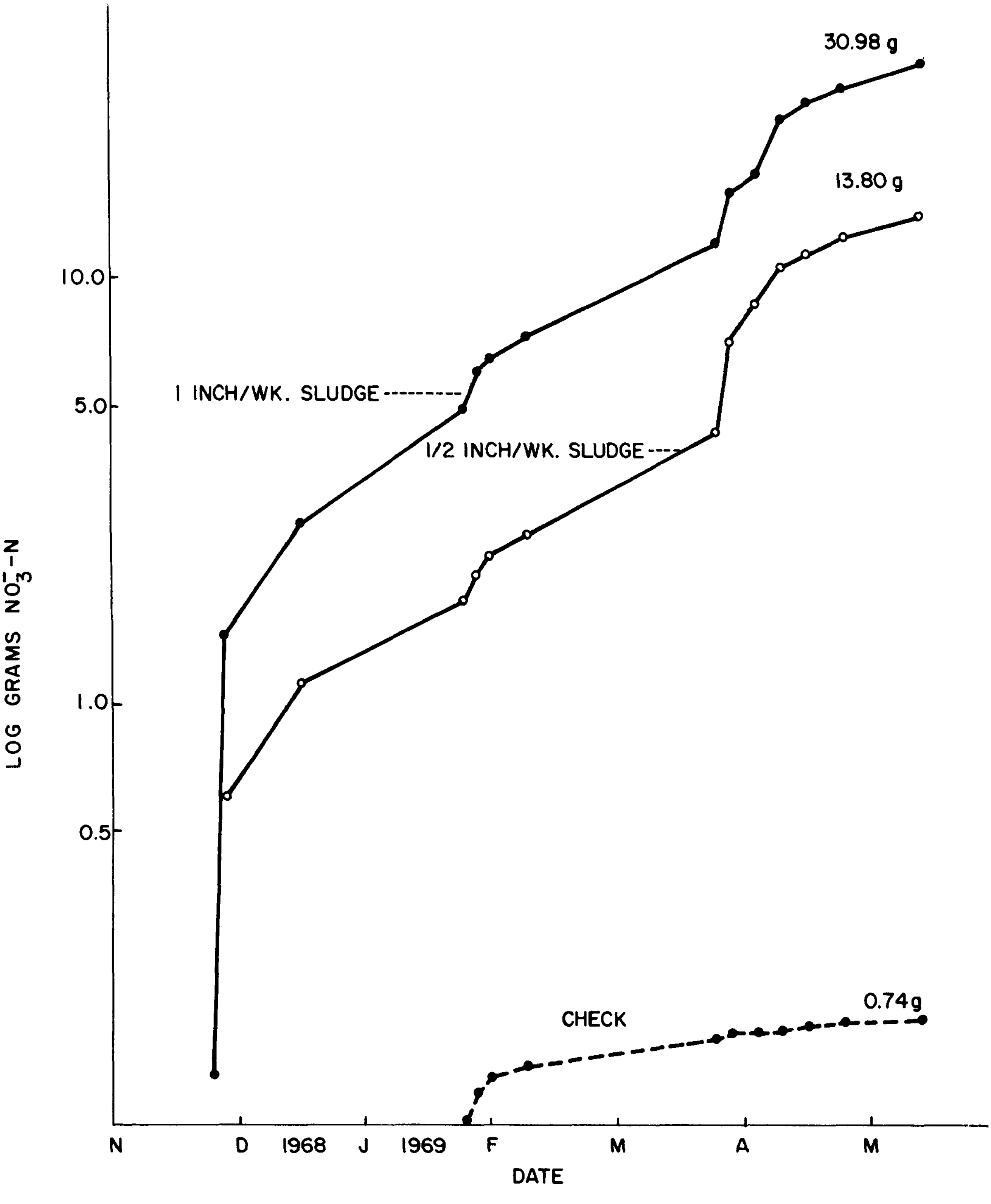

FIGURE 3. TOTAL LOSS OF NITRATE-NITROGEN IN LEACHATE 11/68-5/69

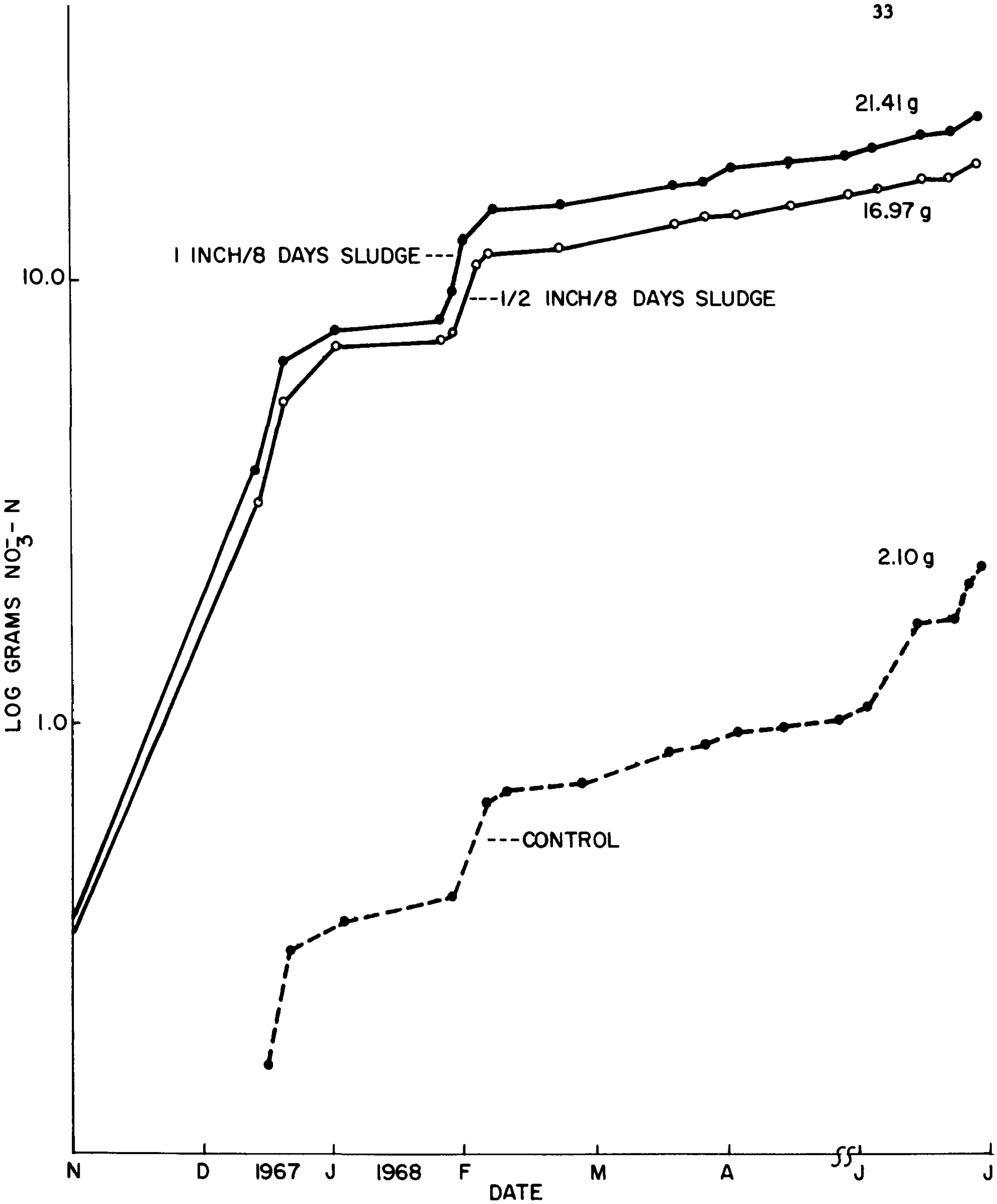

FIGURE 4. TOTAL LOSS OF NITRATE-NITROGEN LEACHATE 11/67 - 7/68

INSTRUMENTED PLOTS AT THE NORTHEAST AGRONOMY RESEARCH CENTER

The Field Research Facility

Plans and specifications for the field research facility were prepared and submitted with the requisition to the University Purchasing Division on June 6, 1967. Construction of the instrument house was completed on September 15, 1967 and the lysimeters were completed on June 18, 1968.

The field research facility was constructed on a small isolated watershed, where the original soil type was Blount silt loam, underlain with glacial till, of very low permeability, from about 30 inches below the soil surface to a depth of about 40 feet. An overall view of the field research facility is presented in Figure 5. The facility consists of 44 plots, each 50 feet long and 10 feet wide. Half of the total 44 plots are in each of 2 blocks: one block on the north and one block on the south side of the instrument house. Each block contains 12 plots of the original Blount silt loam, five plots of simulated Elliott silt loam, and five plots of simulated Plainfield sand. Since the Elliott silt loam soil is a prairie correlate of the forested Blount silt loam, the simulation of a prairie soil was made by removing the Blount silt loam surface to a depth of one foot and replacing it with the surface of Elliott silt loam. Plainfield sand was simulated by excavating all of the original material within the boundaries of a plot to a depth of 5 feet and then filling the pit with Plainfield sand.

A trenching machine was used to excavate a trench around the perimeter of each plot to a depth of 6 feet. After a single line of 4-inch diameter clay tile had been installed at a bottom depth of 34 inches through the longitudinal center of each of the Blount and Elliott silt loam plots, a continuous curtain of nylon reinforced 8 mil black plastic film was

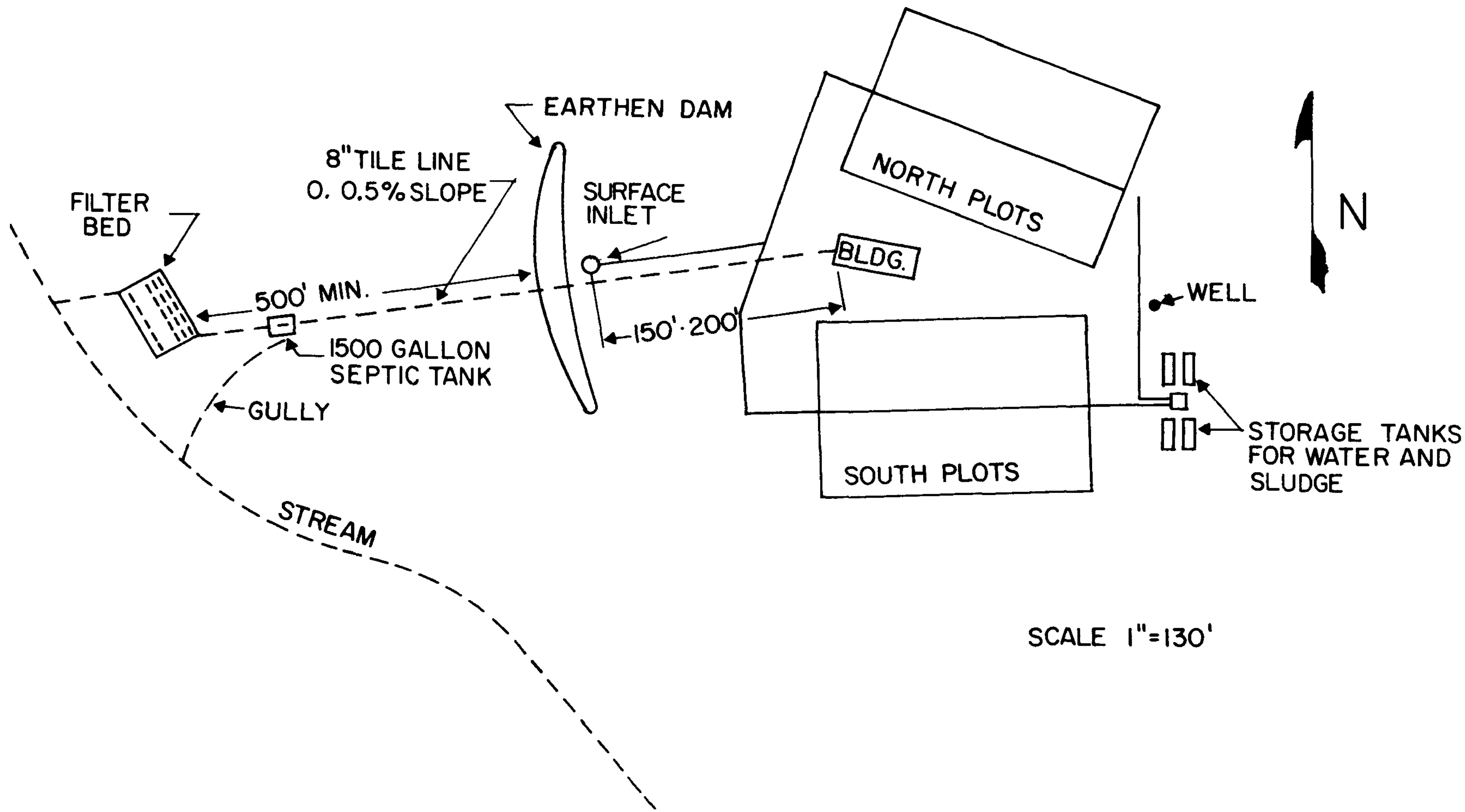

FIGURE 5

VIEW OF FIELD LYSIMETER RESEARCH FACILITY suspended from 8 inches below the soil surface to a depth of 6 feet in the trench surrounding each plot, with the ends overlapped a minimum of 4 feet. With the moisture barrier secured by spikes to the inside wall, the trench was backfilled with the soil removed during excavation. Construction of the sand plots was somewhat different in that the line of clay tile was installed at a depth of 5 feet and the walls lined with the plastic moisture barrier before the pit was filled to ground level with Plainfield sand.

To convey drainage water, a 4-inch diameter rigid plastic drain tube was extended from each plot attached to the end of the 4-inch diameter clay tile line nearest the instrument house to within 2 feet of the basement and 30 inches above the basement floor of the instrument house. The plastic tube was attached to the clay tile by an adapter just inside of the plastic moisture barrier. A mastic material was used to achieve a water proof seal where the plastic tube passed through the moisture barrier.

A second 4-inch PVC tube to convey runoff water was extended from 2 feet inside and 66 inches above the basement floor to within 6 inches of the moisture barrier at each of the plot center end nearest the instrument house. The end of the PVC tube at the end of a plot was located 18 inches below the soil surface and connected to a 90 degree elbow positioned in an upward direction to receive the thimble of the runoff water collection trough.

Each of the 88 plastic tubes for drainage and surface runoff water conveyance was placed on the maximum uniform grade obtainable from a plot to the basement of the instrument house. Grade was never less than 0.5 percent for tubes serving any plot.

The runoff water collection troughs were of a design similar to those used in soil erosion studies, except that they were fabricated from fiber glass. Fiber glass was chosen as the construction material to avoid the introduction of heavy metals in the runoff water and soils. For the same reason, fiber glass strips 10 inches high were used to completely enclose the plots along and above the moisture barrier discussed above. The fiber glass strips insure the collection at the down slope end of all the runoff water from a plot while excluding all foreign water.

All lysimeter plots, side borders (10 feet wide), and end borders (20 feet wide) slope toward the instrument house. Thus, runoff water flows toward the instrument house from both the north and south blocks of lysimeter plots.

The instrument house was constructed in a natural depression of the slightly greater than 2 acre watershed. The 54.75 ft by 12 ft by 8 ft eave-height frame building was constructed on a concrete first floor over a poured steel reinforced 8-inch thick walled basement, which was 9.5 ft high above the footings. Ten 4-inch diameter bell and spigot floor drains were installed in the basement floor to conduct unwanted water discharged from the plot drainage tubes to a 8-inch diameter tile installed below the center of the basement floor.

Heating was provided by 2 wall mounted thermostatically controlled 220 volt electric heaters at each end of the first floor of the instrument house. One end of the first floor of the building was partitioned, to provide a totally air-conditioned room to protect instrumentation circuitry from excessive variations of temperature and humidity.

The 8-inch diameter clay tile line used to drain excess water from inside the basement of the instrument house and basement footing tiles was also connected to a surface inlet located in the natural drainage way of the small water shed and 150 feet west of the instrument house. Behind the surface inlet a small earthen dam was constructed to insure the capture of all run-off water from areas outside of the lysimeter plots. Thus, all water from the research area is disposed of through the 8-inch diameter tile line that conducts water through a 1500 gallon septic tank and finally to a sand and gravel filter field. All water from the research area is filtered through 30 inches of sand and gravel before it is discharged to a stream that flows intermittently.

To provide water for the instrument house and for irrigation of lysimeter check or control plots, a well was drilled to a depth of 200 feet. However, since a sustained flow of only 6 gallons of water per minute was obtainable from the well, two used 10,000 gallon capacity railroad tank car containers were buried near the well to store water for irrigation. Two other used, plastic-lined 8,000 gallon capacity railroad tank car containers were buried end to end with the water tanks to provide storage for digested sludge. The two water tanks were connected with 3-inch diameter metal pipe and a 60 gallong per minute capacity pump was mounted on the end of one water tank. One 2 stage vertical turbine pump with a capacity of 400 gallons per minute was mounted on the ends of each of the separate sludge tanks. Both the water and sludge pumps develop heads of about 180 feet. All pumps, motors, and exposed plumbing were enclosed in an insulated, propane heated pump house. Three-inch diameter metal pipe was used for all plumbing inside the pump house. By the use of check and gate valves, the plumbing from the pumps was installed in such a manner that the main irrigation line could be supplied with either water or sludge. Also, sludge could be circulated in the same storage tank pumped from one sludge storage tank to the other for mixing.

Three-inch diameter PVC pipe was used for the main irrigation line which was installed at a minimum depth of 18 inches below the soil surface. As may be seen from figure 5, the main irrigation line was extended from the pump house through the east-west center border of the north block of plots, to the west side of the instrument house and then returned to the pump house through the center east-west border of the south block of plots. The irrigation system was so designed that a large return flow of sludge could be maintainted to keep solids in suspension in the storage tank and prevent settling of solids in the irrigation pipe. It may also be noted from figure 1 that a "T" joint was installed in the main irrigation line west of the instrument house by which means the line was extended to the surface inlet discussed above. The main irrigation pipeline was laid on a uniform grade of approximately 0.5 percent from 20 feet west of the pump house to the surface inlet so that the line could drain when the gate valve at the surface inlet was opened. The plumbing inside the pump house is so arranged that after irrigation of plots receiving sludge treatments, the gate valve at the surface inlet may be opened and the north and south portions of the irrigation line may be alternately flushed with water. The irrigation line must be flushed with water each time before irrigation of check plots with water.

Risers were installed in the main irrigation line through the north and south block of plots so that one riser, by means of a valve and key, could supply either water or sludge to irrigate any one of four plots.

Although irrigation equipment is commercially available for field applications of digested sludge, equipment for making uniform applications on small research plots could not be obtained. Thus, a self-propelled irrigation machine for uniformly applying digested sludge on the 10 x 50 foot plots was designed and constructed specifically for the research project. Two-inch diameter flexible tubing is used to convey sludge or water from the risers to the irrigation machine.

To collect discrete samples on a preset volume proportional basis of runoff and drainage water from the field-plot size lysimeters, an electrically controlled sampling system was designed, constructed, and put into operation. The system is used to measure rate and total flow of both runoff and drainage water from each of the 44 lysimeters and to collect 400 ml samples after selected volumes of flow have occurred. Sampling may be varied for collecting a sample from 5.0 to as little as 2.4 percent of the total flow.

It may be seen from the block diagram, figure 6, that the system consists of the following five major components: 1) tipping bucket, 2) sample collector meachanism, 3) electrical circuits for counting and control, 4) event recorders and, 5) automatic turn-on and turn-off system. Except for some common circuit elements, each major component was duplicated eighty-eight times to provide complete instrumentation for the forty-four lysimeters. All of the instrumentation is located on the ground floor of the instrument house except the tipping bucket and sample collectors which are positioned below the end of the four inch plastic pipes used to convey runoff and drainage water from the lysimeters to the basement of the instrument house.

To insure against the loss of water samples and data during a storm period in which an electric line power outage might occur, a 120 volt, 2500 watt auxiliary power plant with automatic transfer panel was installed to provide power for the above described sampling and data collection equipment.

Since the irrigation system, data, and water sampling equipment could not be installed until all other construction was completed, sludge was not applied on the lysimeter plots in 1968, although the north block of plots

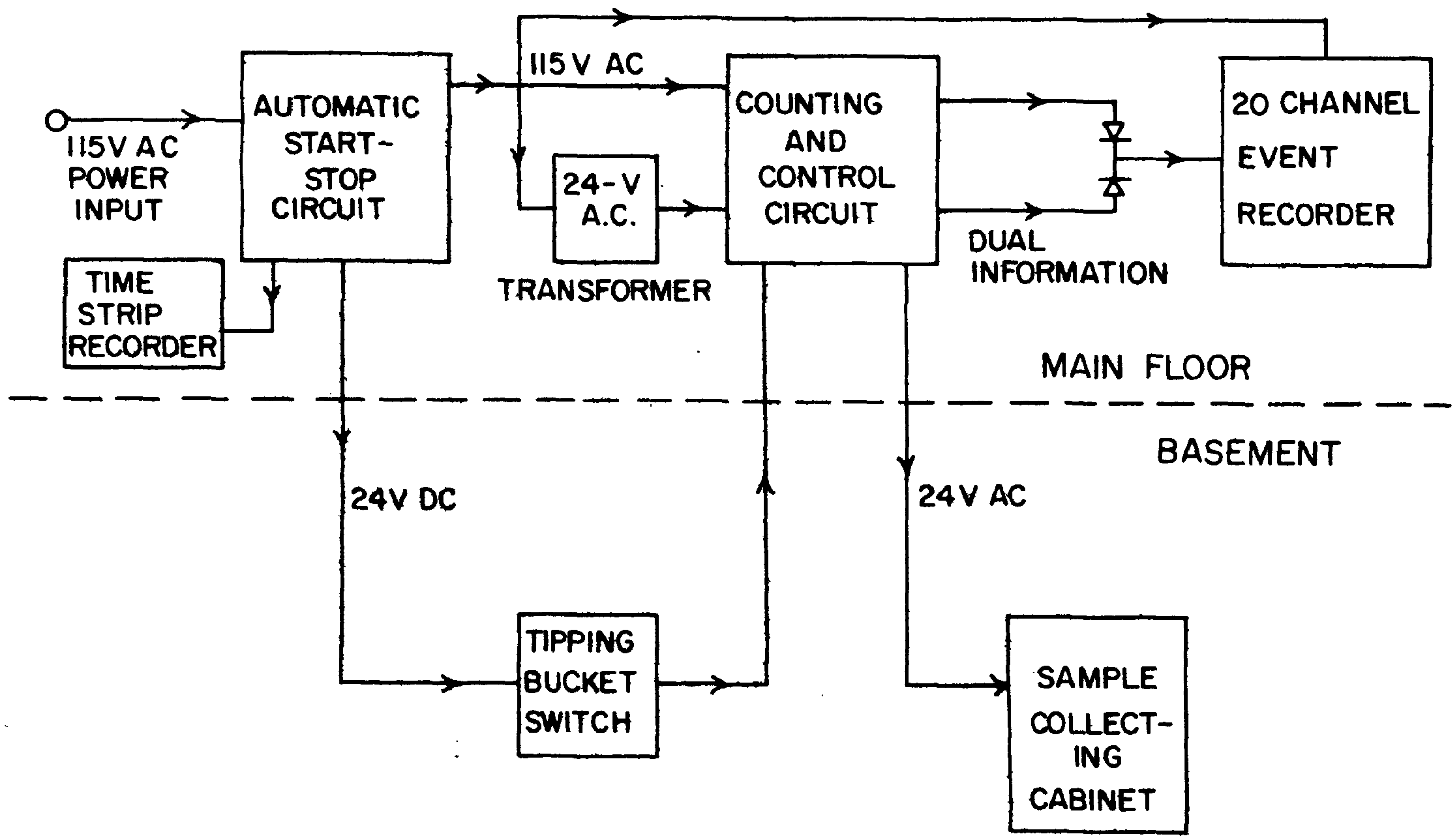

FIGURE 6. BASIC SYSTEM FOR DATA AND SAMPLE COLLECTION

was planted in June with soybeans and the south block with corn. Installation of equipment was completed in December 1968 and snow melt in January 1969 produced considerable runoff and provided an opportunity to check the equipment. A few minor modifications were made on the equipment in February 1969, after which the plots were ready for sludge applications. However, from April 1, 1969 through June 15, 1969, slightly more than 26 inches of rainfall were received at the research site. Although the plots were planted with soybeans and corn, the first application of sludge was not made until the latter part of June 1969. The exceptionally heavy rainfall period did provide several hundred water samples from which base data regarding fecal coliform organisms and the chemical status of drainage and runoff water could be obtained. But sludge applications were delayed too long by wet conditions to expect a treatment response by the crops. With the last irrigation of the lysimeter plots in December 1969, a total of 4 inches of sludge had been applied to the maximum sludge treated plots. For the most part, individual irrigation application rates have been less than 0.2 inches to prevent runoff of the sludge. When conditions are such that evaporation is high, a 0.2 inch application of sludge can be applied every two days and this does not seem to vary significantly with soil type.

Supplemental Field Experiments

At the N. E. Agronomy Research Center, digested sludge was applied by furrow irrigation at weekly intervals on Blount silt loam planted to corn and kenaf in 1968 and 1969. Corn was planted on replicated plots where alfalfa had grown for the two years previous to plowing. No inorganic fertilizer was applied in 1968, but 6 digested sludge applications were made between July 18 and August 28. Another sludge application was made on the plots in the spring of 1969 and a basic fertilizer application to supply 200 lbs per acre of K_2O on all plots before they were again planted to corn. In 1969, all check plots were treated with inorganic fertilizer supplying 240 lbs of nitrogen and 240 lbs of P_2O_5 per acre. Eight digested sludge applications were made in 1969 between the latter part of June and the first week of September. Average corn yields by year and application rate of digested sludge are presented in Table 16.

In the absence of nitrogen and phosphorus fertilizer applications on the check plots in 1968, a considerable increase in yield was realized for even the minimum sludge application. However, in 1969 when an exceedingly high application of nitrogen, phosphorus and potassium was applied on the check plots, the yield response to digested sludge application was not very great and indicates that it compares favorably with high rates of inorganic fertilizers. The corn yields in 1969 are probably the highest ever obtained on Blount silt loam.

The schedule for application of digested sludge on Blount silt loam plots where kenaf was grown in 1968 and 1969 was almost the same as discussed for corn. Also, inorganic fertilizer applications on kenaf plots were the same as those discussed for corn.

Average yields of three varieties of kenaf in 1968 and 1969 are presented in Table 17.

It appears that the application of two inches per year of digested sludge would supply adequate fertility for the kenaf varieties tested in 1968 and 1969.

To evaluate the availability of phosphorus and the response to the additional moisture supplied by sludge applications, plots of soybeans were replicated on Blount silt loam in 1969. A basic application of 200 lbs/acre of K_2O was made over all plots before planting.

The yield response of soybeans to phosphorus, sludge and water are presented in Table 18.

From treatments 1 and 5 it appears that in the absence of sludge the additional phosphorus increased yields from 3.7 to 8.4 bushels per acre depending on the moisture supply in August. Where soybeans were irrigated with sludge the additional phosphorus did not appear to increase yields. The water applications alone increased average yields by slightly more than 9.4 bushels/acre without phosphorus fertilization and 14.7 bushels/acre where 240 lbs/acre of P_2O_5 was applied. Comparing the treatment of 8 inches of sludge to 8 inches of water applied during the growing season in the absence of additional phosphorus fertilizer an increase of 6.6 bushels per acre was obtained with digested sludge irrigation. However, for the same comparison between sludge and water where an additional 240 lbs of P_2O_5 was supplied, there was little difference in yields. From this one-year study it may be concluded that the phosphorus supplied in sludge was readily available to soybeans, but the greater part of the increase in yield with sludge application was the result of the additional water supplied in August. The additional water and phosphorus fertility applied by 8 one-inch applications of sludge resulted in an increase of 16 bushels per acre or a 47 percent yield increase.

Table 16. Corn yields and didgested sludge applications on Blount silt loam on N. E. Illinois Agronomy Research Center, 1968 and 1969.

Inches of sludge per application	Average corn yields in bushels per acre	
	1968	1969
0	66.3	142.8
1/4	96.2	149.0
1/2	114.2	150.2
1	111.9	150.6

Table 17. Kenaf yields in tons per acre (adjusted to 20% moisture).

Sludge Treatment*	1968 Everglad 71	Varieties Cuba 2032	1969 Guatemala 4
0	2.1	4.99	4.55
2	3.6	4.55	5.12
4	3.7	4.81	5.21
8	3.7	5.26	5.38

*0 - Received only basic application of 200 lbs/A of K_2O in 1968 but fertilized with 240-240-200 lbs/acre in 1969.

2 - Sludge, 1.75 inches 1968 and 2 inches 1969.

4 - Sludge, 3.5 inches 1968 and 4 inches 1969.

8 - Sludge, 7 inches 1968 and 8 inches 1969.

Table 18. Yield response of soybeans to phosphorus, sludge and water treatments.

Treatments *	Average yield bu/acre	
	Phosphorus **	No. Phosphorus
1	37.7	34.0
2	44.6	45.0
3	47.0	48.2
4	52.1	50.0
5	51.8	43.4

* treatment 1 - 0 sludge or water application
treatment 2 = $\frac{1}{4}$ inch of sludge, 8 times from April through Sept. 17, 1969
treatment 3 = $\frac{1}{2}$ inch of sludge, 8 times from April through Sept. 17, 1969
treatment 4 = 1 inch of sludge, 8 times from April through Sept. 17, 1969
treatment 5 = 1 inch of water, 8 times from April through Sept. 17, 1969

** 240 lbs/acre P_2O_5 applied to one-half of each plot in October 1968

HYGIENIC ASPECTS OF LIQUID DIGESTED SLUDGE DISPOSAL ON CROPPED LAND

Fecal Coliforms in Liquid Digested Sludge

In this section, data obtained with fecal coliform organisms and with Escherichia coli are presented. The reader who would like to find general considerations on the hygienic aspects of sludge disposal on land is referred to other publications (9, 10).

Microbiological purification of polluted waters by percolation through artificial filters or soils is known to be an effective method of water treatment. Insofar as inferences can be made from traditions and experiences, one may expect the percolated waters from a biofilter four to five feet thick to be free of pathogens. In the present case, the challenge is at the soil-atmosphere interface, where digested sludge will cover acres, accessible to runoff waters, insects, birds and animals. The danger of infection from these fields will, to a great extent, be controlled by the persistence of pathogens on this surface layer.

For routine analyses of water, soil and digested sludge samples, the coliform group of bacteria has been taken as indicator of the degree of microbial pollution. Since non-fecal coliforms are known to the part of the normal soil flora, only the fecal coliforms have been considered.

The determination of fecal coliforms is rapidly and easily performed by the membrane filter technique with incubation at 44.5°C in the M-FC medium (11). This method (referred to as MFC) reveals the presence in the liquid digested sludge of a large population of fecal coliforms which gradually decreases upon removal of the digested sludge from the digester (Table 19). In contrast to this gradual decrease, laboratory grown populations of Escherichia coli (neotype, ATCC 11775) disappear very rapidly when added to the non-treated or autoclaved digested sludge (Table 20). In view of this difference of behavior

Table 19. Number of fecal coliforms per ml of impounded liquid digested sludge.

Sludge sample	Days 0	19	32
Total sludge	4×10^4	7×10^3	2×10^2
Sludge supernatant	3×10^3	2×10^1	0

Table 20. Number of fecal coliforms found per ml of digested sludge incubated on a rotary shaker under aerobiosis.

Additions or treatment done to the digested sludge	Sampling time (hours)	
	0	24
None	25×10^2	20×10^2
Escherichia coli added	25×10^6	41×10^2
Autoclaved and *E. coli* added	26×10^6	0

Table 21. Toxicity of the digested sludge toward *Escherichia coli* as determined by the MFC technique.

Toxic sludge	Non-toxic sludge
Autoclaved	Boiled
Liquid phase (autoclaved or non-autoclaved)	Dried at room temperature and resuspended with water
	Solid phase resuspended with a 1 percent NaCl solution and autoclaved or non-autoclaved
	Aerated for a few days and autoclaved
	Some fresh batches of sludge, autoclaved

the question is raised as to whether the organisms found in the digested sludge by the MFC technique are truly of the fecal coliform groups. Short of serological tagging, the IMViC test and the elevated temperature (EC) method, as a confirmatory test from positive presumptive tubes, are the only other two ways to identify fecal coliforms. Both techniques have indicated the presence of fecal coliforms in the liquid digested sludge. On the basis of the IMViC test, Fuller and Litsky have shown that the digested sludge harbours a population of fecal coliforms, in the order of 10^5 cells per milliliter (12).

The fate of E. coli in autoclaved digested sludge was further investigated. The enumeration of E. coli was performed both by the MFC technique and on eosin methylene-blue agar pour plates (EMB method). Results obtained from the two methods differed. Only rarely did the EMB plates indicate a die-off of E. coli; with the majority of the cases, the decrease in the number of typical colonies was offset by the appearance of atypical colonies, indicating an overall development of E. coli in the autoclaved digested sludge.

Various treatments were performed on the digested sludge in order to determine for the nature of its apparent toxicity toward E. coli as determined by the MFC technique (Table 21). Although the digested sludges were always collected at the same sanitary plant (Calumet, Chicago), a few batches turned out to be devoid of toxicity. This fact rules out many factors which otherwise would have been considered as possible causative agents for the toxicity: the low redox potential, the lack of oxygen, the saturation of the sludge liquid phase with carbon dioxide, methane, and possibly the presence of sulfides.

Reversal of the bactericidal action was achieved by the addition to the digested sludge of 5 gm/l bacto-tryptone (Difco). At 2.5 g/l, the bacto-tryptone had no effect. The energy and usual growth factors brought with tryptone could not be accounted for the reversal since the addition of lactose and/or yeast-extract (Difco) had no effect on the toxicity. Addition of DL-tryptophane and L-tyrosine, however, reduced somewhat the rate of E. coli disappearance although not as potently as tryptone (Difco) did. The addition of tryptone, tryptophane, or tyrosine did not affect the pH of the sludge, which during the incubation in contact with the air, ranged from 7.0 to 8.9 as commanded most likely by the carbonate-bicarbonate buffer. In relation to these facts, the disappearance of Salmonella typhosa in the sludge has been attributed to nutritional deficiency in tryptophane (13).

Reversal of the toxicity by biochemical compounds gives much credit to the assumption that this toxicity is biochemical in nature rather than physical. In view of the low organic carbon content of the sludge supernatant, these compounds ought to act at very low concentrations. Volatile fatty acids have been held responsible for the exclusion of E. coli and salmonellas in the rumen of bovines. However, their range of bacteriostatic and bacteriolytic action is limited to pH values below 7.0 and to concentrations above 60 μ moles per ml, both conditions which are not prevalent in the sludge. Moreover, there are evidences that the elimination of salmonellas and E. coli from bovine rumen cannot be accounted for by volatile fatty acids only (14). The presence of antibiotics in the digested sludge could not be detected by the diffusion techniques on a glucose-yeast extract agar performed under aerobiosis and anaerobiosis with E. coli as an indicator.

Fecal Coliforms in Soils Irrigated With Liquid Digested Sludge

The behavior of the sludge fecal coliforms as determined by the MFC technique has been examined under various environmental conditions. A gradual decrease of the fecal coliform population was observed: 1. in the sludge cake which develops on a soil surface amended with digested sludge (Table 22); 2. in the runoff water samples obtained from sludge-amended fields and stored at room temperature. These results are in agreement with those already obtained from various works done on the behavior of fecal coliforms and *E. coli* in digested sludge, water and soil samples (12, 15, 16).

Routine analyses for fecal coliform densities have been performed on the drain and runoff water samples which originated from the digested sludge amended plots at the Northeast Agronomy Research Center. The data, so far accumulated, indicate that the sandy soils (Plainfield) are performing as expected, i.e. no fecal coliforms detected in drain waters. However, the drain water from many of the Blount and Elliot plots was high in fecal coliform counts. This was totally unexpected and may have resulted from contamination through cracks in the soil of some plots. Following proper settling and compaction of the soil, the plots should produce fecal coliform free drain water. Monitoring of the drain waters is being continued.

Table 22. Disappearance of fecal coliforms in the sludge cake covering a soil surface.

Days after sludge application	No. of fecal coliforms per gm sludge cake (dry weight)
1	3,680,000
2	655,000
3	590,000
5	45,000
7	30,000
12	700

Influence of Soil Moisture on Fecal Coliform Survival

Investigations conducted by Dr. R. I. Dick and assistants, Department of Civil Engineering.

Although appreciable reduction in pathogenic organism density occurs in anaerobic digesters, complete removal cannot be anticipated and land disposal systems must be operated with consideration to the effect of the organisms in the environment. Some of the factors which influence the rate of die-off of enteric pathogens in soil include temperature, the level of organic material in the soil, pH, and the moisture content of the soil. The purpose of this study was to evaluate the effect of the moisture content of Plainfield sand on survival of fecal coliforms.

The soil used in these experiments was conditioned by adding digested sludge over a period of 9 days. Varying amounts of rain water were added to sludge-conditioned soil samples to give moisture levels of 5, 10, 15 and 20 percent by weight. These samples, along with a sample of sludge not mixed into soil, were then monitored for a period of about a month to observe the rate of disappearance of the fecal coliforms originating from the sludge.

With sludge-soil mixtures of 5, 10 and 15 percent moisture, initial sharp increases (up to 100 fold) in the fecal coliform population occurred.

No initial growth is exhibited in the sample maintained at 20 percent moisture. This was due to the fact that at this high moisture concentration the saturation capacity of the soil was exceeded. Essentially, anaerobic conditions were maintained as evidenced by the appearance of black sulfide precipitates. Similarly, no initial growth of fecal coliforms occurred in sludge.

Following the initial period of growth, die-off of fecal coliforms in sludge and in soil containing sludge followed first order kinetics. That is, a constant fraction of remaining organisms died during each time interval.

The only exception to this was for the 5 percent moisture condition where the die-off rate decreased with time.

Table 23 shows the average percentage die-off of fecal coliforms after 30 days. The data show that at 5 percent moisture the fecal coliforms were best able to survive. This is surprising as it might be expected that a higher rate of die-off would occur at lower moisture concentrations due to the unavailability of moisture. Perhaps the "aeration porosity limit" (17) at which the most favorable balance between moisture concentration and aeration exists is near 5 percent moisture for the conditions of this study.

Table 23. Survival of Fecal Coliforms in Soil and Sludge.

Moisture Content (Percent)	Die-off of Average Fecal Coliforms in 30 Days (Percent)
5	72.5
10	99.9
15	99.6
20	96.6
Sludge	99.9

CONCLUSIONS

Established Facilities

The main field research facility - the instrumented plots at the Northeast Agronomy Research Center (NEARC) which was specified in the original proposal - has been completed. Since spring 1969, the sampling equipment has been operational. The soils have been settling since Spring 1968. After this period of equilibration, runoff and drain water should be more representative of undisturbed field conditions.

Crop yield responses to sludge addition have been obtained from undisturbed field plots with corn, soybeans and kenaf.

The lysimeter facility on the Agronomy South Farm has now had a maximum sludge loading of 27 inches over a three year period. Soybeans, grain sorghum, corn and Reed canary grass have been grown on them. Chemical constituents in the crops, soils and drain water have been monitored.

Methodology and instrumentation for routine analysis of samples from the field facilities have been established. Meteorological equipment has been installed at the NEARC instrumented plots.

Results

1. It is easy to advance arguments either to minimize or maximize the dangers of sludge irrigation of soils in respect to public health considerations. Known cases of digested sludge application over agricultural fields have been recorded for many years in several countries. Thousands of individuals in these fields and in waste treatment plants have handled the material without succumbing to disease of sludge origin. On the other hand, the very fact that digested sludge harbors a large population of fecal coliforms renders it

suspect as a potential vector of pathogens. Our studies have shown that the sludge fecal coliform population decreases following application to the soil or upon aging after removal from the digester. Lagooning of digested sludge prior to application would serve the purpose of reducing the fecal coliform population.

2. Nitrogen contained in digested sludge is the most immediate limiting factor to rates of application. Our data indicates that about 2 inches of sludge would satisfy the nitrogen needs of non-leguminous crop without producing excessive nitrate in percolated water. In the interest of higher loading rates, reduction of the nitrogen content of sludge would be desirable.

3. Heavy metals are an ubiquitous constituent of digested sludge and they occur usually in the solid phase. After application to soil, they remain in the plow layer with the sludge residue. Solubilization is negligible in soil of neutral or higher pH. Plant uptake Zn, Mn,and Fe has generally been enhanced by sludge application. There is evidence that the uptake is not a result of direct metal addition with the sludge, but an induced mobility of the metals native to the soil. Plants from the South Farm lysimeters have shown no uptake of Cd or Cr and only occasional uptake of Pb.

4. Digested sludge has been shown to be an effective source of nitrogen, phosphorus, and micronutrients. Crop response to the water content has also been observed.

5. Sludge residue decreases the bulk density of the soil. Grease contained in sludge has not proven to be a problem in clogging soils. Organic carbon has accumulated in amended soils, but has presented no observable problem.

6. The rate of infiltration of digested sludge is low regardless of soil type. Thus, on sloping land special precautions should be taken to control

the distribution of sludge applied to the soil surface. After drying, digested sludge does not affect the infiltration of water into the soil surface. Shallow ponding of sludge in the furrow for even a few days does no apparent harm to plants. Where adequate drainage exists or is induced, salt accumulation in humid region soils is not expected to be a problem.

7. Seed germination is inhibited by fresh digested sludge.

8. Our observations indicate that properly digested sludge will produce no offensive odors after application to soil.

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Northeastern Illinois Research Center, Elwood

Mr. R. Louis Judson, Associate Agronomist

Mr. Raymond J. Keigher, Technician

Department of Agronomy

Mrs. Glee Blossey, Laboratory Technician

Mrs. Barbara Kraybill, Laboratory Technician

Mr. Sobhan-Ardakani, Research Assistant

Mr. Waldemar Miodeszewski, Research Assistant

Mr. Zenon Lis, Research Assistant

Department of Civil Engineering

Mr. Dick Gosset, Research Assistant

Mr. Sze-Ern Kuo, Research Assistant

Mr. James Schwing, Research Assistant

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