Agricultural Utilization of Sewage Sludge

A Twenty Year Study at the Rosemount Agricultural Experiment Station University of Minnesota

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UNIVERSITY OF MINNESOTA

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St. Paul, Minnesota

Cooperators

This is a cooperative summary report of research concerning agricultural utilization of sewage sludge. The cooperating agencies are:

University of Minnesota-Department of Soil, Water and Climate

Agricultural Research Service, USDA

Metropolitan Council Wastewater Services (formerly Metropolitan Waste Control Commission of Minneapolis/St. Paul)

Minnesota Agricultural Experiment Station

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Executive Summary

The Rosemount Watershed study was initiated in 1973 on land of the University of Minnesota's Agricultural Experiment Station in Rosemount, Minnesota. The project was run by the USDA-Agricultural Research Service from 1974 to 1985. It was then run by the University of Minnesota Department of Soil, Water and Climate (formerly the Soil Science Department) from 1986 to 1993. The primary goal of the study was to increase knowledge of the effects of liquid sewage sludge on surface and ground water quality, crop yield and quality, and soils over a period of 20 years.

The long-term study at the Rosemount Watershed is a good example of a detailed analysis of sludge application to land. Sludge was applied at rates to meet the nitrogen (N) needs of high producing corn *(Zea mays L.)* and reed canarygrass *(Phalaris arundinacea L.)*. Control treatments receiving commercial fertilizers without sludge were also included.

The 20 years of research have shown there are many benefits in using sludge as a plant nutrient source. Historically, yields on the sludge-applied land have been slightly better than on the fertilized control areas within the watershed. Reed canarygrass yields averaged nearly 11 Mg ha^{-1} (4.9 T A^{-1}) and corn grain 8.6 Mg ha^{-1} (151 bu A^{-1}). Grass was harvested for hay three times per year and corn for grain or ensilage.

Information was also gathered on the amount of nutrients removed by the crops. In the period from 1973-1984, reed canarygrass was more efficient than corn in removing N, phosphorus (P), and potassium (K) from sludge-treated soil. This indicated that the choice of crop is an important consideration in the land application of sludge.

During the course of the study the variety of corn planted changed with time. This affected the removal rates of N, P, and K. Different corn varieties removed N, P, K and metals at different rates. However, little difference was found between tissue concentrations of N, P, and K in crops grown on sludge versus control areas, when averaged over the life of the experiment. In earlier years of the study, commercial K fertilizers were added to the sludge areas because very low levels of K were provided in the sludge. In later years, based on soil test analyses, no additional K was applied to the sludge terraces.

Large amounts of N and P supplied by sludge did not adversely affect crop yields by creating imbalances of nutrients within the plants. In addition, sludge supplied many of the other nutrients required for plant growth. Because the amounts of N and P removed from sludge and fertilizer control treatments were nearly equal for the corn crop, lower amounts of sludge were applied to the corn area for the 1980 growing season and subsequent years. The lower application rates increased the efficiency of nutrient use while continuing to meet the nutrient needs of the crop.

This study also answered questions concerning sludge application and its effect on the environment. Trace metal levels found in corn tis-

sues grown in sludge areas were not significantly different from the low levels found in corn plants grown with commercial fertilizers, except for zinc (Zn), which was found in slightly elevated concentrations in the corn stover. Corn used the trace elements available in the native soil (or from commercial fertilizers), but did not take up excessive amounts of these elements when they were added in sludge. Only copper (Cu) and chromium (Cr) levels on grass tissues from sludge treatments were slightly elevated over that of grass supplied by commercial fertilizer treatments, possibly a result of surface contamination from rain splash erosion.

From a water quality viewpoint, the Rosemount Watershed study showed that sludges can be applied in an environmentally safe manner. Soil erosion was reduced and surface water quality was protected by constructing terraces on the sloping ground.

More nutrients moved in surface runoff from grass terraces than from corn areas for two reasons. First, the fertilizer and sludge were not incorporated into the soil on the grass areas, so surface runoff had more contact with these materials. Second, grass tissues breakdown over winter losing their nutrients to snow melt runoff. Winter spreading of sludge on sloped land should be discouraged because significant increases in nutrient and trace metal contents were found in snow melt runoff.

It was shown that excessive fertilizer and sludge application rates affected the nitrate concentration in shallow ground water. Nitrate levels peaked in 1981 to 1984 and decreased steadily once N application rates were reduced.

The Rosemount Watershed site has a slowly permeable layer of glacial till 5 to 19 feet below the soil surface. This prevents the nitrate from reaching the ground water aquifer. At other sites where such a slowly permeable layer in these silt loam soils does not exist, excess nitrate could directly affect ground water quality. This points to the importance of monitoring the amount of nutrients, particularly N, applied to sludge-treated sites. Balancing the amount of N applied in the sludge with the amount needed for plant growth given specific soils and crops is an important management technique.

The 1993 cropping season culminated 19 years (1974 to 1992) of sewage sludge application and 20 years (1974 to 1993) of environmental monitoring at the Rosemount Watershed. Sludge was applied to the terraces every year except two. These 20 years of data helped determine the long-term effects of nutrient and metal additions from sewage sludge applications on crop production. Extensive soil, plant, and water sampling and analyses at this site have provided results to show that long-term sludge utilization on agricultural land can be accomplished in an environmentally safe and effective manner.

The long duration of the Rosemount Watershed study represents a unique and valuable site, possibly the only one in the United States with such a detailed database. Continual collaboration among the University of Minnesota, U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS), and the Metropolitan Council Wastewater Services (formerly Metropolitan Waste Control Commission of Minneapolis/St. Paul) is a prime example of the positive relationship involved in agricultural utilization of sewage sludge.

Project Background

Finding environmentally acceptable, socially responsible, and economically feasible ways of using municipal sewage sludge has received much attention from both research and regulatory agencies, as well as the general public. Daily processing of large quantities of sewage sludge under increasingly rigid water and air quality standards, has forced municipal officials, environmental engineers, and wastewater treatment operators to look beyond the conventional systems of treatment and disposal (i.e., incineration, landfilling, and ocean dumping). Land application of sewage sludge and effluent is an alternative that provides a means of returning the materials to a natural cycle that could be agriculturally useful and environmentally sound.

The nationwide environmental movement in the early 1970's heightened our concerns about the need for proper disposal of sewage sludges. From 1973 to 1993, intense worldwide research efforts were conducted to better understand the reaction of sludge constituents in soils. A large part of this research effort has been due to the commitment and support of the U. S. Environmental Protection Agency (USEPA). These research efforts have generated a credible technical database that has led to the development of comprehensive sludge management regulations. As a result, the USEPA can now use regulations that set limits based on risk to human health and the environment (USEPA, 1993).

The USDA and land-grant agricultural universities must also be credited for their research and progress in utilization of sludge on land. Much of the leadership and financial support for the Rosemount Watershed study came from these organizations.

In 1973, when the Rosemount Watershed study was begun, most researchers were in agreement that sludges could be useful soil conditioners and sources of plant nutrients (N, P, and micronutrients), but information was needed to properly assess potential long-term hazards associated with its application to land. The potential for nitrate leaching, food chain transfer of toxic chemicals, pathogens, and phytotoxicity of trace elements were the primary concerns.

BACKGROUND ON SLUDGE

More than $2 billion are spent annually treating and disposing of nearly 5.4 million dry tons of municipal sewage sludge in the United States (Jewell, 1994). Depending upon the treatment alternative used, sludge generation rates are equivalent to an average production of 47 lbs (dry) $\text{person}^{-1}\ \text{yr}^{-1}$ (21.4 kg $\text{person}^{-1}\ \text{yr}^{-1}$). The quantities of sewage sludge applied to land in the United States has steadily increased over the last two decades (Lue-Hing et al., 1994). For

Table 1. State sludge management practices by volume generated (by percent).[†]

State	*Composting*	*Land Application*	*Landfilling*	*Incineration*	*Ocean Dumping*	*Monofill*	*Lagoon/ Storage*	*Other*
Arkansas	—	64	20	2	—	4	10	—
Colorado	2	96	1	1	—	—	—	—
Connecticut	3	4	25	68	—	—	—	—
Florida	0.4	73.8	17.4	8.4	—	—	—	—
Indiana	1	40	20	17	—	2	20	0.2
Maine[‡] (solids-cu. yd.)	15.8	29.5	3.8	—	—	43	—	7.9
Mississippi	—	2	8	—	—	—	90	—
Missouri	—	37	6	53	—	—	4	—
Nebraska	<1	35	24	<1	—	—	40	—
New Jersey	—	10[§]	—[¶]	22	58	—	2	8[‡‡]
New York	4	1	26	27	40	—	1	1
North Carolina	5	40	40[#]	2	—	3	10	—
Ohio	6	45.7	3.9	43.2	—	—	0.2	1
Oregon	4.5	90	0.5	5	—	—	—	—
Rhode Island	9	—	16	58	—	17	—	—
Tennessee	5	45	30	5	—	5	10	—
Utah	—	5	30	—	—	5	60	—
Virginia	14	35	16	33	—	—	2	—
Washington	4.5	72.2	5.5[††]	13.2	—	—	(see[††])	4.7
Wyoming	—	30	13	—	—	—	57	—

Totals may reflect rounding errors.

[†] Source: Goldstein (1991). Based on data from a 1990 survey of state sludge management officials; 21 states responded to the survey.

[‡] Maine reports that in liquids (gallons), 96.2% of sludge generated in the state is land applied.

[§] This 10% amount includes composting.

[¶] New Jersey banned landfilling of sludge except in emergency situations.

[#] North Carolina banned landfilling of sludge in active cells; this figure represents use of sludge in 2-foot cover.

[††] This 5.5% amount represents both landfilling and storage in lagoons.

[‡‡] Sewage sludge taken to out of state landfills in Illinois.

example, 20% of the total sludge produced in the United States in 1972 went to land application while 40% went to landfills. In 1989, about 33% of the total sludge produced went to land application as compared to 34% to landfills. Data from a 1990 survey of state sludge management officials shows this trend continuing (Table 1).

Treatment of municipal wastewater prior to discharge of relatively clean effluent involves a variety of processes designed to remove contaminants and pollutants. The residual material captured in the wastewater treatment process is a dilute suspension of solids called sewage sludge. This sludge may be defined as a semi-liquid waste having a suspended solids content of at least 2500 mg L^{-1} (i.e., 0.25% dry solids) which flows, can be pumped, and exhibits delayed settling characteristics (Galloway and Jacobs, 1977).

The chemical composition of sludges may vary considerably between sewage treatment plants and within a single treatment plant (Sommers et al., 1976). Composition of sewage sludges,particularly trace elements, has also changed over time (Table 2). Tables 3 and 4 provide a comparison of compositions of sewage sludge, soil, and other materials.

Municipal sludges commonly contain an inorganic mineral fraction and a combustible (i.e., organic matter) fraction. Water is usually 90%

or more of the weight. Water content is a function of the sludge handling and dewatering processes used.

BACKGROUND ON SLUDGE AS A CROP NUTRIENT SOURCE

Sludges contain many chemical elements in both mineral and organic forms. Of the principal constituents, N, P, and organic carbon (C) are the most important in promoting plant growth and good soil physical conditions. Although K is important for crop growth, it is present in sludge only in small quantities. Though sludges are not balanced fertilizers, the essential plant nutrients in sludges can have considerable value (Galloway and Jacobs, 1977).

Table 2. Composition of trace elements in sewage sludge over time.

Characteristic	*1977†*	*1988‡*
	mg kg^{-1}	
Zn	2,790	1,202
Cu	1,210	741
Mn	380	—
Cd	110	7
As	43	0.009
Cr	2,620	119
Pb	1,360	134
Hg	733	5
Ni	320	43
B	77	—

† Sommers (1977). Represents mean values for 250 samples from 150 treatment plants.

‡ USEPA (1990). Represents mean values for the entire nation based on the sampling of 208 facilities.

BACKGROUND ON NITROGEN

Application rates of sewage sludges for use on croplands have generally been proposed on the basis of an "agronomic rate" (USEPA, 1993). This is the amount of sludge that will supply enough N for commercial production while minimizing the amount of sludge-borne N that will pass below the root zone of the crop into ground water. Sewage sludges typically contain from 1 to 6% total N (Keeney et al., 1975; Sommers, 1977), but concentrations may range from <1 to >170 g N kg^{-1} of sludge on a dry weight basis (Clapp et al., 1986; USEPA, 1992).

Sewage sludge contains both organic and inorganic forms of N. Both forms must be considered when determining the proper amount of

Table 3. Chemical characteristics of sewage sludge, MSW compost, animal manure, soil, etc.

Characteristics	*Sandy Soils†*	*Silty/Loam Soil†*	*Sewage Sludge‡*	*Phosphate Fertilizers§*	*Nitrogen Fertilizers§*	*MSW Compost Minnesota¶*	*Dairy Manure#*	*Swine Manure#*	*Chicken Manure#*
					mean				
pH	5.9	5.9	— ††	—	—	7.1	7.0	7.5	6.9
EC (dS M^{-1})	5.7	12.7	—	—	—	20.5	—	—	—
					%				
Organic matter	0.7	5.5	30.4	—	—	18.5	—	—	—
N	0.03	0.4	3.3	0–30	4–46	1.24	5.2	6.2	13.1
P	0.02	0.10	2.3	3.5–27	0–55	3.0	1.1	2.1	4.7
K	1.9	1.9	0.3	0–45	0–44	6.93	3.4	3.5	4.7
Ca	1.2	3.0	3.9	0–36	0–54	3.12	1.9	3.9	20.3
Mg	0.1	2.0	0.4	0–14	0–7	0.4	0.8	0.8	2.2
S	0.06	0.12	1.1	0–72	0–20	0.5	0.6	0.9	2.2
Na	0.10	0.50	0.2	—	—	0.5	0.6	0.8	1.6

† Tisdale et al. (1993)

‡ USEPA (1990)

§ Tisdale et al. (1985)

¶ Soil Science Dept. (1994)

\# ASAE Standards (1990)

†† Information was not available.

Table 4. Total concentration of trace elements in sewage sludge, MSW compost, animal manure, soil, etc.

Characteristics	*Sandy Soils*†	*Silty/Loam Soil*†	*Organic Soils*†	*Sewage Sludge*‡	*Phosphate Fertilizers*§	*Nitrogen Fertilizers*§	*MSW Compost Minnesota*§	*Dairy Manure*¶	*Swine Manure*¶	*Chicken Manure*¶
	Range (Mean)	*Range (Mean)*	*Range (Mean)*	*Mean*	*Range*	*Range*	*Range (Mean)*	*Mean*	*Mean*	*Mean*
					mg kg^{-1}					
Zn	3.5-220 (45)	9-362 (60)	5-250 (50)	1,202	50-1,450	1-42	182-1750 (902)	20.9	59.5	296.9
Cu	1-70 (13)	4-100 (23)	1-113 (16)	741	1-300	<1-15	38-1360 (471)	11.6	14.3	13.0
Mn	7-2,000 (270)	45-9,200 (525)	7-2,200 (465)	—#	40-2,000	—	—	22.1	22.6	95.3
Cd	0.01-27 (0.37)	0.08-1.61 (0.45)	0.19-2.2 (0.78)	6.9	0.1-170	0.05-8.5	0.79-22.9 (7.6)	0.03	0.32	0.59
As	<0.1-30 (4.4)	1.3-27 (8.4)	<0.1-66.5 (9.3)	.009	2-1,200	2.2-120	—	0.88	—	0.66
Cr	1.4-530 (47)	4-1,100 (51)	1-100 (12)	119	66-245	3.2-19	10.4-98.5 (40.0)	20.0	—	4.9
Pb	2.3-70 (22)	1.5-70 (28)	1.5-176 (44)	134	7-225	2-27	59-2490 (496)	2.1	1.0	11.5
Hg	0.008-0.7 (0.05)	0.01-1.1 (0.1)	0.04-1.11 (0.26)	5.2	0.01-1.2	0.3-2.9	0.52-10.7 (4.1)	0.05	—	<0.04
Ni	1-110 (13)	3-110 (26)	0.2-119 (12)	42.7	7-38	7-34	10.3-119.0 (43.4)	3.3	—	3.9
B	1-134 (22)	<1-128 (40)	4-100 (25)	—	5-115	—	—	8.2	36.9	28.1

† Kabata-Pendias and Pendias(1992)
‡ USEPA (1990)
§ Soil Science Department (1994)
¶ ASAE Standards (1990)
\# Information not available

sludge to apply to agricultural land. Most of the N in sewage sludge is in organic forms.

N in organic forms is unavailable to plants and is not lost following surface application. In soil, organic N must undergo mineralization (i.e., conversion from organic to inorganic forms) before it can be used by plants. Mineralization of sludge organic N depends on a variety of factors, including the type of sewage sludge treatment process and conditions in the soil following sludge application. Consequently, it is difficult to predict precise N mineralization rates for the various climatic regions, but available data indicate that from 10 to 40% of the organic N can be mineralized during the year of application (Fox and Axley, 1985; USEPA, 1976; USEPA, 1983). Lesser percentages of the remaining N are mineralized in succeeding years. Through this mineralization process, sewage sludge additions to soils can markedly increase the total soil N content (Clapp et al., 1986).

The primary inorganic form of sludge N is ammonium-N (NH_4^+-N), representing up to 30% of the total N contained in anaerobically digested sludge. A small amount of N in sludge exists as nitrate-N (NO_3-N). If liquid sludges are applied directly to the soil surface, some of the NH_4^+-N is lost by volatilization in the form of ammonia (NH_3) as the sludge dries. Incorporation of liquid sludges below the soil surface by injection or by incorporation immediately following application minimizes this effect. In the soil, positively charged NH_4^+-N is retained by the soil cation exchange capacity, but negatively charged NO_3-N is not. Both NH_4^+-N and NO_3-N are taken up and utilized by plants.

NO_3-N is the primary form of N that leaches below the root zone and may eventually reach ground water supplies. High NO_3-N concentrations in drinking water are toxic to humans and livestock. For this reason, sludges must be applied in amounts that do not exceed the crop's N needs. Nitrate leaching below the root zone of sludge-amended soils occurs only when two conditions are met. The first is that excess nitrates be present either from mineralization or direct application, and second, that water leach through the soil profile to move these nitrates deeper. If sludge is applied at agronomic rates, organic N is gradually converted to inorganic N and subsequently taken up by the crop. Consequently, sludge-borne N is less likely to contaminate ground water than chemical N fertilizers (Chaney, 1990).

BACKGROUND ON PHOSPHORUS

Many sewage treatment processes remove phosphates from wastewater while concentrating them in the sludge as an insoluble residue (Kirkham, 1974). Sewage sludges typically contain from 0.1 to 2% total P, but concentrations may range from <0.01 to >90 g P kg^{-1} of sludge on a dry weight basis (USEPA, 1992). Sewage sludge contains both organic and inorganic forms of P, but unlike N, the majority of sludge P (70 to 90%) is inorganic (Wolf and Baker, 1985). When sewage sludge is applied to land, soil chemical adsorption and precipitation processes decrease dissolved P to low levels in the soil solution. In soils that receive excessive fertilizer, P exists as discrete particles, as well as coatings on other particles. P-rich materials in soils tend to be amorphous mixtures of aluminum, silica, and P (Pierzynski et al., 1990). Low concentrations of P in soil water result in very little downward movement during infiltration of rain or irrigation. P levels in drainage water from sludge-treated soils are usually less than 1 ppm.

When sludge is applied at rates sufficient to satisfy the N requirements of crops, the amount of added P will frequently exceed plant requirements. Since P is relatively insoluble and immobile in soil, when added as fertilizer, it tends to accumulate on the soil surface. Erosion of P-loaded sediments into surface water may lead to eutrophication. However, sewage sludge is usually incorporated into soil by injection or tillage, thereby minimizing transport of sludge-derived P to surface waters (Basta, 1995).

BACKGROUND ON ORGANIC MATTER

Unlike fresh plant and animal residues that have been incorporated into the soil, most sewage sludges have been through a biological treatment, where partial decomposition and stabilization have occurred. Therefore, the rate of decomposition in soil may be slower than most fresh organic residues, resulting in longer lasting increases in the levels of soil organic matter (Hinesly et al., 1982) and shifts in the composition of soil organics. Hinesly (1982) reported that 136 dry T A^{-1} of anaerobically digested sludge incrementally applied during four years on a silt loam soil increased its organic C content from 1.2 to 2.4% in the 6 surface inches (15 cm). The presence of organic matter influences many physical, chemical, and biological processes in the soil.

Sludge organic matter additions may also be a valuable soil conditioner. The addition of sludge to a fine-textured clay soil can make the soil less compact and more friable. This increases the amount of pore space available for root growth, and for the entry of water and air into the soil. In coarse-textured sandy soil, sludge can increase the water-holding capacity of the soil, reduce irrigation frequency, and provide chemical sites for nutrient exchange and adsorption.

BACKGROUND ON TRACE FERTILIZER ELEMENTS

Sewage sludge contains significant amounts of trace elements necessary for plant growth, such as boron (B), manganese (Mn), copper (Cu), molybdenum (Mo), and zinc (Zn). The exact ratio of these nutrients will not be that of a well-balanced formulated fertilizer. Nevertheless, many agronomic crops respond favorably to these nutrients in sludge.

With iron (Fe) deficient soils, sludge is a beneficial Fe fertilizer that simply cannot be replaced with any chemical fertilizer (Chaney, 1990). Zn and Cu can be deficient in soils that have been used to produce crops for many decades. Sludge is a superior way to apply Zn or Cu rather than applying metallic salts. Because hydrated lime is sometimes used as a conditioning agent to aid in sludge dewatering, some sludges also contain enough lime (or lime equivalent) to provide cost savings to farmers who need to increase the pH of their soils.

Summary benefits of land application of sludge

- Disposal costs are usually lower than landfilling or incineration.
- Beneficial nutrients are "recycled."
- Farmers' costs may be decreased by reducing commercial fertilizer use.
- Land is used beneficially.

BACKGROUND ON PROBLEM CONSTITUENTS OF SEWAGE SLUDGE

There has been much concern that utilization of sewage sludge be properly regulated because sludge typically contains high amounts of trace elements, toxic organics and pathogens. This doesn't mean, however, that sludge cannot be a valuable resource. The recent (last 10 years) advent of pretreatment of industrial wastes before they are received by wastewater treatment facilities has reduced the concern for problem constituents of sludge. Some cities' sludges have always been low in metals, but others were extremely high before sludge pretreatment regulations were introduced. In most cities, pretreatment by industry addressed most of the problems of sludge contamination by metals at levels unacceptable to agriculture (Chaney, 1990).

BACKGROUND ON TRACE ELEMENTS

Sewage sludge contains an abundance of trace elements necessary for plant growth such as Cu, Fe, Mn, Zn, and sodium (Na), as well as some not essential for plant nutrition [i.e., cadmium (Cd), chromium (Cr), mercury (Hg), nickel (Ni), and lead (Pb)]. After application to soil, trace elements tend to remain in the plow layer, along with other sludge constituents.

The major portion of trace elements are adsorbed on inorganic soil constituents, complexed with insoluble organic matter, or precipitated as pure or mixed solids (Shuman, 1991). Only a small fraction of the total concentrations in soil is available for plant uptake. Therefore, rather than total amounts of sludge-derived trace elements in soils, availability is of primary concern (Kirkham, 1974). Available trace elements are often assessed by calibrated chemical tests and/or by field trials for the uptake of elements by growing crops.

Risks to the feed and food chain from sludge-applied trace elements have been intensively examined during the last 25 years. A Soil-Plant Barrier was described by which sludge, soil and plant chemistry prevents risk to animals from nearly all sludge-applied elements mixed in soil. Some elements are so insoluble or so strongly adsorbed to soil plant roots or sludge organic matter that they are not translocated into edible plant parts (i.e., Pb and Hg) (Chaney, 1989).

Of the elements that are taken up by plants from sludge-treated soils, some can reduce the yield or even kill crops. This phytotoxicity occurs when sludge quality is poor (a high concentration of trace elements) and long-

Table 5. Maximum tolerable levels of dietary minerals for livestock in comparison with forage levels.[†]

Element	Soil-Plant Barrier	Level in Plant Foliage[‡]		Maximum Levels Chronically Tolerated[§]			
		Normal	Phytotoxic	Cattle	Sheep	Swine	Chicken
		$mg\ kg^{-1}$ dry foliage		$mg\ kg^{-1}$ dry diet			
As	yes	0.01-1	3-10	50	50	50	50
B	yes	7-75	75	150	(150)	(150)	(150)
Cd[¶]	Fails	0.1-1	5-700	0.5	0.5	0.5	0.5
Cr^{3+}	yes	0.1-1	20	(3000)	(3000)	(3000)	3000
Co	Fails?	0.01-0.3	25-100	10	10	10	10
Cu	yes	3-20	25-40	100	25	250	300
F	yes?	1-5	—	40	60	150	200
Fe	yes	30-300	—	1000	500	3000	1000
Mn	?	15-150	400-2000	1000	1000	400	2000
Mo	Fails	0.1-3.0	100	10	10	20	100
Ni	yes	0.1-5	50-100	50	(50)	(100)	(300)
Pb[¶]	yes	2-5	—	30	30	30	30
Se	Fails	0.1-2	100	(2)	(2)	2	2
V	yes?	0.1-1	10	50	50	(10)	10
Zn	yes	15-150	500-1500	500	300	1000	1000

[†] Source: Chaney (1990).

[‡] Based on literature summarized by Chaney (1983).

[§] Based on NRC (1980). Continuous long-term feeding of minerals at the maximum tolerable levels may cause adverse effects. Levels in parantheses were estimated (by NRC) by extrapolating between animal species.

[¶] Maximum levels tolerated were based on Cd or Pb in liver, kidney, and bone in foods for humans rather than simple tolerance by the animals.

term sludge applications are made. These conditions only occurred before anyone recognized that sludges were contaminated with excess trace elements (Chaney and Giordano, 1977; Logan and Chaney, 1987). If excessive amounts of Zn, Cu, or Ni are applied to strongly acidic soils, the elements can cause phytotoxicity. However, neither the level of elements in the forage crop, nor the grain, would be high enough to injure livestock or wildlife. Thus, phytotoxicity to plants prevents excessive exposure to animals and the food chain is protected.

There are exceptions to the protections provided by the Soil-Plant Barrier. Selenium (Se) and Mo are easily absorbed by plants when added in high quantities. Fortunately, municipal sewage sludges are not high in these elements. Cd is easily absorbed by crops and reaches levels that are dangerous if improbably large quantities of the crop are consumed for a long period of time (Chaney, 1990). Table 5 summarizes considerations for the trace elements that are considered of concern for land application of sludges. Most elements are of little concern because of the Soil-Plant Barrier. As research is conducted, more and more support is given for the conclusion that low trace element sludges are extremely safe when used in agriculture as a fertilizer and soil conditioner.

BACKGROUND ON TOXIC ORGANICS

Numerous synthetic organic chemicals (i.e., PCB's, CDD's and furans), with a wide range of chemical properties can occur in sewage sludge. The vast majority of sludge-borne toxic organics occur at low concentrations in sludge (Table 6) and are further reduced at least 100 fold during land application (USEPA, 1990). Most toxic organics are so strongly absorbed in the sludge-soil matrix as to have low bioavailabilities to plants. The concentra-

Table 6. Survey results for regulated pollutants in sewage sludge as compared to "503 sludge rule."†

Pollutant	Number of Times Detected	Mean	Minimum	Maximum	Ceiling Amounts USEPA 503 Rule‡
		mg kg^{-1}			
4,4'-DDD	1	0.391	0.391	0.391	
4,4'-DDE	4	0.100	0.030	0.190	
4,4'-DDT	7	0.051	0.015	0.121	
Aldrin	8	0.029	0.019	0.046	—
Arsenic	194	12.390	0.300	315.600	75
Benzene	4	0.098	0.012	0.220	
Benzo(a)pyrene	7	10.785	0.671	24.703	
Beryllium	64	0.660	0.100	3.900	
Bis(2-ethylhexyl)phthalate	189	107.233	0.510	89.129	—
Cadmium	194	65.460	0.700	8220.000	85
Chlordane	1	0.489	0.489	0.489	
Chromium	231	258.515	2.000	3750.000	3000
Copper	239	665.300	6.800	3120.000	4300
Dieldrin	6	0.024	0.013	0.047	
Dimethyl nitrosamine	0	–§	–	–	
Heptachlor	1	0.023	0.023	0.023	
Hexachlorobenzene	0	–	–	–	
Hexachlrobutadiene	0	–	–	–	
Lead	213	195.230	9.400	1670.000	840
Lindane (Gamma-BHC)	2	0.074	0.072	0.076	
Mercury	184	4.120	0.200	47.000	57
Nickel	201	77.010	2.000	976.000	420
PCB-1016	0	–	–	–	
PCB-1221	0	–	–	–	
PCB-1232	0	–	–	–	
PCB-1242	0	–	–	–	
PCB-1248	23	0.740	0.043	5.203	
PCB-1254	13	1.765	0.312	9.347	
PCB-1260	20	0.671	0.031	4.006	
Selenium	163	6.240	0.500	70.000	100
Toxaphene	0	–	–	–	
Trichloroethylene	7	0.848	0.024	3.302	
Zinc	239	1692.760	37.800	68000.000	7500

† Values obtained from the 1990 National Sewage Sludge Survey collected randomly from 209 wastewater treatment plants from all regions of the United States.

‡ USEPA (1993).

§ Indicates that the pollutants were always below detection limit.

tions in the edible portion of food-chain crops are thus very low. These findings, along with other considerations, resulted in toxic organics being unregulated by the "503 sludge rule" with regard to land application (USEPA, 1993) (Table 7). Some have questioned the levels set in the "503 sludge rule" (McBride, 1995).

BACKGROUND ON PATHOGENS

One risk that has received extensive study is the presence and survival of pathogens following land application of sludge (Angle, 1994). Wastewater entering a sewage treatment plant contains a wide variety of pathogenic organisms, including bacteria, viruses, fungi, and parasites. Sewage digestion and treatment helps to eliminate or reduce the pathogen load. The extent of reduction is dependent upon both the type of treatment applied and the type of organisms present.

The length of survival time of pathogens and the waiting period before harvesting a crop on sludge-applied land, if the crop is for human consumption, is an unsettled issue. Survival times for pathogens in soil and on plants are summarized in Table 8. Aerial crops with little chance for contact with soil should probably not be harvested for human consumption for at least one month after the last sludge application; low-growing and subsurface root and tuber crops for human consumption would probably require a six-month waiting period after last application. However, these waiting periods need not apply to the growth of crops for animal feed (Kowal, 1986). The literature to date suggests little danger of bacterial, viral, or protozoan disease to animals grazing on land application sites after a waiting period (Kowal, 1986). Epidemiological studies to date suggest little effect of land application on human disease incidence.

Summary Remarks

On the basis of current knowledge, it appears that the potential health and environmental risks of land application of sewage sludge can be minimized or abated with proper site selection, management and monitoring. As new research information becomes available, the ability to assess and control these risks improves.

Table 7. USEPA 503 sewage sludge rule for ten regulated pollutants.†

Pollutant	Ceiling Concentrations	Cumulative Pollutant Loading Rates	Pollutant Concentrations	Annual Pollutant Loading Rates
	mg kg^{-1}‡	kg ha^{-1}	mg kg^{-1}‡	kg ha^{-1} yr^{-1}
Arsenic	75	41	41	2.0
Cadmium	85	39	39	1.9
Chromium	3000	3000	1200	150
Copper	4300	1500	1500	75
Lead	840	300	300	15
Mercury	57	17	17	0.85
Molybdenum	75	18	18	0.90
Nickel	420	420	420	21
Selenium	100	100	36	5.0
Zinc	7500	2800	2800	140

† Goldstein (1993).
‡ Dry weight basis.

Table 8. Survival times of pathogens on soil and plants.†

	Soil		Plants	
Pathogen	Absolute Maximum	Common Maximum	Absolute Maximum	Common Maximum
Bacteria	1 year	2 months	6 months	1 month
Viruses	6 months	3 months	2 months	1 month
Protozoa	10 days	2 days	5 days	2 days
Helminths	7 years	2 years	5 months	1 month

† Kowal (1986)

The Rosemount Watershed Study

INTRODUCTION

In 1971 the USDA-Agricultural Research Service (USDA-ARS) decided to coordinate their soil structure, tilth, and management activities with new projects involving agricultural utilization of municipal sewage sludge. Early experiences showed that farmers and treatment plant operators were enthusiastic about applying sludge to land, but were desperate for guidelines on rates and methods of application. There was also concern about human safety and contamination of soils and waters.

Plot work concerning the use of sewage sludge as a source of nutrients for crops was started at the University of Minnesota in 1971. It was obvious from the start that the N and P in sludge were readily available to plants and that excellent yields could be obtained. After two years of small plot work, it was determined that a holistic approach to sludge management research on a field scale was needed. The Rosemount Watershed study was designed to provide experimental data on the use of sewage sludge within an entire watershed. The study began in 1973 and was maintained for 20 years.

The Rosemount Watershed study was the longest ongoing liquid sewage sludge research project in Minnesota, and possibly in the United States. Many things currently known about the agricultural utilization of sewage sludge were determined by the research conducted at this site over the two decades. The Rosemount Watershed has been an invaluable resource in demonstrating that crops grown on sludge-amended soils benefit from the plant nutrients in sewage sludge without causing measurable negative effects to humans and the environment.

This report provides a summary of the 20-yr sewage sludge study and the results that were obtained. It addresses the agronomic and environmental issues concerning the application of municipal sewage sludge to agricultural land.

OBJECTIVES

The main objectives of the study were:

- To determine the effects of application of sludge on crop yields, nutrient availability, and nutrient buildup (N, P, K) in plants.
- To determine the effects of sludge application on trace element buildup in soil and the availability to plants.
- To determine the transport of plant nutrients, trace elements, and other constituents in runoff water.
- To determine the effects of application of sludge on the buildup of nutrients and other changes in the soil.

- To implement a soil conservation system for control of runoff and erosion on a steeply sloping soil.
- To determine the transport of chemicals downward through the soil as influenced by sludge application.
- To demonstrate a holistic and practical sludge utilization system on a field scale.

The project was cooperative among a number of state and federal agencies. These agencies were the University of Minnesota, USDA-ARS, the Soil Conservation Service (USDA-SCS), the Metropolitan Sewer Board (subsequently renamed the Metropolitan Waste Control Commission (MWCC) of Minneapolis/St. Paul and then the Metropolitan Council Wastewater Services), the U.S. Environmental Protection Agency (USEPA), the Army Corps of Engineers, the Minnesota Extension Service, and the Minnesota Pollution Control Agency (MPCA). All these agencies contributed substantially in the form of technical and financial support.

SITE LOCATION

A site was chosen at the University of Minnesota's Rosemount Agricultural Experiment Station in southeastern Minnesota (Legal description: NE 1/4 SE 1/4 Section 10, Range 19 West, Township 114 North, Empire Township, Dakota County, Minnesota, USA). The station is located approximately 25 miles southeast of Minneapolis and St. Paul, Minnesota (Fig. 1).

The location is 44° 41' 34" north latitude and 93° 04' 45" west longitude. The site encompasses an entire small watershed (40 acres; 16 hectares) and was chosen because it was available indefinitely and was isolated from surrounding homes and industry. Fig. 2 shows the layout of the watershed subdivided into eight isolated areas by conservation terraces and the associated support facilities at the Rosemount study. These facilities included storage lagoons, electric lines, roads, and a water well. Also shown are permanent sampling stations and wells.

SOILS AND GEOLOGY

A soils and geology investigation was conducted at the site by a soil geomorphologist (King and Finney, 1986). This was to document the earthen materials present in the watershed and interpret the influence of these on subsurface water movement.

GEOLOGIC SEQUENCE

Five borings were made 8.5 to 10.5 m deep (28 to 35 ft) and four more 1.8 to 3.0 m (6 to 10 ft) deep in the watershed area. The youngest sediment found was the surface mantle 1.5 to 6.1 m (5 to 20 ft) thick of wind-deposited silt (loess). Measurements of the underlying glacial till indicated a very high density (low porosity, slow hydraulic conductivity) material. The only exception to the silt-over till sequence is in the main watershed drainageway where a placer of sand and gravel about 2.4 m (8 ft) thick is located about 3 m (10 ft) below the silts, but above the till. Moderately complex slopes in the watershed range from 0 to 12%. Elevation is about 305 m (1000 ft) above mean sea level. Local relief (vertical distance between top and bottom of hills) is about 12 m (40 ft).

WATER MOVEMENT

Water that enters soil and is not stored in the soil or consumed by evapotranspiration percolates down through the silts, but cannot readily enter the dense till. Instead, a portion can flow laterally "downhill" along the silt-till interface contact to the lowest portions of the watershed where it enters the sand placer. Water can remain perched above the dense till and is not able to move directly to the deep ground water aquifer (St. Peter sandstone), which underlies the till, at a depth of 36 to 43 m (120 to 140 ft).

SOIL SERIES

A number of different soils formed in the silty surface mantle were identified in the watershed. These soils form a complex pattern in response to landscape position.

A major soil on the convex hilltops and upper side slopes is the Tallula series (coarse silty, mixed, mesic Typic Hapludoll). This soil has a naturally dark surface horizon with subsurface horizons only slightly different from the buff-colored silty parent material. Subsoil horizons

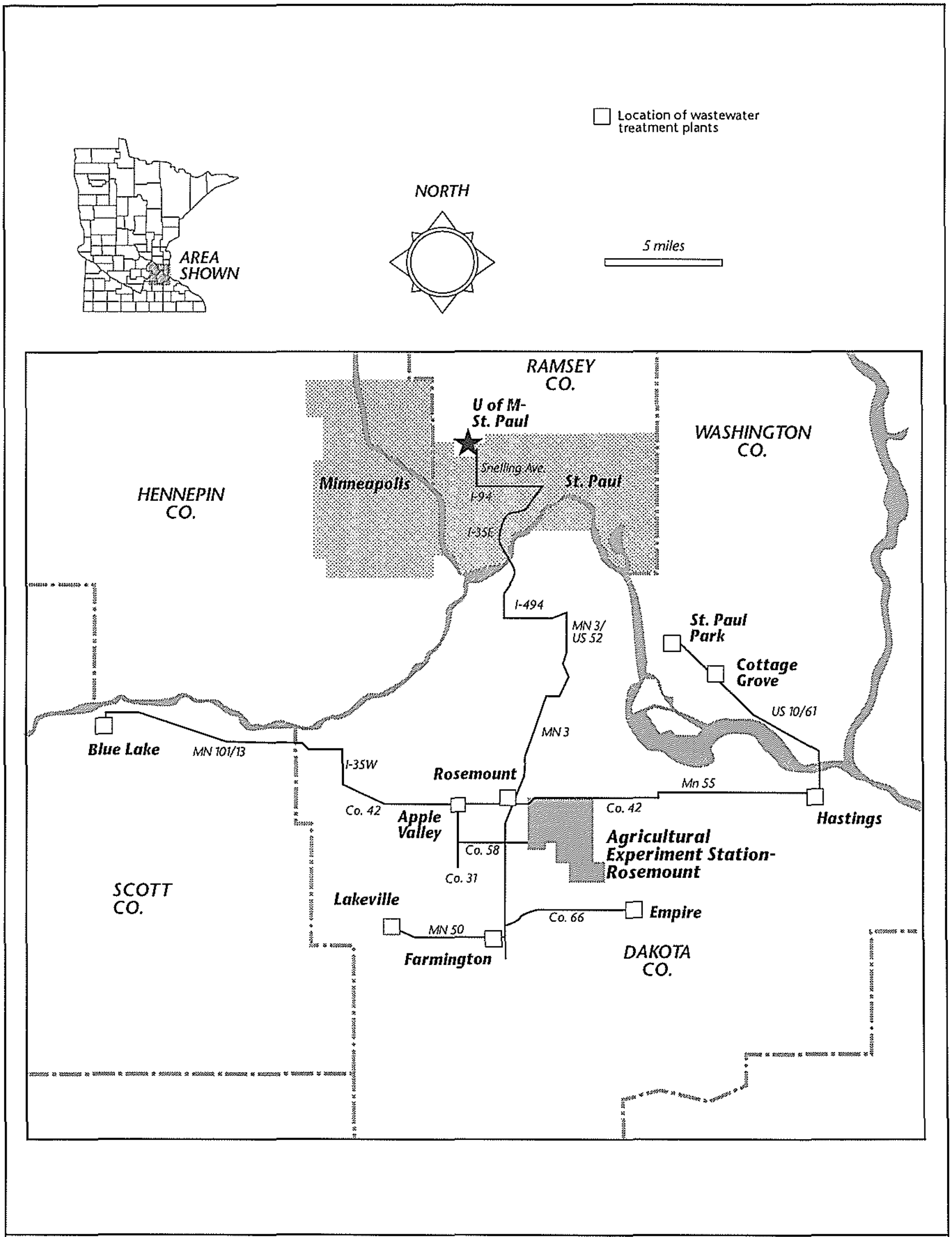

Figure 1. Wastewater treatment plant locations and truck routes to experimental site.

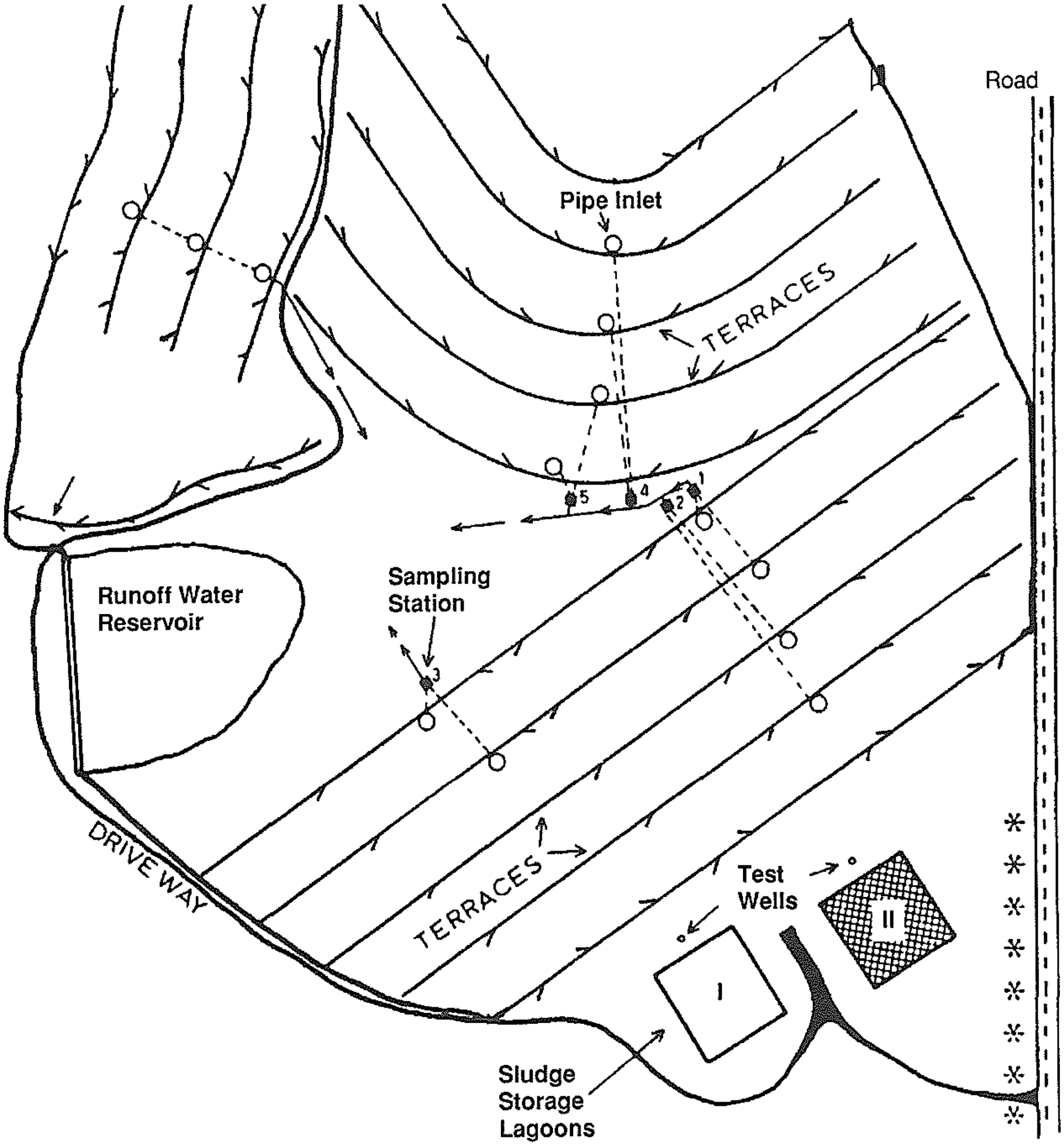

Figure 2. Sewage sludge experiment—general layout.

are redder in color and have better expressed structural aggregates than shallower horizons. On the side slopes, the dominant soil is the Port Byron series (fine silty, mixed, mesic Typic Hapludolls). By virtue of their landscape position, these soils receive additional run-on water and, therefore, form a thick soil with clay accumulation in the subsurface horizon. The major soil in the lower drainageways is the Colo series (fine silty, mixed, mesic Cumulic Haplaquolls). The dark surface horizon of Colo soils is up to 1.2 m (4 ft) thick. These soils are poorly drained with a perched water table at about 0.6 m (2 ft) depth in most years.

Soils in the Rosemount Watershed study area are representative of medium textured soils important to non-irrigated agriculture in southern Minnesota.

SITE CONSTRUCTION

The general design of the site was derived from visual inspection of the watershed. The area was designed to include research plots, sludge storage lagoons, runoff reservoir, runoff disposal, and runoff sampling stations (Table 9) (Jefferey, 1994). The following design criteria were established to meet the objectives of the study:

1. Use parallel terraces constructed with a minimum of land forming.
2. Provide a detention reservoir to collect and hold the runoff from the area that could come in contact with sludge applications either directly or indirectly.
3. Provide a disposal area for the collected runoff.
4. Provide sludge storage sufficient for an application of 7.5 cm (3 in) in the spring before planting.
5. Divert runoff from all nonresearch areas of the watershed away from the sludge-treated area.
6. Provide an underground outlet to direct the collected runoff from each terrace to a sampling station and then through a drainageway to the runoff reservoir.
7. Design the site to contain a 100-yr, 24-h storm runoff of 112 mm (4.4 in).

Table 9. Research watershed characteristics.

Research Areas	*Hectares*	*Acres*
Corn terraces (1973-1985)	6.0	14.9
Grass terraces (1973-1985)	5.5	13.6
Corn terraces (1986-1993)	11.5	28.5
Runoff disposal terraces	2.1	5.2
Corn control terrace (1973-1993)	0.8	2.0
Grass control terrace (1973-1985)	0.8	2.0
Central service area	3.3	8.1
Runoff reservoir	1.7	4.2
Total area draining to runoff reservoir	20.2	50.0
Sludge storage ponds and service area	1.2	3.0
TOTAL	21.4	53.0
Runoff reservoir	32,500 m^3	26.3 ac-ft
Sludge holding lagoons	11,400 m^3	9 ac-ft

The USDA-SCS, in cooperation with the USDA-ARS, the Metropolitan Sewer Board (currently MCWS), Minnesota Agricultural Experiment Stations (MAES), and the MPCA then developed a research area design based on the general layout plan and the above design criteria (Fig. 3).

TERRACES

Grassed steep backslope terraces were used. Terraces were spaced 39.6 m (130 ft) apart and were designed to impound 64 mm (2.5 in) of runoff (Fig. 4).

Terrace channels were graded to vertical plastic intake pipes located at natural low points in the terrace channel. The protruding part of the intake pipe was perforated so that when runoff level reached design height it would allow a minimum discharge of 103 m^3 (1 A-in) per day to prevent crop damage from standing water. Plastic buried outlet pipes discharged flow through a sampling station to shallow field ditches below the lowest terraces. Graded diversions were installed above the terraces to divert natural runoff from the research area.

Observations indicated that occasionally at the start of each growing season it was advisable to remove any accumulated sediment from the area adjacent to the slotted intake pipe. The terraces were designed to store

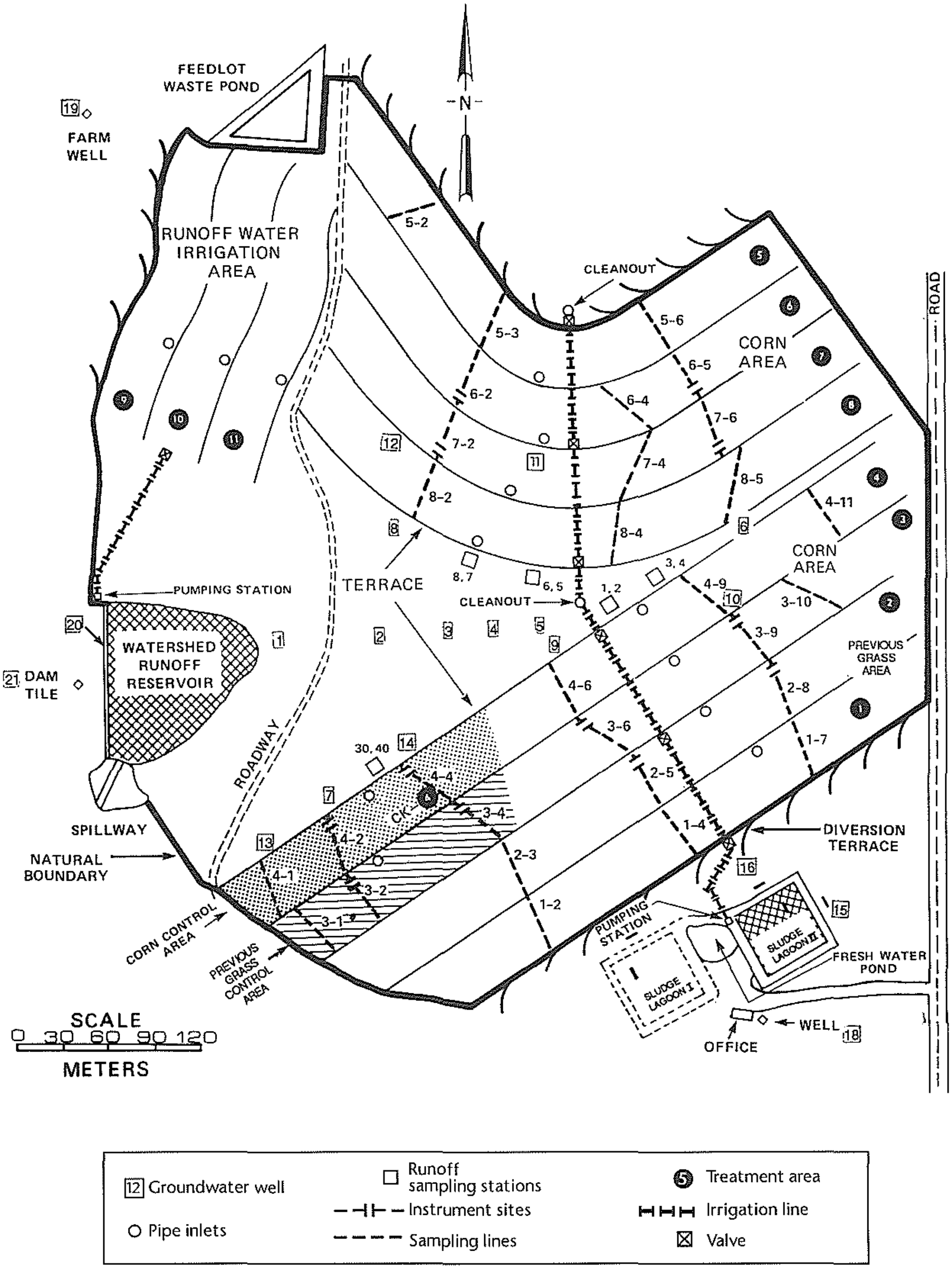

Figure 3. Rosemount sewage sludge watershed.

runoff only and therefore sediment accumulation in the storage area needed periodic removal to maintain terrace storage capacity.

The terraces controlled the runoff and, with the perforated vertical inlet, allowed the soil and sludge solids to settle out of the runoff before it was discharged. Wet spots in the crop area were minimal and could be reduced or eliminated by installing drain tile. The terraces caused only minor isolated interference with normal agronomic practices. Terraces significantly reduced erosion on this steeply sloped cropland.

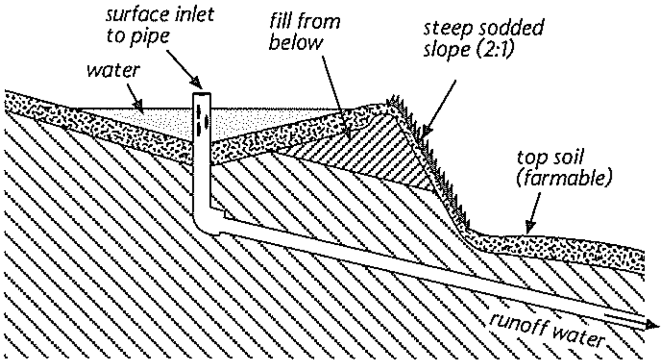

Figure 4. Steep backslope terrace cross-section.

RUNOFF RESERVOIR

The runoff reservoir was formed by a compacted earth fill embankment across the watershed outlet. The embankment was keyed into the natural ground with a core trench extending the full length of the fill. The reservoir was designed to retain all runoff from the watershed of 21 ha (53 A). The design reservoir capacity was to store runoff from a 25-yr, 24-h duration storm, 9.9 by 10^3 m^3 (8 A-ft), and a 100-yr, 24-h duration storm, 22.6 by 10^3 m^3 (18.3 A-ft).

The reservoir was planned to be pumped empty whenever the stored runoff reached the 25-yr storm runoff volume. Therefore, there would always be storage capacity to contain the entire 100-yr storm runoff without outflow. The bottom of the reservoir was lined with a black 0.2-mm polyethylene film to the 25-yr storage level. A vegetated emergency spillway was constructed to provide for outflow and to maintain embankment integrity should the design runoff be exceeded. The emergency spillway has not flowed.

The reservoir provided a source of irrigation water during dry periods. It also served as a water source for cleaning the sludge application system.

SLUDGE STORAGE LAGOONS

Two separate sludge storage lagoons were formed by a combination of excavation and compacted earth fill dikes. The storage lagoons were 2 m (6.5 ft) deep, with 55 m (180 ft) square bottoms and 3:1 slopes on the inside and 2:1 slopes on the outside. The combined capacity of the lagoons was 11 400 m^3 (3 million gallons). This was the approximate winter storage capacity needed for sludge expected from the four treatment plants initially supplying sludge for the study. About 0.460 m (18 in) additional storage was provided in each lagoon for residual solids that could not be pumped, and for contingent sludge volumes. The lagoon bottoms were level except for a 6 m (20 ft) square sump 0.6 m (2 ft) deep at the corner next to the pumping stations.

One lagoon was lined with a black 0.2-mm polyethylene film; the other was lined with compacted soil. This was to provide a comparison to determine whether solids seal the bottom of lagoons sufficiently to prevent seepage and eliminate the need for a synthetic lining. The lagoon bottoms were apparently effectively sealed. Water and soil samples extracted from various depths both under and near the outside of the lagoons indicated no seepage.

FEEDLOT WASTE STORAGE POND

A waste storage pond was installed below a nearby beef feedlot area to isolate the livestock waste from the research area. A storage diversion was constructed above the waste storage pond to divert all runoff from the livestock area of the watershed into the pond. All runoff collected in this waste storage pond was to be pumped to a pasture outside the research watershed.

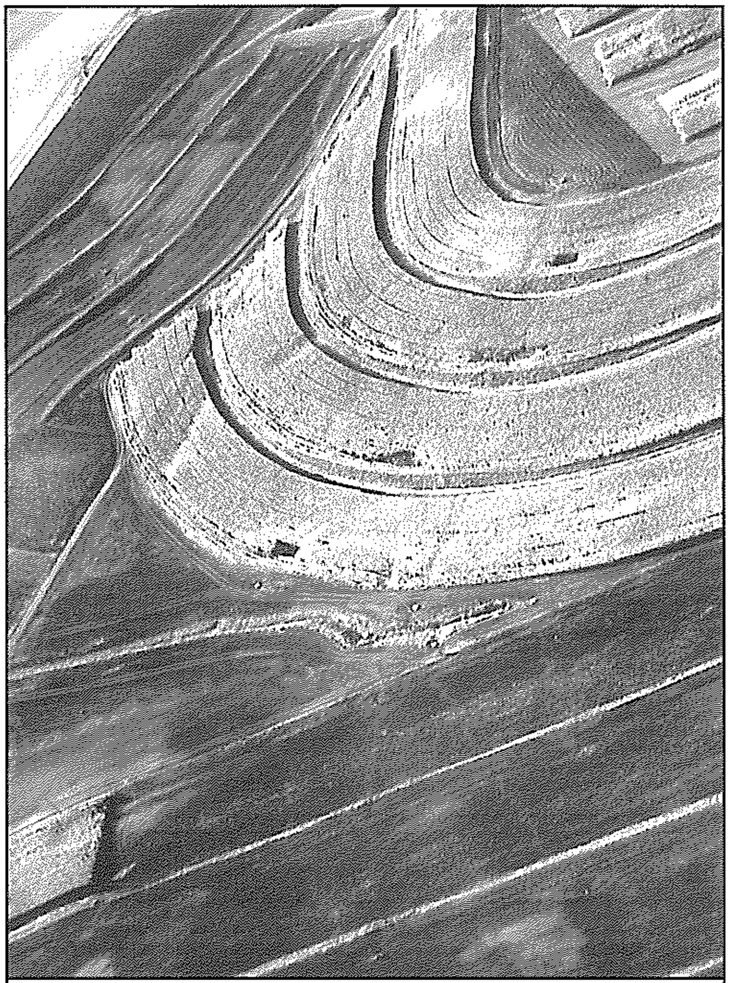

Figure 5. Aerial photograph of the watershed.

CONSTRUCTION SUMMARY

The conservation terrace system on the watershed effectively provided surface water management, controlled erosion, and retained the runoff from all storm events that occurred on the application area. These features also provided convenient monitoring points where experimental controls could be assessed. Farming practices were those generally accepted by the agricultural community for water and erosion control on cropland.

The Metropolitan Sewer Board (currently MCWS) performed construction contract administration and the USDA-SCS provided construction layout and inspection services. Bids were received resulting in Metro Engineering, Osseo, MN, being the successful bidder. Installation was completed in the fall of 1973 for $79,000 (Fig. 5).

METHODS AND MATERIALS

CLIMATE

Climate has an important effect on the growth and yields of crops in Minnesota, as well as on sludge application practices and the effect of sludge on soil properties. The climate is typical of mid-continental humid regions with four distinct seasons. Precipitation averages 78.8 cm year^{-1}, with about 70% falling as rain during the growing season. Average annual air temperature is 44.9° F (7° C). The record high temperature, recorded by the U.S. Weather Service 7 mi (11 km) to the south at Farmington, Minnesota, was 99° F (37° C). The record low was -36° F (-38° C). Growing season length is about 137 days.

Extreme meteorological conditions sometimes occur during the growing season and affect crop yields. These extremes include thunderstorms (an average of 36 per year) with associated high winds, hail, and short duration–high intensity rainfall (record rainfall in a 24-hr period was 5.1 in). Prevailing winds are northwesterly. Average relative humidity is about 60%. Clear skies occur about 65% of summer days.

Table 10. Sewage sludge delivered to the Rosemount Watershed (1973-1992).

Year	Wastewater Treatment Plant†								
	Hastings	Lakeville	Farmington	Apple Valley	Cottage Grove	St. Paul Park	Blue Lake	Empire	Total
	m^3								
1975‡	4090	280	2790	4190	1100	90	2010	—	14550
1976	7370	70	1550	3480	2100	—	—	—	14570
1977	8980	370	490	12560	1320	—	—	—	23720
1978	5770	740	740	7200	1060	—	—	—	15510
1979	3430	—	1070	7050	1090	—	—	—	12640
1980	2490	—	—	—	1840	—	—	—	4330
1981	4300	—	—	—	4330	—	—	—	8630
1982	1410	—	—	—	1930	—	—	—	3340
1983	—	—	—	—	—	—	—	—	0
1984	3318	—	—	—	—	—	—	5375	8693
1985	702	—	—	—	230	—	—	6280	7212
1986	—	—	—	—	—	—	—	—	0
1987	—	—	—	—	—	—	—	—	0
1988	—	—	—	—	—	—	—	5678	5678
1989	—	—	—	—	—	—	—	1420	1420
1990	—	—	—	—	—	—	—	—	0
1991	—	—	—	—	—	—	—	—	0
1992	—	—	—	—	—	—	—	1514	1514
Total	41860	1460	6640	34480	15000	90	2010	20267	121807
Percent	34.37	1.20	5.45	28.31	12.31	0.07	1.65	16.64	100.00

† Hastings, Lakeville, Farmington, St. Paul Park, and Empire used an anaerobic treatment process while Apple Valley and Blue Lake used an aerobic treatment process. Cottage Grove used both processes.

‡ Includes volume of sludge delivered starting in November, 1973. (Note that 264.17 US gallons=one cubic meter)

Temperature, precipitation, and pan evaporation information were recorded on-site or at the Experiment Station headquarters. During the growing season, rainfall and pan evaporation were measured by recording rain gauge and standard U.S. Weather Service pan, respectively. Minimum and maximum daily temperatures were recorded.

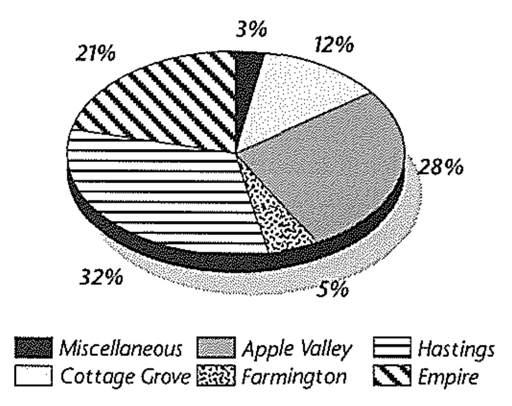

Figure 6. Location and percentages of sludge delivered from wastewater treatment facilities to the Rosemount Watershed (1973-1993).

SLUDGE DELIVERED TO THE SITE

SOURCES AND AMOUNTS

Liquid sewage sludge was delivered by tank truck to the Rosemount Watershed site. The sludge was delivered from eight different wastewater treatment plants over the 20 years of the project. Locations of wastewater treatment plant sites are shown in Fig. 1. Some of these plants have been closed and consolidated since the start of the experiment.

More than 90% of all sludge brought to the site has been from four municipalities: Hastings, Apple Valley, Cottage Grove and Empire. The percentages of sludge delivered from each facility are shown in Fig. 6. The numerical breakdown of sludge delivered to the watershed is shown in Table 10. It should be noted that an initial gross estimate of sludge to be applied was 6 inches over 35 acres or about 22 700 m^3 (6 million gallons) per year. Sludge deliveries approached this amount only one year (1977) during the project.

A total of 121 807 m^3 (32.2 million gallons) of liquid sewage sludge was delivered to the site from 1973 to 1993. This averaged about 1.6 million gallons each year. The amount of sludge delivered each year ranged from 0 to 6.3 million gallons. The composition of the sludge delivered to the site is discussed later in this report.

Volume of sludge delivered was variable over the study period. Apple Valley only delivered sludge during the first five years of the study, but contributed 28% of the total volume delivered to the site. Hastings and Cottage Grove delivered sludge from 1973 to 1985. Empire delivered all the sludge for this project from 1988 to 1992. No sludge was delivered in 1983, 1986, 1987, 1990, and 1991 for a variety of reasons. In 1983, the project leaders decided not to apply sludge prior to the 1984 crop year due to the presence of elevated NO_3-N levels in water samples. The quantity of sludge applied to the terraces was reduced in order to lower these levels. In 1986 and 1987, a moratorium on sludge spreading was self-imposed by the MCWS for public review of the project. In 1990 and 1991, efforts were made to empty the east lagoon. This was done in preparation for its decommissioning at the end of the 20-yr study period.

SLUDGE SAMPLING METHODS

Samples of the liquid sewage sludge were collected from every truckload delivered. A composite sample was made by mixing individual samples from each plant. From 1973 to 1985, these samples were composited monthly, averaged and reported as the sludge composition for each year. From 1985 to 1993, composite samples were made only once a year. This change in procedure was made because the amount of sludge being delivered in the later years of the study was much less than in earlier years. In later years, sludge was delivered at one time, not monthly throughout the summer.

The samples were tested for 23 characteristics and components. A liquid subsample was analyzed for total solids, volatile solids, total N, ammonium nitrogen (NH_4^+-N), electrical conductivity (EC), and pH (reaction). A freeze-dried subsample was analyzed for nine major components of sludge [organic matter, total C, total P, K, calcium (Ca), Na, magnesium (Mg), aluminum (Al), and Fe] and eight trace elements [Cr, Cu, Zn, Pb, Mn, boron (B), Ni, and Cd].

SLUDGE APPLICATION METHODS AND EQUIPMENT

Large scale sludge application experiments like the Rosemount Watershed study require special equipment. Such sludge application equipment was acquired in the early 1970s and was used until 1987. After 1987, new technologies were used which simplified the sludge application process.

A brief summary of the study's sludge application equipment and practices are listed in Appendix A. In general, sludge was injected into the soil in the fall on areas to be cropped to corn and sprayed on the surface to areas cropped to perennial grass.

LAGOON AGITATION AND PUMPING

The general procedure for handling the sludge was related to the on-site lagoon storage system. Sludge solids settled to the lagoon bottom and needed to be re-suspended just prior to application to the land. A tractor-driven high-volume pump (44 000 gallons/hour) was used to agitate the sludge for several hours to do this, but the attempt at homogenization was not fully successful.

In normal operation, liquid sludge was pumped from the lagoon to an underground irrigation pipe extending across the watershed (Fig. 3).

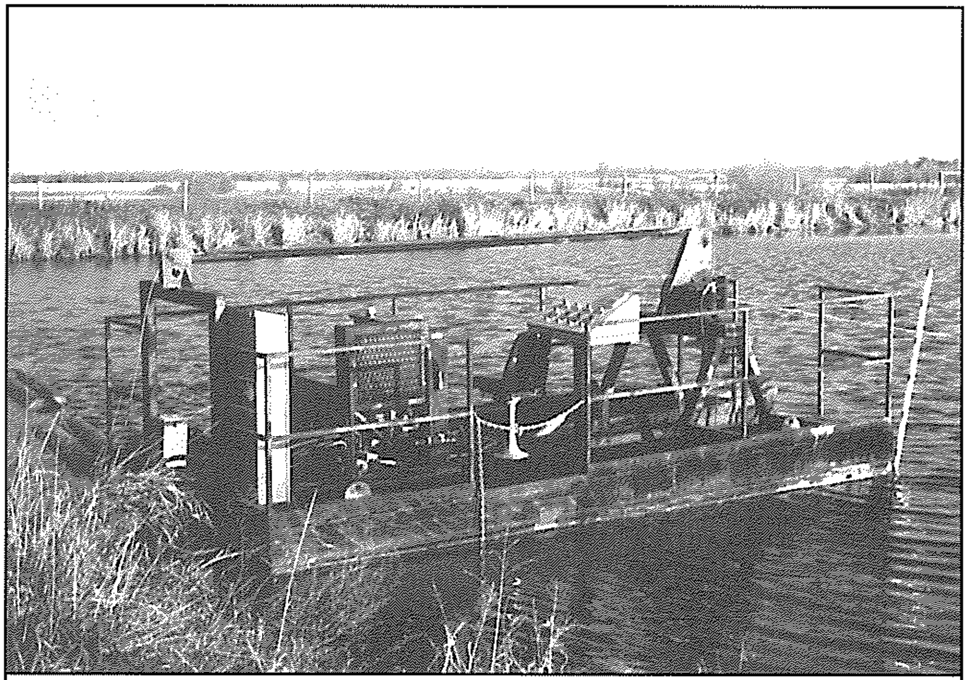

Figure 7. Barge mixing and pumping sludge from the lagoon.

An outlet valve near each terrace on the watershed allowed connection to an above-ground irrigation pipe and a flexible hose. In 1987-88, the west lagoon was decommissioned. Subsequent deliveries of sludge were stored only in the east lagoon.

From 1989 to 1992, a floating mechanical barge was used to mix the sludge in the lagoon and pump it to a tank where the flow to the terraces could be regulated. The barge was able to provide a better mixing of the sludge than previous methods, and could also pump a greater volume of sludge (Fig. 7). An above ground hose carried the sludge to the terraces.

FIELD APPLICATION

As technologies progressed, the sludge mixing and application methods at the Rosemount Watershed study also changed. By the end of the project, the equipment used was extremely effective at mixing and applying the sludge to the terraces.

From 1975 to 1985, sludge was applied to the grass areas in the spring and after each cutting, using a flexible hose connected to a traveling-gun irrigation unit (Fig. 8). From 1975 to 1987, a soil injection toolbar pulled by a track-type tractor was used to subsurface inject sludge on the corn areas (Fig. 9). These applicators were not in service during the project's first year (1974) and sludge application by tank-wagon spreader was used.

Sludge was generally applied to the corn treatment areas in October or November after the removal of the previous corn crop. In 1988, sludge was injected in the field with a tractor and tank-wagon injector. This method was employed due to mechanical problems with the underground irrigation system. In 1989-90, sludge was applied using a tractor and injector toolbar. In 1991, sludge was applied by discing the sludge into the soil rather than subsurface injecting. This method did not work as effectively as past years, requiring additional discing to ensure proper incorporation of sludge.

In 1992, special horizontal disc-injectors (Fig. 10) were used to apply the sludge. These horizontal subsurface discs provided the best method of incorporation of sludge. They provided very accurate depth placement of the sludge, and very little surface runoff as compared to other subsurface injection systems. They also provided more uniform application of the sludge across the entire field as compared to previous chisel-style injectors.

A disadvantage of surface application (tank-wagon and overhead irrigation) versus subsurface injection is that soil infiltration rates limit application rates. Too rapid an application rate (greater than about 1.1 cm h^{-1}) caused surface flow of sludge toward the terrace channel. Injection rates greater than about 1.5 cm h^{-1} caused surface flow with the lightweight injection equipment used. Subsurface injection depth was 8 to 15 cm (3 to 6 in).

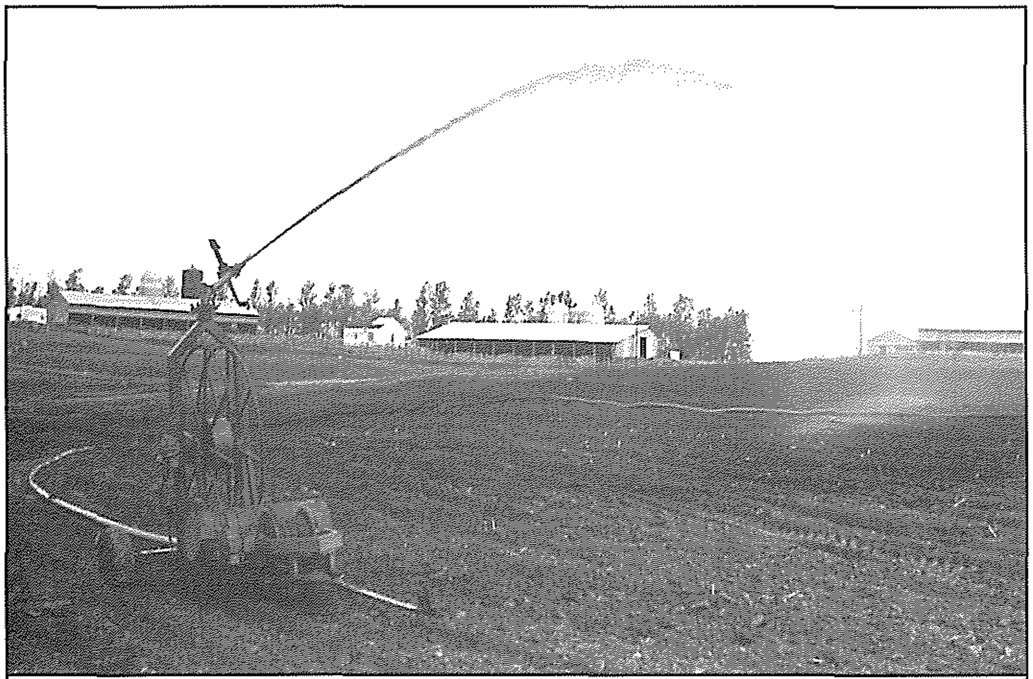

Figure 8. Traveling-gun irrigation unit applying liquid sewage sludge to grass treatment areas.

Figure 9. Injection toolbar applying liquid sewage sludge to corn treatment areas.

Tile inlets were sealed during sludge application to prevent direct runoff. Also, to prevent off-site travel of aerosols, application with the traveling-gun irrigator was limited to times when wind speed was lower than 8 km h^{-1} (5 mph).

SLUDGE SAMPLING METHODS

Sampling of the sludge applied to the terraces was done at designated sampling lines where soil samples were also taken. Each terrace area had three sampling lines. These lines are shown as dashed lines in Fig. 3. The grass areas were sampled by collecting sludge samples in plastic pans at three sites on each terrace sampling line. These samples were then composited for each grass treatment area.

From 1975 to 1985, sludge applied to the corn terraces was sampled from a manifold valve on the injector equipment. During injection, samples were taken over each sampling line and composited for each corn treatment area. From 1987 to 1993, sludge samples were taken at the mixing tank next to the lagoon as the tractor and injectors passed over each sampling line on the terraces. This method was much easier to implement. From 1990 to 1993, a meter was also installed on the irrigation hose near the lagoon that could measure the amount of sludge applied to the terraces in 0.1 gallon increments. This meter increased the accuracy of sludge application and better assured that each terrace received equal amounts of sludge.

SLUDGE IN STORAGE LAGOONS

Core samples of sludge strata were taken in February 1986 and March 1991. These stratified layers included ice, supernatant liquid, liquid sludge, and sedimented sludge in the lagoons. The cores were subdivided by these layers.

In 1986, ice and water were reported on a mass per volume basis (mg L^{-1}). Suspended solids, dense solids, and soil liner were reported on a gravimetric basis (oven-dry-mg kg^{-1}). Averages of 18 core samples on an 18 m grid (nine cores per lagoon) were taken. Strata were listed from lagoon surface to 0.10 m below the sludge-soil liner.

Eleven core samples were taken in the lagoon in 1991. Samples were composited into a single total sample for each of the four distinct lagoon sludge layers. Composition of the sludge in this sampling was reported as percentages.

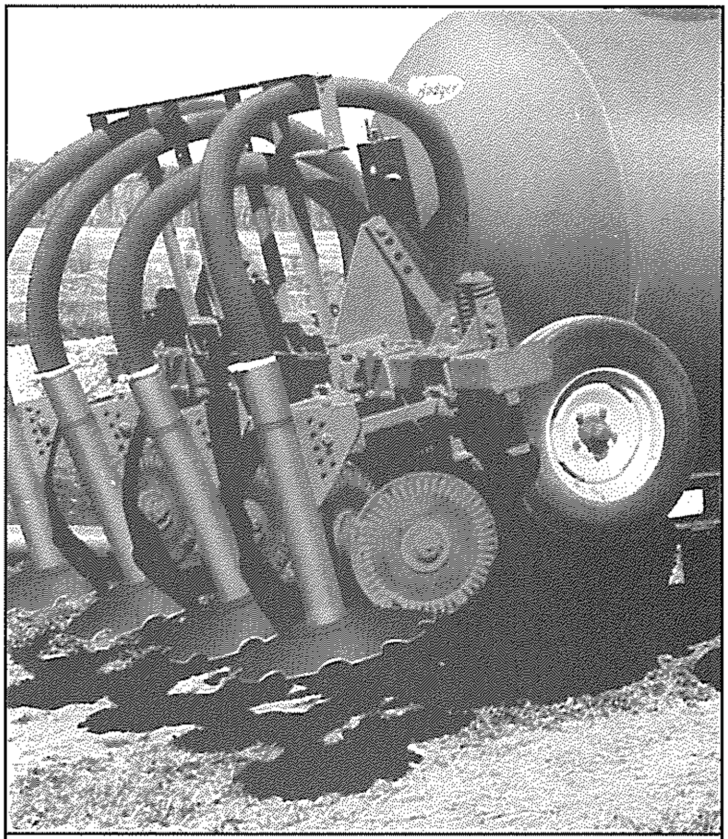

Figure 10. Badger® disc-injectors used in application of sludge.

CONTROL AREAS FOR EXPERIMENTAL COMPARISON

From 1975 to 1985, sludge was applied to 8 of the 10 terraced areas. Portions of terraced areas 3 and 4 (Fig. 3) were kept sludge-free, but fertilized to soil test recommendations to serve as control areas. The control area on terrace area 3 was planted to reed canary–grass, and the control area on terrace area 4 was planted to corn. After reed canarygrass was discontinued in 1984, both control areas served as fertilized control areas for corn. These control portions of terrace 3 and 4 were separated by a natural divide which also separated the runoff. The control area on terrace 3 had sludge applied to it from 1984 to 1993 and was planted to corn.

Table 11. Commercial fertilizer applied to corn and grass treatment areas.[†]

Year	Treatment[‡]	Grass			Corn		
		N	P	K	N	P	K
		kg ha^{-1}					
1974	Control	—	—	—	230	20	66
	Sludge	—	—	—	0	0	66
1975	Control	—	—	—	230	20	66
	Sludge	—	—	—	0	0	66
1976	Control	221	58	59	249	65	88
	Sludge	0	0	59	0	0	88
1977	Control	232	20	69	175	16	43
	Sludge	0	0	69	0	0	43
1978	Control	415	17	170	200	17	100
	Sludge	0	0	100	0	0	80
1979	Control	368	17	0	340	17	100
	Sludge	0	0	0	0	0	80
1980	Control	300	23	110	240	23	110
	Sludge	0	0	110	0	0	110
1981	Control	330	50	230	235	50	150
	Sludge	0	0	230	0	0	150
1982	Control	340	0	340	280	0	135
	Sludge	0	0	340	0	0	135
1983	Control	197	0	0	224	0	0
	Sludge	0	0	0	0	0	0
1984[§]	Control	—	—	—	220	0	0
	Sludge	—	—	—	0	0	0
1985[¶]	Control	—	—	—	340	0	140
	Sludge	—	—	—	0	0	140
1986[#]	Control	—	—	—	315	0	0
	Sludge	—	—	—	0	0	0
1987	Control	—	—	—	134	0	0
	Sludge	—	—	—	0	0	0
1988	Control	—	—	—	216	0	0
	Sludge	—	—	—	0	0	0
1989	Control	—	—	—	216	0	0
	Sludge	—	—	—	0	0	0
1990	Control	—	—	—	0	0	0
	Sludge	—	—	—	0	0	0
1991[††]	Control	—	—	—	267	101	207
	Sludge	—	—	—	0	0	0
1992[††]	Control	—	—	—	253	101	208
	Sludge	—	—	—	0	0	0
1993[††]	Control	—	—	—	0	0	0
	Sludge	—	—	—	0	0	0

[†] N, nitrogen, 34-0-0; P, phosphorus, 0-46-0; K, potassium, 0-0-60.

[‡] Control areas: grass, CK-3; corn, CK-4. Sludge areas: grass, terraces 1, 2, 3; corn, terraces 4, 5, 6, 7, 8.

[§] Control areas: grass, none; corn, CK-3 and CK-4. Sludge areas: corn, terraces 3, 4, 5, 6, 7, 8.

[¶] Control areas: grass, none; corn, CK-4. Sludge areas: corn, terraces 3, 4, 5, 6, 7, 8.

[#] Control areas: corn, CK-4. Sludge areas: corn, terraces 1, 2, 3, 4, 5, 6, 7, 8.

[††] Fertilizer was added to control area in amounts equal to the fertilizer provided in the sludge terrace treatments. Quantities based on sludge and soil samples from previous year.

Commercial fertilizer N (34-0-0) and P (0-46-0) were applied to the control areas. Table 11 summarizes the fertilization schedule used at the Rosemount Watershed. Generally, the fertilizer was broadcast; then, on corn areas, was incorporated. From 1991 to 1993, anhydrous ammonia was used as part of the N fertilizer source for the corn control area. This was injected into the ground prior to planting. Post-planting applications of 28% N were then injected into the soil. Split broadcast applications, following each harvest of the crop, were used on the grass treatments.

In 1990 and 1993, no commercial fertilizer was applied to the control area. In 1991 and 1992, efforts were made to match the amount of N, P, and K applied in the sludge to the control area through commercial fertilizers. Prior to that time, fertilizer amounts were not matched on the control and sludge applied terraces.

The original intent of the study was to match the amount of sludge applied to soil test recommendations. This practice changed over the length of the study. In the first years and last three years of the study, these amounts were matched. The problem with this procedure is that calculating N available to the crops from the sludge is difficult. Trace elements were not matched between the sludge and control areas in this study. The additional water provided in the sludge may have been a factor in yields, especially during the years when water availability was low.

Corn control area CK-4, however, did not benefit from sludge applied bases and, in 1986, was limed with 4 Mg ha^{-1} (2 T A^{-1}) of crushed agricultural limestone to correct a declining soil pH.

CROP SELECTION AND MANAGEMENT

Field corn (*Zea mays* L.) and reed canarygrass (*Phalaris arundinacea* L.) were the two crops grown on the watershed. Corn was grown on areas 5, 6, 7 and 8 (Fig. 3) (the south and west facing areas), starting in 1974. Grass was seeded on areas 1, 2, 3, and 4 (Fig. 3) (the north facing slope), in 1975. The east end of area 4 was reserved for special forage plots. The west ends of areas 3 and 4 were reserved for the fertilized control for grass (CK-3) and corn (CK-4), respectively. The two-crop system was implemented so that sludge could be applied during the growing season.

From an agronomic viewpoint, it is relatively easy to grow an annual crop like corn compared to a perennial grass crop. Reed canarygrass plants are quite vigorous during the first few years of the stand. However, in time, the stand thins due to disease, winter kill, weed competition, and general age, until the stand must be reseeded. After 1984, reed canarygrass plots were discontinued and were planted to corn.

Field management activities were not unlike those practiced by good farmers in the area. Detailed records of tillage, fertilization, weed control, planting, cultivation, and harvest were kept for both corn and grass crops.

CORN

A short-season corn hybrid was selected so that corn could be removed early to allow fall sludge application. Corn hybrids and seeding rates changed over the course of the experiment. Table 12 summarizes these changes in variety and plant population. The varieties used in the Rosemount Watershed study were those in common use by area farmers. It is difficult to ascertain the effect of corn variety on yield and element uptake. Corn varieties can be quite different in their ability to take up nutrients and other elements. Hinesly et al. (1978) examined 20 corn inbred lines grown on sludge-amended soil. Differences of up to 40 times were found in grain Cd content among the inbreeds.

Typically, the cultural operations for corn included: field cultivation in early May; corn planted in 75-cm (30 in) row spacings in early to mid-May, depending upon weather; and insecticide applied with the planter (Furadan, Dyfonate, Counter, Amaze, Thimet, Lorsban, or Force). In 1990, Aatrex Nine O pesticide was also sprayed with oil. Herbicide was applied each year (pre-emergence Lasso plus atrazine or Eradicane and/or a post-emergence application of atrazine plus oil). In later years, the herbicide Banvel was also used to control broadleaf weeds. In some years, the corn was cultivated after planting with 1 or 2 passes by shovel sweep or rotary-hoe row cultivator. All corn treatment areas were fall chisel-plowed.

Table 12. Corn varieties used in the Rosemount Watershed study.

Year	Variety	Population†
1974	Pioneer 3780 (105 day)	67,300
1975	Northrup King PX476 (100 day)	62,900
1976	Northrup King PX448 (95 day)	52,800
1977	Northrup King PX448 (95 day)	65,000
1978	Northrup King PX448 (95 day)	65,900
1979	Northrup King PX448 (95 day)	66,000
1980	Northrup King PX448 (95 day)	63,000
1981	Pioneer 3780 (105 day)	59,300
1982	Pioneer 3780 (105 day)	54,360
1983	Pioneer 3780 (105 day)	59,770
1984	Funks 4256 (95 day)	56,800
1985	Stauffer 4402 (105 day)	58,300
1986	Stauffer 4402 (105 day)	52,800
1987	Stauffer 4414 (100 day)	—
1988	Asgrow 498 (100 day)	—
1989	Dekalb 464 (100 day)	59,300
1990	Coden 3151 (100 day)	59,300
1991	Jacques 4770 (95 day)	64,200
1992	Jacques 4770 (95 day)	59,300
1993	Pioneer 3780 (105 day)	59,300

† Population estimate at harvest in plants ha^{-1}.

REED CANARYGRASS

Grass treatment areas were seeded in June 1975. They were irrigated in July 1975 from the runoff reservoir, and mowed in August 1975 to control broadleaf weeds. In most years, sludge was applied by a traveling overhead sprinkler in April, June, July and September. Grass plots were harvested and sampled in June, July and September. Plots of 0.9-m by 6.1-m were sampled at three sites (in the terrace channel, at the mid-terrace interval, and near the upper terrace interval) along the three permanent sampling lines on each terrace. The grass crop was harvested by either cutting, chopping, and ensiling (usually first cutting), or was cut, raked into windrows to dry, then baled and removed. Sludge application immediately followed these harvests, so that sludge would not contaminate the surface of growing plants.

For the most part, the grass portion of the study resulted from a single 1975 seeding of 'Rise' reed canarygrass. Thus it has a uniform varietal history, although vigor of the stand changed over time. The stands of reed canarygrass, on terraces 1 and 4, declined due to weed competition. They were treated with glyphosate, then reseeded to 'Blaze' alfalfa in 1982. Only terraces 2 and 3, and CK-3 were sampled for grass in 1983. Grass samples were only collected from terrace 2 in 1984. In 1985, CK-3 was changed from a grass control area to a corn sludge area.

In 1985, the alfalfa and grass stands on terraces 1 and 2, respectively, had deteriorated and were plowed and reseeded to 'Flaire' reed canarygrass. Weed competition caused this seeding to fail and terraces 1 and 2 were converted to corn sludge treatment areas in 1986. After 1986, corn was grown on grass treatment areas.

SPECIAL FORAGE PLOTS

Small plots, located on the east end of terrace 4, were used to test grass and alfalfa varieties. Four replicate plots of each of five forage crops were planted in 1975. Forage species studied were 'Fox' smooth bromegrass, 'Rise' reed canarygrass, 'Kentucky 31' tall fescue, 'Agate' alfalfa, and 'Saranac' alfalfa. The purpose of the special forage plots was to evaluate the performance of the crops under sludge treatments. Performance was measured by maintenance of stand population, quantity of forage produced, and feed quality [in vitro digestible dry matter (IVDDM); crude protein (CP); and cell wall constituents (CWC)]. The special forage plots were terminated in 1980 and reseeded to 'Rise' reed canarygrass that year.

CORN AND REED CANARYGRASS TISSUE SAMPLING

From 1975 to 1987, corn leaf samples (center one-third of leaf below and opposite the primary ear) were taken at 75% silking stage along three permanent sampling lines of each corn area. These leaf samples were tested for concentrations of N, P, and K.

Throughout the 20-yr period, grain and stover sampling was done in September near the permanent soil sampling lines. Corn was harvested at late dent stage. Ears were picked, and the rest of the plant (stover) was chopped. Composite samples of ears and stover were taken from an area 15 m^2 (10 rows, 1.5 m long) on the permanent sampling lines. The remainder of the corn crop was harvested for the grain or chopped and ensiled.

On reed canarygrass areas, samples were taken from 0.9 by 6.1-m plots at three sites (in the terrace channel, at mid-terrace, and near the upper terrace) along the three permanent sampling lines on each terrace. Forage quality was measured by IVDDM, CP, and CWC. Ruminant intake is reduced when CWC reaches 55% dry weight or more. The higher the IVDDM and CP content, the better the forage quality.

SOIL SAMPLING

AVAILABLE NUTRIENTS

Soil samples were taken each fall from the sludge and control treatment areas after crop harvest. Estimates of plant available nutrients, soil pH, and agricultural lime requirements were made using standard soil test laboratory procedures. Numerous sampling sites were identified in order to characterize the inherent variety of the soils and sludge applications. These sites are identified as sampling lines on Fig. 3. They represented both convex and concave areas where wash material might be either depleted or concentrated.

PHOSPHORUS ACCUMULATION AND MOVEMENT

Significant amounts of sludge-borne P were added to sludge treatment areas at the Rosemount Watershed during the 20-yr project (Table 13). A study was initiated in 1973 to quantify the accumulation and movement of P into the soil profile of sludge treatment areas. A comparison was made between soil profile samples from the untreated control terrace and the sludge-treated continuous corn terraces.

Soil profile samples were collected to a depth of 0.30 m after 0, 5, 10, and 17 years of sludge applications and to a depth of 0.60 m after 20 years of sludge applications. Samples were subdivided into increments of 0 to 0.15, 0.15 to 0.30, and 0.30 to 0.60 m. Two forms of soil P were extracted from the soils. Plant available P was determined using the Bray P1 extraction method (Bray and Kurtz, 1945; Knudsen and Beegle, 1988). More stable inorganic forms of P (e.g., carbonate bound, Ca-bound) were extracted with 1 M nitric acid (HNO3).

NITROGEN AND CARBON MINERALIZATION

At the end of the 20-yr Rosemount Watershed study, potentially mineralizable nitrogen (N_0) and carbon (C_0) were determined in soil (0 to 15 cm) from three treatment areas. The three treatment areas included:

1. Grass-Corn + Sludge — received 15 Mg solids ha^{-1} yr^{-1} and 830 kg N ha^{-1} yr^{-1} from 1974-1986 and 11 Mg solids ha^{-1} yr^{-1} and 293 kg N ha^{-1} yr^{-1} from 1986 to 1993.
2. Corn + Sludge — received 11 Mg solids ha^{-1} yr^{-1} and 475 kg N ha^{-1} yr^{-1} from 1974 to 1993.
3. Corn control (No Sludge) — received 210 kg N ha^{-1} yr^{-1} fertilizer from 1974 to 1993.

Samples for N_0 determination were aerobically incubated in polyethylene bags at 35° C and constant water condition for 20 weeks. Subsamples were taken at periodic intervals and analyzed for inorganic N. To determine C_0, evolution rates of carbon dioxide (CO_2) were measured for 14 weeks by sampling dissolved inorganic C in alkali (NaOH) traps. Estimates of N_0 and the decomposition rate-constant, k, were determined using a single exponential equation and the NCSOIL computer model. Estimates of C_0 were determined using an incremental single exponential equation.

Table 13. Sludge and nutrients applied by cropping season at the Rosemount Watershed (grouped into 4-year periods).

Season	Applications	Sludge cm	%	Solids Mg ha^{-1}	Nutrients N kg ha^{-1}	P	K
Corn†							
1974-77‡	11	20.3	1.40	39.1	2220	1180	190
1978-81‡	7	24.0	2.75	67.1	3450	1680	191
1982-85‡	3	10.8	2.08	30.3	1440	671	62
1986-89‡	3	6.6	2.25	23.4	936	607	72
1990-93‡	4	6.7	9.50	64.0	1410	973	89
Total	28	68.4	—	224.0	9460	5100	604
Previous Grass§							
1974-77	18	24.3	1.76	43.2	2530	1110	254
1978-81	33	50.0	1.95	101.0	5570	2420	370
1982-85	10	21.9	1.31	28.6	1940	600	79
Total	61	96.2	—	173.0	10040	4130	703

Totals may reflect rounding errors.

† Application by subsurface injection following annual harvest the previous Fall.

‡ 4-year total; no sludge applied in 1984 and 1987.

§ Application by traveling overhead sprinkler irrigation during the growing season. Grass area planted to corn since 1986.

WATER SAMPLING

From 1975 to 1987, water from runoff events on each area was collected in the permanent sampling stations by automatic samplers modified to begin collection when water flow started and at 1-h intervals during runoff. Flow rates were measured by water stage recorder with slotted tube and stilling well. After 1987, these sampling stations were not monitored.

From 1975 to 1979, soil water within the root zone was sampled with sampling tubes at 60 cm and 150 cm depths at 24 sites. Duplicate samplers were installed at each depth. Sampling sites were located in the terrace channel and at the mid-terrace.

Samples from 12 sampling tubes taken at depths from 1.22 m to 4.88 m were collected monthly from 1974 to 1993. Background samples from various water sources, both within and around the watershed, were taken bimonthly for the 1973 season before any sludge was applied on the project site. Water monitoring wells and stations are shown in Fig. 3.

Water sampling was frequent for the first five years of the project. Temporarily saturated soil water, root zone soil water, and deep ground water wells were sampled monthly. From 1980 to 1987, sampling was done once or twice a year, with the exception of 1986 when sampling was done monthly. From 1988 to 1993, monthly sampling was resumed. The same is true for surface watershed and runoff reservoir water.

A summary of laboratory methods used for this analysis is listed in Appendix B. In general, samples were tested for nutrients and trace elements.

RESULTS AND DISCUSSION

Data has been summarized on an annual basis, in yearly *Utilization of Sewage Wastes on Land* reports (Larson et al., 1974 through 1992). The data provided in these annual reports has been compiled and discussed in this section of the 20-yr report.

CLIMATOLOGICAL OBSERVATIONS

Crop growth and yields can be affected by adverse weather. Especially critical are the conditions early in the growing season. Table 14 summarizes the normal monthly climate for the period 1973 to 1993. Appendix C shows the seasonal pattern variations of climatic data over the 20 years of this study. A wet spring in 1975 and a cool spring in 1979 may have depressed crop yields in those years. Precipitation was extremely limited during the 1976 and 1988 growing seasons. In 1992, there was frost damage in June, but the crop seemed to recover. The summer of 1993 was extremely wet and may have depressed crop yields somewhat. Most other years had good growing conditions.

Table 14. Climatic data (1973-1993) –Farmington, Minnesota.†

Month	*Average Daily Temperature (°F)*	*Average Growing Degree Days‡*	*Average Precipitation (cm)*	*Average Snowfall (cm)*
January	13.1	0	1.83	22.9
February	19.1	1	1.85	20.6
March	31.7	25	5.36	22.1
April	47.1	160	7.30	9.4
May	59.7	377	9.22	0
June	68.1	547	10.62	0
July	72.2	674	9.37	0
August	69.1	591	11.76	0
September	60.1	369	8.74	0
October	48.2	170	4.75	0.5
November	32.0	25	5.03	21.8
December	17.6	0	2.84	19.8
Year	44.9	2944	78.80	119.6

Totals may reflect rounding errors.

† Source: University of Minnesota Soil Science Department Climatology Database.

‡ Growing degree day is a unit of heat available for plant growth.

Pan evaporation measurements provided an estimate of potential evapotranspiration. Potential evapotranspiration (PET), which is defined as the amount of water evaporated from a short green crop that fully shades the ground and is always supplied with water. Actual evapotranspiration is usually 60 to 80% of pan evaporation, but varies with crop, soil water availability, and advection (regional movement of air masses). The greatest difference between pan evaporation and precipitation occurred in 1976, a very dry year.

SLUDGE APPLICATION ANALYSIS

SLUDGE DELIVERED TO THE SITE

Composition of the sewage sludge delivered to the Rosemount Watershed varied among the wastewater plants. Over time, there was also variability within each component from any plant. Table 15 presents weighted means and standard deviations of sludge properties from the four major contributing plants to the project and the overall arithmetic mean and standard deviation for all contributors. The values illustrate the differences and similarities among the plants (the mean value) and the annual variation that occurs in sludge from a single plant (the standard deviation). (This does not accurately reflect the actual composition of mixed sludge in the lagoons because it is not weighted by the volume delivered from the plant.)

Total solids in liquid sewage sludge deliveries to the site were about 3% on the average. Apple Valley sludge (aerobic treatment plant) had only about 2% total solids, but proportionately greater organic matter in the solids. Empire sludge also was low in total solids, but had an average level of organic matter. The nature of organics in the sludge was not characterized. Empire sludge, which was delivered during the later years of the study, also contained higher amounts of N, particularly NH_4^+-N. The sludges were very similar among wastewater plants

Table 15. Composition of sewage sludge delivered to the Rosemount Watershed (1973-1993).†

Component	Wastewater Treatment Plant Apple Valley	 Cottage Grove	 Hastings	 Empire	 All Plants‡
% of liquid sample					
Total Solids	1.96 (0.09)	2.70 (0.43)	2.91 (0.65)	1.89 (0.17)	3.14 (1.41)
Volatile Solids	1.29 (0.07)	1.50 (0.34)	1.70 (0.37)	0.90 (0.29)	1.76 (0.59)
Total N (mg L^{-1})	1336 (64)	1480 (312)	1790 (285)	2010 (178)	1822 (568)
NH_4^+-N (mg L^{-1})	351 (23)	660 (182)	743 (230)	1325 (88)	764 (415)
EC (dS m^{-1})	3.55 (0.08)	5.10 (0.88)	5.80 (1.18)	7.80 (3.20)	5.50 (2.10)
pH (pH units)	7.28 (0.04)	7.90 (0.06)	7.90 (0.32)	7.90 (0.62)	7.70 (0.40)
weight % of dry total solids					
Organic matter	70.78 (0.25)	58.14 (6.05)	59.92 (1.97)	61.90 (2.56)	60.70 (5.50)
C	39.90 (1.51)	29.60 (2.87)	31.00 (9.33)	29.00 (2.49)	31.20 (5.80)
P	2.02 (0.08)	2.77 (1.06)	3.23 (0.69)	3.41 (0.26)	2.82 (0.90)
K	0.45 (0.05)	0.24 (0.12)	0.32 (0.06)	0.81 (0.11)	0.55 (0.48)
Ca	2.65 (0.04)	4.09 (1.42)	3.88 (0.17)	4.83 (0.37)	4.31 (1.66)
Na	1.48 (0.13)	1.76 (0.64)	1.56 (0.30)	1.20 (0.22)	1.28 (0.57)
Mg	0.56 (0.05)	0.58 (0.20)	0.59 (0.07)	0.84 (0.11)	0.61 (0.17)
Al	0.55 (0.10)	0.86 (0.37)	1.50 (0.38)	0.99 (0.32)	0.92 (0.47)
Fe	0.81 (0.11)	0.62 (0.22)	0.63 (0.10)	0.74 (0.13)	0.64 (0.20)
mg kg^{-1} of dry total solids					
Cr	32 (3)	49 (1546)	9770 (4458)	59 (29)	2217 (4041)
Cu	578 (44)	392 (103)	1430 (740)	621 (166)	754 (563)
Zn	708 (45)	1000 (69)	881 (365)	1170 (309)	1045 (348)
Pb	113 (4)	180 (28)	294 (70)	92 (31)	938 (2084)
Mn	227 (31)	207 (21)	151 (33)	834 (330)	269 (242)
B	36 (1)	36 (10)	36 (15)	27 (6)	31 (9)
Ni	13 (2)	27 (14)	16 (6)	30 (12)	23 (13)
Cd	8 (1)	8 (1)	7 (2)	6 (2)	9 (4)

† Arithmetic mean over years delivered; refer to Table 2 and text; standard deviation in ( ).

‡ Not weighted by volume delivered. Each plant average added equally to determine total.

and, over time, with respect to major inorganic components.

Trace element levels delivered to the Rosemount Watershed were typical of most municipal sewage sludges with the exception of Cr, Cu and Pb. The Hastings sludge had a much higher level of Cr and Cu than the other sludges, due to the presence of a tannery in that community. This sludge was delivered during the earlier years of the project. Cottage Grove had an extremely high variability in the Cr content of its sludge. Overall, Pb means are biased by a high Pb sludge from Lakeville early in the study. This variability in Pb content is reflected in a high standard deviation in the total for all plants. The majority of material delivered to the site can be characterized as a low Cd sludge, with levels less than 10 mg kg^{-1}.

Polychlorinated biphenyls (PCBs) were tested for two years in the sludge delivered from Hastings and Cottage Grove, and one year in the sludge delivered from Empire. Levels were

Table 16. Weighted mean of sludge metals delivered to the site versus USEPA ceiling concentrations.

Component	*Mean of Sludge Delivered*	*USEPA Ceiling Concentrations*
	mg kg^{-1} of dry total solids	
Cr	2217	3000
Cu	754	4300
Zn	1045	7500
Pb	938	840
Ni	23	420
Cd	9	85

***Table 17. Characteristics of strata in the Rosemount Watershed lagoons (February 1986).*†**

Stratum‡	*Thickness (m)*	*Solids (%)*	*NH_4^+-N*	*NO_3-N*	*Organic N*	*Total P*	*Total Cr*
Ice	0.49	0	288	9	3	600	1
Water	0.62	0	1,360	16	224	1,200	2
Suspended solids	0.28	6	18,500	488	29,800	23,900	1,900
Dense solids	0.52	24	6,200	248	18,400	20,200	4,400
Soil liner	0.10	76	1,430	22	748	1,800	20

† Ice and water are reported on a mass per volume basis, mg L^{-1}; suspended solids, dense solids, and soil liner are reported on a gravimetric basis (oven-dry), mg kg^{-1}; averages of 18 core samples on 18 m grid (nine cores per lagoon).

‡ Strata are listed from lagoon surface to 0.10 m below sludge-soil liner interface.

Table 18. Characteristics of strata in the Rosemount Watershed lagoon (March 1991).

Sludge Type	*Solids (%)*	*N (%)*	*NH_4^+-N (%)*	*Volatile Solids (%)*	*C (%)*	*pH*
Water	0.6	0.6	0.4	37.2	15.8	7.7
Light sludge	6.0	4.7	2.2	14.5	22.6	7.7
Heavy sludge	11.9	5.2	1.9	29.3	12.1	8.0
Solid sludge	29.7	1.5	0.4	46.5	23.4	8.1
Average†	8.2	3.6	1.4	30.1	15.0	7.9

† Average is a weighted number reflecting the total volumes of sludge in each strata.

1.4 and 1.6 mg kg^{-1} from Hastings for 1980 and 1981, respectively. PCB levels were 1.7 and 1.3 mg kg^{-1} from Cottage Grove sludge in 1980 and 1981, respectively. PCB levels were 0.17 mg kg^{-1} from Empire sludge in 1989. Table 16 provides a comparison between the means of the sludge delivered to the Rosemount Watershed and current USEPA limits for these metals. Pb is the only trace metal that, on average, slightly exceeded USEPA limits during this study.

SLUDGE IN STORAGE LAGOONS

Mixing of sludges from the different wastewater treatment plants occurred in the lagoons. Each year the sludge was stored in the lagoons for up to six months before application to the terraces. During this time, some of the volatile components (NH_4^+-N) may have escaped to the atmosphere and sludge organic matter continued to decompose. However, the most significant change was stratification due to sedimentation of sludge materials in the lagoon.

Core samples of sludge strata taken in February 1986 and March 1991 revealed these stratified layers included ice, supernatant liquid, liquid sludge, and sedimented sludge. Analyses of these cores, subdivided by these layers, are shown in Tables 17 and 18. Components of the sludge are concentrated in different layers of the lagoon. For instance, removal of liquid sewage sludge following incomplete mixing would tend to leave Cr, and probably other trace metals, in the lagoon.

SLUDGE APPLIED TO THE TERRACES

Composition of the mixed liquid sewage sludge applied to the sludge treatment areas was quite different from the sludge delivered from any one source. An example comparison of the analyses of incoming sludge additions and that applied to the terraces is shown in Table 19. Composition of the applied sludge also differed between corn and grass treatment areas and from year to year.

Lagoon stratification also explains the differences seen between composition of sludge applied to grass versus sludge applied to corn, even though it came from the same lagoon (Table 20). Often, during summer applications to grass, sludge was taken from the "clear supernatant" of the lagoon (i.e., the lagoon was not thoroughly mixed). This practice tended to separate sludge components. Soluble and suspended sludge components (NH_4^+-N, NO_3-N, K, and Na) were removed with the clear supernatant applied to grass. Total solids content was lower in sludge applied to grass than to corn, but the total N fraction was higher.

From this, one might deduce that the solids applied to grass during the growing season were withdrawn from the "suspended solids" stratum of the lagoon, where solids have a higher N content (refer to Tables 17 and 18). In addition to differences in solids and N content, the average composition of sludge applied to grass had higher K and Na content (along with a slightly higher EC). The fall sludge application to grass and corn treatment areas followed a more thorough mixing of sludge in the lagoons. Sludge composition, therefore, did not vary as much between grass and corn treatment areas in the fall.

In the falls of 1990 and 1991, no new sludge was delivered to the lagoon. Efforts were made to remove the stratified layers of sludge at the bottom of the lagoon and apply this material to the terraces. This was done in preparation for lagoon decommissioning at the completion of the study. This sludge had a relatively high solids content, but relatively low N content. Much of the material pumped onto the terraces in these two years contained sand and grit, as well as sludge. The high solids mixed from the lagoon bottom diluted nutrients and metal concentrations in 1990 and 1992 (Table 21). The lagoon was effectively "cleaned out" during these two sludge applications, and new sludge was added in the fall of 1992, to be applied later that season. After the 1992 sludge application, the lagoon was fairly empty of sludge and contained mainly water.

Table 19. Typical sludge composition for lagoon additions and removals (1982 data).

Characteristic	*Sludge Additions*†	*Sludge Removals*‡
Liquid		
	%	%
Total Solids	2.24	1.91
Volatile Solids	1.62	0.81
Total N	7.9 (1520 mg L^{-1})	4.29 (935 mg L^{-1})
NH_4^+-N	3.85 (719 mg L^{-1})	2.04 (312 mg L^{-1})
EC (dS m^{-1})	6.28	3.04
pH	7.8	7.5
Freeze-dried§		
	%	%
OM	65.1	44.5
C	33.3	23.1
P	2.89	2.31
K	0.34	0.25
Ca	4.16	3.88
Na	1.56	1.12
Mg	0.56	0.82
Al	1.18	1.39
Fe	0.60	1.14
	mg kg^{-1}	*mg kg^{-1}*
Cr¶	5991	15242
Cu	1718	1177
Zn	774	997
Pb	174	29
Mn	138	341
Ni	37	35
B	20	15
Cd	6	5

† Sludge delivered to the lagoons in 1982.
‡ Sludge applied to the terraces in 1982.
§ Values based on 105° C weight as a percentage of total solids.
¶ Cr levels for sludge removed are elevated by high Cr in sludge added the previous years.

SUMMARY OF SLUDGE APPLICATION

During the 20-yr study, municipal sewage sludge was applied on corn areas at an average rate of 4 cm liquid yr^{-1}, 12 Mg solids ha^{-1} yr^{-1}, and 473 kg N ha^{-1} yr^{-1}. A total of 28 sludge applications were made during the 20-yr study, resulting in a total of 68 cm of sludge, 224 Mg ha^{-1} solids, and 9 460 kg ha^{-1} total N. On the original grass areas, sludge was applied at an average rate of 8 cm liquid yr^{-1}, 14 Mg solids ha^{-1} yr^{-1}, and 836 kg N ha^{-1} yr^{-1} for 12 years, followed by 1.7 cm liquid yr^{-1}, 11 Mg solids ha^{-1} yr^{-1} and 293 kg N ha^{-1} yr^{-1} for eight years. During the 20-yr study, a total of 68 sludge applications were made, resulting in a total of 110 cm of sludge, 260 Mg ha^{-1} solids, and 12 386 kg N ha^{-1}. Total sludge and nutrients applied by cropping season are shown in Table 13.

Sludge Zn, Cu, Pb, Ni, and Cd concentrations applied to the terraces were below the pollu-

Table 20. A comparison of sludge applied to corn and grass treatment areas.†

Component‡	Corn (1974-1992)		Grass (1974-1983)	
	Mean	S. D.‡	Mean	S. D.‡
Total solids				
(% of liquid sample)	4.53	3.44	1.94	0.48
Volatile solids				
(% of liquid sample)	1.50	0.85	0.90	0.34
EC (dS m^{-1})	3.9	1.1	4.4	0.8
pH	7.5	0.3	7.8	0.1
Total N				
(% of oven-dry total solids)	4.50	2.83	5.93	2.49
(mg L^{-1})	1489	504	1095	286
NH_4^+-N				
(% of oven-dry total solids)	1.98	2.16	2.58	2.77
(mg L^{-1})	520	127	460	109
	% of oven-dry total solids			
OM	44.1	9.2	47.6	6.4
C	21.4	5.6	25.7	3.4
P	2.38	0.65	2.46	0.20
K	0.31	0.18	0.43	0.29
Ca	4.29	0.55	4.29	0.37
Na	1.00	0.86	1.76	0.49
Mg	0.82	0.16	0.75	0.16
Al	1.28	0.61	1.54	0.39
Fe	0.88	0.24	0.84	0.06
	mg kg^{-1} oven-dry total solids			
Cr	4287	5042	9090	4014
Cu	599	328	1040	257
Zn	808	259	816	327
Pb	242	122	268	72
Mn	387	119	270	83
B	28	17	28	14
Ni	24	11	25	6
Cd	6	2	6	1

† Averages weighted by amount of dry solids (Mg ha^{-1}) applied each year.

‡ S. D. stands for the standard deviation of the mean values.

Table 21. A comparison of sludge composition applied to terraces over time.

Characteristic†	Corn 1974-89	Corn 1990-92‡
	%	
Total solids	2.96	10.0
Total N	6.92	1.83
NH_4^+-N	1.77	0.63
Total C	23.6	15.0
P	2.51	1.75
K	0.33	0.17
Ca	4.48	4.02
Na	1.07	0.17
Mg	0.75	0.98
Fe	0.92	0.88
	mg kg^{-1}	
Cr	5210	1760
Cu	802	350
Zn	841	647
Pb	292	171
Mn	341	517
B	29	26
Ni	23	24
Cd	7	4
EC (dS m^{-1})	4.0	3.3
pH	7.5	7.5

† Total solids based on 105° C dry weight. Other constituents based on percentage of total solids.

‡ High solids mixed from the lagoon bottom diluted nutrients and metal concentrations in 1990-1992.

tant concentrations set by USEPA for limiting total metal loading on a given site. Concentrations of Cr in the sludge were high and variable. Since Cr is insoluble in soil systems, it served as an excellent tracer for following particulate movement in and through the watershed.

NUTRIENT VALUE OF THE SLUDGE

One way to evaluate the effectiveness of sludge as a commercial fertilizer substitute is to look at an assay of elements found in the sludge and simply assume the elements are available to plants. Even though we know many of the elements found in sludge are in organic form, and must be mineralized (changed to inorganic form by decomposition or released from the organic component) before they become available for plant use, this approach assumes that eventually all nutrients will become available. For example, a unit of N in sludge is thought to be equivalent to a unit of N in commercial fertilizers.

Table 22. Corn grain and fodder yields at the Rosemount Watershed.†

Year	Grain						Fodder		
	Mg ha^{-1}			bu acre^{-1}‡			Mg ha^{-1}		
	Control	Sludge	Differ§	Control	Sludge	Differ§	Control	Sludge	Differ§
1974	6.7	6.2	-0.5	106	99	-7	15.1	14.0	-1.1
1975	4.7	6.6	1.9	75	104	29	10.9	14.1	3.2
1976	7.8	7.7	-0.1	125	123	-2	15.2	15.4	0.2
1977	11.0	11.1	0.1	176	176	0	19.0	19.0	0
1978	11.7	12.4	0.7	186	197	11	20.8	19.9	-0.9
1979	8.7	10.3	1.6	138	164	26	16.9	18.2	1.3
1980	7.4	8.5	1.1	118	135	17	12.1	13.4	1.3
1981	8.7	10.2	1.5	138	163	25	17.0	18.7	1.7
1982	9.9	10.6	0.7	157	169	12	16.4	17.5	1.1
1983	8.1	7.5	-0.6	149	158	9	16.7	17.1	0.4
1984	7.2	8.2	1	135	154	19	15.6	16.8	1.2
1985	6.8	7.7	0.9	127	146	19	13.9	15.4	1.5
1986	8.2	8.2	0	154	154	0	15.7	14.7	-1
1987	7.9	8.7	0.8	149	163	14	14.4	15.9	1.5
1988	6.1	6.4	0.3	114	121	7	12.7	13.1	0.4
1989	8.6	9.6	1	162	180	18	17.8	19.2	1.4
1990	6.4	7.4	1	120	139	19	13.4	15.6	2.2
1991	9.7	9.1	-0.6	178	173	-5	17.7	16.7	-1
1992	8.8	9.0	0.2	167	170	3	21.4	19.0	-2.4
1993	6.8	7.1	0.3	129	137	8	13.4	13.8	0.4
Average	8.1	8.6	0.6	140	151	11.1	15.8	16.4	0.6
S. D.¶	(1.7)	(1.7)	(0.7)	(27)	(26)	(10.6)	(2.7)	(2.1)	(1.3)

† Oven dry (65° C) basis; grain is shelled corn; fodder is whole plant.

‡ Bushels per acre of shelled corn at 15.5% water; calculated value.

§ Represents the difference between sludge and control values (Sludge – control = difference)

¶ Standard deviation values are listed in ( ).

CROP YIELDS ANALYSIS

AGRONOMIC YIELDS

Crop yield is perhaps the most important determinant of the economic value of sludge as a substitute for commercial fertilizer. Corn and forage crop yields were compared between areas treated with liquid sewage sludge and areas treated with commercial fertilizer at the Rosemount Watershed.

CORN

Corn has value either as a forage crop (fodder yield) or as a grain crop (grain yield) and both yields are given in this report. Each of these is reported on an oven-dry (65°C) basis. (Note: the term fodder denotes total dry matter for corn.) Corn grain and fodder yields are shown in Table 22 and Fig. 11. Yields in bu A^{-1} (corrected to 15.5% moisture) are also shown. The overall trend of both fodder and grain yields is relatively the same, each showing highs and lows in the same years. Control and sludge treatment yields also follow the same trends indicating a large influence of climate on crop yields. This relation leads one to conclude that environmental conditions, rather than treatments, contribute to most of the variation seen in yields over the years.

Liquid sewage sludge was an effective source of N and P for crops. The sludge treatment area produced significantly greater grain yields (Mg ha^{-1}) than the control treatment area every year except 1974, 1976, 1983, 1986, and 1991. The sludge treatment produced significantly greater fodder yields (Mg ha^{-1}) than

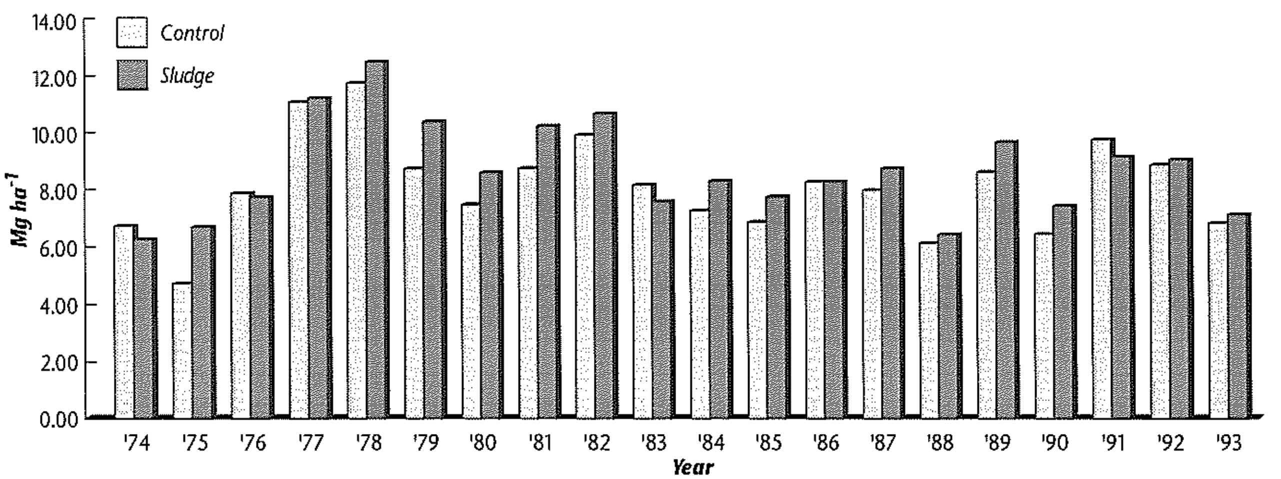

Figure 11a. Corn grain yields (1974-1993).

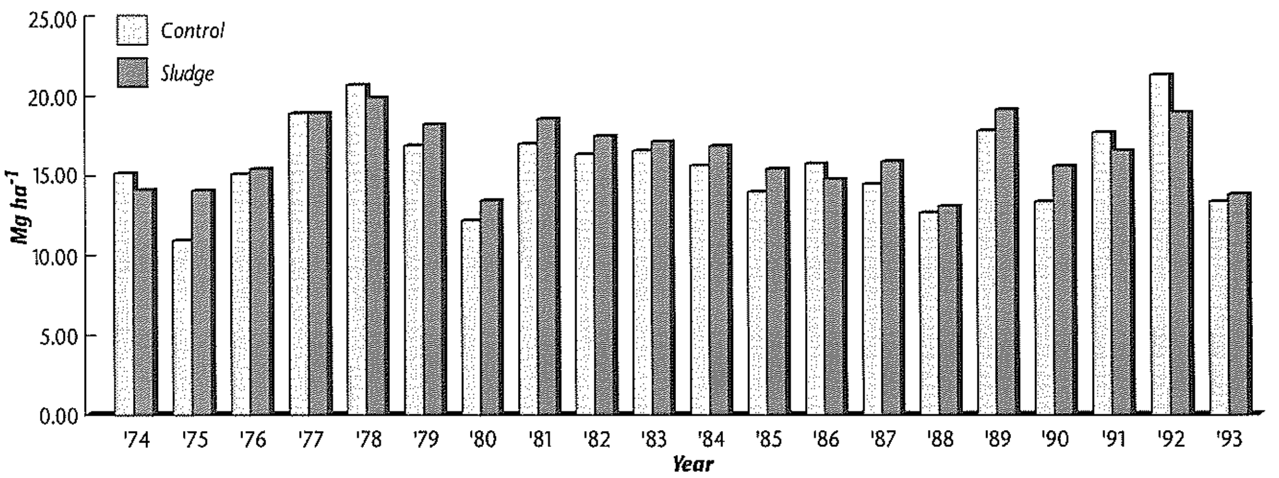

Figure 11b. Corn fodder yields (1974-1993).

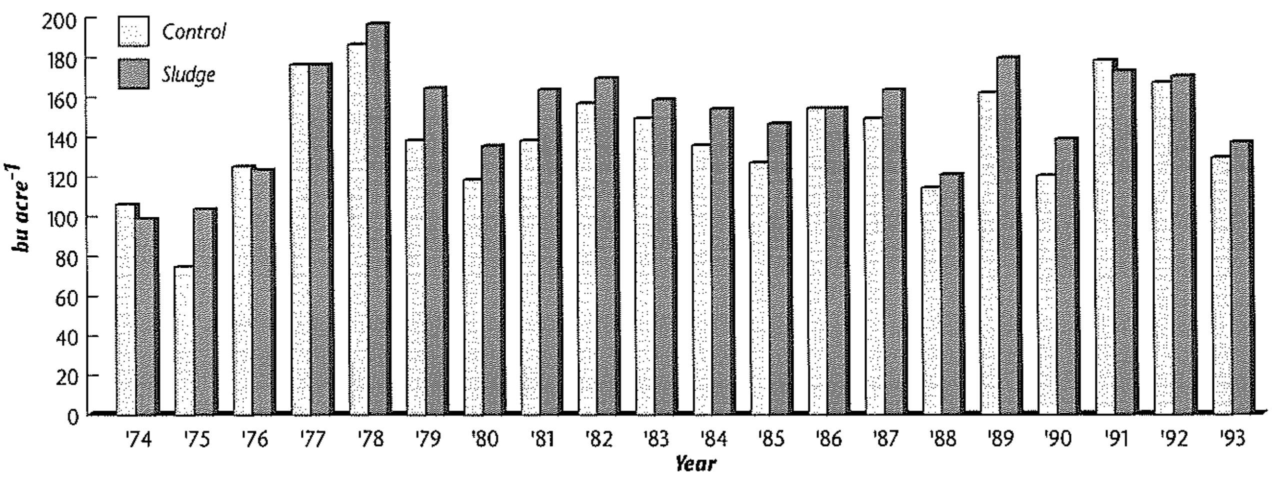

Figure 11c. Corn yield in bushels (1974-1993).

Table 23. Reed canarygrass yields and nutrient composition at the Rosemount Watershed.

Treatment	Yield				Nutrient Concentration			Total Nutrients Removed		
	1st Cut	2nd Cut	3rd Cut	Total	N	P	K	N	P	K
	Mg ha^{-1}†				%			kg ha^{-1}		
Control										
1976	3.9	2.5	1.4	7.8	3.12	0.27	2.95	242	22	233
1977	5.7	2.8	1.8	10.3	2.84	0.31	2.91	293	32	299
1978	4.9	3.4	2.0	10.3	3.03	0.34	3.06	312	35	317
1979	3.5	3.7	2.1	9.3	3.56	0.35	3.10	329	32	287
1980	4.7	1.6	2.5	8.8	—	—	—	276	32	250
1981	6.5	3.1	2.5	12.1	—	—	—	342	38	359
1982	4.9	2.7	2.2	9.8	—	—	—	319	31	316
1983	5.1	3.1	—	8.2	—	—	—	178	32	294
Mean	4.9	2.9	2.0	9.6	3.14	0.32	3.00	286	32	294
Sludge										
1976	4.6	3.4	1.7	9.7	3.03	0.29	3.22	291	28	307
1977	6.1	3.9	3.0	13.0	3.28	0.38	3.18	428	48	406
1978	5.5	2.8	2.5	10.8	3.22	0.45	3.22	349	49	350
1979	4.9	3.3	2.0	10.2	3.45	0.43	2.95	353	44	301
1980	5.9	1.5	3.0	10.4	—	—	—	334	44	303
1981	5.7	4.3	3.0	13.0	—	—	—	389	61	445
1982	5.5	3.7	2.7	11.9	—	—	—	378	54	446
1983	5.5	4.4	—	9.9	—	—	—	213	47	365
Mean	5.4	3.4	2.6	11.1	3.24	0.39	3.14	342	47	365

† 'Rise' reed canarygrass. For 1976-79, means of 9 replicated plots on the control areas; 36 replicated plots on the sludge-treated areas. For 1980-83, means of 9 replicated plots on the control areas; 18 replicated plots on the sludge-treated areas. Dried at 65° C.

the control treatment every year except 1974, 1977, 1978, 1986, 1991, and 1992.

The 20-yr corn grain yield averaged 8.6 Mg ha^{-1} (151 bu A^{-1}) for sludge treatments, whereas corn grain yield averaged 8.1 Mg ha^{-1} (140 bu A^{-1}) on the fertilized control area. The sludge treatments out-yielded the control by 0.5 Mg ha^{-1} (11 bu A^{-1}) averaged over 20 years of corn grain production at the Rosemount Watershed study. Average corn fodder yield on sludge treatment areas was 16.4 Mg ha^{-1}, as compared to a yield of 15.8 Mg ha^{-1} from the control treatment. The sludge treatment again out-yielded the control by 0.6 Mg ha^{-1} for fodder.

Variation in corn grain yield over 20 years was identical for sludge and control treatments (standard deviation 1.7 Mg ha^{-1}). Variation in fodder yield, over the same years, was slightly greater for the control area (2.7 Mg ha^{-1}) than for the sludge treatment area (2.1 Mg ha^{-1}). Grain yields ranged from 6.2 to 12.4 Mg ha^{-1} on the sludge treatment areas, and from 4.7 to 11.7 Mg ha^{-1} on the control areas. Bushel averages ranged from 99 to 197 bu A^{-1} on the sludge treatment areas, and 75 to 186 bu A^{-1} on the control treatment areas. Fodder yields ranged from 13.1 to 19.9 Mg ha^{-1} on the sludge areas, and from 10.9 to 21.4 Mg ha^{-1} on the control areas.

These results may be affected by the fact that twice as much N was applied to sludge areas as to control areas. Also, the sludge areas received more moisture from the sludge itself, which is approximately 90% water (H_2O).

REED CANARYGRASS

Average annual reed canarygrass yields for eight years are shown in Table 23 and Fig. 12. Average annual yield from sludge treatment areas was 11.1 Mg ha^{-1} versus 9.6 Mg ha^{-1} from the fertilized control area. Yields ranged from 9.7 to 13.0 Mg ha^{-1} on sludge treatment areas and 7.8 to 12.1 Mg ha^{-1} on the control area. Grass yields generally decreased from first to third cutting. The influence of water added

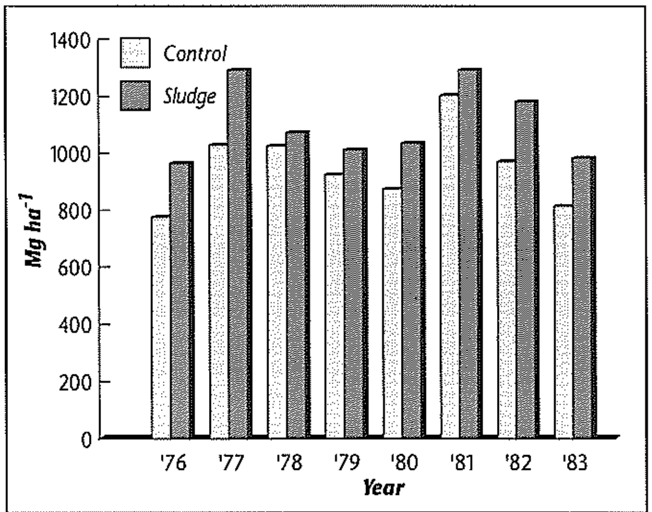

Figure 12. Reed canarygrass yields (1976-1983).

with the sludge on yields is unknown. Overall, grass yields for the sludge areas were markedly higher than the fertilized control areas.

Overall, corn and grass yields are representative of those found in this part of the state. Other than the occasional wet or cold spring, only a few severe conditions for crop growth were noted. Drought was a cause of stress for crops in 1976 and 1988. In 1978, a heavy infestation of army worms caused severe damage to reed canarygrass in localized spots. In 1980, a severe wind and hail storm on July 16 may have reduced yields for that year. In 1992, frost damage occurred on June 21, but did not seem to affect crop growth and yields. In 1993, the watershed received excessive amounts of rain which reduced yields. Weed and fungus problems were significant in the years of 1990 to 1992. Efforts were made to reduce these problems through the use of herbicides and fungicides.

Weed and fungus problems were significant in the final years of the project. After 20 years of continuous corn planting, control of weeds became more difficult. The main weeds were wild proso millet *(Panicum miliaceum)*, a plant very similar in structure and physiology to the corn plant, and velvetleaf *(Abutilon theophrasti)*. Herbicides were applied in an attempt to control both the wild proso millet and the velvetleaf.

There were three fungi found on corn cobs during sampling in 1991. They were *Cladosporium sp.*, *Fusarium sp.*, and *Mucor sp.* These fungi were found consistently on a large percentage of cobs. Growing continuous corn on the terraces for 20 years had allowed an ideal environment for weeds and fungi. In a normal agricultural operation, these problems would be reduced or better managed with regular crop rotations. All corn treatment areas were fall chisel-plowed.

The objectives of the Rosemount Watershed study included finding an overall management system for the use of sludge on agricultural land, and protecting the environment while producing a crop. The study was designed with some assumptions about the rate of application and did not include a variable rate application study which would be necessary for finding optimum sludge application rates for crop production. Therefore, the economic value of sludge, or finding the maximum net return to a producer who substitutes sludge for commercial fertilizer is not addressed in this study.

OTHER FORAGE YIELD TRIALS

The forage trial experiment established in the east end of terrace 4 was a comparison of forage performance under sludge application. These plots were treated with sludge like the rest of the terrace.

Yields and forage quality factors are reported in Table 24. 'Saranac' alfalfa was badly affected by Phytophthera root rot; 'Agate' was also slightly damaged. Sludge application severely affected the smooth bromegrass stands for unknown reasons. Only the tall fescue and the reed canarygrass maintained vigorous stands. 'Rise' reed canarygrass maintained a good stand and high yield throughout the study. Total IVDDM and CP were maximum in reed canarygrass (multiplying the dry weight percentage by the dry matter yield). Alfalfa had slightly better feed quality, but did not maintain a vigorous stand in this study. Reed canarygrass is clearly the superior forage species for long-term utilization of nutrients applied in sludge.

NUTRIENTS REMOVED IN CROPS

Fig. 13 shows that there is little difference between tissue concentrations of N, P, and K in crops grown on sludge versus control areas when averaged over a period of time. Because large amounts of N and P were applied in the sludge compared to the commercial fertilizer treatment, one could say that crops on both

Table 24. Yield and quality of special forage plots (1976-1980).

Variety†	Yield				IVDDM‡		CP‡		CWC‡		Stand§	
	1976	1977	1978	1979	1978	1979	1978	1979	1978	1979	1979	1980
	Mg ha^{-1}				dry mass						%	
Fox	10.2	11.2	9.0	6.3	71	68	18	18	59	59	78	19
Rise	11.9	12.8	13.4	13.1	69	65	19	20	60	57	100	98
Kentucky 31	11.0	11.6	9.7	5.9	71	69	19	18	54	54	65	38
Agate	12.1	10.7	9.5	5.7	76	68	23	22	37	41	61	20
Saranac	13.1	10.2	7.0	1.4	73	72	22	22	38	36	25	5

† 'Fox' smooth bromegrass; 'Rise' reed canarygrass; 'Kentucky 31' tall fescue; 'Agate' and 'Saranac' alfalfa.
‡ IVDDM, in vitro digestible dry matter; CP, crude protein; CWC, cell wall constituents.
§ Stand represents the percentage of crop that germinated.

treatment areas were in the optimum range for crop yield and that yields and uptake were limited by other factors such as climate. For comparison, sufficient levels of N, P, and K in the North Central region (NCR 13 committee recommendations) are reportedly 27.6, 2.5, and 17.1 g kg^{-1}, respectively, for corn ear leaf at tasseling and 30.0, 3.9, and 27.5 g kg^{-1}, respectively, for tall grasses.

CORN

A clear view of the total macronutrients removed by corn versus the amounts applied in sludge or commercial fertilizer is found in Figs. 14, 15, and 16 for N, P, and K, respectively. For N and P, more nutrients were added with sludge than with commercial fertilizer. The amounts removed, however, are nearly equal for sludge and control treatments.

Large amounts of N and P applied by sludge did not adversely affect yields by creating imbalances of nutrients within the plant. The municipal sewage sludge was K-deficient, so control and sludge areas did not receive equal amounts of K fertilizer. The sludge treatments received the same amount of K fertilizer as the control area, plus the amount contained in the sludge. Large amounts of K were removed by the crop indicating a high capacity of the soil to supply this nutrient without replenishment from fertilizer or sludge.

Elemental analyses of plant tissues showed that corn took up N, P, and K equally well from the sludge and control areas, removing an average of 205 and 188 kg N ha^{-1} yr^{-1}, respectively (Table 25). Corn fodder removed a total of 3360, 538, and 2330 kg ha^{-1} of N, P, K,

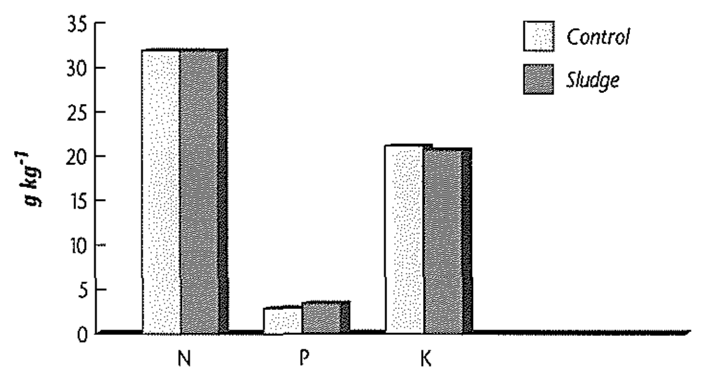

Figure 13a. Average tissue concentration of corn leaf at silking (1974-1986).

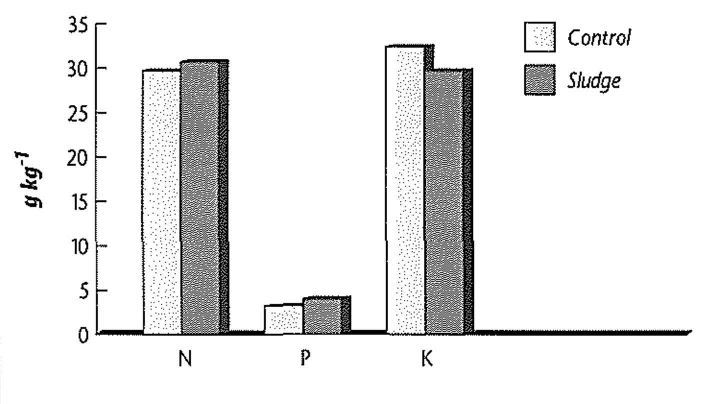

Figure 13b. Average tissue concentration in reed canarygrass (1974-1984).

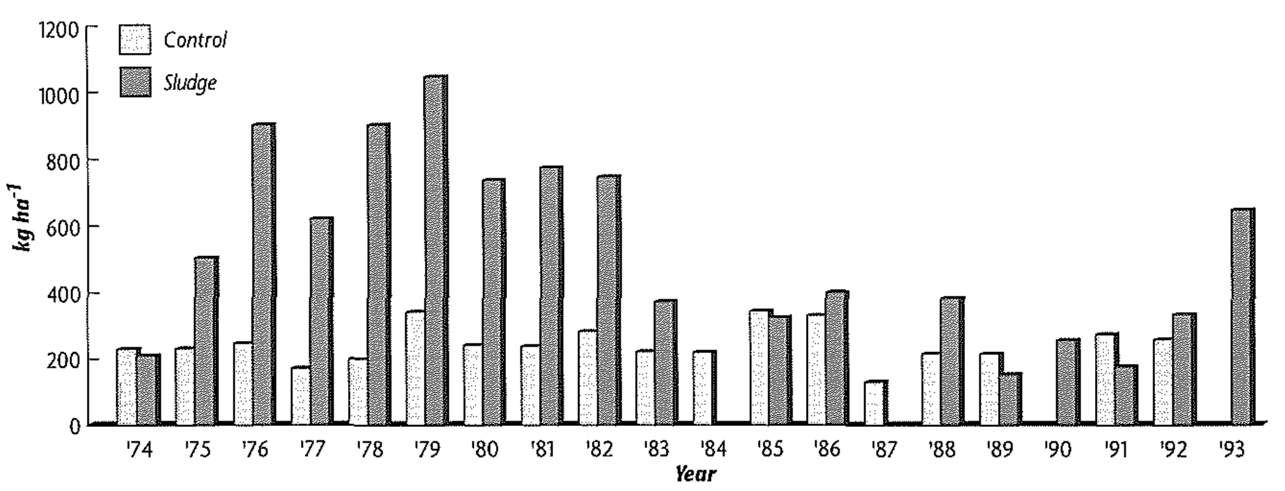

Figure 14a. Amount of N applied to corn (1974-1993).

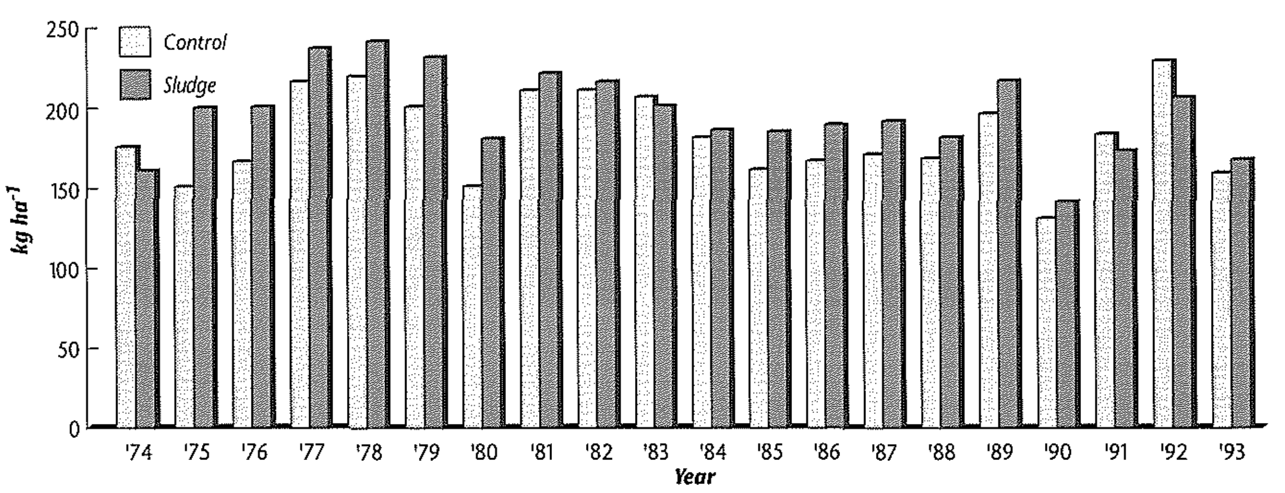

Figure 14b. Amount of N removed by corn (1974-1993).

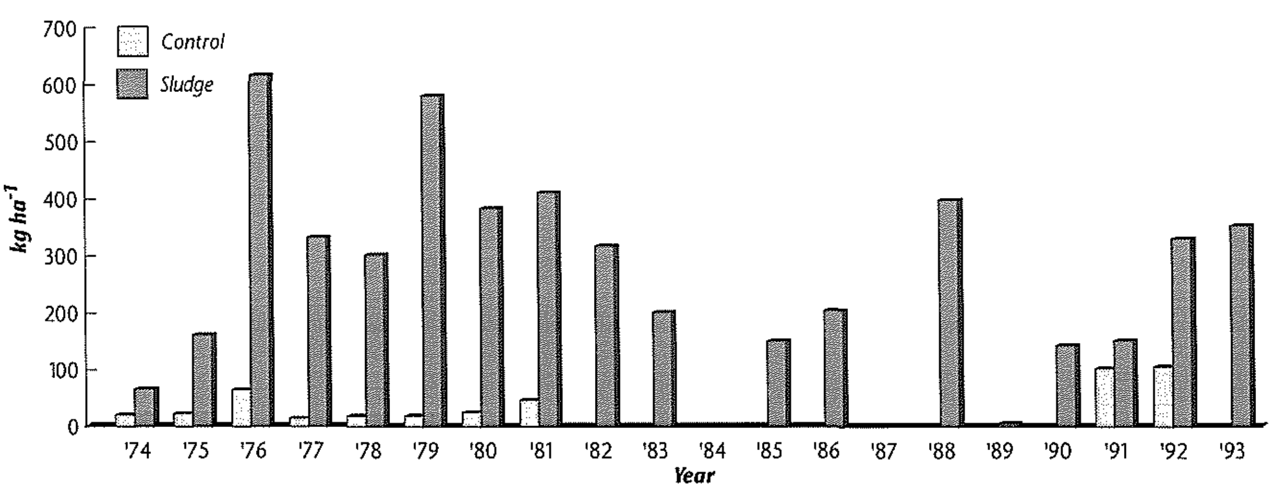

Figure 15a. Amount of P applied to corn (1974-1993).

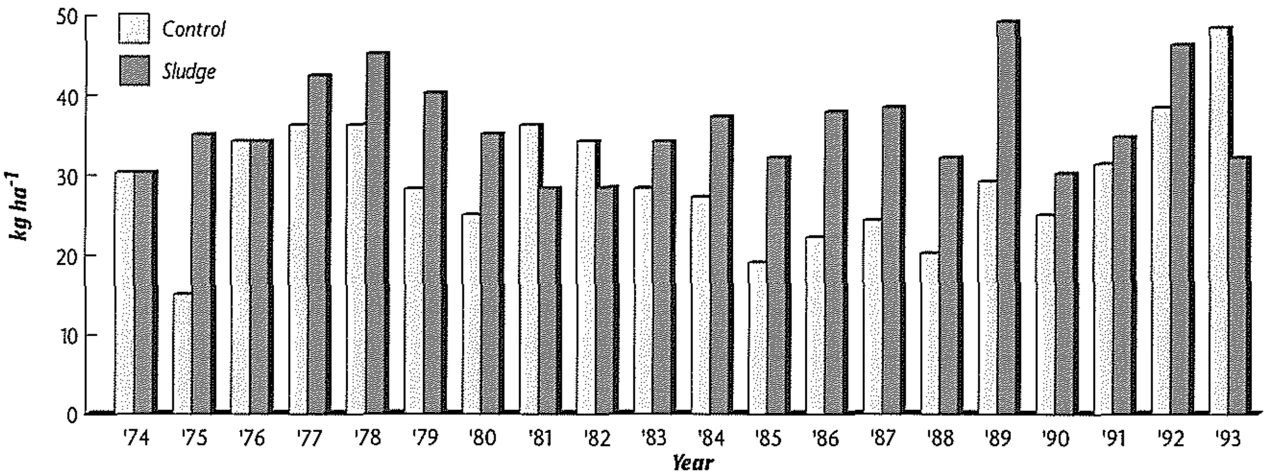

Figure 15b. Amount of P removed by corn (1974-1993).

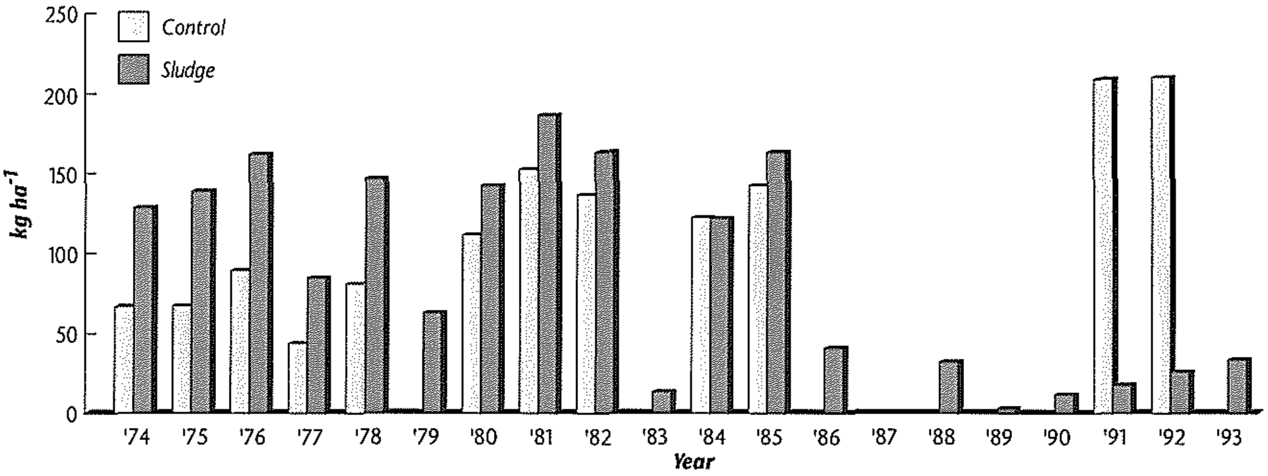

Figure 16a. Amount of K applied to corn (1974-1993).

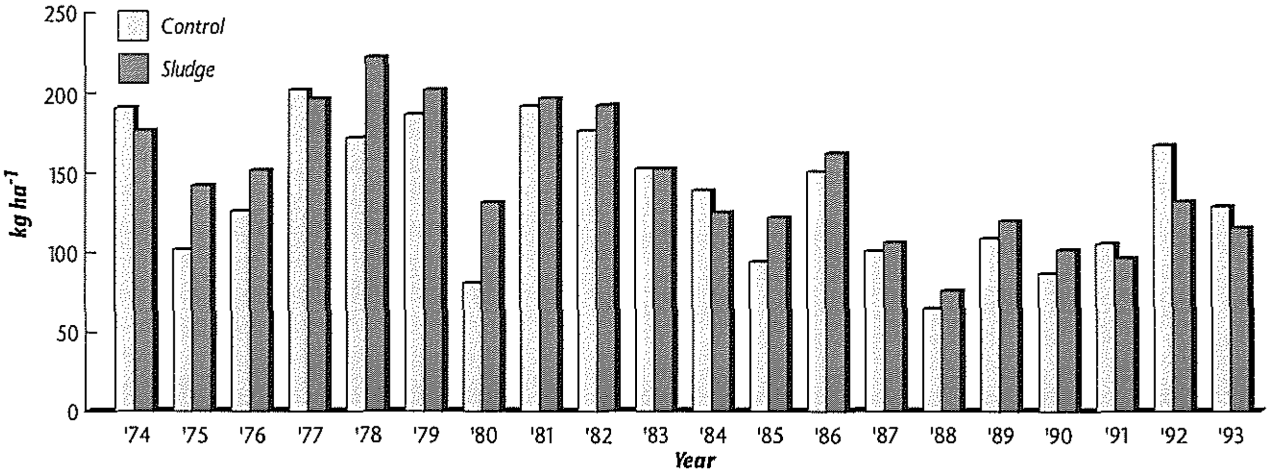

Figure 16b. Amount of K removed by corn (1974-1993).

Table 25. Corn yields and nutrients removed during 4-year periods at the Rosemount Watershed.

Treatment[‡] Year	Yield			Total Nutrients Removed Annually		
	Grain		Fodder[§]	N	P	K
Control	Mg ha^{-1}	bu acre^{-1}	Mg ha^{-1}	kg ha^{-1}		
1976-79[¶]	8.3	156	18.0	203	32	157
1980-83[¶]	7.6	142	15.5	195	32	142
1984-87[¶]	7.4	139	14.7	169	23	120
1988-91[¶]	7.7	144	15.4	176	26	90
1992-93[#]	7.8	147	17.4	194	43	147
mean	7.7	145	15.9	188	29	130
Sludge						
1976-79[¶]	8.8	165	18.1	223	38	165
1980-83[¶]	8.1	152	19.4	232	38	152
1984-87[¶]	8.3	155	15.7	187	36	127
1988-91[¶]	8.1	153	16.1	177	36	97
1992-93[#]	8.0	152	16.4	186	39	122
mean	8.4	156	17.4	205	38	135

[†] For 1976-80, Northrup King PX-4498 (95 day); 1980, Northrup King PX448 (95 day); 1981-83, Pioneer 3780 (105 day); 1984, Funks 4256 (95 day); 1985 and 1986, Stauffer 4402 (105 day); 1987, Stauffer 4414 (100 day); 1988, Asgrow 498 (100 day); 1989, Dekalb 464 (100 day); 1990, Coden 3151 (100 day); 1991 and 1992, Jacques 4770 (95 day); 1993, Pioneer 3780 (105 day).

[‡] Means of 3 replicated plots on the control areas; 6 replicated plots on the sludge-treated areas. Yields represent dry matter at 65°C. Shelled grain calculated in bu A^{-1} at 15.5% H_2O.

[§] Fodder = total dry matter = grain + cob + stover.

[¶] Mean values for 4 years.

[#] Mean values for 2 years.

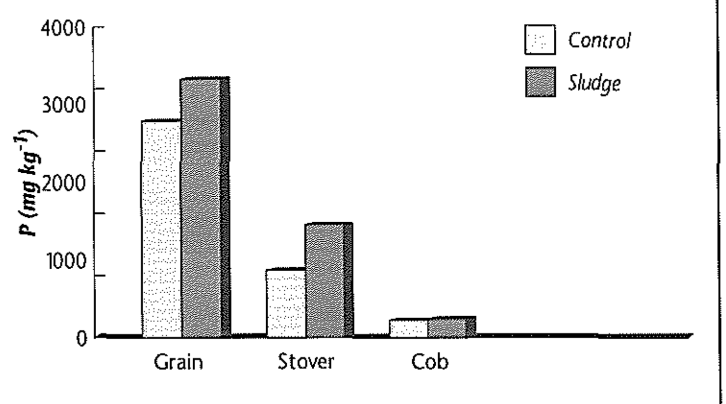

Figure 17. P concentration in corn: Year 20.

respectively, from the control treatment area, over the 1974 to 1993 period. This amount was 73, 101, and 144% of the fertilizer applied to the control treatment area. Corn removed a total of 3648, 670, and 2512 kg ha^{-1} of N, P, and K, respectively, from the sludge treatment areas over the 1974 to 1993 period. This amount was 39, 13, and 150% of total N, P, and K applied to sludge treatment areas. Crop uptake efficiency less than 100% means that excess nutrients remain in the soil system. Uptake efficiency values greater than 100% means that the crop is removing native soil reserves.

Approximately 30% more P was removed annually in corn fodder (grain + cob + stover) grown in sludge-treated soils than in corn from control areas. On average, this corresponded to about 9 kg P ha^{-1} yr^{-1}. However, P concentrations in year-20 corn grain, stover, and cob tissue were not significantly increased by sludge loadings (Fig. 17). Corn grown in sludge-treated soils removed only a small portion (<15%) of sludge-applied P, and did not show a corresponding increase in P concentration, despite massive loadings of more than 250 kg P ha^{-1} yr^{-1}.

REED CANARYGRASS

Reed canarygrass exhibited the same behavior as corn, when considering N and K removal. Nearly equal amounts were removed by the crop in control and sludge treatment areas (Figs. 18, 19, and 20, and Tables 26 and 23). Sludge-treated grass seemed to remove more P, however, than fertilized controls. Again, the amounts of N and P applied to grass in sludge were much larger than amounts applied in the commercial fertilizer treatments (Table 26).

The discrepancy between soil tests and tissue analyses could be due to the nature of application methods. Neither sludge nor commercial fertilizer was incorporated into the soil on grass treatment areas. Commercial fertilizer was broadcast on the surface and required natural rainfall to dissolve and move the fertilizer into the soil. Inorganic P is not very mobile in the soil. It is likely that most fertilizer P was trapped in the first 5 cm of soil where it often is too dry for plants to obtain. Much of the sludge-applied P was in organic form. An application rate of 2.5 cm of liquid sewage sludge

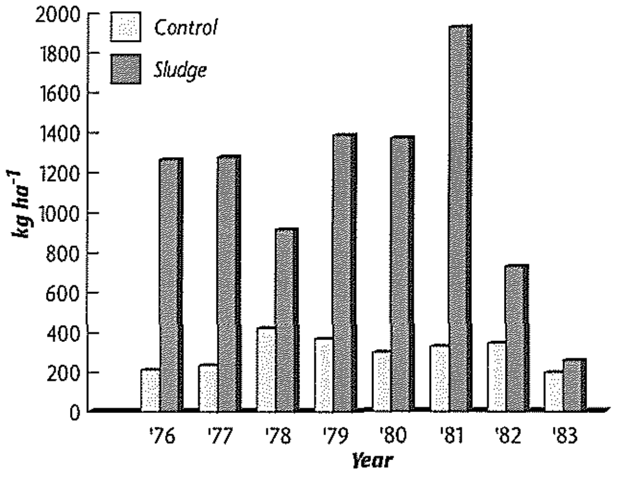

Figure 18a. Amount of N applied to reed canarygrass (1976-1983).

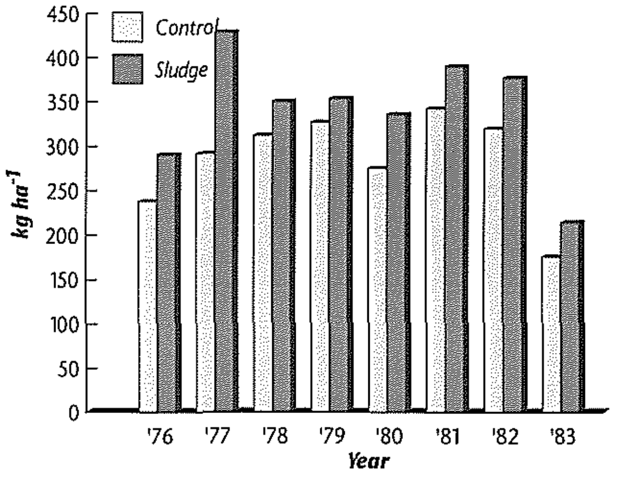

Figure 18b. Amount of N removed by reed canarygrass (1976-1983).

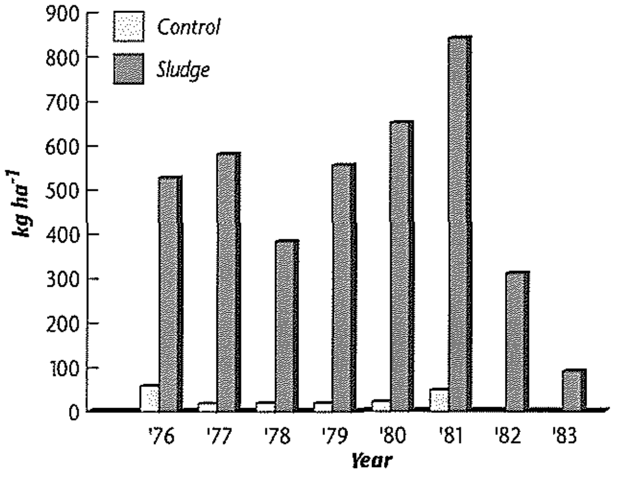

Figure 19a. Amount of P applied to reed canarygrass (1976-1983).

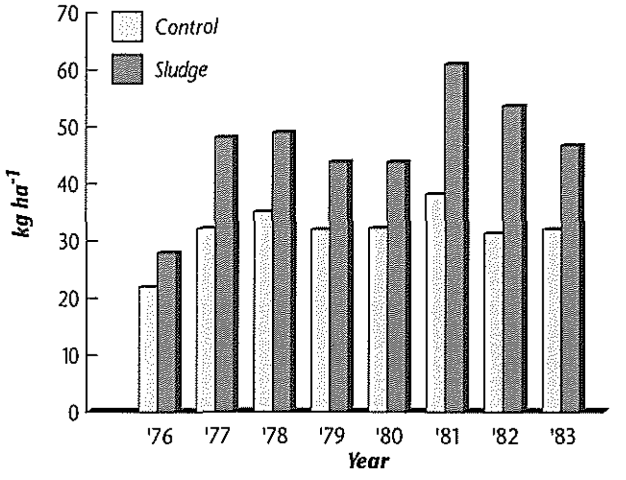

Figure 19b. Amount of P removed by reed canarygrass (1976-1983).

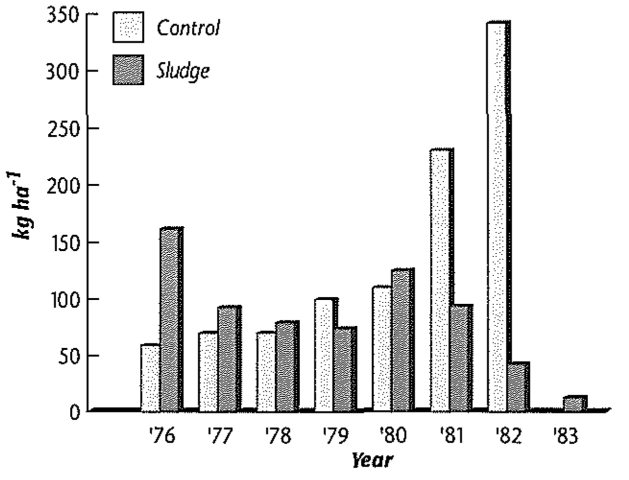

Figure 20a. Amount of K applied to reed canarygrass (1976-1983).

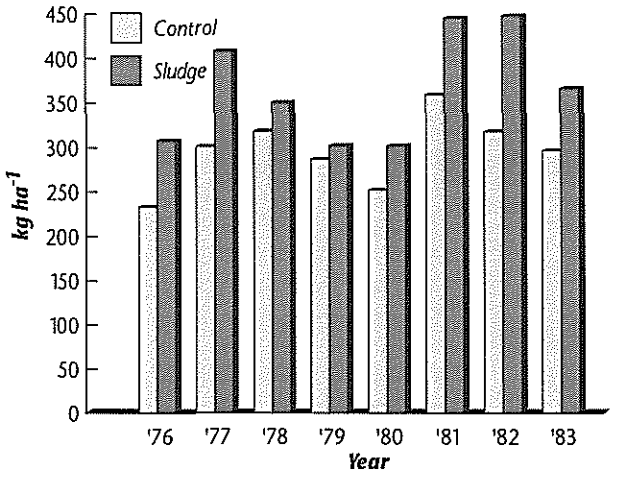

Figure 20b. Amount of K removed by reed canarygrass (1976-1983).

Table 26. Total amounts of N, P, and K applied to reed canarygrass at the Rosemount Watershed.

Year	*Control Treatment*†			*Sludge Treatment*‡			
	N	*P*	*K*	*N*	*P*	*K*	*K Fertilizer*
	kg ha^{-1}						
1976§	221	58	59	1260	528	161	59
1977	232	20	69	1270	583	93	69
1978	415	17	70	908	382	79	0
1979	368	17	100	1380	555	73	100
1980	300	23	110	1360	648	125	110
1981	330	50	230	1920	838	93	230
1982	340	0	340	729	308	42	340
1983	197	0	0	260	93	13	0
1984	0	0	0	0	0	0	0
Total	2403	185	978	9087	3935	679	908

† Commercial fertilizer.

‡ Fertilizer K was used to supplement sludge treatments.

§ Total application of sludge-applied N, P, and K for 1974, 1975, and 1976.

would saturate the top 15 cm of the soil. P in the sludge then mineralized in a soil zone more favorable for plant uptake. Soil test sampling mixed the top 15 cm of soil and could not discriminate P levels within this zone. Sludge appeared to be more effective in delivering P to a forage crop.

Grass removed a total of 2292, 252, and 2356 kg ha^{-1} of N, P, and K, respectively, from the control treatment area over the 1976 to 1983 cropping period. This amount was 95, 136, and 240% of the total applied in commercial fertilizer to the control area. Grass removed a total of 2732, 376, and 2924 kg ha^{-1} of N, P, and K, respectively, from the sludge treatment area over the 1976 to 1983 cropping period. This amount was 30, 10, and 184% of the N, P, and K, respectively, applied to the sludge treatment areas when averaged over the 8-yr period. The reed canarygrass removed 342 and 286 kg N ha^{-1} yr^{-1} for sludge and control treatments, respectively. The grass tissue showed less-than-optimum amounts of P available in the grass control area.

On an average annual basis, reed canarygrass out-performed corn in the ability to remove N, P, and K from sludge-amended soils. Grass removal of N, P, and K was 342, 47, and 366 kg ha^{-1} yr^{-1} respectively, on sludge treatment areas. Average annual removal of N, P, and K by corn from the sludge treatment areas was 205, 38, and 135 kg ha^{-1}yr^{-1}, respectively. High N and P uptake made reed canarygrass an excellent crop for nutrient removal. Low alkaloid varieties of reed canarygrass have been developed for increased levels of palatability to livestock (see current Minnesota Extension Service publications for details).

SUMMARY OF CROP YIELDS AND ANALYSES

In summary, liquid sewage sludge was an effective substitute for commercial N and P fertilizer on corn and forage crops. Yields were equal to or exceeded those of areas of traditional fertilizer management. Elemental analyses of plant tissue showed that corn took up N, P, and K equally well from sludge and control managed areas.

An important point to note is that large amounts of N and P applied by sludge did not adversely affect yields by creating imbalances of nutrients within the plant. Sludge supplied many of the other macro- and micronutrients required for plant growth and development. Because the amount of N and P removed by sludge and control treatments were nearly equal for the corn crop, it appeared that lower sludge application rates (beginning 1985) could be used, thus increasing the efficiency of nutrient use by the crop.

TRACE ELEMENTS

Eight trace elements were monitored in sludge and plant tissue samples from the beginining of the Rosemount Watershed study. Four of these are considered essential for plant growth (micronutrients Zn, Cu, B, and Mn) and four are considered impurities in the food chain (Cr, Pb, Ni, Cd). Some micronutrients such as B, while essential, have a narrow range of sufficiency and can be toxic to plants when they are above critical concentrations in the plant. All eight elements occur naturally in soils of this area (Table 27).

BACKGROUND LEVELS OF TRACE ELEMENTS

A survey of Minnesota soils found amounts of Zn, Cu, Cr, Pb, Ni, and Cd present to different degrees in surface and subsurface soil materials (Pierce et al., 1982). Three kinds of chemical extracting solutions were used to determine total, available, and organic-bound metals in the soils. Table 28 lists the average metal con-

Table 27. DTPA-extractable elements from Rosemount Watershed soils.†

Metal‡	Extractable-DTPA			
	Corn		Grass	
	1973	1977	1973	1977
	mg kg^{-1}			
Zn	1.4	6.7	1.9	3.5
Mn	37.0	25.0	92.0	43.0
Cr	<0.1	0.1	<0.1	0.1
Cu	1.1	6.4	1.1	3.3
Pb	0.7	2.2	1.4	2.7
Ni	1.4	1.2	2.1	2.3
Cd	<0.1	<0.1	0.4	<0.1

† 0-15 cm soil depth.

‡ Total metals added in sludge 1973-1993 to sludge treatment areas.

centrations for 16 soil series in Minnesota and two major soil series in southeastern Minnesota.

The difference between total-metal and available-metal is thought to be metal that is tightly bound within the crystal structure of resistant soil minerals and not available for plant uptake. The metal fraction between available and organic-bound values is metal in easily weathered soil minerals that can become available for active plant uptake. The organic extractant measures metal bound to soil organic matter and inorganic metal ions sorbed to mineral surfaces. This last fraction is considered the most labile, or immediately available, for plant uptake. In southeastern Minnesota, for example, about half of the total Cd in surface soil was in the organic-bound fraction (Table 28). No Cd was found in the available fraction in this layer.

Variation in total- and available-Cd levels in Minnesota was explained by the calcite ($CaCO_3$) content of soils (Pierce et al., 1982). Cd can substitute for Ca in the $CaCO_3$ crystal structure. Higher Cd levels were found in soils with free $CaCO_3$. About one-half of the Cd was in the available form in southeastern Minnesota parent material, probably due to $CaCO_3$ present in the loess parent material. Overall, native levels of metals, especially Cr, Pb, Ni, and Cd, are quite low in Minnesota soils.

Metals were also measured in soil samples before, at 5, and at 20 years of sludge application at the Rosemount Watershed study. Table 27 shows that Zn, Cu, and Pb increased as a result of sludge additions. Cr, Ni, and Cd did not increase over 20 years of application.

Zn is the only micronutrient known to be deficient on some southeastern Minnesota mineral soils. These soil test results prove that Zn was not deficient before sludge was added at the Rosemount Watershed study. Zn concentrations over 1 mg kg^{-1} are considered adequate for crop needs.

TRACE ELEMENT ADDITIONS AND CROP UPTAKE

The amount of trace elements that enter the food chain is always a concern when the subject of sludge-amended land is discussed.

Table 28. Trace element concentrations in Minnesota soils.†

Source Soil Layer	Zn	Cu	Cr	Pb	Ni	Cd
	mg kg^{-1}					
SE Minn						
Surface	59/10/5.5	19/3.6/3.3	14/3.4/1.5	<25/7.8/3.6	18/5.6/4.6	0.32/<0.01/0.15
Subsurface	59/10/0.6	23/4.2/1.8	23/9.0/1.3	<25/5.5/<0.8	22/5.0/0.6	0.15/0.06/0.08
All						
Surface	60/16.3/4.9	23/5.6/3.9	39/4.1/1.4	<25/6.8/<1.4	18/6.7/1.6	0.39/0.26/0.16
PM‡	52/17.7/0.4	27/9.8/2.5	48/4.8/<0.7	<25/3.8/<0.7	24/10.4/0.3	0.30/0.13/0.08

† Pierce et al., 1982. Values are for Total/Available/Organic-bound extractants; ($HCl\text{-}HNO_3\text{-}HF$) / (1 M HNO_3) / (0.1 M $K_2P_4O_7$ 3 H_2O).

‡ Parent materials.

Table 29. Trace elements applied in sludge to corn treatment areas. †

Year	*Sludge*	*Zn*	*Cu*	*Pb*	*Cr*	*Ni*	*Cd*
	Mg ha^{-1}	*kg ha^{-1}*					
5	52	45	35	15	195	0.9	0.3
10	130	115	95	35	875	2.8	0.8
17	164	145	120	42	975	4.0	1.0
19	205	175	135	49	1045	4.9	1.2

† Expressed on a dry weight basis, 105° C.

Sludge has good potential as a fertilizer substitute, and native soils contain small amounts of elements that are considered to be impurities in the food chain (Cr, Pb, Ni, Cd). The concern is with the amount of elements applied versus the uptake (and removal) of these elements by the crop. The amount of trace elements applied in sludge to the corn and grass treatment areas is shown in Tables 29 and 30, respectively. Over 19 years of sludge application, a total of 175 kg ha^{-1} Zn, 135 kg ha^{-1} Cu, 49 kg ha^{-1} Pb, 1045 kg ha^{-1} Cr, 4.9 kg ha^{-1} Ni, and 1.2 kg ha^{-1} Cd were applied to the corn terraces (Table 29). Sludge concentrations of these trace elements were below pollutant concentration standards set for sludge by the USEPA (1993) for limiting total metal loading on a given site.

Corn and grass tissue concentrations — The elements were taken up by corn and grass to different degrees. Corn leaf tissue at silking had adequate amounts of the micronutrients Cu, Zn, Mn, and B for plant growth (Fig. 21a). These micronutrients were well below toxic levels. Very low amounts of Cr, Ni, Pb, and Cd were detected in the corn leaf tissue. Little difference was detected between leaf tissue from control and sludge treatment areas for these metals.

Stover and grain did not have increased concentrations of sludge-borne Cd. The differences in Cd content may be caused by the different corn varieties used. The corn plant used all of the trace elements studied in the native soil environment (or from impurities in commercial fertilizers), but still did not take up excessive amounts of elements when they were added in sludge. Annual variation in trace element uptake can be due to crop yield, environmental conditions, and corn variety.

Concentrations of Cr, Cu, Ni, or Pb (Table 31) in corn stover and grain were not affected by 20 years of continuous corn production with annual sewage sludge applications as a plant nutrient source. Zn uptake in corn stover was higher on sludge-treated areas than control areas over the 20-yr period (Fig. 22), reaching a mean concentration of 60 mg kg^{-1} in stover tissue for the 6 to 10-yr interval. After 10 years, tissue-Zn concentrations appeared to plateau. The overall lack of sludge-borne metal accumulation by corn in the farming system supports the clean sludge concept (Chaney, 1989). This concept embodies the hypothesis that low element sludges can be used as a nutrient source in farming systems without concern for significantly elevated trace element levels in the growing crop. To a much lesser extent, the same trend was observed for Zn levels in corn grain and agrees with the broader observation that greatest element accumulations occur in vegetative tissues.

Table 30. Elements applied in sludge to reed canarygrass treatment areas.

Year	*N*	*P*	*K*	*Zn*	*Mn*	*Cu*	*B*	*Cr*	*Pb*	*Ni*	*Cd*
	kg ha^{-1}										
1976	1256	528	161	17.8	7.4	15.0	0.70	45.0	5.30	0.45	0.16
1977	1270	583	93	17.4	5.1	17.7	1.20	83.1	6.20	0.63	0.14
1978	908	382	79	10.0	3.4	11.6	0.71	70.8	5.80	0.27	0.09
1979	1380	555	73	33.0	6.5	35.6	0.99	182.0	11.40	0.46	0.16
1980	1360	648	125	11.1	4.1	31.5	1.03	324.0	6.10	0.41	0.13
1981	1914	840	95	28.4	8.0	40.5	0.27	348.2	7.92	1.05	0.20
1982	729	309	42	10.3	2.9	15.0	0.28	197.8	2.75	0.50	0.06
1983	260	129	8	4.8	1.0	5.8	0.14	204.7	1.12	0.13	0.03
Total	9077	3974	676	132.8	38.4	172.7	5.32	1455.6	46.59	3.90	0.97

Grass tissue also had adequate micronutrient concentrations for crop growth and no toxic levels. Again, little difference was seen between control and sludge treatment uptake of metals by grass, with the exception of Cr (Fig. 21b). The amount of Cr, Ni, Pb, and Cd in grass tissue was about the same as in corn leaf tissue, except for Cr from the grass sludge treatment area. Cr is not taken up by plants in significant amounts. The high Cr value reported here may be from adsorption of Cr to the surface of grass plants. This may be due to direct contact with the sludge during appli-cation, and/or surface contamination with particulate sludge as a result of rain-splash erosion.

In some research studies, a Zn deficiency has been induced by high levels of P added to a low Zn soil. Although large amounts of P were added by the sludge, no Zn deficiency was detected by plant tissue analysis. This result could have been expected because the sludge also supplied adequate amounts of Zn to the crop. Figure 21 also shows a possible Zn-Mn interaction. Zn seemed to depress Mn concentrations in corn and grass tissue compared to control areas. Depression of Mn in plant tissue might also be related to large amounts of available Fe released by sludge. In any case, Mn concentrations were still within sufficient levels for plant growth.

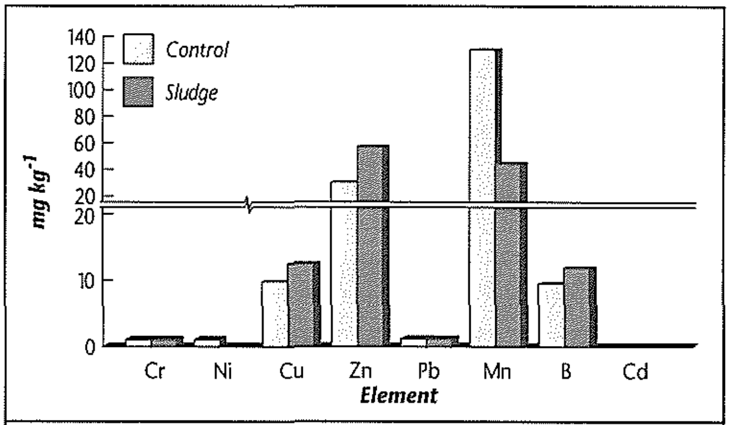

Figure 21a. Average tissue concentrations of trace elements in corn leaf at silking (1976-1979).

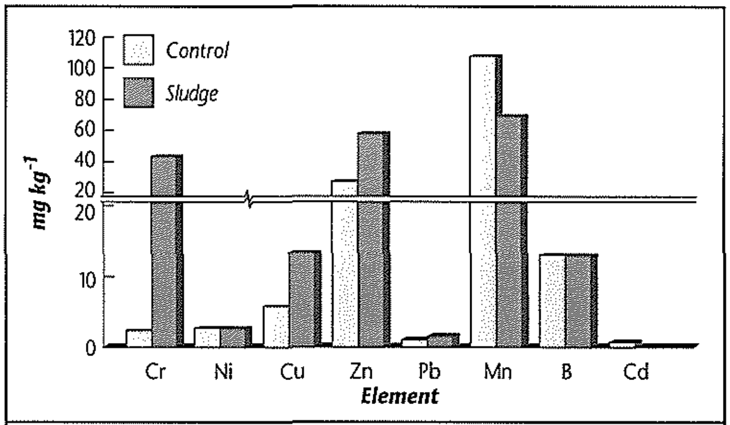

Figure 21b. Average tissue concentrations of trace elements in reed canarygrass (1976-1979).

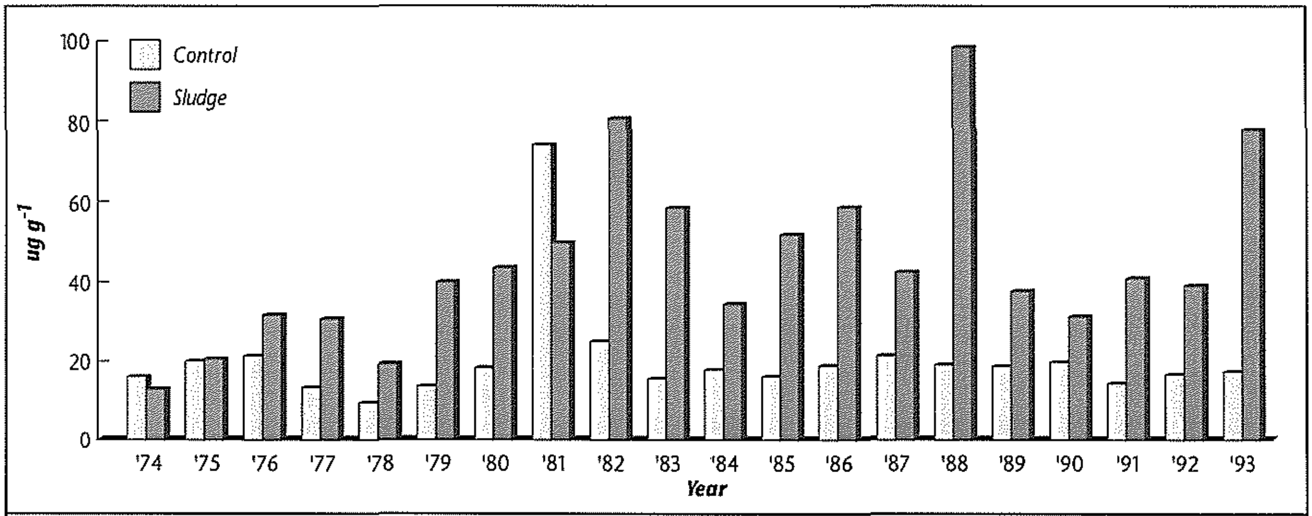

Figure 22. Elemental concentrations of Zn in corn stover (1974-1993).

Table 31. Mean concentrations of trace elements in corn tissues over time.

Year	Treatment	Zn	Cu	Cd	Pb	Ni	Cr
		mg kg^{-1}					
Stover							
1-5	Control	16.1†	5.0	0.14	1.9	0.7	1.0
6-10		17.7	6.0	0.10	0.9	0.8	1.4
11-19		18.0	8.4	0.16	0.9	0.7	0.9
1-5	Sludge	23.0	5.8	0.16	1.6	0.8	1.0
6-10		60.2	7.2	0.18	1.0	1.2	2.8
11-19		46.5	7.0	0.18	0.8	0.6	1.4
Grain							
1-5	Control	21.9	1.7	0.07	0.6	0.4	0.2
6-10		23.2	2.4	0.03	0.3	0.3	0.2
11-19		20.0	3.2	0.29	0.4	0.4	0.2
1-5	Sludge	26.9	1.6	0.07	0.7	0.3	0.3
6-10		31.9	1.8	0.03	0.3	0.3	0.2
11-19		26.0	3.2	0.31‡	0.5	0.3	0.2

† Expressed at 65° C.
‡ May be a result of use of different hybrid varieties.

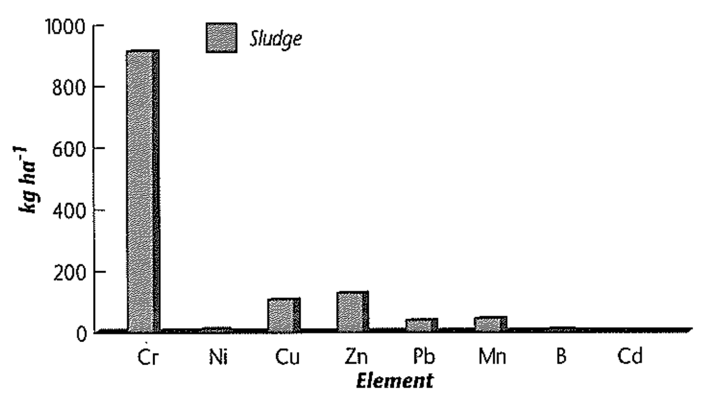

Figure 23a. Total trace elements applied in sludge to corn (1974-1986).

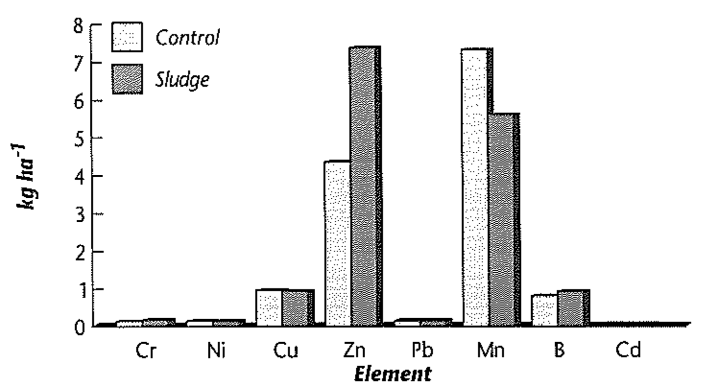

Figure 23b. Total trace elements removed by corn fodder (1974-1986).

Total trace elements applied versus removed by crops — Corn tissue was also sampled for tissue analyses at harvest. Grain, cob, and stover tissue were analyzed separately. With knowledge of dry-matter yields of each component, a weighted average metal concentration for the whole plant and the total amount removed by the crop was calculated. Total amounts of trace elements removed from the site, versus applied in sludge, for corn fodder are shown in Fig. 23. (Corn fodder is commonly ensiled for cattle feed in this region). With the exception of Zn and Mn, only small differences in uptake values exist between control and sludge treatments for corn. The slightly greater values in sludge treatment fodder are largely due to higher yields in those treatment areas. Of primary interest is the comparison between the amount applied versus that which was removed by the crop. The applied:removed ratio ranged from 4:1 for B to 5,000:1 for Cr in the sludge treatments. These ratios are much greater when sludge uptake values are corrected for control uptake.

The distribution of elements within the harvested corn plant should also be considered if only ear corn or shelled corn is to be removed, leaving the residue in the field. Table 32 presents this kind of information for sludge-amended corn from the Rosemount Watershed during the years of 1974-1986. Most of the N, P, and Cd were removed in the corn grain. Significant proportions of Ni, Cd, Cr, and Cu were found in the cob tissue. Much of the K, Mn, Cu, B, Cr, Pb, and Ni, however, were removed with the corn stover. Total Zn removed was evenly divided between the corn ear and corn stover tissue.

Total amounts of elements removed by the grass crop were also small compared to the amounts applied in sludge (Fig. 24). Sludge treated grass removed more Cr and Cu than the control counterpart. This removal was a function of higher yield and tissue concentrations of these metals in sludge treatment areas. The applied:removed ratios ranged from 10:1 for Mn to 700:1 for Cr.

Grass removed more Cr, Ni, and Pb, but less Cd than did corn, in a shorter period of time. Total Cr, Ni, Pb, and Cr removed, however, were low and not much different from amounts removed by these crops grown on fertilized control areas.

Significant amounts of Cr, Zn, and Cu were added to sludge treatment areas. Corn fodder and grass crops removed only a small fraction of the amount applied. Grass, however, removed a greater proportion of these three elements than did corn. Lesser amounts of Pb, B, Ni, and Cd were applied to the treatment areas with sludge. These elements were taken up in only trace amounts by corn and grass crops with no distinction between sludge and control treatment areas, with the exception of Zn. Its uptake was higher on sludge-treated areas than control areas for corn over the 20-yr period.

Zinc uptake is not a concern because levels within plants that might cause toxicity to animals are higher than the levels that cause phytotoxicity to the plants themselves. The Soil-Plant Barrier does apply in the case of Zn. Therefore, the trace elements applied with the sludge (Zn, Mn, Cu, Cr, B, Pb, Ni, Cd) were not a significant source of contamination to the food chain in this study.

Table 32. Amount and distribution of trace elements removed by corn on sludge-amended soil (1974-1986).

	Grain	Cob	Stover	Grain	Cob	Stover
	kg ha^{-1}			percent of total		
N	1680	46	905	64.0	1.7	34.3
P	361	5	122	74.0	1.0	25.0
K	449	85	1400	23.2	4.4	72.4
Zn	3100	501	3760	42.1	6.8	51.1
Mn	655	89	4850	11.7	1.6	86.7
Cu	256	70	660	26.0	7.1	66.9
B	257	33	639	27.6	3.6	68.8
Cr	20	15	145	11.1	8.3	80.6
Pb	41	4	94	29.5	2.9	67.6
Ni	27	18	72	23.1	15.4	61.5
Cd	28	6	15	57.2	12.2	30.6

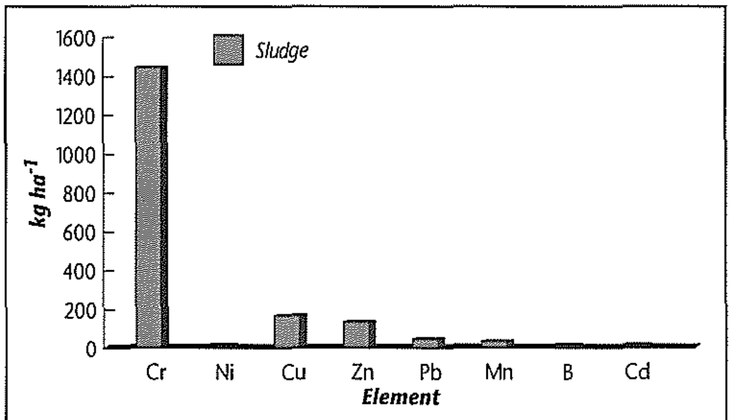

Figure 24a. Total trace elements applied in sludge to reed canarygrass (1976-1983).

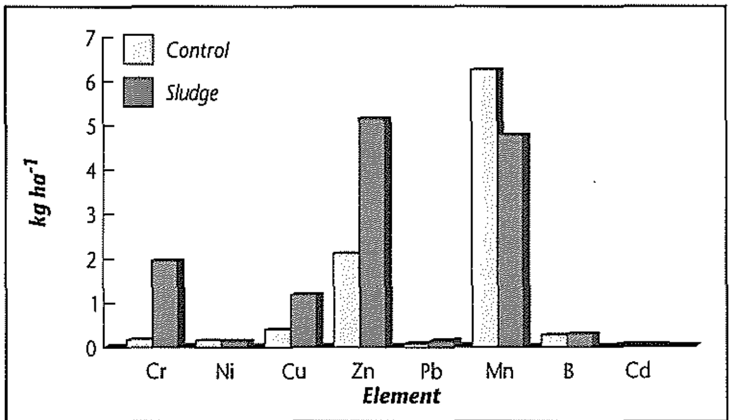

Figure 24b. Total trace elements removed by reed canarygrass (1976-1983).

SOIL RESULTS

EFFECTS OF SEWAGE SLUDGE ON SOIL FERTILITY PROPERTIES

Soil fertility is determined by a combination of soil properties that include nutrient levels, soil pH, organic matter content, and soluble salt concentrations. Soil test values for these properties are presented in Table 33 for treatment areas at the Rosemount Watershed. Nutrient levels, as indicated by P and K soil test results, were in the high to very high range for sludge treatment areas. Extractable soil P levels in sludge-amended soils were in a range beyond that necessary for good crop production. However, excess soil P did not affect crop production by reducing the availability of elements such as Zn, Cu, Ca, and Mg, since these cations were supplied by the sludge.

High soil P on the control area was due to commercial fertilizer additions. In recent years, the number of soils in the United States with plant available P exceeding the levels required for optimum crop yields has

Table 33. Soil test results at the Rosemount Watershed (1993).

Characteristic	*Units*	*Control*	*Sludge*
pH		6.8	6.9
Organic matter	%	3.3	4.2
Extractable P	kg ha^{-1}	604	942
Exchangeable K	kg ha^{-1}	243	260
Soluble salts	dS m^{-1}	0.1	0.2

increased in areas of intensive agricultural and livestock production (Sharpley et al., 1994; Sims, 1992). P accumulates in soils due to chemical properties that allow it to be strongly sorbed by the soil. This occurs whether the P source be chemical fertilizer, manure, or sewage sludge. The implications of this trend are that P inputs to soils will need to be more intensively managed in the future, taking into account both environmental and agronomic concerns (Sharpley, et al., 1994).

Exchangeable K was adequate on all treatment areas from 1974-1985. Even though no additional K was added to the sludge-treated areas from 1986 to 1993, the soil continued to maintain a high level of K. K was available throughout the 20 years in amounts adequate for plant growth.

Soil organic matter on the sludge-treated areas increased over that of the control area (Table 33). Continuous cultivation of soils tends to decrease the organic matter content with time. Organic matter is essential for the maintenance of soil structure and tilth. Although much of the sludge organic matter decomposes after incorporation into soil, a resistant portion remains for many years. Consequently, the physical benefits provided to the soil by sludge last longer than the nutritional benefits.

Sewage sludge inherently contains relatively high amounts of soluble salts. Additional salts are released in the soil as the sludge is mineralized. Soluble salts in the 0 to 15 cm soil layer of the sludge-treated corn and grass areas remained well below the range of tolerance for field crops. Soluble salts move with water as it infiltrates the soil and tend not to accumulate near the soil surface in moderate to high rainfall climates.

Soil pH decreased when commercial fertilizer was applied. The corn control area required agricultural limestone in 1984 and 1985 to restore optimum pH levels for plant growth. The decrease in soil pH was due to the acidifying nature of the nitrification process which occurred when anhydrous- and ammonium-based fertilizers were applied to the soil. Sewage sludge undergoes rapid mineralization and nitrification when initially incorporated into soil, but alkaline components within the sludge help neutralize this acidity. Therefore, soil pH did not decrease on sludge treatment areas. By 1993, pH values on sludge-treated areas ranged from 6.0 to 7.6.

Total soil C and N increased as expected on the sludge areas (Fig. 25 and 26). A comparison of C and N data at low- and mid-terrace positions (not shown) indicated some downslope movement of sludge and soil. Grass sludge areas had an even greater increase in soil N (Fig. 27). This is most likely due to the greater quantity of sludge N applied to these terraces over the 20-yr period. By 1993, total C and total N on sludge-treated areas ranged from 1.9 to 4.8% and 0.14 to 0.41%, respectively. Total C and N for the control areas remained relatively stable during the 20-yr period.

CARBON AND NITROGEN MINERALIZATION

Significant mineralization of organic C and N compounds occurs the first year that sewage sludge is incorporated into soil. Studies have shown that 10 to 50% of total sludge-borne N is mineralized during the first year of application (Fox and Axley, 1985; Hattori and Mukai, 1986; Lerch et al., 1992; Wiseman and Zibilske, 1988). Significantly lower amounts of organic N are mineralized in subsequent years. Mineralization rates for land-applied sewage sludge organic matter depend on such factors as prior decomposition at the wastewater treatment facility, C: N ratios, and soil conditions (i.e., water content, temperature, pH, and aeration).

After 20 years of sewage sludge applications, soils from three treatment areas at the Rosemount Watershed were incubated to determine potentially mineralizable nitrogen (N_0) and carbon (C_0). Pertinent chemical properties of the three soils are shown in Table 34. Total

C and N were higher in sludge-amended soils, compared to soils that received no sludge application. Figures 28 and 29 show net C and N mineralization of soil from the three treatment areas following the incubation. Corresponding N_0, C_0, and k values are given in Table 35. Both N_0 and C_0 values were highest for soil that received the greatest amount of sludge over the 20-yr period followed by soil that received a lesser amount. Soil that received no sludge over the 20 years had the lowest N_0, C_0 and corresponding k values.

Watershed soils treated with sludge received approximately twice the amount of N as control soils fertilized with inorganic N fertilizer during the 20-yr study (Table 36). This is reflected in the higher potentially mineralizable (N_0) values for the sludge-amended soils. Although a major portion of sludge organic N is mineralized in the first year of application, much of the organic N is contained in compounds that are more resistant to mineralization. The presence of "easily" mineralizable and "slowly" mineralizable organic N pools have been proposed and reported by other researchers (Hadas and Portney, 1994; Lerch et al., 1992; Molina et al., 1980). Rates of N and C mineralization (k) were also greater in the sludge-amended soils than the control soil. This suggests that the forms of organic N present in sludge-amended soils were more easily mineralized than organic N present in the control soil. A major portion of organic N in sewage sludge exists as proteins. Low molecular weight nitrogen-containing compounds called amines are degredation products of sludge-borne proteins. These amines are closely correlated to N mineralization rates in sludge-amended soils (Lerch et al., 1992).

MOVEMENT AND DISTRIBUTION OF PHOSPHORUS

Plant available P—The Bray P extraction is used to determine the quantity of soil P that is available for plant uptake during a growing season. Bray P in sludge-amended surface soils increased more than tenfold versus surface soils in the control treatment (467 versus 31 mg kg^{-1}, Fig. 30) during the 20-yr study. The increase was greatest during the first 10 years of sludge application when P loading rates were larger. This data agrees with earlier work by Kelling et al. (1977) showing rapid increases

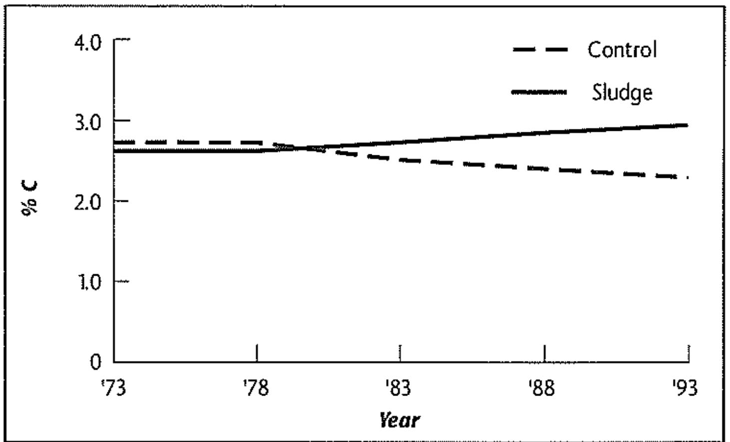

Figure 25. Corn soil C over the 20-year study.

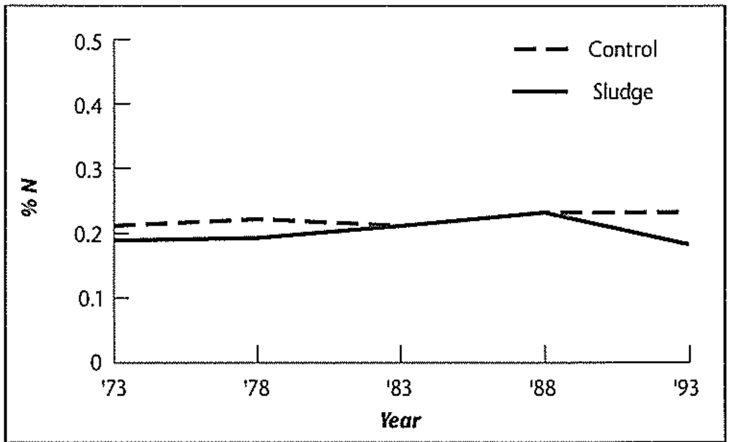

Figure 26. Corn soil N over the 20-year study.

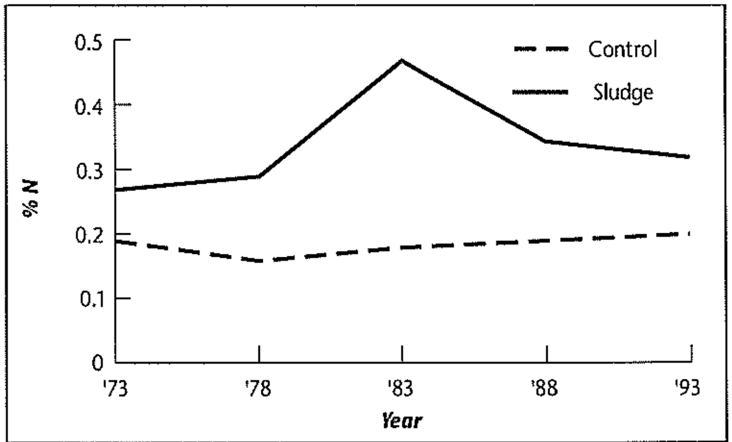

Figure 27. Grass soil N over the 20-year study.

Table 34. Chemical properties of soils used in the incubation study of C and N mineralization.

Treatment	Organic C	Organic N	C:N ratio	pH Before incub.	pH After incub.
	mg g^{-1}				
Grass-Corn + Sludge	38 ± 3.0	3.2 ± 0.3	11.7 ± 0.2	6.7 ± 0.4	5.9 ± 0.4
Corn + Sludge	28 ± 2.3	2.5 ± 0.5	11.4 ± 1.4	6.7 ± 0.6	6.2 ± 0.8
Corn No Sludge	23 ± 5.3	1.9 ± 0.4	12.3 ± 0.1	6.9 ± 1.1	6.2 ± 1.7

Table 35. Nitrogen and carbon mineralization potentials and rate constants for Rosemount Watershed soils.

Treatment	Biological N_0 Single exponential†		Biological N_0 NCSOIL‡	Biological C_0 Incremental single exponential§	
	N_0 ug g^{-1}	k wk^{-1}	N_0 ug g^{-1}	C_0 ug g^{-1}	k wk^{-1}
Grass-Corn + Sludge	225	0.124	390	581	0.155
Corn + Sludge	185	0.113	323	441	0.150
Corn No Sludge	145	0.090	254	394	0.127

† Stanford and Smith, 1972
‡ Molina et al., 1983
§ Ellert and Bettany, 1988

in Bray P in the first two years after sludge applications. Also, Peterson et al. (1993) found fourfold to sevenfold increases in Bray P (455 and 666 versus 98 mg^{-1}) after 12 years of sludge applications using rates of 7 and 13 Mg sludge ha^{-1} (3.1 and 5.8 T A^{-1}).

In 0.15 to 0.30 m soil depths, Bray P in sludge-amended soils also increased by over tenfold with time over the control areas (Fig. 31). However, Bray P levels were generally lower at 0.15 to 0.30 m depths than at 0 to 0.15 m depths, both in sludge-amended and control areas (262 and 14 mg kg^{-1}, respectively). Furthermore, significant Bray P increases in sludge-amended soils were not evident after year 10. Bray P was also not significantly increased in sludge amended, 0.30 to 0.60 m soils in year 20, versus control areas (18 versus 7 mg kg^{-1}, respectively). Kelling et al. (1977) also could not distinguish Bray P in control areas from sludge-treated areas below 0.30 m regardless of sludge treatment.

Extractable (1 M HNO_3) Phosphorus—A stronger extractant (1 M HNO_3) was used to determine stable inorganic forms of P that are relatively immobile in the soil and unavailable for plant uptake. Elevated P was evident in sludge-amended soils extracted with 1 M HNO_3 (Table 37). Surface soils enriched with sludge-borne P had more extractable P than surface soils in control treatments (1361 versus 145 mg kg^{-1}, respectively) after 20 years of sludge loading. Similar increases were evident in soils at 0.15

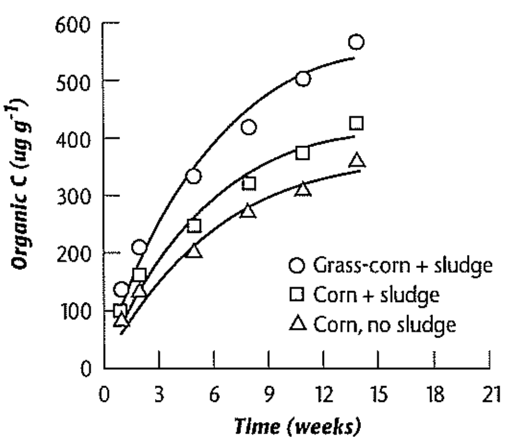

Figure 28. Net C mineralization in soils from three treatment areas at the Rosemount watershed.

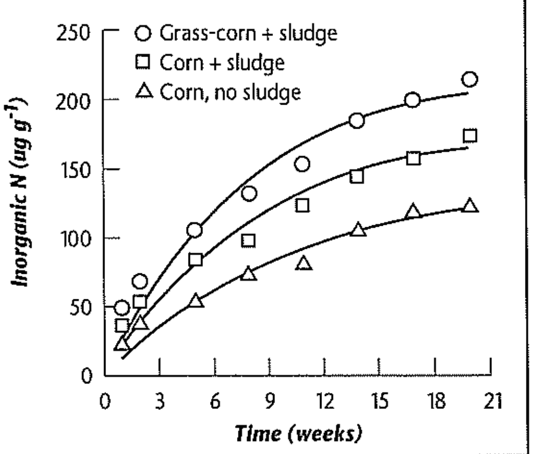

Figure 29. Net N mineralization in soils from three treatment areas at the Rosemount watershed.

to 0.30 m depths. Unlike Bray-extractable P, HNO_3-extractable P continued to increase through year 20 in both 0 to 0.15 and 0.15 to 0.30 m soil depths. Also, extractable P at 0.30 to 0.60 m depths was significantly higher in sludge-amended soils than in control soils (371 versus 46 mg kg^{-1}, respectively, for year 20). This data indicates that some downward movement of sludge-borne P occurred in sludge-treated soils. Sewage sludge contains organic forms of P and P which is associated with soluble organic matter. These forms of P are more mobile in soil than inorganic P. When sludge is incorporated into soil, some downward movement of P occurs. But as the organic compounds are degraded, the inorganic P which is released becomes tightly bound to soil constituents. Thus, while HNO_3 extractable P increased at 0.3 to 0.6 M depths in sludge amended soils, Bray P, which is more biogeochemically active, did not.

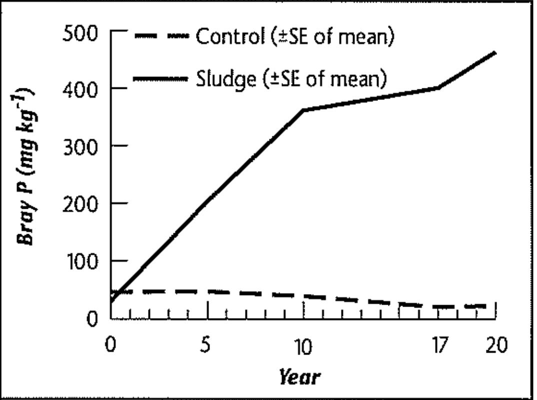

Figure 30. Soil P (Bray) in 0-0.15 m soil depth.

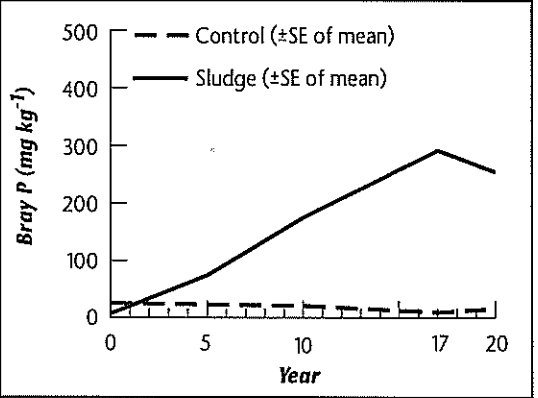

Figure 31. Soil P (Bray) in 0.15-0.30 m soil depth.

Table 36. Total annual amounts of N, P, and K applied to corn at the Rosemount Watershed.

Year	Control Treatments† N	P	K	Sludge Treatments‡ N	P	K	K Fertilizer
	kg ha^{-1}						
1974	230	20	66	211	6	61	66
1975	230	20	66	499	165	71	66
1976	249	65	88	898	614	72	88
1977	175	16	43	617	332	41	43
1978	200	17	80	897	301	65	80
1979	340	17	0	1040	579	62	0
1980	240	23	110	742	382	30	110
1981	235	50	150	770	414	34	150
1982	280	0	135	746	316	26	135
1983	224	0	0	367	201	14	0
1984	220	0	120	0	0	0	120
1985	340	0	140	324	154	22	140
1986	325	0	0	400	203	40	0
1987	134	0	0	0	0	0	0
1988	216	0	0	383	397	31	0
1989	216	0	0	153	7	1	0
1990	0	0	0	254	143	12	0
1991	269	101	207	179	148	18	0
1992	253	101	208	333	331	26	0
1993	253	101	208	644	351	33	0
Total	4629	531	1621	9457	5024	659	998

† Commercial fertilizer.

‡ Fertilizer K was added to supplement sludge-K.

Table 37. Soil P (extractable 1 M HNO_3) as a function of depth after 0, 5, 10, 17 and 20 years of sludge applications.

Depth	Year 0	Year 5	Year 10	Year 17	Year 20
(m)	mg kg^{-1}				
Control					
0 - 0.15	133 ± 22	159 ± 31	133 ± 39	107 ± 31	145 ± 29
0.15 - 0.30	78 ± 5	86 ± 13	88 ± 32	72 ± 11	105 ± 32
Sludge					
0 - 0.15	186 ± 13	544 ± 15	1007 ± 27	1122 ± 36	1361 ± 7
0.15 - 0.30	197 ± 23	342 ± 19	590 ± 42	920 ± 63	1334 ± 54

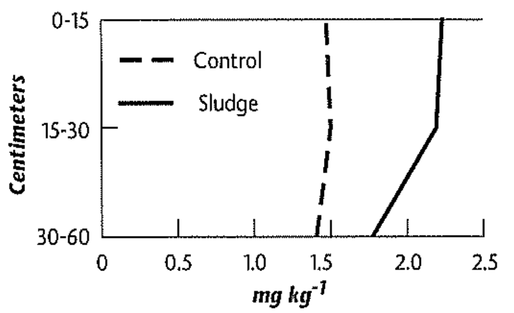

Figure 32. Concentrations of B at different soil depths (1993).

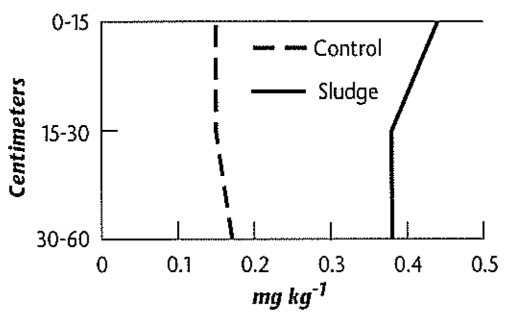

Figure 33. Concentrations of Cd at different soil depths (1993).

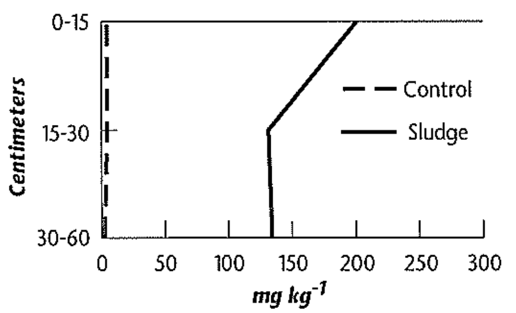

Figure 34. Concentrations of Cr at different soil depths (1993).

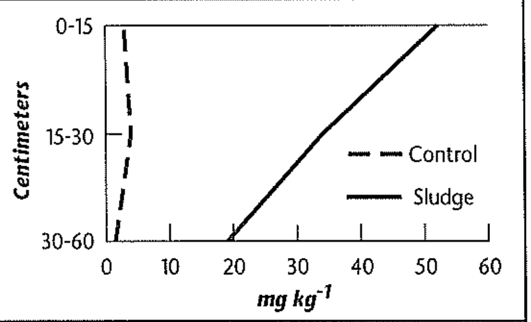

Figure 35. Concentrations of Cu at different soil depths (1993).

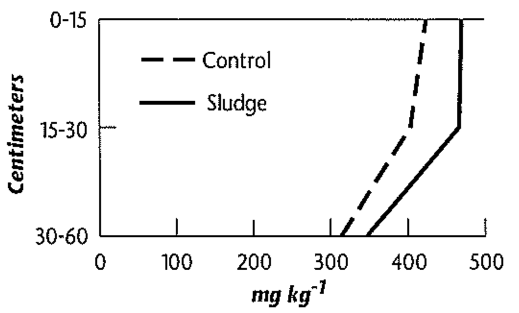

Figure 36. Concentrations of Mn at different soil depths (1993).

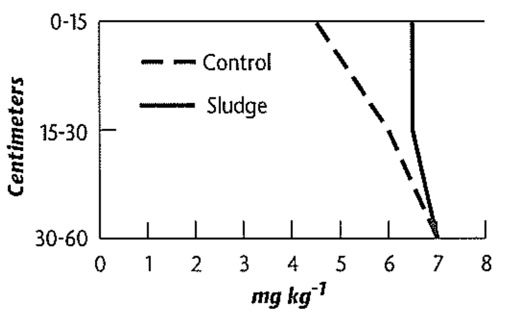

Figure 37. Concentrations of Ni at different soil depths (1993).

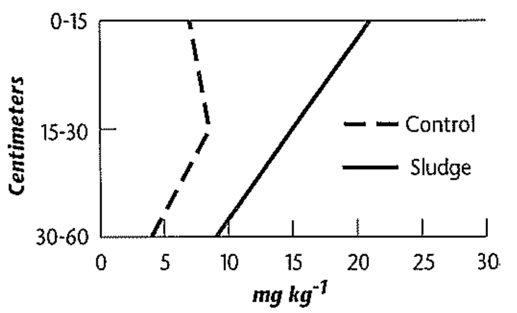

Figure 38. Concentrations of Pb at different soil depths (1993).

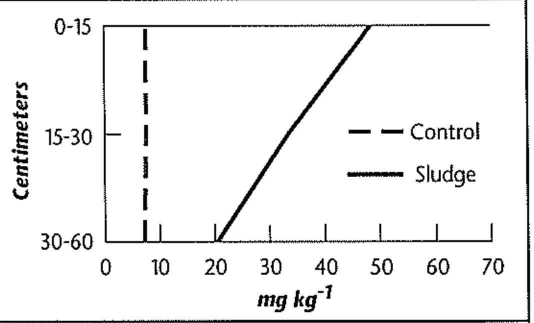

Figure 39. Concentrations of Zn at different soil depths (1993).

Massive loadings of sludge-borne P resulted in increased plant available Bray P in surface soils, and more extractable 1M HNO_3 P to a depth of 0.60 m, through 20 years of sludge additions. However, Bray P increased only through year 10 in 0.15 to 0.30 m depths, and did not increase at all in 0.30 to 0.60 m depths. Although previous reports from this study indicated somewhat more P removed in corn grown in sludge-treated soils, P concentrations in corn tissue were no higher in sludge-amended soils than in control areas. This data supports the hypothesis that agricultural soils can support annual sludge additions, providing a valuable fertilizer source, without over-enrichment of P in crops.

TRACE ELEMENTS

Evidence for trace element migration to a 0.6 m soil depth did not exist during the first 5 years, even though consistently higher concentrations of Na and Ca in soil water extracted from sludge-treated areas at 0.6 and 1.5 m depths demonstrated that water and cations were percolating through the soil profile.

Sludge-borne Cd, Cr, Cu, and Zn moved into the 0.16 to 0.3 m soil layer directly below the zone of incorporation by year 10. Because these increases were at least three times greater than values from the control area, the higher concentrations cannot be explained by variations in tillage depth (nominally 0.15 m). Ni and Pb remained within the zone of incorporation. After 20 years of sludge use, some movement of Cr and Cu into the 0.45 to 0.6 m layer occurred (Table 38 and Figs. 32 through 39). In the case of Cr, this is the result of massive loading (975 kg Cr ha^{-1}). None of the trace elements leached into soil beneath the sludge storage lagoon during 19 years of sludge storage (Table 39).

Table 38. Extractable (1.0 M HNO_3) metals as a function of soil depth from corn terraces after 10 and 17 years of sludge applications.

Depth	Zn	Cu	Cd	Ni	Pb	Cr
m			mg kg^{-1}			
Control						
0.00-0.15	8/7[†]	3/3	0.10/0.20	4/5	8/6	5/4
0.16-0.30	8/7	5/3	0.10/0.17	5/7	12/5	5/3
0.31-0.45	-/7	-/3	-/0.17	-/7	-/4	-/2
0.46-0.60	-/7	-/3	-/0.17	-/6	-/3	-/2
Sludge						
0.00-0.15	46/50	52/52	0.33/0.55	6/7	24/18	200/200
0.16-0.30	27/39	26/41	0.26/0.52	6/7	15/15	100/157
0.31-0.45	-/20	-/19	-/0.38	-/7	-/9	-/61
0.46-0.60	-/12	-/10	-/0.36	-/7	-/5	-/24

[†] 10 yr/17 yr metal concentrations expressed on a 105° C weight basis.

Table 39. Concentration of N, P, and Cr in lagoon subsoil and the percentage of N as NH_4^+-N, NO_3-N, and organic-N.

Depth[†]	Total-N	NH_4^+-N	NO_3^- N	Organic-N	P	Cr
m	mg kg^{-1}		% of total N		mg kg^{-1}	mg kg^{-1}
0.15	1,160	52	<1	47	886	12
0.30	1,020	54	<1	46	539	4
0.45	750	76	1	23	413	5
0.60	1,020	55	<1	44	477	4
0.90	760	51	1	48	456	4
1.20	420	44	2	54	410	5
1.50	300	33	3	64	362	4
1.80	220	24	3	73	287	4
2.10	180	6	4	90	246	3
2.40	240	15	3	82	295	4
2.70	260	13	3	84	260	3
3.00	320	11	2	87	266	4

[†] Depth below the sludge-soil contact point.

SUMMARY OF SOIL RESULTS

C and N have accumulated in the soil due to sludge additions. Soil test levels of extractable P increased due to sludge additions. The higher concentration of P had no apparent antagonistic effect on nutrient uptake due to increased plant nutrient concentrations from sludge additions. Commercial K fertilizer was needed to supplement the K-deficient sludge from 1974 to 1985, however, from 1986 to 1993 no additional K was needed. Soil pH decreased under control corn treatments, requiring additional inputs of agricultural limestone, whereas sludge maintained optimum soil pH throughout the experiment. Some movement of metals occurred on the sludge treated soil, but only to the 0.45 to 0.6 m layer. No leaching of trace elements occurred in the soil beneath the lagoon or to depths greater than 60 cm on the sludge treated watershed.

WATER QUALITY

Another important environmental issue dealing with land application of sewage sludge is protection of surface and subsurface water quality. Water quality information was collected at the Rosemount Watershed in conjunction with sludge spreading and cropping activities at the site.

Four kinds of water were defined based on the physical characteristics of the watershed. Surface waters and solids (runoff) were collected at the terrace outlets and the runoff reservoir from 1975 to 1982. Soil water, defined as water held by the soil against the pull of gravity, was sampled in the root zone at this site from 1974 to 1979. Temporarily saturated soil water was sampled by sampling tubes that extended below the root zone and above the dense till. Deep ground water was sampled from two existing wells (>70-m) next to the site. Temporarily saturated soil water and deep ground water were sampled throughout the 20-yr period.

SURFACE WATER RUNOFF AND EROSION

Two important components of surface water quality are dissolved and suspended materials. Problems can occur in aquatic communities when runoff waters contain excess nutrients, trace elements, organics, or are turbid with eroded soil. The Rosemount Watershed was designed with terraces and a runoff reservoir to reduce erosion and minimize the chance of surface waters leaving the site.

Runoff occurs as either snow melt (often a mixture of water from melting snowpack and spring rainfall) or rainfall runoff (no snowpack present). Runoff was measured and sampled from each separate terrace representing both sludge and control treatments for corn and grass crops.

SNOW MELT RUNOFF

Snow melt runoff was measured from 1975 to 1982, and contributed about one-half of the total annual runoff during this period. Thus it is a significant portion of surface water movement from the watershed. Characteristics of snow melt runoff are summarized in Table 40. The quality of the snow melt runoff was quite good from both sludge and control areas with little soil, N, P, K, or trace elements leaving the fields via this route.

Snow melt runoff amounts were roughly equivalent from each treatment during the 1975 to 1982 period for all but the corn control area that had less runoff. Sediment data show that essentially no erosion occurs from an established grass sod and only trace quantities of sediment from corn areas during snow melt runoff. The small amount of sediment measured in 1975 occurred before the grass crop was fully established. Erosion during snow melt runoff was slightly greater on corn treatments.

Loss of total P and K in snow melt runoff was greater in grass than in corn treatments for control and sludge application areas (1976 to 1981), although only a few kg ha^{-1} yr^{-1} nutrients were removed due to runoff. A mat of sludge on the soil surface and an abundance of above ground plant material in the grass-sludge treatment may have contributed to these losses. Loss of total N was slightly greater in snow melt runoff from the corn-sludge treatment than grass-sludge treatment (1976 to 1981). N losses from both of these sludge treatments were significantly greater than the control areas during the same period.

Amounts of trace elements removed by snow melt runoff were related to treatments. The treatments were ranked in terms of trace element loss, from greatest to least as grass-sludge > corn-sludge > controls. Only very small amounts of trace elements were lost from corn treatments through runoff, because of the injection of sludge below the soil surface.

The relative amount of trace elements in runoff was related to tissue concentrations of the crops. Runoff from grass treatment areas had higher Cu levels than runoff from corn. Also, Zn and Mn levels in runoff from control and sludge grass was in the same proportions as found in plant tissue concentrations (Fig. 21). This evidence suggests that the source of most trace elements in snow melt runoff is through cell rupture of plant tissue by freezing processes.

Cd, Ni, and Pb concentrations in runoff were not affected by the 10 years of sludge applications. Cd concentrations never exceeded

Table 40. Quantity and quality of snow melt runoff and sediment yield from the Rosemount Watershed (1975-1982).[†]

Crop Treatment Year	Precipitation	Runoff	Peak Rate	Sediment	Total N	Total P	K	Ca	Mg	Na	Zn	Cu	Ni	Cr	Pb	Cd	Mn
	cm	cm	cm hr^{-1}	Mg ha^{-1}	kg ha^{-1}						g ha^{-1}						
GRASS																	
Control																	
1975	13.2	2.1	0.18	0.28	1.8	0.0	0.1	—	—	—	—	—	—	—	—	—	—
1976	4.6	2.0	0.16	0.02	1.4	0.1	1.4	—	—	—	4	7	—	1	—	—	—
1977	8.5	3.8	0.16	0.00	1.9	0.3	4.4	—	—	—	14	7	6	—	—	—	—
1978	13.7	2.2	0.09	—	2.3	0.2	2.7	1.0	0.4	0.1	7	2	—	5	—	—	21
1979	14.6	6.2	0.60	0.00	3.6	0.9	6.2	4.2	1.4	0.6	16	6	—	2	3	2	32
1980	—	2.8	—	—	3.0	0.3	2.4	1.4	0.6	0.2	3	2	1	—	—	—	14
1981	—	2.4	—	—	2.1	0.2	3.6	2.6	1.1	0.3	2	1	—	3	—	—	23
1982	—	1.7	—	—	1.3	0.3	1.0	1.0	0.3	0.2	3	2	—	2	—	—	5
Total	—	23.2	—	—	17.1	2.2	21.7	10.7	3.8	1.5	48	26	7	13	3	2	96
Sludge																	
1975	13.2	4.8	0.46	1.02	20.2	0.0	0.9	—	—	—	—	—	—	—	—	—	—
1976	4.6	2.3	0.21	trace	1.8	0.3	2.4	—	—	—	4	8	—	1	—	—	—
1977	8.5	5.4	0.32	0.00	6.8	1.4	9.0	—	—	—	14	31	9	—	11	2	—
1978	13.7	2.9	0.15	—	6.1	1.2	6.0	5.2	1.7	1.9	7	9	—	3	—	—	12
1979	14.6	4.8	0.12	0.00	5.6	1.2	4.9	11.6	3.2	5.2	37	20	3	4	2	1	8
1980	—	5.0	—	—	14.5	1.7	5.3	10.5	3.1	6.0	14	20	5	5	—	—	24
1981	—	1.8	—	—	11.0	0.7	4.1	13.0	4.4	8.4	7	13	2	4	—	—	9
1982	—	3.8	—	—	2.8	1.2	2.6	3.9	1.4	1.1	14	17	2	9	—	—	5
Total	—	30.8	—	—	68.8	7.9	35.2	44.2	13.0	22.0	79	11	21	27	13	3	58
Winter applied sludge on Terrace # 3																	
1978	13.7	3.0	0.06	—	12.5	3.1	5.0	—	—	—	16	28	4	8	4	1	—
1979	14.6	12.3	0.24	0.00	40.6	8.6	18.8	—	—	—	213	118	21	75	20	—	—
CORN																	
Control																	
1975	13.2	0.1	0.02	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1976	4.6	1.2	0.24	0.04	0.4	0.0	0.4	—	—	—	—	—	—	—	—	—	—
1977	8.5	1.8	0.10	0.01	1.4	0.0	0.3	—	—	—	—	—	—	—	—	—	—
1978	13.7	2.1	0.04	—	1.4	0.1	0.7	—	—	—	4	2	1	1	3	0	—
1979	14.6	2.8	0.39	trace	1.8	0.1	0.9	—	—	—	8	2	0	0	2	0	—
Total	54.6	8.0	—	0.05	5.0	0.2	2.3	—	—	—	12	4	1	1	5	0	—
Sludge																	
1975	13.2	4.4	0.36	0.02	11.6	0.1	0.2	—	—	—	—	—	—	—	—	—	—
1976	4.6	1.4	0.33	0.20	0.8	0.0	0.4	—	—	—	—	—	—	—	—	—	—
1977	8.5	5.8	0.33	0.09	9.5	0.5	5.0	—	—	—	—	—	—	—	—	—	—
1978	13.7	3.6	0.02	—	2.8	0.4	1.3	—	—	—	10	6	3	1	4	1	—
1979	14.6	3.5	0.36	trace	12.5	0.4	2.2	—	—	—	9	4	0	3	0	0	—
Total	54.6	18.7	—	0.31	37.2	1.4	9.1	—	—	—	19	10	3	4	4	1	—

Totals may reflect rounding errors.

† Means of four replications on sludge treatment areas and one replication on control treatment areas.

Table 41. Rainfall runoff parameters recorded at the Rosemount Watershed (1975-1979).†

Crop Treatment Year	Period	Precipitation (cm)	Runoff (cm)	Peak Rate (cm hr^{-1})	Sediment (Mg ha^{-1})	Total N	Total P	K
						kg ha^{-1}		
GRASS								
Control								
1975	4/27-4/30	9.3	3.5	0.55	1.86	0.4	0.0	0.3
	5/2-6/23	24.7	1.2	0.09	0.24	0.2	0.0	0.1
	7/1-9/30	17.2	2.2	0.31	0.24	0.2	0.0	0.5
	10/1-12/15	12.5	1.3	0.12	0.02	0.2	0.0	1.3
1976	3/29-3/30	2.2	0.1	0.01	0.01	0.0	0.0	0.0
1977	6/26-10/14	64.2	0.2	0.03	0.00	0.1	0.0	0.2
	11/20-12/18	4.2	0.5	0.06	0.00	0.3	0.0	0.6
1978	5/27-9/18	65.7	5.3	0.35	0.00	2.7	0.6	4.7
1979	4/25-9/13	50.0	0.5	0.17	0.00	1.6	0.2	0.9
Sludge								
1975	4/27-4/30	9.3	5.7	0.47	2.24	5.8	0.0	0.9
	5/2-6/23	24.7	5.1	0.21	0.76	8.8	0.0	0.6
	7/1-9/30	17.2	1.4	0.12	0.26	1.5	0.0	0.4
	10/1-12/15	12.5	0.6	0.05	0.00	0.1	0.1	0.9
1976	3/29-3/30	2.2	0.3	0.09	trace	0.2	0.0	0.3
1977	6/26-10/14	64.2	0.3	0.10	trace	2.4	0.2	0.5
	11/20-12/18	4.2	0.2	0.06	0.00	0.4	0.1	0.3
1978	5/27-9/18	65.7	7.3	0.36	0.00	16.1	5.0	7.4
1979	4/25-9/13	50.0	0.8	0.44	0.00	1.9	0.3	2.3
CORN								
Control								
1975	4/27-4/30	9.3	1.7	0.42		0.1	0.0	0.0
	6/11-9/30	17.2	0.3	0.17	0.06	0.2	0.0	0.1
	10/1-12/15	12.5	0.1	0.00	0.00			
1976	3/29-3/30	2.2	0.1	0.02	trace	0.2	0.0	0.1
1977	6/26-10/14	64.2	0.6	0.13	0.22	0.2	0.0	0.4
	11/20-12/18	4.2	0.0					
1978	5/27-9/18	65.7	9.1	0.58	1.20	1.7	0.3	3.0
1979	4/25-9/13	50.0	5.1	0.70	0.44	2.7	0.3	1.8
Sludge								
1975	4/27-4/30	9.3	5.2	0.38		9.4	0.1	2.6
	6/11-9/30	17.2	1.9	0.09	0.11	2.2	0.0	0.5
	10/1-12/15	12.5	0.0	0.00				
1976	3/29-3/30	2.2	0.0	0.01	trace	0.2	0.0	0.0
1977	6/26-10/14	64.2	1.8	0.43	0.58	1.5	0.2	1.2
	11/20-12/18	4.2	0.0					
1978	5/27-9/18	65.7	8.4	0.37	0.88	2.1	0.6	2.8
1979	4/25-9/13	50.0	3.2	0.51	0.28	3.0	0.3	1.8

† Mean of four replicates for sludge and one for control treatment areas.

3 ug L^{-1}. Sludge applications did enhance Cu concentrations in snow melt runoff. These Cu levels were always 10 times less than U.S. Public Service drinking water standards. Slight, but elevated, Zn levels were observed in runoff waters. In spite of massive Cr loading (875 kg ha^{-1} in the first 10 yr), Cr losses were low and only associated with sediment losses from corn areas. Sediments from early spring storms contained 10 times Cr as sediments from control areas. However, sediment runoff was minimal due to the terrace system; hence, only a very small fraction of applied Cr left the landscape.

Surface application of sludge during winter increased all nutrient and trace element concentrates in runoff. Values for snow melt runoff in 1979 following winter application of sludge alone exceed totals for the 7-yr period (1976 to 1982) for almost all elements measured. Winter application of sludge on sloping land can have a deleterious impact on water quality.

RAINFALL RUNOFF

The other, less predictable component of total runoff at the Rosemount Watershed occurred during rainfall events. Runoff amounts from sludge treatment areas were slightly greater than amounts from control areas (Table 41). Overall, about 6 to 8% of rainfall received was lost as runoff. Discounting 1975, when the grass crop was not yet established, erosion was negligible on grass treatments. Sediment loss was 1.8- to 1.9-Mg ha^{-1} on corn treatments for the 5-yr period (1975 to 1979). No differences in sediment yield were observed between control and sludge corn treatments.

The greatest nutrient (N, P, and K) loss in runoff occurred on sludge treatment areas. Grass-sludge areas lost more nutrients in rainfall runoff than did corn-sludge areas. Even though more sediment was removed from corn treatments, incorporation of sludge into the soil on these areas prevented excessive losses of nutrients to runoff.

Total runoff for the 5-yr period (1975 to 1979) was about 12, 12, 9, and 7% of total precipitation from grass-sludge, corn-sludge, grass-control, and corn-control treatments, respectively (Table 42). P and K loss from grass treatments were greater than the amount lost from corn treatments. N loss was significantly greater on sludge treatments than on control treatment areas. Overall, the corn-sludge treatment lost the most N over the period, whereas the grass-sludge treatment lost the greatest amounts of P and K.

Negligible amounts of Cd were removed in runoff events. Runoff from sludge-treated areas contained higher amounts of Zn and Cu than the control, particularly in the sediments (Table 43). Trace element concentrations in selected runoff water from corn terraced areas after 5 and 10 years of annual sludge applications are shown in Table 44.

Erosion and runoff can be problems on sloping land used for row crops. Sediment and nutrients adsorbed on soil particles can cause environmental problems in surface waters. Controlling erosion, as was done on the Rosemount Watershed, prevented excessive sediment loss in runoff waters. Incorporation of fertilizers and injection of sludge into the soil were also important in reducing loss of nutrients in runoff. Crop type also had an effect on nutrient movement. Runoff waters from reed canarygrass treatment areas had higher P and K levels than those from corn areas, in spite of the fact that corn areas had much less surface protection during the winter. Trace element levels were very low in runoff from the watershed, except when sludge was surface-applied to grass in winter. Some trace metals leached out of the sludge mat on the frozen grass areas.

SOIL WATER

Water was extracted from the root zone in situ from 60 cm and 150 cm depths in the soil. Analysis data are presented in Table 45. Most striking was the high NO_3-N concentration during the first five years of the study. For corn, both control and sludge treatments experienced a general increase of NO_3-N in the soil water. For grass, the NO_3-N levels increased more under the sludge treatment than under the control treatment. This data was instrumental in adjusting the annual application rates to reduce the level of N in the soil water thus minimizing the risk to surface and ground water sources.

Table 42. Season total runoff from the Rosemount Watershed (1975-1979).

Crop Treatment Year	Precipitation	Runoff	Sediment	Total N	Total P	K
	(cm)	(cm)	(Mg ha^{-1})	kg ha^{-1}		
GRASS						
Control						
1975	76.9	10.3	2.64	2.8	0.0	2.3
1976	31.6	2.1	0.03	1.4	0.1	1.4
1977	77.2	4.5	0.00	2.3	0.3	5.3
1978	81.2	7.5		5.0	0.8	9.4
1979	71.3	6.7	0.00	5.2	1.0	7.1
Total	338.2	31.1	2.67	16.8	2.2	25.4
Sludge						
1975	76.9	17.6	4.28	3.6	0.1	3.7
1976	31.6	2.6	trace	2.0	0.4	2.8
1977	77.2	5.9	trace	9.7	1.7	9.9
1978	81.2	10.3		23.8	6.7	13.2
1979	71.3	5.6	0.00	7.5	1.6	7.2
Total	338.2	42.0	4.28	46.6	10.5	36.7
CORN						
Control						
1975	76.9	2.4	0.13	1.2	0.1	0.4
1976	31.6	1.3	0.04	0.5	0.0	0.4
1977	77.2	2.4	0.23	1.5	0.1	0.7
1978	81.2	11.2		3.1	0.3	3.7
1979	71.3	7.9	0.44	4.6	0.4	2.8
Total	338.2	25.2	0.84	11.0	0.9	7.9
Sludge						
1975	76.9	12.5	0.29	24.3	0.2	3.5
1976	31.6	1.4	0.20	1.0	0.0	0.4
1977	77.2	7.6	0.67	10.9	0.7	6.2
1978	81.2	12.0		4.9	1.0	4.1
1979	71.3	6.7	0.28	15.5	0.6	4.0
Total	338.2	40.2	1.44	56.6	2.5	18.2

Totals may reflect rounding errors.

Concentrations of trace elements in the soil water were variable and, not different between sludge and control treatments. However, Cu and Ni levels were slightly greater in corn-sludge treatments than corn control areas. Under grass, elevated levels of P were found in the sludge treatment areas, whereas elevated levels of Zn were found in the control area. Overall, Cr, Pb, and Cd concentrations were very low, near detection limits of the analysis.

Table 43. Elements removed in selected storm events from the corn area.

Terrace	Date	Sample	Runoff Water	Runoff Sediment	Metal Zn	Metal Cu	Metal Cd
			cm	$kg\ ha^{-1}$	$mg\ ha^{-1}$		
Control	4/18/75[†]	Water	0.10		70	45	—
		Sediment		22	260	700	—
Sludge	4/18/75[†]	Water	7.40		3330	3700	—
		Sediment		18	990	625	—
Control	4/23/75	Water	0.05		35	20	—
		Sediment		5	145	55	—
Sludge	4/23/75	Water	0.04		15	10	—
		Sediment		4	215	70	—
Control	4/27/75	Water	1.70		850	810	—
		Sediment		—	3400[‡]	—	—
Sludge	4/27/75	Water	3.10		1860	—	—
		Sediment		640	22 970	9000	—
Control	6/11/75	Water	0.25		925	190	27
		Sediment		16	960	190	3
Sludge	6/11/75	Water	0.48		6 000	375	48
		Sediment		30	9 525	1140	30

[†] Represents cumulative snowmelt.

[‡] Sediment yield missing. Value estimated by assuming that partitioning of Zn loss between water and sediment was the same for this runoff as it was for previous events.

Table 44. Trace element concentrations in runoff water from corn terrace areas during selected events after 5 and 10 years of annual sludge applications.

Year	Date	Treatment	Runoff	Zn	Cu	Cd	Ni	Pb	Cr
			m	$ug\ L^{-1}$					
5	Snowmelt	Control	0.021	22	10	<1	<10	<15	11
		Sludge	0.036	46	72	<1	<10	<15	33
	Rainfall[†]	Control	0.021	19	10	<2	4	<12	3
		Sludge	0.039	27	18	<2	9	<12	5
10	Snowmelt	Control	—	16	4	<1	4	<15	26
		Sludge	—	38	10	<1	<3	<15	21
	Rainfall[‡]	Control	0.028	10	9	<1	5	<15	15
		Sludge	0.031	20	11	<1	5	<15	16

[†] Runoff event on 7 April 1978.

[‡] Runoff event on 9 May 1983.

Table 45. Soil water at the Rosemount Watershed (1976-1981).

Treatment	Depth	Constituent NO_3-N	Zn	Cu	EC
	cm	mg L^{-1}	ug L^{-1}		dS m^{-1}
Corn	60				
Control		116	64	7	1.10
Sludge		173	50	12	2.14
Grass	60				
Control		20	286	36	0.76
Sludge		90	172	39	1.71
Corn	150				
Control		97	59	7	0.96
Sludge		160	55	10	1.99
Grass	150				
Control		22	155	17	0.07
Sludge		52	68	19	1.34

TEMPORARILY SATURATED SOIL WATER

Water was sampled from sampling tubes that reached temporarily saturated soil water below the root zone and above the till layer in the watershed. The depth of these samplers ranged from about 1.22-m to 4.88-m depending on location and rainfall conditions. NO_3-N levels in the 12 samplers over the 1974 to 1993 period are presented in Table 46 and Fig. 40. Other characteristics of this water are presented in Table 47. A general increase in NO_3-N concentration occurred in the temporarily saturated soil water over time. NO_3-N levels peaked in 1981 to 1984 and have been decreasing steadily since N application rates were reduced in 1981. Average NO_3-N concentrations over this period were 18, 35, 42, and 37 mg L^{-1} for samplers in the central drainage, fertilized control, corn-sludge, and grass-sludge areas, respectively. Therefore, as expected, higher levels of NO_3-N moved from the root zone soil to the temporarily saturated soil water under the sludge treatments. However, during 1990 to 1993, when commercial fertilizers were added in amounts equal to the N levels in the sludge, the control areas had considerably higher NO_3-N levels (Fig. 39).

DEEP WELLS

The deep wells located within and near the Rosemount Watershed area were also sampled to complete the picture of ground water quality. Activities at the watershed have not affected water quality of the potable ground water supply in this area. NO_3-N was very low in the deep wells over the 1973 to 1993 period, much below the 10 mg L^{-1} NO_3-N standard for potable water (Table 48). Other water quality levels are within normal ranges for ground water in this area. Fecal coliform counts (an index to pathogens), measured from 1973 to 1979, were negligible. The thick, dense glacial till at this site prevented deep leaching of materials located in the near surface layers.

SURFACE RESERVOIR

Surface runoff water stored in the watershed reservoir and the tile drainage system beneath the reservoir dam and line also had remarkably high quality (Tables 47 and 48). Concentrations of N and P were low in this water over the 1973 to 1993 period. Water quality was not unlike that of the deep well, but fecal coliform counts were higher, as might be expected in surface waters.

SOIL WATER NEAR AND UNDER LAGOONS

Water samples taken from sampling tubes outside and downslope from the sludge lagoons from 1985 to 1992 showed neither nutrient nor trace element seepage from the lagoons (Table 49).

SUMMARY OF WATER QUALITY

Protection of water quality is an important consideration when applying fertilizers and sludge as soil amendments. Erosion can be a problem on sloping land used for row crops. Sediment and nutrients attached to the soil particles can cause environmental problems in surface waters. Controlling erosion, as was done in the Rosemount Watershed study, prevented excessive sediment loads in runoff waters. Incorporation of fertilizers and injection of sludge into the soil were also important in reducing loss of nutrients in runoff.

Crop type also had an effect on nutrient movement. Runoff waters from reed canarygrass treatment areas had higher P and K levels than those from corn areas that had much less residue on the surface over winter. Trace element levels were very low in runoff from the watershed, except when sludge was

Table 46. Mean NO_3-N concentrations in shallow ground water wells by location, growing season and rainfall.[†]

Years	Central Service Area Wells: 1-5	Fertilizer Control Area 7, 13, 14	Sludge Treatment Area Corn Area 8,11,12	Sludge Treatment Area Previous Grass Area 6, 9, 10	Range	Number of Wells Sampled	Sampling Schedule	Rainfall[‡]
	mg L^{-1}							cm
1974	1.9	1.4	8.5	1.4	0.3 - 8.5	9	2-4 week interval (May-Oct.)	47.4
1975	6.0	9.8	26.4	32.0	1.3 - 65	11	3 week interval (June-Nov.)	58.6
1976	7.3	0.8	29.3	23.9	0.8 -45	12	Monthly (April-Nov.)	22.7
1977	—[§]	—	—	—	—	—	Monthly (April-Nov.)	59.5
1978	2.3	7.6	60.0	55.3	0.4 - 141	12	Monthly (April-Nov.)	74.1
1979	16.1	20.9	61.7	47.8	0.7 - 65	12	Monthly (April-Nov.)	58.2
1980	5.8	—	5.8	5.8	2.2 - 10.2	9	Annually (Oct.)	61.0
1981	20.2	—	54.1	54.4	5.2 - 105	11	Twice (April & Nov.)	68.4
1982	17.5	20.4	66.9	62.2	4.2 - 114	12	Twice (April & Nov.)	58.6
1983	29.0	52.4	87.8	49.6	16.0 - 108	12	Twice (April & Nov.)	68.2
1984	49.3	59.4	84.1	30.1	6.6 - 111	12	Twice (April & Nov.)	81.0
1985	33.6	41.6	44.7	26.8	0.1 - 72	12	Twice (April & Nov.)	64.7
1986	21.8	51.1	38.1	41.7	0.1 - 77	12	Monthly (April-Nov.)	89.2
1987	32.9	32.9	56.2	43.6	16.1 - 61.5	7	Twice (April & Nov.)	51.5
1988	32.9	36.6	45.7	33.6	8.1 - 59.2	10	Monthly (May-Oct.)	31.5
1989	14.5	—	39.8	21.2	1.0 - 43.2	6	Monthly (May-Nov.)	49.9
1990	10.6	50.6	34.9	51.0	5.2 - 71.4	13	Monthly (April-Oct.)	76.3
1991	9.5	62.9	17.8	31.4	0.1 - 69.8	12	Monthly (May-Oct.)	78.3
1992	21.3	65.9	17.6	52.4	0.3 - 86.3	12	Monthly (May-Sept.)	69.4
1993	14.9	41.5	17.5	42.6	0.2 - 61.26	12	Monthly (June-Oct.)	99.1

[†] See detail plan on Figure 3 for location of groundwater wells.
[‡] Total rainfall between April 1 to October 31.
[§] No sample because of dry wells.

surface-applied in winter. Overall, surface water quality was very good at the study site.

High levels of NO_3-N impaired quality of temporarily saturated soil water, but not the deep ground water at the Rosemount Watershed. Other water quality parameters, including trace elements, were not affected by activities at the site. The NO_3-N problem occurred due to rates of N-supplying fertilizer and sludge applied to the site that were in excess of that needed by crops. NO_3-N levels in the temporarily saturated soil water were decreasing in recent years in response to decreased application rates. At this site, the NO_3-N did not enter the deep ground water because of a dense glacial till overlaying the deep aquifer. It is likely that the NO_3-N of the temporarily saturated soil water is converted to gaseous N forms (denitrified) when this water flows to the surface at a lower position in the landscape. Periodic monitoring of the small stream below the watershed showed no decrease in water quality over the study period.

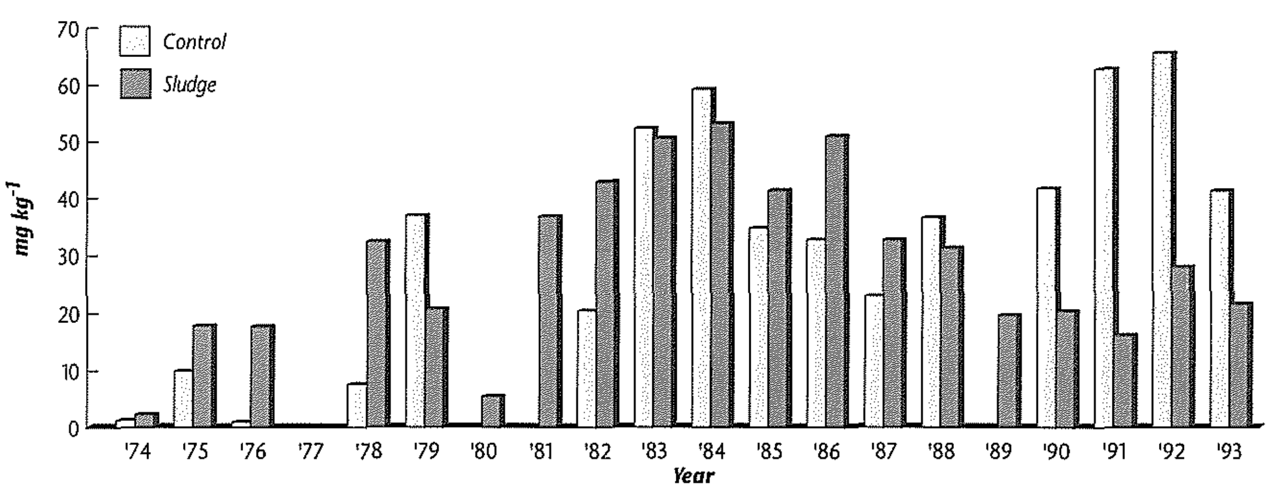

Figure 40. NO$_3$-N concentrations in water samples from shallow wells (1974-1993).

Table 47. Summary of water analyses from various sources at the Rosemount Watershed.

Sample Location[†]	*Year*[‡]	*pH*	*EC*	*NO$_3$-N*
			dS m^{-1}	*mg L^{-1}*
Shallow well # 1[§]	1974-93	7.9	0.80	11.3
2	1974-93	8.0	0.87	15.9
3	1974-93	7.9	0.83	13.0
4	1974-93	8.0	0.92	21.4
5	1974-93	8.0	1.06	27.8
6	1974-93	8.0	1.05	19.1
7	1974-93	8.0	0.81	28.5
8	1974-93	7.8	1.18	51.5
9	1974-93	8.0	0.99	32.2
10	1974-93	7.8	1.47	74.6
11	1974-93	7.7	1.11	54.5
12	1974-93	7.9	1.08	31.1
13	1974-93	7.9	1.03	59.5
14	1974-93	8.1	1.17	59.1
Lagoon Porous Cup (15)	1991-93	8.0	1.22	25.8
Lagoon Porous Cup (16)	1990-93	8.0	1.20	18.9
Lagoon Deep Well (18)	1990-93	8.1	0.68	0.7
Farm Well (19)	1973	8.3	0.56	0.8
	1973-93	8.0	0.59	0.6
	1993	8.1	0.65	1.05
Watershed Reservoir (20)	1973	7.8	0.18	2.1
	1973-93	8.0	0.45	2.0
	1993	8.1	0.56	2.0
Dam Tile (21)	1973	8.0	0.68	6.2
	1973-93	8.0	0.76	11.4
	1993	8.2	0.80	12.0

[†] See Figure 3 for location of sampling wells.
[‡] See Table 46 for sampling schedule.
[§] Shallow wells sample soil water in saturated zone at 0.5-1.5 m deep.

Table 48. Water quality parameters of the deep well and watershed runoff reservoir at the Rosemount Watershed.

Year	Source	Parameter											
		Total N	NO_3^--N	NH_4^+-N	Total P	PO_4^--P	Ca	Mg	Na	K	EC x 10^{-4}	pH	Fecal coliform‡
		mg L^{-1}									dS m^{-1}		
1973†	Reservoir	2.7	2.1	0.1	0.06	0.06	21	10	2	2	180	7.8	150
	Well	1.6	0.8	0.1	0.02	0.01	70	24	4	1	560	8.3	0
1975	Reservoir	3.0	2.8	0.2	0.04	0.01	27	14	4	2	282	8.3	41
	Well	0.8	0.6	0.0	0.04	0.01	75	25	4	1	557	8.1	0
1976	Reservoir	1.6	0.0	0.3	0.09	0.02	29	15	6	5	310	8.3	29
	Well	0.9	0.8	0.0	0.05	0.01	79	25	5	1	560	8.0	0
1977	Reservoir	1.6	0.1	0.6	0.20	0.11	26	11	9	10	317	8.1	1
	Well	1.1	0.8	0.0	0.07	0.01	84	24	5	1	577	8.0	0
1978	Reservoir	0.8	0.5	0.3	0.50	0.29	38	13	11	8	350	8.1	30
	Well	0.5	0.5	0.0	0.20	0.02	81	27	5	1	570	8.3	0
1979	Reservoir	2.0	1.2	0.1	0.60	0.09	77	33	11	5	350	8.1	40
	Well	2.1	2.0	0.0	0.20	0.03	101	31	5	4	570	8.3	1
1980	Reservoir	—	0.4	—	—	—	—	—	—	—	660	7.7	—
	Well	—	0.7	—	—	—	—	—	—	—	540	7.9	—
1981	Reservoir	—	1.5	—	—	—	—	—	—	—	540	7.9	—
	Well	—	0.2	—	—	—	—	—	—	—	550	7.9	—
1982	Reservoir	—	1.0	—	—	—	—	—	—	—	370	7.4	—
	Well	—	0.2	—	—	—	—	—	—	—	550	7.6	—
1983	Reservoir	—	15.4	—	—	—	—	—	—	—	580	8.2	—
	Well	—	1.0	—	—	—	—	—	—	—	620	8.2	—
1984	Reservoir	—	4.2	—	—	—	—	—	—	—	610	8.4	—
	Well	—	0.1	—	—	—	—	—	—	—	1160	8.0	—
1985	Reservoir	—	0.1	—	—	—	—	—	—	—	550	8.3	—
	Well	—	0.1	—	—	—	—	—	—	—	520	8.3	—
1986	Reservoir	—	2.3	—	—	—	—	—	—	—	660	8.1	—
	Well	—	0.1	—	—	—	—	—	—	—	530	8.2	—
1987	Reservoir	—	0.3	—	—	—	—	—	—	—	490	7.9	—
	Well	—	0.3	—	—	—	—	—	—	—	490	7.8	—
1988	Reservoir	—	<0.1	—	—	—	—	—	—	—	460	8.7	—
	Well	—	0.7	—	—	—	—	—	—	—	480	8.4	—
1989	Reservoir	—	0.7	—	—	—	—	—	—	—	330	8.4	—
	Well	—	0.2	—	—	—	—	—	—	—	500	7.8	—
1990	Reservoir	—	0.9	—	—	—	—	—	—	—	340	8.0	—
	Well	—	0.7	—	—	—	—	—	—	—	610	8.1	—
1991	Reservoir	—	0.9	—	—	—	—	—	—	—	340	8.0	—
	Well	—	0.7	—	—	—	—	—	—	—	610	8.1	—
1992	Reservoir	—	3.1	—	—	—	—	—	—	—	770	8.2	—
	Well	—	0.8	—	—	—	—	—	—	—	750	8.2	—
1993	Reservoir	—	1.95	—	—	—	—	—	—	—	556	8.1	—
	Well	—	1.05	—	—	—	—	—	—	—	647	8.1	—

† Sampled prior to sludge application at this site.

‡ Total coliform colonies divided by 100 mL.

Table 49. Analyses of samples taken from sampling tubes outside the sludge storage lagoons at 300-cm depth.[†]

	Sampling Site							
	Lagoon I (unlined)[‡] north		Lagoon II (lined) north (16)			Lagoon II (lined) east (15)		
Year	1975[§]	1985	1975[§]	1985	1986-93	1975[§]	1985	1986-93
	mg L^{-1}							
NO_3-N	0.4	0.6	2.2	9.3	17[¶]	0.0	6.7	22[¶]
NH_4-N	—	<0.1	—	<0.1	0.2	—	<0.1	0.2
PO_4-P	0.01	<0.01	0.00	<0.01	<0.02	0.01	<0.01	0.09
Cl	—	32	—	92	111	—	64	68
	ug L^{-1}							
Zn	0.03	40	0.03	<10	0.4[#]	0.03	<10	1.5[#]
Cu	0.01	<10	0.01	<10	2.6	0.01	<10	5.6
Ni	<0.005	0	<0.005	<10	1.8	<0.005	<10	2.6
Cr	<0.02	——	<0.02	——	1.4	<0.02	——	1.2
Pb	<0.01	<3	<0.01	<2	<4	<0.01	<4	<4
Cd	<0.005	<1	<0.005	<1	<0.3	<0.005	<1	<0.3

[†] Samples: means of analyses of water samples taken from May to October at a depth of 300 cm.

[‡] Lagoon decommissioned in 1988. Samples taken in 1985.

[§] Trace metal concentrations on composite samples from this site in mg L^{-1}.

[¶] NO_3-N, NH_4-N, PO_4-P, and Cl: means of analyses taken during 1986-1993.

[#] Trace metals: means of analyses taken during 1991-92.

SUMMARY AND CONCLUSIONS

The long-term study of the Rosemount Watershed is a landmark example of a detailed environmental and agronomic analysis of sludge application to land. The value of sludge as a fertilizer substitute was established for corn and grass crops. Yields on sludge-treated areas were on the average slightly better than those on fertilized control areas within the same watershed. Choice of crop is important if land application of sludge is primarily a disposal method. Grass was more efficient than corn in removing N, P, and K supplied in the sludge. It was also found that reed canarygrass thrived on sludge amendments, whereas some other forages performed poorly.

This study also answered questions concerning sludge application and the integrity of the environment. From a food chain viewpoint, it was shown that negligible amounts of trace elements are removed by crops grown on sludge-amended soils. For corn, trace element levels in plant tissue were not different from the low levels found in corn grown with commercial fertilizer. Only Cu and Cr levels in grass tissue from sludge treatments were slightly elevated over that of grass supplied with commercial fertilizer. No health problems are foreseen to animals or humans for the low levels observed.

From a water quality viewpoint, the Rosemount Watershed study showed that sludge application can be conducted in an environmentally safe fashion. Surface water quality was protected by adequate soil erosion measures taken at the site. Terraces installed on sloping ground and soil conservation practices were very important to prevent water quality deterioration. Nutrient losses due to runoff and erosion were quite low in comparison to the amount of nutrients applied to the soil.

More nutrients moved in surface runoff from grass terraces than from corn areas for two reasons. First, the fertilizer and sludge were not incorporated into the soil on the grass areas so surface runoff had greater contact with these materials. Second, grass tissue exposed to the elements over the winter lost nutrients to snow melt runoff. Snow melt was found to be an important source of runoff in this region. Winter spreading of sludge significantly increased the nutrient and trace element content of snow melt runoff at the study area. Surface application of sludge on sloping land during winter should be discouraged.

It was shown that fertilizer and sludge application rates, rates that supplied N in excess of crop uptake, affected the NO_3-N concentration of near-surface water. At this study site, high NO_3-N concentration in the near-surface, perched ground water did not affect the quality of the deep aquifer. In other areas, excess NO_3-N may directly affect ground water quality. This issue emphasizes the need for proper management of all nutrient sources in agriculture to protect ground water resources.

C and N accumulated in the soil due to sludge application. Soil test levels of extractable P increased due to sludge additions. The higher concentration of P had no apparent antagonistic effect on nutrient uptake due to increased plant nutrient concentrations from sludge additions. Commercial K fertilizer was needed to supplement the K deficient sludge from 1974 to 1985, however, from 1986 to 1993 no additional K was needed. Soil pH decreased under control corn treatments, requiring additional inputs of agricultural limestone, whereas sludge maintained optimum soil pH throughout the experiment. Some movement of metals occurred on the sludge-treated soil, but only to the 0.45 to 0.6 m layer. No leaching of trace elements occurred in the soil beneath the lagoon or to depths greater than 60 cm on the sludge-treated watershed.

The Rosemount Watershed study is one of very few studies to address the agronomic and environmental issues concerning sludge application to land. Overall, the recommendation is that sludge is a very good soil amendment to supply the nutrient needs of crops. The quality of the field crops grown on sludge-amended soil is good, and water resources can be protected if proper soil conservation and nutrient management methods are used. There are more benefits than costs in using this sludge resource.

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Effects of Sewage Sludge on Corn Silage and Animal Products†

INTRODUCTION

Use of municipal sewage sludge as a source of plant nutrients is of current interest because of environmental and economic concerns. Applications of sludge to soil at rates consistent with the nutrient requirements of a crop are believed to be more beneficial. Use of sludge as a crop fertilizer would not greatly affect the demand for fertilizer in the United States, since the total amount of sludge produced would supply only 1 to 2% of the annual N required for crop production. But the impact of sludge additions to any given land area is significant where applications are feasible. Occurring along with the essential plant nutrients present in sludge are also nonessential elements or those potentially toxic to crops, animals, or humans.

Heavy metals are typically present in municipal sludges. Transfer of metals from sludge to soil and subsequently to plants that enter the food and feed chain present a significant health concern. Animals exposed to subclinical levels of heavy metals are not easily identified and may be slaughtered or used as a source of milk. Limited information is available concerning the effects of feeding sludge-fertilized crops to large ruminants, though varying degrees of metal accumulation in animal liver and kidneys have been shown. Most studies have involved direct ingestion of sewage sludge, either as a component of the ration or as an adherent to leaf surfaces of forages.

The purpose of these studies was to document the impact of sludge-fertilized corn on the food chain under controlled experimental conditions that eliminated direct ingestion of sewage sludge. Specific objectives were to answer the following questions:

1. Does the feeding of sludge-fertilized corn silage affect the performance of dairy goats and market lambs?
2. Are sludge-borne heavy metals that accumulate in corn secreted into the milk of dairy goats fed the silage for three consecutive years?
3. Does Cd accumulate in the organ and muscle tissues of the dairy goats and market lambs that consumed corn silage containing high concentrations of Cd?

To answer these questions, corn silage produced on sludge-amended soil was fed to dairy goats for three consecutive years and to a group of market lambs in each of the three years. Determination of the effects on human health of consuming food products from animals that were fed sludge-fertilized corn silage was not included in this study.

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PROCEDURES

The soil was a well-drained, Typic Hapludoll, with a pH of 6.2. Waste-activated sewage sludge was applied initially at rates of 0, 30, 60, or 90 Mg ha^{-1}. Before the second and third croppings, sludge was applied at rates of 0, 15, 30, or 45 Mg ha^{-1} (Table 1). These treatments are referred to as the control, low, medium, and high treatments, respectively. Though sludge metal concentrations varied from year to year, Cd was the only metal that was atypically high.

Table 1. Sludge application rates and Cd, Cu, and Zn concentrations in sewage sludge and corn silage.

	Treatment				
Item	***Control***	***Low***	***Medium***	***High***	***Average Standard Deviation within Treatments***
Sewage sludge applied (metric tons ha^{-1})†					
Year 1	0	30	60	90	
Year 2	0	15	30	45	
Year 3	0	15	30	45	
Cd content of sewage sludge (mg kg^{-1})†					
Year 1	—	156	161	156	14
Year 2	—	186	133	137	7
Year 3	—	108	105	112	5
Cu content of sewage sludge (mg kg^{-1})†					
Year 1	—	703	712	717	34
Year 2	—	640§	629	730	53
Year 3	—	711	699	653	40
Zn content of sewage sludge (mg kg^{-1})†					
Year 1	—	1700	1590	1675	136
Year 2	—	2065	2580	2680	123
Year 3	—	1625	1570	1605	63
Cd content of corn silage (mg kg^{-1})†					
Year 1	<0.02¶	0.71	1.27	1.73	0.29
Year 2	<0.02¶	1.84	2.68	4.25	0.77
Year 3	<0.06¶	1.39	2.73	5.26	0.70
Cu content of corn silage (mg kg^{-1})†					
Year 1	3.6¶	3.9	4.4	4.4§	0.36
Year 2	3.5	3.7	3.8	3.6	0.54
Year 3	4.2#	4.1	4.8	5.3	0.44
Zn content of corn silage (mg kg^{-1})†					
Year 1	31¶	40	50	60‡	6.1
Year 2	44#	52	67	113‡	32.0
Year 3	35¶	74	75	107‡	14.6

† 70° C weight basis.

‡ Linear effect within sludge levels is significant ($P<0.01$).

§ Linear effect within sludge levels is significant ($P<0.05$).

¶ Control versus all sludge levels is significant ($P<0.01$).

Control versus all sludge levels is significant ($P<0.05$).

Goats and lambs were fed silage ad libitum. Free choice trace mineral salt that contained <0.2 mg Cd, 2.4 mg Cr, 128 mg Cu, and 125 mg Zn kg^{-1} was offered throughout the study. The corn silage composition data (Table 1) showed Cd and Zn as the only elements that increased consistently as a result of sludge applications. Cd levels in corn plant tissue showed the largest relative increases and reached a high of 5.26 mg kg^{-1} during the third year. These high Cd levels resulted in low Zn:Cd ratios and enhanced the potential for Cd absorption by the animals, since Zn may inhibit Cd absorption from the intestines of animals.

Milk samples collected during each lactation, blood samples taken annually, and animal organ tissues collected at necropsy were analyzed for Al, As, B, Ca, Cd, Cr, Cu, Fe, Hg, K, Mg, Mn, Na, Ni, P, Pb, Se, and Zn.

RESULTS

ANIMAL PERFORMANCE

Goat performance was measured by dry matter intakes and did not differ among treatments in any of the three years (the study period constituted about half of their productive lives). Intake ranged from 0.84 to 1.67 kg and was generally lower the first year. Daily milk production and feed efficiency did not differ substantially among the control, the medium, and the high sludge treatments.

Though the effect was significant only in the second year, lambs fed sludge-fertilized corn silage tended to average higher daily gains (0.19 kg) than lambs fed control silage. Daily feed intakes and efficiencies of lambs were not significantly affected by treatment, except in the first year, when feed efficiencies of lambs fed sludge fertilized corn silage were slightly higher than for lambs on control silage.

MILK COMPOSITION

Cd, the major trace metal that was bioaccumulated in the corn silage, was not transferred to milk from lactating goats (Table 2), even though animals on the high treatment consumed silage that contained more than 5 mg Cd kg^{-1} (approximately 5 mg Cd per day). The Cd concentration in milk from goats fed the highest level of dietary Cd was only 0.009 mg kg^{-1} (approximately 0.001 mg L^{-1} on a fluid basis). This figure is considerably lower than some of those reported in the literature.

When averaged across all sludge treatments, the Zn concentrations in milk from control goats did not differ from those of goats fed sludge-fertilized corn silage. But Zn in milk decreased as amounts of applied sludge increased within sludge treatments (Table 2), in spite of the fact that Zn concentrations in the silage ratio increased with increasing sludge applications.

Control goats had higher Cu concentrations in milk in each year, but they were significant only in the third year, as the amount of sludge used as fertilizer increased. Possibly the increased levels of Cd and Zn in the corn silage from sludge-fertilized soil caused Cu to be less readily absorbed by the goats.

The concentrations of the other measured elements in milk were unaffected by treatment. The elemental content of colostrum was usually higher than that of regular milk, but it was unaffected by treatment.

BLOOD COMPOSITION

The elemental composition of goat and lamb blood was essentially unaffected by feeding sludge-fertilized corn silage. The significance of no Cd increase in blood is that blood Cd levels are determined by current exposure and that exposure is apparently not high enough to affect blood concentrations.

Table 2. Concentrations of Cd, Cu, and Zn in milk collected from goats fed corn silage grown on sludge-amended soil.

Metal	Year	Treatment (mg kg^{-1})†				Average Standard Deviation within Treatments
		Control	Low	Medium	High	
Cd	1	<0.005	<0.005	<0.004	<0.003	—
	2	0.013	0.011	<0.009	<0.009	—
	3	0.011	0.017	0.012	0.009‡	—
Cu	1	0.42	0.32	0.29	0.28	0.40
	2	0.79	0.63	0.58	0.53	0.52
	3	0.64§	0.43	0.26	0.29	0.42
Zn	1	35.1	37.2	33.8	30.8¶	5.61
	2	34.1	40.8	34.5	32.8¶	7.13
	3	39.4	40.1	34.6	36.9	12.86

† 70° C weight basis.
‡ Linear effect within sludge levels is significant ($P<0.05$).
§ Control versus all sludge levels is significant ($P<0.01$).
¶ Linear effect within sludge levels is significant ($P<0.01$).

Table 3. Concentrations of Cd, Cu, and Zn in the liver and kidney of goats following 3 years of feeding with corn silage grown on sludge-amended soil.

Organ and Metal	Treatment (mg kg^{-1})†				Average Standard Deviation within Treatments
	Control	Low	Medium	High	
Liver					
Cd	0.26‡	1.72	2.10	2.94	1.41
Cu	16.6‡	8.6	10.3	10.7	4.33
Zn	90.3	91.2	85.9	88.8	22.4
Kidney					
Cd	3.1‡	10.8	24.8	22.4§	8.1
Cu	15.8‡	13.5	14.9	13.5	1.2
Zn	76.6‡	82.7	90.4	91.8	7.7

† 70° C weight basis.
‡ Control versus all sludge levels is significant ($P<0.01$).
§ Linear effect within sludge levels is significant ($P<0.05$).

ORGAN COMPOSITION

GOATS

Selected metal concentrations in tissues collected from goats at necropsy are listed in Table 3. After three years, goats fed corn silage that received control, low, medium, and

Table 4. Concentrations of Cd, Cu, and Zn in the liver and kidney of lambs fed corn silage grown on sludge-amended soil.

Organ and Metal	Year	Treatment (mg kg^{-1})[†]				Average Standard Deviation within Treatments
		Control	Low	Medium	High	
Liver						
Cd	1	0.56[‡]	8.82	1.06	1.31	0.53
	2	0.29[§]	1.97	3.56	5.29[¶]	1.32
	3	0.52[§]	1.13	2.52	3.58[¶]	1.29
Cu	1	185	196	215	210	111
	2	53	64	89	66	50
	3	164	163	168	128	50
Zn	1	102	110	103	98	14
	2	79	89	85	84	21
	3	105	105	118	114	15
Kidney						
Cd	1	1.57	1.38	1.90	3.11[¶]	0.97
	2	2.09[§]	5.07	10.89	18.94[¶]	4.03
	3	0.78[§]	2.70	7.31	10.19[§]	3.72
Cu	1	15.3[§]	16.9	15.4	16.8[§]	2.31
	2	16.0[§]	16.9	17.8	18.0	1.21
	3	19.4	20.5	19.5	19.6	1.66
Zn	1	109	103	109	113	14
	2	103[§]	110	124	126	7
	3	100	103	111	113	11

[†] 70° C weight basis.

[‡] Control versus all sludge levels is significant ($P<0.05$).

[§] Control versus all sludge levels is significant ($P<0.01$).

[¶] Linear effect within sludge levels is significant ($P<0.01$).

high sludge rates had consumed approximately <40, 1300, 2200, and 3900 mg Cd, respectively. Cd, the element that accumulated in the corn silage most dramatically, was present at 0.26, 1.72, 2.10, and 2.94 mg kg^{-1} in goat livers for the control, low, medium, and high sludge treatments, respectively. These levels tended to increase as the amount of sludge applied increased. Kidney Cd concentrations were approximately 10 times those observed in liver, ranging from 3 to 22 mg kg^{-1} for animals on control and high treatments, respectively. Kidney Cd levels for control animals were significantly lower than those in kidneys of animals fed sludge-fertilized corn silage, and they increased linearly with increasing sludge applications. Cd levels in heart and muscle were minimal and averaged 0.08 and 0.07 mg kg^{-1}, respectively.

Zn concentrations in liver and heart did not differ significantly among treatments. Kidney Zn ranged from 76.6 to 91.8 mg kg^{-1} with control animals having less Zn than animals fed sludge-fertilized corn silage. Cu concentrations in livers and kidneys were significantly lower (approximately 2 mg kg^{-1}) in animals receiving sludge-fertilized corn silage treatments than in animals fed control silage. The reason for this result may have been that the elevated Cd and Zn levels in the sludge-fertilized corn silage caused Cu to be less readily absorbed by the goats.

None of the other measured elements had accumulated in the goat tissues as a result of fertilizing corn with sewage sludge.

LAMBS

Concentrations of selected metals in lamb tissues are presented in Table 4. For each year, livers and kidneys from control animals had a lower concentration of Cd than those of animals fed sludge-fertilized corn silage. The latter lambs showed linear increases in the amounts of Cd in liver and kidney with increasing sludge applications. Cd concentrations in heart and muscle were low and unaffected by sludge treatments.

Zn concentrations in liver, heart, and muscle were not significantly affected by sludge treatments. Kidneys from control animals tended to contain less Zn than those of animals fed sludge fertilized corn silage. The lack of a major dose-related increase in kidney Zn may be a result of high dietary Cu (trace mineral salt) and Cd (corn silage) interacting to reduce the absorption of Zn.

Although significant only in the second year, Cu levels in kidneys from control lambs were lower than those from lambs fed sludge-fertilized corn silage. Elemental concentrations of Al, B, Ca, Fe, K, Mg, Mn, Na, Ni, P, and Pb in liver, kidney, heart, and muscle were not consistently affected by sludge treatment. Histological examinations of lamb liver and kidney tissues showed no observable morphological differences among sludge treatments.

CONCLUSIONS

Total dry matter intake, daily milk production, and feed efficiency of dairy goats were not reduced by feeding a high-Cd corn silage continuously for three years—approximately half of their productive lives. Similarly, daily gains and feed efficiencies of market lambs were not affected by treatment.

Cd from corn silage was not secreted into the milk from lactating goats, even though some animals were receiving approximately 5 mg Cd per day. Zn concentrations in milk from control animals did not differ from those of goats fed sludge-fertilized corn silage, but Cu concentrations were higher in milk from the control goats. The bioavailability of Cu may have been limited by the elevated levels of Cd and Zn in silage from sludge treatments.

The elemental concentrations of 15 other metals and minerals in milk were not affected by treatment. The composition of goat and lamb blood was not affected by treatment, except that Cu was higher in the blood of control goats.

The Cd concentrations in livers of both goats and lambs were always lower in control animals, and they increased with increasing sludge applications. This result was particularly true for lambs, where Cd concentrations as high as 5.29 mg kg^{-1} were found. Accumulations of Cd in animal kidneys were 5 to 10 times greater than those observed in livers, but they followed the same general patterns. Cd concentrations in animal heart and muscle were low and not affected by treatment.

Zn, the only other element found to accumulate in silage as a result of treatment, did not increase in animal liver, heart, and muscle as a result of feeding Zn-enriched silage. Small, but significant, increases in Zn content were observed in lamb kidneys for animals fed sludge-fertilized corn silage.

Cu concentrations in goat and lamb kidneys and goat livers were lower for animals fed sludge-fertilized silage than for control animals. The concentrations of 15 other elements in the various animal tissues were not consistently affected by sludge fertilization of corn silage.

Thus corn silage produced on soil amended at moderate to high rates with sewage sludge containing high levels of bioaccumulated Cd can be fed to dairy goats and market lambs without impairing their performance. Trace metals, particularly Cd, taken up by the corn and ingested by the animals did not accumulate in milk or muscle tissue—foods consumed directly by humans. Cd did accumulate in the kidneys of goats and lambs, reaching concentrations of 25 mg Cd kg^{-1} in goat kidney when corn silage containing as much as 5.26 mg Cd kg^{-1} of silage (an ingestion rate of approximately 5 mg Cd per day) was consumed continuously for three years. Though Zn is taken up by corn to a smaller extent than Cd, it did accumulate in lamb kidneys, but not in goat kidneys or livers of either species. Histological examinations of lamb livers and kidneys showed no observable morphological differences as a result of consuming Cd-enriched silage.

The Effect of Lime-cake Municipal Sewage Sludge on Corn Yield, Nutrient Uptake and Soil Analyses[†]

INTRODUCTION

The increased interest and demand for application of lime-cake sewage sludge on agricultural land has required the investigation of several potential problems which may be created with the use of this type of sludge. Sewage sludge treated with hydrated lime is easily dewatered by vacuum filters and is biologically stabilized.

The material produced by this process is a cake-like solid containing approximately 70 to 80% water, has a pH of >11.0, and contains 30% lime as $CaCO_3$ equivalent. The lime-cake sludge is normally incinerated, but has been applied to agricultural land. The addition of large amounts of hydrated lime to sludge makes it uniquely different from other sludge materials studied.

The high pH and lime content of the filter-cake could create problems with nutrient uptake by growing plants. Competition with K by the Ca for colloidal exchange sites could pose availability problems for K uptake. Increases in soil pH from lime-cake sludge application could reduce the availability of certain plant nutrients.

Solubility of some of the trace metals may be decreased by the lime, thus reducing their toxic potential. Higher application rates of lime-cake sludge not only could affect plant and soil chemistry, but may cause excessive leaching of pollutants through the soil profile. Thorough examination of these potential problems will assure the safe and productive use of lime-cake sludge on agricultural land.

STUDY OBJECTIVES

This study was conducted for the following reasons:

1. Determine the effect of lime-cake sewage sludges on corn yield, on corn nutrient uptake, and on soil chemical properties.
2. Determine the effects of cations from lime-cake sludge on the cation balance in the soil and on corn nutrient content.
3. Determine the effect of trace metals in the sludge on corn nutrient content and trace metals in soil.

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EXPERIMENTAL DESIGN AND PROCEDURES

A 0.2-ha site was selected adjacent to the Rosemount Watershed study at the Rosemount Agricultural Experiment Station. The site is situated on a Port Byron silt loam soil (Typic Hapludoll). The top soil is 30 to 45 cm deep, with 2 to 5% slope, formed from a deep loess cap (< 240 cm). Twelve 0.01-ha plots (four treatments by three replicates) were arranged on this site allowing for eight corn rows, 16 m in length at 0.75-m spacing, on each plot. The following treatments were then assigned to each replicated block of three plots:

1. Control (fertilized in a manner for maximum crop production, but with no additional K application).
2. Fifteen dry Mg ha^{-1} of lime-cake sewage sludge per year (application in this range approaches limits for yearly Cd applications).
3. Thirty dry Mg ha^{-1} sludge per year (applications in this range approaches limits set for yearly N applications).
4. Sixty dry Mg ha^{-1} of sludge per year (excess nutrients and metals).

The lime-cake sludge was applied before corn planting in the spring, before the first crop, and then each fall after corn harvest for five consecutive years (total of six applications). Sludge was applied using a manure spreader and then incorporated with a tractor-mounted rototiller. Samples of the sludge were taken during spreading on each plot and composited for laboratory analysis. Soil samples were taken prior to each sludge application.

Corn was planted in early May at 65 000 kernels ha^{-1}. Corn rootworm insecticide was applied at planting, followed by a preemerge broadcast application of herbicide for weed control. Stover and grain yields were taken and tissue samples were collected for laboratory analyses in late September. Soil samples were also taken after corn harvest.

Laboratory analyses were conducted to determine: 1) nutrient content of the corn plant tissue, including trace metal concentrations; 2) change in soil pH due to sludge treatment; and 3) effect of the lime-cake sludge on the soil exchangeable cations.

In order to examine the effects of lime-cake sludge on corn yield and plant uptake of nutrients, the experiment was continued for four years following the last sludge application.

RESULTS AND DISCUSSION

SLUDGE APPLICATION

Analyses of the lime-cake sludge are shown in Table 1. The concentration of trace metals was moderately high in this sludge, particularly in respect to Cd. Ca content was >14%, accounting for the high pH and very low NH_4^+-N concentration. The major portion of the N was in the organic form.

Total amount of sludge and nutrients applied for the six-year period is shown in Table 2. The three sludge treatments received annual applications of about 20, 30, and 60 dry Mg ha^{-1} yr^{-1} for low, medium, and high rates, respectively. The sludge contained considerable lime and averaged 7, 11, and 21 Mg ha^{-1} yr^{-1} $CaCO_3$ equivalent for the three treatments. Total N applied was quite high, with average annual additions of 260, 560, 930, and 1720 kg ha^{-1} yr^{-1}. K was only applied in two years, since there was adequate soil K initially, and it was important to study the effects of high Ca on K uptake.

Table 1. Composition of lime-cake municipal sewage sludge for six annual applications.

Constituents†	*Mean*
	%
Total solids	24.8
Total C	25.7
Total N	2.98
NH_4^+-N	0.25
P	1.20
K	0.07
Ca	14.1
Fe	3.6
Al	1.0
Mg	0.5
Na	0.1
	mg kg^{-1}
Zn	1300
Cr	1000
Mn	700
Cu	670
Pb	300
Ni	160
Cd	86
B	18
EC (dS m^{-1})	4.3
pH	11.6

† Total solids based on 105° C dry weight. Other constituents based on percentage of total soils.

Table 2. Lime-cake sewage sludge and fertilizer applications for six years.

Treatment	*Application Rate*		*$CaCO_3$*	*Total N*	*Total P*	*Total K*	*Total Cd*
	Mg ha^{-1} yr^{-1}	*Mg ha^{-1}*	*Mg ha^{-1} yr^{-1}*	*kg ha^{-1} yr^{-1}*			
Control	0	0	0	260	28	90	0
Low	19.5	117	6.8	560	230	13	2.0
Medium	31.8	188	11.5	930	370	20	3.2
High	58.6	352	21.2	1720	700	39	5.9

CORN YIELDS

There does not appear to be any significant difference in yields for the sludge-treated plots compared with the fertilized controls for the 6-yr mean value (Table 3). Control yields were equal to or greater than sludge yields for most years, with greater differences occurring in the final two years after sludge application ceased. Yields for all treatments were average to high for the southeastern area of Minnesota. During the third cropping season a wind and hail storm severely damaged the corn crop, substantially reducing yields. Corn fodder yields from the sludge treatments were reduced during the fifth, sixth, and seventh cropping years, possibly caused by reduced K uptake.

PLANT ANALYSES AND NUTRIENT UPTAKE

Values for the major plant nutrients N and P for lime-cake plots were within adequate ranges for normal corn growth. N removed annually during the 6-yr period by the corn crop averaged 68 and 10% of the N added as fertilizer and sludge for the control and high sludge application, respectively. Corresponding values of P removed were relatively small in comparison to the amount applied, with 11, 7, and 4% uptake for the low, medium, and high plots, respectively.

Summaries of macro-nutrient and trace metal concentrations for the 10-year period are given for corn grain (Table 4) and corn stover (Table 5). Elemental analysis of corn tissue showed adequate N and P contents, but a definite K deficiency for stover tissue for all sludge treatments. The high sludge rate showed slightly increased corn tissue K because about 40 kg ha^{-1} yr^{-1} of sludge-derived K was applied. Imbalances in Ca and K, soil pH, carbonates, neutral salts, organic matter, and CO_2 in the soil profile could have had an effect on corn uptake of K. All plots received K for the seventh and eighth growing seasons, slightly increasing corn yields.

Zn, Cu and Cd concentrations increased with sludge applications, but remained in the range for normal crop growth. A decrease in Cd was

Table 3. Corn yields and nutrients removed at the Rosemount lime-cake sewage sludge project for 10 years.

Treatment	Season	Yield†			Nutrients Removed		
		Grain		Fodder‡	N	P	K
		Mg ha^{-1}	bu $acre^{-1}$	Mg ha^{-1}	kg ha^{-1}		
Control	1-6 yr§	6.8	128	14.2	173	26	107
	7 yr	8.6	162	17.0	198	31	112
	8 yr	7.4	138	14.8	193	27	99
	9 yr	9.4	178	16.6	255	28	113
	10 yr	9.0	169	16.7	251	28	110
Low	1-6 yr§	6.6	122	13.5	159	26	82
	7 yr	6.5	122	11.8	137	26	55
	8 yr	7.2	133	14.3	153	28	76
	9 yr	7.3	137	13.1	130	27	67
	10 yr	7.2	136	13.4	138	34	68
Medium	1-6 yr§	6.8	127	13.6	165	26	83
	7 yr	6.8	128	12.3	145	25	57
	8 yr	8.2	152	14.7	163	26	80
	9 yr	7.8	148	14.2	158	28	83
	10 yr	8.6	165	15.1	191	38	81
High	1-6 yr§	6.8	127	13.6	169	26	93
	7 yr	7.0	132	12.9	151	23	65
	8 yr	7.9	148	14.8	184	27	88
	9 yr	9.0	170	15.5	226	27	86
	10 yr	7.7	146	14.7	208	30	86

† Means of three replicated plots. Yields represent dry matter at 65° C. Shelled grain calculated in bu A^{-1} at 15.5% H_2O.

‡ Fodder = total dry matter = grain + cob + stover.

§ Mean value for 6 years.

observed in stover in years following final sludge application. Elemental concentrations for corn grain showed essentially no treatment effect due to sludge application.

SOIL ANALYSES

Six sludge applications supplied a considerable amount of lime, greatly exceeding the liming requirements of the Port Byron soil. Examination of soil samples taken in year 1 prior to sludge application, one year after sludge application stopped (year 7), and after corn harvest in the final year (Table 6) showed significant changes in several soil properties due to six years of lime-cake sludge additions. Soil pH increased significantly with lime-cake additions, reducing the availability of trace metals and decreasing the potential for entering the food chain. The presence of free Ca CO_3 was observed for all sludge treatments in the surface 15 cm after six annual sludge applications, elevating soil pH to the 7.7 to 7.8 range.

Increasing application rates raised the soil EC above the control values. Multiplying the 1:1 dilution EC by the conversion factor 3 would give the approximate values for a soil saturated-paste extract. The soil EC for the high sludge treatment would be approximately 1.5 dS m^{-1} for the 0 to 15 cm depth, still below the 2.0 to 4.0 dS m^{-1} range found in slightly saline soils where low salt-tolerant crops will still grow.

Table 4. Elemental concentrations of corn grain tissue grown on sludge-amended soil at the lime-cake project for 10 years.

Treatment and year	*Element*†								
	N	*P*	*K*	*Zn*	*Cu*	*Pb*	*Cr*	*Ni*	*Cd*
	%			$ug\ g^{-1}$					
Control									
1-6 yr‡	1.61	0.30	0.42	26	2.2	< 0.3	< 0.2	< 0.4	< 0.04
7 yr	1.55	0.29	0.37	22	2.2	0.1	< 0.1	0.7	0.52
8 yr	1.70	0.29	0.38	29	1.4	0.4	0.1	0.3	0.32
9 yr	1.50	0.25	0.35	25	2.3	0.4	0.1	0.2	0.40
10 yr	1.62	0.26	0.39	26	2.2	0.4	0.2	0.4	0.17
Low									
1-6 yr‡	1.53	0.30	0.42	28	2.0	< 0.3	< 0.2	< 0.3	< 0.04
7 yr	1.50	0.31	0.39	28	3.0	0.2	< 0.1	0.7	0.54
8 yr	1.47	0.28	0.38	28	2.0	0.4	0.2	0.4	0.32
9 yr	1.10	0.30	0.41	30	2.3	0.4	0.1	0.3	0.50
10 yr	1.08	0.35	0.47	31	2.7	0.4	0.2	0.3	0.15
Medium									
1-6 yr‡	1.56	0.31	0.42	25	2.0	< 0.3	< 0.2	< 0.3	< 0.04
7 yr	1.51	0.29	0.37	28	2.5	0.2	0.1	0.1	0.51
8 yr	1.45	0.28	0.39	27	2.4	0.4	< 0.1	0.3	0.28
9 yr	1.20	0.30	0.40	30	2.3	0.4	0.1	0.2	0.40
10 yr	1.29	0.35	0.46	31	2.2	0.4	0.2	0.3	0.15
High									
1-6 yr‡	1.61	0.31	0.42	31	1.9	< 0.3	< 0.2	> 0.3	> 0.04
7 yr	1.50	0.27	0.36	29	2.2	0.2	0.1	1.2	0.51
8 yr	1.64	0.28	0.39	25	1.8	0.4	< 0.1	0.2	0.28
9 yr	1.50	0.26	0.35	27	2.0	0.4	0.2	0.2	0.50
10 yr	1.47	0.31	0.42	30	2.3	0.6	0.2	0.3	0.17

† Means of three replicated plots. ‡ Mean value for six years.

SUMMARY

Corn grain and fodder yields obtained on the lime-cake sludge plots were not significantly different between treatments and were approximately equal to the control plots.

Nutrient uptake of major plant nutrients was in the range for normal corn growth, except for stover K. All sludge treatments were near K deficiency range, although the high application plots had greater stover-K concentrations. The high sludge treatment supplied 40 kg K ha^{-1} with the sludge.

Trace metal concentrations in lime-cake corn tissue remained within the range for normal growth. Slight increases in stover Zn and Cd were noted. Soil pH increased significantly with lime-cake sludge additions, reducing the availability of trace metals and decreasing the potential for entering the food chain. EC increased with higher lime-sludge application rates due to soluble salts in the soil.

Results indicate that lime-cake municipal sewage sludge can be applied to agricultural land with no detrimental effect on the environment, while maintaining good crop yields.

Table 5. Elemental concentrations of corn stover tissue grown on sludge-amended soil at the lime-cake project for 10 years.

Treatment and year	Element[†]								
	N	*P*	*K*	*Zn*	*Cu*	*Pb*	*Cr*	*Ni*	*Cd*
	%			$ug\ g^{-1}$					
Control									
1-6 yr[‡]	0.97	0.09	1.17	20	5.8	1.0	1.2	< 0.9	0.13
7 yr	0.89	0.08	1.08	23	9.3	0.6	0.8	0.7	0.26
8 yr	0.92	0.08	0.96	31	8.2	0.4	0.8	0.7	0.16
9 yr	0.91	0.08	1.19	23	11.6	0.4	0.7	0.4	0.12
10 yr	0.81	0.06	1.13	30	6.8	0.5	1.5	1.2	0.16
Low									
1-6 yr[‡]	0.95	0.10	0.83	27	6.1	1.5	1.4	< 1.0	0.33
7 yr	0.86	0.14	0.60	36	8.1	0.6	0.5	0.4	0.56
8 yr	0.68	0.11	0.69	30	5.3	0.5	0.9	0.6	0.30
9 yr	0.48	0.10	0.65	34	5.9	0.4	1.0	0.6	0.48
10 yr	0.52	0.16	0.63	49	5.4	1.4	1.7	1.4	0.29
Medium									
1-6 yr[‡]	0.99	0.10	0.82	32	6.5	1.5	0.9	1.2	0.45
7 yr	0.96	0.12	0.63	37	9.1	0.3	0.5	0.3	0.67
8 yr	0.77	0.08	0.69	31	6.8	0.5	1.0	0.6	0.34
9 yr	0.59	0.08	0.87	40	8.7	0.4	0.8	0.4	0.29
10 yr	0.65	0.15	0.68	48	5.8	1.0	1.6	1.2	0.33
High									
1-6 yr[‡]	1.02	0.10	1.01	45	7.0	1.0	1.6	1.1	0.82
7 yr	0.91	0.09	0.74	44	7.7	0.3	0.5	0.3	0.61
8 yr	0.85	0.08	0.80	42	8.3	0.5	1.3	0.8	0.59
9 yr	0.75	0.08	0.92	43	10.8	0.4	0.7	0.4	0.49
10 yr	0.74	0.10	0.84	52	6.6	0.9	1.3	1.0	0.38

[†] Means of three replicated plots.
[‡] Mean value for six years.

Table 6. Effect on soil properties before (year 1) and after (years 7 and 10) additions of lime-cake sludge at the lime-cake project for 10 years.

Treatment[†]	*pH*[‡]			*EC*[‡] *dS* m^{-1}			*Extr. P*[§] *kg* ha^{-1}			*Exch. K kg* ha^{-1}		
Year	*1*	*7*	*10*	*1*	*7*	*10*	*1*	*7*	*10*	*1*	*7*	*10*
Control	6.4	5.9	6.4	0.3	0.3	0.5	> 134	84	82	78	263	193
Low	6.3	7.7	7.4	0.3	0.3	0.3	> 134	> 134	> 134	108	218	186
Medium	6.4	7.8	7.6	0.3	0.4	0.4	> 134	>134	> 134	149	200	182
High	6.3	7.8	7.5	0.3	0.4	0.5	> 134	> 134	> 134	149	236	172

[†] Means of soil samples taken at 0-15 cm for three replicated plots.
[‡] Soil pH and EC determined at 1:1 soil to water dilution.
[§] Bray # 1 P test for control; Olsen P test for calcareous soils for sludge treatments.

Future Research Needs†

The Rosemount Watershed study has spanned a 20-yr period in which intense research has been conducted on the land application and agricultural utilization of sewage sludge. These research efforts have greatly enhanced our understanding of the nutritive value of sewage sludge for agricultural production and the relatively low level of environmental impact that the use of sewage sludge creates. Out of these 20 years of research, both new state and federal regulations have been developed to safely guide the use of sewage sludge as an agricultural amendment. After 20 years, what additional research needs to be done?

Further research needs are as follows:

LONG-TERM STUDIES

Long-term (decades) studies are needed to determine slow, but real, changes in soil and plant composition affected by continuous applications of sludge-borne pollutants. Changes such as soil binding capacity as the soil and sludge attributes interact and the effect of aging on the susceptibility for transport need to be documented for both agricultural and natural ecosystems.

BENEFICIAL EFFECT

Further fundamental knowledge is needed for predicting beneficial effects obtainable after sludge and sludge-compost applications. Interactions between soil organic matter decomposition level, sludge- and soil-borne plant pathogens and plant roots must be explored further. Better, more reliable methods for predicting N mineralization rates for different sludges and admixtures of sludge and alternate C and mineral sources are required for minimizing the potential for NO_3-N leaching.

RISKS

The risks from introduction of toxic organics, trace metals, and pathogens into the farm ecosystem and possible introduction into the food chain, and water resources for both humans, and agricultural and wildlife animals need further elucidation. It is vitally important to provide information on uncertainty associated with risk assessment and the size of the population at risk. New methods must be developed that include, but differentiate, among sources of uncertainty and are capable of displaying the uncertainty.

SYSTEMS RESEARCH

Systems research is needed to define viable, management options for the farm operator. Synthesis of current information and new research into practical, easily understood management systems could make sludge usage on

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† List of research needs excerpted from *Sewage Sludge: Land Utilization and the Environment*, SSSA Miscellaneous Publication, 1994.

farms more acceptable. The risks and benefits need to be clearly defined. Responsibilities and liabilities of farm operators and sewage agencies must be more clearly spelled out.

TRACE ELEMENTS

The shape of the rate response curve for trace metal uptake by plants in addition to corn and grass crops needs to be confirmed with field data. The assumption that plant response is relative (i.e., all crops can be represented by the response of a single crop) must be field tested and validated. The bioavailability of metals in plant tissues, sludges, and soil-sludge mixtures ingested by livestock and wildlife needs to be more fully characterized. This includes the case in which earthworm-consuming mammals and birds ingest high amounts of soil. A better understanding of pollutant desorption is needed to support models that consider transport in non-uniform media.

ECOLOGICAL EFFECTS

Information is needed on the ecological effects of organic and inorganic constituents of sludge on wildlife, water resources, and non-cultivated crops and impacts on unmanaged plant and animal communities. The impacts on adjacent plant and animal communities and the distances over which impacts may occur needs study.

DESIGN, USE, AND COST CONSIDERATIONS

A need exists to develop a concise quantitative understanding of the magnitude of sludge generation, and the impact of various alternatives on the costs of sludge utilization. Various design alternatives are possible. Processes in wastewater treatment plants, as well as post plant-treatment handling alternatives, need careful study. A current National Sewage Sludge Survey is needed to update the concentrations of constituents in sludge and to determine what changes have occurred in sludge management practices.

SOCIOLOGICAL-ECONOMIC MARKETING CONSIDERATIONS

Reusing wastes in a beneficial way has not always been an integral part of U.S. culture. As a result, recycling of waste into agriculture raises many concerns, both real and imagined. A rational use policy needs to provide economic compensation for property impacts, both real or imagined. The impacts of the practice of sludge use in food production and on international trade need to be carefully considered. This may require establishing international sludge surveys that include background levels of various microbiological and inorganic constituents not only in sludge, but also in foods.

TECHNICAL SPECIFICATIONS FOR SEWAGE SLUDGE AND SIMILAR PRODUCTS

Sewage sludge, animal manure, municipal solid wastes, composts, green waste, and other organic amendments are all applied on land. Benefits of using these materials, however, are dependent upon properties of the applied products. At present, marketing and promotion of their uses on land are hampered because their chemical and physical properties vary considerably, even among the same type of material. Technical specifications need development. These specifications will serve as industry-wide standards for product performance and will be helpful to establish consumer confidence in the products.

Considerable progress has been made in understanding the scientific principles and in reducing the uncertainty in each of these broad areas. From the practitioner's standpoint, additional progress is needed because when regulators are faced with uncertainty, they generally respond (and rightly so) with conservative regulations which, in turn, result in a waste of limited resources.

Although much of the research on land application of sewage sludge has been done, there still is a need to continue these efforts. There are many unanswered questions and it is important to invest research funding in these areas.

APPENDIX A:

Yearly Record of Sludge Application Practices and Equipment

Lagoon agitation and pumping equipment and practices used over the 20-year study.

Year	*Type of Equipment Used/Practices Used* †
1975	Sludge in the lagoon was mixed using a tractor-driven pump with a flexible outlet hose connected to a floating movable raft in the lagoon. The intake of the sludge irrigation pump was connected by a flexible suction hose to another movable raft. The inlet of the suction hose was mounted on a movable boom which could be lowered from the raft to the bottom of the lagoon. Sludge was moved to the terraces from the lagoon through an underground pipeline. Sludge was applied to the corn terraces in the spring using a Nelson Big Gun sprinkler attached to a Hydro Sprinkler Winch. The gun capacity was 1230 L min^{-1} (325 gal min^{-1}) at 7.0 kg cm^{-2} (100 psi) with a 2.7 cm (1.05-in) nozzle covering a half circle area with a 45-m arc. Application rate was 0.6 to 1.1 ha-cm hr^{-1}. A 1700 L min^{-1} (450 gal min^{-1}) positive displacement electric pump was used for pumping the runoff water and sludge to the traveling gun. Sludge was also applied in the fall using a Briscoe-Maphis subsurface injector. The subsurface injector consisted of a toolbar mounted on a high flotation wide-tracked tractor. Seven spring-loaded shanks with 40-cm sweeps were attached to the toolbar covering a 300-cm width. Application rate was 1.5 ha-cm hr^{-1}. Sludge was applied to the reed canarygrass by traveling gun two times in the period of August to October.
1976	Sludge mixing and pumping in lagoon was the same as in 1975. Sludge was applied to corn terraces by subsurface injection only in November. Terraces then chiseled to eliminate runoff. Sludge was applied to grass terraces by traveling gun. The sludge-treated grass areas received sludge in the spring (April) and before significant regrowth after each of the cuttings in the summer (June) and early fall (October).
1977	Sludge mixing and pumping in lagoon was the same as in previous year. Sludge applied to corn terraces by subsurface injection at a rate of 1.5 ha-cm hr^{-1} in three applications in September and October. In December, sludge was applied to one snow covered grass area by tractor and tank wagon to measure the effects of sludge application on frozen ground. Sludge was applied to grass terraces by traveling gun in April, June, and July.
1978	Sludge mixing and pumping in lagoon was the same as in previous year. Sludge applied to corn terraces in October. A second application of sludge was applied to the snow covered grass area in December. Sludge applied to grass areas in April, June, August, and October.
1979	Sludge mixing and pumping in lagoon was the same as in previous year. Sludge applied to corn terraces in October. Terraces chisel-plowed after application. Sludge applied to grass areas in May, June, August, September, and October.
1980	Sludge mixing and pumping in lagoon was the same as in previous year. Sludge applied to corn terraces in October and chisel-plowed. Evidence of NO$_3$-N movement to 150-cm depth. Lower sludge application rates were used. Sludge applied to grass areas in May, June, July, and October.
1981	Sludge mixing and pumping in lagoon was the same as in previous year. Corn terrace sludge applied in October. Lower sludge application rates used to reduce NO$_3$-N movement. Grass terrace sludge applied by traveling gun in April, June, and August.

1982 Sludge mixing and pumping in lagoon was the same as in previous year.

Corn terrace sludge applied in October. No chisel-plowing due to inclement weather.

Grass terrace sludge applied in May, June, and August. No fall application was made.

1983 No sludge applied to the corn terraces due to NO_3-N accumulation in the soil.

Sludge was applied on the grass areas only in July.

1984 Sludge applied to corn terraces in October/November. No chisel-plowing done due to frozen soil.

Sludge applied in two applications in July, and one application in August.

1985 Sludge applied to corn terraces and absence of chisel plowing was same as in 1984.

Sludge applied to grass terraces only in July. Reed canarygrass experiment discontinued, and terraces planted to corn. Data from 1985 crop not used because reed canarygrass failed to develop a productive stand because of weed competition.

1986 No sludge applied to terraces due to a 1-year moratorium.

1987 Decommissioning of Lagoon I begun. Lagoon dredged and sludge applied to field.

Sludge applied to corn terraces in October.

1988 Lagoon I decommissioning completed.

Sludge was injected in the field by a tractor and tank wagon injector. This method was employed due to mechanical problems encountered with the equipment used in past years. Sludge injected in November.

1989 A mechanical barge was used to mix the sludge and pump it to a tank where the flow to the irrigation hose was regulated. This method was used due to mechanical problems encountered with the equipment used in past years. An above ground hose was hooked up to this lagoon system and carried the sludge to the terraces.

Sludge was applied in the field by a tractor with injectors attached to the toolbar. The above ground hose carrying sludge was attached to this injector bar. Sludge was injected in November.

1990 Pumping and mixing method was the same as in 1989. No new sludge was added to the lagoon. Efforts were made to clean out the lagoon and apply remaining sludge. This was done in preparation for the closing of the project.

Sludge application was the same as in 1989. Sludge applied in October.

1991 Pumping and mixing method was the same as in 1990. No new sludge was added to the lagoon. Efforts were made to clean out the lagoon and apply remaining sludge. This was done in preparation for the closing of the project.

Sludge application was done by discing the sludge into the soil, rather than subsurface injecting. This method did not work as effectively as past years, requiring additional discing to ensure proper incorporation of sludge. Sludge applied in October.

1992 A larger mechanical barge was used to mix and pump the sludge. New sludge was added to the lagoon. Efforts were made to entirely clean out the lagoon.

Special disc-injectors were used to apply sludge. The Badger 56 cm horizontal subsurface discs spread the sludge in a 56 cm wide even pattern approximately 15 cm below the soil surface. This technique was very effective in distributing sludge with very little surface runoff.

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† Mention of trade names is for the convenience of the reader only and does not imply endorsement by the University of Minnesota, U.S. Department of Agriculture (USDA), or Metropolitan Waste Control Commission (MWCC) over similar products of other companies not mentioned.

APPENDIX B:

Laboratory Methods †

Laboratory methods have not changed significantly over the 20-yr period. The exception was a change in research equipment in 1978, when samples were analyzed by an inductively coupled plasma spectrometer as opposed to the previous spark emission spectrometer. The chemical analyzer for NO_3 and P was changed from a Technicon autoanalyzer II to an ALPKEM RFA in 1985.

Water and sludge samples were refrigerated after collection. Analyses of organic components were performed within one week or the samples were acidified. Soil samples were air-dried at 35° C. Plant samples were oven-dried at 65° C.

SLUDGE MATERIAL METHODS

(Determination of both total and volatile solids is subject to error due to the loss of ammonium carbonate and volatile organic matter while drying, making the results lower than they should be).

1. Total Solids: Samples dried for 24 h at 105°C. Weight loss was used to calculate H_2O content based on the total oven-dry weight.
2. Volatile Solids: Dried samples were ignited at 550°C for 1 h. The weight loss on ignition is calculated as a percentage of total sample.
3. Total Nitrogen: Determined using the semimicro-Kjeldahl procedure of Bremner which involves digestion, distillation and titration of liquid samples. Digested samples were steam-distilled with 50% NaOH into 2% boric acid. Distillates were titrated with standardized 0.01 M H_2SO_4 on an automatic titrator interfaced with a microprocessor.
4. NH_4^+-N: Determined by steam distillation of liquid samples with 50% NaOH into 2% boric acid containing mixed indicator solution. The distillate was then titrated with standardized 0.01 M H_2SO_4.
5. Electrical Conductivity (EC): Determined on a YSI Model 32 conductance meter following centrifugation. The EC was read on the supernatant solution.
6. pH: Determined using supernatant following centrifugation. The pH was read on the supernatant solution using a Fisher Accumet Model 620 pH meter.
7. Organic Matter: Dried samples were ignited at 650°C for 2 h.
8. Carbon: A dry combustion method using a Leco model CR-12C determinator was used to determine the total C content of the freeze-dried sludge.
9. Multi-elements (P, K, Ca, Na, Mg, Al, Fe, Cr, Cu, Zn, Pb, Mn, B, Ni, Cd): Samples oven dried for 24 h at 70°C and then cooled for at least 1.5 h in a desiccator prior to weighing. Weighed out 2.0 g of sample. Ash crucibles on low setting for 2 h, then at 450°C for 24 h. Oven allowed to cool for 24 h. Added 7 mL of 10% HCl and equilibrated for 24 h. Centrifuged for 15 min at 15 000 rpm. Elements determined by Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES), Applied Research Laboratory (ARL) Model 137.

PLANT MATERIAL METHODS

1. Kjeldahl Nitrogen (semi-micro): Same procedure was used as for the determination of total N in the sludge material.
2. Multi-elements (K, P, Cu, Zn, Cd, Cr, Ni, and Pb): Determined using the same method as used with multi-elements in the sludge samples.

WATER METHODS

1. Electrical Conductivity (EC): Determined using a YSI model 32 conductance meter.
2. pH: Determined using a Fisher Accumet Model 620 pH meter.
3. Nitrate and Nitrite: Determined using an ALPKEM RFA autoanalyzer. NO_3 is reduced to nitrite in a Cd reductor column. The nitrite ions react with sulfanilamide under acidic conditions to form a diazo compound that couples with N-1-Naphthylethylenediamine dihydrochloride to form a reddish purple azo dye, then measured at 543 nm.
4. Chloride: Determined using a Colorimetric Technicon AutoAnalyzer II.
   Ferric cyanide, automated.
5. Ammonia: Determined using an ALPKEM RFA autoanalyzer. Ammonia reacts with alkaline hypochlorite and phenol to form indophenol blue. Sodium nitroferricyanide accelerates the formation of indophenol blue which is measured at 640 nm.
6. Orthophosphate: Determined using automated colorimetry, ascorbic acid.
7. Multi-element (ICP): Cu, Zn, Cd, Ni, and Pb determined simultaneously by ICP Atomic Emission Spectrometry on samples acidified with 2M HCl. Applied Research Laboratory (ARL) Model 137.

SOIL MATERIAL METHODS

1. Organic Matter: Determined by mixing soil with dichromate-sulfuric acid digestion solution. Heated mixture at 90°C for 1.5 h and allowed suspension to stand 3 h or overnight. The blue color intensity of the supernatant was read on a colorimeter at 645 nm.
2. Bray Phosphorus: Use the Fiske-Subbarow method. Mixed 5 mL of soil extract with acid molybdate solution. Added aminonaphthol-sulfonic acid. Allowed color to develop 15 min before reading samples. Measured optical density on a colorimeter or spectrophotometer at 660 nm.
3. Potassium: Determined by mixing soil with extracting solution (distilled water, glacial acetic acid, and ammonium hydroxide). Filtered the suspension. Measured the concentration of K with an atomic absorption/emission spectrometer.
4. Soluble Salts: Determined by use of the Soil:Water method. Mixed soil in distilled water (1:2.5). Inserted a conductivity cell calibrated with KCl into the suspension and read the conductivity in mmhos cm^{-1} ($dS\ m^{-1}$).

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APPENDIX C:

Meteorological Conditions at the Rosemount Watershed

		Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Year*
1975	MIN[†]	-16.2	-15.0	-10.5	-0.7	9.5	13.6	17.0	15.2	8.3	4.2	-2.4	-11.0	
	MAX[‡]	-5.6	-5.2	-1.8	6.7	21.1	23.9	29.0	26.4	19.5	16.3	17.1	-3.9	
	PRECIP[§]	5.5	1.0	2.8	15.9	11.1	13.6	3.0	11.0	3.2	0.8	10.1	2.4	80.4
	PAN[¶]					17.7	18.9	25.2	16.0	11.9	12.3			88.3
1976	MIN		-8.8	-5.6	2.8	7.2	14.4	16.1	13.9					
	MAX		0.6	2.8	15.5	19.4	27.2	30.5	27.8					
	PRECIP	0.8	1.1	5.5	2.8	1.2	6.3	4.5	3.8	2.7	1.4	0.6	0.9	31.6
	PAN					17.6	26.7	27.2	23.3	17.3	6.1			118.2
1977	MIN			-1.0		11.0	12.0	16.0	12.0	11.0	2.0	-4.0	-9.0	
	MAX			6.0		22.0	23.0	26.0	23.0	20.0	11.0	-1.0	-6.0	
	PRECIP	1.2	2.8	9.0	7.3	6.7	9.6	8.1	9.6	11.9	6.3	2.8	1.9	77.2
	PAN					19.9	19.3	21.5	16.6	10.3	6.0			93.6
1978	MIN	-17.0	-18.0	-7.0	1.0	9.0	14.0	16.0	16.0	13.0	5.0	-3.0	-13.0	
	MAX	-10.0	-6.0	0.0	10.0	21.0	24.0	26.0	27.0	25.0	15.0	3.0	-4.0	
	PRECIP	0.1	1.9	0.9	8.1	10.4	16.1	11.7	14.6	12.9	0.3	3.3	0.9	81.2
	PAN				9.0	21.7	17.0	13.2	24.4	13.7				99.0
1979	MIN				6.0	7.0	13.0	16.0	15.0	11.0	4.0			
	MAX				14.0	16.0	24.0	26.0	24.0	21.0	21.0	11.0		
	PRECIP	1.1	2.1	6.8	2.3	6.1	12.0	9.0	12.1	9.0	7.7	2.1	1.0	71.3
	PAN					15.3	16.0	20.4	14.8	14.4				80.9
1980[#]	MIN					10.0	14.0	16.0	16.0	10.0				
	MAX					25.0	25.0	29.0	26.0	20.0				
	PRECIP	4.0	2.3	2.6	4.1	3.2	8.8	3.1	14.2	10.1	2.8	0.9	0.8	53.7
	PAN													
1981[#]	MIN					9.0	13.0	15.0	14.0	6.0				
	MAX					19.0	25.0	28.0	24.0	19.0				
	PRECIP	0.3	6.9	1.8	10.5	6.0	8.6	8.2	16.0	2.4	6.0	3.5	2.3	72.4
	PAN					11.6	16.6	16.9	13.7	11.2				70.0
1982[#]	MIN					11.0	10.0	16.0	14.0	11.0				
	MAX					22.0	23.0	29.0	27.0	20.0				
	PRECIP	6.5	1.1	5.6	6.6	9.8	3.5	3.8	8.0	6.0	11.6	8.8	8.8	80.1
	PAN					14.8	18.8	20.1	10.8	7.9				72.4
1983[#]	MIN					9.0	16.0	21.0	30.0	14.0				
	MAX					19.0	26.0	31.0	32.0	23.0				
	PRECIP	1.4	3.1	8.7	9.9	13.6	9.9	8.8	4.0	9.8				
	PAN						18.3	22.7	16.2	11.9				
1984[#]	MIN					9.0	16.0	16.0	18.0	9.0				
	MAX					19.0	26.0	27.0	28.0	20.0				
	PRECIP	1.3	4.6	4.7	11.2	4.8	11.6	12.6	11.2	5.6	15.4	2.1	5.8	90.9
	PAN					19.6	21.3	19.5	14.3	8.2				82.9
1985[#]	MIN					11.0	12.0	16.0	14.0	11.0				
	MAX					23.0	23.0	28.0	23.0	20.0				
	PRECIP	1.6	1.1	11.4	3.7	6.9	5.3	4.2	11.4	10.3	10.3	5.5	3.7	75.4
	PAN					23.5	17.9	22.0	14.4	9.2				87.0
1986[#]	MIN					9.0	14.0	17.0	13.0	11.0				
	MAX					21.0	26.0	28.0	25.0	20.0				
	PRECIP	2.2	2.0	7.4	15.5	10.1	14.9	10.3	8.2	18.8	5.9	1.6	0.7	97.5
	PAN					17.4	23.0	16.8	14.4	5.0				
1987	MIN	12.7	19.4	26.0	37.5	50.8	58.4	64.1	58.6	50.0	33.5	28.8	16.9	38.1
	MAX	31.6	43.0	49.8	69.2	77.2	86.9	87.0	79.8	75.4	56.4	46.5	32.0	61.2
	PRECIP	0.45	0.0	1.2	0.2	2.8	2.3	12.1	3.3	1.7	1.0	2.4	1.3	28.7
	PAN													
1988	MIN	-1.3	3.2	22.0	32.5	47.1	57.9	61.5	60.7	49.8	31.7	24.0	9.8	33.3
	MAX	21.1	25.6	45.4	62.6	81.7	90.1	91.6	88.0	78.2	57.4	41.7	30.7	59.5
	PRECIP	1.9	0.3	1.5	1.8	3.2	0.1	2.3	5.0	4.1	0.9	3.9	0.7	25.7
	PAN													
1989	MIN	9.6	-3.8	16.9	32.0	44.8	53.7	62.4	57.7	47.5	36.7	19.2	0.8	31.5
	MAX	32.8	22.0	36.6	59.9	72.1	81.3	87.7	83.6	75.2	66.2	39.5	21.2	56.5
	PRECIP	0.6	0.9	2.8	2.9	4.1	4.7	2.4	3.8	1.4	0.6	2.0	0.3	26.5
	PAN													
1990	MIN	14.1	10.8	25.0	33.9	43.7	58.5	60.4	58.5	52.9	35.8	27.2	6.5	35.6
	MAX	37.2	35.8	47.2	61.7	70.2	81.1	81.9	80.5	76.1	61.7	49.0	25.4	59.0
	PRECIP	0.2	0.8	3.8	3.8	5.0	7.5	6.8	1.5	1.9	1.8	0.7	1.2	34.9
	PAN													

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
1991	MIN	0.9	13.1	24.1	37.6	52.3	61.2	60.6	60.2	50.0	36.6	16.7	12.1	35.5
	MAX	22.4	35.4	44.7	61.8	70.5	83.6	80.3	80.8	69.8	59.2	30.9	28.8	55.7
	PRECIP	0.2	1.1	3.3	3.6	7.5	1.5	8.1	3.7	7.1	1.7	5.9	1.0	44.7
	PAN													
1992	MIN	13.9	21.1	23.6	34.4	48.1	54.1	55.5	54.4	48.9	36.4	26.0	13.3	35.8
	MAX	29.0	33.9	40.8	53.0	74.3	76.5	75.4	75.6	71.6	58.9	35.3	28.3	54.4
	PRECIP													
	PAN													
1993	MIN	3.3	7.0	18.4	32.8	47.3	54.8	61.0	60.3	45.3	36.3	22.9	15.1	33.7
	MAX	22.7	24.4	37.7	55.6	67.5	73.8	77.8	79.4	64.6	58.8	38.0	27.2	52.3
	PRECIP	3.6	1.6	4.3	7.3	14.6	19.1	12.1	18.7	61.7	2.5	5.2	1.7	99.1
	PAN													

† Mean minimum daily temperature (° C)

‡ Mean maximum daily temperature (° C).

§ Total precipitation (cm)

¶ Total pan evaporation during growing season (cm).

1980 to 1986: May through June data collected at tillage research area one mile from Watershed; other data collected at Rosemount Experiment Station headquarters.

APPENDIX D:

List of Related Publications and Presentations

1. Larson, W. E., C. E. Clapp, and R. H. Dowdy. 1972. *The Agricultural Value of Sewage Sludge.* Interim report for the Metropolitan Sewer Board. Mimeographed—Out of print.
2. Larson, W. E., C. E. Clapp, and R. H. Dowdy. 1973. *Research efforts and needs in using sewage wastes on land.* Proc. 28th Annual meeting SCSA, September 30-October 3, 1973, Hot Springs, AR. p. 142-147.
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4. Larson, W. E., J. R. Gilley, and D. R. Linden. 1974. *Consequences of waste disposal on land.* Proc. to Annual Meeting SCSA, August 11-14, 1974, Syracuse, NY. p. 127-132.
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