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Abstract approved: ______________________________
V. V. Volk

Metropolitan areas today must dispose large volumes of sewage sludge produced during the wastewater treatment process. This research was conducted to study the effect of large applications of municipal sewage sludge on (a) the distribution of N and trace elements (Cd, Cr, Cu, Mn, Ni, Zn) in the soil profile, (b) the uptake of these elements by plants growing on the sludge-treated soil, and (c) the potential for groundwater contamination.

Five sludge disposal sites in the Willamette Valley were selected for the project, Milwaukie, Eugene, Hillsboro, Forest Grove, and Woodburn, Oregon. The soils were sampled quarterly, July, 1974, December, March, and June, 1975, as a function of depth. Surface soil samples (8 to 10 cores) were collected in September, 1974, from each disposal location to determine the uniformity and amount of sludge applied. Plant samples from the disposal area and water samples from wells adjacent to each area were also collected.

The soil, plant, water, and sludge samples were analyzed for total N, NH_4-N, NO_3-N, Cd, Cr, Cu, Mn, Ni, and Zn; the water, plant, and sludges were also analyzed for P. The soil samples collected during the winter, spring, and summer, 1975, were analyzed for NH_4-N and NO_3-N.

An estimated 500, 290, 96, 72, and 20 dry m tons/ha of sludge were applied to the Eugene, Hillsboro, Forest Grove, Woodburn, and Milwaukie disposal areas, respectively. The total N and P content of the five sludges ranged from 3.9 to 6.3% and 0.5 to 2.9%, respectively. The inorganic N was primarily in the form of NH_4-N. The trace element (Cd, Cr, Cu, Mn, Ni, Zn) content of the sewage sludge fell within general ranges reported for municipal sludges, except for the Cr content (17,700 ppm) of the Milwaukie sludge.

The Cd, Cr, Cu, Ni, Zn, NH_4-N, NO_3-N, and total N content increased in the surface soil of each sludge disposal area. The Cd, Cr, Cu, Mn, Ni, Zn, NH_4-N and total N content of the treated soils compared closely to the control soils below 50 cm in the soil profile suggesting restricted movement of heavy metals.

The NO_3-N content in the soil profile increased with the sludge application rate. The NO_3-N level of the Eugene and Hillsboro disposal areas was as high as 120 and 20 ppm, respectively. During the winter and spring, 1975, increased rainfall and cooler temperatures combined to decrease the NO_3-N content in the surface soil and increase NO_3-N levels in the lower soil horizons.

The pH of the surface soil at the Eugene and Hillsboro disposal areas decreased from pH values of 6.4 to 4.6 and pH 4.8 to 4.4, respectively, a result of the nitrification reaction. The pH values of the other disposal areas compared closely to the control soil.

The N and Zn content of the grass growing on the sludge-treated areas increased at the high sludge application rate compared to the grasses growing in the control area. The Cd, Cr, Cu, Mn, Ni, and P concentration increased in the grass sampled from the Eugene disposal area, while the Cd, Cr, Cu, Mn, Ni, and P content of grasses from the other sludge-treated areas compared more closely to the grasses from the control areas. The lower pH at the Eugene disposal area and the high sludge application rate combined to enhance the trace element uptake by plants.

The NO_3-N, NH_4-N, P, Cd, Cr, Cu, Mn, Ni, and Zn content in the water samples from the Eugene, Milwaukie, Forest Grove, and Woodburn disposal areas were below the Public Health Service drinking water limits.

The long-term disposal of municipal sewage sludges on agricultural land appears to be a viable waste disposal method, providing the sludge application rate and metal content are not excessively high. In any land disposal program for sewage sludge, the heavy metal accumulation in the soil surface and plants growing in the sludge-treated soil should be monitored.

Nitrogen and Heavy Metal Distribution in Soils Utilized as Sludge Disposal Sites

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INTRODUCTION

One of the major problems facing metropolitan areas today is the disposal of large volumes of sewage sludge collected during the waste treatment process. The public concern about pollution of surface waters and trace element contamination of percolation water from landfill sites has prompted municipalities and other governmental agencies to look at recycling sewage sludge on agricultural lands.

Sewage sludges are a source of essential plant nutrients. When used on agricultural land, macronutrients, such as nitrogen, phosphorus, and potassium, and micronutrients, such as zinc and copper, can be recycled through the plant-animal food chain.

Some trace element constituents of sludge (Cd, Cr, Cu, Mn, Ni, Zn), when present in sufficiently high concentration, are toxic to vegetation, human beings, animals, and aquatic life (Lisk, 1972). For example, cadmium is toxic to humans and animals when present at elevated concentrations in foods or beverages, 0.01 ppm is the tolerance limit set by the U.S. Public Health Service drinking water standards (Anonymous, 1971). Copper, manganese, nickel, and zinc are toxic to many varieties of crops when present in soil at excessive levels. Potential problems associated with trace elements can be avoided if the soil is properly managed and application rates are controlled.

Since the nitrate anion is mobile in most soils, it may present a groundwater contamination problem if considerable quantities should move through the soil profile and into the groundwater. The organic nitrogen containing compounds in sewage sludge will mineralize and oxidize to form nitrate anions. Sewage sludge application rates to land need to be determined for specific sludges so that mineralized nitrogen will be used by the crop rather than leached into groundwater.

The objective of this research project was to determine the long term effect of applying nitrogen and heavy metals in sewage sludge to land in the Willamette Valley, a xeric moisture regime with cool wet winters and warm dry summers. Field and laboratory studies were designed to determine the effect of sewage sludge on the plant elemental constituents, groundwater pollution, and the distribution of nitrogen and heavy metals in the sludge-treated soils.

LITERATURE REVIEW

Sewage Sludge Characterization

Sewage sludge varies widely in composition depending directly on the treatment process, industrial activity, and size of the area served. The elemental composition of sewage sludge from any single treatment plant tends to remain relatively uniform in a given year, although, seasonal variation of waste input, such as a food processing operation, will affect the composition of the sewage sludge.

Nitrogen in sewage sludge varies from 1 to 6% on a dry weight basis dependent upon the treatment process (Table 1). Activated sewage sludges, by-products from aerobic wastewater treatment process, are high in organic N content, averaging 6.2% N, but contain little soluble NH_4-N compared to digested sludges, by-products from the anaerobic wastewater treatment process. Digested sludges are higher in soluble NH_4-N, often up to 50% of the total N, but exhibit a lower total N content, averaging 2.25% (Teller, 1971). Negligible nitrite (NO_2^-) and nitrate (NO_3^-) levels are found in digested sewage sludge due to denitrification caused by anaerobic conditions during the treatment process (Wolf, 1973). Organic N in the form of protein averages 37.5% of the total N in activated sludges and 16 to 21% of the total N on a dry weight basis in digested sludges (Teller, 1971; Table 2).

Table 1. Variation in N, P, and K content of sewage sludge.[1]

Element	Observed Range	Average	
		Activated	Digested
	- - - - - - - -% (dry weight)- - - - - - -		
Total N	1-6	6.20	2.25
NH_4-N	12-55 of total N		
P	0.4-3.1	0.55	0.33
K	0.04-0.25	--	0.25

[1]Menzies and Chaney, 1974.

The total P content of digested sewage sludges from 10 Ohio cities ranged from 0.14 to 0.70%, averaging 0.3%, on a dry weight basis (Anderson, 1955). Activated sewage sludges exhibit a higher average P content than digested sludges (Table 1).

Since most K salts are quite soluble, the K in the waste usually remains with the effluent water during the treatment process. The soluble K content of digested sewage sludges from 10 Ohio cities ranged from 0.02 to 0.7% with only one sewage sludge exceeding 0.25% (Table 1).

The organic matter content of sludges varies from 25 to 80% dry weight, the level depending on the amount of sand and silt collected by the sewer system (Menzies and Chaney, 1974). Activated sludge has a higher organic matter content, contains increased levels of easily degradable organics, and has a considerably lower carbon/nitrogen ratio, ranging from 4:1 to 7:1, compared to the carbon/nitrogen ratio of digested sewage sludge, ranging from 14:1 to 22:1 (Howe, 1965; Table 2).

Table 2. Average chemical constituents of sewage sludge.[1]

Item	Activated	Digested
	- - - - % (dry weight)	- - - -
Organic matter	65-75	45-60
Pentosans	2.1	1.5
Grease and fat	5-12	3.5-17
Hemicellulose	-	1.6
Cellulose	7.0 (incl. lignin)	0.6
Lignin	-	8.4
Protein	37.5	16-21
Carbon-nitrogen ratio	4-7	14-22
Total solids	0.2-4	3-8
pH	7.0-9.0	6.5-8.0

[1]Teller, 1971; Howe, 1965.

The concentration of trace elements occurring in sewage sludges varies widely, as illustrated by data obtained from sludges assayed in 42 locations in England and Wales (Berrow and Webber, 1972; Table 3). Zinc and copper are generally at higher concentration in sewage sludge than other trace elements.

Anaerobic digestion and secondary activation of wastewater contributes to the disappearance of pathogenic microorganism (Burge, 1974). Sewage sludges are not completely free of pathogens after the waste treatment process. Sludges contain viruses (e.g. poliovirus, coxakievirus, echovirus), bacteria (e.g. Salmonella and Shigella), protozoans (e.g. amebae), and helmiths (e.g. tapewor, roundworm) which are disease agents that afflict man, but at reduced levels compared to raw fecal material. Danger to people from pathogens in sludges can best be assessed by looking at health records of sewage plant workers. It has been observed that sewage workers have fewer sick days than the general population (Burge, 1974).

Table 3. Contents of trace elements in 42 sludges from locations in England and Wales.[1]

Element	Range	Mean	Median
Ag	5-150	32	20
B	15-1000	70	50
Ba	150-4000	1700	1500
Cd	60-1500	200	--
Co	2-260	24	12
Cr	40-8800	980	250
Cu	200-8000	970	800
Mn	150-2500	500	400
Mo	2-30	7	5
Ni	20-5300	510	80
Pb	120-3000	820	700
Sn	40-700	160	120
V	20-400	75	60
Zn	700-49,000	4100	3000

[1]From Berrow and Webber, 1972.

Municipal sewage sludge contains considerable amounts of N, P, and other plant nutrients essential for crop growth; however, some sludges from highly industrialized areas can contain very high levels of heavy metals, generally Cu and Zn are at higher concentration than the other metals.

Interactions of Nitrogen Compounds in Sewage Sludges with Soils and Plants

Organic N Transformations in Sewage Sludge Applied to Soil

When sewage sludge is added to a soil, decomposition of the organic compounds by fungi, actinomycetes, and bacteria progresses very rapidly (Viets, 1974). Carbon is lost as CO_2 or incorporated into organisms as structural components. If the material has a high carbon-nitrogen ratio, from 33:1 to 17:1, the N released by decomposition is re-incorporated into organic N compounds, largely proteins. The carbon content of the sludge decreases and the organic N content increases until the carbon-nitrogen ratio narrows. When the carbon-nitrogen ratio is below 17:1 nitrogen may be released in an inorganic form, (NH_3), in the process called N mineralization (Equation 1).

$$\text{Protein (Organic N)} \xrightarrow{\text{Microorganisms}} \text{Ammonia } (NH_3) \qquad (1)$$

The decomposition of sewage sludge, and mineralization of N, after application to soil depends on soil texture, moisture content, temperature, and sludge loading rate (Viets, 1974). The decomposition of anaerobically digested sewage sludge added to three different soils of different texture (Ottokee fine sand; Celina silt loam; Paulding clay) at rates of 90 and 224 m tons/ha was measured as a function of CO_2 evolved (Miller, 1974). After a 6 month equilibration at optimum temperature and moisture, approximately 20% of the C added in the sewage sludge evolved as CO_2. The majority of CO_2 evolution (55 to 70%) occurred during the first month of equilibration. The maximum CO_2 evoluation from the sludge-treated Ottokee sand occurred under saturated moisture conditions at both the 90 and 224 m tons loading rates. There was no difference in CO_2 evolution from the Celina silt loam maintained at 1/3 bar and saturated moisture condition treated with 224 m tons of sludge; however, a marked reduction in CO_2 evolution occurred under saturated conditions at the lower application rate. With the Paulding clay, saturated soil moisture conditions severely restricted CO_2 evolution at both loading rates. These results suggest that, in Ottokee sand, sufficient O_2 can diffuse into the soil column at saturated moisture conditions to maintain an active microbial population, while in the Paulding clay, saturated conditions reduce the diffusion of O_2 into the soil columns which results in anaerobic conditions and reduced microbial activity. The Celina silt loam is similar to the Paulding clay at the lower application rate, but the high microbial activity at the high application rate was more difficult to explain.

The rate of N mineralization from sewage sludge applied to agricultural land is an important factor in determining available N for plant growth from any sewage sludge application. A decay series to indicate the percent N mineralized in successive years from digested sewage sludge, which contains 2.5% N, was suggested to be 0.35, 0.10, and 0.05 (Pratt, Broadbent, and Martin, 1973). For any given application, this decay series suggests 35% of the organic N is mineralized the first year, 10% of the residual organic N is mineralized the second year, and 5% the third and all subsequent years.

Ammonia Interactions in Soils

When sewage sludge is applied to a soil, ammonium (NH_4^+) initially in the sludge and that mineralized from organic N compounds may accumulate in the soil. The NH_4^+ ions may be adsorbed, incorporated into plant and microbial tissue, nitrified, or may be volatilized as NH_3.

The volatilization of NH_3 from soil solution is affected by soil pH and moisture content. Ammonia exists in equilibrium with NH_4^+ ions in solution (Equation 2). As the pH is raised, the equilibrium shifts so that a greater proportion of the N occurs as gaseous NH_3. Volatilization of significant quantities of NH_3 also requires considerable air-water contact (Lance, 1972). Ammonia volatilization also increases with temperature and air velocity. Relative humidity at 100% will decrease NH_3 volatilization (King and Morris, 1974).

$$NH_4^+ + OH^- \rightleftharpoons NH_3 + H_2O \qquad (2)$$

$$\frac{[NH_4][OH]}{[NH_3]} = 1.8 \times 10^{-5}$$

When 3,192 kg/ha total N in municipal sewage sludge was applied to a bare soil surface of a Cecil sandy loam at pH 5.9 and 1/3 bar moisture tension, the NH_3 volatilization over a 20 day period was 36% of the applied NH_4-N or 4.9% of the total N. When sewage sludge was applied at similar rates to the Cecil soil planted to Coastal bermuda grass 24% of the NH_4-N applied or 3.4% of the total N was volatilized as NH_3-N. When the bermuda grass was clipped prior to application of the sewage sludge, the NH_3 volatilization decreased from 24% to 12%. It was suggested that the actively growing bermuda grass utilizes NH_3 applied in sewage sludge more readily than mature bermuda grass. The NH_3 losses were largest during the first 5 days after the sludge application with no significant losses noted beyond that time (King and Morris, 1974).

The NH_4^+ can be adsorbed by negatively charged soil colloids, clays, and organic matter. After the ion has been adsorbed it may be replaced on some adsorbent surfaces by divalent and trivalent cations also in the sewage sludge (Lance, 1972; Buckman and Brady, 1969). Since the lattice layers of some silicate minerals such as vermiculite can collapse and fix NH_4^+ ions, the extent of NH_4-N exchange by higher charged ions will vary with the nature of the adsorbent material. Once the NH_4^+ ions are trapped they are very resistant to nitrification or crop removal (Young, 1964; Young and Cattani, 1962).

Organic portions of the soil can react with NH_4^+ ions forming complexes resistant to leaching and decomposition (Burge and Broadbent, 1961). Ammonium fixation in organic soils which contained from 14% to 43% carbon content correlated linearly with % carbon. In the presence of oxygen, 1 molecule of NH_3 was fixed for every 29 atoms of carbon, while 1 molecule of NH_3 was fixed for every 45 atoms of carbon in the absence of oxygen.

Under aerobic conditions, the NH_4^+ in the soil will oxidize to nitrite, and nitrite to nitrate (Equation 3 and 4).

$$2NH_4^+ + 3O_2 \xrightarrow{\text{Nitrosomonas}} 2NO_2^- + 2H_2O + 4H^+ + \text{Energy} \quad (3)$$

$$2NO_2^- + O_2 \xrightarrow{\text{Nitrobacter}} 2NO_3^- + \text{Energy} \quad (4)$$

The nitrification reactions are the result of microbial oxidation of NH_4^+ by the obligate autotrophic aerobes nitrosomonas and nitrobacter. Nitrification rates are reduced in soils below pH 5.5 at temperatures below 5°C and above 40°C, and saturated conditions limiting the diffusion of oxygen to the microbes (Buckman and Brady, 1969).

Major changes in soil pH can result from adding sewage sludge to soil. The release of H^+ during nitrification of NH_4^+ to NO_3^- may cause a reduction in pH. When 0, 19.7, 41, and 83 m tons/ha sewage sludge was added to a Blount silt loam soil over a 3 year period, the pH decreased from an initial pH of 5.6 to a pH of 4.9 at the highest sludge application rate. The extent of pH reduction related directly to the sludge application (Hinesly, Jones, and Ziegler, 1972).

Nitrate Interactions and Transformations in Soil

Nitrate movement from the soil surface through the soil profile into the groundwater is a function of excess water passing through the soil. Because of the negative charge on most soils, NO_3^- will be excluded from the attraction of the negatively charged colloids and move with the soil solution (Gardner, 1965).

Soil texture will influence downward infiltration and percolation rates of NO_3^- in soil solution and the upward movement of NO_3^- in capillary water. The percolation rate of NO_3^- through a sandy soil is faster than through clay soils when they are above field capacity because of the abundance of large pores which transport the soil solution quickly, but the reverse becomes true at lower water contents because the large pores do not exert the necessary tension, generally, to move water by capillary flow from areas of higher to lower water content (Buckman and Brady, 1969). Water evaporation at the soil surface will cause an upward movement of NO_3^- anions in fine textured soil. The capillary conductivity of a sandy soil will decrease much more rapidly at lower soil moisture contents than will the finer textured soils (Gardner, 1965).

Since the NO_3^- ion may be readily leached from the soil profile, it presents a possible groundwater pollution hazard (King and Morris, 1972). High NO_3^- level in drinking water, above 10 ppm, can result in death in infants and animals (e.g. methemoglobinemia) (Luhrs, 1973; Simon, 1973). Nitrate pollution has been of particular concern where high rates of sludge have been added to coarse textures soil (Hinesly, Briads, and Molina, 1971).

The NO_3^- ion is readily assimilated by most plants and microorganisms and incorporated into cell tissue. When cellular bound N is released as NH_3 upon death and decay of the organism, the N has been effectively converted from NO_3^- to NH_3 through a process referred to as assimilatory nitrate reduction (Gray and Williams, 1971).

Denitrification, the reduction of NO_3^- to a gas (N_2, N_2O), occurs when oxygen becomes limiting and aerobic microorganisms use chemically combined oxygen in NO_3^- as a terminal electron acceptor (Gray and Williams, 1971). For denitrification to occur, the presence of an effective energy source is required, it was calculated that 1.3 mg of carbon is needed for every mg of NO_3-N reduced to N_2 (Lance, 1972).

Denitrification proceeds slowly below pH 5.5 and below 10°C (Lance, 1972). It is much more rapid in soils saturated with water than in soils at lower moisture levels because the supply of oxygen in water-saturated soil is not adequate to meet the requirements of the soil-microorganisms (Bremner and Shaw, 1958).

When digested sewage sludge was applied, 980 kg/ha, to a Cecil sandy loam soil, the apparent denitrification, total N loss less the NH_3-N loss, was 17% after 4.5 weeks whether the sludge was incorporated or surface applied. After 22 weeks the apparent denitrification was 15% when the sludge was incorporated into the soil and 20% when the sludge was surface applied (King, 1973). When 3,192 kg/ha nitrogen in sewage sludge was applied to a Cecil sandy clay soil, the apparent denitrification after 20 days was 20% of the total N applied (King and Morris, 1974).

Summary

When sewage sludge is applied to a soil, an interlocking succession of largely biochemical reactions occurs commonly called the nitrogen cycle (Buckman and Brady, 1969; Figure 1). Nitrogen in the sewage sludge occurs an inorganic and organic N compounds. The inorganic compounds are mainly in the form of NH_4^+ due to the lack of oxygen during the anaerobic sewage digestion process, smaller amounts of NH_4^+ are present in activated sludges, while the organic N compounds are mainly in the form of proteins. Once these compounds are applied to soils, the organic N compounds mineralize to NH_4^+ at a of about 35% the first year. The NH_4^+ compounds formed from the mineralization reaction and the inorganic NH_4^+ in the sludge originally can be oxidized to NO_3^- or sorbed or fixed by certain inorganic or organic colloids. Ammonia gas can be lost from the soil by volatilization, from 1.7 to 4.9% of the total N applied, especially with high pH soils. The NO_3^- formed during the nitrification reaction can be denitrified when oxygen is limiting. The NO_3^- and NH_4^+ ions can also be used by plants and become incorporated into organic compounds. The NO_3^- lost to groundwater would thus depend upon a complex series of N reactions, as well as soil, management, and climatic conditions.

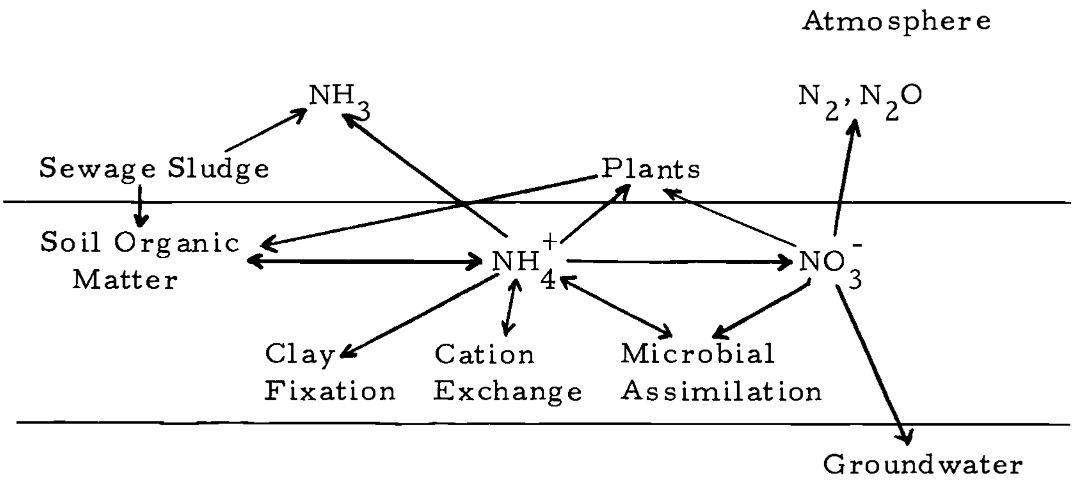


Figure 1. Nitrogen cycle.

Interactions of Cd, Cr, Cu, Mn, Ni, and Zn Added in Sewage Sludges with Soils and Plants

Trace Element Enrichment of Plants and Soils Amended with Sewage Sludge

Applying sewage sludge to land can increase the level of Cd, Cr, Cu, Mn, Ni, and Zn in soils and result in increased uptake by plants (Page, 1974). Enrichment of soils beyond the normal concentrations of these elements is potentially harmful due to the toxicity of Cd, Cr, Cu, Mn, Ni, and Zn when they are readily available and accumulate in plant tissue (Table 4; Leeper, 1972).

Table 4. Concentrations of trace elements typically found in soils and plants.[1]

	Conc. in Soil (ppm)		Conc. in Plants (ppm)	
Element	Common	Range	Normal	Toxic[2]
Cd	0.06	0.01-7	0.2-0.8	2
Cr	100	5-3000	0.2-1.0	2
Cu	20	2-100	4-15	30
Mn	850	100-4000	15-100	300
Ni	40	10-1000	1	25
Zn	50	10-300	15-200	500

[1] From Allaway, 1968; Leeper, 1972; Melsted, 1973.

[2] Toxicities listed do not apply to certain accumulator plant species.

The level of trace elements (Cd, Cr, Cu, Mn, Ni, Zn) typically found in soils and plants varies considerably (Table 4). Plants vary in their accumulation of trace elements depending on their species and genus (Chaney, 1973).

The amount of sewage sludge (2.5% N) necessary to supply 100 kg/ha nitrogen to agricultural land is 4000 kg dry sludge/ha, or 133 m tons/ha liquid sewage sludge at 3% solids. The amount of trace elements (Cd, Cr, Cu, Mn, Ni, Zn) added to the soil with the nitrogen in the sewage sludge would not raise any of these heavy metals above the normal range for soil (Table 4 and 5).

Table 5. Trace elements (Cd, Cr, Cu, Mn, Ni, Zn) applied with 100 kg/ha N in sewage sludge.

Element	Average Concentration of Element in Sludge[1]	Amount Applied to Soil
	%	kg/ha
N	2.5	100
	mg/kg	
Cd	10	0.04
Cr	400	1.6
Cu	700	2.8
Mn	500	2.0
Ni	50	0.2
Zn	2000	8.0

[1] Page, 1975.

The accumulation of Cr, Cu, Ni, and Zn in soil is exemplified by the Woburn Market-Garden experiment in 1942 when 636 m tons/ha of digested sewage sludge, dry weight, was applied to a soil (series not given) over a 19 year period. The level of Cr, Cu, Ni, and Zn in the soil extracted with 0.5 N HOAc increased from 0.5 to 2.8 ppm, 5.0 to 20 ppm, 4.3 to 18 ppm, and 88 to 395 ppm, respectively, for each element. Eight years after the cessation of the sludge applications, the sludge treated soil was analyzed again for these elements. The Cu level increased from 20 to 63 ppm, the Zn and Ni concentration decreased from 395 to 275 and 18 to 8.1 ppm, respectively, still at considerably higher levels than the control, while the Cr concentration remained unchanged (Le Riche, 1968).

In Illinois, digested sewage sludge was applied (0, 15, 30, 59, 118 m tons/ha) to a Blount silt loam soil and the levels of Cd, Cr, Cu, Mn, Ni, and Zn assayed. The Cd, Cr, Cu, Mn, Ni, and Zn content of the soil extracted with 0.1 N HCl increased with sludge application rate, from 0.22 to 1.5 ppm, 0.94 to 3.3 ppm, 3.9 to 8.4 ppm, 304 to 306 ppm, 2.3 to 3.5 ppm, and 13 to 41 ppm, respectively, at the lowest sludge application over a 4 year period. When sludge was applied at the highest rate to the soil, concentrations of these elements increased to 7.0, 19.0, 32.0, 402, 7.0, and 181 ppm, respectively (Hinesly, Jones, and Zielger, 1972). Evidently, the trace elements, Cd, Cr, Cu, Mn, Ni, and Zn are retained in the soil for several years and their concentrations increase with sewage sludge application. This accumulation emphasizes the danger of trace elements when sludge containing these elements is repeatedly applied to agricultural land.

The accumulation of Cd, Cr, Cu, Mn, Ni, and Zn applied in sewage sludge to soil affects the amount of these elements taken up by plants. In the study where sewage sludge was applied to the Blount silt loam soil at rates of 0, 34, 66, and 132 m tons/ha, corn plants grown on the soil contained increased levels of Cd, Cr, Mn, Ni, and Zn with increasing amounts of sewage sludge applied. As the sludge application rate increased, the Zn concentration increased steadily both in the soil (13, 41, 98, 181 ppm) and in the plant tissue (58, 85, 138, 212 ppm), respectively. The concentration of Cd, Cr, Mn, and Ni in the corn tissue also increased with increased soil content. At the high rate of sludge application the Cd, Cr, Mn, and Ni content of the corn tissue increased from 3.3 to 11.6 ppm, 4.1 to 4.5 ppm, 81 to 116 ppm and 2.8 to 4.3 ppm, respectively, while the Cu levels increased in the soil but remained unchanged in the corn tissue (Hinesly, Jones, and Zielger, 1972).

Application of trace elements such as Cd, Cr, Cu, Mn, Ni, and Zn to soil with sewage sludge treatments increases the soil trace element levels and results in increased plant uptake. Continued sludge applications may increase the concentrations of these metals in the soil to levels sufficiently high that plants accumulate toxic quantities (Chaney, 1974). Plants differ in their tolerance to heavy metals such that careful selection of plant species must be followed when plants are integrated with a sludge application program.

Soil Factors Controlling Metal Availability to Plants

pH. Soil pH is the most important factor affecting the plant availability of heavy metals added to soils with sewage sludge. Increasing the pH of the soil from 5 to 7 will increase the hydrolysis of Cd, Cr, Cu, Mn, Ni, and Zn, accompanied by precipitation, and a decrease in plant availability (Leeper, 1972).

Chromium can exist in several oxidation states (+2, +3, +6), but in soils is rapidly reduced to Cr^{+3} (Chaney, 1973). At normal soil pH values Cr will precipitate as the very insoluble hydrated oxide $Cr(OH)_3$ which is stable in soils (Leeper, 1972). The Cr concentration in the first corn forage crop was not affected when sewage sludge which contained 0, 68, 340, and 1,360 ppm Cr was applied to a Hartsells fine sandy loam soil. As the pH decreased from 6.2 to 6.0 due to the nitrification reaction over an 18 month period, the Cr concentration in the corn forage of the third crop harvested from the highest Cr treatment increased from 1.4 to 2.0 ppm. Similar increases in the plant Cr concentration were reported for the lower Cr applications as the pH decreased over the 18 month period (Mortvedt and Giordano, 1975).

Copper, zinc nickel, cadmium, and manganese mobility and solubility are greatly lowered by increases in soil pH (Chaney, 1974). Trace elements which exist in solution as cations (Mn, Cu, Zn, Ni, Cd) occur, in neutral (pH 7) soil solution at concentrations less than 0.05 ppm (Page, 1974). In acid soils (pH 5-6) the concentration in solution of the same elements increases while in alkaline and calcareous soils (pH 7.5-8.5) they decrease. In the pH range common to soils generally (pH 5-8.5), concentrations of the cationic trace elements (Mn, Cu, Zn, Ni, Cd) do not exceed 0.25 ppm (Page, 1974).

In pot experiments designed to measure Cd uptake by wheat, sewage sludge was added, 19 m tons/ha, to soil adjusted to pH 5.1, 6.2, and 7.2 with CaO. With increased pH, the Cd uptake by wheat decreased from 170 to 50 (Linnman, Andersson, Nilsson, Lind, Kjellstrom, and Friberg, 1973).

Similar to Cd, the Ni uptake by wheat from a soil (series not given) adjusted to pH 5.1 and 6.5 and treated with 0, 10, and 40 ppm Ni decreased with pH increase. The Ni concentration in the plant tissue decreased from 2.5 to 1.0 ppm, 3.0 to 2.2 ppm, and 10.0 to 2.75 ppm, respectively, for each Ni application (Patterson, 1971).

When Cu, Mn, and Zn were added with sewage sludge, 0, 42, 84, 121, 242 m tons/ha, to a Cecil sandy clay loam soil seeded to rye, their concentration in the rye tissue decreased with increased pH. When the soil was limed, from an initial pH of 4.2, with dolomitic limestone at a rate equivalent to 6.7 m tons/ha, the Cu, Mn, and Zn concentration in the rye tissue grown on the soil with no sludge applied changed from 10 to 10.2 ppm, 128 to 93 ppm, and 32 to 30 ppm, respectively, while the Cu, Mn, and Zn content of the rye tissue grown on the highest sludge treated soil decreased from 20.0 to 16.0, 227 to 161 ppm, and 775 to 579 ppm, respectively (King and Morris, 1972).

Organic Matter. The organic material in sewage sludge will chelate many heavy metals, dependent upon the functional groups on the organic constituents and the heavy metals present (Stevenson and Ardakani, 1972). Organic matter may form insoluble chelates with trace metals and make them less available to injure plants or may increase heavy metal availability (Chaney, 1974). Zinc uptake by corn grown in Hartsells fine sandy loam soil was lower when the Zn was added in sewage sludge as compared to inorganic Zn as $ZnSO_4$. The Zn concentration in the corn tissue decreased from 143 to 36 ppm, 438 to 68 ppm and 1,575 to 149 ppm corresponding to Zn treatments of 12, 60, and 240 ppm, respectively, when added in sewage sludge (Mortvedt and Giordano, 1975). The organic chelates will eventually decompose and lose their protective effect if no further additions of organic matter occur (Leeper, 1972).

Soluble chelates can combine with heavy metals and increase trace element availability to plants. Soluble metal-chelates in anionic form allow the metal ions to be more mobile (Stevenson and Ardakani, 1972). At lower pH values, organic matter will be less soluble and therefore reduce the mobility of chelated heavy metals. As the pH rises, the metal ions in organic combination in soil solution will increase compared to the aqueous phase (Hodgson, Lindsay, and Trierweiler, 1966).

Adsorption by Soil Colloids. Clay minerals and organic colloids may adsorb heavy metal cations (Cd, Cr, Cu, Mn, Ni, Zn) on exchange sites. The valence, ionic size, and ion hydration influence the ease which ions are adsorbed and replaced. Increases in the cation concentration in the soil solution will cause a greater exchange by that cation due to the law of mass action (Leeper, 1972).

Soil Inactivation of Trace Metals. With time, metals added in sewage sludge react with the soil to become inactivated and therefore less toxic to plants; a process which has been termed reversion (Chaney, 1974). The process is poorly understood but has been clearly established for Zn, Cu, and Mn. Eleven soils were fertilized with Zn, Mn, and Cu and analyzed periodically with DTPA. The soils were cropped with both corn and oats. After 14 weeks the Cu content of the soils declined to 61% of the original value, Zn to 44%, and Mn to 14% (Follett and Lindsay, 1971). The rate of reversion is lower at higher metal levels and occurs most rapidly in calcareous soils (Chaney, 1974).

Plant Factors Controlling Metal Uptake

Uptake of metals by plants depends on rooting depth and metal distribution in the soil (Melsted, 1973). Plant roots grow and elongate at the root tip and assimilate immobile plant nutrients as they extend in the soil. Once the root matures to where the cortex layer forms, the epidermal cells lose most of their capacity to absorb water and nutrients with the most active plant nutrient uptake occurring at the root tips. Melsted (1973) speculates that surface applications of sewage sludge high in Zn, Cu, Cd, and Ni could have little effect on deep rooted crops. Plant roots which have penetrated below the soil plow layer assimilate plant nutrients in uncontaminated areas and accumulate normal levels of metals. Thus placement of sludge waste can greatly influence the heavy metal composition of different portions of a crop.

Uptake of metals by plants will vary depending on the species, variety, and part of the plant sampled (Chaney, 1973). A study of 14 different vegetable species grown on a Domino silt loam soil mixed with sewage sludge which contained variable amounts of $CdSO_4$, 0 to 640 ppm, demonstrated that the Cd content of plants vary widely. Cereals and legumes accumulate less Cd in the shoot than leafy plants such as lettuce, curlycress, and spinach. The least Cd was found in the tuber, seed, and fruit tissue, while the greatest Cd concentration occurred in the leaf tissue (Bingham, Page, Mahler, and Ganje, 1975).

Ion competition can effect the metallic uptake by plants. Zinc uptake by bean plants is inhibited upon increases in the Cd, Cu, and Mn content of a nutrient solution (Hawf and Schmid, 1967). The phosphate anion interferes with the metabolism of Cu and Zn at a deficient or marginal levels (Spencer, 1966). A study of the affect of P and Cu on citrus seedlings showed that a level of 100 ppm Cu stunted the seedlings. An increase in the soil P level to 250 ppm lessened Cu toxicity and thereby increased yields from 0.85 to 8.23 grams of dry matter per plant (Spencer, 1966).

Plant Response to Application of Sewage Sludge

Sewage sludge used as a fertilizer can have both good and bad effects on plant yield, germination of seedlings, and soil fertility.

Germination and emergence of sorgum, sudangrass, and millet grown in Truckton loamy sand soil decreased after application of sewage sludge at rates from 25 to 125 m tons/ha (Sabey and Hart, 1975). The sorgum and sudangrass stand decreased from 132 to 32 plants per plot when the sewage sludge was added at rates of 25 m tons/ha. The millet stand decreased from 524 to 13 plants per plot with a similar sludge treatment. When the sludge was applied at a rate of 100 m tons/ha, all grasses decreased to four plants per plot. After harvesting the grass forage, winter wheat was planted. The wheat germinated and emerged equally well on all treated and check plots. Either the inhibitory factor was eliminated during the warm summer period or wheat was not as susceptible to the inhibitive factor. Wheat yields increased from 681 kg/ha on the control plots to 931 kg/ha with the 25 m ton/ha treatment. As the sludge application rates further increased, the wheat yield decreased to 398 kg/ha on the 125 m ton/ha soil treatment (Sabey and Hart, 1975).

Sludge additions had no adverse effects on the growth of potatoes grown in Hubbard coarse sand. Potatoes yielded 185, 448, 532, and 672 q(100 kg)/ha for 0, 112, 225, and 450 m tons/ha rates of sludge applied (Dowdy and Larson, 1975).

The growth of 30-day-old barley seedlings grown in a Nicollet loam at pH 5.9 and in a Canisteo silty clay loam at pH 7.9 were studied after a sewage sludge application of 0, 3.8, 7.6, 15.2, and 30.4 m tons/ha. Barley plant weight increased from 1.64 to 2.01 grams per pot and 1.26 to 1.84 grams per pot in the Canisteo and Nicollet soil, respectively. Although yields increased with increasing rates of sludge applied on the acid soil, plants grown on soil treated with the higher rates of sludge showed tip burning. It was suggested that organometallic complexing of Fe may have induced the greatly depressed Fe concentration in the leaf tissue (Dowdy and Larson, 1975).

Rye was seeded in a coastal bermuda grass sod on a Cecil sandy clay loam soil treated with sludge at rates of 0, 42, 84, 121, and

242 m tons/ha (King and Morris, 1972). The maximum forage yields for the first clipping occurred when the sludge was applied at the rate of 84 and 121 m tons/ha; increasing from 130 kg/ha on the control soil to 2,530 kg/ha. The forage yield from plots treated with the highest sludge rate decreased to 1,960 kg/ha. When rye was planted a second year on the sludge-treated soils, the yields decreased to 390 kg/ha at the highest sludge application rate. When 6.7 m tons/ha dolomitic lime was applied to those soils, the forage yield increased to 900 kg/ha, still considerably below the maximum yield of 1,650 kg/ha recorded for the 121 m ton/ha sludge treatment. The reduced rye growth on the soil treated with the high sludge application was associated with Cu levels of 20.0 ppm and Zn levels of 775 ppm in the plant tissue. After liming, the Cu and Zn levels in the plant tissue decreased to 16.0 and 579 ppm, respectively.

Corn grown on Blount silty clay loam soil for four years increased in yield as the sludge application rate increased (Hinesly, Jones, and Zielger, 1972). The average yields over the four years increased from 244 to 328 bushels/ha for the control and 132 m ton/ha sewage sludge application rates, respectively.

Movement of Cd, Cr, Cu, Mn, Ni, and Zn through Sewage Sludge Treated Soil

The extent to which groundwater supplies may become contaminated with trace metals from sewage sludges applied to soil depends on the soil chemical properties which retard metal movement and the distance the metal must move through the soil to reach the groundwater (Page, 1974).

In a recent study, Zn moved to a 30 cm depth and Cd, Cr, and Cu to a 15 cm depth in a Davidson clay loam soil planted to fescue which had received surface applications of sewage sludge totaling 16.8 m tons/ha over a 17 week period (Boswell, 1975). Rainfall was measured at 176 cm over the entire 17 week period.

Movement of Cd, Cr, Cu, Ni, and Zn below the 15 cm depth in a Blount silt loam soil was observed after sewage sludge applications of 132 dry m tons/ha over a 4 year time span (Hinesly, Jones, and Ziegler, 1972). Approximately 40 percent of the Ni and Zn applied were retained in the surface 15 cm of soil. About 30% of the Cu, and 20% of the Cr and Cd were retained in the 15 cm depth (Page, 1974). Trace metals not retained in the surface 15 cm are removed by plants, transported to depths below 15 cm, eroded from the soil surface, or reverted to a less available form not easily extracted by 0.1 N HCl.

Sewage sludge applied at rates of 242 m tons/ha over two years increased the Mn concentration in a Cecil sandy clay loam soil from approximately 140 to 240 kg/ha in the surface 15 cm, while the Zn levels increased from 6 to 28 kg/ha (King and Morris, 1972). The Mn concentration increased from 40 to 140 kg/ha in the 15 to 30 cm depth, while Zn levels were not significantly different from the control. The increased Mn content of the soil was considered to result from decreased pH from 5.2 to 4.2 associated with the sludge application rather than appreciable amounts of Mn supplied by the sludge (King and Morris, 1972).

When sewage sludge was applied, 84 m tons/ha, to soil over a 12 year period, the Cd, Cr, Cu, Mn, Ni, and Zn remained in the surface 20 cm of soil. The recoveries of trace elements in the surface 20 cm, computed from data of Andersson and Nilsson (1972), exceeded 100% for all elements except Mn, which was 98% recovered (Page, 1974).

The available information indicates that movement of Cd, Cr, Cu, Mn, Ni, and Zn in sludge-amended soils is quite restricted and a high percentage of these elements will remain in the surface 30 cm of soil. The heavy metals (Cd, Cr, Cu, Mn, Ni, Zn) appear to be relatively insoluble in soil which should act to protect the groundwater from possible trace element contamination beneath soils which receive sludge applications.

Summary

Municipal sewage sludge can be considered a valuable natural resource when applied as a soil amendment to agricultural land. It supplies both macro- and micronutrients to the soil. Sludge supplies some N, P, and K needed for plant growth with amounts available dependent upon treatment process, soil properties, and equilibration time. Zinc and copper found in sewage sludge can increase levels in deficient or marginally sufficient agricultural soils. Crop yields generally increase after application of sewage sludge, although some decreased crop yields were reported at high sludge rates of from 125 to 242 m tons/ha for wheat and rye, respectively.

Application of sewage sludge to agricultural land generally increases the extractable heavy metal content of the soil. Whether the metals are taken up in toxic amounts by plants depends on the soil pH, organic matter, cation exchange capacity, ion competition, the ratio of different elements in the soil, and the plant species and genus. Liming a soil generally reduces toxic metal uptake by plants.

The NO_3^- anion presents the greatest threat of groundwater contamination from sludge applications. The N containing organic compounds mineralize to form NH_4^+ which may be nitrified to the NO_3^- anion. The ammonification reaction is controlled by the soil temperature, moisture content, sludge loading rate, soil texture, and the ease that the microbes can decompose the sludge. The nitrification reaction is controlled by the amount of NH_3 volatilized, fixed by clays and organic matter, incorporated into microbial and plant tissue, and oxygen availability. The NO_3^- yielded by the nitrification reaction can be incorporated into plant and microbial tissue, denitrified under the proper conditions, and leached into the subsoil.

Sludges stabilized by anaerobic digestion or secondary activation are considered safe to use on all crops that are not used raw for human consumption. They can also be used on parks, roadways, golf courses and on lawns and landscape plantings without significant disease hazard.

Application of sewage sludge to agricultural land properly managed can serve as an excellent method of recycling valuable nutrients through the plant-animal food chain. Potential problems associated with heavy metal toxicity to crops and NO_3^- accumulation in the groundwater can be controlled by pH and application rate adjustments. Choosing the proper crop can limit potential accumulation of heavy metals in plant tissue and decrease hazardous accumulations in animals and man.

METHODS AND MATERIALS

Soil Series Determination

The soil series at each disposal site were identified from aerial photographs and recent soil survey base maps obtained from the local Soil Conservation Service offices (Appendix I).

Soil Sample Collection

Soil samples were collected from sewage sludge disposal sites located near Eugene, Hillsboro, Milwaukie, Forest Grove, and Woodburn, Oregon (Figures 2-6). The locations were selected from a list supplied by the Oregon Department of Environmental Quality listing those cities using land disposal of sewage sludge. The number of years the sludge had been applied to the soil, availability of sludge application records, and site accessibility were principal factors used to choose the study location.

The soil samples from each sludge disposal site were collected in July, 1974, December, March, and June, 1975. Soil samples were collected from 10 cm out of each 20 cm of soil (0-10, 20-30, 41-51, 61-71, 81-91) in the surface meter, and then from every 10 cm in 30 cm of soil (122-132, 152-163, 183-192, . . .) until either groundwater or a hard soil layer (e.g. rock, hard pan) was reached (Table 6). Untreated soil adjacent to each disposal area was sampled at similar

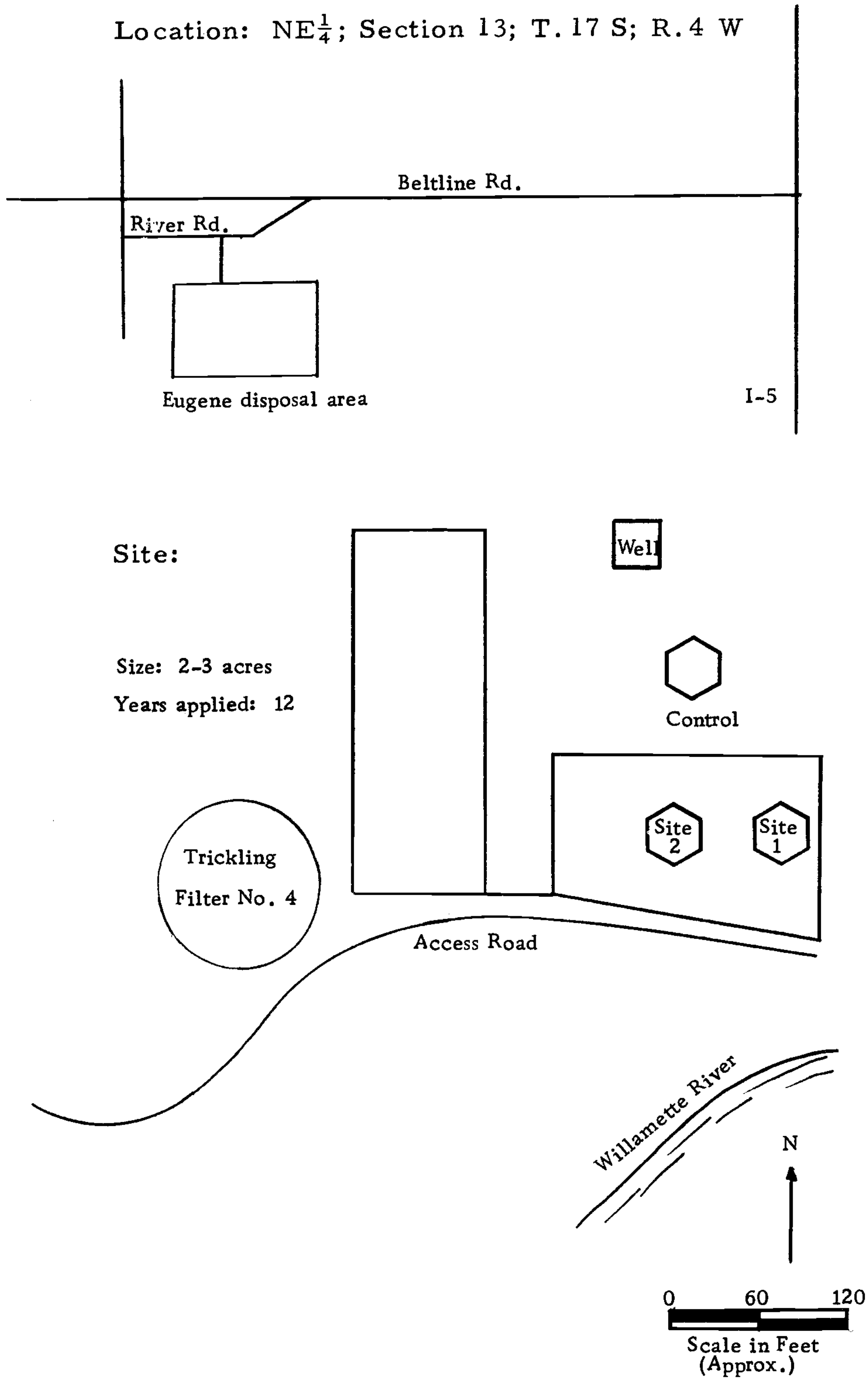
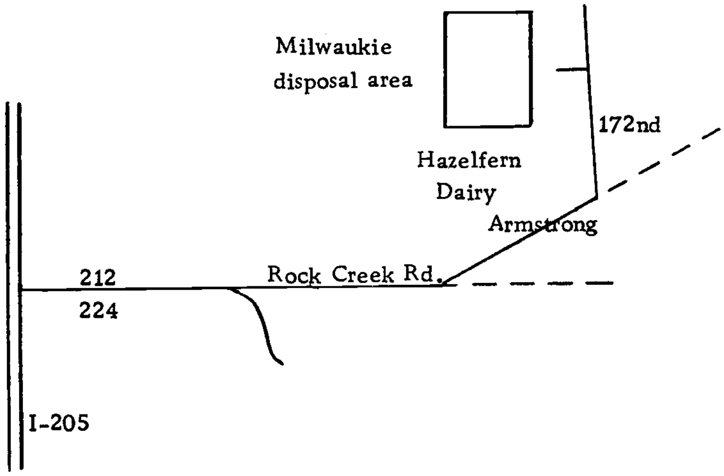


Figure 2. Eugene sewage sludge disposal site.

Location: Section 6; T. 2 S; R. 3 E



Site:

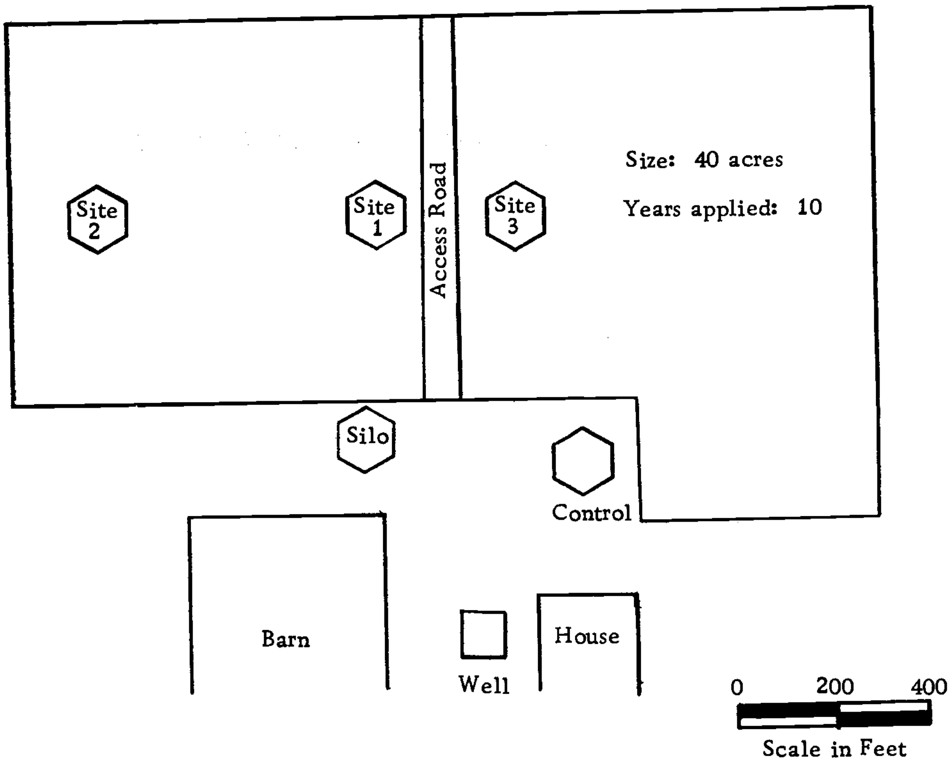
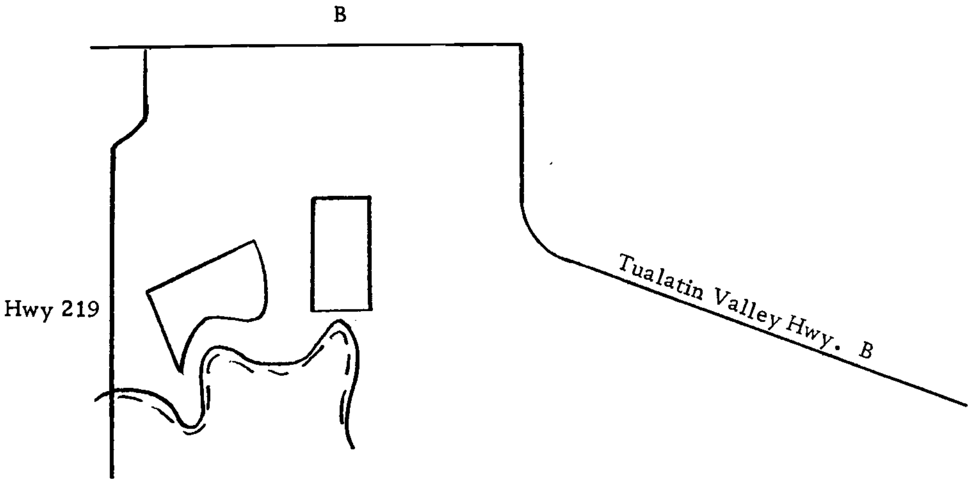


Figure 3. Milwaukie sewage sludge disposal site.

Location: W½; Section 7; T. 1 S; R. 2 W



Site:

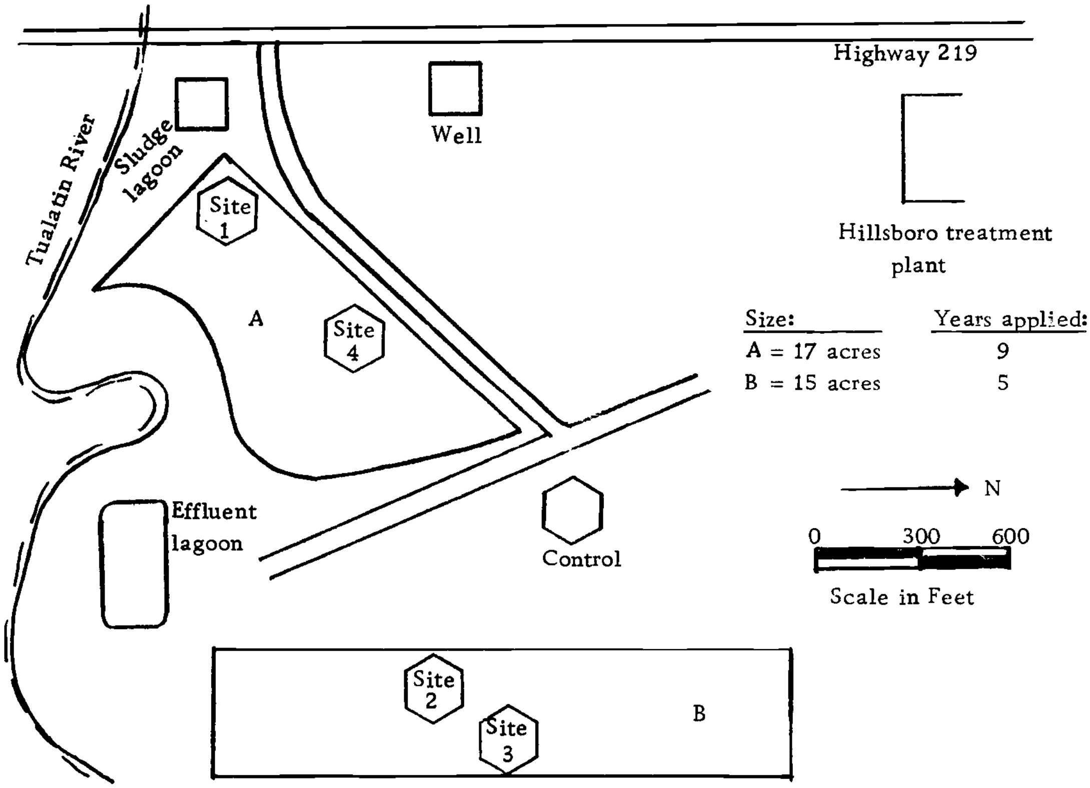
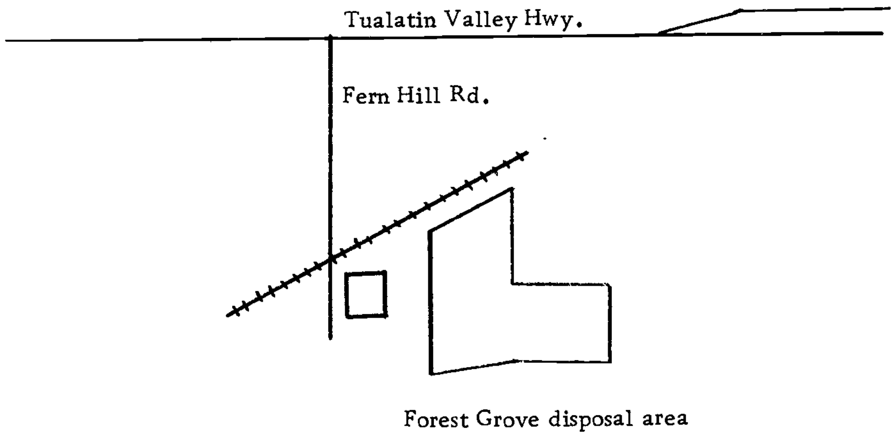


Figure 4. Hillsboro sewage sludge disposal site.

Location: $W\frac{1}{2}$; Section 5; T. 1 S; R. 3 W



Site:

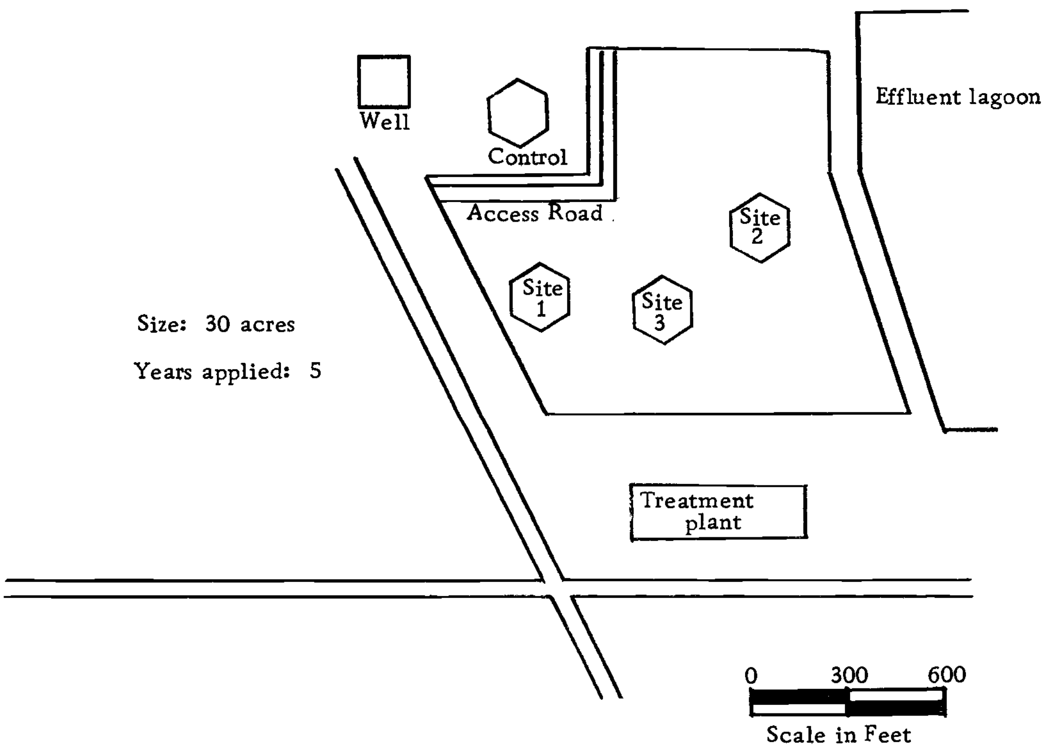
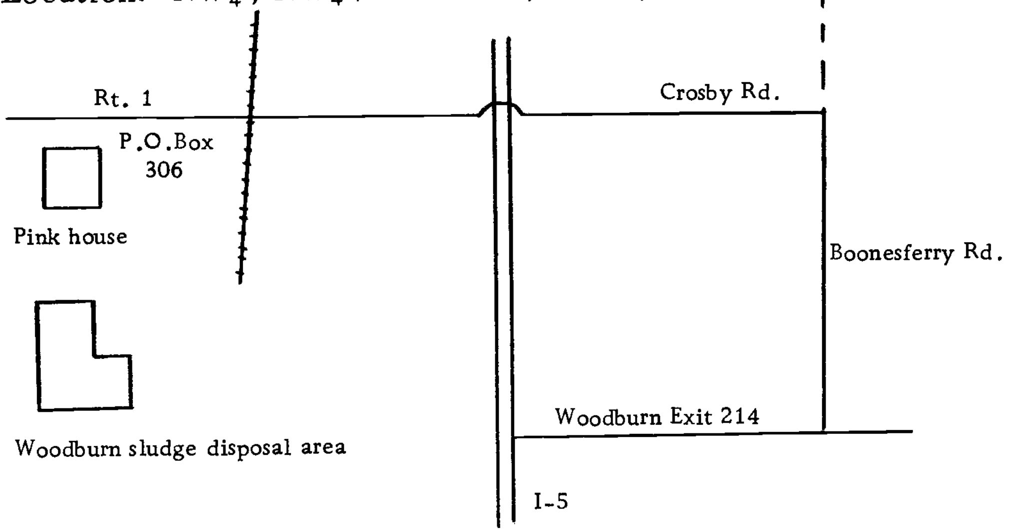


Figure 5. Forest Grove sewage sludge disposal site.

Location: NW¼; NW¼, Section 2; T.5 S; R.2 W



Site:

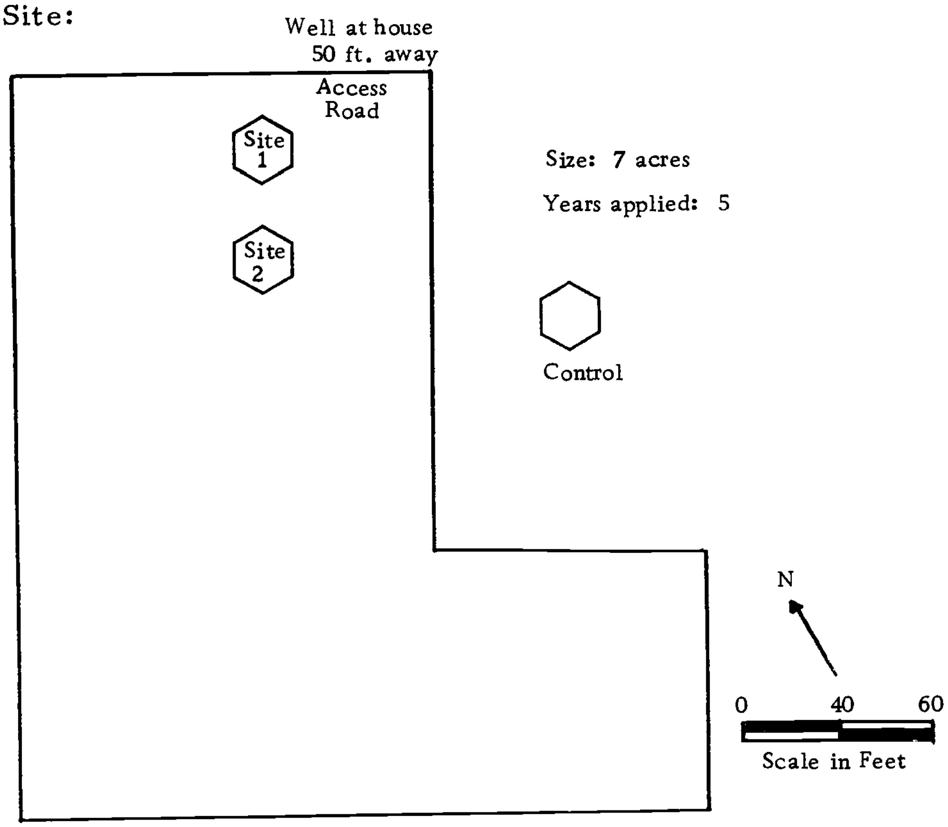


Figure 6. Woodburn sewage sludge disposal site.

Table 6. Soil series and total soil depth of the study area.

		Eugene		Hillsboro		Milwaukie		Woodburn		Forest Grove	
Date	Site Number	Depth Sampled	Soil Series	Depth Sampled	Soil Series	Depth Sampled	Soil Series	Depth Sampled	Soil Series	Depth Sampled	Soil Series
		cm		cm		cm		cm		cm	
July, 1974	Control	376	Newberg fsl	376	Cove sicle	437	Bornstedt sil	498	Woodburn sil	163	Woodburn sil
	1	437		376	Woodburn sicl	437		498		163	
	2	345		376	McBee sicl	254		498		91	
	3			345	McBee sicl	406					
	4			315	Cove sicl						
December, 1975	Control	406		Sites flooded during		193		467		163	
	1	437		Winter and Spring		193		498		163	
	2	224				163		498		91	
March, 1975	Control	345				193		376		163	
	1	406				193		467		163	
	2	224				163		467		91	
June, 1975	Control	345		315		193		467		163	
	1	437		274		193		467		163	
	2	254		315		193		467		132	

soil depths. Additional soil samples (8 to 10 cores) were collected in September, 1974, from the surface meter of each disposal location to determine the uniformity of sludge application. The soil samples were placed in plastic bags and stored on ice during transport to Corvallis, Oregon, where they were then stored in a refrigerated room (4° C).

Soil Chemical Analysis

A portion of each soil sample was dried (105°C), crushed with a mortar and pestal to pass a 2 mm sieve, and stored in plastic bags until analysis. The NH_4-N, NO_3-N and the soil moisture content were measured on moist samples.

Ammonium and Nitrate Nitrogen

Wet soil samples (45 g) were extracted with 150 ml of 2 N KCl (Bremner and Keeney, 1966). A 100 ml aliquot of the extractant was steam distilled in the presence of magnesium oxide (1 g). About 75 ml of the distillate was collected in dilute boric acid and titrated with standard 0.02 N HCl. The NH_4-N content of the dried soil was calculated (Formula 1).

The NO_3-N remaining in the KCl extract solution was reduced to NH_4-N by addition of Devarda alloy (1 g). The sample was again distilled and the distillate collected in boric acid and titrated with the standard 0.02 N HCl. The NO_3-N content of the dried soil was calculated (Formula 1).

$$\frac{[\text{Sample - Blank (ml HCl)}] \times \underline{N}\ \text{HCl} \times 14,000\ \mu\text{g/meq.}}{\text{Dry soil (g)}}$$

$$= NH_4\text{-N} \quad \text{or} \quad NO_3\text{-N} \quad \text{(ppm)} \qquad (1)$$

Soil Moisture Content

A weighed portion of each soil sample (100 g) was dried at 105°C for 24 hours and reweighed to determine the moisture content of each soil sample.

Heavy Metals

The zinc, copper, manganese, and nickel content of each soil sample was determined after extraction with DTPA (diethylenetriaminepentaacetic acid) (Lindsay and Norvell, 1969). A 5 g portion of each dried soil sample was placed in a centrifuge tube and shaken with 20 ml of DTPA for 2 hours. The extractant solution was filtered with Whatman #42 filter paper and the heavy metal content measured by air/acetylene flame atomic absorption. The concentration of Zn, Cu, Mn, and Ni in the extracts were diluted to be within the linear concentration range for each element, from 0.015 to 5 ppm, 0.1 to 5 ppm, 0.05 to 3 ppm, and 0.1 to 5 ppm, respectively.

The total Cd and Cr in the July, 1974 samples and the Zn in the surface 1 meter of soil collected in July and September, 1974, were determined by extraction of 5 g dried soil samples with 25 ml of 4 N HNO_3 for 24 hours at 70°C. The extract solution was filtered and diluted with distilled water to a 100 ml volume (Ganje and Page, 1974). The extracts were diluted, when necessary, to be within the linear concentration range for Cd, below 0.03 ppm, and determined by flameless atomic absorption, using the Perkin-Elmer HGA 2000 graphite furnace. The Cr and Zn content of the extract was measured by nitrous oxide/acetylene and air/acetylene flame atomic absorption, respectively. Extracts were diluted to be within the linear range of 0.25 to 10 ppm and 0.015 to 1 ppm for Cr and Zn, respectively.

Total Nitrogen

The total nitrogen content of each soil sample was determined by digestion of 3 g of dried soil with concentrated sulfuric acid, salicylic acid, and digestion accelerator (100 parts K_2SO_4, 5 parts $CuSO_4$, and 1 part Se metal) for 5 hours. The digested sample was transferred to a distillation flask and 40 ml of concentrated sodium hydroxide was added. The sample was steam distilled into 10 ml of boric acid indicator solution until about 75 ml of the distillate was collected. The distillate was titrated with standardized 0.1 N HCl and the percent total nitrogen was calculated (Formula 2; Jackson, 1958).

$$\% \text{ N} = [\text{Sample - Blank (ml)}] \times \underline{\text{N}} \text{ HCl} \times \frac{0.014 \text{ g/meq}}{\text{Dry soil (g)}} \qquad (2)$$

Soil pH

The pH of each soil sample collected in July, 1974, was measured on a 1:2 soil to solution suspension using a Corning Model 7 pH meter equipped with a glass and calomel electrode (Jackson, 1958).

Sewage Sludge Collection

Sewage sludge samples were collected from sewage treatment facilities in Hillsboro, Forest Grove, Milwaukie, Woodburn, and Eugene in July, 1974. Anaerobically digested sludges are produced in all the wastewater treatment facilities. The samples were collected in plastic bottles and stored on ice during transport to Corvallis, Oregon, where they were then stored in a refrigerated room (4°C).

Sewage Sludge Analysis

Ammonium and Nitrate Nitrogen

Wet sewage sludge samples (5 g) were extracted with 150 ml of 2 N KCl. A 100 ml aliquot of the extractant was steam distilled into a flask containing 10 ml of indicator boric acid which was then titrated with 0.02 N HCl. Devarda alloy (1 g) was added to the remaining KCl extract solution and the sample was again distilled and the distillate collected in boric acid indicator solution and titrated with standard 0.02 N HCl. The NH_4-N and NO_3-N were calculated on a wet weight basis (Formula 1).

Total Solids

A weighted portion (1000 g) of each sewage sludge slurry was dried for 24 hours at 60°C and reweighed to determine the solids content (Formula 3).

$$\% \text{ Solids} = \frac{\text{Dry weight (g)}}{\text{Wet weight (g) - Dry weight (g)}} \times 100 \qquad (3)$$

Heavy Metals

Sub-samples (1 g) of each dried sewage sludge were ground with a mortar and pestal to pass a 2 mm sieve. Cadmium, chromium, copper, manganese, nickel, and zinc were determined using a nitric acid-perchloric acid digestion procedure routinely used for plant analysis (Jackson, 1958). The digestate solution was filtered with Whatman #42 filter paper and diluted to 100 ml volume with distilled water. Zinc, copper, nickel, and manganese were diluted such that concentrations could be measured by air/acetylene flame atomic absorption. Cadmium content was determined by flameless atomic absorption, using the Perkin-Elmer HGA 2000 graphite furnace. Chromium content was measured by nitrous oxide/acetylene flame atomic absorption. The heavy metal content of the sewage sludge was calculated on a dry weight basis (Formula 4).

$$\text{Cd, Cr, Cu, Mn, Ni, Zn (ppm)} = \text{Metal in extract (ppm)} \times \text{Dilution factor} \quad (4)$$

Total Nitrogen

Total nitrogen in a sub-sample (0.5 g) of the dried sewage sludge was determined as previously described for the soil samples. The total N content was calculated on a dry weight basis (Formula 2).

pH

The pH of each sludge slurry was measured with a Corning Model 7 pH meter equipped with a glass and calomel electrode.

Sewage Sludge Application Rate Calculation Methods

The total amount of sewage sludge applied to each disposal site was determined by two methods when possible.

Zinc Method

The excess Zn in the soil which had received the sewage sludge was determined from the difference in the average Zn concentration in

10 or more cores, distributed evenly over the disposal area, and the untreated soil. When the Zn concentration in the sewage sludge is known, the excess Zn measured in the soil is related to the total sewage sludge applied (Formula 5).

$$\frac{\text{Sewage sludge (kg)}}{\text{Ha}} = \left[\frac{\text{Zn excess (kg)}}{\text{Soil (kg)}}\right]\left[\frac{13.4 \times 10^{6}\ \text{kg soil}}{\text{Ha (1 m depth)}}\right]\left[\frac{\text{Dry sludge (kg)}}{\text{Zn in dry sludge (kg)}}\right] \qquad (5)$$

Past Records Method

A less exact method of estimating the amount of sludge applied to the disposal site involved estimates of the number of times the field was covered with liquid sewage sludge during a single year. The number of truckloads necessary to cover a field of a certain size could be calculated (Formula 6). The assumptions built in to this formula are (1) the truck spreads the liquid sewage sludge evenly, (2) the truck moves at a constant rate of speed when delivering the sewage sludge, (3) the truck if full upon delivery and is completely empty after delivery, (4) similar number of deliveries each year, (5) the total solids remain fairly constant from year to year, and (6) one truckload covers an area of 595 m^2.

$$\frac{R\text{ (liters)}}{\text{Ha Year}} = \frac{10,000\text{ m}^2}{\text{Ha}} \; \frac{\text{Truckload}}{595\text{ m}^2} \; \frac{A\text{ (liters)}}{\text{Truckload}} \; \frac{B\text{ (times)}}{\text{Month}} \; \frac{C\text{ (months)}}{\text{Year}} \qquad (6)$$

A: Size of sludge delivery truck

B: Number of times the truck covered the disposal site with liquid sewage sludge

C: Number of months sludge is delivered during any year.

Plant Analysis

Grasses growing on the sludge disposal areas, except Hillsboro, were collected in June, 1975, at the time of the final sampling. The sludge applied at the Hillsboro disposal area was constantly plowed into the soil and no plants grew. Samples were cut 8 cm above the soil surface, stored in plastic bags while being transferred to Corvallis, then dried at 60°C for 48 hours. The grasses from the Eugene, Forest Grove, and Woodburn areas were sampled prior to the development of seed heads, while grasses from the Milwaukie area were sampled immediately after they were cut for hay. The samples were ground in a Wiley Mill to pass a 40 mesh screen and stored in coin envelopes.

Heavy Metals

Samples (2 g) of the plant tissue were digested using the nitric acid-perchloric acid procedure (Jackson, 1958). The solution was filtered with Wahtman #42 filter paper and diluted to 100 ml volume with distilled water. Zinc, copper, nickel, manganese were diluted to concentrations within the linear operating range of the element for atomic absorption analysis. Each element was measured by air/acteylene flame atomic absorption. Cadmium was measured by flameless atomic absorption using the Perkin-Elmer HGA 2000 graphite furnace. The Cr content of the solution digestate was measured by nitrous oxide/acetylene flame atomic absorption. The heavy metal content of the plant tissue was calculated on a dry weight basis (Formula 4).

Total Nitrogen

Total nitrogen in plant samples (0.5 g) was determined as previously described for soil samples and calculated on a dry weight basis (Formula 2).

Phosphorus

Phosphorus in the plant tissue was measured in the nitric acid-perchloric acid extracts previously used for heavy metal analysis (Jackson, 1958). A sample (5 ml) of extract and coloring agent (10 ml) were mixed in a 50 ml volumetric flask and brought to volume with distilled water. The coloring agent was made by combining equal volumes of 0.25% ammonium vanadate and 5% ammonium molybdate solutions. Standard solutions, from 0 to 8 ppm, were prepared and the percent transmittance for the standards and samples were read at 420 nm on a Bausch and Lomb Spectronic 20 spectrophotometer.

Water Sample Collection

Water samples were collected from wells (Figures 2-6) in close proximity to the sewage sludge disposal locations. The water samples were stored in plastic bottles on ice during transport to Corvallis, Oregon, where they were then stored in a refrigerator (4°C) for one day then analyzed the following day.

Water Analysis

Ammonium and Nitrate Nitrogen

A 100 ml aliquot of each water sample was steam distilled in the presence of magnesium oxide (1 g). About 75 ml of the distillate were collected in a boric acid indicator solution and titrated with standard 0.02 N HCl.

The NO_3-N remaining in the solution was reduced to NH_4 by addition of Devarda alloy (1 g). The sample was again distilled and the distillate collected in a fresh boric acid indicator solution which was then titrated with 0.02 N HCl. The NH_4-N and NO_3-N concentrations were calculated in each water sample (Formula 1).

Heavy Metals

The Cu, Mn, Ni, Zn concentrations in the water samples was measured by air/acetylene flame atomic absorption, while the Cd and Cr concentration were measured using flameless atomic absorption using procedures noted previously.

Phosphorus

The P concentration in the water samples (40 ml) were measured by mixing 10 ml of coloring agent, equal volumes 0.25% ammonium vanadate and 5% ammonium molybdate solutions, with 40 ml of each water sample. Standards and samples were read at 420 nm on a Bausch and Lomb Spectronic 20 and the P content calculated (Jackson, 1958).

pH

The pH of the water samples was measured with a Corning Model 7 pH meter.

RESULTS AND DISCUSSION

Sewage Sludge Analysis

The total N content of the Eugene, Milwaukie, Hillsboro, Forest Grove, and Woodburn sewage sludges collected July, 1974, was 3.9, 6.1, 5.1, 6.3, and 5.2%, respectively (Table 7). The inorganic N was primarily in the form of NH_4-N, a range from 1.4 to 4.4%, while the NO_3-N content ranged from 0.002 to 0.2%. The total N content of the sludges was from one-fourth to three-fourths inorganic NH_4-N. When the solids content decreased, a greater fraction of the total N was in the form of inorganic NH_4-N indicating that the organic N compounds were in the solid portion of the sludge.

The trace element (Cd, Cr, Cu, Mn, Ni, Zn) content of the sludges (Table 7) fell within general ranges reported for a number of municipal sludges, with the exception of the Cr content of the Milwaukie sludge. The Cr content of the Milwaukie sludge, 17,700 ppm, exceeded the highest Cr level, 8,800 ppm reported for 42 sludges from England and Wales (Berrow and Webber, 1972). The high Cr content of the Milwaukie sludge was the result of high Cr containing waste from a chrome plating facility. The Zn content of the five sludges was generally at higher levels compared with other trace elements assayed, from 1,600 to 16,900 ppm; however, the Cr content of the Eugene and Milwaukie sludges, 875 and 17,700 ppm, respectively, also exhibited increased levels. The increased Zn and Cr content of the Eugene and Milwaukie sewage sludges was probably because the treatment facilities were collecting waste from more industrialized communities.

Table 7. Elemental analysis of selected sewage sludges in Oregon.

Item	Eugene	Milwaukie	Hillsboro	Forest Grove	Woodburn
	%				
Total N	3.9	6.1	5.1	6.3	5.2
NH_4-N	1.4	2.3	3.7	4.1	4.4
NO_3-N	0.009	0.023	0.002	0.002	0.008
Solids	5.6	3.1	2.0	0.6	0.5
Phosphorus	1.6	2.9	2.0	1.5	1.7
	ppm, dry weight				
Cadmium	11	9.5	12.5	2.2	1.8
Chromium	875	17,700	190	60	40
Copper	215	330	382	365	220
Manganese	375	450	450	167	1500
Nickel	235	145	35	35	32
Zinc	4400	16,900	2250	1750	1600
pH	7.4	7.1	7.3	7.0	6.7

Chaney (1973) recommends that levels of Cd, Cr, Cu, Ni, and Zn should not exceed 15, 1000, 1000, 200, and 2000 ppm, respectively, and the Cd should not exceed 1% of the Zn concentration for a sewage sludge to attain a reasonably minimum toxic-metal content and hence a good benefit:risk ratio when applied to agricultural crops. The Zn and Ni content of the Eugene sludge, 4,400 and 235 ppm, respectively, the Cr and Zn content of the Milwaukie sludge, 17,700 and

16,900 ppm, respectively, and the Zn content of the Hillsboro sludge, 2250 ppm, exceeded the levels considered appropriate for land application. With these criteria, the Eugene, Milwaukie, and Hillsboro sewage sludge would be considered inappropriate for land application.

The P content of the sludges ranged from 0.5 to 2.9% (Table 7). The level of P in the sludge generally increased with increasing solids content, from 0.5 to 3.1%, suggesting that P was associated with the solid portion of the sludge. Contrary to the preceding assertion, the Eugene sludge had a lower P content, 1.6%, than either the Hillsboro or Milwaukie sludges but displayed a higher solids content, 5.6%, indicating that sludges from different treatment facilities may vary widely in their elemental content.

The pH of the sludges ranged from 6.7 to 7.4 (Table 7). The pH values measured for these sludges fell within the common pH range measured for anaerobically digested sludges, 6.5 to 8.0 (Table 2).

Because the sludges contain valuable plant nutrients, such as N, P, Cu, and Zn, the material may serve as a valuable fertilizer source; however, the high metal (Cr, Ni, Zn) content of the Eugene, Hillsboro, and Milwaukie sludges may limit the amount of sludge that can be applied. The Forest Grove and Woodburn sludges could be applied to agricultural crops on a long-term basis without presenting any potential problems.

Disposal Area Description

Eugene Disposal Area

A portion of the anaerobically digested sewage sludge produced in the Eugene wastewater treatment facility had been applied to a 0.8 to 1.2 ha disposal area since 1962. Pasture grasses planted on the disposal area appeared considerably greener and thicker than grass surrounding the disposal area, with no visual toxicity symptoms (e.g. tip burning) observed. The sewage sludge is normally hauled in a 9,460 gallon tank truck to the site and spread throughout the entire year. In addition, sewage sludge from evaporation lagoons was spread over the surface of the disposal area during the fall of 1972 and 1974.

The soil series in the disposal area was identified from aerial photographs and on-site inspection as a Newberg sandy loam, a member of the coarse-loamy, mixed, mesic family of Fluventic Haploxerolls (Appendix I). Newberg soils are somewhat excessively drained, have moderately rapid permeability, minimal runoff, and slight erosion hazard, except from flooding. The mean annual precipitation is 100 cm and the mean air temperature is 11 to 12°C. Typically the color of the surface layer is dark brown, but the surface of the sludge treated soil had a blackish appearance to a depth of 30 cm.

Milwaukie Disposal Area

A portion of the anaerobically digested sewage sludge produced in the Milwaukie wastewater treatment facility had been applied to a 16 ha disposal area since 1964. Until 1970, the disposal area was used alternately for hay production and cattle grazing. The soil, before 1970, had been limed and fertilized to maximize hay yields. The sewage sludge was hauled by a 3000 gallon tank truck to the site and spread throughout the entire year.

The soil series in the disposal area was identified from a recent soil survey base map and on-site inspection as a Bornstedt silt loam, a member of the fine silty, mixed, mesic family of the Typic Fragioochrepts (Appendix I). Bornstedt soils are moderately well-drained, have slow permeability, minimal runoff, and slight erosion hazard. The mean annual precipitation is 120 to 162 cm and the mean annual temperature is 10 to 11°C. It is underlain by a massive, very firm, brittle fragipan layer from 50 to 100 cm below the soil surface.

Hillsboro Disposal Area

A portion of the anaerobically digested sewage sludge produced in the Hillsboro wastewater treatment facility had been applied to a 5.7 ha disposal area since 1965. The sewage sludge was disked into the soil immediately after sludge applications. The sewage sludge was only applied 6 months out of the year since the site was flooded by the Tualatin River during the remaining 6 months. Because the soil in the disposal area was constantly disked or flooded during the major portion of each year, no plants grew.

From aerial photographs and on-site inspection, several soil series were identified within the sludge disposal area. Site 1 was identified as a Woodburn silt loam (fine-silty, mixed, mesic, Aquultic Argixeroll), site 2, 3, and the control area were identified as a McBee silty clay loam (fine-silty, mixed, mesic, Cumulic Ultic Haploxeroll), and site 4 was identified as a Cove silty clay loam (Vertic Haplaquoll) (Appendix I).

Woodburn soils are moderately well drained, have slow permeability, slow to medium runoff, and slight erosion hazard. McBee soils are moderately well drained, have moderate permeability, slow runoff potential, and slight erosion hazard. Cove soils are poorly drained, have very slow permeability, slow runoff potential, and slight erosion hazard. The mean annual precipitation is 100 to 125 cm and the mean air temperature is 10 to 11°C.

Forest Grove Disposal Area

Anaerobically digested sewage sludge produced in the Forest Grove wastewater treatment facility had been applied to a 12 ha disposal area since 1969. In addition to sludge being applied, effluent water produced during the treatment process was regularly applied using a sprinkler irrigation method. The disposal area was also used for cattle grazing, although the principle purpose was for the disposal of large amounts of effluent water and smaller amounts of sewage sludge produced during the wastewater treatment process.

The soil series in the disposal area was identified from aerial photographs and on-site inspection as a Woodburn silt loam (Appendix I).

Woodburn Disposal Area

Anaerobically digested sewage sludge produced in the Woodburn wastewater treatment facility had been applied to a 2.8 ha disposal area since 1968. The greatest portion of the sewage sludge, approximately 1,196,000 liters, was applied in 1969. The amount of sewage sludge delivered to the disposal area decreased through 1973, to approximately 75,700 liters, as land closer to the treatment plant was utilized. Finally, sludge disposal on this area was discontinued in 1973. The primary use of the disposal area was for sheep grazing.

The soil series in the disposal area was identified from a Marion county soil survey report and on-site inspection as a Woodburn silt loam (Appendix I).

Soil Chemical Analysis

Determination of Sludge Application Rate and Variability

Eugene Disposal Area. The 11 soil cores collected in the disposal area displayed increased Cr and Zn levels in the upper 50 cm of the soil profile, a range of 18 to 228 ppm and 60 to 1070 ppm, respectively, compared to the Cr and Zn level of the control, 10 and 52 ppm, respectively (Table 8). Below 50 cm in the sludge-treated soil, the Cr and Zn content generally compared closely to the control soil.

The amount of sewage sludge applied to various parts of the disposal area varied widely (Table 8). The Zn concentration, averaged for the 1 meter depth for 9 soil cores, ranged from 134 to 400 ppm. The Zn concentration in the surface 10 cm ranged from 330 to 1050 ppm. The dry solids applied at each soil core calculated from the excess Zn, the difference in the average Zn content in each soil core and the control, ranged from 250 to 1060 m tons/ha in those 9 cores (Table 9). The average amount of sewage sludge applied over the entire soil surface estimated by the Zn method was 564 m tons/ha since 1962.

The excess Cr in the surface meter of the 9 soil cores was also used to estimate the amount of sewage sludge applied to the soil surface. The excess Cr (Table 9) in the 9 soil cores varied widely, from

Table 8. Zinc and chromium concentration in the surface meter of a Newberg fine sandy loam soil from the Eugene disposal area treated with sewage sludge.

Depth	Control	Soil Core 1	2	3	4	5	6	7	8	9	10	11
cm	ppm, Zn											
0-10	52	790	440	1070	330	720	480	820	780	530	1050	970
20-30	52	180	760	142	136	178	82	154	196	150	630	820
41-51	52	800	94	100	66	100	60	74	88	66	160	190
61-71	52	142	58	74	76	80	60	60	84	62	NS[1]	NS
81-91	52	86	54	64	64	66	52	64	70	66	NS	NS
Average	52	400	281	290	134	229	147	236	244	175		
	ppm, Cr											
0-10	10	140	83	196	51	71	78	145	153	75	208	228
20-30	8	28	104	20	24	28	22	29	33	26	92	157
41-51	10	96	12	19	18	22	21	20	20	24	28	24
61-71	12	14	12	17	21	24	21	15	24	22	NS	NS
81-91	13	10	10	18	10	22	21	18	19	21	NS	NS
Average	11	58	44	54	25	33	33	45	50	34		

[1]NS: no sample collected.

Table 9. Increase in Cr and Zn levels in a Newberg fine sandy loam soil related to calculated sewage sludge applied.

Item	Soil Core 1	2	3	4	5	6	7	8	9	Mean
Excess Zn, ppm	348	229	238	82	177	95	184	192	123	
Total dry sludge applied (m tons/ha)	1062	699	726	251	540	289	560	585	374	564
Excess Cr, ppm	47	33	43	14	22	22	34	39	23	
Total dry sludge applied (m tons/ha)	721	506	659	215	354	336	522	598	354	475

14 to 47 ppm. The dry solids applied to each soil core, calculated from the excess Cr, ranged from 215 to 721 m tons/ha. The average amount of sewage sludge applied over the entire soil surface calculated by the Cr method was 475 m tons/ha since 1962, comparing closely to the Zn method.

The accuracy of the Zn and Cr method in estimating the amount of sludge applied to the soil surface depends on the fluctuation in the Zn and Cr content in the sludge. Part of the discrepancy between the amount of sludge applied, as calculated by the Cr and Zn method, may result from variation in the Cr or Zn content of the sludge during prior applications.

From the yearly reports, the average amount of sewage sludge delivered to the disposal area was 3,354,000 gallons/year, which was calculated to be approximately 180 m tons/year if the material maintained 5.6% solids. The total applied over 12 years at that rate was 2150 dry m tons to the disposal area, or approximately 717 m tons/ha to a 3 acre site since 1962. Variation in the solids content for different sludge applications will influence the estimated amount of sludge applied.

The calculated amount of sludge applied to the soil surface by the 3 methods were relatively close. The sludge application rate was probably between 475 and 720 m tons/ha.

Milwaukie Disposal Area. The 11 soil cores collected from the disposal area exhibited increased Cr and Zn content in the surface 10 cm of the soil profile, a range from 33 to 142 ppm and 58 to 184 ppm, respectively, compared to the Cr and Zn content of the control, 42 and 58 ppm, respectively (Table 10). Below 10 cm in the sludge-treated soil profile, the Cr and Zn content generally compared closely to the control soil.

The amount of sludge applied to various parts of the disposal area varied widely (Table 11). The Zn concentration, averaged for the 1 meter depth for 11 soil cores, ranged from 51 to 78 ppm. The dry solids applied at each soil core calculated from the excess Zn ranged from 1 to 19 m tons/ha (Table 11). The average amount of sewage sludge applied over the entire soil surface, estimated by the Zn method, was 11 m tons/ha since 1964.

The dry solids applied to each soil core, calculated from the excess Cr, ranged from 0 to 25 m tons/ha. The average amount of sewage sludge applied over the soil surface, calculated by the Cr method, was 11 m tons/ha since 1964.

The amount of sewage sludge delivered to the disposal area was estimated to be approximately one-half of the total sludge accumulated in the wastewater treatment process during a single year, from 600,000 to 800,000 gallons/year. It was calculated, assuming 3.1% solids and 8.3 lb/gallon sludge, that between 87 and 116 m tons/year

Table 10. Zinc and chromium concentration in the surface meter of a Bornstedt silt loam soil from the Milwaukie disposal area treated with sewage sludge.

Depth	Control	Soil Core 1	2	3	4	5	6	7	8	9	10	11
cm	ppm, Zn											
0-10	58	112	184	112	130	116	106	152	110	134	188	58
20-30	56	74	64	64	52	62	56	64	64	54	54	56
41-51	54	64	54	50	52	46	46	48	44	42	44	54
61-71	44	64	54	50	52	46	46	48	44	42	44	54
81-91	38	54	38	40	32	34	40	42	42	38	36	42
Average	50	74	78	62	62	60	58	70	60	62	72	51
	ppm, Cr											
0-10	42	88	140	100	127	76	100	142	89	106	186	33
20-30	44	50	62	66	47	46	32	61	61	42	41	35
41-51	46	44	60	46	60	36	36	37	41	47	35	38
61-71	50	48	62	54	52	42	43	36	52	44	49	45
81-91	52	58	76	58	70	46	37	44	52	47	44	55
Average	47	57	80	65	71	49	50	64	59	57	71	41

Table 11. Increase in Cr and Zn levels in a Bornstedt silt loam soil related to calculated sewage sludge applied.

Item	Soil Core 1	2	3	4	5	6	7	8	9	10	11	Mean
Excess Zn, ppm	24	28	12	12	10	8	20	10	12	22	1	
Total dry sludge applied (m tons/ha)	19	22	9.6	9.6	8.1	6.3	16	8.1	9.6	17	1	11.4
Excess Cr, ppm	10	33	18	24	2	3	17	12	10	24	0	
Total dry sludge applied (m tons/ha)	7.6	25	14	18	1.6	2	13	9	7.6	18	0	10.5

were delivered to the disposal area, or 520 to 870 m tons since 1964. The average amount delivered to each ha of the 16 ha disposal area was between 22 and 29 m tons/ha since 1964.

The 3,000 gallon tank covered the disposal area with sewage sludge approximately twice a year. The amount of sewage sludge delivered to the sludge disposal area, assuming 3.1% solids and the past records method (Formula 6), was 12 m tons/ha.

The calculated amount of sludge applied to the soil surface of the Milwaukie disposal area by the 4 methods were comparatively close. The Cr and Zn method probably were low estimates of the amount of sludge applied to the soil surface since hay had been harvested from the field since 1964 removing some Zn and Cr with the crop. The sludge applied since 1964 was probably between 10 to 30 m tons/ha.

<u>Hillsboro Disposal Area.</u> The 11 soil cores sampled from the Hillsboro disposal area reflect several different soil series, Cove, McBee, and Woodburn. The Zn content in the soil cores identified as McBee soils, cores 2, 3, 8, 9, 10, and 11, have considerably higher Zn levels throughout the entire soil profile, a range from 104 to 320 ppm, compared to the control, a range from 68 to 122 ppm (Table 12). The McBee soil also exhibits a higher Zn level, below 10 cm in the soil profiles, than cores sampled from treated areas but on Cove or Woodburn soil series, ranging from 48 to 86 ppm (Table

12). This would suggest that either considerable amounts of Zn have moved through the soil profile of the McBee soils, or the McBee soil normally have a higher Zn content in the soil profile. Similar to Zn, the Cr content of the soil cores sampled on the McBee soil series displayed increased Cr levels compared to Cove and Woodburn soil series.

The soil cores sampled on the Cove and Woodburn soil series, cores 1, 4, 5, 6, 7, and the control, reflected increased Zn and Cr content in the surface 30 cm of the soil profile, a range from 64 to 940 and 46 to 59 ppm, respectively, compared to the Zn and Cr content of the control, a range from 70 to 122 ppm and 37 to 50 ppm, respectively (Table 12). Below 30 cm in the cores sampled on the Cove and Woodburn soil series, the Zn and Cr content compared relatively close to the control. Because the soil cores were sampled from a variety of soil series, it is difficult to make broad inferences concerning Zn and Cr movement through the soil profile.

The Zn concentration in the surface 10 cm of the 11 soil cores ranged from 108 to 940 ppm (Table 12). The Zn concentration, averaged for the 1 meter depth for the 11 soil cores, ranged from 90 to 264 ppm. The dry solids applied at each soil core, calculated from excess Zn, ranged from 36 to 1090 m tons/ha since 1964 reflecting the wide variability of sludge application in the disposal area (Table 13). The average amount of sewage sludge applied was calculated

Table 12. Zinc and chromium concentration in the surface meter of a Woodburn silt loam, McBee clay loam, and Cove clay soils from the Hillsboro disposal area treated with sewage sludge.

	Soil Core[1]											
Depth	Control	1	2	3	4	5	6	7	8	9	10	11
cm	ppm, Zn											
0-10	122	700	132	200	138	124	148	940	108	320	280	198
20-30	70	76	150	100	102	90	64	210	96	132	120	140
41-51	76	80	132	100	68	80	76	64	90	114	110	98
61-71	72	78	122	126	74	70	70	48	96	108	110	82
81-91	68	86	114	100	82	88	82	60	120	114	104	84
Average	82	122	130	125	93	90	88	264	102	158	145	120
	ppm, Cr											
0-10	50	59	63	61	51	48	49	53	54	60	62	53
20-30	37	69	60	51	50	48	46	54	51	61	59	49
41-51	44	65	60	52	44	46	50	51	49	59	50	50
61-71	42	61	60	58	42	42	43	41	56	58	51	51
81-91	38	61	60	52	36	36	36	40	63	57	50	53
Average	44	63	61	55	45	44	45	48	55	59	54	51

[1] Cove series: cores control, 4, and 5; Woodburn series: cores 1, 6, and 7; McBee series: cores 2, 3, 8, 9, 10, 11.

Table 13. Increase in Zn in the soils in the Hillsboro disposal area related to calculated sewage sludge applied.

	Soil Core											
Item	1	2	3	4	5	6	7	8	9	10	11	Mean
Excess Zn, ppm	40	48	43	11	8	6	142	20	76	43	38	
Total dry sludge applied (m tons/ha)	237	287	258	65	47	36	1090	119	455	376	226	291

(Formula 5) to be 290 m tons/ha since 1964.

The disposal area was covered with sewage sludge, using a 3,000 gallon tank truck, approximately 20 times/year. At 2% solids, the total amount of sludge delivered to the disposal area was calculated to be 76 m tons/year (Formula 6).

The large discrepancy between the Zn method and the past records method may be the result of (1) variability in the solids content of different applications of sludge, (2) inaccurate estimates of the number of times the sludge disposal area was covered each year, (3) variability of the Zn content in the sludge from year to year, or (4) higher levels of Zn in the soil cores sampled from the McBee soil served to enhance the estimated sludge application rate.

Forest Grove Disposal Area. Of the 10 soil cores sampled randomly over the disposal area, 9 exhibited increased Zn levels in the upper 10 cm of the soil profile, a range of 80 to 164 ppm, compared to the control, 70 ppm (Table 14). The Cr content in the upper 10 cm of the 10 soil cores from the sludge-treated area compared closely to the control reflecting the low Cr content in the sludge, 60 ppm (Table 7). Below 10 cm in the soil profile, the Zn and Cr content generally compared closely to the control soil.

The amount of sewage sludge applied to the disposal area was estimated by the Zn method alone since minimal records of past sludge applications were maintained. The Zn content of the sludge-treated soil, averaged for a 1 meter depth for 10 soil cores, ranged from 69 to 93 ppm. The dry solids applied at each soil core, calculated from the excess Zn (Table 15) ranged from 22 to 213 m tons/ha indicating the wide variability of the sludge application rate in the disposal area. The average amount of sludge applied over the entire soil surface, estimated by the Zn method, was 96 m tons/ha since 1969.

Woodburn Disposal Area. Of the 10 soil cores sampled randomly over the disposal area, 8 exhibited increased Zn levels in the upper 10 cm of the soil profile, a range of 77 to 152 ppm, compared to the control, 68 ppm (Table 16). The Cr content in the upper 10 cm of the 10 soil cores from the sludge disposal area compared closely to the control reflecting the low Cr content in the sludge, 40 ppm (Table 7). Below 10 cm in the soil profile, the Zn and Cr content in the sludge-treated soil compared closely to the control.

Similar to the Forest Grove disposal area, the amount of sewage sludge applied to the disposal area was estimated by the Zn method alone. The Zn content of the sludge-treated soil, averaged for 1 meter depth for the 10 soil cores, ranged from 66 to 94 ppm. The dry solids applied at each soil core, calculated from the excess Zn (Table 17), ranged from 0 to 202 m tons/ha indicating the wide variability of the sludge application rate over the field. The average

Table 14. Zinc and chromium concentration in the surface meter of a Woodburn silt loam soil at the Forest Grove disposal area treated with sewage sludge.

Depth	Soil Core										
	Control	1	2	3	4	5	6	7	8	9	10
cm	ppm, Zn										
0-10	70	164	80	94	98	126	68	100	114	84	96
20-30	66	84	60	134	96	70	74	74	76	72	60
41-51	62	62	60	66	74	54	66	68	66	62	56
61-71	64	66	70	76	64	60	66	78	64	68	62
81-91	64	88	72	72	68	66	72	78	76	68	64
Average	65	93	68	88	80	75	69	80	79	71	68
	ppm, Cr										
0-10	19	23	21	22	80	21	22	20	20	24	20
20-30	20	21	22	23	22	20	20	20	20	24	20
41-51	20	22	22	24	20	20	20	18	21	22	21
61-71	22	22	22	22	20	21	20	20	21	21	23
81-91	22	22	22	22	20	18	19	20	21	20	24
Average	21	22	22	23	32	20	20	20	21	22	22

Table 15. Increase in Zn in a Woodburn silt loam soil related to calculated sewage sludge applied.

Item	Soil Core										Mean
	1	2	3	4	5	6	7	8	9	10	
Excess Zn, ppm	28	23	15	10	4	13	12	6	3	12	
Total dry sludge applied (m tons/ha)	213	175	114	76	31	99	92	45	22	92	96

Table 16. Zinc and chromium concentration in the surface meter of a Woodburn silt loam soil from the Woodburn disposal area treated with sewage sludge.

	Soil Core										
Depth	Control	1	2	3	4	5	6	7	8	9	10
cm	ppm, Zn										
0-10	68	152	116	132	98	98	62	70	90	77	78
20-30	62	80	68	99	66	65	57	69	58	76	56
41-51	70	69	76	78	71	70	65	72	58	65	68
61-71	77	76	82	84	78	75	63	81	67	63	68
81-91	74	78	75	77	97	70	88	82	70	79	62
Average	70	91	84	94	82	76	67	75	70	72	66
	ppm, Cr										
0-10	18	20	22	20	16	20	18	16	19	15	16
20-30	19	20	22	20	18	26	21	18	19	17	18
41-51	22	24	24	21	19	26	21	20	20	17	24
61-71	27	20	23	22	22	24	21	20	22	18	23
81-91	26	22	21	21	20	21	25	18	20	18	21
Average	22	21	22	21	19	23	21	18	20	15	20

Table 17. Increase in Zn levels in a Woodburn silt loam soil related to calculated sewage sludge applied.

	Soil Core										
Item	1	2	3	4	5	6	7	8	9	10	Mean
Excess Zn, ppm	21	14	24	12	6	0	5	0	2	0	
Total dry sludge applied (m tons/ha)	177	119	202	101	52	0	43	0	17	0	72

amount of sludge applied over the soil surface, estimated by the Zn method, was 72 m tons/ha since 1968.

Summary. An estimated 500, 290, 96, 72, and 10 m tons/ha of sludge was applied to the Eugene, Hillsboro, Forest Grove, Woodburn, and Milwaukie disposal areas, respectively. The Cr and Zn content in the upper portion of the shallow soil cores increased depending on the sludge application rate and the Cr and Zn content of the sludge. Most of the Cr and Zn added to the soils in the sludges remained in the upper 50 cm of the soil profile indicating that movement by these elements (Cr, Zn) in sludge-amended soils is quite restricted.

The variability of sludge application over the disposal areas was due primarily to the uneven sludge application by the tank trucks. When determining the amount of a sludge to apply to agricultural land to minimize the potential dangers from metal accumulation, the application variability must be considered. Spreading the sewage sludge more evenly or adjusting the application rate so the maximum applied will not exceed safe limits are two alternatives.

Movement of Nitrogen and Heavy Metals (Cd, Cr, Cu, Mn, Ni, Zn)

Nitrate-Nitrogen. The NO_3-N content of the untreated soil from the Eugene disposal area sampled during the summer, 1974, winter, spring, and summer, 1975, did not exceed 14 ppm, with most samples lower than 5 ppm (Table 18). No marked accumulation of NO_3-N was observed at any depth in the soils which received no sewage sludge. The surface 10 cm of the control soil displayed the greatest variation seasonally in NO_3-N content, ranging from 0.1 to 8 ppm.

The NO_3-N content in the sludge-treated soil from the Eugene disposal area sampled during the summer, 1974, reflected a marked accumulation in the surface 50 cm of soil as compared to the untreated soil (Table 18). Below 50 cm in the soil profile, the NO_3-N level ranged from 9 to 120 ppm suggesting that considerable amounts of N must be nitrified at the soil surface, since less than 5 ppm NO_3-N was added in the sludge, and leached into lower soil horizons. The NO_3-N content in the soil below 3 meters decreased abruptly due to a buried log which supplied a source of carbon for microorganisms to reduce NO_3-N to NH_4-N, assimilatory nitrate reduction, resulting in a large accumulation of NH_4-N, increasing from 0.3 to 70 ppm (Table 23). The high NH_4-N content in the lower soil horizon was not observed in the second soil core.

During the winter, the NO_3-N content in the surface 50 cm decreased, from a high level of 240 ppm in the summer to 72 ppm, while the average NO_3-N content below a 50 cm depth generally increased (Table 18). Increased rainfall during the winter months resulted in more water percolating through the soil profile carrying minearlized NO_3-N from the surface to lower soil horizons.

Table 18. Nitrate-nitrogen concentration in a Newberg fine sandy loam soil treated with sewage sludge from the Eugene disposal area.

	July, 1974			December, 1975			March, 1975			June, 1975		
	Site			Site			Site			Site		
Depth	Control	1	2	Control	1	2	Control	1	2	Control	1	2
cm	NO_3-N, ppm											
0-10	1.9	240	130	7.0	71	52	6.5	18	20	0.1	35	17
20-31	3.3	30	51	3.7	72	12	4.3	0.9	2.7	0.6	36	29
41-51	2.8	57	12	3.0	30	10	1.2	16	3.0	0.2	35	29
61-71	2.2	20	9.7	2.1	46	9.6	0.6	2.9	13	0.6	41	34
81-91	14	12	9.3	1.3	40	14	1.0	3.4	5.1	0.6	64	13
122-132	1.8	11	14	1.7	48	12	1.1	12	8.5	0.4	67	37
152-163	2.0	9.9	11	0.6	89	6.6	1.2	38	15	0.2	74	43
183-193	2.1	10	13	1.0	48	29	0.5	40	19	0.4	62	44
213-224	2.9	15	16	1.2	22	15	0.3	22	17	0.1	46	17
244-254	3.2	56	29	0.9	23		1.0	17		0.7	9.5	18
274-284	3.1	100	53	1.4	19		0.2	14		0.4	11	
305-315	4.5	120	63	0.3	25		0.9	19		0.4	14	
335-345	2.9	6.4	50	0.2	37		1.0	13		0.8	17	
366-376	4.5	4.5		0.3	60			21			36	
395-406		0.3		0.7	64			24			52	
427-437		0.3			46						39	

During the spring, the NO_3-N content in the sludge-treated soil decreased further compared to the summer and winter months, ranging from 20 to 40 ppm throughout the entire soil profile (Table 18). Additional water supplied by rainfall carried NO_3-N to lower soil depths and possibly into the groundwater, or at least beyong the depth that could be sampled. Lower temperatures during the winter and spring restricted microbiological activity and decreased the mineralization of NO_3-N at the soil surface resulting in decreased NO_3-N in the upper part of the soil profile.

During the summer, 1975, the NO_3-N content in the sludge-treated soil from the Eugene disposal area increased, as compared to the spring sampling, ranging from 10 to 75 ppm, the result of increased mineralization and a continued percolation of NO_3-N containing water from the soil surface to lower soil horizons (Table 18). The upper 50 cm of soil, sampled in the summer, 1975, exhibited a lower NO_3-N level than the previous summer, possibly due to sample collection early in June rather than July. With a June sample collection date, less nitrification of the organic N compounds would have occurred.

The NO_3-N content of the untreated soil from the Milwaukie disposal area sampled during the summer, 1974, winter, spring, and summer, 1975, did not exceed 11 ppm, with most NO_3-N levels below 5 ppm (Table 19). The NO_3-N content in the surface 10 cm of the

Table 19. Nitrate-nitrogen concentration in a Bornstedt silt loam soil treated with sewage sludge from the Milwaukie disposal area.

Depth	July, 1974 Site				December, 1975 Site			March, 1975 Site			June, 1975 Site		
	Control	1	2	3	Control	1	2	Control	1	2	Control	1	2
cm	NO_3-N, ppm												
0-10	1.3	2.0	79	1.1	11	62	30	9.9	20	39	1.2	0	3.5
20-30	0.9	0.8	2.5	0.4	4.6	23	1.7	4.1	2.3	4.0	0.9	0	0.7
41-51	0.4	0.3	1.6	0.3	0.9	3.1	2.1	1.2	1.3	2.4	0.4	0	0.8
61-71	0.4	1.0	3.3	0.7	0.2	1.8	1.2	0.3	1.1	1.6	0.2	0	0.2
81-91	0.4	1.3	1.2	0.7	0.1	1.5	1.5	0.4	1.6	0.8	0.6	1.1	1.1
122-132	0.7	0.7	3.5	0.6	0.5	1.1	0.4	0	2.1	0	0.6	2.3	0.6
152-163	0.4	1.0	3.7	1.3	0	0.6	1.1	0	2.6	1.6	0.5	1.8	1.6
183-193	0.4	1.4	3.3	1.5	0.3	1.2		1.1	3.7		0.4	3.8	2.2
213-224	3.4	1.9	2.8	1.8									
244-254	2.7	1.2	3.1	1.3									
274-284	1.9	1.0		1.1									
305-315	2.0	1.0		0.6									
335-345	1.1	0.6		0.7									
366-376	1.4	0.4		0.4									
395-406	1.4	0.7		0.3									
427-437	1.2	0.3											

untreated soil exhibit the greatest seasonal variation, a range from 1.2 to 11 ppm. No marked accumulation of NO_3-N greater than 4 ppm was observed in the control soil below 30 cm in the soil profile.

The NO_3-N content in the surface of the sludge-treated soil from the Milwaukie disposal area during the summer, 1974, reflected an increase level of 80 ppm in one soil core, while the remaining cores compared closely to the control (Table 19). The NO_3-N content of the sludge-treated soil compared closely to the control soil below 30 cm. The different NO_3-N levels measured in the soil cores sampled from the disposal area probably reflects the wide variability in sludge application.

During the winter and spring, the NO_3-N content in the surface of the sludge-treated soil remained at increased levels compared to the control, a range from 30 to 62 ppm (Table 19). The NO_3-N content below 30 cm in the sludge-treated soil compared closely with the control soil.

During the summer, 1975, the NO_3-N content in the surface of the sludge-treated soil from the Milwaukie disposal area decreased when compared to the winter and spring samples (Table 19). This decreased NO_3-N content in the upper portion of the soil may be due to (1) plant utilization of excess NO_3-N as the growth-rate increases in the spring, (2) increased rainfall in the spring leaching some NO_3-N to lower soil horizons, or (3) variability in sludge application. The

NO_3-N content of the entire soil profile compared closely to the control soil.

The NO_3-N of the untreated soil from the Hillsboro disposal area did not accumulate at any depth during the summer, 1974 and 1975, a range from 0 to 4 ppm (Table 20). In contrast, the NO_3-N content of the sludge-treated soil during the summer, 1974, ranged from 9.2 to 330 ppm in the upper 50 cm of the soil profile (Table 20). Below 50 cm in the soil profile, the NO_3-N content in the upper portion of the sludge-treated soil reflected increased levels, a range from 4 to 320 ppm, compared to the control, generally below 4 ppm (Table 20). One soil core consistantly had a higher NO_3-N level below 50 cm in the soil profile during the summer, 1974 and 1975, due to larger amounts of sludge applied from a nearby sludge drying lagoon. In addition, the heavy clay layer in site 2 limited water precolation rate through the soil profile, promoting reduced conditions and probably resulting in considerable denitrification.

The NO_3-N content of the untreated soil from the Forest Grove disposal area generally ranged from 0.3 to 4 ppm during the summer, 1974, winter, spring, and summer, 1975, with no marked accumulation at any depth (Table 21). The increase in NO_3-N content in the soil surface of the control soil during the spring could have resulted from dairy cow activity.

Table 20. Nitrate-nitrogen concentration in soils on the Hillsboro disposal area treated with sewage sludge.

	July, 1974 Site					June, 1975 Site		
Depth	Control	1	2	3	4	Control	1	2
cm	NO_3-N, ppm							
0-10	0.7	330	37	79	46	1.6	320	5.8
20-30	0	77	45	10	5.2	1.4	47	5.4
41-51	0	33	9.2	17	17	2.4	46	4.5
61-71	1.0	19	3.8	15	16	3.7	45	4.3
81-91	0.2	7.1	5.3	17	4.2	0.7	13	2.6
122-132	0	2.2	0.8	16	0	0.2	3.2	0
152-163	0	1.5	0.4	18	0	0.1	11	0
183-193	0	6.2	2.1	20	0	0.1	11	0
213-224	0	2.3	0.4	15	0	0.5	5.5	0.1
244-254	0	0.5	0	12	0.1	0.2	9.5	0.2
274-284	0	15	0	5.5	0	0.2	4.6	0.7
305-315	0	4.6	0	3.0	0.5	0.2		0.9
335-345	0	2.7	0	4.3				
366-376	0	0.3	0					

During the summer, 1974, the soil treated with sludge exhibited a marked accumulation of NO_3-N in the upper 30 cm of the soil profile, a range from 4.6 to 38 ppm, compared to the control, below 4 ppm (Table 21). Deeper in the soil profile, the NO_3-N content compared closely to the control soil.

During the winter, 1975, the sludge-treated soil from the Forest Grove disposal area exhibited a slightly deeper penetration of NO_3-N accompanied by a decrease in NO_3-N content at the soil surface. Evidently, increased NO_3-N in the surface soil has moved with infiltrating rainwater to lower soil depths.

Table 21. Nitrate-nitrogen concentration in a Woodburn silt loam soil treated with sewage sludge from the Forest Grove disposal area.

	July, 1974 Site				December, 1975 Site			March, 1975 Site			June, 1975 Site		
Depth	Control	1	2	3	Control	1	2	Control	1	2	Control	1	2
cm	NO_3-N, ppm												
0-10	4	38	20	14	1.0	21	10	26	18	47	1.5	1.1	7.0
20-30	0.8	8.0	4.6	9.7	2.2	7.1	4.8	7.2	3.1	4.3	0.8	1.9	3.5
41-51	1.1	3.3	0.5	1.3	0.8	4.6	1.2	2.1	0.8	2.1	0.3	2.3	2.4
61-71	1.2	1.1	0.5	1.0	0.2	4.3	1.2	1.6	0	1.0	0.7	1.3	2.6
81-91	0.6	1.4	0.5	0.5	0.3	3.3	0.4	0.9	0	0.3	1.1	1.3	4.5
122-132	0.3	1.0			0.1	1.8		1.2	0		1.1	1.9	0
152-163	0.7	0.8			0.4	1.9		1.1	0		0.8	3.1	

During the spring, the upper 30 cm of the sludge-treated soil compared closely to NO_3-N levels observed in the sludge-treated soil sampled during the summer, 1974 and winter, a range from 18 to 48 ppm (Table 21). Below 30 cm in the sludge-treated soil profile, the NO_3-N content compared closely to the control.

During the summer, 1975, the NO_3-N content of the upper 30 cm of the sludge-treated soil from the Forest Grove disposal area decreased, ranging from 1.1 to 7 ppm, compared to the control soil sampled during the spring (Table 21). Only one soil core displayed an increased NO_3-N content in the soil surface compared to the control, from 3.5 to 7 ppm, while below 30 cm in the soil profile the same soil core also exceeded the control by 3 ppm. Below 30 cm in soil profile the NO_3-N level compared closely to the control soil.

The untreated soil sampled during the summer, 1974, from the Woodburn disposal area had no marked NO_3-N accumulation at any depth and ranged from 0 to 0.7 ppm throughout the entire soil profile (Table 22). The untreated soil during the winter, spring, and summer, 1975, did not exceed 1.5 ppm NO_3-N and compared to values from the summer, 1974, samples.

During the summer, 1974, the sludge-treated soil reflected increased NO_3-N content in the surface 30 cm of soil, a range from 2.6 to 100 ppm, compared to below 1 ppm in the control (Table 22). Below 30 cm in the soil profile, the NO_3-N content of the

Table 22. Nitrate-nitrogen concentration in a Woodburn silt loam soil treated with sewage sludge from the Woodburn disposal area.

Depth	July, 1974 Site				December, 1975 Site			March, 1975 Site			June, 1975 Site		
	Control	1	2	3	Control	1	2	Control	1	2	Control	1	2
cm	NO_3-N, ppm												
0-10	0.7	7.8	100	11	1.5	24	27	1.5	18	25	1.0	3.3	4.6
20-30	0.5	3.3	3.2	2.6	1.2	2.3	2.8	0.2	2.3	1.6	0.5	0.6	1.0
41-51	0.5	1.1	2.7	0.7	1.2	0.9	0.6	0.4	0.9	0.8	0.6	0.4	1.2
61-71	0.2	1.5	1.2	0.8	0	0.6	0	0.1	0.3	1.0	0.7	0.2	0.2
81-91	0	3.3	0.9	0.6	0	2.3	0.7	0	0.6	1.0	0.5	0.2	0.3
122-132	0	2.0	1.6	0.7	0	1.6	0	0	1.7	1.3	0.4	2.7	0.5
152-163	0.2	3.0	1.4	0.3	0	1.4	0	0	1.3	1.6	0.3	2.4	1.0
183-193	0	2.2	1.3	0.7	0	1.9	0.1	0	1.2	1.8	0.5	2.1	1.1
213-224	0.1	2.0	1.0	0.7	0	1.6	0	0	1.2	1.5	0.9	2.4	1.3
244-254	0.1	2.4	1.4	1.2	0	1.8	0.6	0	0.3	1.7	0.6	2.3	1.0
274-284	0.1	1.9	1.2	2.1	0	2.0	0.6	0	1.0	1.2	0.5	2.2	1.0
305-315	0.5	2.9	0.9	1.7	0	1.8	0.8	0	0.8	1.4	0.3	1.7	1.6
335-345	0	3.1	2.5	1.3	0.2	1.9	1.5	0	0.7	1.4	0.3	1.9	1.3
366-376	0.3	3.3	2.4	1.4	0	1.9	0.9	0.3	1.0	1.3	0.3	2.1	1.2
395-406	0.4	2.6	0.8	1.4	0	1.9	0.6		1.3	0.8	0.3	2.6	1.9
427-437	0.5	3.9	3.0	1.3	0	1.8	0.5		0.7	1.2	0.3	2.3	2.2
457-467	0.1	4.7	4.2	1.5	0	2.1	0.7		0.3	1.8	0.3	1.4	2.1
488-498	0.3	6.1	3.6	2.4		2.2	1.1						

sludge-treated soil ranged from 0.3 to 6.1 ppm. Small amounts of NO_3-N appear to be moving with the soil solution deep into the soil profile, although the NO_3-N was not high enough to rule out sampling error.

During the winter, the NO_3-N content of the surface 30 cm of the sludge treated soil ranged from 2.3 to 27 ppm compared to the NO_3-N level observed in the control soil (Table 22). Below 30 cm in the soil profile, the NO_3-N content decreased slightly in the sludge-treated soil compared to the summer, 1974, but remained at increased levels compared to the control. Evidently, water movement through the soil profile during the winter has carried some NO_3-N down the soil profile.

During the spring, the NO_3-N content of the sludge-treated soil from the Woodburn disposal area compared closely with the winter samples. The sludge-treated soil during the spring reflected increased NO_3-N concentration compared to the control, generally exceeding the control samples by more than 1 ppm (Table 22).

During the summer, 1975, the NO_3-N content of the surface 30 cm of the sludge-treated soil decreased compared to the winter and spring, but still exhibited an increased NO_3-N content compared to the control (Table 22). Below 30 cm in the soil profile, the NO_3-N content of the sludge-treated soil compared closely to the winter and spring samples, with an increased NO_3-N level compared to the control.

Summary: The NO_3-N content in the soil surface of the sludge disposal areas increased compared to the control after large amounts of sludge had been applied. Generally, the more sludge applied, the greater the NO_3-N content in the soil surface. The Eugene and Hillsboro disposal sites that had large amounts of sewage sludge applied, rates greater than 250 m tons/ha, had NO_3-N levels in the surface soil as high as 240 and 330 ppm, respectively. The Forest Grove, Milwaukie, and Woodburn disposal areas which received less than 100 m tons/ha contained NO_3-N levels generally below 80 ppm.

The NO_3-N content below 1 meter in the soil profile also increased with sludge application rate. With the highest sludge application rate, a NO_3-N level of 120 ppm, deep in the soil profile, was observed. One site at the Hillsboro disposal area where large amounts of sludge were added from a sludge drying lagoon reflected NO_3-N levels as high as 20 ppm. Soils sampled from the Milwaukie, Forest Grove, and Woodburn disposal areas where less sludge was applied compared closely to the control soil below 50 cm in the profile.

During the winter and spring, 1975, increased rainfall percolating through the soil profile and cooler temperatures, slowing the microbial production of NO_3-N, combined to decrease the NO_3-N content of the soil profiles. The NO_3-N content in the surface 50 cm of soil during the summer, 1975, increased, a reflection of warmer temperatures, decreased rainfall, and increased nitrification.

Ammonium-Nitrogen. The NH_4-N content of the untreated soil sampled from the Eugene disposal area during the summer, 1974, winter, spring, and summer, 1975, was generally less than 4 ppm throughout the entire soil profile, with the highest level in the soil surface (Table 23). No marked accumulation of NH_4-N was observed at any soil depth in the control samples.

During the summer, 1974, the NH_4-N content of the sludge-treated soil from the Eugene disposal area increased in the upper 50 cm compared to the control (Table 23). The NH_4-N content of the sludge-treated soil below 50 cm compared closely to the control soil.

The NH_4-N content in the surface 50 cm of the sludge-treated soil from the Eugene disposal area progressively decreased from levels measured during the summer, 1974, over the winter, spring, and summer, 1975 (Table 23). This progressive decrease through the season is probably due to decreasing temperatures during the winter and spring months resulting in decreased microbial activity and N mineralization. During the winter, spring, and summer, 1975, the NH_4-N content ranged from 0 to 15 ppm in the upper 50 cm of the sludge-treated soil, generally at increased levels compared to the control. The NH_4-N content of the sludge-treated soil below 50 cm compared closely to levels observed in the untreated soil.

Table 23. Ammonium-nitrogen concentration in a Newberg fine sandy loam soil treated with sewage sludge from the Eugene disposal area.

Depth	July, 1974 Site			December, 1975 Site			March, 1975 Site			June, 1975 Site		
	Control	1	2	Control	1	2	Control	1	2	Control	1	2
cm	NH_4-N, ppm											
0-10	2.2	29	11	1.3	10	12	4.0	15	7.0	0.2	8.3	8.1
20-30	0.9	6.7	3.8	0.7	5.1	4.3	0.7	2.1	0.6	0.6	1.5	3.5
41-51	0.6	7.4	0.3	3.4	2.6	1.5	0	0.5	0.2	0.2	1.1	0
61-71	0.9	3.4	0.2	1.4	0.7	0.9	0	0.4	1.3	0.5	0.8	0
81-91	12	0	0.3	0.7	0.5	1.6	0	1.8	0.6	0.6	0.5	0
122-132	0.2	0.1	0.6	0.8	0.6	0.6	0.3	0.1	0.8	0.3	0.7	0
152-163	0.3	0	0.9	0.6	1.0	1.1	0.9	0.3	0.7	0.2	1.1	0
183-193	0.1	0	0.2	2.3	0.7	1.5	0	0.7	0.3	0.2	0.7	0.2
213-224	1.0	0.2	0.2	1.1	1.2	1.3	0	1.4	0	0.2	0.6	0.4
244-254	0.8	1.2	0.2	0.9	1.5		0.7	2.5		0.4	1.0	0.4
274-284	1.2	0.4	0.4	0.8	0.5		0.1	2.8		0.2	0.7	
305-315	3.1	0.3	0.7	0.7	1.6		0	1.0		0.3	1.0	
335-345	1.0	36	1.4	0.9	0.7		0	0.2		0.5	0.3	
366-376	1.0	42		0.5	0.6			0.5			0.5	
395-406		71		0.7	0.7			0.2			0.9	
427-437		53			1.4						1.7	

The NH_4-N content of the untreated soil from the Milwaukie disposal area sampled during the summer, 1974, winter, spring, and summer, 1975, was generally less than 1 ppm with only two samples in the surface 30 cm exceeding that level (Table 24). No marked accumulation of NH_4-N was observed in the control soil at any depth.

During the summer, 1974, the NH_4-N content of the upper portion of the sludge-treated soil from the Milwaukie disposal area increased, a range of 5.3 to 53 ppm, compared to the control (Table 24). Below 10 cm in the soil profile the sludge-treated soil generally compared closely to the control soil.

During the winter, spring, and summer, 1975, the NH_4-N in the sludge-treated soil from the Milwaukie disposal area remained primarily in the surface 10 cm, a range of 0.4 to 32 ppm (Table 24). Below 10 cm in the sludge-treated soil profile, the NH_4-N content compared closely with the control soil.

The sludge-treated soil from the Hillsboro disposal area sampled during the summer, 1974, reflected increased NH_4-N levels in the surface 10 cm of soil, a range from 7.4 to 100 ppm, compared to the control, ranging from 0.6 to 3.4 ppm (Table 25). During the summer, 1975, the NH_4-N content in the upper 10 cm of the sludge-treated soil increased to 30 ppm in only one soil core while the second core compared closely to the control, 2.6 ppm. Below 10 cm in the sludge-treated soil during the summer, 1974 and 1975, the NH_4-N

Table 24. Ammonium-nitrogen concentration in a Bornstedt silt loam soil treated with sewage sludge from the Milwaukie disposal area.

	July, 1974 Site				December, 1975 Site			March, 1975 Site			June, 1975 Site		
Depth	Control	1	2	3	Control	1	2	Control	1	2	Control	1	2
cm	NH_4-N, ppm												
0-10	0.9	13	53	5.3	0.8	3.4	12	6.4	3.6	32	1.1	0.4	5.5
20-30	0.3	1.0	7.4	1.7	0.4	1.7	3.2	0.1	0.8	4.0	1.6	0.7	1.5
41-51	0.5	1.3	3.8	0.6	0	0.8	0.4	0	0.7	2.9	0.1	0.2	1.4
61-71	0.4	1.0	12	1.6	0.2	0.4	1.1	0	0.7	1.3	0.5	0	0.5
81-91	0.3	0.7	1.7	0.7	0.4	0.3	0.6	0.5	0.7	1.2	0.5	0.3	0
122-132	0.2	0.3	0.8	0.4	0.3	0.4	0.3	0	0.1	0	0.4	0	0
152-163	0.6	0.2	1.8	0.3	0.1	0.3	0.3	0	0	0.5	0.4	0	0
183-193	0.3	0	0.7	0.5	0.3	0.1		0	0.6		0.2	0.3	0.1
213-224	0.7	0.6	0.5	0.2									
244-254	0.4	0.1	1.7	0.4									
274-284	0.4	0.3		0.3									
305-315	0.3	0.1		0.8									
335-345	0.1	0.3		0.3									
366-376	0.1	0.2		0.7									
395-406	0.1	0.2		0.4									
427-437	0.3	0.4											

Table 25. Ammonium-nitrogen concentration in soils from the Hillsboro disposal area treated with sewage sludge.

Depth	July, 1974 Site					June, 1975 Site		
	Control	1	2	3	4	Control	1	2
cm	NH_4-N, ppm							
0-10	3.4	100	7.4	21	25	2.6	30	1.9
20-30	0.6	0.6	35	1.2	1.9	0.9	0.1	1.1
41-51	0.5	0.7	1.8	1.3	1.3	0.9	0.5	0.9
61-71	0.6	0.7	1.2	1.3	0.4	1.0	0.8	0.1
81-91	0.3	0.7	0	0	1.3	0.2	1.0	0
122-132	0	0.8	1.0	0	1.3	0.2	0.8	0
152-163	0.2	0.1	1.3	1.6	0.2	0.1	0.6	0
183-193	0.2	1.1	3.6	3.0	0.6	0.1	0.2	0
213-224	0.7	1.6	1.2	1.2	0.3	8.0	0.8	0.4
244-254	2.3	2.2	0.2	0.6	0.5	9.3	0	0.6
274-284	1.6	3.9	0.9	0	0.8	12	0	0.8
305-315	1.7	2.1	3.2	0.2	1.3	8.1		
335-345	2.4	2.9	3.9	0.5				
366-376	3.0	2.3	3.9					

content of the sludge treated soil compared closely to the control soil.

The NH_4-N content of the sludge-treated soil from the Forest Grove disposal area generally increased in the soil surface, a range from 2.2 to 21 ppm, when compared to the control, a range from 1.2 to 1.7 ppm (Table 26). Below 10 cm in the soil profile, the NH_4-N content of the sludge treated soil compared closely to the control soil.

The NH_4-N content in the sludge-treated soil from the Woodburn disposal area generally compared closely to the control soil throughout the entire soil profile (Table 27). The discontinuation of the sludge applications in 1973, may have contributed to the low NH_4-N content of the soil surface because the most easily decomposeable organic N compounds had already disappeared.

Summary: The NH_4-N mineralized from the organic N compounds in the sludge added to the soil surface appears to remain in the upper portion of the soil profile. The NH_4-N content of the soil surface generally increased during the summer months, due to increased microbial activity reflecting warmer temperatures, then decreased during the cooler winter and spring months. Below 10 cm in the soil profile, the NH_4-N content remained relatively constant indicating that NH_4-N remained in the surface soil.

Total Nitrogen. The total N content of the untreated soil from the Eugene disposal area ranged from 0.03 to 0.11% with the highest N content in the surface 10 cm and decreasing with soil depth (Table

Table 26. Ammonium-nitrogen concentration in a Woodburn silt loam soil treated with sewage sludge from the Forest Grove disposal area.

	July, 1974 Site				December, 1975 Site			March, 1975 Site			June, 1975 Site		
Depth	Control	1	2	3	Control	1	2	Control	1	2	Control	1	2
<u>cm</u>	NH_4-N, ppm												
0-10	1.7	21	2.2	1.4	6.4	1.3	0.9	6.2	22	4.3	1.2	9.3	2.0
20-30	0.7	1.6	0.5	0.4	1.3	0.4	0.3	0.7	0.5	0	0.8	1.0	1.9
41-51	0.9	0.2	0.4	0.7	0.8	0.1	0.3	0	0.9	0	1.0	1.2	2.1
61-71	0.8	0.1	1.1	0.5	0.1	0.2	0.4	0.2	0.6	0	0.7	1.0	1.5
81-91	0.4	0.6	0	0.1	0.4	0.1	0.3	0.5	0	0.3	1.1	1.2	0.7
122-132	0.4	0.8			0.4	0.2		0.3	0		0.9	0.5	0.2
152-163	0.8	0.8			0.3	0.5		0	0		0.7	1.1	

Table 27. Ammonium-nitrogen concentration in a Woodburn silt loam soil treated with sewage sludge from the Woodburn disposal area.

	July, 1974 Site				December, 1975 Site			March, 1975 Site			June, 1975 Site		
Depth	Control	1	2	3	Control	1	2	Control	1	2	Control	1	2
cm	NH_4-N, ppm												
0-10	8.8	8.0	50	7.9	1.9	1.3	0.3	3.2	1.4	3.1	0.6	2.5	1.4
20-30	1.2	15	1.2	0.9	0.5	0	0.1	0	0.5	0.2	0.7	10	0.5
41-51	0.9	0	1.1	0	3.8	0.6	0.4	0	0.9	0.1	0.6	0.5	0.7
61-71	1.8	0	0.9	1.0	3.0	0.3	0	0.3	0.3	0.1	0.7	0.2	0.2
81-91	0.2	0.9	0.3	0.5	0	0.3	0	0.3	0	0.5	0.7	0.8	0.1
122-132	0	1.1	0.5	0.9	0	0.7	0	0	0.4	0.4	0.5	0.1	0.7
152-163	0.2	0.2	0.2	0.1	0	0.3	0	0	0.6	0.7	0.2	0.2	0
183-193	0	0	1.1	0.1	0	0.7	0	0	0.5	0	0.1	0.2	0
213-224	0.3	0	0.2	0.1	0	0.4	0	0	0.4	0.1	0.1	0.1	0
244-254	0.2	0	0.2	0.5	0	0.7	0.4	0	0.3	0.6	0.1	0.8	0
274-284	0.7	0	0.6	0.7	0	0.3	3.1	0	0.8	0.1	0.4	0.2	0.8
305-315	0.1	0.2	0.1	0.8	0	0.2	0	0	0.6	0	0.3	0.4	0.7
335-345	0.1	0	0.2	0.7	0	0.1	0	0	0.2	0.1	0.3	0.4	0.2
366-376	0.7	0	0.2	0.5	0	0	0	0.6	0	0.1	0.3	0.1	0.3
395-406	0.4	0.2	0.8	0.6	0	0.1	0		0.3	0.1	0.3	0.1	0.4
427-437	0.7	0	0.2	0.8	0	0.1	0		0.5	0.1	0.3	0.2	0.4
457-467	0.8	0	0.4	0.2	0	0.1	0		0.5	0.1	0.2	0	0
488-498	0.2	0	0.9	0.5		0.1	0						

28). The total N content of the total soil profile which received the sewage sludge ranged from 0.04 to 0.74%, with the highest N level in the upper 50 cm, a range from 0.23 to 0.74% (Table 28). The total N level in the sludge-treated soil below 50 cm exceeded the N content of the control soil slightly. The increased total N content below 50 cm in the soil profile corresponds to a NO_3-N accumulation in the same soil sample, indicating that the N accumulation is probably related to NO_3-N movement.

Table 28. Total N and pH in a Newberg fine sandy loam soil treated with sewage sludge from the Eugene disposal area.

Depth	Site, Control		Site 1		Site 2	
	Total N	pH	Total N	pH	Total N	pH
cm	%	2:1	%	2:1	%	2:1
0-10	0.11	6.4	0.60	4.6	0.52	4.9
20-30	0.08	5.9	0.23	5.5	0.42	5.7
41-51	0.07	6.1	0.74	5.4	0.09	5.9
61-71	0.07	6.2	0.10	5.3	0.07	5.8
81-91	0.08	6.4	0.07	5.5	0.05	6.0
122-132	0.06	6.3	0.05	5.9	0.10	6.1
152-163	0.05	6.4	0.05	6.0	0.08	6.0
183-193	0.04	6.4	0.06	6.0	0.05	6.2
213-224	0.06	6.2	0.06	6.0	0.04	6.1
244-254	0.04	6.3	0.11	5.9	0.06	6.1
274-284	0.03	6.4	0.12	5.8	0.07	6.0
305-315	0.04	6.2	0.09	5.9	0.08	6.1
335-345	0.04	6.3	0.07	4.6	0.07	6.4
366-376	0.04	6.4	0.09	4.6		
396-406			0.10	4.7		
427-437			0.08	5.1		

The total N content of the untreated soil sampled from the Milwaukie disposal area during the summer, 1974, ranged from 0.03 to 0.19% with the highest N content in the surface 10 cm and decreasing with soil depth (Table 29). The total N content of the total soil profile which received the sewage sludge ranged from 0.04 to 0.29% with the highest N level in the upper 30 cm, a range from 0.08 to 0.29%. The total N level in the sludge-treated soil below 50 cm compared closely to the control soil.

Table 29. Total N and pH in a Bornstedt silt loam soil treated with sewage sludge from the Milwaukie disposal area.

	Site, Control		Site 1		Site 2		Site 3	
Depth	Total N	pH	Total N	pH	Total N	pH	Total N	pH
cm	%	2:1	%	2:1	%	2:1	%	2:1
0-10	0.19	5.1	0.23	5.1	0.29	5.2	0.22	5.0
20-30	0.09	5.3	0.08	5.3	0.08	5.3	0.09	5.0
41-51	0.06	5.2	0.06	5.2	0.04	5.3	0.06	4.95
61-71	0.05	5.51	0.05	5.0	0.04	5.1	0.05	5.0
81-91	0.05	5.0	0.05	4.95	0.04	4.9	0.05	4.85
122-132	0.05	4.95	0.04	5.0	0.03	5.2	0.05	4.85
152-163	0.05	4.95	0.04	5.2	0.03	5.05	0.05	5.15
183-193	0.04	5.0	0.04	5.2	0.03	5.05	0.04	5.25
213-224	0.04	5.0	0.04	5.2	0.03	5.1	0.05	5.2
244-254	0.05	5.05	0.04	5.3	0.02	5.3	0.05	5.4
274-284	0.05	5.1	0.04	5.3			0.04	5.2
305-315	0.04	5.2	0.04	5.45			0.04	5.2
335-345	0.04	5.1	0.04	5.25			0.04	5.3
366-376	0.03	5.2	0.04	5.2			0.04	5.4
396-406	0.05	5.15	0.05	5.2			0.05	5.3
427-437	0.04	5.1	0.04	5.2				

The total N content of the untreated soil sampled from the Hillsboro disposal area ranged from 0.01 to 0.41% with the highest concentration at 61 cm in the soil profile (Table 30). The increased N content at 61 cm in the soil profile to 0.41% corresponds with increased NH_4-N and NO_3-N levels and probably is an extraneous effect caused by a decomposing piece of wood, although nothing was observed at that depth. Below 61 cm in the soil profile, the total N content decreased steadily to a low level of 0.01%.

Table 30. Total N and pH in the soils from the Hillsboro disposal area treated with sewage sludge.

	Site, Control		Site 1		Site 2		Site 3	
Depth	Total N	pH	Total N	pH	Total N	pH	Total N	pH
cm	%	2:1	%	2:1	%	2:1	%	2:1
0-10	0.20	4.8	0.72	4.7	0.19	4.4	0.31	4.7
20-30	0.05	5.1	0.13	5.1	0.34	4.2	0.09	5.0
41-51	0.10	5.1	0.12	5.2	0.23	4.2	0.10	4.5
61-71	0.41	5.1	0.06	5.7	0.15	4.4	0.10	4.5
81-91	0.27	5.0	0.05	5.8	0.11	4.7	0.08	4.4
122-132	0.04	5.0	0.04	6.0	0.09	4.9	0.07	4.7
152-163	0.03	5.3	0.04	6.1	0.06	5.0	0.07	5.0
183-193	0.05	5.4	0.04	6.1	0.06	5.1	0.05	5.3
213-224	0.02	6.0	0.04	6.3	0.06	5.1	0.06	5.3
244-254	0.02	6.1	0.07	6.3	0.07	5.1	0.04	5.6
274-284	0.02	6.5	0.06	6.4	0.07	5.4	0.04	5.6
305-315	0.01	6.6	0.04	6.3	0.04	5.6	0.05	5.8
335-345	0.01	6.7	0.02	6.5	0.03	5.4	0.04	5.9
366-376	0.01	6.7	0.02	6.5	0.02	5.4		

The total N content of the sludge-treated soil from the Hillsboro disposal area ranged from 0.02 to 0.72% with the greatest accumulation in the surface 50 cm (Table 30). The sludge-treated soil below 50 cm reflected a slightly increased N level compared to the control soil, although not exceeding the control by more than 0.05%.

The total N content of the untreated soil profile sampled from the Forest Grove disposal area ranged from 0.02 to 0.22% with the greatest accumulation in the soil surface (Table 31). The sludge-treated soil ranged from 0.02 to 0.30% throughout the entire soil profile and reflected a moderate N increase compared to the control in the surface 30 cm, a range from 0.15 to 0.30%. The N content of the sludge-treated soil below 30 cm compared closely to the untreated soil.

Table 31. Total N and pH in a Woodburn silt loam soil treated with sewage from the Forest Grove disposal area.

	Site, Control		Site 1		Site 2		Site 3	
Depth	Total N	pH	Total N	pH	Total N	pH	Total N	pH
cm	%	2:1	%	2:1	%	2:1	%	2:1
0-10	0.22	5.5	0.25	5.5	0.30	5.5	0.26	5.5
20-30	0.12	5.6	0.19	5.7	0.15	5.7	0.15	5.7
41-51	0.09	5.6	0.07	5.85	0.07	5.8	0.08	5.7
61-71	0.07	5.7	0.05	6.05	0.04	6.05	0.04	5.85
81-91	0.05	5.8	0.04	6.0	0.03	6.0	0.03	5.85
122-132	0.02	5.95	0.03	6.1				
152-163	0.02	6.05	0.02	6.15				

The total N content of the untreated soil from the Woodburn disposal area ranged from 0.01 to 0.35% with the highest N content at the soil surface (Table 32). The soil treated with sewage sludge compared closely with the control, a range from 0.01 to 0.30%, with the greatest N accumulation in the soil surface and decreasing with soil depth. The comparable N levels of the sludge-treated and untreated soil would suggest that most of the organic N compounds that were applied in the sewage sludge through 1973 have already mineralized to NH_4-N and NO_3-N.

Table 32. Total N and pH in a Woodburn silt loam soil treated with sewage sludge from the Woodburn disposal area.

	Site, Control		Site 1		Site 2	
Depth	Total N	pH	Total N	pH	Total N	pH
cm	%	2:1	%	2:1	%	2:1
0-10	0.35	5.0	0.25	5.9	0.30	5.05
20-30	0.08	4.8	0.08	5.95	0.07	4.35
41-51	0.06	4.95	0.06	5.8	0.05	5.0
61-71	0.05	5.25	0.04	5.85	0.03	5.5
81-91	0.04	5.4	0.01	5.8	0.03	5.75
122-132	0.02	6.45	0.02	5.95	0.02	5.95
152-163	0.01	6.8	0.01	5.9	0.01	6.0
183-193	0.02	6.9	0.02	5.9	0.02	5.95
213-224	0.01	6.9	0.01	5.8	0.02	5.95
244-254	0.01	6.8	0.01	5.95	0.02	6.0
274-284	0.01	6.8	0.01	5.95	0.01	6.0
305-315	0.0	6.6	0.02	5.9	0.02	6.0
335-345	0.01	6.7	0.01	5.95	0.02	6.0
366-376	0.02	6.4	0.01	6.05	0.02	6.0
396-406	0.01	6.55	0.01	6.0	0.01	6.1
427-437	0.01	6.5	0.01	6.1	0.01	6.25
457-467	0.01	6.6	0.02	6.15	0.02	6.3
488-498	0.01	6.85	0.01	6.2	0.02	6.3

Summary of Total N Distribution. When the Eugene sewage sludge was applied, approximately 500 m tons/ha, to the Newberg fine sandy loam soil, the total N, NH_4-N, and NO_3-N increased in the surface 50 cm to levels of 0.6%, 29 ppm, and 240 ppm, respectively. Below 50 cm in the soil profile, the NO_3-N levels increased as high as 120 ppm, while the other forms of N remained primarily in the soil surface. During the winter and spring, the decreased temperature restricted microbial activity and thus decreased the rate of N mineralization from organic N compounds in the sewage sludge. The NO_3-N mineralized during the warmer summer months moved to lower soil horizons with the increased leaching due to winter rainfall. Thus, NO_3-N levels in the soil surface generally decreased and NO_3-N levels in the lower soil horizons increased during December and March, 1975. As the warmer seasons approached, increased mineralization of organic N compounds increased the NO_3-N level in the soil surface. In conclusion, it appeared that NO_3-N was being mineralized in the soil surface and carried with the soil solution, supplied by rainfall, while NH_4-N and organic N compounds generally remained in the soil surface.

When the Hillsboro sludge was applied, 290 m tons/ha, to the bare soil surface of the disposal area, the total N, NH_4-N, and NO_3-N content increased in the surface 50 cm of the soil profile to levels of 0.72%, 330 ppm, and 100 ppm, respectively. Below 50 cm in the soil profile, the NO_3-N content exceeded the control by as much as 15 ppm in those soils which had large amounts of sludge added from the sludge drying lagoon indicating some NO_3-N had moved into the soil profile. The NH_4-N content in the soil profile below 50 cm did not increase above the levels measured in the control during either sampling period.

When the Milwaukie sewage sludge was applied to the Bornstedt silt loam soil at a rate of approximately 20 m tons/ha since 1964, the total N, NH_4-N, and NO_3-N content increased in the surface 30 cm of soil to levels of 0.29%, 53 ppm, and 79 ppm, respectively. Below 30 cm in the soil profile, the total N, NH_4-N, and NO_3-N content generally compared closely to the control soil indicating that the N applied in the sludge remained primarily in the surface 30 cm of soil.

The Forest Grove sludge was applied to a Woodburn silt loam soil at a rate of approximately 96 m tons/ha since 1969 along with large amounts of effluent water applied by sprinkler irrigation. The total N content in the upper 30 cm of the sludge-treated soil profile increased as compared to the control soil. Below 30 cm in the soil profile, the total N content of the sludge-treated soil compared closely to the control soil. The NH_4-N and NO_3-N content increased in the surface 30 cm of the sludge-treated soil profile compared to the control, from 1.7 to 21 ppm and 4 to 38 ppm, respectively. The NO_3-N and NH_4-N level in the sludge-treated soil below 1 meter and

30 cm, respectively, compared closely to the control soil. The total N and NH_4-N forms of nitrogen remain primarily in the soil surface while NO_3-N moved with the percolating water to much greater depths in the soil profile.

The Woodburn sludge was applied to a Woodburn silt loam soil at application rates of approximately 72 m tons/ha with the largest amounts applied during 1969 and 1970. The total N content of the sludge-treated soil compared closely to the control throughout the entire soil profile indicating that much of the organic N compounds added in the sludge had already mineralized and was either leached away or utilized by growing plants since the final sludge application in 1973. The NH_4-N and NO_3-N content of the sludge-treated soil increased in the surface 30 cm of the soil profile compared to the control from 9 to 50 ppm and 0.7 to 100 ppm, respectively. Small amounts of NO_3-N had moved with percolating water deeper into the soil profile, while the NH_4-N content of the sludge-treated soil compared closely with the control below 30 cm in the soil profile. The NO_3-N content of the sludge-treated soil did not exceed the control by more than 6 ppm throughout the soil profile.

pH. The pH of the untreated soil sampled from the Eugene and Hillsboro disposal areas ranged from 5.9 to 6.4 and 4.8 to 6.7, respectively, with the lowest pH values in the soil surface and increasing with soil depth (Tables 28 and 30). The sludge-treated soil was much more acid in the upper portions of both the Eugene and Hillsboro disposal sites, ranging from 4.6 to 4.9 and 4.4 to 4.7, respectively, when compared to the control. The large pH decrease in the surface of the sludge-treated soil from Eugene and Hillsboro disposal areas was the result of the ammonification and oxidation of organic N compounds. The nitrification reaction produced H ions resulting in a large pH decrease. The remaining portion of the soil profile from the Eugene and Hillsboro disposal areas was slightly more acid than the control due to nitrification as well as movement of organic acids through the soil profile.

The pH of the untreated soil from the Milwaukie and Forest Grove disposal areas ranged from 4.9 to 5.3 and 5.5 to 6.05, respectively, throughout the entire soil profile (Tables 29 and 31). The sludge-treated soils compared closely to the control soils from the Milwaukie and Forest Grove disposal sites. This would suggest little acidification of the soil surface.

The pH of the untreated soil from the Woodburn disposal area ranged from 4.8 to 6.8 (Table 32). The low pH value of the surface of the untreated soil was probably due to the decomposition of leaves falling from trees surrounding the control site.

The pH of the sludge-treated soil from the Woodburn disposal area varied considerably in the upper 70 cm of the two soil cores, such that valid comparisons to the control soil could not be made.

Below 70 cm in the sludge-treated soil profile, the two soil cores compared closely, but were slightly more acid than the control, a range from 5.9 to 6.3. The variability of the surface pH values of the two soil cores may be due to management practices, such as liming the soil, or to the wide variation in the amount of sludge applied.

Summary: The pH of the soil surface at the Eugene and Hillsboro disposal areas decreased from pH values of 6.4 to 4.6 and 4.8 to 4.4, respectively, as a result of sludge applications of more than 250 m tons/ha. The large pH decrease in the sludge-treated surface soil was the result of the ammonification and oxidation of organic N compounds added in the sludge. The pH values of the Milwaukie, Forest Grove, and Woodburn disposal areas compared more closely to the control soils.

Heavy Metals. The sludge-treated soil from the Eugene disposal area extracted with DTPA contained an increased Cu, Mn, Ni, and Zn content in the upper portion of the soil cores when compared to the control soil. The Cu, Mn, Ni, and Zn content in the upper 50 cm of the sludge-treated soil ranged from 3.3 to 33 ppm, 15 to 65 ppm, 2.6 to 10 ppm, and 51 to 220 ppm, respectively, and was considerably enhanced when compared to the Cu, Mn, Ni, and Zn content of the control soil, a range from 2.3 to 4.2 ppm, 10 to 40 ppm, 0.4 to 0.8 ppm, and 0.9 to 2.6 ppm, respectively (Tables 33 and 34).

Table 33. Cadmium, chromium, and nickel concentration in a Newberg fine sandy loam soil treated with sewage sludge from the Eugene disposal area.

	Site; July, 1974								
	Cd			Cr			Ni		
Depth	Control	1	2	Control	1	2	Control	1	2
cm	ppm, dry weight								
0-10	0.3	4.5	2.8	12	140	96	0.5	10	10
20-30	0.2	0.7	13	12	28	94	0.5	2.6	6.4
41-51	0.2	7.5	0.4	12	81	14	0.8	10	1.1
61-71	0.2	0.9	0.2	14	18	14	0.7	2.0	0.8
81-91	0.2	0.2	0.2	16	14	14	0.6	1.4	0.6
122-132	0.2	0.2	0.3	16	14	18	0.5	0.9	1.0
152-163	0.2	0.2	0.2	16	14	20	0.8	1.2	0.6
183-193	0.2	0.2	0.2	18	14	22	0.6	1.0	0.5
213-224	0.2	0.2	0.2	16	16	18	0.8	0.7	0.4
244-254	0.2	0.3	0.2	18	22	18	0.6	1.0	0.8
274-284	0.2	0.3	0.2	18	18	22	0.4	1.0	0.8
305-315	0.1	0.2	0.2	16	26	24	0.8	1.0	0.6
335-345	0.2	0.2	0.3	18	22	20	0.8	0.9	0.5
366-376	0.2	0.2		20	24		0.8	0.9	
395-406		0.2			28			1.1	
427-437		0.1			20			1.0	

Table 34. Copper, manganese, and zinc concentration in a Newberg fine sandy loam soil treated with sewage sludge from the Eugene disposal area.

	Site; July, 1974								
	Zn			Mn			Cu		
Depth	Control	1	2	Control	1	2	Control	1	2
cm	ppm, dry weight								
0-10	2.0	210	194	25	53	58	2.3	14.6	25.4
20-30	1.8	60	180	27	45	65	2.8	5.5	33.0
41-51	2.6	221	27.0	28	53	30	3.4	34.0	3.3
61-71	1.6	51	4.3	40	58	15	2.8	3.6	2.7
81-91	1.4	16	2.5	25	15	18	3.1	2.4	2.6
122-132	1.2	3.1	4.0	25	15	30	3.7	2.3	3.6
152-163	0.8	3.2	3.3	25	13	20	3.8	2.1	3.2
185-193	0.8	5.0	1.7	23	10	18	3.7	2.6	3.3
213-224	1.0	3.3	0.9	23	10	15	3.4	2.6	3.5
244-254	1.1	5.0	1.3	18	15	18	3.2	3.6	3.9
274-284	0.9	1.7	1.1	13	45	13	3.0	7.6	4.1
305-315	1.1	1.9	3.4	13	10	10	3.5	11	3.8
335-345	1.0	1.9	3.6	10	130	15	4.2	5.0	3.6
366-376	1.4	1.2		10	78		4.1	3.0	
395-406		1.6			30			4.0	
427-437		2.8			50			5.9	

The Cu, Mn, and Ni content of the sludge-treated soil below 50 cm compared closely to the control except for a slight increase in Cu and Mn levels in one soil core due to an abrupt pH decrease caused by the buried log. The Zn content below 90 cm soil depth reflected a slightly higher level, a range from 0.9 to 5.0 ppm, compared to the control ranging from 0.8 to 1.6 ppm (Table 34).

The Zn, Mn, Cu, and Ni content of the Eugene sludge was 4,400, 375, 215, and 235 ppm, respectively, suggesting that the soil should contain these elements at increased levels in an approximate ratio of 20:1.7:1:1. The average increase of the Zn, Mn, Cu, and Ni content in the surface meter of the sludge-treated soil when compared to the control was 95, 12, 9.6, and 4.0 ppm, respectively, or a ratio of these elements in the sludge-treated soil of 24:3:2.4:1 indicating the Zn, Mn, Cu, and Ni added to soil in sludge are extracted at similar ratios as they exist in the sludge. The slight variation in the ratio in the soil compared to the sludge ratio for these metals may be due to differing metal content of sludge added to the soil in the past, or related to the fact that DTPA is a more efficient extracting agent for some metals (e.g. Cu).

The sludge-treated soil sampled from the Eugene disposal area, extracted with 4 N HNO_3, contained Cd, Cr, and Zn levels in the upper 50 cm of soil from 0.7 to 13 ppm, 14 to 140 ppm, and 94 to 800 ppm, respectively, and exhibited substantially increased levels of Cd, Cr, and Zn compared to the control at levels less than 0.3, 12, and 52 ppm, respectively (Tables 8 and 33). Below 50 cm in the soil profile, the Cd, Cr, and Zn content of the sludge-treated soil generally compared closely with the control soil.

The Zn, Cr, and Cd content of the Eugene sludge was 4,400, 875, and 11 ppm, respectively, indicating that the soil should contain these elements at increased levels in an approximate ratio of 400:79:1. The average increase of the Zn, Cr, and Cd content in the surface meter of the sludge-treated soil when compared to the control was 289, 38, and 2.85 ppm, respectively, or a ratio of Zn:Cr:Cd of 400:52:4 in the sludge-treated soil. The average increase of Zn, Cr, and Cd in the sludge-treated soil approximates the ratio of these elements in the sludge; however, the ratio depends on the metal content of the past sludges applied.

The soil samples collected from the sludge-treated and untreated disposal areas during the winter, spring, and summer, 1975, were not assayed for the heavy metals (Cd, Cr, Cu, Mn, Ni, Zn) due to the time involved and the general awareness that these metals, except for Mn, are not solubilized by anaerobic conditions brought on by the rainfall during the winter and spring months. Manganese, on the other hand, is reduced under waterlogged conditions in the soil, the reduced state being more soluble than the oxidized forms (Buckman and Brady, 1969).

The sludge-treated soil from the Milwaukie disposal area, extracted with DTPA, contained an increased Cu, Ni, and Zn content in the upper portion of the soil, from 1.8 to 3.1 ppm, 0.5 to 1.2 ppm, and 1.4 to 41 ppm, respectively, compared to the Cu, Ni, and Zn content of the control (Tables 35 and 36). The sludge-treated and control soil samples contained similar Mn levels throughout the soil profile (Table 36). Below 10 cm in the soil profile, the Cu and Ni levels in the sludge-treated soil compared closely with the control soil, while higher Zn levels were observed in the surface 30 cm. Below 30 cm in the soil profile, the Zn level in the treated soil compared closely to the control soil. Zinc appeared to penetrate deeper into the soil profile of the sludge-treated soil indicating a greater potential for movement.

The sludge-treated soil sampled from the Milwaukie disposal area, extracted with 4 $\underline{N}$ HNO_3, contained Cd, Cr, and Zn levels in the upper 50 cm of soil from 0.004 to 0.017 ppm, 36 to 180 ppm, and 42 to 188 ppm, respectively, and exhibited substantially increased levels of these elements in the upper portion of the sludge-treated soil compared to the control soil (Table10 and 35). Below 30 cm in the soil profile, the Cd, Cr, and Zn content of the sludge-treated soil compared closely with the control soil. The Cr content below 1 meter in one soil core is probably not the result of sludge applied to the soil surface since the Cr content of most soils below 50 cm (Table 10)

Table 35. Cadmium, chromium, and nickel concentration in a Bornstedt silt loam soil treated with sewage sludge from the Milwaukie disposal area.

	Site; July, 1974											
	Cd				Cr				Ni			
Depth	Control	1	2	3	Control	1	2	3	Control	1	2	3
cm	ppm, dry weight											
0-10	0.01	0.01	0.017	0.01	42	88	140	100	0.4	0.5	1.2	0.7
20-30	0.007	0.007	0.006	0.01	44	50	62	66	0.1	0.2	0.1	0.1
41-51	0.006	0.007	0.004	0.004	46	44	60	46	0.1	0	0.1	0.1
61-71	0.004	0.01	0.005	0.005	50	48	62	54	0	0	0	0.1
81-91	0.003	0.01	0.003	0.005	52	58	76	58	0.1	0.1	0	0.1
122-132	0.003	0.009	0.005	0.003	62	60	94	58	0	0	0	0.1
152-163	0.004	0.008	0.004	0.003	52	60	110	56	0.1	0.1	0	0.1
183-193	0.003	0.007	0.004	0.004	50	68	100	52	0.1	0.2	0	0.1
213-224	0.004	0.007	0.003	0.003	52	60	100	50	0.1	0.1	0	0.1
244-254	0.003	0.007	0.005	0.004	50	64	130	60	0.1	0.1	0.2	0.1
274-284	0.003	0.005		0.003	64	74		56	0.1	0.1		0.1
305-315	0.003	0.003		0.004	66	64		52	0.1	0.1		0.1
335-345	0.003	0.004		0.003	36	58		44	0.1	0.2		0
366-376	0.003	0.008		0.004	48	52		42	0.1	0.1		0.1
396-406	0.003	0.004		0.004	44	58		46	0	0.2		0.1
427-437	0.003	0.003			52	58			0.1	0.1		

Table 36. Copper, manganese, and zinc concentration in a Bornstedt silt loam soil treated with sewage sludge from the Milwaukie disposal area.

	Site; July, 1974											
	Zn				Mn				Cu			
Depth	Control	1	2	3	Control	1	2	3	Control	1	2	3
cm	ppm, dry weight											
0-10	10	16	41	15	170	130	150	110	2.1	1.8	3.1	1.9
20-30	1.2	1.4	6.3	5.0	54	35	31	60	0.7	0.6	0.5	0.9
41-51	0.5	0.6	0.8	0.3	14	25	9.5	15	0.3	0.3	0.2	0.3
61-71	0.3	0.8	1.0	0.5	13	27	11	16	0.2	0.4	0.2	0.3
81-91	0.2	0.4	0.2	0.5	13	4.5	11	45	0.2	0.3	0.1	0.3
122-132	0.3	0.7	0.1	0.5	65	62	4.0	92	0.3	0.4	0	0.5
152-163	0.5	0.9	0.1	0.6	99	53	3.0	45	0.4	0.3	0	0.4
183-193	0.5	0.6	0.1	0.6	40	15	2.0	16	0.3	0.2	0.1	0.3
213-224	0.4	0.5	0.2	0.5	11	7.0	1.0	7.4	0.3	0.2	0.1	0.2
244-254	0.4	0.6	0.4	0.4	10	7.0	8.0	7.8	0.3	0.2	0.1	0.3
274-284	0.3	0.6		0.4	8.6	13		8.7	0.3	0.3		0.3
305-315	0.2	0.3		0.3	7.4	5.5		7.4	0.2	0.2		0.2
335-345	0.2	0.3		0.5	12	5.5		21	0.2	0.2		0.2
366-376	0.3	0.2		0.4	14	8.0		21	0.2	0.2		0.2
395-406	0.3	0.2		0.4	17	5.5		26	0.3	0.1		0.2
427-437	0.3	0.4			9.2	8.0			0.2	0.1		

compared closely with the control soil.

The sludge-treated soil sampled from the Hillsboro disposal area, extracted with DTPA, contained increased Cu and Zn levels, a range from 3.8 to 80 ppm and 5.1 to 23 ppm, respectively, compared to the Cu and Zn content of the control soil, a range from 0.8 to 5.5 ppm and 0.5 to 5.0 ppm, respectively (Table 38). The Ni content of the sludge-treated soil profile compared closely to the control throughout the soil profile. The Mn content of one soil core increased above the level of the control, while the remaining soil cores compared closely to the control. The increased Mn content of one soil core was probably the result of a lower pH in the surface and strong reducing conditions caused by the presence of a heavy clay layer in a lower soil horizon.

The sludge-treated soil sampled from the Hillsboro disposal area, extracted with 4 N HNO_3, contained increased Cd, Cr, and Zn levels in the upper 30 cm of the soil profile, a range from 0.4 to 3.1 ppm, 49 to 63 ppm, and 76 to 940 ppm, respectively, compared to Cd, Cr, and Zn levels of the control, ranging from 0.2 to 0.3 ppm, 37 to 50 ppm, and 70 to 122 ppm, respectively (Tables 12 and 37). Below 30 cm in the soil profile, the Cd content compared closely to the control; however, several soil cores exhibited increased Cr and Zn levels throughout the soil profile. The increased Cr and Zn levels were observed to occur primarily in the McBee soil series. This

Table 37. Cadmium, chromium, and nickel concentration in soils from the Hillsboro disposal area treated with sewage sludge.

Depth	Site; July, 1974											
	Cd				Cr				Ni			
	Control	1	2	3	Control	1	2	3	Control	1	2	3
cm	ppm, dry weight											
0-10	0.3	3.1	0.3	0.4	50	59	63	61	1.0	0.8	0.6	1.5
20-30	0.2	0.2	0.4	0.3	37	69	60	51	1.6	0.5	0.7	0.4
41-51	0.2	0.1	0.3	0.3	44	65	60	52	1.3	1.0	0.5	0.5
61-71	0.2	0.1	0.3	0.3	42	61	60	58	1.9	0.9	0.8	0.9
81-91	0.2	0.2	0.3	0.2	38	61	60	52	1.0	0.9	1.1	0.7
122-132	0.2	0.2	0.3	0.2	32	62	58	51	1.1	0.9	1.1	0.6
152-163	0.2	0.2	0.3	0.2	32	57	59	48	2.0	1.0	1.2	0.6
183-193	0.4	0.2	0.2	0.3	44	51	68	50	3.6	0.7	0.8	0.9
213-224	0.2	0.2	0.2	0.2	37	50	56	44	1.2	0.9	0.9	0.6
244-254	0.1	0.2	0.3	0.2	36	61	60	40	0.5	3.0	1.0	0.6
274-284	0.2	0.4	0.2	0.2	36	55	52	52	0.5	1.3	0.6	0.8
305-315	0.2	0.2	0.2	0.3	37	49	44	50	0.3	0.7	0.5	0.7
335-345	0.3	0.2	0.2	0.2	28	49	54	47	0.4	0.6	0.5	0.7
366-376	0.3	0.3	0.2		26	44	42		0.2	0.4	0.5	

Table 38. Zinc, manganese, and copper concentration in soils from the Hillsboro disposal area treated with sewage sludge.

	Site; July, 1974											
	Zn				Mn				Cu			
Depth	Control	1	2	3	Control	1	2	3	Control	1	2	3
cm	ppm, dry weight											
0-10	5.0	80	2.2	20	130	110	130	120	5.5	22	2.0	23
20-30	1.3	0.6	3.8	1.2	40	5.0	110	23	4.3	1.1	5.1	1.3
41-51	1.5	0.6	1.9	0.9	33	10	120	25	4.0	1.8	0.9	0.9
61-71	1.8	0.6	1.7	1.1	33	5.0	140	23	4.7	1.9	1.0	1.2
81-91	1.4	0.8	1.1	0.7	20	15	100	23	3.8	1.8	1.0	0.8
122-132	0.4	0.3	1.2	1.1	23	13	85	13	2.3	2.5	1.4	1.9
152-163	1.3	2.1	1.3	1.4	55	15	53	20	4.1	3.1	1.6	1.2
183-193	1.6	1.4	1.4	2.2	35	15	100	25	4.2	2.6	1.9	1.9
213-224	1.2	1.7	1.1	1.8	75	18	113	18	2.8	3.0	1.7	2.0
244-254	0.7	1.6	1.0	1.3	180	63	120	10	4.8	5.5	1.7	2.0
274-284	0.9	4.0	0.6	1.4	150	70	310	15	4.3	4.4	2.2	1.8
305-315	0.6	2.7	0.6	1.2	85	68	380	18	2.0	2.6	2.4	2.5
335-345	0.6	1.4	0.7	1.3	73	88	380	20	1.0	1.9	3.8	2.3
366-376	0.5	1.7	0.5		50	100	250		0.8	1.8	2.8	

would suggest that McBee soil had a normally higher Cr and Zn content than the control or other soil series sampled on the disposal area.

The sludge-treated soil from the Forest Grove disposal area, extracted with DTPA, reflected increased Cu, Mn, Ni, and Zn levels in the upper portion of the soil profile, a range from 0.7 to 2.1 ppm, 14 to 42 ppm, 0.2 to 0.7 ppm, and 1.4 to 25 ppm, respectively, compared to the Cu, Mn, Ni, and Zn levels in the control soil, a range from 0.3 to 0.4 ppm, 3.0 to 9.2 ppm, 0 to 0.1 ppm, and 0.2 to 1.2 ppm, respectively (Tables 39 and 40). Below 50 cm in the soil profile, the Cu, Ni, and Zn content of the sludge-treated soil compared closely with the control soil. The increased Mn content in the sludge-treated soil compared to the control was probably the result of anaerobic conditions from continuous irrigation with effluent water producing a reducing environment acting to solubilize Mn.

The sludge-treated soil from the Forest Grove disposal area, extracted with 4 $\underline{N}$ HNO_3, contained slightly increased Cd, Cr, and Zn levels in the surface soil, a range from 0.23 to 0.25 ppm, 20 to 24 ppm, and 70 to 164 ppm, respectively, compared to the Cd, Cr, and Zn content of the control, ranging from 0.14 to 0.18 ppm, 19 to 20 ppm, and 66 to 70 ppm, respectively (Tables 14 and 39). Below 30 cm in the sludge-treated soil, the Cd, Cr, and Zn levels compared closely to the control soil.

Table 39. Cadmium, chromium, and nickel concentration in a Woodburn silt loam soil treated with sewage sludge from the Forest Grove disposal area.

	Site; July, 1974											
	Cd				Cr				Ni			
Depth	Control	1	2	3	Control	1	2	3	Control	1	2	3
cm	ppm, dry weight											
0-10	0.18	0.23	0.25	0.25	19	23	21	22	0.1	0.7	0.2	0.3
20-30	0.14	0.12	0.14	0.18	20	21	22	23	0	0.3	0.1	0.2
41-51	0.15	0.10	0.12	0.11	20	22	22	24	0	0.2	0.1	0.3
61-71	0.13	0.10	0.14	0.13	22	22	22	23	0	0.1	0.2	0.2
81-91	0.12	0.11	0.14	0.12	22	22	22	22	0.2	0.2	0.2	0.2
122-132	0.16	0.13			20	21			0.2	0.2		
152-163	0.13	0.15			18	17			0.2	0.2		

Table 40. Copper, manganese, and zinc concentration in a Woodburn silt loam soil treated with sewage sludge from the Forest Grove disposal area.

	Site; July, 1974											
	Zn				Mn				Cu			
Depth	Control	1	2	3	Control	1	2	3	Control	1	2	3
cm	ppm, dry weight											
0-10	1.2	14	25	8.5	9.2	24	42	32	0.4	2.1	1.6	1.3
20-30	0.3	5.1	1.4	4.1	3.0	14	33	23	0.3	1.1	0.8	0.9
41-51	0.2	0.7	0.6	1.0	6.9	22	21	17	0.4	0.7	0.9	0.8
61-71	0.2	0.4	0.5	0.4	8.0	8.9	4.2	10	0.4	0.6	0.5	0.5
81-91	0.2	0.4	0.7	0.5	7.2	8.1	6.0	4.2	0.4	0.6	0.6	0.5
122-132	0.5	0.7			3.6	10			0.4	0.6		
152-163	0.5	0.4			3.3	5.3			0.4	0.4		

The sludge-treated soil from the Woodburn disposal area, extracted with DTPA, reflected increased Cu and Zn content in the upper portion of the soil profile, a range from 1.3 to 5.0 ppm and 1.8 to 3.8 ppm, respectively, compared to the Cu and Zn levels in the control soil, a range from 0.6 to 2.5 ppm and 0.4 to 4.3 ppm, respectively (Tables 41 and 42). Below 30 cm in the soil profile, the Cu and Zn levels compared closely to the control soil with no marked accumulation at any depth. The Mn and Ni content of the sludge-treated soil compared closely to the control throughout the soil profile.

The sludge-treated soil from the Woodburn disposal area, extracted with 4 N HNO_3, contained an increased Zn content in the upper portion of the soil profile, a range from 77 to 152 ppm, compared to the control at 68 ppm (Tables 16 and 41). Below 30 cm in the soil profile, the Zn level in the sludge-treated soil compared closely to the control soil. The Cd and Cr content of the sludge-treated soil compared closely to the control soil throughout the soil profile.

Summary: The concentrations of Cd, Cr, Cu, Ni, and Zn in the surface soil of the Eugene, Milwaukie, Hillsboro, Forest Grove, and Woodburn disposal areas generally increased depending on the amount of sludge applied and the metal content of the sewage sludge. The Mn content of these soils generally fluctuated more in response to moisture and pH variation than from large amounts of Mn added in the

Table 41. Cadmium, chromium, and nickel concentration in a Woodburn silt loam soil treated with sewage sludge from the Woodburn disposal area.

	Site; July, 1974								
	Cd			Cr			Ni		
Depth	Control	1	2	Control	1	2	Control	1	2
cm	ppm, dry weight								
0-10	0.2	0.4	0.4	18	20	22	1.1	0.5	0.5
20-30	0.2	0.2	0.2	19	20	22	0.5	0.2	0.4
41-51	0.2	0.1	0.1	22	24	24	0.6	0.2	0.2
61-71	0.2	0.1	0.1	27	20	23	0.3	0.3	0.3
81-91	0.2	0.2	0.2	26	22	21	0.3	0.3	0.2
122-132	0.2	0.2	0.2	22	16	20	0.2	0.3	0.3
152-163	0.2	0.2	0.2	20	20	18	0.2	0.3	0.3
183-193	0.2	0.2	0.2	28	18	18	0.3	0.3	0.2
213-224	0.2	0.2	0.2	21	22	18	0.3	0.2	0.2
244-254	0.2	0.2	0.2	21	16	20	0.3	0.2	0.2
274-284	0.2	0.2	0.2	21	16	19	0.3	0.2	0.3
305-315	0.2	0.2	0.2	16	18	19	0.1	0.2	0.4
335-345	0.2	0.2	0.2	18	18	20	0.2	0.2	0.3
366-376	0.2	0.2	0.2	16	16	19	0.1	0.2	0.3
396-406	0.2	0.2	0.2	18	16	15	0.2	0.2	0.3
427-437	0.2	0.2	0.2	23	18	17	0.3	0.3	0.2
457-467	0.2	0.2	0.2	20	24	18	0.2	0.4	0.2
488-498	0.2	0.2	0.2	16	20	20	0.2	0.4	0.2

Table 42. Copper, manganese, and zinc concentration in a Woodburn silt loam soil treated with sewage sludge from the Woodburn disposal area.

	Site; July, 1974								
	Zn			Mn			Cu		
Depth	Control	1	2	Control	1	2	Control	1	2
cm	ppm, dry weight								
0-10	4.3	38	20	63	53	76	1.6	4.8	5.0
20-30	1.1	1.8	2.4	10	9.4	52	1.8	1.3	2.8
41-51	1.3	0.9	1.3	15	12	19	2.3	1.3	2.3
61-71	1.3	1.1	0.8	10	11	6.8	2.2	0.8	0.7
81-91	0.9	0.8	0.8	6.2	8.0	5.8	1.5	0.8	1.0
122-132	0.7	0.8	0.7	3.2	6.4	4.2	1.2	0.6	0.9
152-163	0.6	0.8	0.7	3.2	6.6	3.8	1.0	0.8	1.1
183-193	0.6	0.8	0.8	3.8	6.0	3.8	1.1	0.7	0.9
213-224	0.6	1.0	0.6	2.4	6.6	5.6	1.0	0.7	0.9
244-254	0.4	0.8	0.7	2.2	5.8	4.0	1.9	0.7	0.9
274-284	0.5	0.8	0.7	1.4	6.0	3.8	1.3	0.7	1.5
305-315	0.4	0.9	0.7	2.8	7.8	4.4	0.6	0.8	0.8
335-345	0.5	0.7	0.8	4.2	6.0	4.4	0.8	0.6	1.1
366-376	0.5	0.6	0.8	1.2	4.8	4.4	1.4	0.6	1.3
396-406	0.5	0.7	0.7	3.4	4.2	3.8	2.0	0.5	0.6
427-437	0.5	0.9	0.6	1.8	6.6	2.2	2.3	0.7	1.0
457-467	0.5	0.9	1.0	5.0	6.4	2.6	2.2	1.2	1.1
488-498	0.9	1.0	0.9	1.4	4.4	2.4	2.5	1.0	2.0

sludges. The heavy metals (Cd, Cr, Cu, Mn, Ni, Zn) remained in the upper 50 cm of the soil profile, and Zn appeared to penetrate to slightly deeper soil depths than the other metals.

The heavy metals (Cd, Cr, Cu, Mn, Ni, Zn) in the sludge-treated soil were extracted in a ratio similar to the ratio of these metals in the sewage sludge applied indicating that most metals remained in the soil surface. The 4 N HNO_3 extractant removed considerably more Zn from the sludge-treated soil than the soil extracted with DTPA suggesting that the acid extracting agent is a considerably stronger extractant than the organic chelating agent (DTPA).

Plant Analysis

Nitrogen. The average N content of the forage grass collected from the Eugene and Forest Grove disposal areas increased, compared to the control, from 1.1 to 2.2% and 0.7 to 1.3%, respectively, while the average N content of the Milwaukie and Woodburn forage grass did not exhibit a significant increase over the control (Table 43). The increased N content of the forage grass was greatest at the Eugene disposal area where the greatest amount of sludge had been applied.

Phosphorus. The average P content of the forage grass collected from the Eugene disposal area increased, compared to the control, from 0.18 to 0.31% (Table 43). The P content of the forage grass from the Milwaukie, Forest Grove, and Woodburn disposal

Table 43. Elemental analysis of grasses from the disposal areas.

Element		Eugene	Milwaukie	Forest Grove	Woodburn
		- - - - - - - - - -	- - - - - %	- - - - - - - - - -	- - - - - - -
N	Control	1.05	1.16	0.74	1.49
	Site 1	2.09	1.24	1.45	1.49
	Site 2	2.17	1.39	1.28	1.67
P	Control	0.18	0.17	0.18	0.24
	Site 1	0.36	0.20	0.18	0.26
	Site 2	0.27	0.21	0.23	0.22
		- - - - - - - - - -	- - - - - ppm	- - - - - - - - - -	- - - - - - -
Cd	Control	0.34	0.49	0.31	0.44
	Site 1	1.04	0.18	0.54	0.28
	Site 2	0.83	0.16	0.49	0.18
Cr	Control	2.58	1.33	1.67	2.17
	Site 1	4.92	1.08	1.75	2.00
	Site 2	2.50	1.83	1.17	1.58
Cu	Control	5.75	6.76	8.50	8.00
	Site 1	16.5	6.00	5.00	9.50
	Site 2	11.5	8.75	5.50	9.50
Mn	Control	70.0	94.0	90.0	99.0
	Site 1	225	85.5	75.0	62.5
	Site 2	260	55.3	50.5	63.0
Ni	Control	9.25	7.00	4.50	7.00
	Site 1	11.3	7.50	4.50	6.50
	Site 2	9.25	14.0	4.50	5.60
Zn	Control	18.5	27.5	15.8	30.5
	Site 1	236	41.0	27.8	32.3
	Site 2	343	125	34.8	35.0

areas compared closely to the grass grown on the control soil. Similar to N, the P content of the forage grass from the Eugene disposal area showed the largest increase compared to the other disposal areas.

Heavy Metals. The average Cd, Cu, Mn, and Zn content of the grass collected from the Eugene disposal area increased, as compared to the control samples, from 0.3 to 1 ppm, 5.8 to 14 ppm, 70 to 240 ppm, and 19 to 290 ppm, respectively (Table 43). The average Cr and Ni content in the plant tissue from the Eugene disposal area compared closely with the control samples. The average Zn content of the forage grass collected from the Milwaukie and Forest Grove disposal areas increased substantially, as compared to the control, from 28 to 80 ppm and 16 to 30 ppm, respectively (Table 43). The Cd, Cr, Cu, Mn, and Ni levels in the grass tissue from the Milwaukie, Forest Grove, and Woodburn disposal areas did not increase measurably over the levels in the control plants.

The increased Zn content of grass from the Eugene, Milwaukie, and Forest Grove disposal areas, when compared to adjacent untreated areas, was the result of large amounts of sludge added to the soil. In addition, the uptake of other heavy metals (Cd, Cr, Cu, Mn, Ni) was enhanced at the Eugene disposal area by a pH decline from 6.4 to 4.6 on the sludge-treated area.

The concentration of Cd, Cr, Cu, Mn, Ni, and Zn in the plant tissue collected from Eugene, Milwaukie, Forest Grove, and Woodburn disposal areas did not exceed the toxic limits for plant tissue set at 2, 2, 30, 300, 25, and 500 ppm, respectively (Table 4).

Grass grown on sludge-treated soils aids in the removal of many elements applied in the sludge. The amount of N, P, Cd, Cr, Cu, Mn, Ni, and Zn added to the Eugene disposal area in the sewage sludge was approximately 2,370, 1,150, 0.8, 63, 16, 27, 17, and 316 kg/ha/year, respectively. The estimated amount of N, P, Cd, Cr, Cu, Mn, Ni, Zn, removed by the pasture grass from the Eugene disposal area, assuming a yield of 15 m tons/ha/year, would be 319, 45, 0.013, 0.05, 0.2, 3.7, 0.15, and 4.4 kg/ha/year, respectively. Less than 10% of the N, P, and heavy metals (Cd, Cr, Cu, Mn, Ni, Zn) added in the sewage sludge were recycled through the plant tissue at the Eugene disposal area. The grasses from the other disposal areas removed a considerably lower percentage of the N, P, and metals (Cd, Cr, Cu, Mn, Ni, Zn) applied in these sludges compared to the Eugene disposal area. This would suggest that a small portion of the N, P, and heavy metals (Cd, Cr, Cu, Mn, Ni, Zn) are recycled through the plant-animal food chain. The increased N and Zn content of the plants collected from all the sludge disposal areas suggests that these elements were most readily recycled.

Water Analysis

Near the Eugene, Milwaukie, Hillsboro, Forest Grove, and Woodburn disposal areas, groundwater was sampled from wells during the final sample collection, June, 1975.

Nitrate-Nitrogen. The NO_3-N content of the water from two wells, 6.1 and 24 meters deep within 15 meters of the Eugene disposal area was 0.5 ppm (Table 44). The NO_3-N content of the water from wells near the Milwaukie, Hillsboro, Forest Grove, and Woodburn disposal area did not exceed 0.1 ppm (Table 44). The NO_3-N level of the water samples from these wells was considerably below the 10 ppm limit set by the Public Health Service drinking water standards.

Table 44. Elemental analysis of well water.

Item	Eugene 6 m	Eugene 20 m	Milwaukie	Hillsboro	Forest Grove	Woodburn
	ppm					
Phosphorus	0.28	0.32	0.37	1.63	0.37	0.51
NO_3-N	0.50	0.36	0.08	0	0.11	0.06
NH_4-N	0	0.04	0.08	1.4	0.08	0.11
Zinc	0.02	0.42	0.003	0.05	0.16	0.03
Copper	0.002	0.03	0.004	0	0.005	0.007
Manganese	0.01	0.01	0.07	1.2	0.01	0.01
Nickel	0	0	0	0	0	0
Chromium	0	0	0	0	0	0
Cadmium	0	0	0	0	0.002	0
pH	7.0	6.6	6.4	7.1	6.8	7.4

Ammonium-Nitrogen. The NH_4-N content of the well water from the Eugene, Milwaukie, Forest Grove, and Woodburn disposal areas did not exceed 0.1 ppm; however, the NH_4-N content of the well water from the Hillsboro disposal area was 1.4 ppm, exceeding the Public Health Service permissible limit for NH_4-N of 0.5 ppm (Table 44). The NH_4-N increase in the groundwater may be due to the flooded conditions during the winter and spring causing strong reducing conditions resulting in NO_3-N reduction deep in the soil profile.

Heavy Metals. The Cd, Cr, and Ni content of the well water was generally undetectable, while Cu, Mn, and Zn did not exceed 0.3, 0.01, and 0.4 ppm, respectively, except for the Mn content of the well water sampled at the Hillsboro disposal area (Table 44). The increased Mn content, 1.2 ppm, compared to the other well water samples, apparently was due to strong reducing conditions solubilizing Mn. The Mn concentration in the Hillsboro well water sample had increased to 25 times the Public Health Service limit of 0.05 ppm for drinking water. The other well water samples were below the maximum allowable concentration for Cd, Cr, Cu, and Zn set by the Public Health Service for drinking water at 0.01, 0.05, 1.0, and 5.0 ppm, respectively. Most heavy metals (Cd, Cr, Cu, Mn, Ni, Zn) are extremely insoluble in water and probably would not exceed 0.05 ppm at pH 7.0.

pH. The pH of the water from wells near the disposal areas ranged from 6.4 to 7.4 (Table 44), well within safe limits since most unpolluted waters have pH values within a range of 6.0 to 8.5 (McDermott, 1972).

Phosphorus. The soluble P content of the water from wells near the disposal areas ranged from 0.28 to 1.6 ppm (Table 44). Evidence indicates that a soluble P content of less than 0.09 ppm will inhibit optimal growth of various algae (Hutchinson, 1957). The soluble P content appears to be great enough to encourage algal growth; however, other considerations may limit algal growth such as requirements for light, temperature, and other nutrients.

The elemental content of the well water samples near each disposal area did not appear to pose any long-term threat, except for the Hillsboro water sample, to the drinking water quality. Because only one or two water samples were collected near each disposal area, interpretation of the data is extremely limited. To determine whether significant amounts of NO_3-N was moving into the groundwater, more samples should be collected in all directions from the source of potential groundwater pollution to insure the interception of the groundwater flow.

SUMMARY AND CONCLUSIONS

This research was conducted to study the effect of large applications of municipal sewage sludge on (a) the distribution of nitrogen and trace elements (Cd, Cr, Cu, Mn, Ni, Zn) in soil and changes in pH, (b) the uptake of these elements by plants growing on the disposal area, and (c) the potential for groundwater contamination.

An estimated 500, 290, 96, 72, and 20 dry m tons/ha of sludge was applied to the Eugene, Hillsboro, Forest Grove, Woodburn, and Milwaukie disposal areas, respectively. The total N and P content of the five sludges ranged from 3.9 to 6.3% and 0.5 to 2.9%, respectively. The inorganic N was primarily in the form of NH_4-N with relatively low amounts of NO_3-N, a range from 1.4 to 4.4% and 0.002 to 0.023%, respectively. The total N content of the five sludges ranged from one-fourth to three-fourths inorganic NH_4-N. The trace element (Cd, Cr, Cu, Mn, Ni, Zn) content of the sewage sludge from each wastewater treatment facility fell within general ranges reported for a number of municipal sewage sludges, except for the Cr content of the Milwaukie sludge measured at 17,700 ppm, approximately twice the highest Cr level measured in 42 sludges from England and Wales.

The concentration of Cd, Cr, Cu, Mn, Ni, Zn, NH_4-N, NO_3-N, and the organic N compounds in the soil surface of each disposal area increased with sewage sludge applied, while Mn fluctuated more in response to moisture and pH variation than from large amounts of Mn added in sludge. The Cd, Cr, Cu, Mn, Ni, Zn, NH_4-N, and organic N compounds remained primarily in the upper portion of the soil profile suggesting that movement of these elements in soil is quite restricted.

The NO_3-N content below one meter in the soil profile increased, compared to the untreated soil, dependent on the sludge application rate. The highest sludge application rate, 500 dry m tons/ha, exhibited a NO_3-N level of 120 ppm to 3 meters in the soil profile. One site at the Hillsboro disposal area where large amounts of sludge were added from a sludge drying lagoon reflected NO_3-N levels as high as 20 ppm. Soils sampled from the Milwaukie, Forest Grove, and Woodburn disposal areas where less sludge was applied compared closely to the control soil below 50 cm in the profile. During the winter and spring, 1975, increased rainfall percolating through the soil profile and cooler temperatures, slowing the microbial production of NO_3-N, combined to decrease the NO_3-N content in the upper portion of the soil profile and generally increase the NO_3-N in the lower horizons. The NO_3-N content in the upper portion of the soil increased during the summer, 1975, a reflection of warmer temperatures, decreased rainfall, and increased nitrification.

The pH of the surface soil at the Eugene and Hillsboro disposal areas decreased from pH values of 6.4 to 4.6 and 4.8 to 4.4, respectively, as a result of sludge application of more than 500 dry m tons/ha. The pH values of the other disposal areas with lower amounts of sludge added compared more closely to the control soils.

The Zn and N content of the various grasses growing on the disposal areas increased compared to the control at the highest sludge application rates; however, the Cd, Cu, Mn, and P increased in the grasses sampled from the Eugene site, while the Cd, Cr, Cu, Mn, Ni, and P content of the forage grass from the Milwaukie, Forest Grove, and Woodburn disposal areas compared closely to the control samples. The lower pH at the Eugene disposal area and the high sludge application rate combined to enhance the trace element uptake in grasses growing in that soil.

The application of sludge to the soil surface of the Eugene and Hillsboro disposal areas at rates of 500 and 290 m tons/ha, respectively, may pose a threat of NO_3-N or NH_4-N pollution to groundwater. The largest amounts of NO_3-N moved through the soil profile at the Eugene disposal area. The Hillsboro disposal area was flooded nearly 6 months of each year and the well water sample collected near the disposal area contained 1.5 ppm NH_4-N. Interpretation of the results from the well water samples is limited since only one or two water samples were collected near each disposal area.

Sewage sludge produced in large municipalities can be dispersed by application to agricultural land. The soil has a great potential to assimilate constituents in the sewage sludge. However, heavy metal assimulations in the soil surface and plant tissue and the movement of NO_3-N through the soil profile must be monitored when implementing a land disposal program for sewage sludge. Eventually, the metal content of the soil will build up to the maximum recommended levels over a period of years. Other management practices (i. e. liming) may be needed to maintain soil productivity.

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APPENDICES

APPENDIX I

Soil Series Description of a Bornstedt, Cove, McBee, Newberg, and Woodburn Soil Series

Bornstedt Series

The Bornstedt series is a member of the fine-silty, mixed, mesic family of the Typic Fragiochrepts. This is a tentative placement. The soils have very dark brown silt loam A horizons and reddish brown or brown silty clay loam B horizons underlain by fragipans.

Typifying Pedon: Bornstedt silt loam - cultivated
(Colors are for moist soil unless otherwise noted.)

Ap 0-8"--Very dark brown (10YR 2/2) silt loam, grayish brown (10YR 5/2) dry; moderate fine subangular blocky structure; friable, slightly sticky, slightly plastic; few fine roots; many very fine pores; medium acid (pH 5.7); abrupt smooth boundary. (6 to 9 inches thick)

B21t 8-21"--Reddish brown (5YR 4/4) silty clay loam, brown (7.5YR 5/4) dry; moderate fine subangular blocky structure; firm, slightly sticky, plastic; few fine roots; many very fine pores; few moderately thick clay films; strongly acid (pH 5.5); clear wavy boundary. (7 to 15 inches thick)

B22t 21-28"--Reddish brown (5YR 4/4) silty clay loam, light reddish brown (5YR 6/4) dry; moderate fine and medium subangular blocky structure; firm, slightly brittle, slightly sticky, plastic; many very fine pores; few moderately thick clay films; strongly acid (pH 5.4); clear wavy boundary. (5 to 8 inches thick)

B3t 28-33"--Brown and dark brown to brown (7.5YR 5/3, 4/4) silty clay loam, light brown (7.5YR 6/4) dry; weak medium subangular blocky structure; firm, brittle, slightly sticky, plastic; many very fine pores; common thin, few moderately thick clay films; few fine black stains; strongly acid (pH 5.5); abrupt smooth boundary. (0 to 6 inches thick)

BX1 33-48"--Reddish brown and reddish gray (5YR 4/4 to 5/2) clay, brown and pinkish gray (7.5YR 5/4 to 7/2) dry; massive with vertical and diagonal fractures with gray silty surfaces; very firm, brittle, sticky, plastic; many very fine pores; continuous brown (7.5YR 5/2) 1 mm thick silty coating on upper boundary of horizon; many fine black stains; very strongly acid (pH 5.0); gradual wavy boundary. (13 to 17 inches thick)

BX2 48-70"--Variegated reddish brown and brown (5YR 4/4, 7.5YR 5/3) silty clay, light reddish brown, reddish brown and pinkish gray (5YR 6/4 to 5/4 and 7.5YR 7/2) dry; massive with vertical and diagonal fractures with gray silty surfaces; firm, brittle, slightly sticky, slightly plastic; many very fine pores; common moderately thick clay films on surfaces and in pores; common fine black stains; very strongly acid (pH 4.8).

Type Location: Clackamas County, Oregon; about 900 feet west of Deep Creek road on long driveway, 900 feet north on field road, 100 feet east on field road and 10 feet north of road, NW$\frac{1}{4}$, SE$\frac{1}{4}$, NW$\frac{1}{4}$, section 10, T.2 S., R.3 E., Willamette Meridian.

Range in Characteristics: The soils are usually moist but are dry throughout between 4 and 12 inches for more than 60 consecutive days. The mean annual soil temperature ranges from 52° to 55°F. Depth to bedrock is over 60 inches. Depth to the fragipan ranges from 20 to 40 inches. The A horizon has hues of 10YR and 7.5YR, values of 2 or 3 moist and 5 dry, and chromas of 2 or 3 moist and dry. It is light silty clay loam or silt loam. The B horizon has hues of 5YR to 7.5YR, values of 3 to 5 moist and 5 or 6 dry, and chromas of 2 to 6. It is a silty clay loam with 27 to 35 percent clay and less than 10 percent coarser than very fine sand. Clay films range to few to common and thin and moderately thick. The BX horizon has hues of 10YR to 5YR, values of 4 to 5 moist and 5 to 7 dry, and chromas of 2 to 6 moist and dry. It has very coarse prismatic structure or massive with irregular fractures. It is silty clay or clay with 40 to 50 percent clay.

Competing Series and Their Differentiae: These are the Cascade, Dollar, Goble, Kinton and Powell series. All of the soils have base saturation greater than 35 percent in the fragipan. Also, Cascade, Dollar, and Goble soils have umbric epipedons and lack clay films in the B horizons above the fragipan. Kinton soils have silt loam cambic horizons and silty clay loam fragipans and lack hues as red as 5YR in any part of the profile. Powell soils have silt loam cambic horizons and fragipans and the B horizon is mottled above the fragipan.

Setting: The Bornstedt soils are on smooth or gently rolling old high terraces with convex long slopes on all exposures at 400 to 650 feet elevation. They have formed in very old alluvium on old gravelly terraces. The climate is characterized by cool moist winters and warm dry summers. The average July temperature is 65°F.; average January temperature is 37°F.; average annual temperature is 50° to 52°F.; and the average annual rainfall ranges from 48 to 65 inches. The frost-free season is 140 to 200 days.

Principal Associated Soils: These are the Dubay soils. They are somewhat poorly drained and mottled in the B horizon. The Cazadero and Cottrell soils are on adjacent higher terraces and lack fragipans.

Drainage and Permeability: Moderately well drained; slow to medium runoff; slow permeability.

Use and Vegetation: The soils are cropped to row crops, specialty crops, berries, nursery, hay, pasture, and cereal grains; also, they are used for homesites, recreation, and wildlife. Native vegetation consists of Douglas-fir, western red cedar, hazel, bracken fern, and wild blackberry.

Distribution and Extent: Very old high alluvial terraces of northeastern part of Willamette Valley, Oregon. The series is inestensive.

Series Proposed: Clackamas County, Oregon, 1963. The name was taken from Bornstedt Creek of northeast Clackamas County.

Remarks: The Bornstedt soils were formerly classified as Reddish Brown Lateritic soils.

Additional Data: Characterization data on two profiles (S70 Oreg - 3-3 and 3-4) reported in Riverside Soil Survey laboratory Computer print-out for soils sampled in Clackamas, Multnomah and Washington Counties, Oregon, 1971. The pedons barely meet the clay increase requirement of an argillic horizon. With an argillic horizon, they are Ultisols but there is no provision for a fragipan in Haploxerults.

Cove Series

The Cove series is a member of the very fine, montmorillonitic, noncalcareous mesic family of Vertic Haplaquolls. Typically, these soils have very dark gray silty clay loam A horizons, very dark gray clay Bg horizons, and dark grayish brown clay Cg horizons and they are mottled throughout.

Typifying Pedon: Cove silty clay loam - cultivated
(Colors are for moist soils unless otherwise noted.)

Ap 0-8"--Very dark gray (10YR 3/1) silty clay loam, dark gray (10YR 4/1) dry; many fine distinct yellowish brown and dark reddish brown mottles; moderate fine subangular blocky structure; hard, firm, sticky, plastic; common fine roots; common very fine and fine pores; medium acid (pH 5.6); abrupt smooth boundary. (7 to 8 inches thick)

B21g 8-16"--Very dark gray (10YR 3/1) clay, dark gray (N 4) dry; many fine distinct dark yellowish brown and dark reddish brown mottles; weak medium prismatic structure breaking to moderate fine subangular blocky structure; very hard, very firm, very sticky, very plastic; few fine roots; many very fine pores; slightly acid (pH 6.1); clear smooth boundary. (7 to 10 inches thick)

B22g 16-41"--Very dark gray (N 3) clay, dark gray (N 4) dry; common fine faint dark yellowish brown mottles; moderate medium and coarse prismatic structure; very hard, very firm, very sticky, very plastic; few fine roots; common very fine pores; few slickensides that do not intersect; few framents of igneous and sedimentary rocks; slightly acid (pH 6.4); clear smooth boundary. (15 to 26 inches thick)

Cg 41-52"--Dark grayish brown (2.5YR 4/2) clay, gray (N 5) dry; many fine dark reddish brown and dark yellowish brown mottles; structureless, massive; very hard, very firm, very sticky, very plastic; common very fine pores; slightly acid (pH 6.4).

Type Location: Yamhill County, Oregon; about 50 feet north of the Amity-Bellvue Road and 75 feet west of ditch, NE$\frac{1}{4}$ NW$\frac{1}{4}$ SE$\frac{1}{4}$ sec. 25, T.5 S., R.5 W., Willamette Meridian.

Range in Characteristics: The mean annual soil temperature ranges from 47° to 55°F. The soils are saturated 4 to 6 months of the year unless drained and remain moist below 20 inches nearly continuously. During summer the soil cracks at some depth above 20 inches, usually at depths between 7 and 20 inches. The column ranges in thickness from 30 to 45 inches. The reaction ranges from slightly to medium acid. Depth to clay ranges from 7 to 16 inches. The surface layer generally has 10YR hue but some is 2.5Y. The soil has color value of 2 or 3 moist, and chroma of 1 or less throughout except that in the A horizon chroma may be as high as 3. When the soil is dry value is 4 or 5. Texture of the Ap or A1 horizon is silty clay loam or silty clay. The B horizon generally has 2.5Y or neutral hue but some is 10YR. Structure is moderate to strong. Mottling is distinct or prominent within 20 inches. Fine fragments of rock range from none to few. Some pedons have a few slickensides but they do not intersect.

Competing Series and Their Differentiae: Related or similar soils are in the Bashaw, Carson, and Panther series. The Bashaw soils have slickensides that intersect and have weak structure or are structureless, massive below the A horizon. The Carson soils are alkaline and calcareous between 10 and 20 inches depth. The Panther soils have mollic epipedons less than 24 inches thick, lack cracks and have moist color value of 4 or more in the B horizon.

Setting: The Cove soils are on floodplains along both large and small streams at elevations of 150 to 400 feet. Slopes are nearly level and plane to slightly concave. The regolith is deep clayey recent alluvium washed mainly from areas underlain by sedimentary and basic igneous rocks. Winters are cool and moist, and summers are warm and dry. Average July temperature is 66°F., average January temperature is 37°F., and average annual temperature is 53°F. The growing season is about 212 days. Average annual precipitation is 40 to 60 inches.

Principal Associated Soils: These are the Chehalis, Dollar, Hockinson, Labish, McBee, and Wapato series. Chehalis soils are well drained and have moderately fine texture. The Dollar soils have fragipans. The Hockinson soils have medium texture. The Labish soils have block, highly organic Z horizons, dark fine-textured, nearly massive B horizons, and a few peaty lenses. McBee soils have moderately fine texture and chroma of 3 and mottles below depths of

20 inches. The Wapato soils have moderately fine texture and chroma of 2 or less.

Drainage and Permeability: Poorly and very poorly drained. Surface runoff is slow to very slow and internal drainage is very slow. Permeability is very slow.

Use and Vegetation: Most of these soils are cultivated. Most of the soil is in hay and pasture, and some spring grain is grown. Native vegetation is sedges, grasses and a few ash, willows, and other trees.

Distribution and Extent: Northern Willamette Valley in western Oregon and southwestern Washington. The soil is inextensive.

Series Established: Yamhill County, Oregon, 1917.

Remarks: The Cove series was formerly classified as Humic Gley soils or Grumusols. The soils now placed in the Bashaw series, were formerly included in the Cove series.

McBee Series

The McBee series is a member of the fine-silty, mixed, mesic family of Cumulic Ultic Haploxerolls. Typically, McBee soils have very dark brown silty clay loam A horizons and very dark brown, very dark grayish brown, and dark brown silty clay loam B2 horizons.

Typifying Pedon: McBee silty clay loam-cultivated
(Colors are for moist soil unless otherwise noted.)

Ap 0-7"--Very dark brown (10YR 2/2) silty clay loam, dark grayish brown (10YR 4/2) dry; moderate coarse medium and fine granular structure; friable, sticky, plastic; many fine and very fine irregular pores; common very fine roots; medium acid (pH 6.0: abrupt smooth boundary. (6 to 9 inches thick)

A12 7-10"--Very dark brown (10YR 2/2) silty clay loam, dark grayish brown (10YR 4/2) dry; few faint dark brown mottles; seak coarse and medium prismatic and moderate medium and fine subangular blocky structure; firable, sticky, plastic; common very fine roots; many very fine tubular pores; slightly acid (pH 6.2); clear smooth boundary. (0 to 5 inches thick)

B1 10-22"--Very dark brown (10YR 2/2) silty clay loam, dark grayish brown (10YR 4/2) dry; common fine faint dark brown mottles; moderate medium prismatic and strong fine and very fine subangular blocky structure; friable, sticky, plastic; many very fine tubular pores; few roots; many worm casts; slightly acid (pH 6.2); gradual smooth boundary. (0 to 15 inches thick)

B2 22-35"--Faintly mottled dark brown, very dark brown, and very dark grayish brown (10YR 3/3, 2/2, and 3/2) silty clay loam, grayish brown (10YR 4/2) and brown (10YR 4/3) dry; weak medium prismatic and moderate coarse and medium subangular blocky structure; friable, sticky, plastic; many very fine and few fine tubular pores; few very fine roots; slightly acid (pH 6.4); gradual smooth boundary. (8 to 16 inches thick)

B3 35-42"--Dark grayish brown (10YR 4/2) clay loam; grayish brown (10YR 5/2) dry; many fine and medium mottles of very dark brown, brown and dark yellowish brown (10YR 2/2, 3/3 and 4/4) and common fine mottles of strong brown (7.5YR 5/6); weak medium and fine subangular blocky structure; friable, sticky, plastic; very few roots; many very fine and few fine tubular pores; slightly acid (pH 6.4); gradual smooth boundary. (4 to 11 inches thick)

Cg 42-65"--Dark gray (10YR 4/1) clay loam, gray (10YR 5/1) dry; many medium and fine distinct mottles of very dark brown and dark brown (10YR 2/2 and 3/3); massive; many very fine and few fine pores; slightly acid (pH 6.4).

Type Location: Marion County, Oregon; about 3/16 mile east of Farmstead, north edge of Walnut Orchard; SE$\frac{1}{4}$ SE$\frac{1}{4}$ sec. 6, T.6 S., R.1 E.

Range in Characteristics: The mean annual soil temperature ranges from 53° to 55°F. The solum is 30 to 48 inches thick. The soil is dry throughout the 4- to 12-inch control section for 60 to 70 consecutive days during the summer months. The A and upper B horizons are slightly to medium acid becoming less acid with depth; the lower B and C horizons are slightly acid to neutral. The 10- to 40-inch section has less than 35 percent clay. Coarse fragments are commonly absent in the series control section but the content ranges to 20 percent below 35 inches and up to 50 percent below 40 inches. The mollic epipedon is 20 to 40 inches thick. Mottles with croma of 2 or less occur above 30 inches. The A horizon has hue of 10YR or 7.5YR, value of 2 and 3 moist, and chroma of 2 and 3 moist or dry. The B horizon has hue of 10YR or 7.5YR, value of 2 through 4 moist, 4 through 6 dry, and chroma of 2 through 4 moist or dry. It is silty clay loam or clay loam with less than 15 percent coarser than very fine sand and averages less than 35 percent clay. The C horizon is clay loam to clay.

Competing Series and Their Differentiae: These are the Abiqua, Chehalis, Chehalem, and McAlpin series. Abiqua and McAlpin soils are fine textured. Abiqua soils lack mottles with chroma of 2 or less above 30 inches. Chehalis soils lack mottles with chroma of 2 or less within 30 inches of the surface. Chehalem soils have more than 35 percent clay in the control section.

Setting: The McBee soils are at elevations of 25 to 500 feet in flat depressed areas often some distance from large streams, and flat areas adjacent to small streams. The soils formed in moderately fine textured alluvium from sedimentary and igneous uplans of mixed mineralogy. Summers are warm and dry and winters are cool and moist. The annual precipitation is 40 to 60 inches. The average annual air temperature is 50° to 54°F., the average January air temperature is 39°F., and the average July air temperature is 67°F. The average frost-free period is 165 to 210 days.

Principal Associated Soils: These are the Cloquato, Wapato, and the competing Chehalis soils. Cloquato soils are well drained. Wapato soils are poorly drained.

Drainage and Permeability: Moderately well drained; slow runoff; moderate permeability. Soils are subject to overflow.

Use and Vegetation: Production of small grain, truck crops, hay, and pasture. Native vegetation is Douglas-fir, ash, wild rose, snowberry, blackberry and grass.

Distribution and Extent: Northern Willamette Valley in Oregon. The series is inextensive.

Series Established: Benton County (Benton Area), Oregon, 1970.

Remarks: The McBee soils were formerly classified as Alluvial soils integrading to Humic Gley soils.

Newberg Series

The Newberg series is a member of the coarse-loamy, mixed, mesic family of Fluventic Haploxerolls. The Newberg soils typically have dark brown sandy loam A and AC horizons, and dark brown and dark grayish brown stratified sandy loam and loamy sand C horizons.

Typifying Pedon: Newberg sandy loam-cultivated
(Colors are for moist soil unless otherwise noted.)

Ap 0-7"--Dark brown (10YR 3/3) sandy loam, brown (10YR 4/3) dry; moderate fine granular structure; soft, very friable; few fine roots; many irregular pores; medium acid (pH 6.0); clear smooth boundary. (7 to 12 inches thick)

AC 7-19"--Dark brown (10YR 3/3) sandy loam, dark yellowish brown (10YR 4/4) dry; weak fine subangular structure; soft, very friable; few fine roots; many irregular pores; medium acid (pH 5.8); clear smooth boundary. (6 to 12 inches thick)

C1 19-28"--Brown (10YR 4/3) coarse sandy loam, pale brown (10YR 6/3) dry; massive; soft, friable; few roots; many irregular pores; medium acid (pH 5.8); clear smooth boundary. (8 to 14 inches thick)

C2 28-48"--Dark grayish brown (10YR 4/2) loamy fine sand, pale brown (10YR 6/3) and light brownish gray (10YR 6/2) dry; single grain; loose; many irregular pores; medium acid (pH 5.8); gradual smooth boundary. (18 to 24 inches thick)

C3 48-64"--Dark grayish brown (10YR 4/2) loamy sand, light brownish gray (10YR 6/2) dry; single grain; loose; many irregular pores; medium acid (pH 6.0).

Type Location: Linn County, Oregon, five miles north of Albany, Oregon; 300 feet west of Interstate Highway No. 5. SE$\frac{1}{4}$ SE$\frac{1}{4}$ sec. 4, T.10 S., R.3 W.

Range in Characteristics: The soils are usually moist; they are dry between depths of 8 and 24 inches for 60 to 80 consecutive days. The mean annual soil temperature ranges from 52° to 55°F. The mollic epipedon is 7 to 20 inches thick. The control section averages loamy very fine sand or sandy loam and lacks contrasting texture. Depth to loamy fine sand containing less than 50 percent fine and coarser sand ranges from 25 inches to 40 inches. Amount of coarse fragments in the control section is as much as 15 percent by volume. The upper 10 inches has hue of 10YR, value of 2 or 3 moist and 4 or 5 dry, and chroma of 2 or 3. Horizons below the A1 or Ap horizon are structureless or have weak grades of subangular blocky structure. Below the A1 or Ap horizons the soil has hue of 10YR or 7.5YR, value of 3 or 4 moist and 5 or 6 dry, and chroma of 3 or 5; except that below depths of 2 or 3 feet chroma ranges from 2 through 4. Very gravelly or sandy substrata are below 40 inches.

Competing Series and Their Differentiae: These are the Cloquato, Clato, Evans, Gauldy, Kodak, Malo, Martini and Puyallup series. Clato soils have chroma of 4 at depths of less than 10 inches, and they contain less than 15 percent fine and coarser sand. Cloquato soils have mollic epipedons more than 20 inches thick, and contain less than 15 percent fine and coarser sand in the control section. Evans soils have medium texture in the control section. Gauldy and Puyallup soils have contrasting texture with the 40-inch control section. Gauldy soils have umbric epipedons. Kodak soils are very strongly calcareous. Malo soils are neutral to moderately alkaline. Martini soils are moderately calcareous.

Setting: Newberg soils are on floodplains at elevations of 100 to 650 feet. They formed in sandy alluvium derived from sedimentary and basic igneous rocks. Summers are dry and cool and winters are moist. The mean annual precipitation is 40 to 60 inches. The mean January temperature is 39°F., the mean July temperature is 67°F., and the mean annual temperature is 50° to 54°F. The frost-free season is 165 to 210 days.

Principal Associated Soils: These are the competing Clato and Cloquato soils and the Camas and Chehalis soils. Camas soils have coarse texture and are very gravelly in the control section. Chehalis soils have moderately fine texture.

Drainage and Permeability: Newberg soils are somewhat excessively and well drained. Surface runoff is slow; permeability is moderately rapid.

Use and Vegetation: These soils are used mainly for growing vegetables, fruit, and pasture. Native vegetation is ash, oak, Douglas-fir, willows, wild roses, blackberry, annual grasses and weeds.

Distribution and Extent: These soils are distributed along main stream channels in the Willamette Valley of Oregon and western Washington. The soils are of moderate extent.

Series Established: Yamhill County, Oregon, 1917.

Remarks: The Newberg soils were formerly classified as Alluvial soils.

Woodburn Series

The Woodburn series is a member of the fine-silty, mixed, mesic family of Aquultic Argixerolls. Typically, Woodburn soils have very dark brown or dark brown silt loam A horizons, and dark brown silty clay loam or heavy silt loam mottled Bt horizons.

Typifying Pedon: Woodburn silt loam-cultivated
(Colors for moist soil unless otherwise noted.)

Ap 0-9"--Very dark brown (10YR 2/2) silt loam, brown (10YR 5/3) dry; cloddy, with very weak subangular blocky structure; slightly hard, friable, slightly sticky, slightly plastic; many roots; many very fine and fine tubular pores; few fine irregular pores; common medium and fine reddish brown and black concretions; medium acid (pH 5.9); abrupt smooth boundary. (6 to 10 inches thick)

A12 9-17"--Dark brown (10YR 3/3) silt loam, brown (10YR 5/3) dry; moderate medium subangular blocky structure; hard, friable, slightly sticky, slightly plastic; common silt and sand grains on surfaces of peds; many roots; many very fine and fine tubular pores, and few medium pores; few thin darker colored (10YR 2/2) coatings on surfaces of peds; few reddish brown and black concretions; slightly acid (pH 6.2); clear smooth boundary. (0 to 8 inches thick)

B21t 17-25"--Dark yellowish brown (10YR 3/4) silty clay loam, brown (7.5YR 5/4) dry; moderate coarse and medium subangular blocky structure; hard, friable, sticky, plastic; common roots; many very fine tubular pores and few fine pores; few thin clay films on peds; few reddish brown and black concretions; few black stains on faces of peds; medium acid (pH 6.0); clear smooth boundary. (7 to 9 inches thick)

B22t 25-32"--Dark brown (7.5YR 4/4) silty clay loam, brown (10YR 5/3) dry; few fine and medium distinct mottles, dark gray (10YR 4/2) and light brownish gray (10YR 6/2) dry; few fine black concretions and stains on faces of peds; moderate medium and coarse subangular blocky structure; hard, friable, brittle, sticky, plastic; common roots; many very fine tubular pores; few fine tubular pores; continuous moderately thick clay films on surfaces of peds and in pores; medium acid (pH 5.8); abrupt smooth boundary. (6 to 10 inches thick)

B31t 32-39"--Dark brown (10YR 4/3) silt loam, brown (10YR 5/3) dry; distinct dark grayish brown (10YR 4/2) mottles in a few root channels, thin dark grayish brown (10YR 4/2) coating on plane surfaces, light gray (10YR 7/2) dry; massive but some planes of weakness that are indistinct; vertical planes are more distinct than horizontal planes; very hard, very firm, brittle, slightly sticky, slightly plastic; few roots; many very fine and fine tubular pores; continuous moderately thick clay films on plane surfaces and in some root channels and pores; few fine and medium black concretions and few black coatings on plane surfaces; medium acid (pH 5.7); gradual smooth boundary. (7 to 10 inches thick)

B32t 39-54"--Dark brown (10YR 4/3) silt loam, pale brown (10YR 6/3) dry; massive, with some indistinct vertical planes of weakness; very hard, very firm, brittle, slightly sticky, slightly plastic; many very fine and fine tubular pores; continuous thin clay films in pores and old root channels; few black concretions, and some patchy coatings on plane surfaces; medium acid (pH 5.9); gradual wavy boundary. (10 to 17 inches thick)

C1 54-68"--Dark brown (10YR 4/3) silt loam, pale brown (10YR 6/3) dry; massive; very hard, very firm, brittle, slightly sticky, slightly plastic; many very fine tubular pores; common moderately thick clay films in the larger pores and old root or worm channels; few black coatings in pores and channels; medium acid (pH 5.9); gradual wavy boundary. (14 to 16 inches thick)

C2 68-80"--Dark brown (10YR 4/3) very fine sandy loam, pale brown (10YR 6/3) dry; massive; very hard, firm, slightly sticky, slightly plastic; many very fine pores; few thin clay films in the larger pores and old channels; few small black stains or coatings in pores and channels; medium acid (pH 6.0); abrupt wavy boundary. (10 to 14 inches thick)

IIC3 80-92"--Dark brown (10YR 4/3) fine sandy loam, pale brown (10YR 6/3) dry; single grained; loose, friable; many fine interstitial pores; medium acid (pH 6.0).

Type Location: Marion County, Oregon; about 200 feet west of paved road to Champoeg; SW$\frac{1}{4}$ SE$\frac{1}{4}$ sec. 2, T.4 S., R.2 W.

Range in Characteristics: Soils are usually moist but are dry in all parts between 4 and 12 inches for 60 to 80 consecutive days during the summer months. The mean annual soil temperature ranges from 53° to 55°F. The soil is over 60 inches deep and the solum is 36 to 60 inches thick. Distinct mottles with chroma of 2 occur above 30 inches. The soils are slightly or medium acid. The A horizon to 10 inches or more has value of 2 or 3 moist and 4 or 5 dry, and chroma of 2 or 3 moist and dry. The B2 horizon has hue of 10YR or 7.5YR, value of 3 or 4 moist and 5 or 6 dry, and chroma of 3 or 4 moist and dry. It is heavy silt loam to silty clay loam with 20 to 30 percent clay. Its structure ranges from weak to moderate, medium or coarse prismatic and moderate fine to coarse subangular blocky. Some pedons have B3 and C1 horizons that are firm or very firm, and have weak structure or are massive, with vertical planes of weakness having gray silt coatings on faces. These horizons may or may not be brittle.

Competing Series and Their Differentiae: These are the Coburg, Hood, Silverton and Willamette series. Coburg soils have more than 35 percent clay in the Bt horizons. Hood soils have ochric epipedons. Silverton soils are well drained and lack mottles above 30 inches and are fine textured at depths of 25 to 40 inches. Willamette soils are well drained and lack mottles of chroma of 2 above 30 inches.

Setting: The Woodburn soils are on nearly level to gently sloping broad valley terraces formed in indistinctly stratified alluvium or lacustrine Willamette silts of upper Pleistocene age. The soils are at elevations of 150 to 400 feet above sea level. The climate is composed of warm, dry summers, and cool, moist winters. Mean annual precipitation is 40 to 50 inches. The mean annual temperature is 50° to 54°F., the average January temperature is 39°F., and the average July temperature is 67°F. The average frost-free period is 165 to 210 days.

Principal Associated Soils: These are the Aloha, Amity, Concord, and Dayton soils and the competing Willamette soils. Aloha soils have distinct mottles at less than 20 inches and lack Bt horizons. Amity and Concord soils have A2 horizons and are mottled and somewhat poorly and poorly drained. Dayton soils have an A2 horizon and a clay Bt horizon with an abrupt textural change.

Drainage and Permeability: Moderately well drained; slow to medium runoff; slow permeability.

Use and Vegetation: Used for growing berries, orchards, cannery crops, grain, hay and pasture. Native vegetation is Douglas-fir, oak and grass.

Distribution and Extent: Woodburn soils occur throughout the Willamette Valley in western Oregon. It is moderately extensive.

Series Established: Benton County (Benton Area), Oregon, 1970.

Remarks: The Woodburn soils were formerly classified as a Gray-Brown Podzolic intergrade to Brunizems.

Additional Data: Chemical data from Riverside SCS lab of typifying pedon (S62 Oreg. -24-4) in Marion County Area, Oregon Soil Survey Manuscript.