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EFFECTS OF SEWAGE SLUDGE ON THE CADMIUM AND ZINC CONTENT OF CROPS

by

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communications link between the researcher and the user community.

This report evaluates the available data on the effects on plants of single and repeated additions of cadmium (Cd) and Zinc (Zn) to soils in the form of sewage sludge. The influence of sludge, soil, plant and climatic factors also is addressed.

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PREFACE

Sewage sludge contains substantial quantities of nitrogen and phosphorus, both of which are nutrients required by plants and are important constituents of animal manures and commercial fertilizers. In addition to plant nutrients and organic matter, sludge contains small but variable quantities of other unwanted substances, such as toxic metals, in concentrations that may be much higher than those usually found in household wastes. Cadmium is of greatest concern. The Office of Research and Development of the Environmental Protection Agency requested CAST to prepare a report on the effects of sewage sludge on the cadmium and zinc content of plants as a way of collecting the latest published and unpublished information on this subject in a form that could be cited in connection with proposed regulations being developed to control the application of sludge to agricultural soils.

A task force of 25 scientists involved in research on sewage sludge was accordingly assembled by CAST at Ohio State University February 27 to 29, 1980, to discuss the assignment and to prepare a rough draft of a report. The task force chairman then circulated two more drafts to task force members for review and comment, and the CAST office circulated one more edited draft to the CAST Editorial Review Committee and two to task force members for further review and comment before the final version was reproduced for transmission to the Environmental Protection Agency.

On behalf of CAST, I thank members of the task force and all the others who gave of their time and talents to prepare this report as a contribution of the scientific community to public understanding. Thanks are due also to members of CAST. The unrestricted contributions they have made in support of the work of CAST have financed the report. Task force members are reimbursed on request for travel and subsistence expenses they incur when participating in official CAST activities, but they receive no honoraria for their work. Their salaries are paid by their employers.

This report is being distributed to the Environmental Protection Agency and the media, to institutional members of CAST, and to an additional selected list of persons. Individual members may receive a copy on request.

Charles A. Black
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ABSTRACT

This report evaluates the available data on the effects on plants of single and repeated additions of cadmium (Cd) and zinc (Zn) to soils in the form of sewage sludge. The influence of sludge, soil, plant and climatic factors also is addressed. The major findings are as follows:

1. The concentrations of Cd and Zn in plants vary with (a) the species and cultivar grown, (b) environmental and management factors, (c) soil properties - pH is the most critical factor in controlling plant uptake of Cd and Zn, (d) the annual and cumulative amounts of Cd and Zn applied to soils and (e) the plant part sampled - vegetative tissues usually show greater concentrations of Cd and Zn and greater absolute increases in concentration of Cd and Zn from sludge applications than do the fruit, grain or tubers.

2. Nearly all sewage sludges contain Cd and Zn at levels that will increase the total concentration of Cd and Zn in soils.

3. The availability to plants of a given quantity of sludge-borne Cd or Zn varies with the characteristics of the sludge.

4. Soil cation exchange capacity does not adequately reflect the properties that control the availability to plants of Cd and Zn in sludge-treated soils.

5. The concentrations of Cd and Zn in plants generally increase with a decrease in soil pH.

6. In noncalcareous soils, the concentration of Cd and Zn in most crops increases with increasing amounts of Cd and Zn applied.

7. In calcareous soils, the increases in Cd and Zn concentrations in plants due to additions of these elements to soils are usually substantially less than those observed under comparable conditions in noncalcareous soils.

8. At a given soil pH value, the concentrations of Cd and Zn in crops after repeated annual sludge additions appear to be either approximately the same as, or less than, those resulting from a single addition of the same sludge supplying amounts of Cd and Zn equivalent to the sum of the repeated annual additions.

9. Considerable increases in concentrations of Cd and Zn in many crops cannot be avoided when sludges high in these metals are applied unless annual and cumulative additions of the metals are limited and unless the soil reaction is maintained near or above neutrality.

10. Even at a soil pH of 6.5, the Cd added in many sludges is sufficient to increase the Cd concentrations in most crops.

CONTENTS

Overview 1

Introduction 4

Sewage sludge characteristics 7

Cadmium and zinc in sewage sludge 7
Theoretical mechanisms for retention of cadmium and zinc in sludges 9

Crop response to cadmium and zinc additions in sludge 12

Differential uptake of cadmium and zinc by crop species 12
Differential uptake of cadmium and zinc by crop cultivars 13
Environmental influences on the cadmium and zinc content of crops 14

Effect of soil properties on the response of crops to cadmium and zinc additions 16

Soil cadmium and zinc concentration 16
Soil pH 18
Soil cation exchange capacity 20
Other soil factors 22
Extractable metals 23

Crop response to cadmium and zinc in single and repeated applications of sludge 24

Single and repeated additions of sludge-borne cadmium and zinc . . 26
Availability of sludge-borne cadmium and zinc to plants after termination of sludge applications to soils 27

Literature cited 30

Tables and figures 39

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OVERVIEW

This report evaluates the available data on the effects on plants of single and repeated additions of cadmium (Cd) and zinc (Zn) to soils in the form of sewage sludge. The influence of sludge, soil, plant and climatic factors on the Cd and Zn content of plants is addressed.

Sewage sludges generally contain Cd and Zn at concentrations which exceed those found in most soils, and their addition thus increases the total concentration of Cd and Zn in soils. The concentrations of Cd and Zn in sewage sludges depend upon the characteristics of the sewage influent and the treatment processes employed.

The availability of sludge-borne Cd and Zn to plants after application of sludge to soils appears to depend upon the chemical forms present and other characteristics of the sludge as well as the soil. A variety of inorganic and organic forms of Cd and Zn of low solubility may coexist in sludges. A hypothesized mechanism for retention of Cd and Zn in sludge solids is coprecipitation of these metals with iron, aluminum and manganese oxides, hydroxides, carbonates and phosphates. Further research is needed to elucidate the chemical species of Cd and Zn in sludges. This information is expected to improve estimations of solubility and relative availability to plants of Cd and Zn after application of sludges to soils.

Plant species differ markedly in their ability to accumulate Cd and Zn from soils. In general, under similar soil conditions, Cd and Zn concentrations are greater in leafy vegetables and the vegetative parts of crops than in fruit, grain or tubers. The content of Cd depends also upon the cultivar grown; the Cd content of corn grain and leaves may vary tenfold among cultivars. Environmental factors, including temperature and soil moisture, also may modify the concentration of Cd and Zn in crops. Frequently the concentrations of Cd and Zn in plant tissues increase when plants are grown under suboptimal (stress) conditions.

The primary soil factors controlling the uptake by plants of Cd and Zn added to soils in sewage sludge are the amounts of these metals present as a result of the treatment, and the pH of the treated soil. At any given level of Cd or Zn, the concentration of the metal in plant tissue decreases with increasing soil pH. The impact of sludge-borne Cd and Zn on plants is least in calcareous soils.

Experiments to evaluate the effect of soil cation exchange capacity (CEC) on uptake of Cd and Zn have yielded conflicting results. In greenhouse studies, increasing the soil CEC by adding organic matter or bentonite altered the soil pH, and the effects of CEC and pH could not be separated. Similarly, in studies involving untreated soils differing in CEC, the soils have differed in pH and other properties as well, and these differences have prevented identifying unambiguously an effect of CEC. The CEC of a soil cannot be modified without altering other soil properties. However, the pH buffering capacity of soils increases with the CEC; hence, the potential for increased Cd and Zn uptake by plants associated with acidification of soil following sludge application is less in soils with high CEC than in those with low CEC. CEC is viewed more appropriately as a general, but imperfect, indicator of the content of soil components that limit the solubility of Cd and Zn than as a specific factor in the availability of these metals.

The uptake of Cd and Zn by plants increases with the total concentration of these metals in soils. In calcareous soils, however, the amounts of Cd and Zn added have only a relatively small effect on the content of these elements in plants because the metals have relatively low solubility in the presence of calcium carbonate.

In agricultural operations, sewage sludges are generally applied annually over a number of years. Although the concentrations of Cd and Zn which occur in crops in the first year following sludge application can be expressed as a function of the amounts of Cd and Zn applied, these data cannot necessarily be extrapolated to estimate the effect of the same total amount applied in small increments over a number of years. To accomplish this, data are needed on the changes in the chemical properties of sludge-treated soils with time and on the influence of these changes on the availability of Cd and Zn. The effect of time superimposed on changes in the chemical properties of soils receiving repeated additions of sludge has not been adequately investigated. The experimental data available permit only a qualitative or possibly semiquantitative assessment of the effects of single and repeated additions of sludge on the content of Cd and Zn in plants.

Most of the available data were obtained from field experiments in which repeated applications of sewage sludge were made over a period of years. With calcareous soils, only small increases in Cd and Zn concentrations in plants have occurred with either single or repeated applications. With noncalcareous soils, the concentrations of Cd and Zn in the crops in most experiments have increased with the amounts of Cd and Zn applied following the first sludge application. After repeated annual sludge applications, the concentrations of Cd and Zn in crops have been found to be either approximately equal to or less than those expected on the basis of the effects of applying the same total amount of the metals in a single year.

Some data indicate that the availability to plants of Cd and Zn added to soils decreased with time after termination of repeated sludge applications. In one instance reviewed, the Cd content of corn grain was no greater in the third year following termination of sludge applications than it was in the control soil, although the Cd content of the corn leaves was still greater on the sludge-treated soil than on the control.

Other data indicate that there was no clear decrease in availability to plants with time. In one instance reviewed, the increases in Cd concentrations in both the leaves and grain of sweet corn for the first 4 years following termination of annual sludge applications appeared to be in the same range as those observed during the applications.

Management of soil pH is the most critical factor in evaluating the impacts of single and repeated additions of sludge on uptake of Cd and Zn by plants. For plants which tend to accumulate Cd (e.g., leafy vegetables), a decrease in soil pH from 6 to 5 will likely result in greater increases in Cd and Zn content than either (1) doubling the amount of Cd or Zn in single or repeated applications to a soil at pH 6.5 or (2) allowing the soil pH to decrease from 7 to 6.

In view of the effects of single and repeated additions of sludge-derived Cd and Zn on the content of these metals in plants, the residual effects after sludge applications have ceased, and the effects of soil pH on the availability of these metals to plants, it seems evident that considerable increases in concentration of Cd and Zn in many crops cannot be avoided when sludges high in these metals are applied unless the total amounts of the metals supplied in single and repeated additions are limited and unless the soil reaction is maintained near or above neutrality. Even at a soil pH of 6.5, the Cd added in many sludges is sufficient to increase the Cd concentration in most crops.

INTRODUCTION

Cadmium (Cd) and zinc (Zn) are naturally occurring trace metals that are ubiquitous in soils. Zn has been established as an essential element for plant and animal life. Although essentiality has not been demonstrated conclusively for Cd, it has been shown in one study to improve the growth of rats at low concentrations (Schwarz and Spallholz, 1978). Native concentrations of these metals in soils vary considerably depending upon the geological origin and weathering of the soil materials. The concentrations of Cd and Zn in soil can be increased by atmospheric depositions, addition of Zn and phosphate fertilizers, and addition of plant residues and wastes including sewage sludge.

The Cd and Zn content of plants reflects the total Cd and Zn content of the soil as well as a number of interacting sludge, soil, plant and climatic factors. Under certain conditions, Cd and Zn may accumulate in crops to levels which may reduce crop yields. Elevated levels of Cd in food crops due to applications of sewage sludge or other causes are of concern as a potential hazard to human health.

Increased emphasis is being placed on applying municipal sewage sludges to agricultural land because of constraints on alternative disposal methods, such as the ban on dumping sludge in the ocean and air pollution problems and fuel requirements associated with sludge incineration. Although sewage sludges can be applied to drastically disturbed lands and to lands used in silviculture and ornamental horticulture, the primary focus of this report is the application of sewage sludge to agricultural land used for growing crops which enter human or animal diets.

Two basic approaches are considered when developing the appropriate sludge application rate for agricultural soils: (1) using the sludge as a fertilizer for its content of plant nutrients and (2) using the sludge on sites dedicated to sludge application on which the rates of application may or may not be based upon the plant nutrient content. When used as a source of plant nutrients, usually nitrogen or phosphorus, the amount of sludge applied per year can be based on (1) an annual Cd limitation, e.g., 2 kilograms per hectare (kg/ha) per year, (2) the amount of nitrogen or phosphorus required by the crop grown or (3) a combination of both criteria. The third approach is typically used for privately owned agricultural land on which food or feed crops are grown and on which the farmer uses a conventional soil testing program to monitor the soil after sludge application. The rationale for limiting sludge additions on the basis of the nitrogen required by the crop is that nitrate leaching and subsequent contamination of ground water will be no greater than that caused by use of commercial fertilizers.

The concern over Cd entering the human diet prompted the Environmental Protection Agency (1979) (EPA) to establish limits on both the annual and cumulative amounts of Cd that may be added to soils in the form of sewage sludge. The criteria limit annual Cd loadings from sludge additions to soil, but do not directly limit the amount of nitrogen applied. In addition, the criteria stipulate the following for all soils receiving solid wastes which are currently used or may in the future be used to grow crops for the food chain: (1) the pH of the mixture of soil and solid waste is to be 6.5 or greater at the time of each solid waste application (no pH limitation is imposed if on a dry-weight basis the waste contains Cd at a concentration of 2 milligrams per kilogram (mg/kg) or less); (2) a maximum annual application of 0.5 kg of Cd/ha for soils growing tobacco, leafy vegetables or root crops; and (3) a maximum annual Cd application for other crops of 2 kg/ha from the present to 6/30/84, 1.25 kg/ha from 7/1/84 to 12/31/86 and 0.5 kg/ha after 1/1/87.

The number of years that soils can receive sewage sludge is based on the cumulative amounts of Cd applied.[1] The EPA criteria established cumulative Cd limits of 5 kg of Cd/ha for soils having a "background pH" of <6.5. For soils with a background pH >6.5 or for soils that will be maintained at pH 6.5 or above whenever crops entering the human food chain are grown, the cumulative amount of Cd allowed increases with increasing soil cation exchange capacity (CEC) as follows: <5 milliequivalents per 100 grams (meq/100 g), 5 kg of Cd/ha; 5 to 15 meq/100 g, 10 kg of Cd/ha; and >15 meq/100 g, 20 kg of Cd/ha.

When sewage sludge is applied to agricultural land dedicated to sludge application, the quantities of Cd applied may exceed those described in the preceding paragraph, and this results in the need to monitor the sludge application site to preclude nitrate movement into surface and ground water. The EPA criteria specify that all crops grown on such sites, including pasture crops, forages and grains, must be used for animal feed and that the soil pH must be maintained at 6.5 or above. Crop residues and animal wastes must be returned to the sludge application site.

Although Cd-Zn interactions may influence the absorption of Cd from soils by plants (Walsh et al., 1976) and from the diet by animals or humans (Fox et al., 1979), the principal reason for discussing both Cd and Zn in plants grown on soils treated with sewage sludges is that Zn contents of plants may be useful as a model for Cd behavior in many soil-plant systems in which Cd data do not yield a discernible trend due to experimental or analytical limitations. Cd and Zn have some similar chemical and biochemical properties.

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[1] An alternative approach was suggested by a North Central Regional Research Committee which recommended that total sludge loadings be limited by cumulative additions of lead, zinc, copper, nickel and cadmium (NC-235, 1976).

Some of the research data presented in this report are from experimental plots on which sludge has been applied in quantities 50 to 100 times greater than those recommended on the basis of the nutrient requirements of the crop grown. The data from such plots, however, are valuable in evaluating the effect of sludge application on the concentration of Cd and Zn in various plant tissues.

Current guidelines on sludge application rates are based on an assortment of data from greenhouse and field studies in which soils were treated with sludges, sludges supplemented with metal salts or metal salts alone. Plant data derived from studies involving addition of metal salts to soils should be viewed with caution as an indicator of the effects of adding comparable rates of Cd to soils in the form of sludges. Concentrations of Cd and Zn in plants grown on sludge-treated soils are usually much higher when the plants are grown in the greenhouse than in the field (DeVries and Tiller, 1978), and their use is questionable in quantitative predictions of metal concentrations in the human diet. Consequently, this report will make use of field data whenever possible.

This report summarizes available data on the relative effects on crop composition of single and repeated additions of Cd and Zn to soils in the form of sewage sludge, as influenced by sludge properties, crop species and cultivar, soil properties, and climatic factors. The experimental findings are not always as definitive as might be desired because of limitations in experimental design, experimental error, variations in soil pH values, seasonal differences in growing conditions that may affect the results, and differences among sludges, soils and other factors that are not understood.

SEWAGE SLUDGE CHARACTERISTICS

Wastewaters are derived from a variety of domestic and industrial sources and have a wide range of Cd and Zn contents (Table 1)[2]. In general, industrial sources tend to contribute greater amounts of Cd and Zn to wastewaters than do domestic sources (Gurnham et al., 1979).

Industrial sources of Cd in wastewaters include metallurgical alloying, ceramics manufacturing, electroplating, inorganic pigments, textile printing, and chemical industries (Patterson, 1975). Of the total industrial Cd use, 90% is utilized in electroplating, pigments, plastic stabilizers, alloying and battery manufacturing (Page and Bingham, 1973). Most of the remaining 10% is used for television tube phosphors, fungicides, rubber curing agents and nuclear reactor shields and rods.

Industries which discharge Zn in their wastewater include steel works with galvanizing units, Zn and brass metal works, Zn and brass plating works, silver and stainless steel tableware manufacturing, viscose rayon yarn and fiber production, ground wood pulp production, news print paper production, and pigment manufacturing. The primary source of Zn in wastewaters from plating and metal processing industries is the solution adhering to the metal product after removal from pickling or plating baths. Wastewaters with little, if any, industrial contribution can still contain appreciable Zn concentrations, probably because of the wide use of galvanized pipes in residential water supply and wastewater transport systems.

Several different wastewater treatment processes have been developed and are used in the United States. They include primary treatment, which removes only suspended solid materials; secondary treatment, which removes additional suspended solids; and tertiary treatment, which involves addition of coagulants to remove certain dissolved solids. The residue remaining after wastewater treatment is referred to as sewage sludge and must be removed from the treatment plant. The Cd and Zn in wastewaters tend to accumulate in the sewage sludge (Table 1).

Cadmium And Zinc In Sewage Sludge

The chemical composition of sewage sludges has been evaluated in numerous localities including Wales and England (Berrow and Webber, 1972), Sweden (Berggren and Oden, 1972), Michigan (Blakeslee, 1973), eight states in the north central and eastern regions of the United States (Sommers, 1977), Iowa (Tabatabai and

[2] Tables and figures are found on page 39 et seq.

Frankenberger, 1979), Indiana (Sommers et al., 1972), Pennsylvania (Doty et al., 1977), and Wisconsin (Konrad and Kleinert, 1974). A common finding of these surveys was the high degree of variability in the chemical composition of sludges. This finding is illustrated for Cd and Zn by Table 2. The composition of sewage sludges varies also with time at a given treatment plant (Doty et al., 1977; Sommers et al., 1976).

The concentrations of Cd and Zn in municipal sewage sludges exceed those in the wastewater because of bioaccumulation, adsorption and coprecipitation. Other important factors, however, influence the Cd and Zn concentrations in sludges.

The distribution of metals through municipal sewage treatment plants is predictable in a quantitative manner (Patterson, 1975, 1979). Each influent metal is distributed between the sewage soluble phase and the suspended particulate material. The relative distribution of Cd and Zn between the soluble and particulate phases is extremely variable, and is believed to be a function of total concentration, concentration of other chemical constituents, and other sewage characteristics (e.g., pH, organic carbon, cyanide, etc.). The principal points of sludge generation in sewage treatment are primary sedimentation, including Imhoff sedimentation of raw sewage, and secondary sedimentation of waste (excess) biological activated sludge mass or of chemically treated primary effluent. Chemical treatment processes such as additions of calcium hydroxide or salts of iron or aluminum increase sludge production substantially (Metcalf and Eddy, 1974). During both primary sedimentation and secondary treatment, soluble metals are removed from solution through sorption by suspended solids and uptake by the microorganisms therein.

Table 1 shows some performance features relating to Cd and Zn concentration for three activated sludge sewage treatment plants of the Metropolitan Sanitary District of Greater Chicago. These plants vary in size and in the characteristics of their raw sewage, and they cover a wide range of sources of Cd and Zn, ranging from primarily domestic to heavy industrial input (Lue-Hing, 1979). It seems clear from these data that metal concentrations in raw sewage directly influence the sludge metal concentrations. However, the values for the sludge concentration factor show that the degree to which metals are concentrated in the sludges differs among plants, being five times greater for Zn at the Hanover Park plant than at the West-Southwest plant. On the other hand, the Zn content of the West-Southwest sludge is four times greater than that of the Hanover Park sludge.

Sludge treatment processes used following primary and/or secondary sedimentation and prior to application to land may include concentration by gravity or centrifugation; stabilization by chemical addition (e.g., calcium hydroxide), digestion or composting; dewatering by mechanical means; and drying by heat treatment or solar drying beds.

There seems to be little direct scientific evidence which relates sludge processing schemes to Cd and Zn availability to plants following sludge application to agricultural soils. However, there is evidence indicating that the combination of sludge type and processing may influence the retention of sludge-derived Cd and Zn by soils.

Stover et al. (1976) used a sequential extraction procedure to fractionate the metals in a range of sludges. Their findings indicated that organically bound Zn is the predominant form of this metal and that zinc carbonate may also be present in significant quantities in some sludges. For Cd, the predominant form appears to be cadmium carbonate with lesser amounts of organic and sulfide forms. According to Sommers (1977), available data suggest that several forms of Cd and Zn are present in sludges and that different forms may predominate in different sludges. Moreover, changes in chemical forms probably occur after sludges are incorporated into soils, with resulting changes in Cd and Zn availability to plants.

Theoretical Mechanisms For Retention Of Cadmium And Zinc In Sludges

The availability of Cd and Zn to plants is consistently lower when the metals are applied to soils in the form of sewage sludge than when they are applied in the form of inorganic salts. For example, greenhouse experiments by Dijkshoorn and Lampe (1975) showed Cd concentrations in plants to be about twice as great when Cd was added to soil in the form of cadmium sulfate as when an equal amount was added in sludge. Some studies have shown large differences in Cd availability for sludges with similar Cd contents, but the reasons are not known.

One theory that seems to be in accord with most of the available data on relative availability of Cd in different sludges to plants is that the Cd is coprecipitated as a trace constituent in the inorganic precipitates in the sludge. These precipitates are generally hydrous oxides of iron and aluminum; phosphates of iron, aluminum and calcium; ferrous sulfide; and/or calcium carbonate. The relative amounts of these major components, as well as the amounts of Cd and Zn present in the sludges, depend on waste sources and treatment processes, and particularly on the use of iron, aluminum or calcium compounds for phosphate removal or sludge conditioning.

According to solid-solution theory (Stumm and Morgan, 1970), when a compatible trace cationic constituent is incorporated into a crystal, the concentration of the trace cation at a particular point in the crystal depends on the relative activities of the two cations in solution at the time precipitation was occurring at that point and on a distribution function. If the trace cation is not compatible, it cannot be incorporated into the crystal because of differences in size, charge or bond type. However, the cation may be adsorbed onto the surface of the growing crystal and subsequently occluded as the crystal grows around it. In either case, the cations inside the crystal are not exchangeable with ions in the soil solution and, while in that form, do not contribute to the availability of the cation to plants.

Cd and Zn have been shown to be adsorbed on surfaces of hydrous oxides of iron and aluminum (Kinniburgh et al., 1976, 1977), and they would probably coprecipitate with these compounds under the conditions existing in a sewage treatment plant. Coprecipitation with phosphates, carbonates and sulfides would also be expected, as most of the heavy metals form precipitates of low solubility with these anions.

If a coprecipitation mechanism is responsible for immobilization of much of the Cd and Zn in sludge, only the labile, adsorbed metal ions on the surface of the precipitates and in the organic adsorption sites will be in equilibrium with the solution phase. The quantities of these labile metal ions may be estimated experimentally by the method of isotopic exchange. If an adsorbed phase controls metal solubility in soils, the concentration of the metal in solution will be governed by the adsorbed phase. Following addition of sludge to soil, adsorption sites on the soil will tend to lower the Cd concentration in solution. When large amounts of sludge are applied, the Cd adsorption capacity of the sludge may dominate the system, and the soil may have little effect on the Cd solubility.

Support for this theory in studies of sludge is found in the results of experiments by Cunningham et al. (1975a). In comparing Cd uptake from two noncalcareous sludges in the greenhouse, they found that the average concentration of Cd in plant tissue was about the same for the two sludges (1.5 vs. 1.4 mg/kg) even though the Cd content of the sludges differed by a factor of 3 (76 vs. 220 mg/kg). The sludge with the lower Cd content had a lower iron content (1.2 vs. 7.9%) and also a lower phosphorus content (2.9 vs. 6.1%). Thus, the low Cd availability occurred in the sludge with a relatively high content of substances with which Cd could coprecipitate.

Additional support is found in unpublished work conducted in Wisconsin (Keeney et al., 1980). In a field study, the Cd concentration in corn leaves from plots treated with a sludge containing 229 mg of Cd/kg, 3.0% iron, 1.1% aluminum, 4.7% calcium and 1.6% phosphorus was nearly three times as high (1.7 vs. 0.6 mg/kg) as in corn leaves from plots treated with the same amount of Cd supplied by a sludge containing 180 mg of Cd/kg, 7.8% iron, 2.5% aluminum, 1.5% calcium and 3.0% phosphorus. The isotopically exchangeable or labile Cd was also found to be three times higher for the sludge low in iron and phosphorus even though the total Cd concentrations in the two sludges were similar.

The unpublished work at Wisconsin also included a greenhouse study in which Cd concentrations in corn tissue were compared using sludge additions with similar Cd applications (1.6 vs. 1.8 kg/ha) from sludges with approximately the same concentrations of iron (7.8 vs. 7.2%), aluminum (2.5 vs. 4.7%), calcium (1.5 vs. 1.5%) and phosphorus (3.0 vs. 3.5%), but differing in total Cd concentration (180 vs. 9 mg/kg). The sludge containing the higher content of Cd increased the Cd concentration from 0.6 mg/kg in the control plants to 1.2 mg/kg. The Cd content of the corn tissue from the soil treated with low-Cd sludge was not different from the control. The low-Cd sludge apparently supported a lower level of available Cd even though the total amounts of Cd added were the same. However, the total additions of iron and organic matter were about 20 times as great for the low-Cd sludge as for the high-Cd sludge, so that the total Cd adsorption capacity of the added sludge was much higher for the low-Cd sludge.

In another greenhouse study, Bates et al. (1979) added a number of sludges to soils cropped to annual ryegrass over a period of about 5 years. A total of 14 crops of ryegrass was grown, with the sludge being added prior to seeding each crop. The cumulative Cd loadings were 10.6 kg/ha for the Sarnia sludge and 12.1 kg/ha for the Guelph sludge. The sludges had similar ratios of phosphorus to Cd at the start of the 14th crop, but the ratios of iron to Cd were 889 to 195 for the Sarnia and Guelph sludges, respectively. The average Cd concentrations in the 14th crop of ryegrass were 1.35 mg/kg for the Sarnia sludge and 2.35 mg/kg for the Guelph sludge. Again, with nearly equal additions of total Cd, the lower Cd availability was associated with the sludge having the higher iron content.

For the seemingly few sludges in which much of the Cd is not isotopically exchangeable and does not contribute directly to the supply of Cd available for plants, marked differences in the trend of Cd availability with time could occur when different sludges are applied to different soils. If Cd were coprecipitated with calcium carbonate or calcium phosphate in the sludge and if the sludge were applied to an acid soil, the precipitates would dissolve over a period of time, and the coprecipitated Cd would be released. On the other hand, if the same sludge were applied to a calcareous soil, the coprecipitated Cd would probably remain immobilized. Cunningham et al. (1975a) found an average of 10.5 mg of Cd/kg in leaf tissue when plants were grown in a soil at pH 6.8 which had been treated with a calcareous sludge containing 460 mg of Cd/kg and 18% calcium. Only 1.4 mg of Cd/kg was found in plant tissue from the same soil to which similar quantities of a noncalcareous sludge with a higher content of iron and phosphorus and 220 mg of Cd/kg had been applied. In this case, it would appear that either the calcium precipitates were less effective than the iron phosphate precipitates in immobilizing the Cd or Cd was released due to dissolution of some of the calcium compounds (e.g., calcium carbonate) in the slightly acid soil.

The Cd in noncalcareous sludges that is not associated with organic matter would likely be coprecipitated primarily with hydrous oxides or phosphates of iron and aluminum. These forms would not be expected to be altered rapidly by interaction with either acid or alkaline soils. However, the solubility of the isotopically exchangeable or labile Cd fraction would be affected by the soil pH. If the Cd were coprecipitated with ferrous sulfide, some Cd would probably be released to a more labile form on oxidation of the sulfide.

CROP RESPONSE TO CADMIUM AND ZINC ADDITIONS IN SLUDGE

Crop response to Cd and Zn varies with crop species. Various classes of vegetation exhibit differential uptake patterns, which have been well documented in the literature and in a previous CAST report by Walsh et al. (1976). Important crops including small grains, vegetables, legumes and forage crops show different tolerances or sensitivities to substrate Cd and Zn concentrations. Crop varieties and parts of individual plants may vary considerably in content of Cd and Zn. Vegetative parts generally contain higher concentrations of Cd and Zn than does the fruit. Moreover, Cd and Zn uptake by plants may vary from season to season due to differences in factors such as moisture, temperature and disease. Evidence continues to appear in the literature that uptake of Cd and Zn by plants from sludge-treated soils increases with increased rate of application of a given sludge, increased Cd and Zn content of the sludge at a constant application rate, and decreased soil pH at a constant metal loading.

Differential Uptake Of Cadmium And Zinc By Crop Species

In recent years, a large number of plant species have been screened with respect to Cd accumulation. Leafy vegetables are generally the greatest accumulators, whereas the edible portions of squash, tomato and radish tend to have low Cd levels (Dowdy et al., 1975; Giordano et al., 1979b). Giordano et al. (1979b) found that cabbage absorbs less Cd than other leafy vegetables and is an apparent excluder of Cd compared with lettuce (Table 3). Cadmium concentrations observed in lettuce, chard, radish and carrot increased with the quantity of sludge applied to a calcareous Domino soil (Chang et al., 1979) (Table 4). Concentrations of Cd in radish tubers were approximately half of those in the tops. In contrast, only 15% as much Cd appeared in potato tubers as in the tops (Giordano et al., 1979b). Cd uptake by sorghum, soybean, potatoes and wheat increased with increasing Cd applied to the soil (Baker et al., 1979a, 1979b) (Table 5). The Cd concentration in potato tubers was approximately one-tenth that found in the leaves.

Analysis of the leaves of corn, cotton and soybeans grown on sludge-treated soils showed concentrations of Cd to be <1 mg/kg in all cases except in one cultivar of corn which contained 1.4 mg/kg with the greater application of sludge (Table 6). Concentrations of Cd were considerably higher in soybean grain than in corn grain and were usually higher in soybean grain than in cotton seed although levels were <1 mg/kg (Table 7). Concentrations of Zn were higher in both leaf and grain of soybeans than in the other crops, as has been found for other elements (e.g., calcium and magnesium) (Tables 6 and 7).

Tobacco grown on soils (pH 5.6 to 6.3) treated with various sources and quantities of sewage sludge (0.8 to 4 kg of Cd/ha) showed Cd concentrations ranging from 14 to 33 mg/kg in leaves from the upper portion of the plant, and 20 to 55 mg/kg in lower leaves. According to these unpublished findings by R. L. Chaney, tobacco must be considered as much of an accumulator of Cd as leafy vegetables, at least when grown on acid soil.

Additional data on relative concentrations of Cd or Zn in various crop species are available. For both Cd and Zn, concentrations are greater in Swiss chard and lettuce than in soybeans or oat grain (Tables 15 and 16). A study involving Cd applications of 14 to 203 kg/ha indicated that the increases in Cd content of the grain from application of sludge were greatest with oats, less with soybeans and least with corn (Tables 27 and 28). Mahler et al. (1978) and Bingham (1979) have identified several plant species which are sensitive to Cd toxicity (spinach, lettuce, curly cress and soybean) and some that are relatively tolerant (tomato, squash, cabbage and paddy rice). Toxicity to plants is more acute and occurs at lesser total concentrations of Cd in acid than in calcareous soils.

Differential Uptake Of Cadmium And Zinc By Crop Cultivars

Cultivar differences in uptake of trace metals have long been recognized. Millikan (1961) concluded that differences in efficiency of nutrient absorption and utilization by plants are often greater among cultivars of the same species than among related species or genera. Similarly, evidence exists for genetic control of translocation of elements within plants (Epstein and Jefferies, 1964). More recently, evidence has been presented for genetic control of Cd and Zn uptake and translocation, and attempts have been made by plant breeders to select for low accumulation of these metals (Hinesly et al., 1980).

The differential response of soybean cultivars to soil Cd was recently evaluated by Boggess et al. (1978) in a greenhouse study. Cultivars grown on a sludge-treated soil showed variable uptake of Cd (Table 8). The maximum plant shoot Cd concentration was 6.0 mg/kg, and the minimum was 1.4 mg/kg.

Cultivar differences in Cd and Zn uptake by lettuce were reported by Giordano et al. (1979b) (Table 8). The two lowest accumulators of Zn were also the two lowest accumulators of Cd. Chaney and Feder (1980) reported a Cd uptake of 8.1 mg/kg for the Summer Bibb cultivar of lettuce and an uptake of 3.8 mg/kg for the Valmaine cultivar.

Data obtained by Hinesly et al. (1978) showed that inbred lines of corn grown on a sludge-treated soil differed in accumulation of Cd and Zn in leaves and grain, again suggesting that the capacity to accumulate Cd and Zn may be under genetic control. The different lines varied in uptake and translocation of Cd and Zn (Table 8), with accumulation of Zn not necessarily correlated with Cd. Similarly, Cd and Zn concentrations in the leaves were not always correlated with concentrations in the grain. Zn concentrations varied from 62 to 282 mg/kg in the leaves and from 34 to 70 mg/kg in the grain. Cd concentrations varied from 2 to 63 mg/kg in the leaves and from 0.1 to 3.9 mg/kg in the grain. These data suggest that the mechanisms controlling uptake and translocation of Cd and Zn are independent of each other. In the same study, Cd and Zn analyses of the plants grown with different applications of sludge suggest that variations of Cd and Zn in corn leaves and grain are determined as much by heritable differences as by differences in plant-available Cd and Zn in the soil (Table 9).

Overall, the available data suggest that Cd and Zn uptake and translocation can be genetically controlled and that cultivars can be selected for their low uptake of these metals and for limiting their translocation to edible parts.

Environmental Influences On The Cadmium And Zinc Content Of Crops

The existence of seasonal differences in concentrations of Cd and Zn in crops is well known. Except for several soil temperature studies, however, the environmental influences that may be responsible for these differences do not seem to have been investigated. In general, concentrations of Cd and Zn in plant tissue appear to increase with increasing temperatures. Occasionally, however, plant tissue concentrations are unaffected. Sheaffer et al. (1979) reported increased Zn concentration in ear leaves, grain and stover of corn as soil temperature increased from 16° to 35°C (Table 10). The Cd content in corn seedlings increased significantly while only slight elevations in Cd content of the ear leaf and grain occurred with increasing soil temperature. In corn stover, the Cd concentration decreased with increasing temperature. In contrast, the concentration of Cd in soybean shoots increased with increasing temperature and was further elevated by small (25 mg/kg of soil) applications of Zn. Large applications of Zn (400 mg/kg of soil) depressed the Cd concentrations in shoots below those in plants grown on soil which received no Zn (Haghiri, 1974).

Heating sludge-treated soil at or above 27°C to simulate the effect of a different season did not increase the Cd or Zn concentration in edible parts of lettuce, eggplant, tomato, potato, corn, squash or bean (Giordano et al., 1979b). Heating the soil appeared to increase the levels of Zn in broccoli. As the temperature of the soil increased, Cd concentrations in pepper increased in one year, but were unaffected two years later. Heating increased the concentrations of Zn in foliage of tomato, potato and corn, and increased the concentrations of Cd in eggplant, potato, corn and squash.

Chang et al. (1979) observed seasonal effects on the relationship between Cd in crops and available Cd in the soil during a 3-year field study. The behavior pattern varied with the crop; some crops had higher Cd concentrations in the fall than in the spring (e.g., radish leaves and tubers), while others exhibited higher Cd concentrations in the spring than in the fall (e.g., Swiss chard). The results were probably affected by the timing of the sludge applications, which were made twice a year over the 3-year period.

The effect of season on the absorption of Cd and Zn by crops is likely to be inconsistent in view of the many factors (e.g., moisture, temperature, aeration and disease) that can vary and interact substantially from season to season to modify Cd and Zn uptake. Representative seasonal effects on Cd and Zn concentrations in corn, lettuce and pepper are shown in Table 11. Where trends do occur with time, fixation and solubilization reactions that affect the solubility of Cd and Zn in the soil are likely to have a greater influence on the concentrations of these elements in plants than are seasonal effects.

In summary, Cd and Zn uptake and accumulation by crops are affected by plant species and cultivar, soil and other environmental factors. Often, Cd concentrations in plant tissues are low (<1 mg/kg), and changes in concentration may not be attributable to a specific factor. In general, the levels of Cd and Zn found in plant tissues increase with increasing metal loading rates irrespective of whether the metal is applied as an inorganic metal salt or as sewage sludge.

Seasonal variation may affect the levels of Cd and Zn in plants. Higher accumulations usually occur at higher soil temperatures. Moisture stress, often occurring with high summer temperatures, can also lead to higher concentrations. With increased plant stress, less biomass is produced, and the resulting Cd and Zn concentrations in the plant are higher than when the plant is growing under optimum conditions. Plant species vary in the amounts of Cd they accumulate. Leafy vegetables usually show greater concentrations of Cd than do most other crops. Cultivars also have been shown to absorb different amounts of Cd and Zn. The vegetative parts of plants contain more Cd than do the grain, fruit or tubers.

EFFECT OF SOIL PROPERTIES ON THE RESPONSE OF CROPS TO CADMIUM AND ZINC ADDITIONS

Soil chemical properties may affect the partitioning of Cd and Zn between the soil solution and the solid phase and thus influence their absorption by plants. Several investigators have suggested that adsorption is the predominant mechanism of trace metal removal from dilute solutions by clay minerals, metal oxides and organic matter, and by whole soils (Farrah and Pickering, 1977; James and MacNaughton, 1977; Riffaldi and Levi-Minizi, 1975; Street et al., 1977). As is true for many other trace metals, adsorption-desorption processes involving Cd and Zn show a strong pH-dependence. Since a change in pH may affect not only the metal species in solution (e.g., hydroxy, carbonate or phosphate complexes), but also the surface properties of the adsorbate (i.e., charge characteristics), a quantitative description of the exact mechanism involved in trace metal adsorption by naturally occurring soil components is not possible (Davis et al., 1978). In studies with silicate clay minerals, Farrah and Pickering (1977) found that increasing the pH from 4.5 to 7.5 sharply increased Cd adsorption. In similar studies with iron and aluminum oxides, Kinniburgh et al. (1977) found that adsorption of Cd and Zn was strongly pH-dependent and occurred at a pH less than the zero point of charge for the oxides (i.e., the surface was positively charged). Studies with whole soils have shown a similar pH-dependent nature for both Cd (Singh, 1979) and Zn (Cavallaro and McBride, 1978) adsorption. In addition to the adsorbed forms, Cd and Zn may be present in soils in discrete precipitates or coprecipitates with iron or aluminum oxides or alkaline earth carbonates (see the section on sewage sludge characteristics), or bound to soil organic matter through either exchange or chelation mechanisms. In either case, metal solubility will be a function of pH. One property that reflects the combined contributions of soil clay minerals and organic matter is the cation exchange capacity. The Environmental Protection Agency (1979) assumed that there is a relationship between this property and the availability to plants of sludge-borne Cd. This section summarizes the available data on the effect of soil metal concentration, soil pH, soil cation exchange capacity and other soil factors that influence the concentration of Cd and Zn in plants grown on soils treated with sewage sludge.

Soil Cadmium And Zinc Concentration

The concentrations of Cd and Zn in plants tend to increase with the total Cd and Zn concentrations in the soil. The Cd and Zn concentrations in soils cover a wide range because of differences in the Cd and Zn content of soil parent materials, additions of metal-containing fertilizers and contamination through industrial activities.

Published data show that the background concentrations of Cd in soils typically range from a few tenths of a mg/kg to 1 mg/kg. In certain regions of the United States native Cd concentrations in soils are atypically high. In California, certain soils derived from a shale parent material contain unusually high concentrations of Cd (5 to 20 mg/kg). Although the current data base is limited, concentrations of Cd in native vegetation collected from soils naturally high in Cd tend to exceed concentrations in the same plant species in adjacent locations grown on soils low in natural Cd (Olson et al., 1978; Cannon, 1955) (Table 12). The availability of Cd to Swiss chard from soils naturally high in Cd has been evaluated in greenhouse studies (Lund and Page, 1980). Data obtained from these studies show that, as the concentration of Cd in the soil increases, the concentration in Swiss chard leaves increases also (Table 13). Chang and Page (1979) also observed greater concentrations of Cd in Swiss chard leaves from plants grown on a soil naturally high in Cd (>5 mg/kg) than were normally observed for Swiss chard leaves from plants grown on typical agricultural soils. In summary, the information reviewed indicates that the availability of Cd to plants from natural sources of Cd in soils tends to increase with the total quantity present in the soil.

Phosphorus fertilizers frequently contain greater concentrations of Cd than are typically found in soils, and published reports show increased concentrations of Cd in surface soils following long-term repeated applications of such fertilizers (Williams and David, 1973; Mulla et al., 1980). Studies by Williams and David (1973, 1976), for example, show that long-term applications of Australian superphosphates (20 or more years) containing concentrations of Cd less than 50 mg/kg resulted in concentrations of 0.212 mg of Cd/kg in topsoil versus 0.046 mg of Cd/kg in similar soils receiving no phosphorus fertilizer. In a greenhouse study, concentrations of Cd in oats, subterranean clover and alfalfa grown on soils treated with phosphorus fertilizers were consistently greater than those of similar crops grown on nontreated soils. Reuss et al. (1978) observed that the concentrations of Cd in peas, radish and lettuce were increased by, and linearly related to, the Cd concentration of the P fertilizer applied to the soil. Mulla et al. (1980) determined concentrations of Cd and phosphorus in soils fertilized with the equivalent of approximately 175 kg of phosphorus/ha/yr (as treble superphosphate) over a 36-year period. Concentrations of Cd in surface soil (0-15 cm) were highly correlated (r = 0.89) with the concentrations of total phosphorus, indicating that the source of Cd in the soil was the phosphorus fertilizer. The concentrations of Cd in surface soil receiving the phosphorus fertilizer for the 36-year period averaged 1.0 mg of Cd/kg, and were considerably greater than the concentrations in the controls (0.07 mg of Cd/kg). Concentrations of Cd in barley (grain and leaves) grown in the field on the soils subjected to long-term phosphorus fertilization were not increased above those in barley grown on the control soil. Concentrations of Cd in Swiss chard grown in the greenhouse on surface soil collected from the phosphorus-fertilized plots, however, were significantly greater than those from the control soil (1.6 vs. 0.26 mg of Cd/kg of tissue).

Processing of industrial metals is an important source of emission of trace metals, including Cd and Zn, into the atmosphere. Smelting and sintering of nonferrous metals result in Cd and Zn contamination of the nearby environment. The major sources of emission are the ore-smelting furnaces in which metals enter the flue gas stream as fine particulates or volatiles, are discharged from the stack, and eventually are deposited onto soils and vegetation. Airborne dusts and fumes from charging furnaces, transporting metal ores, and sintering and metal-reducing furnaces are also sources of metals found in and near the operations. There are numerous published results which show increased concentrations of Cd and Zn in soil and vegetation close to and downwind from metal processing operations (Cartright et al., 1976; Severson and Gough, 1976; Buchauer, 1973; Lagerwerff and Brower, 1974; U.S. Environmental Protection Agency, 1972; Munshower, 1977). Data derived from the U.S. Environmental Protection Agency (1972) (Table 14) are representative of the extent of contamination which occurs. The data, obtained adjacent to a lead smelter which began operations in 1888, show high levels of contamination near the plant site.

The data in this section show that differences in Cd and Zn content of vegetation are associated with differences in the Cd and Zn content of soils that result from factors other than addition of sludge. This information, plus that from the section on crop response to additions of Cd and Zn in sludge, supports the view that the total Cd and Zn concentrations in soils are a major factor in controlling the uptake of these metals by plants.

Soil pH

Several studies have evaluated the effect of soil pH on Cd and Zn uptake by crops grown on sludge-treated soils. Decker et al. (1978) (Table 15) studied Cd and Zn uptake by lettuce, Swiss chard, soybeans and oats at different soil pH levels. The content of both Cd and Zn in lettuce and Swiss chard decreased with increased pH on both control and sludge-treated plots. The concentration of Cd in soybean and oat grain was relatively low and was not strongly influenced by soil pH. The concentrations of Cd and Zn in lettuce and Swiss chard grown on soil treated with Chicago Nu-Earth sludge in quantities of 20, 50 and 100 metric tons/ha (Decker et al., 1978) (Table 16) decreased with an increase in pH. The Cd concentration in soybean grain was relatively low and was not significantly affected by pH, but there was some decrease in Zn concentration with increased pH. The concentration of both Cd and Zn in soybean grain was increased by addition of sludge. In these studies, soil pH was adjusted by liming to 6.7 to 6.9.

Field plot data (Tables 15 to 19) show that Cd and Zn concentrations in leafy vegetables and corn leaves tend to decrease with increasing soil pH. However, a significant reduction in Cd and Zn concentrations in corn grain may not be observed after liming acid soils to approximately pH 6.5. The concentration of these metals in corn grain is generally low regardless of soil pH. A reduction in the Cd and Zn concentration in corn grain may result from liming only when relatively large amounts of these metals are applied to soils.

Following the application of sludge to soil, the soil pH is likely to decrease due to the acidity generated by microbial oxidation of nitrogen present in ammonium and organic compounds and oxidation of sulfur present in sulfides and organic compounds contained in the sludge. The magnitude of the pH decrease will be a function of the pH buffering capacity of the soil/sludge mixture and the quantity of sludge applied. The pH buffering capacity of a soil increases with increasing CEC. A number of multiyear field studies on plant uptake of metals from sludge-treated soils have been conducted in which the soil pH was changed through microbial processes or was altered by addition of elemental sulfur or limestone. As shown in Table 20, the Cd and Zn concentrations in corn leaves and grain increased with increasing additions of sludge at a soil pH of 5.2 to 5.5 in the presence and absence of fertilizer. Liming the soils in 1975 and 1976 decreased the concentrations of Cd and Zn in corn plants in a number of the comparisons. An Illinois study (Hinesly et al., 1979a) evaluated the concurrent changes in soil pH and concentrations of Cd and Zn in corn leaves following annual applications of sewage sludge. Figure 1 shows that, with continued sludge applications, the ratio of the concentrations of Cd and Zn in corn leaves to the increase in concentration of these elements in the soil as a result of sludge application decreased as the pH increased due to liming. When the soil pH decreased, the ratio of plant Cd to added Cd increased to a greater extent than did the corresponding ratio for Zn.

Baxter (1980) found that the application of sludge to a calcareous soil significantly lowered the soil pH, whereas equivalent loadings of Cd and Zn salts had only a relatively small effect on pH. Presumably because of the pH effect, the uptake of Cd and Zn by corn was greater from soil treated with sludge than from soil treated with the metal salts (Table 21). This effect appeared to be temporary, as suggested by the increase in soil pH and the similar concentrations of Cd and Zn in corn leaves from both sludge- and metal salt-treated soils after 3 years.

In a study by Chaney et al. (1978) (Table 19), sulfur was applied to plots to lower the pH because both the sludge and compost used tended to increase the soil pH. The concentration of Cd and Zn in lettuce was increased in a number of treatments when the soil pH was reduced following the addition of sulfur. The increased Cd levels in lettuce persisted in a few of the treatments in the 1977 crop year even though the soil pH increased somewhat. Similarly, in a study by Giordano et al. (1980) (Table 38) the concentrations of Cd and Zn in the plants increased when the soil pH was decreased by sulfur additions. Subsequent addition of limestone raised the soil pH to about 6, resulting in a decrease in Cd and Zn concentrations in the plants.

Metal uptake by crops typically decreases with an increase in soil pH, but the results of several studies suggest that liming acid soils to increase pH does not result in a marked change of metal uptake by plants. Giordano and Mays (1980) found little effect of increased (limed) soil pH on Cd and Zn uptake by two corn varieties (Tables 6 and 7). The concentration of Cd and Zn in cotton seed or soybean grain also showed little change when the pH was increased from about 5.0 to 6.6. Keeney et al. (1980) found some reduction in Cd concentrations in corn grain with increased pH (Table 17). The Cd additions in both of these studies were <5 kg/ha. Other studies (Table 18) have shown that the Zn concentration in corn leaves was decreased more consistently than the Cd concentration when soil of pH 4.7 was limed to pH 6.5 (Pepper and Bezdicek, 1980).

A complicating factor in evaluating the effect of sludge addition on soil pH is the properties of different types of sludges. For example, in work of Chang et al. (1979), application of a liquid digested sludge caused the soil pH to decrease while compost addition did not result in a pH change. To evaluate the relationship between the Cd and Zn concentrations in the plants and the Cd and Zn applied in the sludges, it was necessary to take into account the effect of soil pH. This was done by dividing the soils into two arbitrary groups, those with pH values <6.5 and those with pH values >6.5. In each group, the Cd and Zn contents of the leaves were significantly correlated with the Cd and Zn in the soil. In agreement with results shown previously, the ratios of Cd and Zn concentrations in the plants to the increases in concentration of Cd and Zn in the soil as a result of sludge application were higher at soil pH values <6.5 than at soil pH values >6.5.

The concentration of Cd and Zn in plants generally increases as soils are acidified. Soil management programs which include the addition of acid-forming fertilizers decrease soil pH values and result in increased uptake of Cd and Zn by plants unless sufficient limestone is also added.

Soil Cation Exchange Capacity

The CEC of soil is largely determined by the amount and kind of clay, organic matter, and iron and aluminum oxides. These soil components have different cation exchange properties, and their exchange capacities respond differently to changes in soil pH.

Determining the influence of CEC on the uptake of Cd and Zn by plants from soils treated with sludge presents some problems. Sludge adds Cd and Zn, and it also changes the CEC and other properties of the soil.

Research workers have used different techniques to study the influence of CEC on the uptake of Cd and Zn by plants. Latterell et al. (1976) adjusted the CEC of a sludged-treated (0,23.2 and 46.7 metric tons/ha) soil from 18.5 to 5.2 meq/100 g by diluting the soil with sand. The results obtained are shown in Table 22. In the original article, the authors presented the data as Cd and Zn uptake (meq/100 g of soil) instead of using concentrations as presented in Table 22. The authors concluded that for a given sludge application rate, there was no significant difference in Cd or Zn uptake with a change in CEC. The results presented by Latterell et al (1976) were recalculated by Task Force members to express the Cd or Zn in the plant material on a concentration basis. Recalculation of the data changes the interpretation of the results to some extent. The concentration of Cd in the plant material increased with increasing CEC in the control cultures and in the cultures with sludge added at 23.3 metric tons/ha, and it decreased with an increase in CEC when sludge was added at 46.7 metric tons/ha. The test plants made poor growth on the cultures with the lowest CEC (greatest dilution with sand), and the high Cd concentration in these plants was primarily responsible for the downward trend of Cd concentration in the plants with increasing CEC of the culture medium. All changes in Cd concentrations, however, were relatively minor. A decrease in Zn concentration in the soybean shoots occurred with increasing CEC with both additions of sludge.

Haghiri (1974) modified the CEC of a Toledo clay soil by first removing the organic matter with H_2O_2 and then adding organic matter (muck) at rates of 0, 1, 3.5 and 5% by weight to give CEC values ranging from 17.1 to 30.5 meq/100 g. The influence of CEC on dry weight and Cd concentration of oat shoots is shown in Table 23. The author concluded that the Cd concentration in oat shoots decreased with increasing CEC from organic matter. However, yield also increased with increasing CEC, and the lower Cd concentration may be a reflection of dilution rather than lowered uptake through a Cd-CEC interaction.

Sims and Boswell (1978) added bentonite at rates of 0, 5 and 10% to a sludge-treated Cecil loam soil to produce a range of CEC values from 7.4 to 20.4 meq/100 g of soil. The addition of bentonite resulted in a significant decrease in the concentrations of Cd and Zn in the leaves and grain of wheat. However, the addition of bentonite also increased the soil pH, and this may have been partially responsible for the observed decrease in Cd and Zn uptake.

Other research workers have used multiple regression techniques to determine the influence of CEC on the uptake of Cd and Zn by plants grown on different soils with varying CEC. Mahler et al. (1978, 1980) used this technique to study the influence of CEC on the uptake of Cd by lettuce, sweet corn, tomato and Swiss chard grown in the greenhouse. Eight soils with pH values varying from 4.8 to 7.8 and CEC values varying from 6.5 to 37.9 meq/100 g were used in these studies. Their data show that CEC resulted in a significant positive contribution to the multiple regression coefficient. However, CEC was not nearly as important in determining the amount of Cd accumulated by the different crops as was total Cd in saturation extracts of the soils or soil pH. Keeney et al. (1980) included CEC and pH as variables in a study of factors influencing the uptake of Cd by corn seedlings grown in the greenhouse (Table 24). The authors used eight mineral soils with CEC values ranging from 3 to 41 meq/100 g for the correlation analysis. Two organic soils with very high CEC values were also included in the study. A statistical summary of the data obtained is given in Table 25. An examination of these data shows that CEC had no significant effect in determining the uptake of Cd by corn.

Haq et al. (1980) studied the effect of various soil factors on Cd concentration in Swiss chard in a greenhouse study involving 45 Ontario surface soils. These soils ranged in pH from 5.2 to 7.9, in organic matter content from 1.4 to 17.0% and in CEC from 5.4 to 67.4 meq/100 g. In this study the Cd concentration in Swiss chard was associated with the organic matter content of the soil but not with the CEC at the 0.05 level of probability. Some of the statistical findings are given in Table 26. Soil CEC was also relatively unimportant as an estimator of the Zn concentrations of plants in this study.

Keeney et al. (1980) point out the difficulties encountered in studies of this nature in their statement, "When a number of soils are used, the role of the increasing content of a certain soil parameter may be obscured by a variation in another parameter." Furthermore, most experiments show that where CEC has been changed by adding materials to a soil, it may have some influence on concentration of Cd and Zn in plant tissue. Thus, the influence of CEC may not be as important as other factors in determining the concentration of Cd and Zn in plants.

Indications are that CEC is best viewed as a general, but imperfect, indicator of the soil components that limit the solubility of Cd and Zn (i.e., organic matter, clays, and hydrous oxides of iron, aluminum and maganese) instead of a specific factor in the availability of these metals. The reason is that less than 1 percent of the total Cd and Zn applied to soils in sludge is found in the exchangeable form (Silviera and Sommers, 1977; Latterell et al., 1978). Limited evidence indicates that most of the Cd in most sludges is in a form exchangeable with radioactive Cd added in solution even though it is not exchangeable in the usual sense of an exchangeable cation. Such isotopically exchangeable Cd is probably the principal source of the Cd absorbed by plants.

Other Soil Factors

Several studies have evaluated the effect of nitrogen, phosphorus and potassium fertilizers on the uptake of Cd and Zn by plants grown on metal-treated soils. Many studies on the effect of type of nitrogen fertilizer have shown that the Zn concentrations in plants are higher where the nitrogen is supplied as ammonium than where it is supplied as nitrate. This effect is believed to be due to a combination of several effects of ammonium and nitrate behavior on soil pH: (1) ammonium is oxidized microbiologically to nitrate throughout the soil with generation of acidity, (2) roots take up more equivalents of ammonium than of anions, which lowers the pH of the soil immediately adjacent to the roots, and (3) roots take up more equivalents of nitrate than of cations, which raises the pH of the soil in the immediate vicinity of the roots (Smiley, 1974; Viets et al., 1957; Giordano et al., 1966).

Williams and David (1976) grew wheat on soils which had become enriched in Cd from superphosphate application and found that fertilization with ammonium nitrate increased the concentration of Cd in wheat. Soon et al. (1980) found increased Cd and Zn concentrations in bromegrass as a result of ammonium nitrate fertilization.

Williams and David (1977) evaluated the role of phosphorus fertility and placement of applied Cd on Cd uptake by plants. This work indicated that, because plant roots proliferate more in soil regions of greater fertility, plants absorb more Cd if it is present in the soil region of greater fertility.

A study by Haghiri (1976) evaluated the relative effects of use of potassium and calcium hydroxides for adjusting soil pH. Soybeans were grown in a Canfield silt loam which had been leached with hydrochloric acid to remove exchangeable cations, and then treated with calcium or potassium hydroxide to adjust the exchangeable cations and pH. A Cd salt was added at 14.3 mg of Cd/kg of soil. By comparing calcium- and potassium-treated soils at similar pH values, it was observed that the Cd level in soybean shoots was lower with potassium than with calcium. This difference might be explained by the greater affinity of calcium than of potassium for Cd sorption sites in the soil, resulting in higher soluble Cd in the soil solution when calcium is the dominant cation present.

When sewage sludge is applied to cropland, the amounts of Cd applied are normally smaller than the amounts of Zn, copper and nickel and much smaller than the amounts of organic carbon, nitrogen and phosphorus applied therewith. The other metals added or present in the soil may affect the behavior of Cd in soil-plant systems by (1) competing with Cd for metal sorption sites in the soil, (2) competing with Cd for uptake by plants or translocation within plants or (3) causing toxicity to the plants.

Most metal interaction experiments have been conducted under greenhouse conditions. One example is the high-Zn, low-Cd Waukesha sludge studied by Cunningham _et al_. (1975a). Zn toxicity occurred at very low soil Cd, and little Cd was taken up by the plants. Cunningham _et al_. (1975b) added metal salts to sludge-treated soils and found that additions of copper increased the concentration of Cd in corn seedlings. Bingham _et al_. (1979) found that the concentration of Cd in the grain of wheat grown on an acid soil was reduced by adding Zn but was increased by adding copper. In the same soil after treatment with calcium carbonate, the concentration of Cd was reduced by adding Zn and increased by adding copper and nickel. Chaney and Hornick (1978) and Chaney and White (1979) reported the results of a Cd-Zn study with soybeans and oats grown on Sassafras sandy loam adjusted to pH 5.5 or 6.5. They found that the Cd concentration in the plants increased linearly with the concentration of Cd in the soil within each Zn level. With large additions of Zn and small additions of Cd, soybean yield was severely reduced, and the concentration of Cd in the crop was not appreciably increased. Haghiri (1974) obtained similar results.

Additional studies have examined interactions of Cd and Zn in nutrient solutions to characterize plant properties as opposed to soil-plant properties. Cataldo and Wildung (1979) found that Zn was a competitive inhibitor of Cd absorption by soybean roots during short-term isotopic studies at low concentrations of soluble Cd (less than 1 micromolar). In studies of Cd absorption by Romaine lettuce, Zn significantly inhibited Cd translocation from roots to shoots when plants were grown for 3 weeks in nutrient solutions (Chaney and White, 1979). Behel and Giordano (unpublished data) measured Zn uptake by rice seedlings grown in solutions varying in Cd concentration. Absorption of Zn after intervals ranging from 6 to 72 hours decreased in roots with increasing Cd level while concentrations in the shoots were unaffected.

Extractable Metals

Various chemical extractants have been employed to provide an index of the availability to plants of Cd and Zn in sludge-treated soils. The amounts of Cd and Zn extracted invariably fail to provide a satisfactory index of the Cd and Zn concentrations in plants on some soils when the extractants are used on a large enough number of soils with different chemical characteristics. There has been some success in obtaining a correlation between metal concentration in plant tissue and extractable metal for a given plant species in a limited number of soils (Bingham _et al_., 1975; Lagerwerff, 1971; Jones _et al_., 1975). Recent studies with 46 Cd- and Zn-contaminated soils and nine different chemical extractants showed that extractable metal alone was not a good index of the concentration of Cd and Zn in the test plants (Haq _et al_., 1980). However, a combination of two variables--ammonium acetate-extractable Zn and soil pH -- yielded a good index of the concentration of Zn in the test plants.

CROP RESPONSE TO CADMIUM AND ZINC IN SINGLE AND REPEATED APPLICATIONS OF SLUDGE

The previous sections of this report have summarized the influence of sludge, plant and soil factors on the Cd and Zn concentrations found in plants grown on soils treated with sludge. The discussion emphasized the response of plants to sludge-borne Cd and Zn rather than the effect of time following sludge application. This section of the report will address two questions: (1) Do the same metal concentrations in plants result from equal total applications of sludge-borne Cd and Zn in (a) a single sludge application and (b) sludge applications repeated over a period of years? (2) Do the concentrations of Cd and Zn in crops change with time after termination of sludge applications to soils? These questions represent two different ways of addressing the change of availability of sludge-borne Cd and Zn with time after application. The first relates to estimating long-term crop responses from short-term responses on the assumption that the availabilities of Cd and Zn do not change with time.

Field experiments with sludge typically include a control treatment in which no sludge is added along with one or more additional treatments in which sludge is added, each treatment being applied to replicated plots. Each plot designated to receive a particular treatment receives the assigned quantity of sludge each year for a number of years. The data obtained on Cd and Zn can be expressed in several ways, the simplest being graphs of the concentrations of Cd and Zn in the plants vs. the quantities of sludge or metals applied annually. If the effect of the Cd and Zn in one application disappears completely before the next is added, the concentrations of the metals in the crops will remain the same from year to year except for the effect of other factors. If the effect of the Cd and Zn in individual annual applications does not disappear in the course of a year but is dissipated over several years, the concentrations of Cd and Zn in plants on plots that receive a given application of sludge each year will increase somewhat with time and eventually will reach a constant level for each metal. And, if the effects of the applied metals do not decrease with time after application of sludge, the concentrations of Cd or Zn in the plant tissue associated with a given total application of Cd or Zn will be the same, whether the metals have been applied in a single quantity in any year of the experiment or in smaller quantities in two or more years. For example, in the model in which the concentrations of Cd and Zn in plants increase linearly with the quantities added and in which equal quantities are added each year, a plot of the concentration of Cd or Zn in the plants against the total quantity added will be represented by a single straight line (Figure 2-B), and the increase in Cd or Zn content in the plants per unit of metal added per year will be twice as great in the second year as in the first, three times as great in the third year as in the first, and so on (i.e., interval $D_1 = D_2 = D_3$ in Figure 2-A). This model has been employed in some health-related projections as a very conservative means of estimating the increases in concentrations of certain metals to be expected in plants grown on soils receiving repeated applications of sludge over a period of years on the basis of the increases in concentration of the metal or metals observed in the year in which a single quantity of sludge is applied.

Parenthetically, it should be emphasized that the model represented by Figure 2 refers to hypothetical conditions in which soil pH and other factors remain constant from year to year. Environmental factors vary from one year to another but show no significant trend over a long period of years. In many non-calcareous soils, however, the pH changes significantly with time, particularly where sludge is applied, and this may have marked effects on the concentrations of Cd and Zn in plants. Maintaining the soil pH at an approximately constant value in such soils under field conditions is difficult, both practically and experimentally.

If the availabilities of sludge-borne Cd and Zn decrease with time after application, as has been found when micronutrients are added as fertilizers, the cumulative effect of repeated applications will be less than the product of the effect in the first year and the number of years the sludge has been applied. These circumstances are represented by the model in Figures 3-A and 3-B, where the concentrations of the metals in the plants are still assumed to increase linearly with the quantities added to the soils.

If the relationship of metal concentration in the plants versus quantity applied exhibits saturation effects in the plants, or if adding a calcareous sludge to an acid soil causes a considerable increase in soil pH, the curves will be concave downward. Under these circumstances also, the cumulative effect of repeated applications generally will be less than the product of the effect in the first year and the number of years the sludge is applied.

If the availabilities of sludge-borne Cd and Zn increase with time as a result of an increase in soil acidity, different situations are theoretically possible. If the increase in acidity is independent of the quantity of sludge applied, intervals D_2 and D_3 in Figure 2-A might exceed interval D_1. A more likely situation is one in which the sludge contributes to the increase in acidity. The lines in Figure 2-A might then be concave upward because large additions of sludge would produce greater acidification than would small additions. The cumulative effect of repeated applications could then be greater than the product of the effect in the first year and the number of years the sludge is applied.

The value of the effects of single additions on the Cd and Zn content of plants as a basis for estimating the cumulative effects of repeated additions has been debated, and various views are held. The data used in this report to illustrate the importance of single versus repeated applications of metals (Hinesly et al., 1976, 1977; Baker et al., 1979a, 1979b; Dowdy et al., 1977; Pietz et al., 1980; and Giordano et al., 1979a) have been derived from field experiments in which a number of rates of annual application were repeated on their respective plots each year. In these experiments, single applications were made only in the first year, and a fresh batch of sludge was obtained for use in each succeeding year. In such experiments, the cumulative application is approximately proportional to the annual application, and the results may be affected by year-to-year variations in sludge composition, soil pH and environmental conditions.

Single And Repeated Additions Of Sludge-Borne Cadmium And Zinc

The response to a single application of Cd and Zn in sewage sludge has been studied with numerous crops, including vegetables (Tables 3, 15, 16 and 19), corn (Tables 17, 18, 20, 21, 27 and 29), oats (Tables 15, 28 and 30), soybeans (Tables 15, 16, 28 and 30) and sorghum (Tables 28 and 30). The data indicate that concentrations of both Cd and Zn in vegetative plant parts tend to increase with increasing rates of metal addition. Although exceptions can be found (e.g., Zn in oat straw), the absolute concentrations of Cd and Zn are increased to a greater extent in the leaves than in the grain of corn, sorghum, soybeans and oats. The relative increase in metal concentration in plants with successively greater quantities of sludge added in a single application is generally greater for Cd than for Zn.

To compare the effects of a single addition of sludge-borne Cd and Zn in a given year with the cumulative effects of additions that are repeated in successive years, an experiment must be continued for two or more years. Only a few such experiments have been carried out. Representative data obtained from them will be presented and discussed.

The available evidence indicates the existence of a range of effects of repeated additions of Cd in sewage sludge. At the one extreme are marked effects in which the increase of Cd concentration in plants grown at the conclusion of a period of years in which sludge has been added in annual increments is essentially the same as the increase expected if all the sludge had been applied in a single addition in the final year.[3] Data obtained by Pietz et al. (1979) are an example. These investigators found that the concentration of Cd in leaves of corn grown on calcareous strip mine spoil increased markedly as repeated applications of sludge were made over a period of 6 years (Table 31). The results seem to approach those postulated in the hypothetical model in Figure 2 in which the effectiveness of applications made in the first and succeeding years does not decrease with time (although the soil pH decreased somewhat through the years). The rate of increase of Cd concentration in the corn leaves per unit of Cd added in the sludge was 0.31 for the single addition of sludge and 0.30 for the repeated additions (Table 33).

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[3] In the experiments available, the effect of single additions was measured in the first year of the experiment, and the effect of repeated additions was measured in later years after repeated additions had been made; hence, the comparisons of the effects of single vs. repeated additions of sludge are not independent of the effect of years. If the experiments had been designed to make the comparisons of interest to EPA at this time, the single additions would be made in the year their effects are to be compared with those of repeated additions.

At the other extreme are limited effects in which the increase of Cd concentration in plants grown at the conclusion of a period of years in which sludge has been added in annual increments is much smaller than the increase expected if all the sludge had been added in a single application in the final year. Work by Wolf and Baker (1980) provides an example (Table 32). In this experiment on a neutral, noncalcareous, silt loam soil, the concentration of Cd in leaves of corn increased to only a relatively small degree with repeated additions of sludge. The rate of increase of Cd concentration in the corn leaves per unit of Cd added in the sludge was 0.20 for the single addition of sludge and 0.09 for the repeated additions (Table 33).

Tables 31 to 33 provide information on Zn as well as that just described for Cd. In both experiments, the increase of Zn concentrations in the plants at the conclusion of a series of annual additions of sludge was much smaller than the increase expected if all the sludge had been added in a single application in the final year.

Additional observations on the effects of single vs. repeated additions of sludge on the Cd concentrations in corn leaves, stover and grain have been made in published data by Hinesly _et al_. (1979c), Dowdy _et al_. (1977), Giordano and Mays (1977) and Soon _et al_. (1980) as well as in unpublished data by Hinesly _et al_. (1979b), Giordano _et al_. (1979a) and Wolf and Baker (1980). These observations further illustrate the range of effects that may be found.

Improved quantification of the effects of single vs. repeated additions of sludge in individual experiments is desirable, and further information is needed to provide a reliable basis for predicting the effects that will occur under different circumstances. There is no doubt that plant species respond differently with regard to Cd uptake when sludge-borne Cd is applied to soils. It is also quite clear that soil pH has a marked effect on the Cd concentration in plants. Information is not available at this time, however, to determine whether crop species and soil pH alter the cumulative effect of repeated Cd applications on plant Cd as much as they influence the effect of a single application. It does seem probable that most cumulative effects will fall within the wide range reported here regardless of plant species or soil pH. The data available thus far do not provide a basis for predicting the cumulative effects of repeated Cd additions in sludge on the Cd content of plants. The data on cumulative effects of repeated additions of Zn suggest that the range of values may be slightly narrower than with Cd but that in most cases the trends with Zn are similar to those with Cd.

Availability Of Sludge-Borne Cadmium And Zinc To Plants After Termination Of Sludge Applications To Soils

Seasonal variations in soil and environmental conditions influence the concentrations of Cd and Zn in all crops. Nonetheless, data from controlled studies indicate that, in at least some instances, Cd applied to noncalcareous soils in sludge may remain available to plants for a number of years after sludge application has ceased (Tables 17, 34-39).

Studies by Baker et al. (1979a, 1979b) and Hinesly et al. (1979d) have shown that Cd concentrations in corn grain, wheat grain, soybean seed and potatoes remained above background levels for 4 years after the cessation of sludge applications, while data by Hinesly et al. (1979c) indicate that concentrations of Cd in corn grain returned to background levels within a 4-year period.

Other data from field studies demonstrate the residual effect of sludge applications on Cd uptake by vegetable crops for up to 8 years after sludge application (Tables 15, 19 and 38). A greenhouse experiment performed by Chang and Page (1979) also showed that Cd availability to radish crops grown on a sludge-treated soil remained essentially the same for a 2-year period. Similarly, sweet corn (Tables 36 and 38) and bush beans (Table 38) showed elevated Cd concentrations for 4 to 7 years after sludge applications were stopped. Concentrations of Cd were increased in both vegetative and reproductive plant parts of both crops and were related to the cumulative amount of Cd applied.

Zn also has been shown to remain available to plants after the application of sewage sludge to land has ceased (Hinesly et al., 1979d; Baker et al., 1979b). Data on the residual availability of Zn and/or Cd to crops are available for selected vegetables (Tables 15, 16, 19 and 38), soybeans (Tables 15 and 16), potatoes (Tables 5 and 34), wheat (Tables 5 and 34), oats (Table 15), sweet corn (Table 36 and 38) and field corn (Tables 17, 18, 20, 21, 34, 35 and 37).

The references cited indicate that the length of time sludge-derived Cd and Zn remain available to crops after sludge applications have ceased is indeterminate. Although the evidence indicates that the concentrations of Cd and Zn in plants may remain constant or may decrease for a period of years after termination of sludge applications if the soil pH remains constant or is increased, it is likely that the concentrations will increase if the soil pH decreases.

Old sludge disposal sites have been used by Chaney and Hornick (1978), Otte and LaConde (1978), Kirkham (1975), Ryan (1977) and Webber et al. (1980) as an additional source of information on the residual effects of sludge-borne Cd and Zn on plants. For example, Chaney and Hornick (1978) grew lettuce, Swiss chard, soybeans, oats and orchardgrass in 1976 on soils that had received sludge from 1961 to 1973. The total quantity of Cd in the soil was 2.8 mg/kg, and all crops grown on the sludge-treated soil showed higher concentrations of Cd than did the crops on the controls at the same soil pH. Table 39 shows the Cd and Zn concentrations found in Swiss chard and oats grown on soils used for sludge disposal by six cities in northeastern United States.

One of the limitations associated with data from old sludge-disposal sites is that accurate records of the rates and frequencies of sludge application and sludge composition are not available. The findings by the investigators cited, however, indicate that Cd applied to soils in the form of sludge remains available to crops for an indefinite time after termination of sludge applications.

In summary, the information presented indicates that factors such as soil and sludge properties and plant species and cultivars influence the concentrations of Cd and Zn in plants following either a single application or repeated applications of sludge to soils. Most data indicate that Cd and Zn concentrations in plants increase with the quantities of these elements added in single or repeated applications of sludge to soils, but some studies, especially those on calcareous soils and those in which assays were made of plant tissues such as corn grain that tend to exclude Cd, have shown no significant correlation between amounts of metal applied and concentrations in the plants. Similarly, the metal concentrations in plants may or may not increase significantly with the cumulative metal input to soils over a period of years during which repeated applications have been made. The seeming contradictions are probably related to (1) differences in the chemical, physical and biological properties of the soils receiving the sludge-borne Cd and Zn, (2) differences in the chemical properties of the sludge applied, differences in plant species and variety tested as well as differences in the plant part used to evaluate the response (vegetative parts are nearly always more responsive than the fruit or seed) and (4) variations in other factors including climate and management.

In view of the effects of single and repeated additions of sludge-derived Cd and Zn on the content of these metals in plants, the residual effects after sludge applications have ceased, and the effects of soil pH on the availability of these metals to plants, it seems evident that considerable increases in concentration of Cd and Zn in many crops cannot be avoided when sludges high in these metals are applied unless the total amounts of the metals supplied in single and repeated additions are limited and unless the soil reaction is maintained near or above neutrality. Even at a soil pH of 6.5, the Cd added in many sludges is sufficient to increase the Cd concentration in most crops.

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TABLES AND FIGURES

Table 1. Concentrations of cadmium and zinc in the influent, effluent and sludge of three activated sludge treatment plants of the Municipal Sanitary District of Greater Chicago (Lue-Hing, 1979)

Treatment plant[a]	Metal	Metal concentration: In influent	In effluent	In dry digested sludge	Sludge concentration factor[e]
		mg/1	mg/1	mg/kg	
West-Southwest (3009)[b]	Cd	0.045	0.001	248	5,511
	Zn	0.699	0.034	2,917	4,173
Calumet (765)[c]	Cd	0.005	0.001	56	11,200
	Zn	0.413	0.009	2,391	5,789
Hanover (20.4)[d]	Cd	0.011	<0.001	72	6,545
	Zn	0.034	0.002	710	20,882

[a] Number in parentheses is flow in thousands of m^3/day.

[b] Heavy industrial input with high metal content.

[c] Heavy industrial input with low metal content.

[d] Primarily domestic input with low metal content.

[e] Ratio of sludge concentration to influent concentration.

Table 2. Concentrations of cadmium and zinc in sewage sludge (Sommers, 1977)

Metal	Sludge		Concentration in dry sludge		
	Type	Number of samples	Range	Median	Mean
			mg/kg		
Cadmium	Anaerobic	98	3–3410	16	106
	Aerobic	57	5–2170	16	135
	Other[a]	34	4–520	14	70
	All	189	3–3410	16	110
Zinc	Anaerobic	108	108–27800	1890	3380
	Aerobic	58	108–14900	1800	2170
	Other[a]	42	101–15100	1100	2140
	All	208	101–27800	1740	2790

[a] Lagoon, primary and miscellaneous types of sludges.

Table 3. Concentrations of cadmium and zinc in edible parts of vegetables grown on sludge-treated soil at pH 4.6 and 6.7 (Giordano *et al*., 1979b)

Plant species	Sludge added[a]	Concentration of metals in edible tissue of plants grown at indicated pH values			
		Soil pH 4.6		Soil pH 6.7	
		Zn	Cd	Zn	Cd
	metric tons/ha	mg/kg			
Lettuce (cv. Romaine)	0	35	0.88	31	0.78
	224	53	2.25	51	1.78
Cabbage (var. capitata)	0	48	0.19	29	0.16
	224	59	0.35	46	0.19
Carrot (var. sativa)	0	39	0.96	22	0.71
	224	30	7.29	29	1.25
Pepper (cv. California Wonder)	0	29	0.24	24	0.19
	224	33	0.97	29	0.98
Potato (cv. Red Irish)	0	16	0.11	--	--
	224	19	0.10	--	--
Tomato (cv. Better Boy)	0	26	0.52	--	--
	224	40	1.04	--	--
Egg Plant (cv. Black Beauty)	0	15	0.54	--	--
	224	22	1.64	--	--

[a] The sludge added 403 kg of Zn/ha and 11.2 kg of Cd/ha to a Decatur silt loam with a CEC value of 10 meq/100 g.

Table 4. Effect of sludge application to a calcareous soil on the cadmium and zinc content of vegetables (Chang *et al.*, 1979)

Sludge applied[a]	Metal added		Concentration of metals in tissue of indicated plants											
			Lettuce		Swiss chard		Radish tops		Radish tubers		Carrot tops		Carrot tubers	
	Cd	Zn	Cd	Zn	Cd	Zn	Cd	Zn	Cd	Zn	Cd	Zn	Cd	Zn
metric tons/ha	kg/ha		mg/kg											
0	0	0	0.60	52	0.27	--	0.25	39	0.12	41	0.30	24	0.60	41
67.5	2.9	175	1.50	--	0.60	--	0.95	64	0.50	62	0.60	34	1.20	53
135	5.6	349	1.70	68	1.60	--	1.37	90	0.72	86	0.80	33	1.60	71
270	11.1	698	3.80	105	2.60	--	2.03	134	1.16	154	0.90	40	2.20	72
540	22.2	1,397	7.90	116	2.90	--	3.16	177	1.76	158	1.40	50	3.50	98

[a] Sludge was applied bi-annually over a 3-year period.

Table 5. Cadmium uptake by sorghum, potatoes and wheat from sludge-treated soils (Baker *et al.*, 1979a, 1979b)

Cumulative Cd added[a]	Cadmium concentration in indicated plant tissues					
	Sorghum grain	Potato tubers		Potato leaf	Wheat grain	
	1975	1976	1977	1977	1976	1977
kg/ha	mg/kg					
0	0.035	0.32	0.21	1.92	0.07	0.06
4.1	0.470	1.10	0.88	7.45	0.89	0.60
8.3	0.876	1.35	1.02	10.95	1.73	1.00
16.6	0.855	1.37	1.45	17.47	1.91	1.42

[a] Cd added in sludge in 1974 and 1975 to a silt loam soil with a CEC of 12 meq/100 g. Soil pH levels were 6.6, 6.4, and 6.6 for 1975, 1976, and 1977, respectively.

Table 6. Concentrations of cadmium and zinc in diagnostic leaves of corn, cotton and soybeans grown on sludge-treated soils with and without liming (Giordano and Mays, 1980)

		Metal concentration in indicated plant varieties											
		Corn				Cotton				Soybean			
		Funk		Pioneer		Stoneville		Coker		Essex		Ransom	
Treatment	Limestone[a]	Zn	Cd	Zn	Cd	Zn	Cd	Zn	Cd	Zn	Cd	Zn	Cd
		mg/kg											
Control	-	13	0.28	8	0.20	19	0.40	19	0.43	46	0.29	57	0.31
	+	12	0.25	9	0.26	18	0.33	20	0.40	37	0.29	42	0.31
Fertilizer	-	34	0.32	24	0.36	25	0.65	25	0.51	59	0.31	64	0.31
	+	27	0.20	17	0.38	24	0.34	26	0.50	40	0.27	45	0.33
Sludge[b] (11 metric tons/ha)	-	49	0.17	27	0.62	26	0.36	28	0.39	98	0.35	90	0.22
	+	48	0.17	27	0.61	27	0.36	28	0.34	61	0.21	54	0.23
Sludge[c] (78 metric tons/ha)	-	66	0.60	39	1.35	30	0.64	30	0.63	125	0.47	111	0.47
	+	76	0.46	39	1.39	32	0.52	30	0.55	84	0.52	84	0.49

[a] Limestone applied at the rate of 10 metric tons/ha. Resulting soil pH values were 4.7 - 5.5 and 6.5 - 6.8 for - and + limestone treatments, respectively. The soil used was a Decatur silt loam.

[b] The sludge added 7.7 kg of Zn/ha and 0.16 kg of Cd/ha.

[c] The sludge added 54.6 kg of Zn/ha and 1.2 kg of Cd/ha.

Table 7. Concentrations of cadmium and zinc in corn grain, cotton seed and soybean grain grown on sludge-treated soil with and without liming (Giordano and Mays, 1980)

		Metal concentration in indicated plant varieties											
		Corn				Cotton				Soybean			
		Funk		Pioneer		Stoneville		Coker		Essex		Ransom	
Treatment	Limestone[a]	Zn	Cd	Zn	Cd	Zn	Cd	Zn	Cd	Zn	Cd	Zn	Cd
		mg/kg											
Control	-	25	0.16	23	0.16	28	0.17	29	0.18	40	0.54	43	0.48
	+	24	0.15	21	0.18	31	0.16	30	0.13	37	0.53	36	0.50
Fertilizer	-	25	0.14	21	0.26	26	0.41	30	0.39	45	0.29	45	0.59
	+	25	0.18	21	0.24	30	0.36	28	0.38	39	0.24	41	0.52
Sludge[b] (11 metric tons/ha)	-	23	0.18	23	0.24	32	0.28	33	0.34	49	0.28	48	0.58
	+	28	0.18	22	0.18	31	0.25	30	0.25	44	0.17	46	0.49
Sludge[c] (78 metric tons/ha)	-	33	0.13	28	0.21	34	0.33	36	0.35	54	0.57	46	0.53
	+	31	0.18	26	0.25	32	0.35	34	0.38	53	0.65	47	0.77

[a] Limestone applied at the rate of 10 metric tons/ha. Resulting soil pH values were 4.7 - 5.5 and 6.5 - 6.8 for - and + lime treatments. The soil used was a Decatur silt loam.

[b] The sludge added 7.7 kg of Zn/ha and 0.16 kg of Cd/ha.

[c] The sludge added 54.6 kg of Zn/ha and 1.2 kg of Cd/ha.

Table 8. Cadmium and zinc concentration in different cultivars of soybean, lettuce and corn

Soybean[a]		Lettuce			Corn[d]				
Cultivar	Cd in shoot	Cultivar	Zn in leaf	Cd in leaf	Inbred line	Zn in leaf	Cd in leaf	Zn in grain	Cd in grain
	mg/kg		mg/kg	mg/kg		mg/kg	mg/kg	mg/kg	mg/kg
Clark 63	1.4	Romaine[b]	51	1.8	B77	61.8	14.7	44.6	1.1
Mandarin	2.0	Boston[b]	63	1.9	R177	88.0	5.0	52.4	0.3
Corsoy	2.2	Bibb[b]	68	4.2	H96	94.3	5.0	54.0	0.2
Amsoy 71	2.4	Valmaine[c]	77	3.8	H99	102.9	6.8	33.8	0.2
Grant	2.9	Tania[c]	72	4.4	H100	140.1	15.4	46.9	0.5
Jackson	3.2	Dark Green			R805	148.1	2.5	43.7	0.1
Richland	3.5	Boston[c]	68	5.0	B37	164.2	62.9	64.3	3.9
Dunfield	4.3	Belmay[c]	89	5.2	Oh545	170.6	9.6	51.6	0.2
Arksoy	4.8	Butterhead 1033[c]	100	5.3	A619	193.3	8.1	70.0	0.3
Harosoy 63	6.0	Butterhead 1044[c]	124	5.7	H98	217.2	48.8	54.5	2.4
		Buttercrunch[c]	94	5.8	Oh43	281.8	11.3	70.0	0.2
		Butterhead 1034[c]	104	6.2					
		Summer Bibb[c]	125	8.1					

[a] Boggess et al. (1978).

[b] Giordano et al. (1979b). The lettuce was grown in soil with pH = 6.7. At pH = 6.0, Romaine, Boston and Bibb contained 2.3, 3.1 and 8.4 mg of Cd/kg, respectively.

[c] Chaney and Feder (1980). Soil Zn, Cd and pH were 7,120 mg/kg, 53 mg/kg and 7.8, respectively. According to a regression analysis of the data on lettuce composition, mg Zn/kg = 11.6 x mg Cd/kg + 33; $R^2 = 0.55$.

[d] Hinesly et al. (1978).

Table 9. Response of corn inbreds to sludge-borne cadmium and zinc (Hinesly *et al.*, 1978)[a]

Metal	Metal applied: Cumulative (1969-1975)	Metal applied: During 1976 growing season	Soil pH	Metal concentration in plant tissue: Leaf[b] Inbred A	Leaf[b] Inbred B	Grain[b] Inbred A	Grain[b] Inbred B
	kg/ha	kg/ha		mg/kg	mg/kg	mg/kg	mg/kg
Zn	0	0	7.4	16	15	30	26
	463	69	7.6	43	36	41	27
	926	137	7.3	62	48	47	31
	1852	273	7.0	193	103	70	34
Cd	0	0	7.4	0.9	<0.06	0.12	0.06
	24.8	4.8	7.6	12.0	0.30	0.66	0.09
	49.5	9.6	7.3	36.9	0.90	2.33	0.08
	99.0	19.1	7.0	62.9	2.50	3.87	0.08

[a] Data from 1976 growing season. Sewage sludge was applied by furrow irrigation during the growing season.

[b] Inbreds for Zn data: A = A619 and B = H99
Inbreds for Cd data: A = B37 and B = R805

Table 10. Effect of temperature on cadmium and zinc concentrations in various parts of corn plants (Sheaffer *et al.*, 1979)[a]

Soil temperature	Zn				Cd			
	Seedling	Ear leaf	Grain	Stover	Seedling	Ear leaf	Grain	Stover
°C	mg/kg[b]							
16	222b	92d	28d	180b	0.74c	0.29b	0.09	1.09a
22	253b	109c	32c	163b	0.86b	0.34a	0.08	0.66b
27	248b	120b	36b	168b	0.76c	0.31a	0.07	0.72b
35	300a	143a	40a	226a	1.10a	0.33a	0.10	0.86b

[a] Corn grown on a Sassafras sandy loam soil treated with 246 kg of Zn/ha and 0.9 kg of Cd/ha. Soil pH = 5.6. CEC = 5.6 meq/100 g.

[b] Numbers in a given column followed by the same letter are not significantly different by Duncan's Multiple Range Test ($p < 0.05$).

Table 11. Effect of season (year) on cadmium and zinc concentration in several crops after one application of sewage sludge in 1975

Metal	Crop	Metal concentration in plant tissue in indicated year		
		1975	1976	1977
		mg/kg		
Zn	Corn[a]	116	96	-
	Lettuce[b]	92.8	58.3	-
	Pepper[b]	40.0	-	30.0
Cd	Corn[a]	0.33	0.37	-
	Lettuce[b]	5.33	2.24	-
	Pepper[b]	0.91	-	0.64

[a]Sheaffer et al. (1979). The soil pH values were 5.6, 5.3, and 5.2 in 1975, 1976 and 1977, respectively.

[b]Giordano et al. (1979b). The soil pH values were 6.0, 6.1, and 6.0 in 1975, 1976 and 1977, respectively.

Table 12. Cadmium in native vegetation from soils with different natural levels of cadmium (Lund and Page, 1980)[a]

Total Cd in soil	Soil pH	Cd concentration in indicated plants: Wild oats	Mustard
mg/kg		mg/kg	
22	6.4	-	2.0
15	5.8	2.0	-
12	6.0	7.6	-
6	6.0	-	4.0
5.6	7.1	-	0.5
4.2	6.7	1.0	1.0
3.7	7.4	0.5	1.6
3.5	6.7	-	3.6
2.9	6.2	1.3	-
2.1	6.2	0.7	-
0.26	6.4	0.4	0.14
0.15	6.3	-	0.39
0.13	4.9	0.22	0.27
0.10	5.3	0.11	-
0.01	6.0	0.09	-

[a]Soils and plants collected from Malibu Canyon, California.

Table 13. Cadmium concentrations in Swiss chard grown in the greenhouse on soils containing different levels of natural cadmium (Lund and Page, 1980)[a]

Soil series	Soil pH	Total soil Cd	Plant Cd
		mg/kg	mg/kg
Hambright	6.8	0.02	0.6
Los Osos	7.1	6.5	5.0
Saugus	5.7	1.4	5.8
Salinas	6.7	6.8	9.6
Castiac	6.0	12.0	72.0
Malibu	5.7	20.0	72.0
Millsholm	6.4	22.0	82.0

[a]Soils collected from Malibu Canyon, California.

Table 14. Cadmium and zinc concentrations in surface soil and vegetation adjacent to an industrial smelting complex (U.S. Environmental Protection Agency, 1972)

Distance from stack	Direction from source	Metal concentration in soil		Metal concentration in vegetation	
		Cd	Zn	Cd	Zn
km		mg/kg			
0.65	Northeast	56	418	7.5	52
1.3	East	21	455	8.6	60
4.0	Southwest	6.5	126	1.3	13
7.3	West	2.0	82	0.7	12
Control		0.5	44	0.1	6.8

Table 15. Concentrations of cadmium and zinc in lettuce, Swiss chard, soybean grain and oat grain grown on sludge-treated soils (Decker *et al.*, 1978)

Metal addition Zn	Metal addition Cd	Limestone added[b]	Year	Soil pH	Zn in lettuce	Cd in lettuce	Cd in Swiss chard	Cd in soybean grain	Cd in oat grain
					Metal concentrations in indicated crops				
— kg/ha —					mg/kg				
0	0	No	1976	5.3	31.7	0.80	–	–	–
			1977	5.7	59.9	0.94	1.03	0.34	0.04
			1978	5.7	71.4	0.56	0.71	0.05	0.09
		Yes	1976	5.9	17.8	0.41	–	–	–
			1977	6.4	46.3	0.76	0.73	0.14	0.05
			1978	6.7	38.0	1.36	0.33	0.05	0.08
		Excess	1976	7.3	13.4	0.33	–	–	–
			1977	7.5	38.8	0.44	0.29	0.28	0.03
			1978	7.5	24.5	1.83	0.26	0.05	0.06
74	0.7	Yes	1976	6.3	26.3	0.54	–	–	–
			1977	6.4	61.7	0.85	1.21	0.11	0.07
			1978	6.6	48.9	0.59	0.81	0.11	0.11
		No	1976	5.6	44.9	1.53	–	–	–
			1977	5.6	108.9	2.16	2.68	0.24	0.11
			1978	5.9	101.0	1.18	3.52	0.07	0.15
148	1.4	Yes	1976	6.0	30.1	0.71	–	–	–
			1977	6.2	69.2	1.05	1.64	0.19	0.08
			1978	6.6	55.3	0.59	0.73	0.13	0.09
		No	1976	5.6	41.7	1.28	–	–	–
			1977	5.6	96.6	1.61	2.31	0.21	0.08
			1978	6.0	101.0	1.02	4.55	0.08	0.09
296	2.8	Yes	1976	5.9	47.9	1.31	–	–	–
			1977	6.1	80.3	1.19	1.98	0.20	0.09
			1978	6.8	58.7	0.49	0.98	0.08	0.14
		No	1976	5.6	72.9	1.70	–	–	–
			1977	5.5	148.0	2.43	3.76	0.23	0.13
			1978	5.7	147.0	0.98	1.64	0.09	0.13

[a] Heat-treated sludge was applied in 1976 to a Christiana fine sandy loam, CEC = 6.5 meq/100 g.

[b] Dolomitic limestone was applied each year to maintain the soil pH at about 6.5. Excess refers to the normal dolomitic limestone application plus an excess of 44 metric tons/ha.

Table 16. Effect of soil pH on cadmium and zinc concentrations in crops grown in 1978 on soils treated with Nu-Earth sludge (Decker *et al.*, 1980)

Metal applied[a] Zn	Metal applied[a] Cd	Limestone applied[b]	Soil pH	Zn Lettuce	Zn Swiss chard	Zn Soybean grain	Cd Lettuce	Cd Swiss chard	Cd Soybean grain
— kg/ha —				— mg/kg —					
0	0	-	5.7	71	98	46	0.56	0.71	0.05
		+	6.7	38	39	43	1.36	0.33	0.05
		Excess	7.5	24	40	40	1.83	0.26	0.05
83	4.2	-	6.4	91	296	56	6.59	8.43	0.36
		+	6.7	73	96	52	4.29	3.92	0.26
208	10.5	-	6.6	192	427	68	16.8	15.5	0.65
		+	6.9	98	122	57	8.01	5.80	0.61
416	21	-	6.3	222	383	72	23.9	20.6	1.00
		+	6.7	112	169	71	8.66	8.62	1.24

[a] The experiment was carried out on a Christiana fine sandy loam, CEC = 6.5 meq/100 g.

[b] The amount of dolomitic limestone applied was based on a buffer method. Dolomitic limestone was applied each year to maintain the soil pH at about 6.5. "Excess" refers to the normal dolomitic limestone application plus an excess of 44 metric tons/ha.

Table 17. Concentrations of cadmium in corn grain grown on sludge-treated soils as affected by soil pH (Keeney *et al.*, 1980)

		Plainfield sand				Plano silt loam			
		Soil pH[b]		Cd in corn grain		Soil pH[b]		Cd in corn grain	
Cd applied[a]	Year	Control	Limestone added	Control	Limestone added	Control	Limestone added	Control	Limestone added
kg/ha				mg/kg				mg/kg	
0	1978	4.7	5.8	0.008	0.006	5.3	6.1	0.014	0.012
	1979	5.0	6.0	0.010	0.014	–	–	–	–
1.7	1978	4.9	6.2	0.010	0.012	5.4	6.4	0.014	0.012
	1979	5.0	6.0	0.020	0.012	–	–	–	–
8.3	1978	4.9	5.7	0.016	0.016	5.1	6.4	0.030	0.032
	1979	4.9	5.9	0.030	0.016	–	–	–	–
16.7	1978	4.8	6.3	0.034	0.032	4.9	6.2	0.041	0.038
	1979	4.8	5.8	0.046	0.026	–	–	–	–
33.3	1978	4.8	5.7	0.032	0.034	5.1	5.8	0.058	0.048
	1979	–	–	–	–	–	–	–	–

[a] Applied in fall of 1976.

[b] Soil pH in 2:1 (v/w) 0.01 M $CaCl_2$.

Table 18. Concentrations of cadmium and zinc in corn leaves as affected by sewage sludge and limestone additions (Pepper and Bezdicek, 1980)

Metal	Metal applied		Year	Cd or Zn in corn leaves grown on indicated soil			
				Sultan silt loam[a]		Puyallup fine sandy loam[a]	
	Annual	Cumulative		Control	Limestone added	Control	Limestone added
	kg/ha			mg/kg			
Cd	0	0	1976	1.0	0.8	0.2	0.2
	0	0	1977	2.4	1.6	0.9	0.6
	0.75	0.75	1976	5.3	3.7	1.2	0.7
	0.75	1.50	1977	7.0	6.0	8.4	2.7
	1.5	1.5	1976	7.5	6.7	1.5	2.1
	1.5	3.0	1977	10.2	9.3	5.1	6.4
	3.0	3.0	1976	8.3	8.5	3.1	5.0
	3.0	6.0	1977	13.4	15.8	7.2	7.1
Zn	0	0	1976	28.0	26.8	28.7	27.3
	0	0	1977	49.7	57.1	55.8	77.5
	56	56	1976	115	70.3	137	72
	56	112	1977	137	123.8	186	107
	112	112	1976	183	132	193	147
	112	224	1977	338	190	486	240
	224	224	1976	424	207	375	248
	224	448	1977	588	343	677	504

[a] Limestone was added prior to sludge application in 1976. Soil pH: control, 4.7; limestone added, 6.5.

Table 19. Effect of digested sludge and composted digested sludge applied in 1973 and sulfur applied in 1976 on soil pH and concentrations of cadmium and zinc in Romaine lettuce grown from 1974 to 1977 (Chaney *et al.*, 1978; and unpublished data)

Treatment[a]	Sludge applied	Total concentration of metal in soil		Soil pH			Zn in lettuce				Cd in lettuce			
		Zn	Cd	1974	1975	1976	1974	1975	1976	1977	1974	1975	1976	1977
	metric tons/ha	mg/kg					mg/kg							
Control	-	24	0.12	6.2	6.2	6.2	76	41	27	52	1.3	0.6	1.1	1.6
Sludge[b]	40	69[b]	0.40[b]	5.6	5.6	5.2	419	162	153	191	6.9	4.6	5.8	5.5
	80	91	0.77	6.0	6.0	5.3	497	303	393	428	8.0	9.4	15.0	12.2
	160	154	1.23	6.5	6.5	5.1	212	231	803	536	4.2	7.4	20.3	10.9
	240	216	2.10	6.7	6.7	4.5	310	268	954	805	5.9	8.3	15.1	14.0
Sludge + dolomitic limestone	80	99	0.77	7.0	7.0	6.7	80	38	38	84	1.8	1.9	2.7	3.1
	160	177	1.56	7.0	7.0	6.8	127	55	54	104	1.9	2.2	3.9	2.2
	240	242	2.18	7.0	7.0	6.6	161	87	74	116	3.2	3.0	3.0	2.8
Compost[b]	40	45	0.18	6.1	6.1	5.2	117	63	52	90	1.5	2.6	4.1	3.3
	80	46	0.29	6.2	6.2	5.3	117	77	78	112	2.1	2.9	5.7	5.0
	160	66	0.38	6.6	6.6	4.8	89	48	111	126	1.4	1.9	7.4	5.2
	240	79	0.51	7.0	7.0	5.0	70	44	120	108	1.0	1.5	8.4	5.5
Compost + dolomitic limestone	80	47	0.21	7.0	7.0	6.8	80	33	21	46	1.2	1.1	1.3	2.8
	160	63	0.37	7.1	7.0	7.0	77	35	24	53	1.2	0.9	0.9	1.2
	240	83	0.57	7.2	7.1	7.0	65	31	22	45	1.0	0.8	1.4	1.7

[a] The soil used was a Woodstown silt loam; CEC = 5.9 meq/100 g.

[b] Sulfur added in 1976 to achieve planned pH values of 5.5 or below.

Table 20. Effects of sludge, limestone and fertilizer on cadmium and zinc concentrations in corn silage and grain (Chaney *et al.*, 1978)

Metal applied[a]		Year	Soil pH		Metal concentration in plant tissue							
					Corn silage[d]				Corn grain[d]			
					Zn		Cd		Zn		Cd	
Zn	Cd		Unfertilized	Fertilized[b]	Unfertilized	Fertilized	Unfertilized	Fertilized	Unfertilized	Fertilized	Unfertilized	Fertilized
—— kg/ha ——					—— mg/kg ——							
0	0	1974	5.5	5.2	24	35	0.61	0.86	23	22	0.07	0.12
		1975[c]	6.2	5.9	28	28	0.48	0.46	15	17	0.06	0.20
		1976[c]	6.5	5.9	48	17	0.51	0.21	20	17	0.08	0.09
		1977	6.7	6.8	34	20	0.22	0.30	23	23	0.06	0.07
		1978	6.8	6.5	42	16	0.28	0.15	18	16	0.05	0.09
		1979	7.2	6.7	22	19	0.17	0.35	-	-	-	-
90	0.9	1974	5.3	5.3	131	120	3.16	3.00	39	34	0.39	0.41
		1975[c]	5.9	5.9	95	83	1.42	1.15	21	23	0.30	0.38
		1976[c]	6.2	5.7	51	44	0.54	0.83	21	22	0.22	0.26
		1977	6.4	6.4	53	42	0.67	0.62	37	28	0.24	0.24
		1978	6.6	6.5	48	35	0.58	0.88	18	19	0.15	0.26
		1979	6.9	6.7	50	35	1.39	1.25	-	-	-	-
180	1.8	1974	5.3	5.3	218	179	4.59	4.08	50	49	0.58	0.59
		1975[c]	5.6	5.5	172	132	2.24	1.67	24	24	0.38	0.41
		1976[c]	5.8	5.6	105	91	1.68	2.04	24	27	0.28	0.44
		1977[c]	6.2	6.2	84	95	1.42	1.56	38	33	0.47	0.40
		1978	6.3	6.2	59	63	1.91	2.02	21	23	0.33	0.40
		1979	6.7	6.5	63	68	2.53	2.33	-	-	-	-
360	3.6	1974	5.3	5.3	288	268	3.95	5.33	60	60	0.68	0.68
		1975[c]	5.5	5.5	123	120	1.47	1.57	28	27	0.44	0.41
		1976[c]	5.7	5.4	133	123	2.08	2.28	25	30	0.37	0.52
		1977[c]	6.2	6.0	113	160	1.59	2.00	49	43	0.68	0.52
		1978	6.2	6.1	78	84	2.54	2.34	23	32	0.39	0.51
		1979	6.5	6.4	71	101	2.11	2.66	-	-	-	-

[a] Digested sludge was applied in 1972 to a Sassafras sandy loam, CEC = 5.6 meq/100 g.

[b] Fertilizer applications were 180 kg of N/ha, 40 kg of P/ha, and 71 kg of K/ha.

[c] Limestone was applied.

[d] Pioneer 3369A.

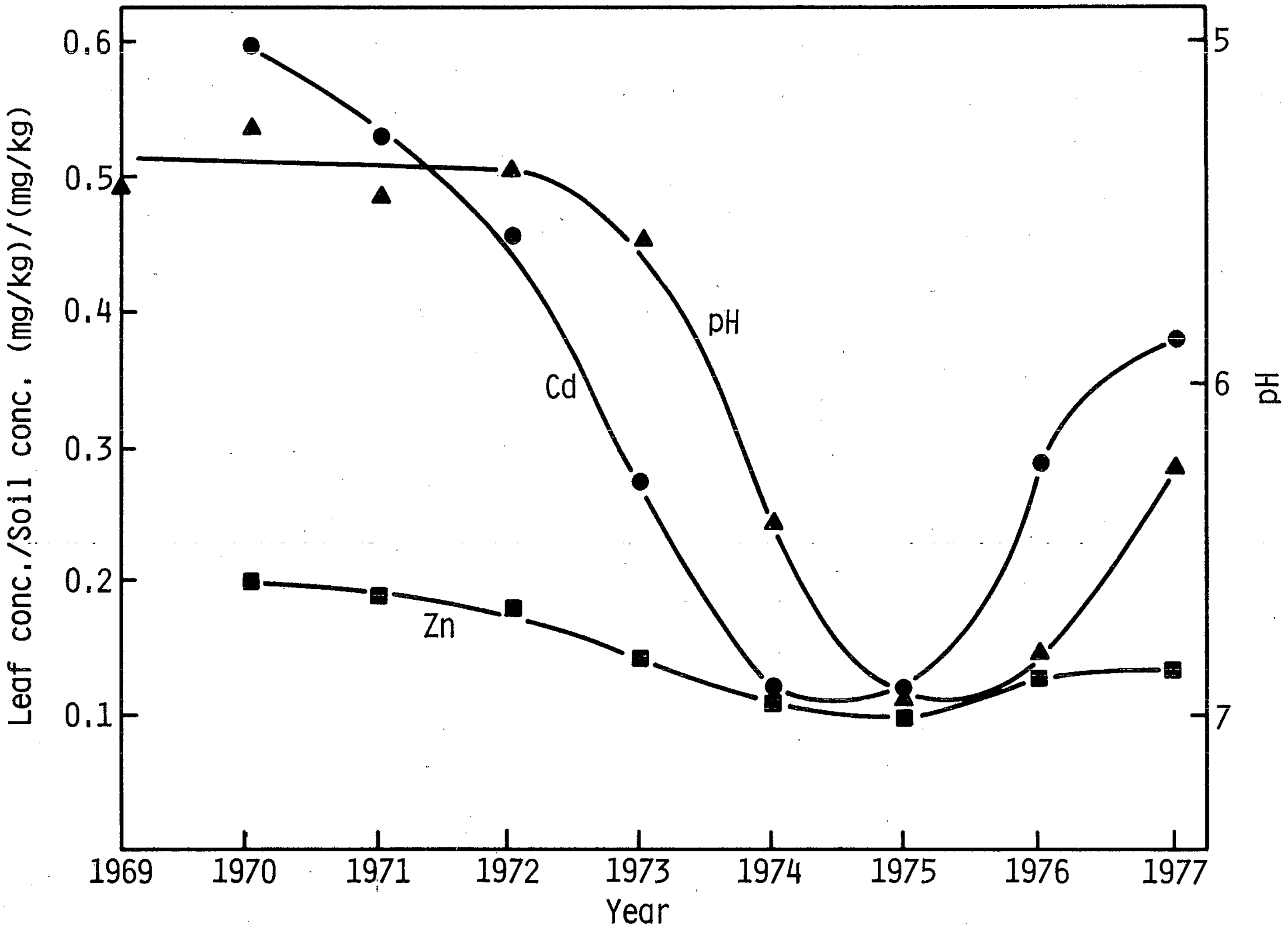

Figure 1. Ratio of concentration of cadmium and zinc in corn leaves to concentration in soil, and pH value of soil during a period of years when annual applications of sludge were being made to a soil in Illinois. The pH change beginning in 1973 was due to application of limestone to the soil. (Hinesly et al., 1979a)

Table 21. Concentrations of cadmium and zinc in corn grown on soils treated with either sludge or metal salts (Baxter, 1980)[a]

Sludge applied	Metals applied Zn	Metals applied Cd	Soil pH 1976	Soil pH 1979	Metal concentrations in corn leaves[b] Zn 1976	Zn 1979	Cd 1976	Cd 1979
metric tons/ha	kg/ha	kg/ha			mg/kg	mg/kg	mg/kg	mg/kg
0	0	0	7.7a	7.7a	22a	35a	0.23a	0.44a
0	306	4.9	7.6a	7.6a	41ab	56b	0.39ab	-
318	306	4.9	7.0a	7.4a	75c	54b	0.52b	-
0	612	9.7	7.5a	7.6a	53bc	58b	0.58bc	0.50a
636	612	9.7	6.8b	7.3a	126d	56b	0.72c	0.85a

[a] Corn grown on Weld silt loam; CEC = 15 meq/100 g.

[b] Values within a column followed by the same letter are not significantly different at the 5% level according to Duncan's Multiple Range Test.

Table 22. Influence of sludge additions and soil cation exchange capacity on yield and concentrations of cadmium and zinc in soybean shoots grown in the greenhouse (Latterell *et al.*, 1976)

Sludge added	CEC	Yield	Metal concentrations in soybean shoots	
			Cd	Zn
metric tons/ha	meq/100 g	g/100 g of soil	mg/kg	
0	5.2	0.24	0.16	33
	9.7	0.26	0.16	34
	14.1	0.28	0.19	37
	18.5	0.30	0.26	24
23.3	5.2	0.26	0.29	83
	9.7	0.29	0.30	70
	14.1	0.28	0.34	62
	18.5	0.30	0.36	59
46.7	5.2	0.16	0.54	163
	9.7	0.21	0.39	139
	14.1	0.27	0.48	118
	18.5	0.30	0.31	98

Table 23. Yield and cadmium content of greenhouse-grown oat shoots as influenced by soil CEC (Haghiri, 1974)

CEC[b]	Exchangeable soil Cd[a]	Dry weight of oat shoots[a]	Cd in oat shoots[a]
meq/100 g	mg/kg	g/pot	mg/kg
17.1	2.94a	0.99c	13.7a
18.9	2.90a	1.34b	12.9a
23.1	2.55b	1.34b	11.0b
26.9	2.34b	1.66a	9.5c
30.5	1.95c	1.76a	7.9d

[a]Values in a column followed by the same letter are not significantly different at $p = 0.05$.

[b]The soil CEC was increased by adding muck, the pH was adjusted to 6.5 and Cd was added as $CdCl_2$ at 20 mg/kg.

Table 24. Effect of soil properties and calcium carbonate additions on cadmium content of corn seedlings grown on sludge-treated soils (80 metric tons/ha) in the greenhouse (Keeney et al., 1980)

Soil series	Clay	Organic C	CEC	Soil pH in 0.01 M $CaCl_2$		Cd in corn seedlings	
				$CaCO_3$ added[a]	Excess $CaCO_3$ added[b]	$CaCO_3$ added[a]	Excess $CaCO_3$ added[b]
	%	%	meq/ 100 g			mg/kg	
Sphagnum[c]	-	46.80	400	5.0	6.7	4.6	2.2
Plano	24	2.07	18	5.6	6.9	3.4	2.6
Plainfield	6	0.33	3	5.7	7.0	4.7	2.8
Briggsville	7	0.74	5	5.7	6.7	4.7	2.4
Granby	7	4.80	25	5.7	6.9	2.5	1.7
Houghton[c]	-	31.90	150	5.8	6.6	1.7	1.6
Kewaunee	56	0.98	26	6.4	7.0	3.1	2.0
Adolf	34	4.32	36	6.5	7.1	1.4	1.3
Poygan	33	3.63	41	6.7	7.1	1.4	1.3
Wausau	14	1.95	15	7.1	7.2	2.5	2.3

[a] Based on a lime requirement method.

[b] $CaCO_3$ added in quantities found in a plus one CEC in excess (i.e., the soil was calcareous).

[c] Estimated CEC. These two soils were excluded from the statistical analysis shown in Table 25.

Table 25. Coefficients of determination (R^2) for the regression of the cadmium concentration in plants on selected properties of the eight mineral soils shown in Table 24, and the significance of the regression (F ratio) for individual properties in different combinations (Keeney et al., 1980)

	F ratio for indicated variables				
Crop	Organic C	Clay	CEC	pH	R^2
1st	4.89**	0.62			0.04
2nd	4.72*	0.61			0.04
3rd	5.80*	1.82			0.15
1st	3.20			13.08**	0.12
2nd	2.19			34.88	0.23
3rd	4.24*			30.54**	0.48
1st		0.00		14.20**	0.10
2nd		0.59		37.90**	0.22
3rd		0.05		29.98**	0.43
1st			2.64	11.02**	0.12
2nd			1.40	31.40**	0.22
3rd			3.88	24.42**	0.47
1st	3.27	0.09		12.41**	0.12
2nd	2.59	0.97		35.09**	0.23
3rd	4.16*	0.07		27.06**	0.48

*Significant at 0.05 probability level.

**Significant at 0.01 probability level.

Table 26. Regression equations for estimating the concentration of cadmium in Swiss chard using DTPA-extractable cadmium and other soil characteristics as independent variables (Haq *et al.*, 1980)

Regression step	R^2	Variable added[a]	Final equation[b] Coefficient	F Ratio
1	0.347	Cd	1.10	13.3**
2	0.622	pH	-12.1	11.9**
3	0.720	pH^2	0.825	10.2**
4	0.766	OM x Cd	0.00859	0.3
5	0.805	pH x Cd	-0.119	8.8**
6	0.813	Cd^2	-0.00537	4.0
7	0.824	OM x CEC	-0.00267	2.4

[a] OM = organic matter; Cd = DTPA extractable Cd.

[b] Constant = 44.54.

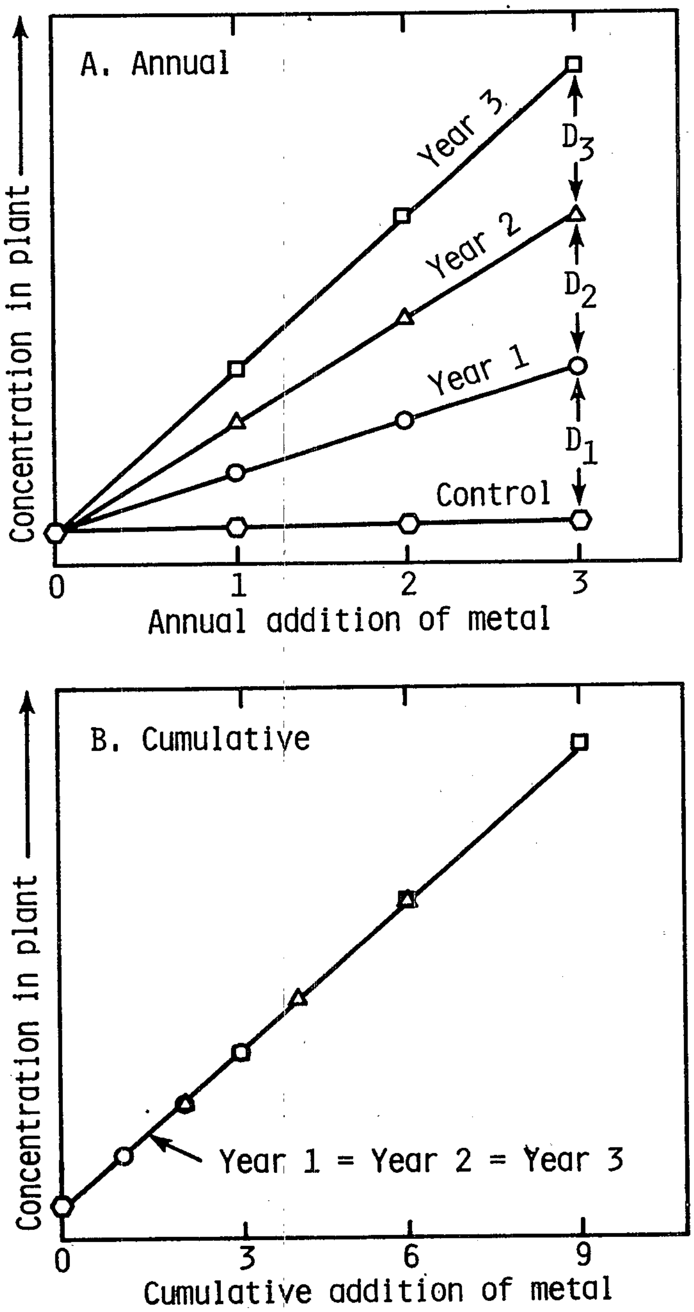

Figure 2. Hypothetical relationships between the concentration of a trace metal in plants and the quantity of the metal added to soil in three successive annual increments under circumstances in which the availability of the metal to plants remains constant with time: A. Plot of concentration in plants against quantity added annually. B. Plot of concentration in plants against cumulative addition.

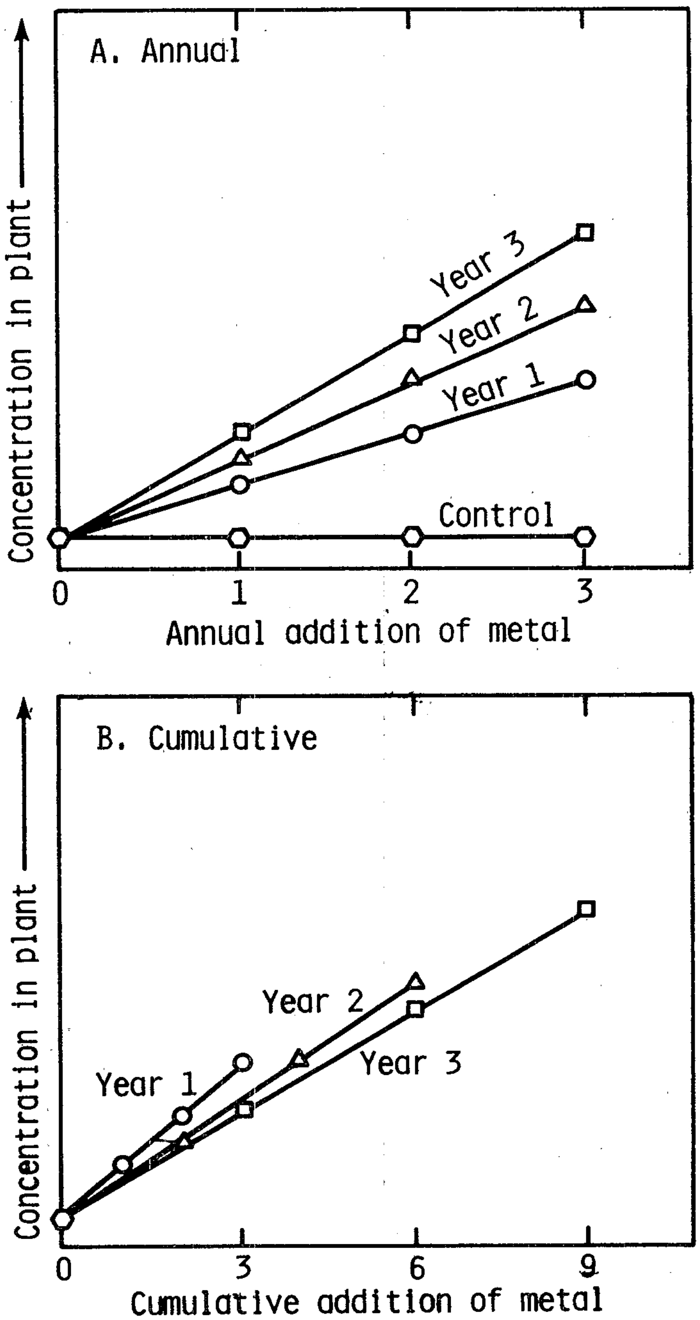

Figure 3. Hypothetical relationships between the concentration of a trace metal in plants and the quantity of the metal added to soil in three successive annual increments under circumstances in which the availability of the metal to plants decreases with time: A. Plot of concentration in plants against quantity added annually. B. Plot of concentration in plants against cumulative addition.

Table 27. Effect of a single sludge application on cadmium concentrations in corn

Crop	Cd applied	Soil pH	Concentration of Cd in corn: Leaves	Grain
	kg/ha		mg/kg	
Corn[a]	0	5.9	0.11	0.06
	5.9	6.8	2.67	0.14
	11.9	6.4	4.06	0.18
	23.8	6.1	2.89	0.20
Corn[b]	0	7.8	0.34	0.06
	0.98	7.7	0.32	0.12
	1.96	8.0	0.75	0.12
	3.92	8.0	1.45	0.21
Corn[c]	0	6.0	0.42	<0.05
Sludge A	16	6.7	1.07	<0.05
	32	7.0	1.55	<0.05
	64	7.1	2.04	<0.05
	128	7.3	1.66	<0.05
Sludge B	68	6.5	5.08	0.06
	136	6.6	7.81	0.14
Sludge C	14	7.2	1.13	<0.05
	28	7.3	1.62	<0.05
	42	7.4	0.92	<0.05

[a] Dowdy *et al*. (1977). Sandy soil, CEC = 6.7 meq/100 g.

[b] Pietz *et al*. (1979). Strip-mine spoil, CEC = 15 meq/100 g.

[c] Sommers *et al*. (1980). Silt loam soil, CEC = 23 meq/100 g.

Table 28. Effect of a single sludge application on cadmium concentrations in sorghum, soybeans and oats

Crop	Cd applied	Soil pH	Cd concentration in plant tissue: Leaf	Grain
	kg/ha		mg/kg	
Sorghum[a]	0	6.0	0.30	0.10
	0.86	5.9	1.20	0.10
	1.57	5.7	1.60	0.09
	2.26	5.8	1.90	0.05
Soybeans[b]	0	6.0	1.59	0.41
Sludge A	16	6.7	2.24	0.51
	32	7.0	1.78	0.75
	64	7.1	1.80	0.78
	128	7.3	2.42	0.93
Sludge B	68	6.5	4.62	2.07
	136	6.6	5.02	3.31
	203	6.6	5.97	3.36
Sludge C	14	7.2	2.10	0.48
	28	7.3	1.72	0.55
	42	7.4	2.13	0.52
Oats[b]	0	6.0	0.77[c]	0.16
Sludge A	16	6.7	1.14	0.49
	32	7.0	1.64	0.76
	64	7.1	1.96	0.84
	128	7.3	3.11	1.66
Sludge B	68	6.5	8.96	1.65
	136	6.6	17.22	3.42
	203	6.6	17.22	3.42
Sludge C	14	7.2	0.96	0.24
	28	7.3	0.82	0.29
	42	7.4	1.07	0.39

[a]Chang *et al*. (1979). Sandy loam, CEC = 7 meq/100 g.

[b]Sommers *et al*. (1980). Silt loam, CEC = 23 meq/100 g.

[c]Data for oat straw.

Table 29. Effect of a single sludge application on zinc concentrations in corn plants

Crop	Zn applied	Soil pH	Zinc concentration in plant tissue	
			Leaf	Grain
	kg/ha		mg/kg	
Corn[a]	0	5.9	13	29
	31	6.8	29	28
	62	6.4	44	27
	123	6.1	50	27
Corn[b]	0	7.8	15	5
	14	7.7	34	23
	28	8.0	43	34
	57	8.0	80	36
Corn[c]	0	6.0	37	13
Sludge A	381	6.7	40	14
	762	7.0	62	19
	1523	7.1	69	19
	3046	7.3	77	16
Sludge B	106	6.5	50	21
	213	6.6	49	22
Sludge C	291	7.2	44	23
	582	7.3	37	18
	1164	7.4	53	12

[a] Dowdy et al. (1977). Sandy soil, CEC = 6.7 meq/100 g.

[b] Pietz et al. (1979). Strip-mine spoil, CEC = 15 meq/100 g.

[c] Sommers et al. (1980). Silt loam soil, CEC = 23 meq/100 g.

Table 30. Effect of a single sludge application on zinc concentrations in sorghum, soybeans and oats

Crop	Zn applied	Soil pH	Cd concentrations in plant tissue	
			Leaf	Grain
	kg/ha		mg/kg	
Sorghum[a]	0	6.0	25	17
	46	5.9	53	23
	80	5.7	80	20
	114	5.8	120	31
Soybeans[b]	0	6.0	42	39
Sludge A	381	6.7	53	44
	762	7.0	67	47
	1523	7.1	55	44
	3046	7.3	63	59
Sludge B	106	6.5	54	42
	213	6.6	59	47
	320	6.6	63	46
Sludge C	291	7.2	44	46
	582	7.3	48	42
	1164	7.4	51	43
Oats[b]	0	6.0	10[c]	30
Sludge A	381	6.7	21	30
	762	7.0	20	35
	1523	7.1	32	39
	3046	7.3	66	51
Sludge B	106	6.5	20	37
	213	6.6	19	34
	320	6.6	14	32
Sludge C	291	7.2	17	25
	582	7.3	17	28
	1164	7.4	14	28

[a] Chang et al. (1979). Sandy loam, CEC = 7 meq/100 g.

[b] Sommers et al. (1980). Silt loam, CEC = 23 meq/100 g.

[c] Data for oat straw.

Table 31. Concentration of cadmium and zinc in corn leaves and grain as affected by application of sewage sludge to calcareous strip mine spoil (Pietz et al., 1979)

Year	Metal addition				Soil pH	Metal concentrations in plant tissue			
	Annual		Cumulative			Leaves		Grain	
	Zn	Cd	Zn	Cd		Zn	Cd	Zn	Cd
	kg/ha					mg/kg			
1973	0	0	0	0	7.8	15	0.34	15	<0.06
1974	0	0	0	0	8.0	13	0.29	19	<0.06
1975	0	0	0	0	7.8	21	0.12	18	0.08
1976	0	0	0	0	7.7	33	1.42	20	<0.06
1977	0	0	0	0	7.2	33	1.94	25	0.08
1978	0	0	0	0	7.3	49	1.91	27	0.16
1973	14	1	14	1	7.7	34	0.32	19	0.12
1974	64	5	78	6	8.0	43	0.78	28	0.12
1975	64	4	142	10	7.7	74	1.84	29	0.16
1976	75	4	217	14	7.7	109	6.15	32	0.14
1977	119	7	336	21	7.5	81	5.60	33	0.21
1978	84	6	420	27	7.5	114	7.20	37	0.28
1973	28	2	28	2	8.0	43	0.75	22	0.12
1974	128	10	156	12	8.1	51	1.47	33	0.18
1975	126	9	282	21	7.6	93	3.90	32	0.21
1976	139	9	421	30	7.8	124	8.50	35	0.46
1977	238	14	659	44	7.0	132	15.53	39	0.46
1978	167	12	826	56	7.4	201	16.95	44	0.41
1973	57	4	57	4	8.0	80	1.49	26	0.21
1974	255	21	312	26	8.1	72	4.06	32	0.24
1975	253	18	565	44	7.5	121	7.45	37	0.38
1976	278	18	843	62	7.6	191	22.59	41	0.54
1977	475	28	1318	90	7.3	200	28.72	45	0.78
1978	334	23	1652	113	7.2	317	33.68	51	0.83

Table 32. Concentration of cadmium and zinc in corn leaves and grain as affected by sludge application to a Murrill silt loam[a] (Wolf and Baker, 1980)

Year	Metal addition[b]				Soil pH	Metal concentration in indicated crops							
	Annual		Cumulative			Corn				Soybeans			
						Leaves		Grain		Leaves		Grain	
	Zn	Cd	Zn	Cd		Zn	Cd	Zn	Cd	Zn	Cd	Zn	Cd
	kg/ha					mg/kg							
1974	0	0	0	0	6.7	20	0.26	19	0.02	39	0.10	41	0.10
1974	74	4.1	110	4.1	7.2	40	1.09	16	0.07	48	0.66	48	0.64
1975[c]	74	4.1	184	8.3	7.2	69	1.34	33	0.05	55	0.55	53	0.68
1976	74	4.1	258	12.4	7.1	81	0.64	27	0.05	62	0.75	61	0.49
1977	74	4.1	332	16.6	7.1	89	2.91	35	0.07	74	1.27	61	0.50
1978	74	4.1	406	20.7	7.1	89	2.14	50	0.10	56	1.02	65	0.74

[a] Soil CEC = 13 meq/100 g.

[b] The cumulative and annual applications of Zn in 1974 are shown to be unequal because the experiment was started in 1972, and a total of 36 kg of Zn/ha was applied in 1972 and 1973. The cumulative and annual applications of Cd in 1974 are shown to be equal because the sludge applied in 1972 and 1973 contained almost no Cd.

[c] In 1975 the corn hybrid was changed from Pioneer 3773 to Pioneer 3780.

Table 33. Correlation (r) of metal concentrations in corn leaves (y) with quantities of metals applied to soil in sludge (x), and slope of the corresponding linear regression coefficients in two investigations

Data used	Independent variable (total quantity of metal applied)	Statistics for cadmium		Statistics for zinc	
		r	Slope[a]	r	Slope[a]
Pietz *et al*. (1979)	Single application (1973)	0.965	0.31	0.994	1.11
	Repeated applications (1973-1978)	0.976	0.30	0.962	0.16
Wolf and Baker (1980)	Single application (1974)	–	0.20	–	0.27
	Repeated applications (1974-1978)	0.645	0.09	0.91	0.16

[a] x = kg of Zn or Cd applied/ha; y = mg of Zn or Cd/kg of plant tissue.

Table 34. Concentration of cadmium in crops in four growing seasons after final sludge application[a] (Baker *et al.*, 1979a, 1979b)

Year	Cd addition		Cd concentration in indicated crops			
	Annual	Cumulative	Corn leaves	Corn grain	Wheat grain	Potato tubers
	kg/ha		mg/kg			
1	0	0	0.08	-	-	-
	4.1	4.1	1.66	-	-	-
2	0	0	0.33	0.015	-	-
	4.1	8.3	0.95	0.065	-	-
3	0	0	0.06	0.007	0.07	0.32
	0	8.3	0.87	0.036	1.73	1.35
4	0	0	0.06	0.004	0.06	0.21
	0	8.3	1.06	0.033	1.00	1.02
5	0	0	0.07	0.010	-	-
	0	8.3	0.57	0.039	-	-
6	0	0	0.05	-	-	-
	0	8.3	0.83	-	-	-

[a]Silt loam soil; pH = 6.5; CEC = 13 meq/100 g.

Table 35. Concentrations of cadmium and zinc in corn leaves and grain during applications of sewage sludge and for four years after the final sludge application[a] (Hinesly et al., 1979c)

Year	Metal addition		Metal concentrations in plant tissues			
			Corn leaves		Corn grain	
	Annual	Cumulative	Control	Sludge	Control	Sludge
	kg/ha		mg/kg			
			Cadmium			
1	30.5	30.5	0.5	11.6	0.15	0.20
2	13.2	43.7	0.5	10.4	0.15	0.43
3	7.8	51.5	0.3	2.5	0.16	0.27
4	6.8	58.3	0.1	0.9	0.18	0.15
5	0	58.3	0.7	1.9	0.15	0.22
6	0	58.3	0.3	1.3	0.14	0.14
7	0	58.3	0.3	1.3	0.10	<0.06
8	0	58.3	0.4	1.9	<0.06	<0.06
			Zinc			
1	585	585	42	112	24	32
2	265	850	24	85	16	28
3	192	1042	21	58	18	36
4	248	1290	28	55	20	27
5	0	1290	22	63	25	29
6	0	1290	35	38	24	26
7	0	1290	23	36	25	25
8	0	1290	20	25	28	26

[a] Silt loam soil, pH = 7.3, CEC = 12 meq/100 g. The control plots received no Cd or Zn.

Table 36. Concentrations of cadmium and zinc in sweetcorn leaves and grain during applications of sewage sludge and for four years after the final application of sludge[a] (Giordano et al., 1979a)

Year	Metal addition		Soil pH	Metal concentration in corn tissue			
				Leaves		Grain	
	Annual	Cumulative		Control	Sludge added	Control	Sludge added
	kg/ha			mg/kg			
			Cadmium				
1972	10	10	5.6	1.0	4.1	0.3	1.2
1973	10	20	6.1	1.1	7.9	0.5	1.0
1974	10	30	6.3	0.6	5.4	0.2	0.7
1975	10	40	5.7	0.7	7.0	0.2	1.2
1976	0	40	4.5	1.0	5.9	–	–
1977	0	40	5.1	0.8	5.8	0.6	1.2
1978	0	40	6.0	2.1	9.2	0.4	0.9
1979	0	40	6.3	1.1	5.5	0.4	1.0
			Zinc				
1972	360	360	5.6	41	97	37	44
1973	360	720	6.1	53	241	35	61
1974	360	1080	6.3	28	250	40	75
1975	360	1440	5.7	46	400	32	64
1976	0	1440	4.5	72	497	–	–
1977	0	1440	5.1	78	906	44	70
1978	0	1440	6.0	114	724	41	71
1979	0	1440	6.3	62	434	38	65

[a] Decatur silt loam; CEC = 10 meq/100 g.

Table 37. Concentration of cadmium in corn stover and grain during applications of sewage sludge and for three growing seasons after the final sludge application[a] (Webber and Beauchamp, 1979)

Year	Cd addition		Cadmium concentration in plant tissue			
			Stover		Grain	
	Annual	Cumulative	Control[b]	Sludge	Control[b]	Sludge
	kg/ha		mg/kg			
1	7.6	7.6	0.17	1.49	0.02	0.07
2	7.2	14.8	0.18	1.68	0.01	0.12
3	4.4	19.2	0.07	0.98	0.01	0.10
4	0	19.2	0.19	1.64	0.05	0.10
5	0	19.2	0.20	2.05	0.04	0.11
6	0	19.2	0.26	1.36	0.03	0.06

[a] Silt loam soil, pH = 7.6, CEC = 26 meq/100 g.

[b] No Cd was applied to the control plots.

Table 38. Concentrations of cadmium and zinc from 1972 through 1979 in plants grown on soil without previous additions of these metals and with a single application of the metals in sludge in 1971[a] (Giordano et al., 1979a)

Metals applied in 1971				Metal concentration in indicated crops							
				Snapbean leaves		Snapbean pods		Sweetcorn			
								Leaves		Grain	
Zn	Cd	Year[b]	Soil pH	Zn	Cd	Zn	Cd	Zn	Cd	Zn	Cd
— kg/ha —				— mg/kg —							
0	0	1972	4.9	60	0.5	45	0.2	41	0.9	37	0.3
		1973	5.6	44	0.3	49	0.1	47	1.1	35	0.3
		1974	6.4	53	0.4	59	0.1	28	0.6	35	0.2
		1975	6.3	42	0.2	53	0.1	30	0.7	36	0.2
		1976	4.2	93	0.7	52	0.3	72	1.0	–	–
		1977	4.6	124	1.3	64	0.2	86	0.9	44	0.6
		1978	6.0	47	0.3	48	0.2	94	2.2	39	0.5
		1979	6.4	–	–	–	–	63	1.1	30	0.4
90	2.5	1972	5.3	158	1.1	61	0.2	94	3.7	43	0.9
		1973	4.9	171	1.0	72	0.2	153	3.9	47	0.7
		1974	5.2	282	1.2	86	0.2	98	2.8	48	0.5
		1975	5.5	128	0.8	71	0.2	130	3.4	45	0.8
		1976	4.2	253	3.0	66	0.5	209	2.7	–	–
		1977	4.5	191	2.9	88	0.5	126	1.8	54	0.7
		1978	5.9	68	0.4	60	0.2	164	4.8	47	0.8
		1979	6.4	–	–	–	–	107	3.0	43	0.7
180	5.0	1972	5.3	189	1.2	75	0.2	95	3.5	49	1.0
		1973	5.2	184	0.8	90	0.2	184	5.4	46	0.8
		1974	5.6	254	1.0	91	0.2	94	3.5	49	0.5
		1975	5.7	141	1.0	82	0.2	158	4.7	48	0.9
		1976	4.3	356	4.3	92	0.7	244	4.1	–	–
		1977	4.6	319	6.3	77	0.5	161	2.5	66	1.2
		1978	5.9	79	0.5	61	0.2	204	5.7	48	0.8
		1979	6.3	–	–	–	–	138	5.2	38	0.8
360	10	1972	5.6	164	1.2	83	0.3	97	4.1	44	1.2
		1973	5.4	187	0.9	90	0.2	207	7.2	54	1.0
		1974	5.9	296	1.1	87	0.2	130	4.8	63	0.6
		1975	6.1	128	0.8	79	0.2	172	5.9	51	1.0
		1976	4.4	499	4.6	92	0.8	234	5.7	–	–
		1977	5.0	408	9.1	77	0.2	159	1.9	65	1.2
		1978	6.1	137	0.8	83	0.3	273	7.8	60	0.9
		1979	6.6	–	–	–	–	137	5.5	44	1.0

[a] Decatur silt loam, CEC = 10 meq/100 g.

[b] Sulfur was applied in the fall of 1975 and limestone in the fall of 1977.

Table 39. Cadmium and zinc found in 1977 in soils and crops of sludge utilization farms in northeastern United States (Chaney and Hornick, 1978 and unpublished data)

City and treatment[a,b]	Total content in soil		Soil pH^c	Metal concentration in crops			
				Zn		Cd	
	Zn	Cd		Swiss chard	Oat grain	Swiss chard	Oat grain
	mg/kg			mg/kg			
4C	73	0.22	5.4	179	31	1.48	0.034
4C-L	63	0.16	6.4	49	29	0.63	0.025
4S	156	0.98	4.9	800	50	3.24	0.209
4S-L	154	0.94	6.0	105	34	0.82	0.065
9C	53	0.18	4.9	189	34	3.34	0.104
9C-L	51	0.15	6.4	52	32	0.94	0.052
9S	82	1.66	4.9	1230	63	94.8	1.96
9S-L	91	2.10	6.3	66	36	2.20	0.259
13C	59	0.10	5.3	183	30	2.65	0.076
13C-L	61	0.10	6.1	50	27	0.37	0.064
13S	146	9.10	5.5	823	47	54.3	2.24
13S-L	128	7.02	6.2	90	31	5.34	0.277
1C	53	0.07	5.9	63	24	0.44	0.051
1C-L	52	0.07	6.3	52	22	0.33	0.044
1S	146	3.26	5.5	896	38	9.51	0.299
1S-L	212	4.50	6.2	212	34	3.68	0.193
1S-H	150	2.54	6.6	109	32	1.89	0.125
19C-H	52	0.09	6.1	99	28	0.41	0.065
19S-H	156	0.41	5.9	41	33	0.64	0.060
39C-H	56	0.05	5.6	32	24	0.30	0.022
39S-H	602	12.7	6.7	162	60	3.32	1.22

[a]Anaerobically digested liquid sludge was applied from 1962-1975 on Hagerstown silt loam (CEC = 9 meq/100 g) at city 4; for 1961-1973 on Lonsdale silt loam (CEC = 8 meq/100 g) at city 9; from 1967-1974 on Readington silt loam (CEC = 9.5 meq/100 g) at city 13; from 1967-1975 on Lonsdale loam (CEC = 11 meq/100 g) at city 1; from 1960-1976 on Genesee silt loam (CEC = 10 meq/100 g) at city 19; and from 1960-1971 on Hagerstown silt loam (CEC = 10 meq/100 g) at city 39. Plots were established on the sludge farm and on a paired control farm in 1975 at cities 4, 9 and 13, and in 1976 at cities 1, 19 and 39.

[b]C = control farm; S = sludge farm; L = limestone applied the year plots were established to reach pH 6.5 according to a lime requirement test; H = plots initially at or above pH 6.5.

[c]1:1 soil:H_2O, measured on samples taken in May 1977.

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16. ABSTRACT

This report evaluates the available data on the effects on plants of single and repeated additions of Cd and Zn to soils in the form of sewage sludge. The concentrations of Cd and Zn in plants vary with (a) the species and cultivation grown, (b) environmental and management factors, (c) soil properties, (d) the annual and cumulative amounts of Cd and Zn applied to soils and (e) the plant sampled.

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