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Benefits and Potential Hazards

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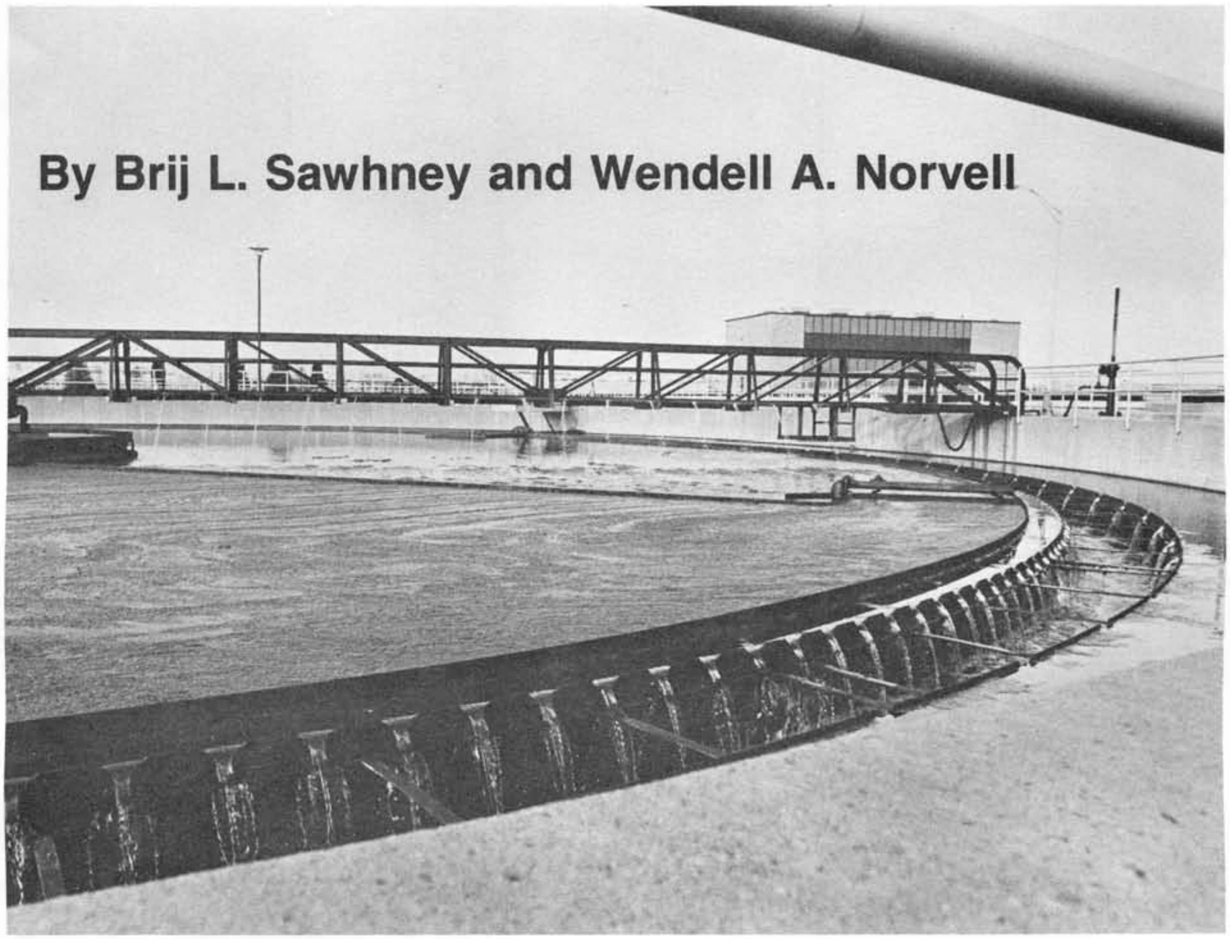

THE CONNECTICUT AGRICULTURAL EXPERIMENT STATION NEW HAVEN

SEWAGE SLUDGE FOR PLANT GROWTH: Benefits and Potential Hazards

By Brij L. Sawhney and Wendell A. Norvell

About one hundred thousand tons of sewage sludge are produced in Connecticut and over six million tons are produced in the United States annually. These large quantities of sludge need disposal that is economical and at the same time least harmful to the environment.

In the past, incineration, ocean-dumping and landfill have been the common methods of disposal. Because of expense and possible pollution of air and water supplies, these methods are now severely restricted. For example, incineration requires fuel and pollutes the air, while ocean dumping adversely affects marine life. Scarcity of suitable sites and possible pollution of ground water limit disposal in landfills.

Because sewage sludge contains valuable plant nutrients and considerable organic matter, its application to cropland may provide an alternate means of disposal and a useful resource. During the 1940s and early 1950s H.A. Lunt of this Station pioneered in investigating the usefulness of sludge as a soil amendment. The results were reported in 1959 as Station Bulletin 622: "Digested Sewage Sludge for Soil Improvement". Lunt's work and other studies have established that application of sludge to soils improves their physical properties, particularly water-holding capacity and soil structure. In addition, sludge applications usually increase crop yields. During the past decade, numerous laboratory, greenhouse and field investigations on various aspects of land application of sludge have been conducted to determine whether land application would be the most logical option for sludge disposal. Several recent reviews on the subject include: Page (1974), Baker and Chesnin (1975), Chaney and Giordano (1977), Chaney et al. (1978), Leeper (1978) and EPA (1976).

Despite the benefits, sludge application to cropland involves actual or potential hazards from the presence of disease-causing organisms, the release of excess nitrogen to ground water, and relatively high concentrations of heavy metals which can be toxic to plants and may be harmful to animals or humans consuming these plants.

As shown in Table 1, the heavy metal composition of sewage sludge varies over a wide range, depending primarily upon the sources of the waste entering the treatment plant. When the sewage reaching the treatment plant is primarily of domestic origin, the resulting sludge is relatively low in heavy metals. Contamination with industrial wastes, however, can result in sewage sludge containing excessive amounts of heavy metals. The kind of industry determines the dominant metals present. The suitability of a sludge for land application depends on the type and degree of contamination.

We report here results of our experiments on growth and uptake of heavy metals by corn grown in soils amended with large quantities of digested sewage sludge. We chose a high application rate, 80 tons/acre, for two reasons. First, it is the equivalent of 5-10 years of moderate use and thus affords an opportunity to determine the effects of cumulative applications. Second, it represents a more economical application rate for sludge disposal when there is less concern about growing crop plants on the land. In addition to presenting our results, we discuss potential hazards from human disease organisms associated with land application of sewage wastes and suggested application rates of sludge in relation to its composition and to soil characteristics.

EXPERIMENTAL

Anaerobically digested sewage sludge (filter cake) obtained from the Town of Milford treatment plant was dried and pulverized for use. Two different soils, a coarse-textured soil (Merrimac fine sandy loam) and a fine-textured soil (Buxton silt loam) were used as planting media. To obtain equal soil volume, 600 g of Merrimac soil and 500 g of Buxton soil were weighed into 5" plastic pots and mixed uniformly with the various amendments added in different treatments. The five soil treatments included sewage sludge and inorganic heavy metal treatments as described below and in Table 2.

1. C -- Control soil with adequate inorganic fertilizer, for comparison with soils treated with sewage sludge and heavy metals.
2. SS -- Sewage Sludge, no other fertilizer.
3. M(I) -- Heavy metals as inorganic salts equivalent to amounts in the added sludge plus adequate inorganic fertilizer. This treatment is comparable to treatment 2, except that the heavy metals were added in readily available form.
4. SS + M(II) -- Sewage sludge plus inorganic salts of heavy metals roughly equivalent to the amounts present in a municipal sludge. This treatment is designed to evaluate the ability of sewage sludge to alter the availability of additional inorganic heavy metals which might, for example, arise from industrial contamination.
5. M(I) + M(II) -- Heavy metals as inorganic salts added in amounts equal to the inorganic salts in treatments 3 and 4 plus adequate inorganic fertilizer. This treatment is comparable to treatment 4 except that all metals were added in readily available forms.

These treatments were applied in triplicate at two phosphorus levels (normal and high) and three pH levels (very acid, moderately acid and slightly acid). Soils were leached with water to remove excess soluble salts and incubated in the greenhouse for 4 weeks at field moisture capacity before planting. Five seeds of field corn were planted in each pot. Seedlings were thinned to two plants per pot and allowed to grow for a six-week period. Pots were watered with deionized water as needed. Two crops of corn were grown during April and May of two successive years. The soils between crops were wetted and dried occasionally to encourage reaction of heavy metals and sludge with soils.

The corn tops were harvested, washed with a weak detergent solution to remove any soil particles adhering to foliage, rinsed in distilled water, and dried at 70 C. After the second crop, roots also were harvested, washed to remove soil and dried. Dried corn samples were ground in a stainless steel Wiley mill, digested in nitric-perchloric acid, and analyzed by atomic absorption spectrophotometry. Differences in yield were analyzed using the Duncan Multiple Range Test.

As shown in Table 1, the Milford sludge used in our experiments was relatively low in Zn and Cu, moderate in Ni, and high in Cd. The amounts of various heavy metals added in different treatments (Table 2) lie within the range of these metals found in soils, except for Cd, which was above the observed range and well above the average concentration. For comparison, Table 3 shows the concentrations of Zn, Cu, Ni, and Cd found commonly in soils and both the required and toxic levels of these metals in plants and in animal diets (from Allaway, 1968).

RESULTS AND DISCUSSION

The main effects of different treatments on plant growth and metal uptake are discussed below while detailed results are given in the appended tables.

Effect of Sewage Sludge, Inorganic Metals, and Lime on Yield of Corn:

Visual observations as well as measured yields affirmed that plants often grow better on soil amended with sewage sludge than on control soils receiving conventional fertilizer. For example, the results in Fig. 1 show that corn yield on Buxton silt loam soil treated with sludge was 22-23% higher than on the control soil at very acid and moderately acid soil pH. The yield was not significantly different on slightly acid soil. Corn yield on Merrimac fine sandy loam soil treated with sludge was also higher than on the controls on moderately and slightly acid soil, but was lower than the control on very acid soil. Similar increases in crop yield from sludge application to soil have been noted by others in vegetables (Lunt, 1959), forage (Boswell, 1975), lucerne (Wells and Whitton, 1976), wheat (Sabey et al., 1977), corn (Struble, 1974), soybeans (Hinesly et al., 1976) and other crops. These increases in yield when compared to conventional fertilizers are attributed to better soil structure (Epstein et al., 1976) resulting from sludge application and to increased water holding capacity of the soil. In our experiments, the addition of sludge increased the water holding capacity by 53% in Merrimac soil and by about 30% in Buxton soil.

The results in Fig. 1 and Table 4 also show that when heavy metals in amounts equivalent to those present in the sludge were added as inorganic salts the yield of corn was greatly reduced at all pH levels. The reduction was greatest in very acid soils; less than one fourth as much corn was

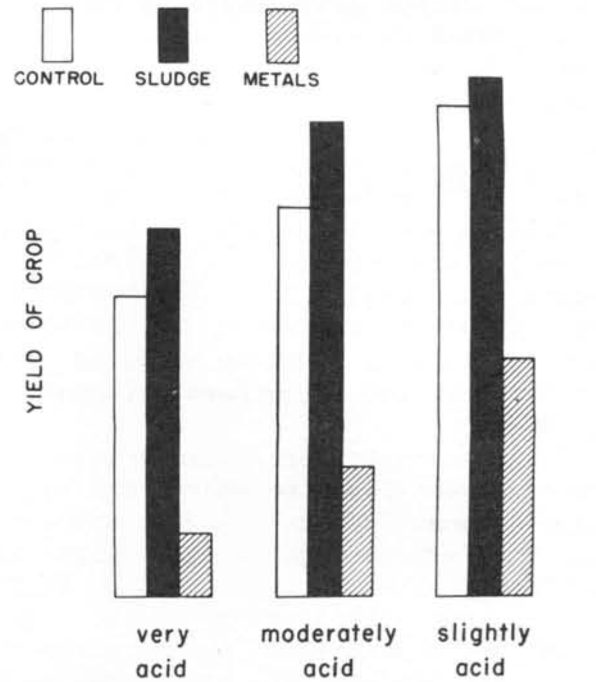

Fig. 1. Effect of sewage sludge and inorganic metals on yield of corn grown in very acid, moderately acid and slightly acid Buxton silt loam soil.

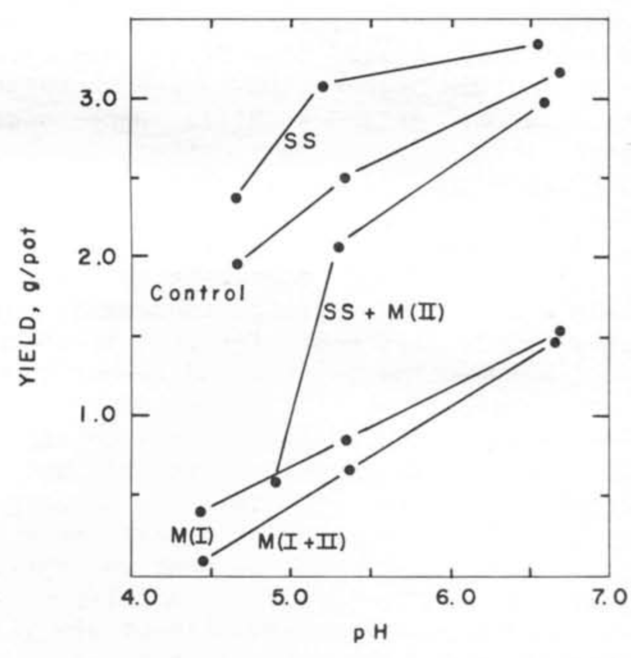

Fig. 2. Effect of sewage sludge, inorganic metals and combinations of sewage sludge and inorganic metals on yield of corn grown in Buxton silt loam soil at different pH values.

produced in the presence of inorganic metals as in the control soil where no metals were added. Added as sludge, however, the same amount of heavy metals was not detrimental. Instead, corn yields were higher. Although the toxicity of heavy metals in sludge is far less than in inorganic forms, excessive or repeated additions of sludge from industrial areas may produce toxic effects of metals and reduce crop yield. For example, applications of 50 tons/acre of sludge containing excessive metals to soils at pH 5.5 reduced snapbean yield to 34% of the control in pot experiments (Chaney et al., 1978).

Other examples of yield reduction of crops have been reported where land was used as sludge farms (Rhode, 1962), where field soils received sewage sludge with large concentrations of heavy metals (Webber, 1972) or metal salts (Walsh et al., 1972), and in pot experiments where soils were amended with sludges of high metal content (Cunningham et al., 1975) or heavy metal salts (Bingham et al., 1976).

Data in Fig. 2 show that maximum corn yield was obtained on Buxton soil treated with sewage sludge (SS) and minimum yield was obtained on soil where the highest rates of inorganic metals M(I) + M(II) were added. Where the mixture of sewage sludge and inorganic metals SS + M(II) was added, the yield was higher than where inorganic metals alone M(I) + M(II) were added, showing that high organic matter in sludge may reduce the toxicity of the inorganic metals.

Data in Fig. 2 also show that additions of lime increased corn yields in all treatments. The yield increases were significantly different for all treatments except between the control and sewage sludge at the highest pH. In treatments where heavy metals were added, the increase in yield on liming may in part be due to decreased toxicity of metals. Hinesly et al., (1977) grew corn on a soil to which sludge with a high metal content was applied annually from 1968 to 1975. A total of 417 T/A of sludge was applied without any yield decreases when the pH of the soil was maintained above 6. Thus, frequent liming may prevent heavy metal toxicity to plants even where excessive sludge is applied to soil.

Sometimes, heavy metal toxicity can be reduced by additions of phosphate to soils. Our data in Fig. 3 show that much higher yields were obtained on the Buxton soil to which extra phosphate (equivalent of 1000 lbs. P/A) was added in addition to the inorganic metals (curve M(I) + P) than on the soil where only inorganic metals and standard fertilizer additions were made (curve M(I)). Again, all yields increased with increasing pH. Extra phosphate increased the yield in the control soil also, but the increases in yield above pH 5 were much greater in metal treated soils. Application of additional phosphate to sludge-treated soil did not produce additional increases in yield (Table 4), presumably because the sludge contained adequate phosphorus (Table 1).

Increasing reaction time also decreases the toxicity of metals added to soil. In our experiments, toxic effects were markedly reduced in the second crop grown on the soils amended with inorganic metals. The data in Fig. 4 compare the yields of corn in the first and the second years on the moderately acid Merrimac soil with different treatments. The greater yields in the second than in the first year on the soil with metal treatments demonstrate that the toxic effect of metals was reduced with time. However, the yield losses from inorganic metals were not completely eliminated as the yields did not equal the control or the sludge treatment. The reduction in toxicity undoubtedly results from conversion of the metals to less available forms. Decreased uptake of metals by plants with time after applications of sludge and in successive crops have been observed by others (Hinesly et al., 1977; Kelling et al., 1977).

Uptake of Heavy Metals:

The concentrations of Zn, Cu, Ni, and Cd in corn grown in the two soils with different treatments are given in detail in Tables 5-12 in the Appendix while their concentrations in Buxton soil treated with sewage sludge and with inorganic salts of heavy metals are illustrated in Figs. 5-7.

Zinc. The results in Fig. 5 show the uptake

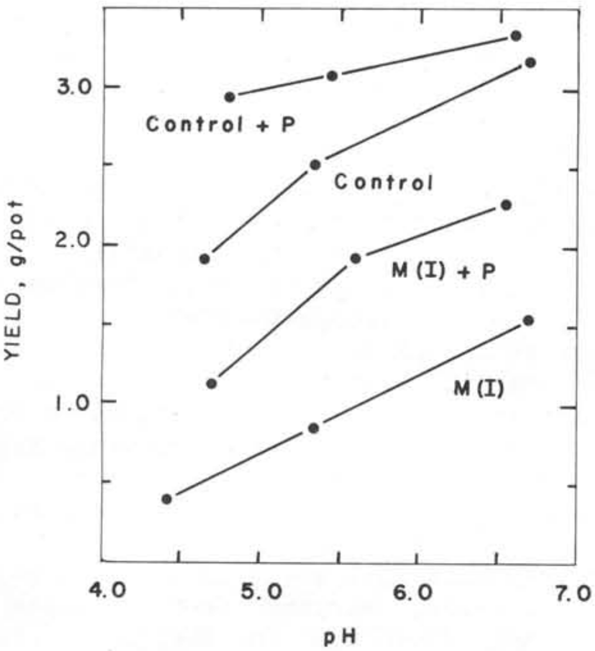

Fig. 3. Effect of P additions on yield of corn grown in Buxton silt loam soil at different pH values.

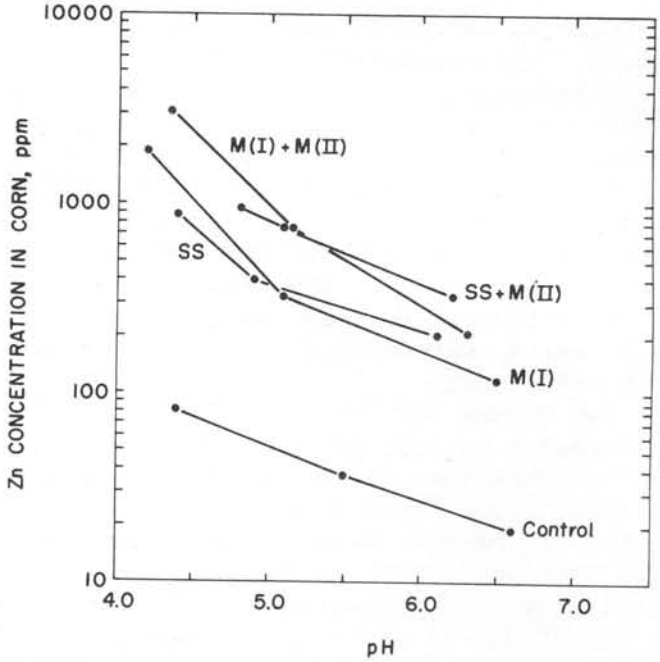

Fig. 5. Effect of sewage sludge and inorganic metals on Zn uptake by corn grown in Merrimac fine sandy loam soil at different pH values.

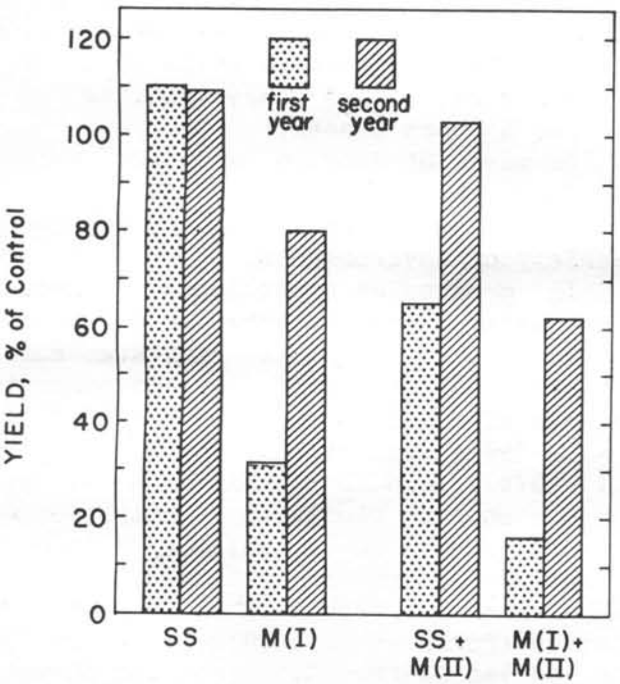

Fig. 4. Comparison of yields of corn, grown in first and second year, on the moderately acid Merrimac fine sandy loam soil with different treatments.

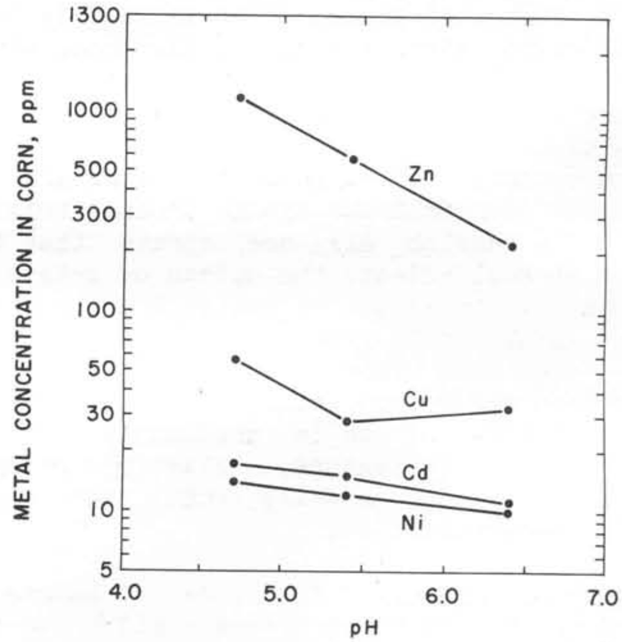

Fig. 6. Effect of pH on uptake of Zn, Cu, Cd, and Ni by corn grown in Merrimac fine sandy loam treated with inorganic metals.

of Zn for different treatments. At the lowest soil pH, the concentrations of Zn in corn plants were lowest in the control treatment, followed by the sludge treatment, then by the inorganic metal salts in amounts equal to the metals in sludge, then by sludge with metal salts added, and finally by the treatment receiving the double rate of metals as inorganic salts. At pH values below 5, the concentrations of Zn in plants in all treatments, except the control, were in the range generally considered toxic to plants. Nevertheless, no toxicity symptoms were observed and growth was excellent in sludge-amended soil despite Zn concentrations as large as 900 ppm Zn in the corn tissue. However, similar concentrations of Zn taken up from inorganic metal salts were associated with drastic yield reductions.

The uptake of Zn was markedly reduced by increases in soil pH. At the highest pH, the concentrations of Zn in the corn plants decreased below toxic levels, yet the yield in the inorganic metal salts treatment, M(I), was less than half the maximum yield obtained by sludge treatment, SS. Whether the reduction in yield by inorganic metal salt treatment was due to their greater toxicity than to the metals in sludge is not known. Results reported by Chaney (1973) and Chaney, White and Simon (1975) also show that increased pH reduced the uptake of Zn by a number of crops. It is likely that many toxic effects occur at the root where the readily available heavy metals from inorganic sources may injure roots and reduce crop yield even though the amounts of metals translocated into the tops are no greater than from the sludge treated soil.

The results also demonstrate that the type of soil affects the uptake of metals by crops. A comparison of Tables 5 and 6 shows that uptake of Zn from the Buxton silt loam is much less than the uptake from the Merrimac sandy loam soil. The differential availability of Zn is presumably due to differences in texture, clay mineralogy, cation exchange capacity (CEC) and other soil characteristics.

Copper and Nickel. The uptake of Cu and Ni by corn plants shows trends similar to the uptake of Zn. For example, the results in Figs. 6 and 7 and Tables 7-10 show that at low pH, concentrations of these metals in corn grown on inorganic metal treated soils are higher than in the corn on the sludge treated soils, while at high pH, similar concentrations are found in both treatments. Again, uptake of these metals from the fine-textured Buxton soil is less than from the coarse-textured Merrimac soil. Compared to the amounts of metals added in the two treatments, the uptake of Cu and Ni is much less than Zn.

Cadmium. Uptake of Cd by corn plants grown in the two soils is shown in Fig. 8 and in Tables 11 and 12 in the Appendix. The results show that the Cd concentrations in corn grown on sludge-amended soils were similar at all pH values, varying only from 16-18 ppm in Buxton and 11-17 ppm in Merrimac soil. Concentrations of Cd in corn grown on soils amended with inorganic salts were very high in the very acid soils: 130 ppm in Buxton and 42 ppm in Merrimac soil. However, the concentrations in corn grown on moderately acid soil and slightly acid soils were much lower, varying from 18-23 ppm in Buxton and 11-14 ppm in Merrimac soils. Similarly, Chaney et al., (1975) found a dramatic reduction in Cd uptake by soybeans with increased pH.

The concentration of Cd in corn grown on untreated soils was very low, only about 1 ppm. Clearly, when the sludge containing 126 ppm Cd was applied to soils at a rate of 80 tons/acre, high concentrations of Cd occurred in corn plants.

Because of concern about Cd entering the food chain, plant scientists have examined Cd uptake by a variety of crops in a variety of environments.

In greenhouse experiments, where Cd salts were added to the soil alone or together with sludge to simulate readily available sources of Cd, yield reductions and excessive Cd uptake was observed (John et al., 1972; Iwai et al., 1975; Bingham et al., 1976). In other experiments, where sludge alone or sludge in combination with smaller amounts of Cd salts were added to the soil, no reductions in yield and only moderate concentrations of Cd in plants were observed (Jones et al., 1973; Kirkham, 1975; John and Van Laerhaven, 1976; and Street et al., 1977). Chaney and Hornick (1978) have recently reviewed these and other investigations concerning Cd uptake by plants.

Effect of Time on Metal Uptake:

Concentrations of different metals in the second corn crop were markedly lower

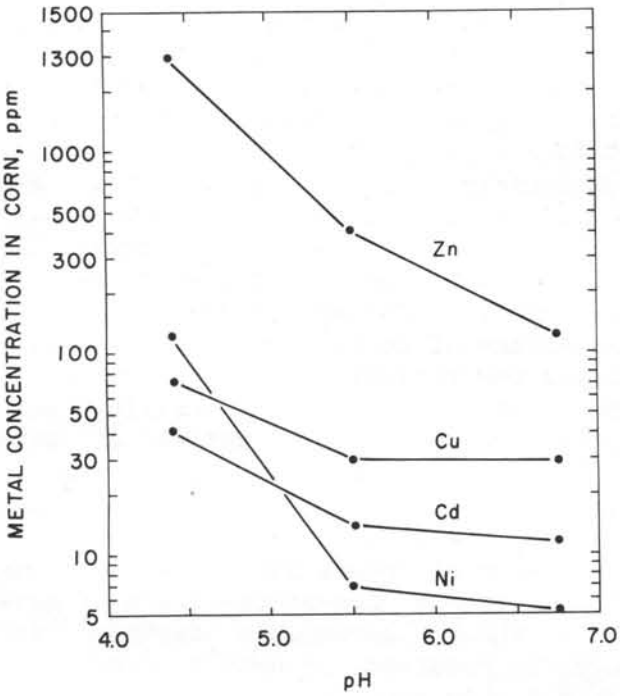

Fig. 7. Effect of pH on uptake of Zn, Cu, Cd, and Ni by corn grown in Merrimac fine sandy loam soil treated with inorganic metals.

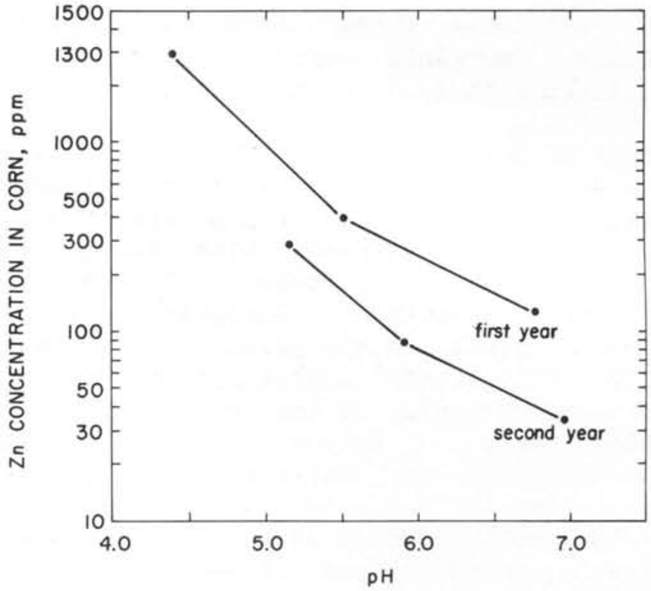

Fig. 9. Comparison of Zn uptake by corn grown in the first and second year on Merrimac fine sandy loam soil treated with inorganic metals.

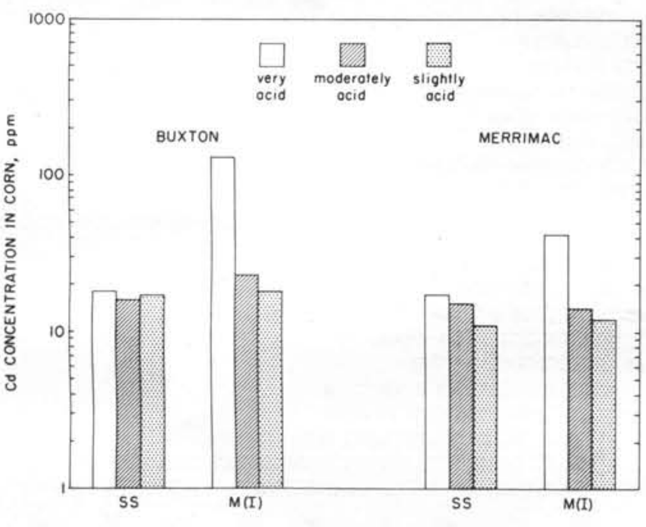

Fig. 8. Effect of sewage sludge and inorganic metals on Cd uptake by corn grown on very acid, moderately acid, and slightly acid Buxton silt loam and Merrimac fine sandy loam soils.

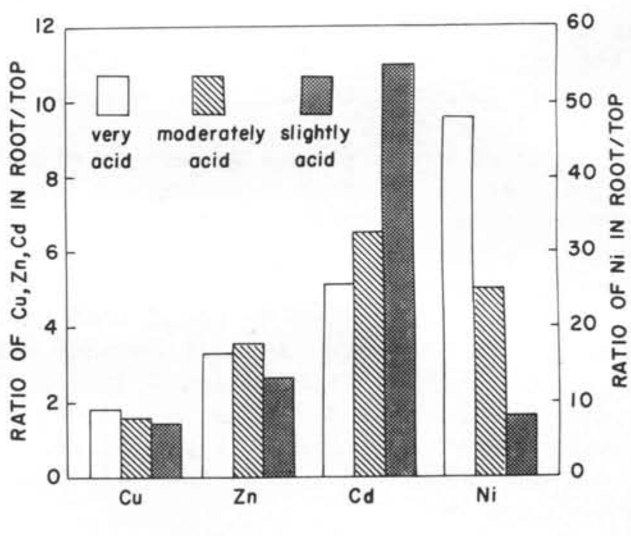

Fig. 10. Ratio of concentrations in root to top of Cu, Zn, Cd, and Ni in corn grown during the second year in Merrimac fine sandy loam soil treated with inorganic metals.

than in the first crop (Tables 5-12). As an illustration, Fig. 9 shows that Zn uptake by the second crop was about one-fourth as much as the first crop. Similar observations have been made by Cunningham et al. (1975) and Hinesly et al. (1976). These reductions in metal uptake in successive croppings are attributed to the conversion of metals to less available forms such as sparingly soluble inorganic compounds or stable complexes with soil organic matter.

Uptake of Heavy Metals by Roots:

Our results on uptake of different metals by the roots of corn plants grown in the two soils amended with sludge and inorganic metals are shown in Tables 13-16 in the Appendix. Concentrations of different metals in the plant roots are much higher than their concentrations in the above-ground parts of the plants given in Tables 5-12. Ratios of the metal concentration in root/top are further illustrated in Fig. 10 for corn grown in Merrimac soil amended with inorganic metal salts. Concentrations of metals in roots divided by the concentrations in tops (root/top ratio) are greater than 1. Concentrations of Zn and Ni in the roots as well as in the plant tops decreased with increases in soil pH, whereas concentrations of Cu change little and concentrations of Cd decreased in corn tops but changed little in roots. The ratios for Cu and Zn vary only slightly with pH whereas the ratio for Ni is almost 5 times higher in the very acid soil than in the slightly acid soil, suggesting that at low pH the high levels of available Ni are much less readily translocated from the roots into the tops. The opposite is true for Cd.

Roots of crop plants grown in sludge-amended soils often contain higher concentrations of metals than stems and leaves, which in turn contain higher concentrations than the fruit or the grain. For example, Kirkham (1975) found that roots of barley plants grown in soil amended with sludge containing 65 ppm Cd and 4,350 ppm Zn contained as much as 8.7 ppm Cd and 446 ppm Zn while leaves contained 2.2 ppm Cd and 295 ppm Zn and grain contained only 67 ppm Zn and <.25 ppm Cd.

Differences Amongst Crops:

Different species and varieties of plants vary greatly in their ability to absorb metals from the soil and translocate them into the tissue. An illustration of the differences amongst crops in Cd uptake from Cd-enriched sewage sludge added to a soil is given in Fig. 11 (taken from Chaney and Hornick, 1978 based on data by Bingham et al., 1975; 1976). Concentrations of Cd in leafy vegetables are many times higher than in grasses. Fruits and grains were significantly lower in Cd than leaves and stems of plants. In general, grains accumulate much less metal than stems and leaves (Giordano et al., 1975 (corn), Clapp, et al., 1976 (corn), Chaney et al., 1976 (soybeans)). Chaney (1973) has reported that uptake of Zn by sugarbeets, chard, and mustard was several times greater than by a number of other crops. Kelling et al. (1977) reported that uptake of various metals by sorghum-sudan grass was much greater than by rye. Dowdy and Larson (1975) observed that lettuce is an accumulator of heavy metals while potatoes and carrots are non-accumulators of metals. Plants which accumulate certain metals could, if required, be used to remove metals from a contaminated soil. Other data on the uptake of metals by various crops are listed in a U.S. EPA report (1976).

Crops also differ in their sensitivity to toxic metals.

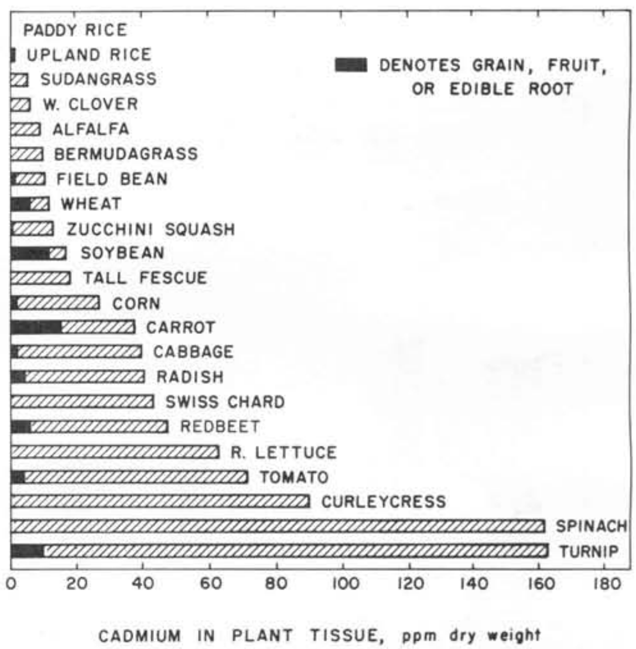

Fig. 11. Cd concentrations in different plant species grown in a soil amended with Cd-enriched sewage sludge (from Chaney and Hornick, 1978).

Vegetable crops are very sensitive to toxic metals while most field crops are less sensitive and most grasses are generally tolerant of high metal contents.

Possible Health Hazards from Metals in Sewage Sludge:

Amongst the heavy metals in sludge, Zn, Cu, and Ni are so toxic that serious plant damage would be expected to occur before these elements are accumulated in amounts that could endanger those consuming the plants. Cadmium, however, enters plants readily and is said to be harmful to man and animals at low levels (EPA, 1975). Based on present estimates of Cd in the human diet in the U.S., it seems prudent to avoid increasing Cd in the food chain and refrain from use of sewage sludge with high Cd content.

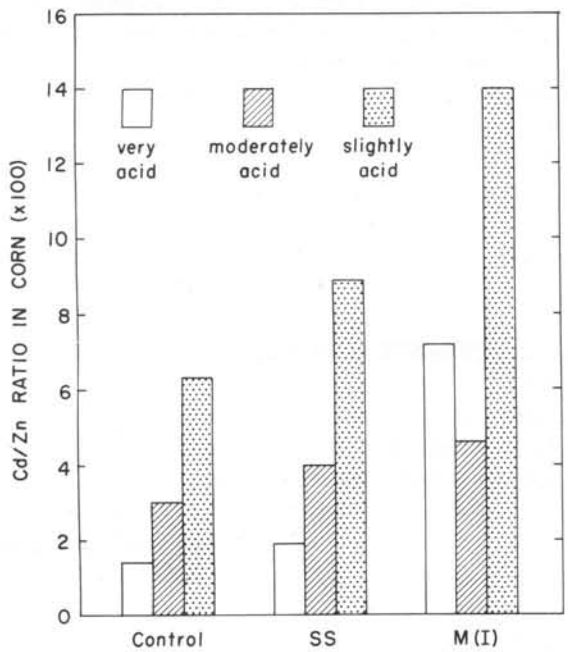

Fig. 12 Effect of sewage sludge and inorganic metals on Cd/Zn ratio in corn grown in very acid, moderately acid, and slightly acid Buxton silt loam soil.

Cd/Zn Ratio:

The accumulation of Cd by crops and the entry of Cd into the food chain is thought to be reduced by competition with available Zn. Relatively large concentrations of Zn, i.e., a low Cd/Zn ratio, should lower the uptake of Cd. The results of Cunningham et al. (1975) show that increased Zn in the soil decreased the Cd/Zn ratio in corn. Similarly, Haghiri (1974) found a depression in Cd concentration in soybean shoots when Zn levels were high in the soil. Competition between the two metals is also demonstrated by the results of Bingham et al. (1975) which show that additions of Cd as $CdSO_4$ decreased Zn accumulation in the leaves and edible tissues of a number of vegetables.

Ratios of the concentrations of Cd/Zn in corn grown in our experiments are given in Tables 17 and 18. The general pattern of the distribution of these metals is illustrated in Fig. 12 for corn grown on Buxton soil. Greater reductions in uptake of Zn relative to Cd occurred at higher pH and resulted in higher Cd/Zn ratios. One of the criteria suggested for application of sludge on cropland is a Cd content of less than 1% of Zn (EPA, 1977). However, precise limits are hard to justify because the uptake of Cd and Cd/Zn ratios in crops vary markedly, with soil characteristics as well as plant type.

Disease Hazards of Land Application of Sludge:

Potential hazards from human disease organisms associated with sewage sludge have been discussed in detail in two recent reviews (Menzies, 1977; Burge and Marsh, 1978). Although pathogenic viruses, bacteria, and other organisms are detected in processed sewage wastes, there are no reports of sewage-caused disease amongst sewage treatment plant workers who are subject to continual exposure during plant operations and handling of the sludge. Neither are there known instances of disease caused by these pathogens in populations living near treatment plants or farms where sewage sludge has been applied. On the other hand, there have been instances of the spread of disease by handling of raw sewage solids, untreated sewage water, night soil, and material pumped from septic tanks for disposal.

From reports in the literature, it appears that sludges from anaerobic digestion, aerobic digestion, and lime stabilization are sufficiently free from pathogens to be suitable for use on land. In addition, since most pathogenic organisms do not multiply outside of living hosts, their numbers are further reduced in the soil environment with time. The Connecticut State Department of Health recommends that if digested sewage sludge is used on root crops that are to be eaten raw, the sludge be applied and worked into the soil at least six months prior to planting.

Acceptable Sludge Application Rate:

Characteristics of the soil and the composition of the sludge are the factors to be considered in determination of the rates of sludge application to agricultural land. The information needed to determine sludge application rates include nitrogen (organic and inorganic) and heavy metal contents of sludge, and the pH, cation exchange capacity, and availability of major nutrients in the soil.

The following two procedures for determination of application rates for agricultural lands are suggested in guidelines of the U.S. EPA (1977).

Nitrogen Content of Sludge.

To prevent ground water pollution with NO_3, it has been suggested (EPA, 1977) that the rate of application should be such that the total available N in the soil does not exceed twice the N requirement of the crop to be grown. The available N includes (1) N mineralized from the soil, (2) inorganic N from sludge (both NH_4 and NO_3), and (3) N released by mineralization of sludge. It is estimated that organic N in sludge becomes available at a rate of 20% during the first growing season and at a rate of 3% for the subsequent three growing seasons.

Based on the 2.5% N contained in a typical city sludge (Table 1), and on the assumptions that 50% of the N is in inorganic form and that the soil is extremely deficient in N, application of about 20 T/A sludge containing about 25% dry matter should supply sufficient N to grow 16-20 tons/acre corn silage.

Heavy Metals in Sludge.

To prevent toxicity of metals to plants and to control the unnecessary entry of certain metals, particularly Cd, into the human food chain, it has been recommended that the total cumulative additions of metals in sludge applied to soils of different cation exchange capacities (CEC) be restricted to the amounts shown below (EPA, 1977):

Total cumulative additions of metals to soils of different CEC

Metal	Cation exchange capacity (CEC), me/100 g		
	0-5	5-15	>15
	lb/A		
Pb	500	1000	2000
Zn	250	500	1000
Cu	125	250	500
Ni	50	100	200
Cd	5	10	20

The recommendations limit the total cumulative amount of Milford sludge to 20, 40, and 80 T/A for soils with the CECs shown above. In contrast, fairly large and repeated applications of the Milford sludge could be made to supply the N requirement of a corn crop. Determinations of the application rates by both methods need to be made, since these guidelines require that the lesser of the two amounts be applied to land.

SUMMARY AND CONCLUSIONS

Land application (of sewage sludge) is an advantageous method of utilizing sludges produced by many municipal sewage treament plants. Valuable plant nutrients contained in the sludge are reused and crop yields usually increase. However, land application poses certain potential hazards which may limit the use of sludge on cropland. Of major concern is the presence of excessive amounts of heavy metals such as Zn, Cu, Ni, and Cd which derive largely from industrial effluents entering the treatment plant. High levels of Zn, Cu, and Ni are very toxic to plants, and usually injure plants before dangerous levels of these metals accumulate in edible plant parts. More serious is the ready uptake of Cd by many crop plants and its subsequent entry into the food chain.

To understand the uptake of various metals by crop plants, we grew corn on a coarse-textured sandy loam soil and a fine-textured silt loam soil, amended with sewage sludge at a rate of 80 tons/acre or with inorganic metals in amounts equal to those present in sludge. Additional inorganic metals were added to soils amended with sludge and inorganic metals in separate treatments. Lime and superphosphate were mixed with the soils to give three pH levels and two phosphate levels.

The results show that the concentrations of different metals in plants grown in soils amended with inorganic metals are often much greater than in soils amended with sewage sludge. Regardless of source, the concentrations of metals in plants increased with increasing metals in the soil. Plants grown in soils of very low pH contained excessively large concentrations of metals in both roots and tops. Inorganic sources of metals reduced yields, especially at low pH. Increasing the soil pH by additions of lime markedly decreased the uptake of the metals, regardless of their source, as did the addition of phosphate. Crops grown in the second year contained much lower concentrations of metals, indicating their conversion in the soil to less available forms.

Guidelines of the U.S. EPA (1977) for determining the rate of sludge application which would prevent ground water pollution from N and metal toxicity to plants and animals are summarized. Selection of safe application rates requires knowledge of the composition of sludge, and the characteristics of the soil and the crop to be grown. These guidelines suggest that sludge application rates should be such that the total amount of plant available N applied to soil does not exceed twice the N requirement of the crop to be grown and the total cumulative additions of metals do not exceed the suggested limits. Furthermore, to minimize entry of Cd in the food chain, these guidelines suggest that land application should be limited to sludge with low Cd content (less than 25 ppm) or with a Cd/Zn ratio of less than 1%.

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APPENDIX

Table 1. Composition of sewage sludge samples from Connecticut and other locations

Location	Year	Organic Matter	N	P_2O_5	Zn	Cu	Ni	Cd	Pb
			%				ppm		
Ansonia	1973								
heat dry		75	2.3	2.8	5650	2200	169	81	5600
bed dry		66	2.4	2.2	5050	2350	38	57	2000
Branford	1972	59	3.3	3.2	1700	1800	30	13	720
Enfield#	1975	-	3.3	2.6	582	665	70	5	220
Fairfield	1977	53	2.9	5.0	2812	1800	305	37	860
Hartford	≈1960	32	1.3	3.6	1875	1100	104	187	660
New Haven									
East Shore	1973	44	2.3	1.9	4380	1567	53	10	1712
	1970	52	2.1	1.1	2000	1500	138	12	2700
Boulevard	1971	66	1.6	1.3	1438	1013	157	67	1373
Milford	1973	36	2.6	2.9	1940	1630	150	126	375
Plainville	1977	-	-	-	1025	550	166	150	185
Michigan##									
median		-	-	-	2200	700	52	12	480
mean		-	-	-	3315	1024	371	74	1380
U.K.##									
median		-	-	-	3000	800	80	-	700
mean		-	-	-	4100	970	510	-	820
Sweden##	1968-1971								
median		-	-	-	1567	560	51	7	180
mean		-	-	-	2055	791	121	13	281
Connecticut									
mean		53	-	2.5	3400	1900	-	-	-
range		37-77	-	0.8-5.0	600-8400	500-4200	-	-	-

undigested, lime stabilized

Page (1974)

Table 2. Application rate of heavy metals added to soils in sewage sludge and inorganic metal compounds

Metal	Soil Treatments*				
	C	SS	M(I)	SS+M(II)	M(I)+M(II)
	lb/acre				
Zn	0	310	280	710	680
Cu	0	260	208	500	448
Ni	0	24	24	48	48
Cd	0	20	16	39	35

* C = Control, no added metals

SS = Sewage sludge addition, equivalent to 80 tons dry sludge/acre

M(I) = Addition of inorganic metals approximately equal to metals in treatment SS

M(II) = Addition of inorganic metals approximately equal to metals in a typical city sludge

Table 3. Heavy metals in soils, plants, and animal diet

Metal	Conc. in Soil		Conc. in Plants		Critical Levels in Animal Diet	
	average	range	required	toxic	required	hazardous
Zn	50	10-300	8-15	>200	10-40	low
Cu	20	2-100	2-4	>20	1-10	low
Ni	40	10-1000	none	>50	none	low to moderate
Cd	.06	.01-7	none	>10	none	moderate to high

Table 4. Yield of corn on Buxton and Merrimac soils in first crop as influenced by additions of sewage sludge and inorganic metals

Soil	Phosphorus Rate	Soil Acidity	pH Range	Yield of Corn in g/pot				
				C	SS	M(I)	SS + M(II)	M(I) + M(II)
Buxton	Normal	Very acid	4.4-4.9	1.93	2.36	0.41	0.57	0.09
		Moderately acid	5.2-5.4	2.51	3.09	0.85	2.09	0.67
		Slightly acid	6.5-6.7	3.17	3.35	1.55	2.99	1.13
	High	Very acid	4.6-4.9	2.98	2.53	1.13	0.80	0.16
		Moderately acid	5.2-5.6	3.08	2.84	1.93	2.43	1.15
		Slightly acid	6.4-6.6	3.35	2.65	2.27	2.65	2.87
Merrimac	Normal	Very acid	4.4-5.0	2.07	1.54	0.14	0.25	0.11
		Moderately acid	5.4-5.7	2.37	2.79	0.79	1.65	0.40
		Slightly acid	6.4-6.7	2.47	2.87	1.37	2.76	1.00
	High	Very acid	4.5-5.0	2.74	1.49	0.45	0.35	0.13
		Moderately acid	5.3-5.9	2.64	2.59	1.68	1.67	0.67
		Slightly acid	6.3-6.7	2.87	2.58	1.98	2.76	1.60

Table 5. Concentration of Zn in corn grown on Buxton soil treated with sewage sludge and inorganic metals

Phosphorus Rate	Soil Acidity	Concentration of Zn, ppm				
		C	SS	M(I)	SS + M(II)	M(I) + M(II)
		First Year				
Normal	Very acid	71	933	1810	957	2680
	Moderately acid	32	399	501	688	645
	Slightly acid	16	191	129	284	277
High	Very acid	36	720	1300	789	1750
	Moderately acid	28	441	326	720	644
	Slightly acid	15	242	117	328	170
		Second Year				
Normal	Very acid	28	448	261	424	525
	Moderately acid	11	46	64	118	425
	Slightly acid	9	23	22	43	72
High	Very acid	18	438	173	425	616
	Moderately acid	10	60	49	84	112
	Slightly acid	10	24	22	39	38

Table 6. Concentration of Zn in corn grown on Merrimac soil treated with sewage sludge and inorganic metals

Phosphorus Rate	Soil Acidity	Concentration of Zn, ppm				
		C	SS	M(I)	SS + M(II)	M(I) + M(II)
		First Year				
Normal	Very acid	40	1075	2922	1522	3639
	Moderately acid	22	583	400	563	498
	Slightly acid	15	213	128	450	137
High	Very acid	20	813	1178	1078	2803
	Moderately acid	20	1008	650	1138	475
	Slightly acid	11	200	86	375	425
		Second Year				
Normal	Very acid	45	425	288	472	623
	Moderately acid	15	76	89	163	313
	Slightly acid	9	29	35	56	99
High	Very acid	70	313	260	725	680
	Moderately acid	9	55	48	128	64
	Slightly acid	6	28	25	49	49

Table 7. Concentration of Cu in corn grown on Buxton soil treated with sewage sludge and inorganic metals

Phosphorus Rate	Soil Acidity	Concentration of Cu, ppm				
		C	SS	M(I)	SS + M(II)	M(I) + M(II)
		First Year				
Normal	Very acid	10	45	50	82	131
	Moderately acid	7	28	32	44	34
	Slightly acid	8	28	29	36	39
High	Very acid	8	44	38	67	49
	Moderately acid	7	34	31	45	41
	Slightly acid	9	30	33	36	35
		Second Year				
Normal	Very acid	10	20	20	20	24
	Moderately acid	7	11	20	16	25
	Slightly acid	7	13	16	15	32
High	Very acid	9	22	20	25	37
	Moderately acid	5	13	17	14	24
	Slightly acid	7	11	11	11	17

Table 8. Concentration of Cu in corn grown on Merrimac soil treated with sewage sludge and inorganic metals

Phosphorus Rate	Soil Acidity	Concentration of Cu, ppm				
		C	SS	M(I)	SS + M(II)	M(I) + M(II)
		First Year				
Normal	Very acid	8	56	73	89	104
	Moderately acid	8	28	30	30	26
	Slightly acid	9	34	31	37	30
High	Very acid	8	56	35	76	56
	Moderately acid	10	47	37	61	51
	Slightly acid	8	26	26	36	36
		Second Year				
Normal	Very acid	77	19	18	28	25
	Moderately acid	8	13	23	20	29
	Slightly acid	10	17	22	18	35
High	Very acid	11	29	34	42	53
	Moderately acid	8	14	23	20	29
	Slighly acid	10	14	17	20	32

Table 9. Concentration of Ni in corn grown on Buxton soil treated with sewage sludge and inorganic metals

Phosphorus Rate	Soil Acidity	Concentration of Ni, ppm				
		C	SS	M(I)	SS + M(II)	M(I) + M(II)
		First Year				
Normal	Very acid	1	12	52	37	161
	Moderately acid	2	9	8	11	17
	Slightly acid	2	2	2	3	3
High	Very acid	1	9	22	22	97
	Moderately acid	2	7	5	12	11
	Slightly acid	1	2	3	3	3
		Second Year				
Normal	Very acid	2	2	3	12	8
	Moderately acid	3	4	3	4	2
	Slightly acid	2	2	2	8	1
High	Very acid	2	12	3	6	10
	Moderately acid	2	2	3	4	8
	Slightly acid	2	2	2	2	3

Table 10. Concentration of Ni in corn grown on Merrimac soil treated with sewage sludge and inorganic metals

Phosphorus Rate	Soil Acidity	Concentration of Ni, ppm				
		C	SS	M(I)	SS + M(II)	M(I) + M(II)
		First Year				
Normal	Very acid	1	14	127	44	186
	Moderately acid	1	12	7	5	14
	Slightly acid	2	8	4	2	4
High	Very acid	1	8	34	30	118
	Moderately acid	3	7	19	17	7
	Slightly acid	2	3	4	4	4
		Second Year				
Normal	Very acid	1	4	3	7	26
	Moderately acid	2	3	2	2	6
	Slightly acid	1	2	3	3	2
High	Very acid	2	5	4	10	24
	Moderately acid	2	2	2	3	2
	Slightly acid	2	2	2	1	3

Table 11. Concentration of Cd in corn grown on Buxton soil treated with sewage sludge and inorganic metals

Phosphorus Rate	Soil Acidity	Concentration of Cd, ppm				
		C	SS	M(I)	SS + M(II)	M(I) + M(II)
		First Year				
Normal	Very acid	1	18	130	47	357
	Moderately acid	1	16	23	28	58
	Slightly acid	1	17	18	38	48
High	Very acid	1	13	75	33	202
	Moderately acid	1	18	16	24	42
	Slightly acid	1	21	12	37	25
		Second Year				
Normal	Very acid	1	11	14	19	23
	Moderately acid	1	7	9	17	16
	Slightly acid	1	4	4	12	11
High	Very acid	1	9	9	12	32
	Moderately acid	1	6	6	10	12
	Slightly acid	1	3	3	7	6

Table 12. Concentration of Cd in corn grown on Merrimac soil treated with sewage sludge and inorganic metals

Phosphorus Rate	Soil Acidity	Concentration of Cd, ppm				
		C	SS	M(I)	M(II)	M(II)
		First Year				
Normal	Very acid	1	17	42	43	297
	Moderately acid	1	15	14	7	34
	Slightly acid	1	11	12	27	14
High	Very acid	1	12	27	33	239
	Moderately acid	2	34	33	20	19
	Slightly acid	1	10	7	25	19
		Second Year				
Normal	Very acid	1	7	9	24	27
	Moderately acid	1	6	9	12	25
	Slightly acid	1	3	3	6	9
High	Very acid	3	12	17	19	40
	Moderately acid	1	4	5	8	8
	Slightly acid	1	3	3	5	7

Table 13. Concentration of Zn in roots of corn grown in the second year in soils treated with sewage sludge and inorganic metals

Soil	Phosphorus Rate	Soil Acidity	Concentration of Zn, ppm				
			C	SS	M(I)	SS + M(II)	M(I) + M(II)
Buxton	Normal	Very acid	55	359	434	1175	1721
		Moderately acid	44	147	144	316	275
		Slightly acid	18	53	40	65	99
	High	Very acid	77	440	500	820	1879
		Moderately acid	23	113	143	194	313
		Slightly acid	23	50	55	94	105
Merrimac	Normal	Very acid	76	800	950	1400	2524
		Moderately acid	72	225	309	525	867
		Slightly acid	70	55	92	152	172
	High	Very acid	40	855	1136	2181	3462
		Moderately acid	55	177	187	346	621
		Slightly acid	45	77	102	128	169

Table 14. Concentration of Cu in roots of corn grown in the second year in soils treated with sewage sludge and inorganic metals

Soil	Phosphorus Rate	Soil Acidity	Concentration of Cu, ppm				
			C	SS	M(I)	SS + M(II)	M(I) + M(II)
Buxton	Normal	Very acid	9	16	24	44	74
		Moderately acid	9	20	30	26	42
		Slightly acid	7	15	21	29	36
	High	Very acid	10	18	29	37	77
		Moderately acid	8	15	24	22	32
		Slightly acid	8	14	21	28	27
Merrimac	Normal	Very acid	10	22	32	38	104
		Moderately acid	6	16	36	30	62
		Slightly acid	8	18	30	32	56
	High	Very acid	6	44	44	52	128
		Moderately acid	6	20	36	34	84
		Slightly acid	12	22	34	32	54

Table 15. Concentration of Ni in roots of corn grown in the second year in soils treated with sewage sludge and inorganic metals

Soil	Phosphorus Rate	Soil Acidity	Concentration of Ni, ppm				
			C	SS	M(I)	SS + M(II)	M(I) + M(II)
Buxton	Normal	Very acid	--	69	87	205	330
		Moderately acid	19	29	41	61	53
		Slightly acid	5	8	11	12	12
	High	Very acid	24	68	128	152	495
		Moderately acid	9	32	51	55	55
		Slightly acid	--	8	11	18	21
Merrimac	Normal	Very acid	23	95	143	235	402
		Moderately acid	7	41	50	58	192
		Slightly acid	12	17	25	17	29
	High	Very acid	12	193	349	489	1365
		Moderately acid	16	67	52	101	333
		Slightly acid	6	33	47	41	73

Table 16. Concentration of Cd in roots of corn grown in the second year in soils treated with sewage sludge and inorganic metals

Soil	Phosphorus Rate	Soil Acidity	Concentration of Cd, ppm				
			C	SS	M(I)	SS + M(II)	M(I) + M(II)
Buxton	Normal	Very acid	3	20	34	77	79
		Moderately acid	4	37	56	72	100
		Slightly acid	2	20	26	54	44
	High	Very acid	3	22	27	34	64
		Moderately acid	2	28	36	38	52
		Slightly acid	2	17	20	45	31
Merrimac	Normal	Very acid	4	37	46	44	72
		Moderately acid	5	31	59	52	85
		Slightly acid	8	20	33	51	61
	High	Very acid	2	41	46	50	111
		Moderately acid	2	23	33	44	63
		Slightly acid	2	18	50	41	41

Table 17. Cadmium to zinc ratio in corn grown on Buxton soil treated with sewage sludge and inorganic metals

Phosphorus Rate	Soil Acidity	Cd/Zn ratio, %				
		C	SS	M(I)	SS + M(II)	M(I) + M(II)
		First Year				
Normal	Very acid	1.4	1.9	7.2	4.9	13.3
	Moderately acid	3.0	4.0	4.6	4.1	9.0
	Slightly acid	6.3	8.9	14.0	13.4	28.2
High	Very acid	2.7	1.8	5.8	4.2	11.5
	Moderately acid	3.4	4.1	4.9	3.3	6.5
	Slightly acid	6.7	8.7	10.3	11.3	14.7
		Second Year				
Normal	Very acid	3.6	2.5	5.4	4.5	4.4
	Moderately acid	9.1	15.2	14.1	14.4	3.8
	Slightly acid	11.1	17.4	18.2	27.9	15.3
High	Very acid	5.6	2.0	5.2	3.1	5.2
	Moderately acid	10.0	10.0	12.2	11.9	10.7
	Slightly acid	10.0	12.5	13.6	17.9	15.7

Table 18. Cadmium to zinc ratio in corn grown on Merrimac soil treated with sewage sludge and inorganic metals

Phosphorus Rate	Soil Acidity	Cd/Zn, %				
		C	SS	M(I)	SS + M(II)	M(I) + M(II)
		First Year				
Normal	Very acid	2.5	1.6	1.4	2.8	8.2
	Moderately acid	4.5	2.6	3.5	1.2	6.8
	Slightly acid	6.7	5.2	9.4	6.0	10.2
High	Very acid	5.0	1.5	2.3	7.5	8.5
	Moderately acid	10.0	3.4	2.9	1.8	4.0
	Slightly acid	9.0	5.0	8.1	6.7	4.5
		Second Year				
Normal	Very acid	2.2	1.6	3.1	5.1	4.3
	Moderately acid	6.7	7.9	10.1	7.4	8.0
	Slightly acid	11.1	10.3	8.6	10.7	9.1
High	Very acid	4.3	3.8	6.5	2.6	5.9
	Moderately acid	11.1	7.2	10.4	6.3	12.5
	Slightly acid	16.7	10.7	12.0	10.2	14.3