EFFECT OF SEWAGE SLUDGE-BORNE CADMIUM ON CROP PRODUCTION AND ON SOIL AND PLANT COMPOSITION

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AND PLANT COMPOSITION

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CHAPTER I

INTRODUCTION

Cadmium (Cd) is known for its harmful effects on soil, crops, animals, and human beings. Sewage sludge is a major source of Cd contamination of crop land. Cadmium enters sewage sludge as a result of industrial activities which may or may not be directly associated with Cd. Among the former is Cd produced from smelting, brazing, roasting, and galvanizing, and from manufacturing alloys, batteries, plastics, pigments, fertilizers, and steel production activities. Cadmium is released by combustion processes involving coal, paper, wood, oil, and urban organic waste. Cadmium-containing wastes may be discharged from factories or sewage plants into lakes or streams, or applied to soil as fertilizers, or introduced to soils as atmospheric depositions. Application of sewage sludge can be beneficial to crop land. Sludge contains many essential plant nutrients, may act as a soil conditioner and increase soil water holding capacity. Sludges having very low concentrations of heavy metals are used for crop production based on the following concepts:

1. Phosphorus and nitrogen basis concept - an application of sludge based initially on supplying the crop with

adequate phosphorus and nitrogen and adding safe, low annual applications of toxic metals,

2. Zinc-equivalent concept - this suggests that the toxicities of copper and nickel can be expressed in terms of some multiple of zinc; and that the toxicities of these trace elements to plants are additive. However, it has been suggested that if addition is based on the total limits of each heavy metal, the concept will not apply, and

3. Zinc-cadmium ratio - this suggests that with applicable ratios zinc will become toxic to plants before excessive levels of Cd accumulate in the plant. It has, however, been pointed out by Giordano and Mays (1976) that this concept is not correct in that many plants grown on nearly neutral to calcareous soils will tolerate high levels of zinc and still show an increase in the concentration of Cd. However, due to the presence of heavy metals, sludges might be toxic to crops, and heavy metal concentrations in edible crops can be toxic or noxious to humans and other consuming animals.

The heavy metals and other potentially toxic elements present in sludge can be divided into two categories based on whether they present a potentially serious hazard to plants, animals, or humans. The metals, Mn, Fe, Cr, As, Se, Sb, Pb, and Hg, pose relatively little hazard to crop production and do not accumulate in a toxic level when the sludge is applied to soil within reasonable limits. This is because they are present in relatively low concentration in the soil and/or have low solubilities. As a result, the availability of these elements to plants is restricted and consequently very little plant uptake occurs. The remaining heavy metals--Cd, Cu, Mo, Ni, and Zn can accumulate in plants and pose a hazard to animals or humans, and to the plants themselves under certain circumstances.

For example, Cd, a nonessential element, can be a serious hazard to animals and humans if the dietary intake level is increased. Cadmium could cause certain health problems due to the cumulative effect of prolonged low-level exposure in animals and humans (Baker et al., 1975; Doyle et al., 1974; Underwood, 1977). The possible hazard to humans from elevated concentrations of Cd in plants is greater than the possible toxicity to the plants themselves, particularly if dietary levels of Ca, Zn, and Cu are low or marginal (Parizek, 1957; Chaney, 1985).

Sewage sludge may contain Cd concentrations from 3 to more than 3,000 $\mu g\ g^{-1}$, with a mean value of 106 $\mu g\ g^{-1}$ and a median value of 16 $\mu g\ g^{-1}$ being reported by Sommer (1976). However, since soil contains from 0.01 to 76 $\mu g\ g^{-1}$ Cd with 0.06 $\mu g\ g^{-1}$ being common, the addition of sewage sludge to soil usually results in a measurable increase in total Cd in the soil, as indicated by Allaway (1968).

The chemistry of Cd in the soil is not adequately understood, but it seems to be influenced by soil organic matter, clay type and content, hydrous oxides, soil pH, and the redox potential. The assumption has been that the total amount of Cd added to the soil would ultimately control the amount of soluble Cd present, and subsequently the uptake of Cd by plants. Apparently, soil has a saturation limit for Cd at which point the addition of any quantity of soluble Cd results in nearly equivalent increase in soluble Cd in the soil (CAST, 1976). Moreover, the increase in Cd content of leaves was found to be more affected by adding a certain amount of Cd at one time to the soil rather than adding it in repeated applications. This has been attributed to the fact that much of the applied Cd is converted to forms of relatively low availability to plants (Baker et al., 1975; Bates et al., 1975).

The toxicity of soil Cd to plants and animals must be minimized or eliminated. This study, which assesses the effects of sludge-borne Cd on crop production and composition and on movement in the soil profile, is an important step in that direction. The study has two specific objectives. The first is to evaluate patterns of the accumulation or movement of Cd in soil as a function of Cd application rate and placement depth. The second is to evaluate the effect of sludge-borne Cd on the Cd content and crop yields.

For this study, two Oklahoma soils, Teller fine sandy loam and Norge loam, and two sludges, a domestic sludge with industrial contamination from Tulsa and a domestic sludge from Stillwater were used. The two sludges were mixed to produce different Cd:sewage sludge ratios, providing for four different levels of Cd. Two application depths were used, surface and subsurface. Sixteen treatment combinations were used to determine the effect of Cd content versus organic waste application rate, and the relative effects of 0 to 15 cm and 15 to 30 cm placement depths in the soils in a greenhouse experiment. Forty cm deep pots were used to allow alternate placement depths for two different crop types, soybeans and grain sorghum. Two sequential crops for each plant species were grown for all treatments.

It was hoped that the results of this study would establish some meaningful parameters on the effect of Cd versus organic residue rates and profile positioning on plant uptake of Cd, and permit an evaluation of soil texture on Cd uptake and/or toxicity to plants and possibly postulate the effect of Cd on consuming populations. Data could be compared to that obtained by the investigators who have added inorganic Cd salts to plant-soil systems.

CHAPTER II

REVIEW OF LITERATURE

Cadmium Properties, Cycle, Occurrence, and Forms in Soils

When Cd is compared with most other biologically important elements in the soil such as Co, Cu, Pb, and Zn, it appears that much less information is known about its behavior soil. All the trace elements, including Cd, are distributed between six major pools within the soil system. A total concentration of Cd in the soil is the sum of the amounts contained within these pools. These include (a) the soil solution, (b) the colloidal phase, (c) the hydrous oxides of manganese, iron and aluminum, (d) soil organic matter, (e) soil phase-insoluble precipitates, and (f) soil phase-mineral, either individually or as rock fragments (Hodgson, 1963).

Properties

Cadmium is a soft element, a silvery white, ductile metal of a faint bluish tinge. Its atomic weight is 112.4, and atomic number 48, with a density of 8.6. Its melting point is 320.9 °C, with a boiling point of 765 °C. Cadmium is easily oxidized by steam. It burns in the air to form the brown oxide that often colors the zinc oxide fumes in smelter plants. It dissolves in most inorganic and organic acids with nitric acid being the best solvent. Some compounds which are associated with Cd include Cd acetate, sulfide, sulfoselenide, stearate, oxide, carbonate, sulfate, and chloride. In addition, there are some synthetic organometallic compounds that are not usually found in the general environment because they decompose rapidly (Nriagu, 1978).

Cycle

Cadmium is found in the atmosphere, soils, lakes, rivers, and ocean waters as a result of Cd input from polluting sources. Cadmium is exchanged between these reservoirs through streams, groundwater flows, ice, volcanoes, subaqueous weathering, sedimentation, atmospheric deposition, and various biological pumps. According to most global models, the amount of Cd in the total system remains stationary, so that the exchange rates for Cd among other reservoirs could be derived by solving the appropriate set of simultaneous mass balance equations (Nriagu, 1980).

Nriagu (1979) gives the various segments of the Cd cycle and the exchange or flux rates for Cd along the different paths connecting the various global reservoirs. About 30% of the global Cd emission is deposited in the oceans. According to Boyle et al. (1976) the current findings suggest that the oceans currently gain 2.4×10^9 g Cd

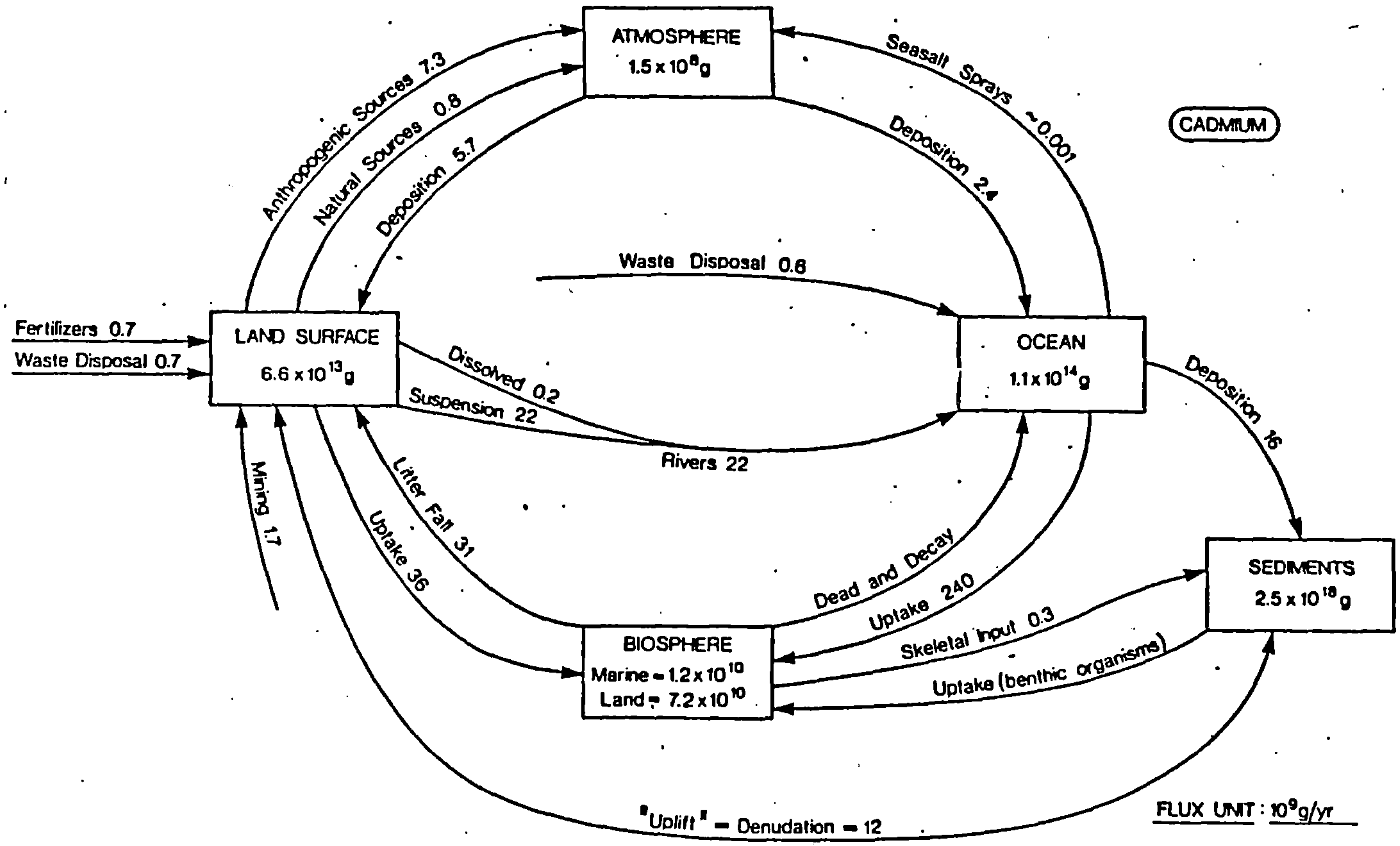

Figure 1. Global Cycle of Cadmium (Nriagu, 1976)

per year through the atmosphere, and 7.5×10^9 g Cd through stream runoff.

Cadmium inputs to land areas come from atmospheric fallout, waste disposal, and fertilizer applications. These are estimated to be 5.7×10^9 and 1×10^9 g per year (Nriagu 1979). Nriagu (1978) indicated that Cd is increasing in soils by 9.4×10^9 g Cd each year through human activities. An estimated 10% of Cd in soils is associated with organic matter. The total amount of Cd that has been released to the atmosphere from weathering is about 320×10^9 g, and 50 $\times 10^9$ g of Cd has been produced and spread over the earth's surface by human activities. The concentration and movement of Cd in many ecosystems is in continuous flux. Human beings have become a major macrobiological agent in the present-day biogeochemical cycle of Cd, with an intake of about 2.2×10^8 g per year (Nriagu, 1979). The global cycle of Cd is shown in Figure 1 (Nriagu, 1980).

Occurrence

Fleischer et al. (1974) agreed that Cd is a rare element, with its concentration in the lithosphere ranging from 0.1 to 0.2 $\mu g\ g^{-1}$, making it the 67th element in order of abundance. As a strongly chalcohilic element, it is concentrated in sulfide minerals.

Cd is found as isomorphic impurities in, or on surface coatings of other sulfide minerals, particularly the zinc sulfides with concentrations as high as 5% (Chizhikov, 1966). Fleischer et al. (1974) reported fourteen other metal sulfides that contain over 500 μg Cd g^{-1}. These include galena (PbS), metacinnabar (HgS), tetrahedrite-tennartite [$(Cu,Zu)_2(SB,As)_4S_{13}$], and chalcopyrite ($CuFeS_2$). Cadmium tends to accumulate in shales, and oceanic and lacustrine sediments.

Forms of Cadmium in Soil

Iskander and Keeney (1974) indicated that Cd contamination from industrial and other sources is shown by the higher levels of Cd in the solid components of sediment-water systems. Cadmium associated with sediment solids may be present in different chemical forms depending on the composition of the sediment and its physiochemical properties. These forms represent different phases: (a) exchangeable phase, (b) carbonate phase, (c) reducible phase, (d) organic phase, (e) sulfide phase, and (f) mineral crystalline lattice phase.

Cadmium Mobility: Under Lab, Greenhouse, and Field Conditions

Lab Conditions

In a study by Lagerwerff et al. (1976), a sewage sludge from Baltimore, Maryland, was compared to that of Washington, D.C. in terms of the tendency to release heavy metals under different circumstances. In this study columned samples of Baltimore sludge were leached either by distilled water or a $CaCl_2$ solution and fractions were collected for chemical analysis over an extended period of time. Concentrations of Cd, Cu, Pb, and Zn in 1.0 N HCl were determined by atomic absorption spectrophotometry (AA). The results indicated that Cd and Zn were more leachable than Cu and Pb. When sludge samples were treated with hydrogen peroxide (H_2O_2) or distilled water (H_2O) in a simulated weathering study, Cu removal increased more than that of Cd or Zn.

In a study to evaluate the potential movement of Cd, Cu, Ni, and Zn through three reconstructed soil profiles by Emmerich et al. (1982), sewage sludge was incorporated into the top 15 cm of soil in liquid or air-dried form in three increments for a total rate of 476 metric tons ha^{-1}. The soil columns were leached with 5 m of Colorado River water over a 25 month period. After leaching, the soil column was sectioned and analyzed. Analysis indicated that no metals moved below the depth of incorporation.

In another study conducted by Emmerich et al. (1982), a sequential extraction procedure was used to fractionate Cd, Cu, Ni, and Zn in sludge-treated soils into the designated forms of exchangeable, absorbed, organically bound, carbonate, and residual. The study indicated that Cd, Ni, and Zn were all shifting to the residual form. The chemical forms of Cu did not change significantly during the study.

<u>Greenhouse and Field Conditions</u>

In a study carried out by Chang et al. (1984) to determine accumulation of heavy metals in sewage sludge-treated soils, it was found that in sludge-treated soils heavy metals such as Cd, Cr, Cu, Ni, Pb, and Zn were retained almost entirely (> 90%) in the 0 to 15 cm soil depth. Small movement of the metals did occur below the 30 cm depth, however. It was found that crop absorption of the heavy metals was insignificant, reaching < 1% of the amount introduced into the soil through sludge application.

In a recent study conducted on metal movement insludge-treated soil by Williams et al. (1983), the metal movement within the profile, after six years of sludge addition, was limited to a depth of 5 cm below the zone of sludge incorporation for Cd, Cu, and Pb, whereas Zinc moved 5 to 10 cm deep. In another study carried out over a three-year period by the same researchers (Williams and David, 1976), metals were added to soil by sewage sludge, as measured by DTPA extraction. Cadmium, Zn, Pb, and Cu were found to be highly available, whereas Mn, Co, and Ni were moderately to slightly available. The metal availability and metal movement in soils were predominantly limited to a depth of 10 to 30 cm below the zone of sludge incorporation, depending on the type of metal.

In contrast, Sidle and Kardos (1977) demonstrated that Cd could be moved to a greater distance through soil after high organic waste treatments. In their study a sludge-treated soil was used and two treatments of sludge with different total solid content, 1.71 and 26.96 mt ha^{-1}, were included. Copper, Zn, and Cd loadings in the high treatment were 24.50, 28.49, and 0.253 g ha^{-1}, respectively. Amounts of Cd leached from the 120-cm depth over the experimental period were calculated to be from 3.6 to 6.6%, suggesting a slightly higher mobility of Cd than Zn in the soil.

Factors Affecting Cadmium Mobility in Soils

A number of chemical forms of Cd are potentially bioavailable. Among these are inorganic solid forms, $CdCO_3$, $Cd(OH)_2$, CdS, Cd precipitated or coprecipitated with hydrous oxides of Mn and Fe, and chelated and insoluble organic-bound. Cadmium present in these bioavailable chemical forms can be mobilized to even more readily available forms as a result of change in the physico-chemical properties of sediments. Hem (1972) and Hahne and Kroontje (1973) discussed redox potential, pH, and salinity as the most common physico-chemical parameters controlling Cd speciation in sediment-water systems and its availability to biota.

Redox Potential and pH

The redox potential of a sediment-water system is a dominant factor in regulating the chemical form of Cd, whereas pH influences the stability of its various forms.

In the natural sediment-water system, the chemical forms of Cd are a net result of interactions between several inorganic and organic components which are in a state of dynamic equilibrium. According to Florence and Batley (1977), the thermodynamic data on organic and inorganic components are not available and, thus, the effects of redox potential and pH changes on Cd speciation cannot be exactly determined with mathematical models. Therefore, Morel et al. (1973) used selective chemical fractionation schemes to determine the effects of changes in pH or redox potential that would occur during dredging and dredged material disposal on the bioavailability of sediment-bound Cd. In another study (Serne and Mercer, 1975) the effects of oxidized and reduced sediments on the release of Cd from San Francisco Bay dredged sediment suspensions were investigated. The analysis of the Cd dissolved after incubation of sediment suspensions under low O_2 (Eh = < 100 mV) and high O_2 (Eh = > 350 mV) partial pressures showed that Cd was released under oxidizing rather than under reducing conditions. Also, the Cd content released in the elutriate increased with agitation time.

A long-term release of sediment-bound Cd to the overlying seawater under oxidizing, slightly oxidizing, and reducing conditions in controlled lysimeter experiments was studied by Chen et al. (1976). The study showed an increase in the water-soluble, exchangeable, and carbonate fractions, and a decrease in the easily reducible, organic + sulfide, and residual fractions for all conditions.

Gambrell et al. (1977) conducted a controlled laboratory study to determine the effects of redox potential and pH on Cd transformations in estuarine and freshwater sediments. The study indicated that both pH and redox potential strongly influence the distribution of Cd in various chemical forms. In a related study, Khalid et al. (1978) reported that the Cd present in the easily bioavailable water-soluble and exchangeable fractions decreased quickly with an increase in the pH of the sediment suspension. Cadmium, as compared to Zn, is a weak competitor for absorption on hydrous metal oxides. The absorption of Cd by freshwater and estuarine sediments is favored with increasing pH (Gambrell, 1977). Frost and Griffin (1977) studied the effects of pH on the absorption of Cd from landfill leachates by kaolinite and montmorillonite clay minerals. Montmorillonite absorbed approximately five times more Cd from solution than kaolinite because of its greater CEC.

Effects of Salinity

In a study by Hahne and Kroontje (1973), the effect of salinity as a control mechanism for increasing Cd mobility was related to the formation of chloride, sulfate, and carbonate salts of greater solubility than those of hydroxide, sulfide, and organic complexes.

Among other studies on the effect of salinity on Cd mobilization, Lee and Plumb (1974) attributed the effect of salinity and salinity changes to sorption-desorption, ion exchange, alteration of clay crystal structure, and flocculation of organic matter and clay particles. De Groot and Allersma (1975) reported that over 90% of the Cd bound to Rhine River sediments were mobilized upon entering the North Sea. They concluded that the release of the Cd was due to chloride salt and organic complexation.

Clay Characteristics

Few studies have been initiated to determine the effect of solution variables on the uptake of Cd by clay. Investigations based on the addition of clay saturated with Pb, Cd, or Ca ions to solutions containing different cations has yielded K values which indicate that Cd ions compete more or less on an equal basis with Ca ions, but are less favored than Pb ions (Bittrell and Miller, 1974). From studies on complexes of Cd and other metals, it has been concluded that clays do not adsorb anionic metal complexes in any significant degree and that the uptake of cationic species can be reduced significantly through competition from protonated solutions such as those of ethylenediamine tetracetric acid (EDTA). This has clearly been demonstrated by an experiment in which a 100 fold increase in Cd adsorption in alkaline soils was demonstrated for each unit increase in pH (Street et al., 1977).

It is worthwhile to mention here that at a certain pH, soils differ in their ability to bind Cd ions. The coefficient of binding energy for Cd on four different groups of soils was found to decrease in the following order: organic > heavy clay > silt loam > sandy soils (John, 1972a).

Organic Matter

Riffaldi and Levi-Minzi (1975) studied the sorption of Cd by humic acids. The uptake of Cd ion by humic acids isolated from three different Italian soils has been shown to be adequately described by Langmuir type adsorption isotherms. The equation parameters on the bonding constant and maximum absorption capacity increased with increasing content of oxygen-containing functional groups. The metal uptake increased with pH but was independent of temperature. Conversion of the Cd into the anionic EDTA complex resulted in zero adsorption of the metal ion by humic acids. Nearly all of the Cd sorbed by the humic acid could be displaced by a 0.25 M copper acetate solution. According to Gardiner (1974), freshwater was found to release about one-fifth of the adsorbed Cd from humic acids into the aqueous phase. In fact, humified organic matter binds Cd in the soil forming soluble or insoluble organometallic complexes at an optimum pH value between 4.8 and 7.2. The high molecular weight insoluble complexes will act as a pool from which Cd ions are gradually released to control the concentration of the available metal in the soil solution.

The Role of Hydrous Metal Oxides

Hydrous oxides, like those of Fe and Mn, are considered to be capable of playing a dominant role in controlling the concentration of metal ions on soils and in water. The intrinsic affinities of the heavy metals for the oxide surfaces decrease in the order Cu > Pb > Zn > Co > Cd (Jenne, 1968).

Upland Disposal of Organic Waste

A rapid shift from open water disposal to confined upland disposal has been made in recent years. According to Johanson and Carlson (1976), this is due to the potential adverse environmental impact of open water disposal on the aquatic and benthic organisms.

Raveh and Avnimelech (1979) studied various effects of upland Cd disposal. The result of simulated laboratory and actual field studies of upland disposal of Cd-contaminated dredged sediments suggested that the movement of Cd between dredged material and disposal site soils is influenced by several unknown factors. Thermodynamic and kinetic influences make transport phenomena difficult to explain and predict. Interaction between some of the major known mechanisms like solubilization, solid solutions, and sorption may have some influence on the mobilization and subsequent migration of sediment-bound Cd into adjacent surface water and groundwater underlying upland disposal sites (Lee and Plumb, 1974).

Effect of Time

Sposito et al. (1983) studied the effect of time on the extraction of trace metals. The metals were fractionated by sequential extractions for four years. The total concentration of each metal in the soils increased with time as composted sludge was annually added. The observed increase in EDTA extractable trace metals with time could be the result of the formation of trace metal carbonates accompanying the gradual mineralization of the organic matter in the applied sludge within the soil environment.

Nitrogen Fertilization

Cation movement in soil under leaching conditions is associated with N fertilization. Giordano and Mortvedt (1975) performed studies to determine whether the mobility of some heavy metals applied in the inorganic form or in sewage sludge is enhanced in the presence of various sources of nitrogen. The mobility of the heavy metals from the inorganic sources was little greater than that from the sewage sludge. Nitrogen fertilization did not affect the downward movement of Zn, Cd, Cr, Pb, or Ni in the soil. The uptake of these metals by fescue was enhanced by nitrogen because of increased growth. The results indicate that heavy metal contamination of groundwater is not likely in heavy textured soils when sewage sludge applications are accompanied by nitrogen fertilization (Giordano and Mortvedt, 1975).

Plant Roots

The movement of trace elements including Cd in the soil has been shown to be affected by growing plants. In trace element-containing soil, the root system constantly absorbs trace elements and accumulates them mainly in the root with small quantities in the shoots. This phenomenon is clearly described by Wallace and Romney (1977) who classified many trace elements taken up by plants into three groupings based on their distribution between plant root and shoot. Cadmium, along with Fe, Cu, Al, Co, and Mo, usually accumulate more in the roots than in the shoots. In contrast, Pb, Sn, Ti, Ag, Cr, Zn, V, and Ga frequently accumulate in the roots with very little concentration in the shoots, whereas Zn, Mn, Ni, Li, and B are generally distributed somewhat uniformly between root and shoot.

The same phenomenon has been reported to occur in bush bean plants growing in solution cultures containing relatively high concentrations of Cd (Wallace et al., 1977). In these plants higher concentrations of Cd were found in the roots than in the stems, with lowest concentrations in the leaves. The process of trace element uptake by the root system and the distribution of the absorbed element within the plant have been demonstrated to be affected by the depth where the trace-element containing material is located. Three different materials, namely inorganic fertilizer (Alston, 1976), dairy-cattle manure (Lund, 1978), and sewage sludge (Kirkham, 1980) have been used for these studies.

Kirkham (1980) investigated the effect of sewage sludge placed at different depths in columns of soil on the maximum growth of plants, as well as the uptakes and distribution of nutrients by sludge-fertilized wheat. The result of this study showed that concentrations of Zn in shoots of the plants grown in columns with sludge at the top was similar to that in shoots of plants in columns with sludge at 18 to 20 cm depth. However, the concentrations of Cu and Cd were highest in shoots of plants in columns with sludge at the top (0 to 2 cm). Kirkham's study (1980) showed that plant roots accumulated high concentration of metals when sludge was at 18 to 20 cm soil depth and only small amounts were transfered to the shoots. The relative increase in metal uptake at the top part of the soil was attributed to the high oxygen concentrations near the soil surface as compared to that at deeper parts.

Cadmium Availability, Uptake, and Toxicity to Plants under both Greenhouse and Field Conditions

Sommers (1977) reported from a survey of 189 sludge samples obtained from 150 sewage treatment plants a median value of 16 $\mu g\ Cd^{-1}\ g$, with a range of Cd concentrations between 3 and 3410 μg g^{-1} indicting a strong positive correlation with the degree of industrialization in the catchments of the treatment plants. Chaney and Hormick (1977) considered heavy metals to be the main factor limiting agricultural use of sewage sludges because relatively large amounts of sludge are required to supply crops with their nitrogen requirement. Bingham et al. (1965) conducted a study to determine yield reductions associated with Cd concentration. Rice plants were grown in $CdSO_4$ spiked sludge amended soil under flooded and nonflooded culture. A 25% yield reduction was associated with a Cd concentration of 320 μg g^{-1} under flooded conditions, while under nonflooded conditions a comparable decrease in grain production was associated with only 17 μg g^{-1} Cd. A reduced Cd phytotoxicity was associated with the production of the insoluble CdS under flooded conditions. Bingham et al. (1976) concluded that the Cd concentration in mature leaves correlated with grain production and its Cd content. Cutler and Rains (1974) and Hemphill and Rube (1975) reached the same conclusion with similar studies.

Greenhouse Conditions

A greenhouse experiment to compare the plant tissue accumulation of Cd and Zn by four cultivars of barley grown on three soils amended with 26 and 100 mt ha^{-1} dried tank sludges was conducted by Chang et al. (1982). The results indicated no significant difference in metal uptakes of the four cultivars of barley that were grown on both sludge-treated and nonsludge-treated soils. The Cd and Zn concentrations of plant tissue from sludge-treated soils were significantly influenced by the sludge application and the soil type.

Another greenhouse experiment was performed by John et al. (1972) to investigate factors affecting plant uptake and phytotoxicity of Cd added to soils. For a set of 30 surface soils, addition of 50 mg of Cd from $CdCl_2$ to 500 g of soil reduced yield and sharply increased Cd levels in analyzed portions of radish and lettuce plants when compared with those plants grown in control soils. In the treated soils, plant Cd was significantly related to Cd extracted from soil by neutral ammonium acetate. On the other hand, a 1N NaCl and a 1N HNO_3 extraction did not indicate Cd availability, but removed most of the soil Cd. However, plant Cd levels were significantly correlated with amounts of Ni, Fe, Zn, and Cu in the same plant portion. In a similar study conducted by Singh and Narrad (1984), an increase in plant uptake of Cd was correlated with amounts of Cd, Ni, Fe, Zn, and Cu in the plant portion.

Field Conditions

Lurick et al. (1982), conducted a study of the nutrient uptake of corn, grain sorghum, and soybeans grown on land to which liquid-digested sludge containing 2.6% solids had been applied as a source of plant nutrients. The sludge was applied over a six-year period to give a total of 0, 87, 174, 241, 288, and 335 mt ha^{-1} dry matter. Corn did not contain Pb in the leaves or grain, but the leaves contained up to 2.0 $\mu g\ g^{-1}$ Cd and 0.23 $\mu g\ g^{-1}$ Hg when high levels of sludge were applied, however, Cd and Hg were not detected in the corn grain. Measurable amounts of Cd and Pb were not found in the leaves or grain of grain sorghum. Mercury accumulated in the leaves up to .06 $\mu g\ g^{-1}$. Soybeans took up Cd and Hg in the leaves, but none was detected in seeds. However, the yield and other plant data indicated that annual applications of sludge equivalent to 28 mt ha^{-1} would be an acceptable rate of disposal by land-spreading for corn, grain sorghum, and soybeans.

Factors Affecting Cadmium Availability, Uptake, and Toxicity to Plants

Soil Factors

Different soil factors influencing the uptake of Cd by plants have been investigated. Lagerwerff (1971) reported that Cd uptake by radish top and roots increased by decreasing the soil pH from 7.2 to 5.9. Fulderson and Goeller (1973) found that liming significantly reduced the uptake of Cd by millet from soils treated with $CdCl_2$. In other studies, John (1972b) and John et al. (1972) reported that changes in soil pH significantly affected the uptake of Cd by radish. Also, the effects of other factors on plant uptake of Cd have been reported including cation exchange capacity, organic matter content, available zinc levels, and soil temperature.

Cation Exchange Capacity

Many researchers reported decreased Cd uptake with increasing soil cation exchange capacity (CEC) due to greater capacity of the higher CEC soils to adsorb Cd ions (Haghiri, 1974; Williams and David, 1973). Williams and David (1973) observed a fivefold difference in the amount of added Cd taken up by oats on two different soils. A third soil indicated an intermediate uptake. The authors concluded that the difference is due largely to the variation in CEC of the soils involved. Haghiri (1974) and Kunze (1965) reported an inverse relationship between Cd concentrations in oat shoots and the CEC of the soil based on a greenhouse pot experiment. Also, they observed decreased exchangeable Cd with increasing CEC of the soil. With the exception of the CEC effect, organic matter did not influence the concentration of Cd in oat shoots. This study indicated that the retaining power of organic matter for Cd is predominantly through CEC properties rather than chelating affects (Kunze, 1965).

Soil Organic Matter

In addition to high CEC, soil organic colloids have chelating ability and certain heavy metals have the tendency to combine with certain chelating groups and become fixed (Leeper, 1972).

Anderson and Nilsson (1974) found that organic soils adsorb Cd more effectively than mineral soils, particularly under acidic conditions, while Haghiri (1974) and Singh and Sekhon (1977) indicate that the effect of organic matter on Cd availability is primarily due to the high CEC of the soil organic colloids rather than their chelating ability.

Soil pH

In a study by King and Morris (1972), an analysis indicated that sludge treatments decreased soil pH and increased exchangeable and water-soluble Mn and exchangeable Zn in the soil. John et al. (1972) experimented with soils of varying pH values and found that decreasing soil pH was associated with increasing concentrations of Cd in radish, lettuce, and soybeans. Similarly, Williams and David (1976) observed that Cd uptake by subterranean clover increased when the pH was lowered and decreased when the pH was raised. Wallace et al. (1977) and MacLean (1976) observed decreased Cd uptake by subterranean clover, lettuce, and corn with the addition of lime or $CaCO_3$ to the soil.

Soil Phosphorus

The effect of soil phosphorus concentration on Cd uptake is somewhat complex. Several studies have been conducted to investigate the effect of soil phosphorus concentration on Cd uptake. Miller et al. (1976a) found that Cd accumulation by soybeans increased with increasing concentration of available phosphorus. However, Maclean's (1976) study indicated a decrease in Cd accumulation by lettuce with the addition of phosphate to acidic soils, whereas Cd accumulation was relatively unchanged by phosphate additions to neutral soils. On the other hand, Haghiri (1974) reported that on phosphorus deficient soils, phosphorus application appears to decrease the Cd content of corn leaves.

Williams and David (1977) suggested that the effects of phosphate addition on Cd uptake differ from soil to soil and from one plant species to another. Further, they concluded that on phosphorus deficient soils, the addition of phosphate may decrease Cd accumulation through a dilution effect caused by increases in plant yield, but when the soil phosphorus supply is adequate, phosphate additions will increase both Cd accumulation and plant yield.

Cadmium and Zinc Ratio

The differential movement of Cd with respect to other elements, mainly zinc, in the food chain has received much attention due to the toxicity of Cd and its ability to accumulate and persist in certain tissues. The expected ratio of Zn to Cd in sludge is 100:1 down to 200:1, but, most commonly, sludges have ratios ranging from 1,000:1 down to 25:1 (Chaney, 1973). Comparisons of sludge and effluent ratios or of efficiency of removal of Zn and Cd from waste water can be used to judge whether the metals behave differently during waste-water treatment. Oliver and Cosgrove (1974), Nomura and Young (1974), and Lester et al. (1979) observed Zn enrichment of sludge (Zn:Cd, 150:1) and conversely Cd enrichment of effluent (Zn:Cd, 30:1). Copper was chosen by the same workers as an additional element for comparison to Zn, and it showed a similar ratio to Zn in both sludge and effluent (Kerfoot and Jacobs, 1976). The study strengthens the notion that Cd should be treated differently from Zn.

<u>Other Cations</u>

The effect of other cations on the uptake of Cd varies depending on soil types and characteristics. For example, John (1976) observed a reduction in Cd uptake by hydrophonically grown lettuce and oats when K concentration in the solution was increased. Anderson (1976) observed that an increased Cd concentration in wheat grain occurred with increasing rates of K fertilization. He stated that this was due to the increased salt concentration from the fertilizer. However, John (1976) further observed that both a complexity of nutrient element interrelationships in the substrate and the resultant element balance within the plant affect Cd concentration in the tissue. Miller et al. (1976b) compared the effect of Cd added to a soil either above or in combination with Pb. Additions of Pb along with Cd increased Cd uptake and concentration in tissue. Similar results were reported by Carlson and Bazzaz (1977).

Soil Temperature

Haghiri (1974) observed an increase in Cd concentration in soybean shoots with increases in soil temperature. In a similar study, Allaway (1968) detected an increase in Cd concentration in lettuce when soil temperature was increased.

Elements Interaction

The interaction of other metals with Cd has been observed in soybeans and corn. Cunningham et al. (1975a) pointed out that an application of Cu increased the Cd content of corn and rye shoots. However, when Cu was added in a mixture with Zn, Mo, and Se, a reduction in the Cd content of soybean seeds was reported. The same effect was obtained when Zn was applied alone (Baker et al., 1975). Although the addition of different levels of Cd salt-amended sewage sludge to the soil did not significantly affect the yield of tomato plants, it did affect the uptake of some other trace elements. The Cd treatments in this experiment were shown to inhibit Fe uptake but enhance Cu uptake with no significant affect on the uptake of Cd, Zn, and Mn.

Incubation Time

In a study to determine the influence of pH, P, Cd, sewage sludge, and incubation time on the solubility and plant uptake of Cd, it was observed that varying the incubation time for the Cd-sludge treatments prior to planting did not significantly affect the Cd concentration of corn seedlings (Jimmy et al., 1978). However, when the Cd-sludge treatments were separated into organic and inorganic Cd treatments, a significant effect of incubation time was observed. The Cd concentration increased with increasing incubation time for the organic (Cd-spiked sludge) and decreased with incubation time for the inorganic ($CdSO_4$) treatment. Similarly, Lagerwerff et al. (1977) observed that incubation time considerably decreased Cu and Pb uptake by rye plants.

Annual Cd Application Rates

An annual Cd application in soil has a major influence on the Cd concentration in plant tissue. Bingham et al. (1975) and Giordano and Mays (1976) observed various concentrations of Cd in different plant species treated with similar rates of Cd. However, the distribution of Cd within the same plant was not uniform. In corn grain, the concentraton of Cd was only 3 to 15% of that found in the leaf tissue, whereas in the seeds of soybeans and grains of wheat, oats, and sorghum, Cd reached 30 to 100% of the foliar levels.

Plant Factors

Crop Species, Varieties, and Plant Tissues

Several studies have shown that plant species exhibit genetic variability in Cd uptake and accumulation. Page et al. (1972), John (1973), and Tumer (1973) observed a degree of variability among 23 different species exposed to very low Cd concentration in a large batch liquid culture. Variation in Cd uptake among these species generally point to genetic differences. Petterson (1977) reported differences in the Cd content of seeds from 15 different barley cultivars grown on adjacent field plots. He found significantly higher Cd concentration in Starke than in Holme. Similar varietal differences were found in lettuce by John and Van-Laerhoven (1976) when nine varieties grown in Cd-amended solutions for 3 to 5 weeks were compared.

Plant Age

Very few studies have been done on the effects of plant age on Cd uptake. A study by Root et al. (1975) points to the general hypothesis that Cd accumulation in plant tissues increases with time of treatment and with the growth medium concentration of Cd when the plants are undergoing rapid vegetative growth. In contrast to the study of Root et al. (1977), Miller et al. (1977) observed that Cd concentration in corn shoots decreased with time. Miller et al. (1977) concluded that either the rate of Cd uptake was not proportional to the rate of biomass production, or the Cd in the soil was becoming less available with time.

Successive Crops

The effect of successive crops, like plant age on Cd availability, uptake, and toxicity has received little attention. The Hinesly et al. (1976) investigation in which Cd addition was discontinued, indicated a decrease in Cd uptake by corn in the first year after application. A similar decrease was observed in the second year. The number of years after termination of sludge application required for plant uptake to approach background levels is yet to be determined.

Forms of Cadmium Application

Cadmium Salt

Cadmium salts may be applied to the soil directly (Matt et al., 1972) or indirectly through incorporation into sewage sludge (Robert et al., 1973; Bingham et al., 1975). The forms of Cd salts commonly used are $CdCl_2$ (Matt et al., 1972), $CdSO_4$ (Bingham et al., 1975), and Cd acetate (Robert et al., 1973). Cadmium concentration can, therefore, be adjusted so that a phytotoxic effect is induced for research studies. In fact, addition of Cd salts to sewage sludge has been shown to cause a more toxic effect than addition of Cd-containing sewage sludge having equivalent amounts of Cd (Cunningham et al., 1975; Singh, 1981; Kiekens et al., 1984). However, Cropper (1969) believes that the addition of inorganic salts to sewage sludge may have the same effect as that obtained when heavy metal-containing sewage sludge is added in equivalent amounts to the metal salt. Reviewing the above studies indicates that caution has be be taken when results of inorganic salt treatments are to be interpreted to evaluate phytotoxicity and toxic metal uptake from sewage sludge-amended soils as recommended by Cunningham et al. (1975b).

Sludge-Borne Cadmium (Cd)

Cadmium containing sludge is the common source of Cd contamination to soils. It is usually applied to the soil at different rates to study the phytotoxic effect of Cd on plant growth and yield. The use of Cd contaminated sewage sludge in such studies is always preferable to the use of organic or inorganic Cd salts or sewage sludge artificially enriched with Cd salts. This has been clearly demonstrated by Singh (1981) who found that the average Cd concentration of lettuce plants grown in soil treated with inorganic forms was five times greater than that of plants from soil treated with sewage sludge containing Cd at the same concentrations. Similar results using raygrass have recently been reported (Kiekens et al., 1984).

Fertilizer (phosphorus)-borne Cadmium

Cadmium frequently occurs in ores used in the production of phosphorus (P) fertilizers. The concentration of Cd in the ores was found to be as great as 980 $\mu g\ g^{-1}$ (USDA-USDI, 1977). Concentration of Cd in treble superphosphate (TSP) fertilizers produced from some western USA sources range from 50 to 200 $\mu g\ g^{-1}$, whereas concentrations from southeastern sources range from 10 to 20 μg^{-1} (Mortvedt and Giordano, 1977). However, in a study by Mulla et al., (1980) to determine the influence of long-term heavy application of TSP on the accumulation of Cd in the soil profile and the extent of uptake of the accumulated Cd by economic crops, it was observed that long-term heavy application of TSP caused measurable increases in the total Cd of surface soil, but the accumulated Cd burden per year was much lower than that reported from application of sewage sludge. Cadmium accumulating in soils as a result of P fertilization seemed to be less available to swiss chard than Cd accumulations resulting from applications of sewage sludge.

CHAPTER III

MATERIALS AND METHODS

Soil

Two soil types from agronomy research stations in Oklahoma were selected for this study: Teller Sandy Loam (fine-loamy, mixed, thermic, Udic, Agriustolls) from Perkins Research Station, and Norge Loam (fine-silty, mixed, thermic, Udic Paleustolls) from Efaw Stillwater Research Station.

Samples were collected from the soil surface (0 to 15 cm) in the Spring of 1983. The samples were air dried, ground, passed through a 20-mesh sieve, and stored in tight plastic bags until the experiment was begun. A small portion of soil was taken from each sample for physical and chemical analysis.

Soil texture was determined by the hydrometer procedure as described by Day (1956) at 25°C using pyrophosphate as a dispersing agent. The results of soil texture analysis are presented in Table I. Soil pH was determined in soil to water ratio of 1:1 (w:v) using a glass electrode. Total organic matter (OM) in the soil was determined by the Walkeley and Black method as described by Jackson (1973). Soil NO_3^--N extractions were made as outlined by Roller and McKaig

(1939), and the contents were measured using a NO_3^--N electrode. Available P was determined with Bray No. 1 extractant with a 20:1 solution:soil ratio. Phosphorus content was quantified using a Turner spectrophotometer (Model 330) with a Fisher concentration computer (Model CDR) attached (840 nm wavelength). The concentration of available Ca, Mg, and K in the extracts were measured via atomic absorption (AA). The Ca and Mg were determined after an addition of a flame enhancement solution of $LaCl_3$ (5%). The concentration of available (DTPA-extractable) Fe, Zn, and Mn were similarly measured by AA. The concentration of available (DTPA extractable) Cd was measured via Perkin-Elmer 5000 AA fitted with a graphite furnace. The results of the soil analysis are shown in Table II.

TABLE I

SOIL TEXTURE ANALYSIS FOR TELLER FINE SANDY LOAM AND NORGE LOAM SOILS

	Composition %			
Soil Type	Sandy	Silt	Clay	Texture
Teller	64	24	13	Sandy Loam
Norge	36	40	25	Loam

TABLE II

INITIAL SOIL ANALYSIS FOR TELLER SANDY LOAM AND NORGE LOAM SOILS

	Soil pH	Organic Matter %	NO_3-N	P	K	Ca	Mg	Fe	Zn	Mn	Cd
					kg ha^{-1}				mg kg^{-1}		
Teller	6.2	0.8	2.52	40	340	1333	300	12.6	1.64	17.0	0.10
Norge	7.4	1.1	50	30	913	6405	1119	11.5	0.52	13.8	0.02

Sludge

Sewage sludges from two cities in Oklahoma (Stillwater and Tulsa) were used to study the effect of sludge-borne Cd on crop production and soil and plant composition: Stillwater sludge obtained from the Stillwater Municipal Sewage Treatment Plant, and Tulsa sludge obtained from the Tulsa Northside Municipal Sewage Treatment Plant. The K, Ca, Mg, Fe, Mn, Zn, and Cd content of the sewage sludge was determined after being extracted using the perchloric-nitric digestion procedure of Shelton and Harper (1941). Methods of determination were the same as those used in the soil analysis and the results obtained are given in Table III.

TABLE III

CHEMICAL COMPOSITION OF TULSA AND STILLWATER SEWAGE SLUDGE UTILIZED FOR EXPERIMENTAL TREATMENTS

Element	Tulsa Sludge	Stillwater Sludge
	$g\ kg^{-1}$	
K	1.53	2.28
Ca	62.40	35.60
Mg	3.13	4.09
Fe	8.43	36.30
	$mg\ kg^{-1}$	
Cd	306.00	7.02
Mn	386.00	504.00
Zn	2,170.00	966.00

Test Crops

Two plant species, soybean (Glycine Max), Essex TE3LI produced by Oklahoma Foundation Seed, and grain sorghum (Sorghum bicolor), OK 632 produced at Oklahoma State University, were selected for this study.

Pots

Eighty pots (18 cm diameter x 40 cm deep) were constructed for each soil type by connecting two No. 10 cans. A plastic bag was used as a liner to contain the soil and prevent root contact with the pot surface.

Soil Preparation

Teller sandy loam soil was treated with 2.2 mt ha^{-1} effective calcium carbonate equivalent (ECCE) to increase the soil pH. A soil pH value above 6.5 found to be necessary to restrict the movement of heavy metals and to minimize phytotoxicity caused by the excessive release of heavy metals from sewage sludge as recommended by the Oklahoma State Department of Health (1983), and Anderson and Nilsson (1974).

Lime was well-mixed to 3 kg units of the Teller soil in plastic bags as finely ground $CaCO_3$. The pH of the Norge loam soil was 7.4 and did not require adjustment by lime application. The sources of N, P, and K for fertilization were ammonium nitrate (35-0-0) and a mixture of $K_2H\ PO_4$ (guarantee equivalent of approximately 0-46.5 - 44.5). The fertilizers were added to 3 kg soil units in plastic bags by spraying the soil with appropriate amounts of the fertilizer solution in several increments and mixing the soil after each addition. The rates applied for N, P, and K were 112, 44.8, and 42.9 kg ha^{-1}, equivalent respectively.

Treatment Preparation

An application of 44 mt ha^{-1} (20 tons/acres) organic waste mixture from Tulsa and Stillwater was added to each pot to obtain four levels of Cd (Table IV).

TABLE IV

SLUDGE MIXTURE REQUIRED FOR ORGANIC WASTE RATE EQUIVALENT TO 44 mt ha^{-1} AND CADMIUM RATES OF 7, 30, 60, AND 120 mg kg^{-1} IN 6 kg POTS

Treatment		Amount of OW from Tulsa	Amount of OW from Stillwater
I	07 mg kg^{-1}	0.000	*60.000
II	30 mg kg^{-1}	4.710	55.290
III	60 mg kg^{-1}	10.853	49.147
IV	120 mg kg^{-1}	23.140	36.860

*60 g/Pot = 44 mt ha^{-1} Organic Waste (20 tons/acre)

Experimental Design

The experimental design was a lattice square with five replications and 2x2x4 factorial arrangement. The design was suggested by Morrison (1983) to minimize variations caused by air movements in the greenhouse. An additional row was added around the treatment blocks to minimize edge effects.

The Experiment Layout in the Greenhouse

The layout of the soybeans and grain sorghum experiments in the greenhouse is given in Figures 2 and 3. Treatments were placed by randomization. There were 16 treatments (Table V) with five replications (See experimental design and Figures 2 and 3). The sixteen soil treatments for the sorghum and the soybean experiments were made in the plastic bags depending on the soil type, depth of application, and rate of Cd application. The sewage sludge was well-mixed with the soil and the prepared surface soil (3 kg) was placed over its respective subsurface soil to produce the 0 to 15 cm depth layer. Both experiments were placed near the center of the greenhouse (Figures 1 and 2) to minimize differences in air circulation and intercepted radiation.

Square 4				Square 2				Square 3			
113	000	103	111	101	010	113	102	000	102	012	001
110	003	102	100	110	103	002	001	103	003	010	013
012	002	011	010	001	013	100	000	111	110	011	101
013	101	112	001	111	003	112	012	113	100	002	112
110	010	012	000					000	003	002	101
002	102	111	013					010	001	111	100
001	113	003	011					112	011	102	103
103	101	112	100					110	113	013	012
Square 1								Square 5			

Soil types 0 = Teller Sandy Loam
1 = Norge Loam

Depth of application 0 = surface (0-15 cm)
1 = subsurface (15-30 cm)

Cd application rate 0 = 07 mg kg^{-1} 2 = 60 mg kg^{-1}
1 = 30 mg kg^{-1} 3 = 120 mg kg^{-1}

Figure 2. The Layout of the Soybean Experiment in the Greenhouse.

Square 3				Square 4				Square 5			
112	100	113	002	101	001	013	112	000	101	002	003
001	102	000	012	003	100	110	102	010	100	111	001
101	110	111	011	000	111	113	103	112	103	102	011
013	003	103	010	002	010	012	011	110	012	013	113
010	110	000	112					001	110	002	103
113	001	011	003					000	011	100	013
101	103	100	012					102	101	113	010
102	002	013	111					012	111	112	003
Square 1								Square 2			

Soil type 0 = Teller Sandy Loam
1 = Norge Loam

Depth of Application 0 = surface (0-15 cm)
1 = subsurface (15-30 cm)

Cd application rate 0 = 07 mg kg^{-1} 2 = 60 mg kg^{-1}
1 = 30 mg kg^{-1} 3 = 120 mg kg^{-1}

Figure 3. The Layout of the Sorghum Experiment in the Greenhouse

TABLE V

EXPERIMENTAL CADMIUM AND SLUDGE TREATMENT UTILIZED

Treatment	Soil Type	Depth of application (cm)	Cd application rate (mg kg^{-1})
000	Teller Sandy Loam	0-15	7
001	Teller Sandy Loam	0-15	30
002	Teller Sandy Loam	0-15	60
003	Teller Sandy Loam	0-15	120
101	Teller Sandy Loam	15-30	7
011	Teller Sandy Loam	15-30	30
012	Teller Sandy Loam	15-30	60
013	Teller Sandy Loam	15-30	120
100	Norge loam	0-15	7
101	Norge loam	0-15	30
102	Norge loam	0-15	60
103	Norge loam	0-15	120
110	Norge loam	15-30	7
111	Norge loam	15-30	30
112	Norge loam	15-30	60
113	Norge loam	15-30	120

Soil Incubation

After the layout of the soybean and sorghum experiments was set in the greenhouse on June 15, 1984, an incubation period of 45 days was allowed before planting on August 25, 1984. A total amount of 1500 ml water was added to the soil in each pot at three times (3 x 500 ml) with an interval of 15 days. This treatment was essential to maintain the soil moisture at a level to allow soil equilibrium processes to proceed.

Planting Methods

Two crops of either soybean and/or sorghum were sequentially planted in the same pots. The first crop was planted on August 25, 1984, after the addition of 500 ml water to the soil in each pot, and harvested on September 31, 1984 (5 weeks). The temperature settings of the greenhouse were kept at 27°C (80°F) in the day and 21°C (70°F) at night.

Five seeds of soybean were sown in each pot. The seeds were equally spaced using hard board template of equally spaced holes. One week after germination and seedling emergence, the seedlings were thinned to three apparently healthy ones. The soybean plants were in very good condition and there were no symptoms of toxicity due to sewage sludge-borne Cd in any treatment. The soybean plants started to flower after 30 days from planting. On September 31, 1984, plants were harvested by cutting them just above the soil surface. The cut plants were placed in paper bags for fresh and dry weight determination. The dry samples were ground, and stored in paper bags in the refrigerator at 4 C. A portion of dry material (0.25 g) was taken from each sample and used for Fe, Mn, Zn, and Cd determinations.

In the case of grain sorghum, nine seeds were sown in each pot. Three of the nine seeds were sown together in a separate hole using a hard board template with three equally spaced holes. One week after germination and emergence of seedlings, the seedlings were thinned to the three healthiest-looking plants. Plants did not show any symptoms of Cd toxicity during the growth period and they were harvested, stored, and analyzed in the same way as described for the soybean experiment.

The second crops of soybean and sorghum were sown on October 2, 1984 and harvested on November 8, 1984 (5 weeks). The growth conditions and all treatments applied were the same as those used with the first crop. However, the growth of both soybean or sorghum was less than that for the first crop. This may be due to lower outside temperature and light intensity during the day. Also, nitrogen fertilizer was not applied as for the first crop. In the case of soybean, there were no symptoms of Cd toxicity, but there was a spider moth infestation just before harvesting, but no control methods were taken. The soybean plants in the second crop started to flower 30 days from planting, as with the first crop. In the case of sorghum, there were no symptoms of Cd toxicity, but there was a corn leaf aphid infestation of the plants when they were 20 days old. This was controlled by spraying the plants with chlordane (2 kg ha^{-1}). Second crops for plant species were were harvested, stored, and analyzed in the same way as the first crops.

Plant Analysis

The perchloric-nitric digestion procedure of Shelton and Harper (1941) was used in preparation for analysis. Total Fe, and Zn were determined by AA. Total Cd was measured via Perkin-Elmer 5000 AA fitted with a graphite furnace.

Final Soil Analysis

After the second crop of soybean and sorghum was harvested, soil samples in each pot were obtained at different depths: 0 to 7.5 cm, 7.5 to 15 cm, and 15 to 30 cm, respectively. Each sample was put in a plastic bag and thoroughly mixed to make the sample homogenious for testing. Each sample was analyzed for soil pH, OM%, and extractable Fe, Zn, and Cd. Methods of analysis were exactly the same as those used for the initial soil analysis.

CHAPTER IV

RESULTS AND DISCUSSION

The effect of four different levels of sewage sludge-borne Cd applied at two different depths (0 to 15 and 15 to 30 cm) in two types of soil, Teller sandy loam and Norge loam on the growth, yield, and response characteristics in terms of Fe, Zn, and Cd content of two plant species, soybean and sorghum was investigated. The accumulation and mobility of the three elements Fe, Zn, and Cd as well as organic matter in the soil have also been studied. The results obtained are presented and discussed below.

Plant Growth, Yield, and Response

The results obtained from analysis of soybean and sorghum are shown in Tables VI and VII. A summary of the analysis of variance for the two successive crops of the two plant species is shown separately in Tables VIII and IX.

Plant Growth and Yield

The plants of the two successive crops (seasons one and two) of both soybean and sorghum grew well and showed no symptoms of toxicity due to the sewage sludge-borne Cd treatments. However, crop two (season two) in both plant

TABLE VI

CHEMICAL ANALYSIS OF SOYBEAN EXPERIMENT

OBS	*Season	ST	DA	CdL	Fe	Zn	Cd	Dry Matter (g 1 pot)
					mg kg^{-1}			
1	1	0	0	0	135.3	46.5	2.5	18.5
2	1	0	0	1	177.7	56.3	2.8	17.9
3	1	0	0	2	156.0	53.0	4.8	18.6
4	1	0	1	0	186.0	46.3	6.1	17.3
5	1	0	1	1	158.7	37.6	3.0	17.3
6	1	0	1	2	159.3	44.7	3.2	18.3
7	1	0	1	3	153.7	51.3	3.5	19.1
8	1	1	0	0	162.7	48.0	5.0	18.3
9	1	1	0	1	138.3	47.9	3.9	18.4
10	1	1	0	1	158.3	49.5	2.6	19.9
11	1	1	0	2	161.0	53.0	2.7	19.0
12	1	1	0	3	183.3	56.2	2.8	19.2
13	1	1	1	0	185.7	61.5	2.6	18.1
14	1	1	1	1	174.3	66.3	2.3	19.0
15	1	1	1	2	161.6	67.2	2.8	19.1
16	1	1	1	3	171.0	53.0	2.3	18.1
17	2	0	0	0	83.6	4.6	0.8	3.9
18	2	0	0	1	129.5	51.6	1.4	3.1
19	2	0	0	2	96.2	50.5	1.1	3.6
20	2	0	0	3	114.6	63.2	1.0	3.0
21	2	0	1	0	94.2	30.9	1.0	3.1
22	2	0	1	1	71.1	35.5	1.0	3.3
23	2	0	1	2	70.3	44.2	0.5	4.2
24	2	0	1	3	125.9	45.9	1.0	3.3
25	2	1	0	0	99.5	57.3	0.4	2.9
26	2	1	0	1	72.1	59.6	0.5	3.7
27	2	1	0	2	92.0	63.3	0.0	4.3
28	2	1	0	3	169.9	65.5	1.2	3.7
29	2	1	1	3	162.6	67.4	0.8	3.7
30	2	1	1	0	175.3	69.0	0.9	4.2
31	2	1	1	1	107.7	69.6	0.9	3.6
32	2	1	1	3	96.1	50.4	1.1	3.5

*Season = Two successive crops
ST = Soil type
0 = Teller sandy loam
1 = Norge loam

CDL = Soil applied Cd
0 = 7 mg kg^{-1}
1 = 30 mg kg^{-1}
2 = 60 mg kg^{-1}
3 = 120 mg kg^{-1}

DA = Depth of Application
0 = 0-15 cm
1 = 15-30 cm

TABLE VII

CHEMICAL ANALYSIS OF SORGHUM EXPERIMENT

OBS	*Season	ST	DA	CdL	Fe	Zn	Cd	Dry Matter (g 1 pot)
					$mg\ kg^{-1}$			
1	1	0	0	0	254.7	54.1	5.5	19.5
2	1	0	0	1	196.3	71.3	7.2	18.2
3	1	0	0	2	208.0	64.7	9.6	17.0
4	1	0	0	3	119.7	54.7	10.5	15.7
5	1	0	1	0	226.3	63.0	8.0	17.5
6	1	0	1	1	216.3	66.3	7.8	17.2
7	1	0	1	2	216.3	67.3	9.1	16.2
8	1	0	1	3	143.0	66.3	10.4	14.1
9	1	1	0	0	208.0	54.7	7.4	30.9
10	1	1	0	1	139.7	57.2	8.3	28.3
11	1	1	0	2	129.7	63.0	7.6	23.8
12	1	1	0	3	254.7	68.0	8.8	27.4
13	1	1	1	0	150.3	71.3	6.5	31.3
14	1	1	1	1	138.0	72.3	7.4	24.9
15	1	1	1	2	198.5	74.7	8.6	26.4
16	1	1	1	3	153.0	44.7	7.8	26.9
17	2	0	0	0	109.6	46.1	1.0	2.8
18	2	0	0	1	62.6	54.8	2.5	2.1
19	2	0	0	2	47.5	51.2	3.1	2.1
20	2	0	0	3	46.9	73.4	5.2	1.8
21	2	0	1	0	122.6	40.7	2.2	1.7
22	2	0	1	1	161.8	47.0	2.2	2.2
23	2	0	1	2	121.2	49.5	3.3	2.1
24	2	0	1	3	85.3	50.8	4.5	1.6
25	2	1	0	0	30.2	44.9	2.5	2.1
26	2	1	0	1	68.6	48.2	3.5	3.3
27	2	1	0	2	186.1	55.8	4.5	3.1
28	2	1	0	3	209.2	62.3	5.5	3.4
29	2	1	1	0	104.6	50.8	2.8	2.7
30	2	1	1	1	139.8	55.3	3.3	2.5
31	2	1	1	2	150.2	57.3	4.1	2.7
32	2	1	1	3	86.1	44.8	4.3	2.6

*Season = Two successive crops
ST = Soil type
0 = Teller sandy loam
1 = Norge loam

CDL = Soil applied Cd
0 = 7 $mg\ kg^{-1}$
1 = 30 $mg\ kg^{-1}$
2 = 60 $mg\ kg^{-1}$
3 = 120 $mg\ kg^{-1}$

DA = Depth of Application
0 = 0-15 cm
1 = 15-30 cm

TABLE VIII

SUMMARY OF ANALYSIS OF VARIANCE FOR THE TWO SUCCESSIVE CROPS OF SOYBEAN EXPERIMENT

Variable		Fe	Zn	Cd	Dry Weight
*Se	F	46.79	0.48	83.13	7053.88
	OSL	0.0001**	0.4907	0.0001**	0.0001**
S-Typ	F	3.42	3.23	0.38	0.63
	OSL	0.0675	0.0754	0.5401	0.4276
Se*S-Typ	F	0.63	1.55	0.06	3.98
	OSL	0.4293	0.2166	0.8039	0.0490*
Dep Ap	F	0.02	0.38	0.00	0.15
	OSL	0.8751	0.5394	0.9758	0.7004
Se* Dep -AP	F	0.11	0.68	0.00	0.45
	OSL	0.7406	0.4103	0.9793	0.5050
S Ty*Dep Ap	F	0.40	0.50	0.03	0.14
	OSL	0.5269	0.4826	0.8556	0.7105
Se*S Ty* Dep Ap	F	0.00	0.04	0.03	0.51
	OSL	0.9751	0.8378	0.8634	0.4779
Cd-Lv	F	0.80	0.23	0.40	0.94
	OSL	0.4995	0.8743	0.7559	0.4238
Se* Cd-Lv	F	0.11	1.41	0.30	0.28
	OSL	0.9565	0.2457	0.8254	0.8400
S-Ty* Cd-Lv	F	0.04	0.91	0.14	0.71
	OSL	0.9906	0.4412	0.9371	0.5463
Se*S Typ*Cd-LvL	F	0.20	0.40	0.21	0.31
	OSL	0.8955	0.7524	0.8899	0.8207
Dep Ap *Cd-Lv	F	1.03	0.77	0.39	0.47
	OSL	0.3822	0.5129	0.7578	0.7065

TABLE VIII (Continued)

Variable		Fe	Zn	Cd	Dry Weight
Se*Dep-A*CdL	F	0.47	1.82	0.72	0.49
	OSL	0.7024	0.1491	0.5432	0.6933
S-Typ* Dep-Ap*Cd-LvL	F	2.48	0.89	4.06	1.55
	OSL	0.0458*	0.4475	0.0092**	0.2060
Se*S-Ty*Dep-Ap*Cd-L	F	1.26	0.10	2.55	0.14
	OSL	0.293	0.9623	0.0601	0.9349
EMS		2494.5281	329.995654	1.89314306	1.26274329
DF		94	94	94	94

*Se = Season, two successive crops of soybeans
S Type = Soil type
Dep-Ap = Depth of Application
Cd-Lv - Soil-applied cadmium
EMS = Error mean square
DF = Degree of freedom
OSL = Observed statistical level

*Significance at 0.05 level
**Significance at 0.01 level

TABLE IX

SUMMARY OF ANALYSIS OF VARIANCE FOR THE TWO SUCCESSIVE CROPS OF SORGHUM EXPERIMENT

Variable		Fe	Zn	Cd	Dry Weight
*Se	F	26.03	1.26	320.00	951.07
	OSL	0.0001**	0.9513	0.0001	0.0001**
S Typ	F	0.73	0.48	0.45	51.37
	OSL	0.3960	0.4883	0.5061	0.0001**
Se*S-Typ	F	2.59	1.11	3.27	62.22
	OSL	0.111	0.2949	0.0736	0.0001**
Dep Appn	F	1.63	0.19	0.03	0.22
	OSL	0.2045	0.6666	0.8660	0.6380
Se*Dep Appn	F	0.00	0.50	1.69	0.01
	OSL	0.9916	0.4831	0.1962	0.9196
Se*S Ty*Dep Appn	F	0.31	0.00	0.03	0.71
	OSL	0.5810	0.9788	0.8642	0.4013
Se*S Typ* Dep Ap	F	1.60	0.59	0.47	0.94
	OSL	0.2096	0.4447	0.4927	0.3336
Cd-LvLN	F	1.22	1.17	3.38	1.34
	OSL	0.3078	0.3268	0.0216*	0.2648
Se*Cd-LvLN	F	1.58	0.46	3.25	1.30
	OSL	0.1985	0.7080	0.0253*	0.0020**
S Typ*Cd-LvLN	F	2.22	0.99	0.33	0.32
	OSL	0.0908	0.4033	0.8038	0.8143
Se*S Tpe*Cd-LvL	F	0.10	0.95	0.54	2.12
	OSL	0.9610	0.4220	0.6532	0.1031
Dep App *Cd-LvLN	F	3.36	1.91	0.76	0.10
	OSL	0.0219*	0.1340	0.5178	0.9599

TABLE IX (Continued)

Variable		Fe	Zn	Cd	Dry Weight
Se*Dep	F	0.50	1.34	0.33	0.05
A*Cd-Lv	OSL	0.6840	0.2662	0.8057	0.9840
S Typ*Dep	F	1.24	0.61	0.43	2.58
Ap*Cd-LvL	OSL	0.3009	0.6122	0.7349	0.0582
Se*S Ty*Dep	F	0.13	0.72	0.46	1.22
*CdL	OSL	0.9440	0.5453	0.7080	0.3058
EMS		9279.629	270.956	3.05978881	17.14212677
DF		94	94	94	94

Se = Season, two successive crops
S-Typ = Soil type
Dep-Ap = Depth of application
Cd-Lv = Soil-applied Cd
EMS = Error mean square
DF = Degree of freedom
OLS = Observed statistical level

* Significance at 0.05 level
** Significance at 0.01 level

species had a lower yield than that of crop one (Figures 4 to 7) The absence of any symptoms of phytotoxicity may be due to the relatively high soil pH values of the two soils used (Figures 20 to 23; Appendix, Figures 56 to 59) which decreased the availability of heavy metals, particularly Fe, Zn, and Cd (Williams and David, 1976; Wallace et al., 1977). In addition, the presence of sewage sludge increased the organic matter content of the soil (Figures 24 to 27; Appendix, Figures 60 to 63) and consequently its chelating ability and total soil CEC, rendering heavy metals less available to plants (Leeper, 1972; Haghiri, 1974; Singh and Sekhan, 1977).

In both soybean and sorghum plants, the four treatments of sewage sludge-borne Cd in Teller sandy loam soil did not have any significant effect on dry matter production in either seasons (Figures 4 to 7). However, season crop one had a significantly higher yield than crop two for both plant species (Figures 4 to 7). The difference in yield between crops one and two was possibly due to the release of nutritive elements, particularly nitrogen and phosphorus, from the decomposition of sewage sludge in the soil during the incubation period that preceded crop one as suggested by Hinesly et al. (1976). Certainly, the addition of 112 kg ha^{-1} nitrogen as a fertilizer to crop promoted a considerable amount of plant growth (Giordano and Mortvedt, 1975) in comparison with crop two, which received no fertilizer. Also, differences in the environmental conditions of crops

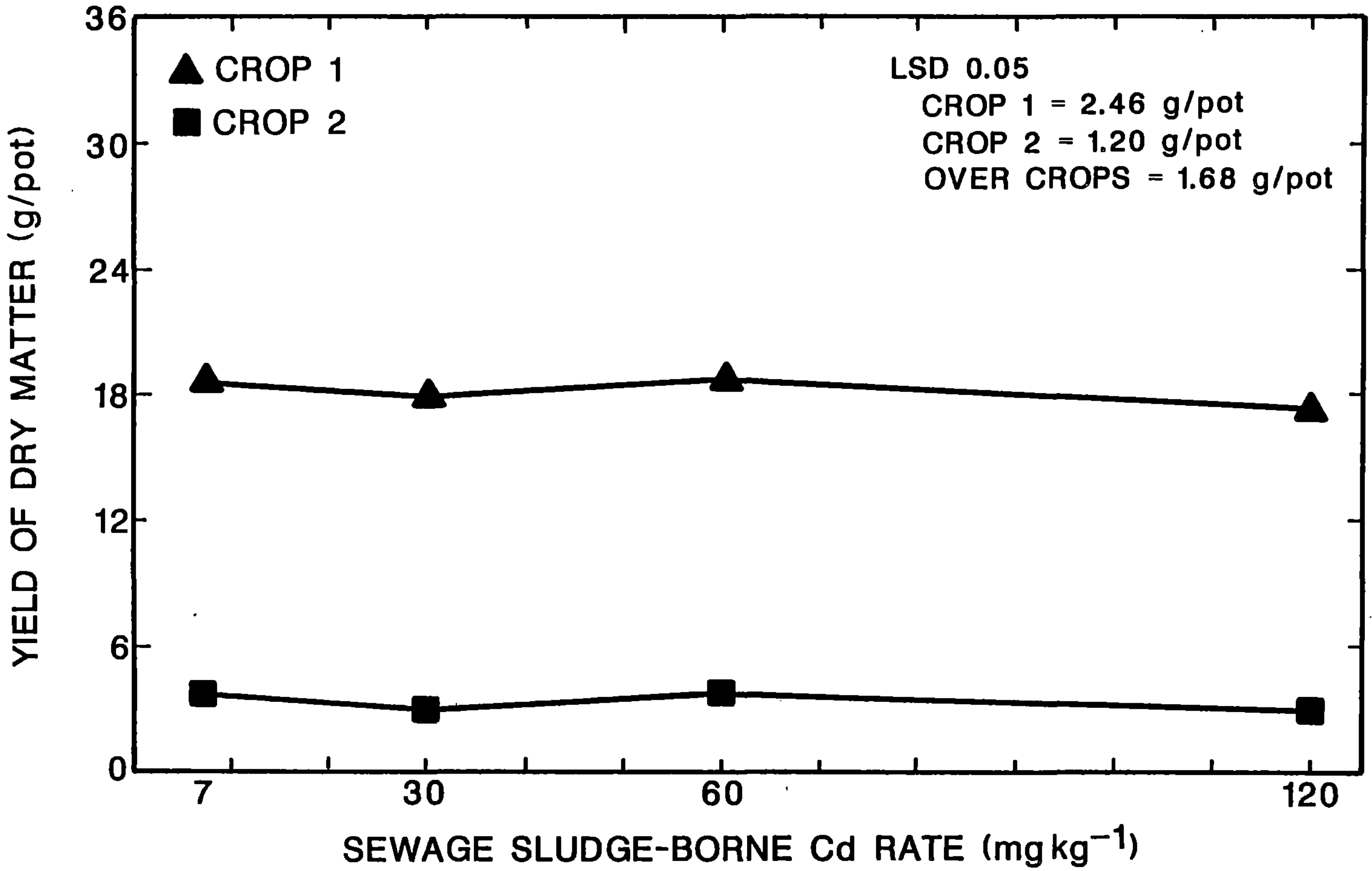

Figure 4. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (0-15 cm) on Yield of Dry Matter by Two Successive Crops of Soybean Plants on Teller Sandy Loam Soil

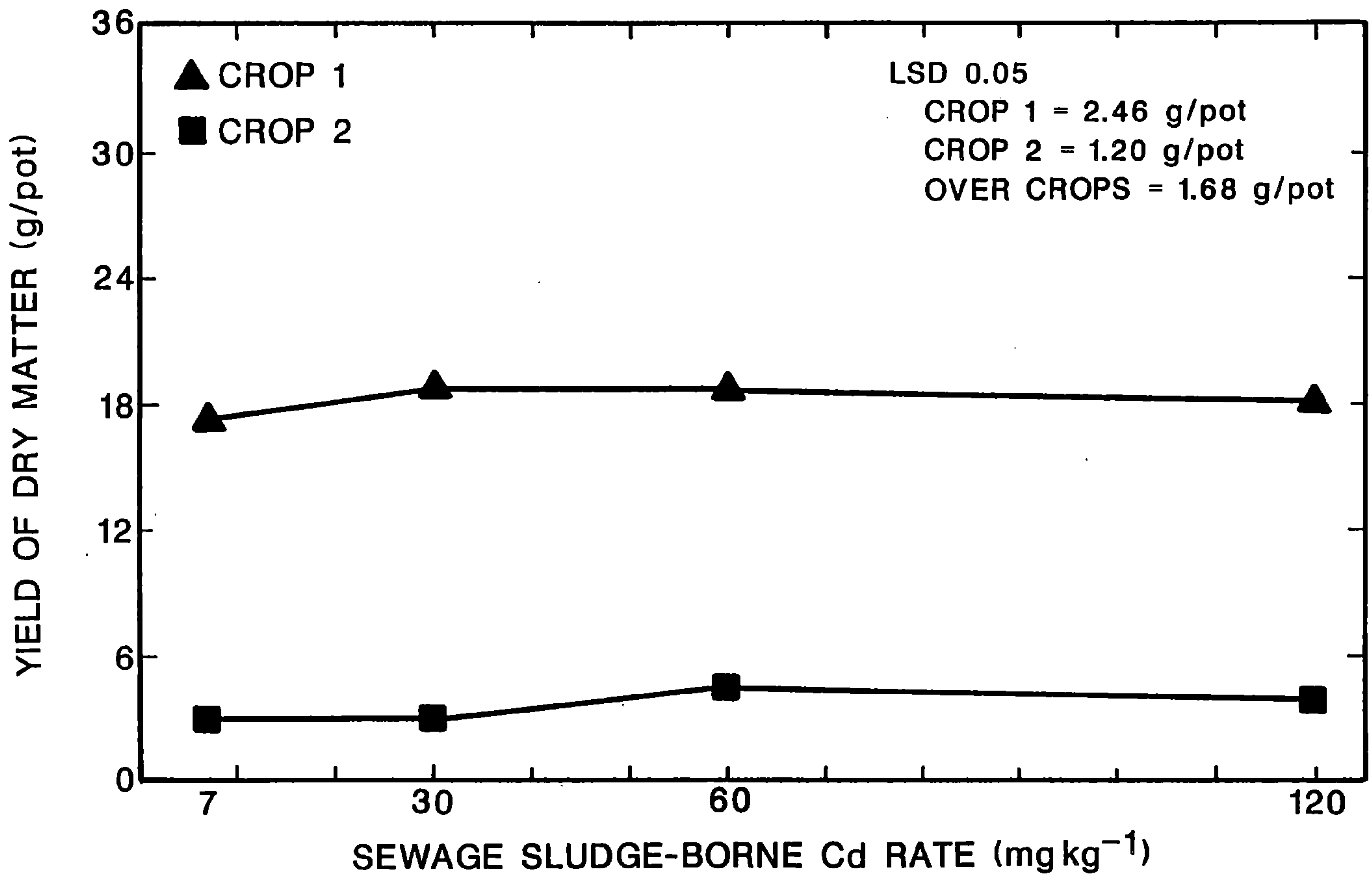

Figure 5. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (15-30 cm) on Yield of Dry Matter by Two Successive Crops of Soybean Plants on Teller Sandy Loam Soil

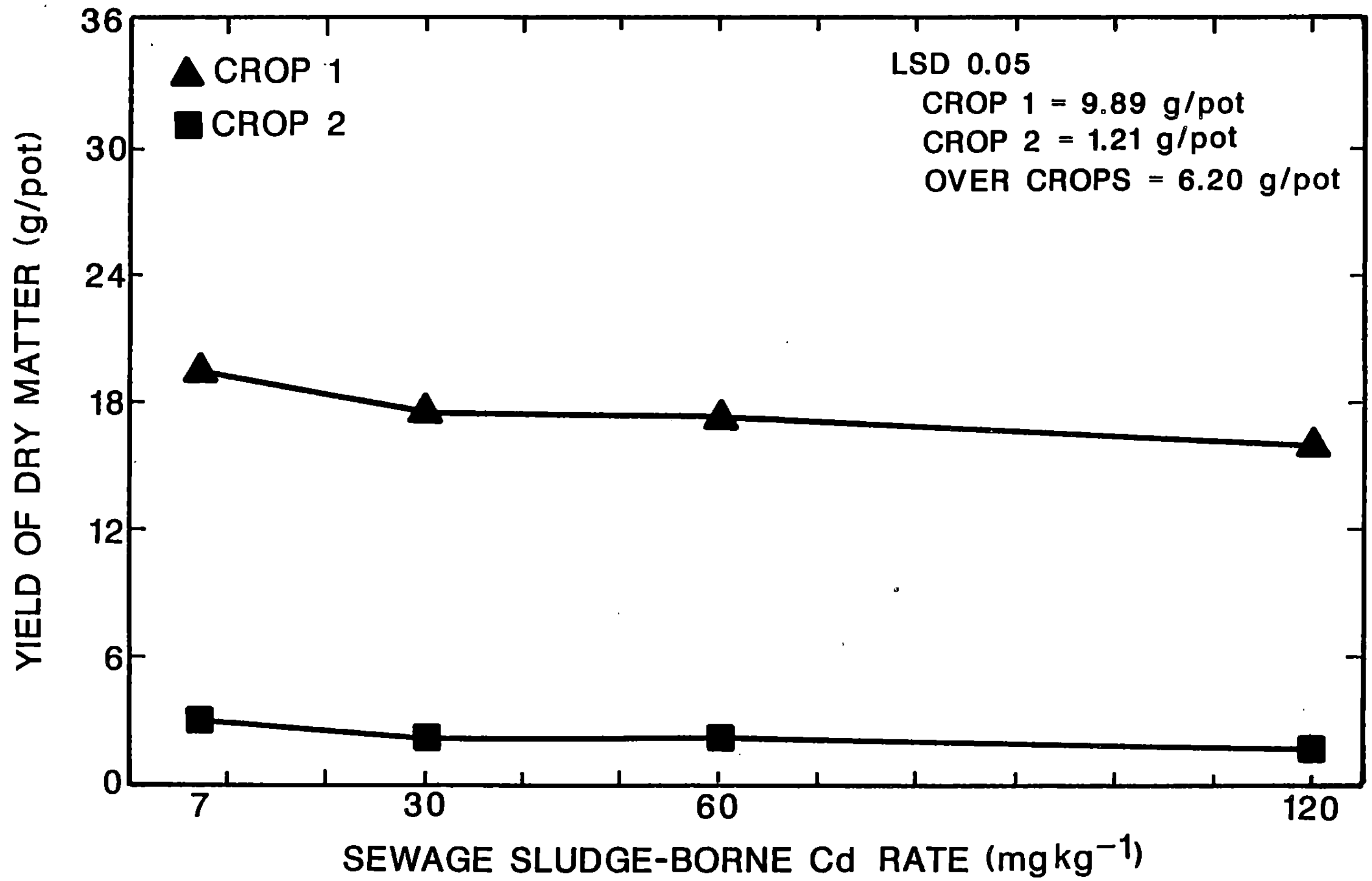

Figure 6. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (0-15 cm) on Yield of Dry Matter by Two Successive Crops of Sorghum Plants on Teller Sandy Loam Soil

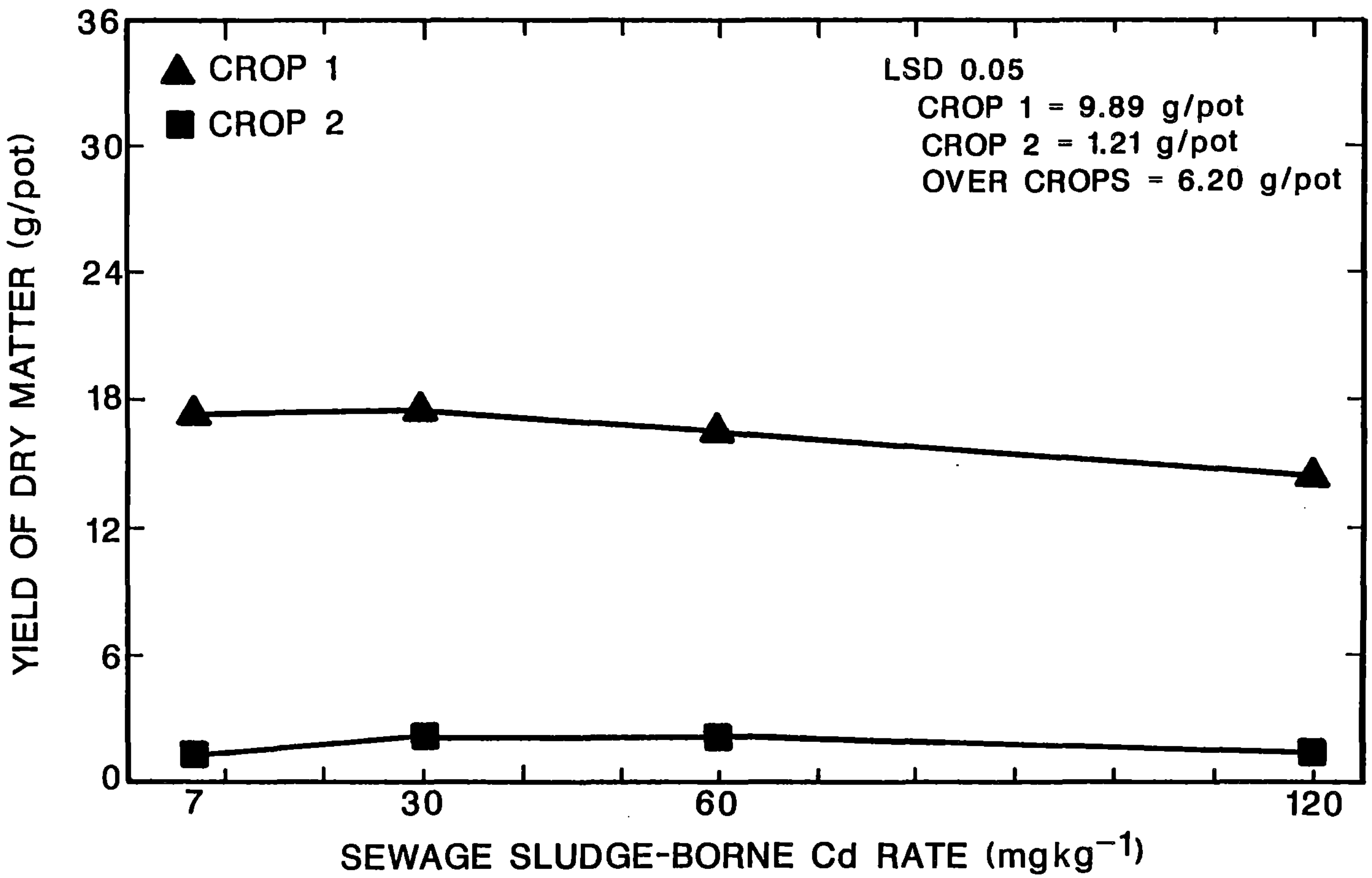

Figure 7. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (15-30 cm) on Yield of Dry Matter by Two Successive Crops of Sorghum Plants on Teller Sandy Loam Soil

one and two in terms of temperature (Mack et al., 1966) and light intensity (Leonard and Martin, 1963) may have contributed to the difference observed in yield. The yield of dry matter was higher in Norge loam soil than Teller sandy loam soil for both plant species (Figures 4 to 7; Appendix, Figures 40 to 43). This could possibly be due to the fact that Norge loam soil had a higher nutrient content (NO_3N, P, K, Ca, and Mg) than Teller soil (Table II).

Element Content

Fe Uptake

While Fe uptake by soybean plants was affected by the interaction among soil types, depths of application, and Cd levels, Fe uptake by sorghum plants was influenced by the interaction between only depth of application and Cd-levels. In both plant species, Fe uptake was affected by the season, although in Teller soil and in soybean with the two depths of application (0 to 15 cm and 15 to 30 cm) there was a gradual increase, though insignificant, of Fe uptake due to an increase in the sewage sludge-borne Cd concentration in Teller soil (Figures 8 and 9). In sorghum, the situation changed and Fe uptake decreased with an increase in Cd-application (Figures 10 and 11). The reduction observed in Fe uptake by sorghum plants could be attributed to an inhibition by sewage sludge-borne Cd, a situation not encountered in soybean (Checkai, 1983; Tiffin et al., 1960; Tiffin and Brown, 1961). The Fe uptake was insignificantly higher

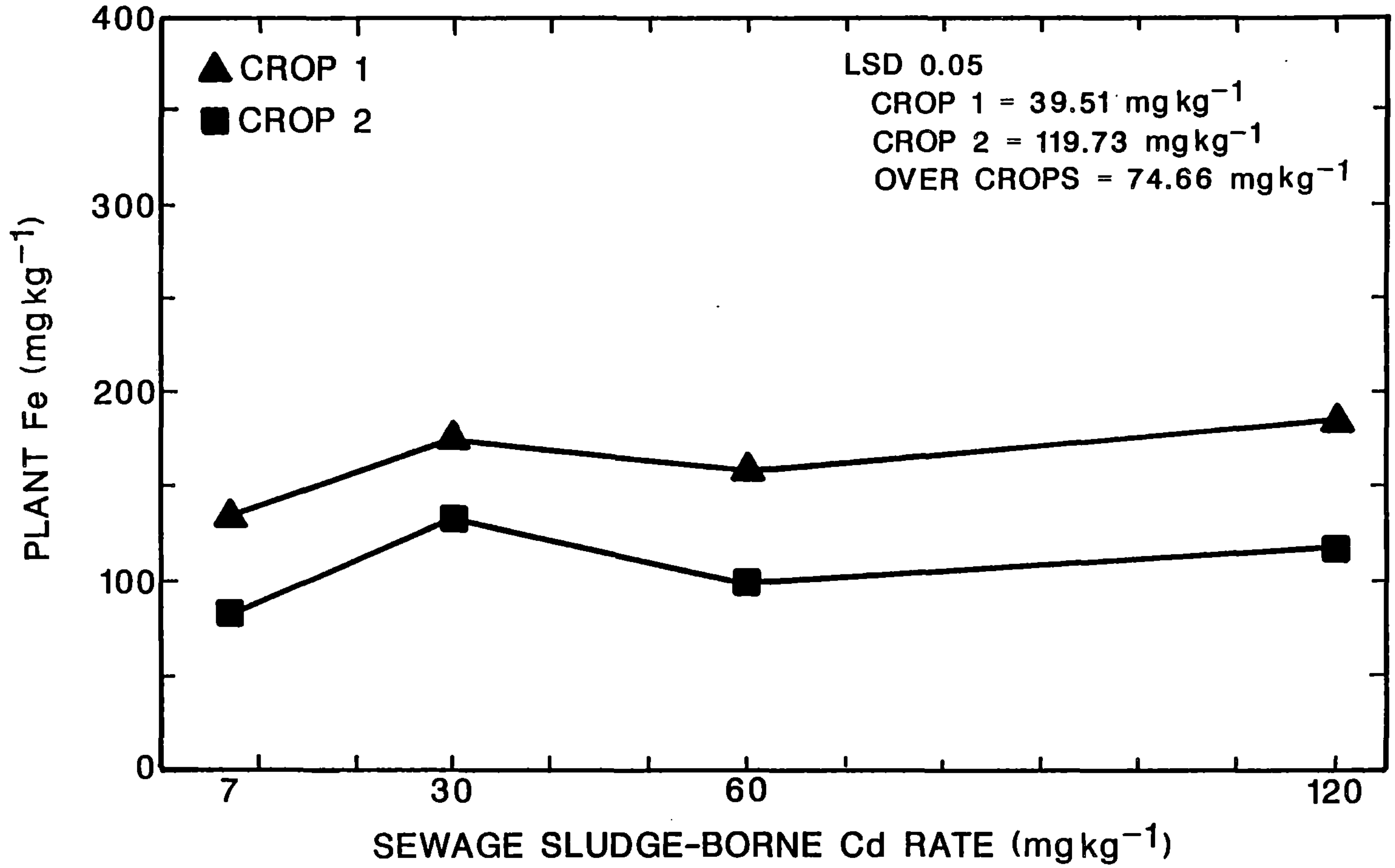

Figure 8. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (0-15 cm) on Fe Uptake by Two Successive Crops of Soybean Plants on Teller Sandy Loam Soil

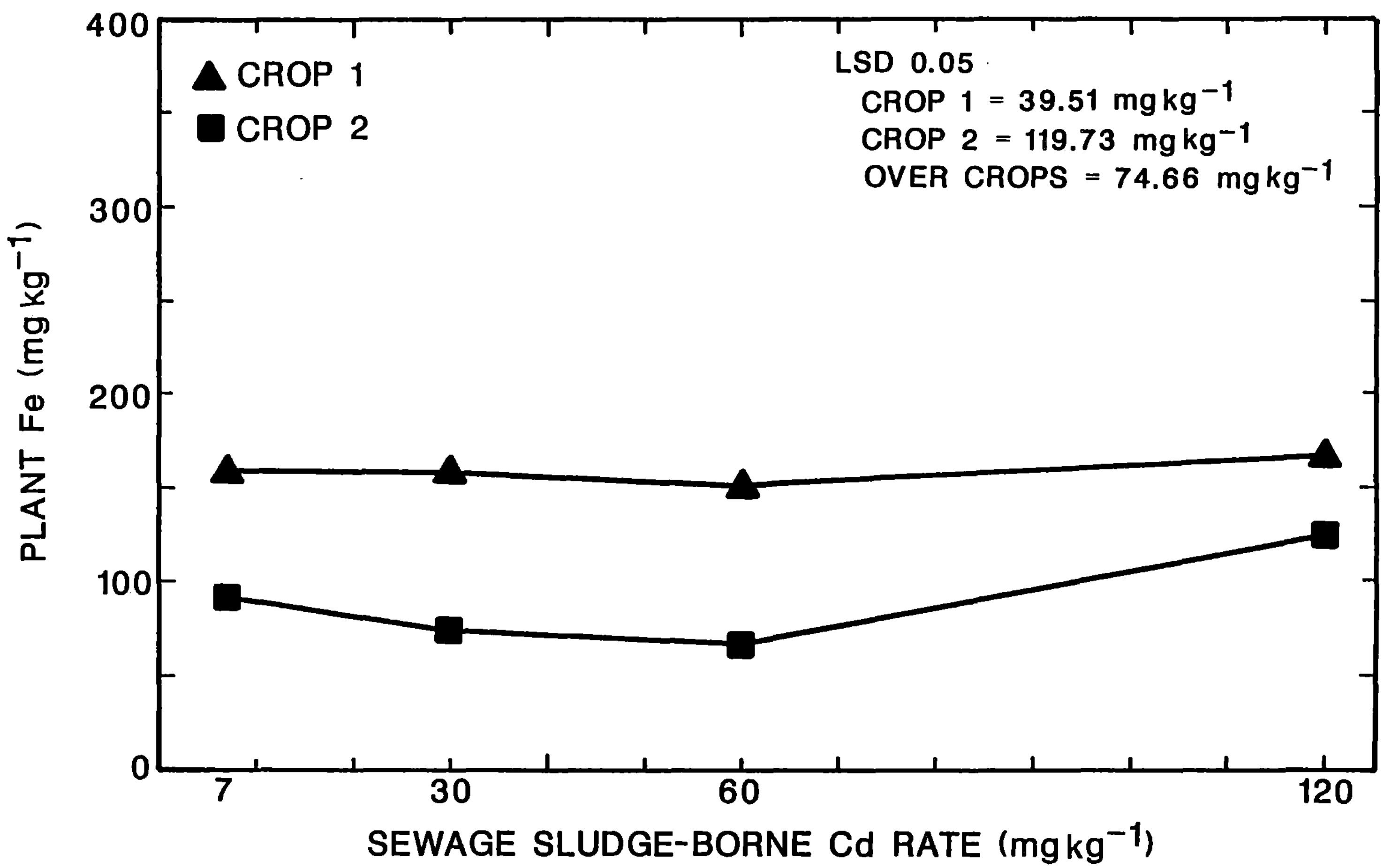

Figure 9. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (15-30 cm) on Fe Uptake by Two Successive Crops of Soybean Plants on Teller Sandy Loam Soil

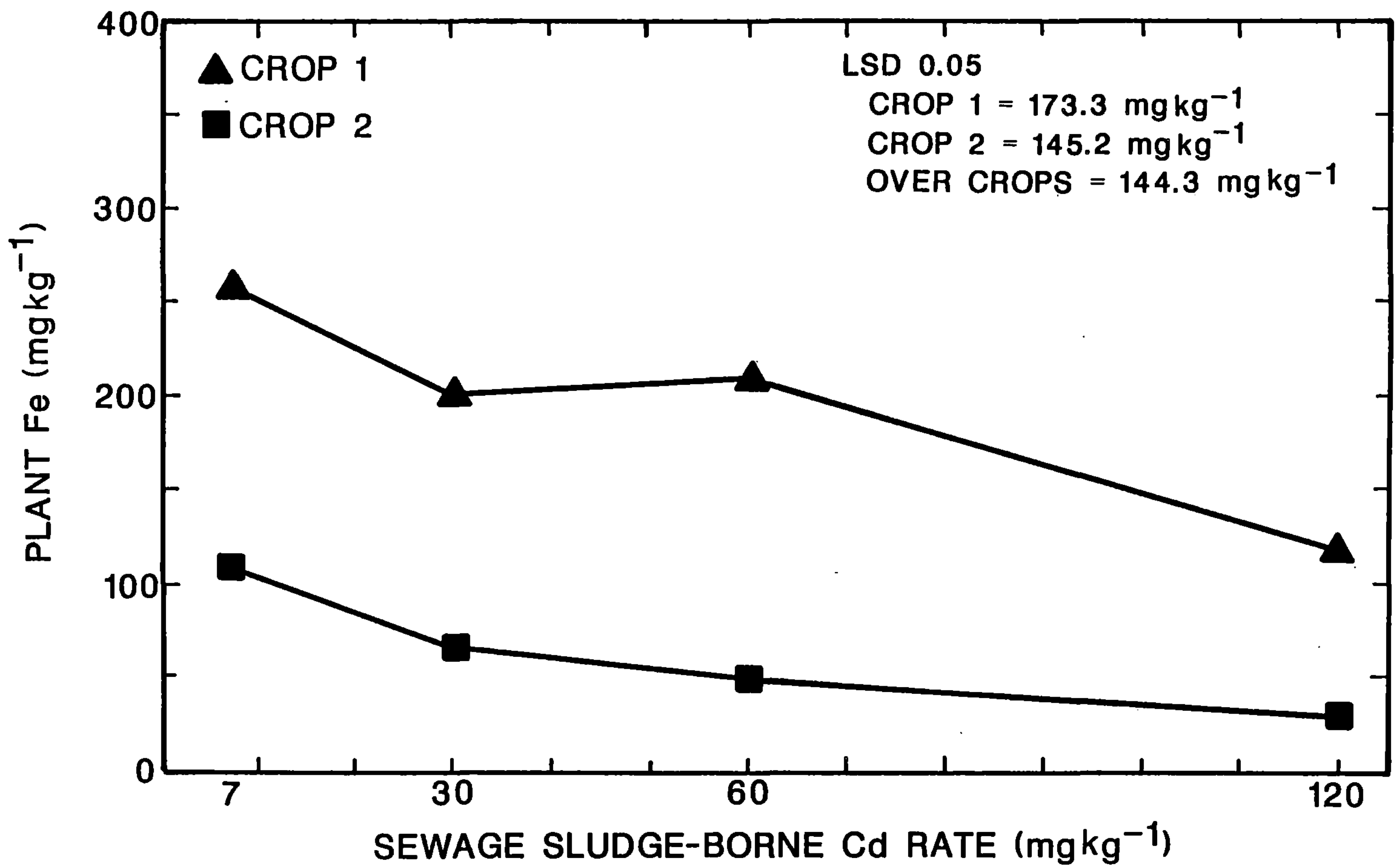

Figure 10. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (0-15 cm) on Fe Uptake by Two Successive Crops of Sorghum Plants on Teller Sandy Loam Soil

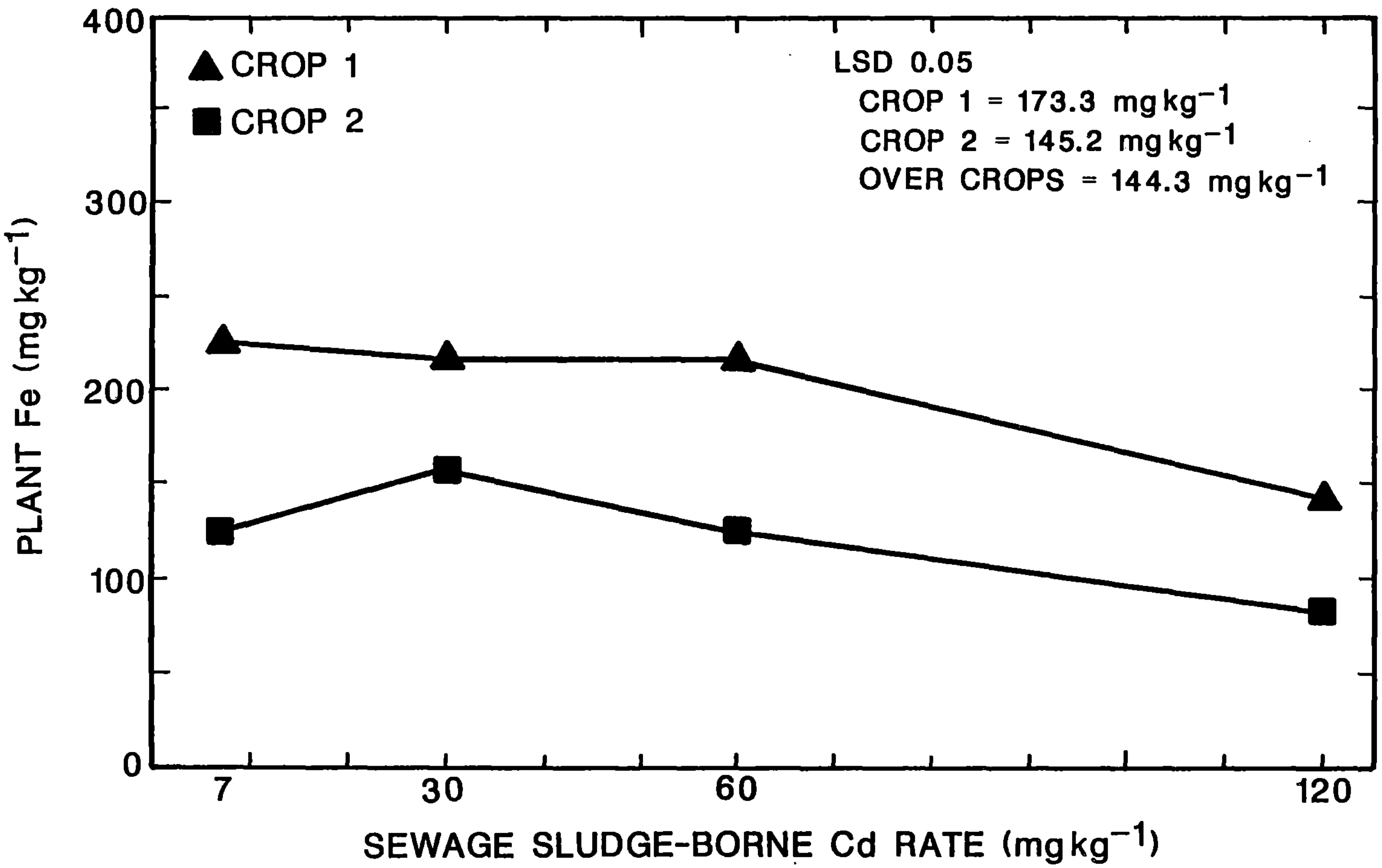

Figure 11. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (15-30 cm) on Fe Uptake by Two Successive Crops of Sorghum Plants on Teller Sandy Loam Soil

in crop one than that of crop two in both soybean (Figures 8 and 9) and sorghum plants (Figures 10 and 11). The Fe uptake from the 0 to 15 cm depth of application was higher than that from 15 to 30 cm. Similar results were previously reported (Kirkham, 1980).

The same results for both plant species were obtained when Norge loam soil was studied except that the plant uptake of Fe from Teller sandy loam soil was higher than that of the Norge loam soil, a likely result of the difference in soil texture (Appendix, Figures 44 to 47). In both soil types, Fe uptake by sorghum was always higher than that by soybean (Figures 8 to 11; Appendix, Figures 44 to 47). This difference is likely due to plant species differences (Page et al., 1972; John, 1973; Chang et al., 1982).

Zn Uptake

The uptake of Zn from both types of soils by soybean (Table VIII; Figures 12 and 13; Appendix, Figures 48 and 49) and sorghum (Table IX; Figures 14 and 15 Appendix, Figures 50 and 51) was not affected by any of the 16 treatments.

Cd Uptake

While Cd uptake by soybean was affected by season and the interaction among soil types, depths of application, and Cd levels at 0.01 probability level, Cd uptake by sorghum was affected by the interaction between season and the Cd level employed.

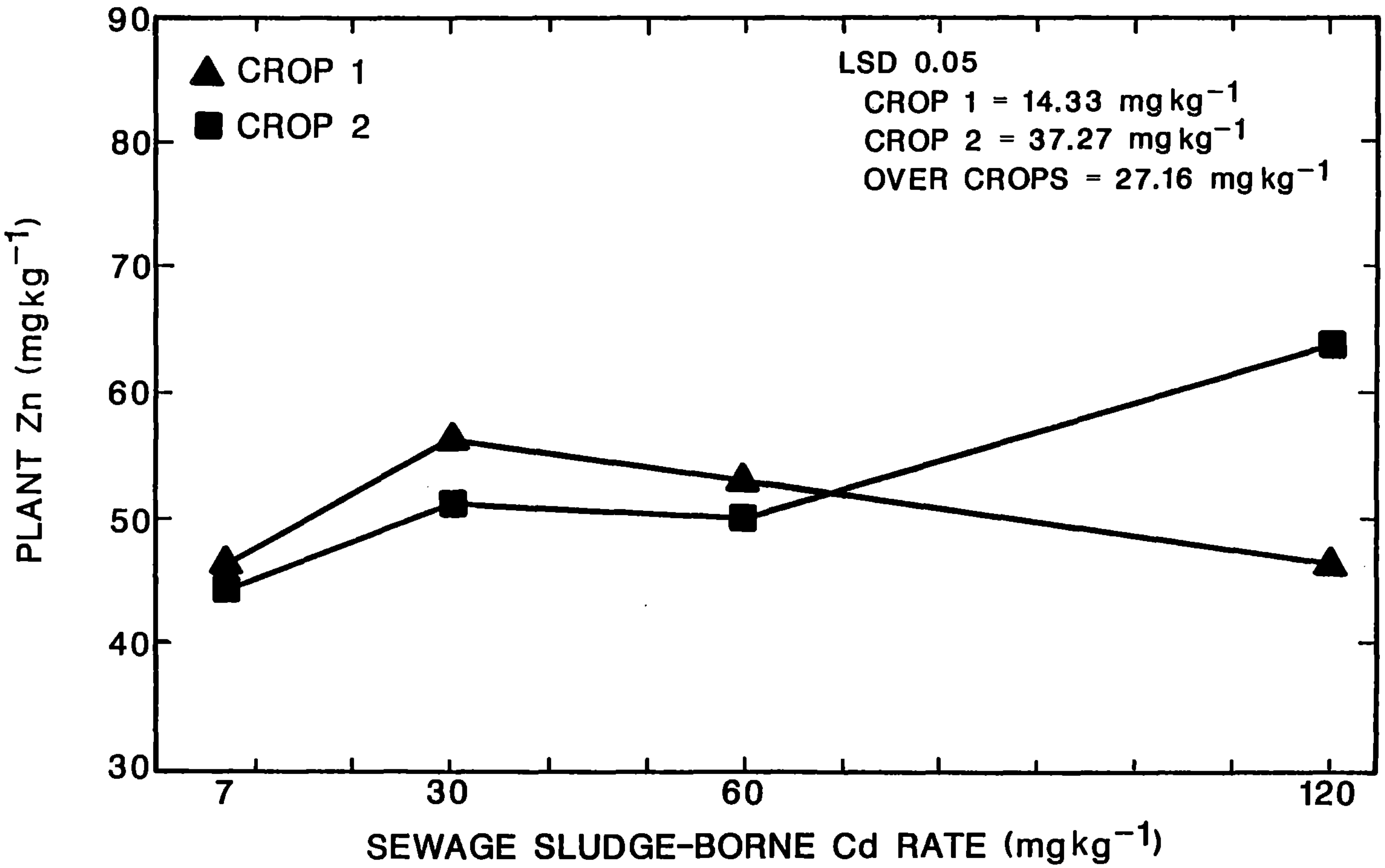

Figure 12. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (0-15 cm) on Zn Uptake by Two Successive Crops of Soybean Plants on Teller Sandy Loam Soil

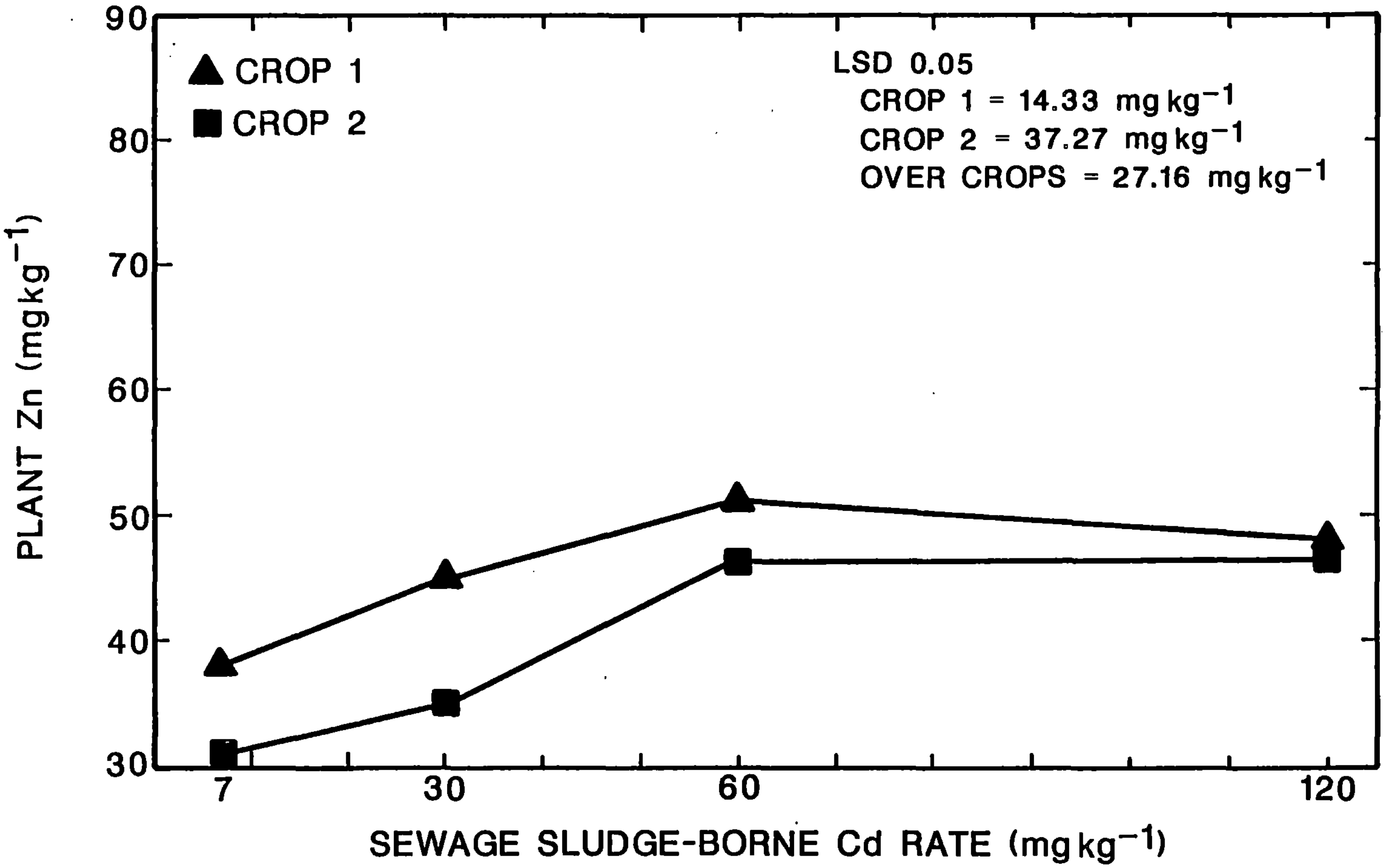

Figure 13. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (15-30 cm) on Zn Uptake by Two Successive Crops of Soybean Plants on Teller Sandy Loam Soil

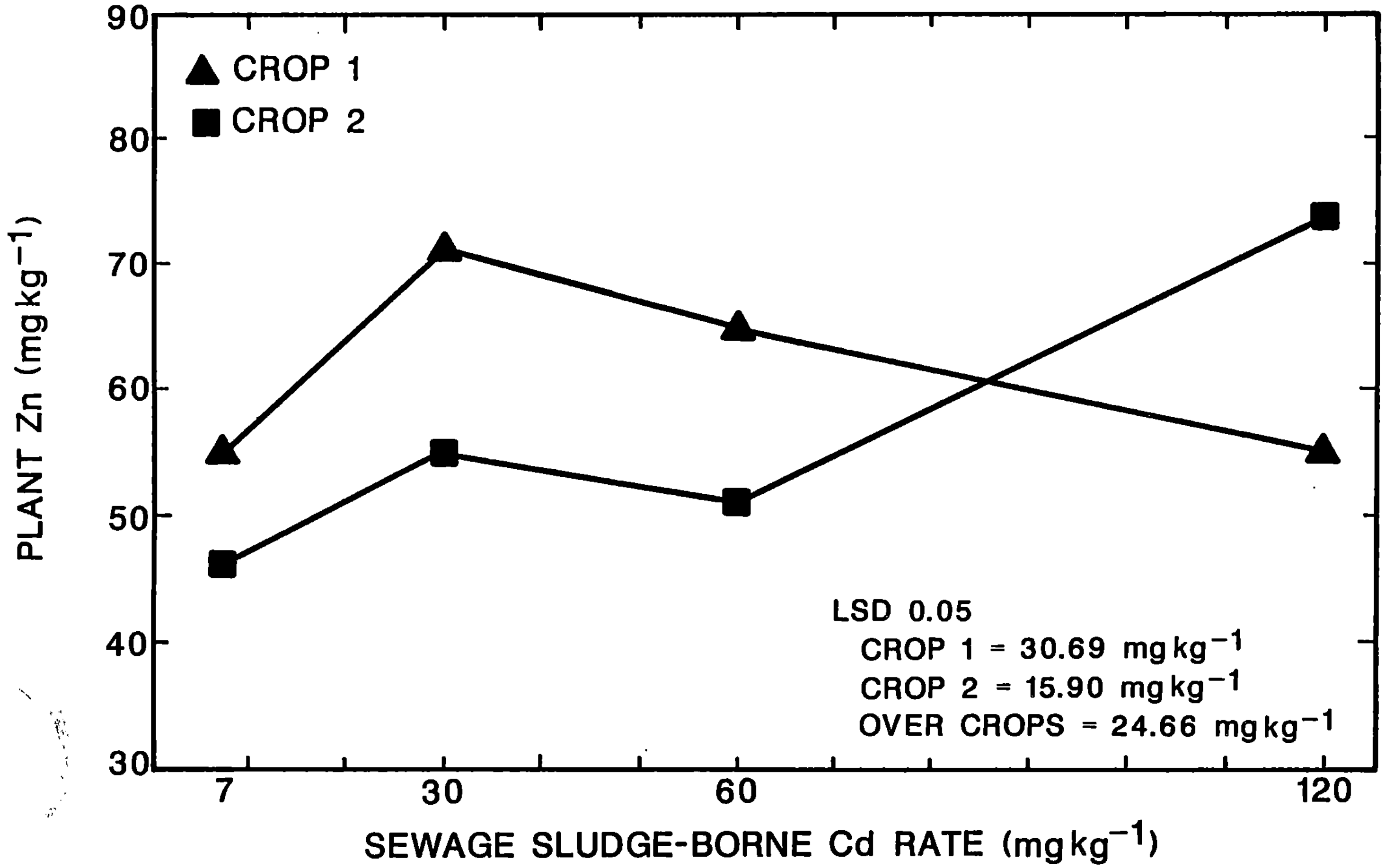

Figure 14. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (0-15 cm) on Zn Uptake by Two Successive Crops of Sorghum Plants on Teller Sandy Loam Soil

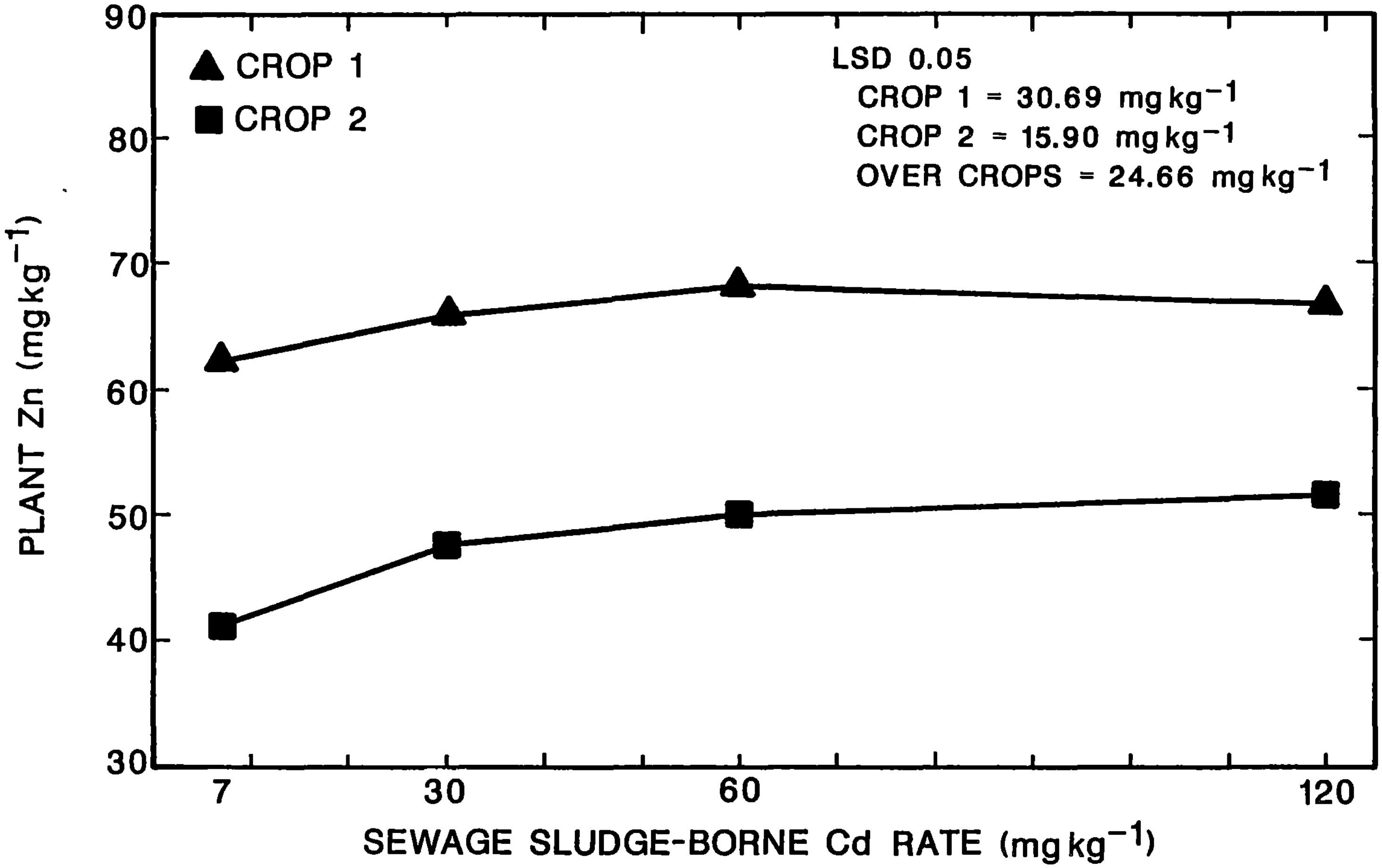

Figure 15. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (15-30 cm) on Zn Uptake by Two Successive Crops of Sorghum Plants on Teller Sandy Loam Soil

Although Cd uptake by soybean (Figures 16 and 17) and sorghum (Figures 18 and 19) in Teller soil increased with the increase in the level of Cd-containing sewage sludge, this increase was insignificant in both cases (Figures 16 to 19). The only exception was at depth of application one (0 to 15 cm), where crop two of sorghum showed significant differences among Cd levels (Figure 16). However, the interaction between Cd level and depth of application in soybean did affect Cd uptake which was higher in depth of application one (0 to 15 cm) than in depth of application two (15 to 30 cm) (Figures 16 and 17). This finding supports similar results previously obtained by Kirkham (1980). The Cd uptake in season one (crop one) was significantly higher than that in season two (crop two) (Figures 16 to 19). This difference between crop one and two in Cd uptake was encountered before with Fe uptake and the difference in both cases may have been due to the fact that crop one, but not crop two, received 112 kg ha^{-1} nitrogen as a fertilizer treatment which is known to increase plant growth with a subsequent increase in uptake of elements from soil (Giordano and Mortvedt, 1975). In addition, the 45 day incubation period that preceded crop one may have enhanced the decomposition of sewage sludge in the soil and made Cd more available to crop one leaving less Cd available to crop two, as suggested by Hinesly et al. (1976). However, this seems unlikely in itself for the highest Cd rates. Also, temperature and photoperiod (day length) differences between the two crops can-

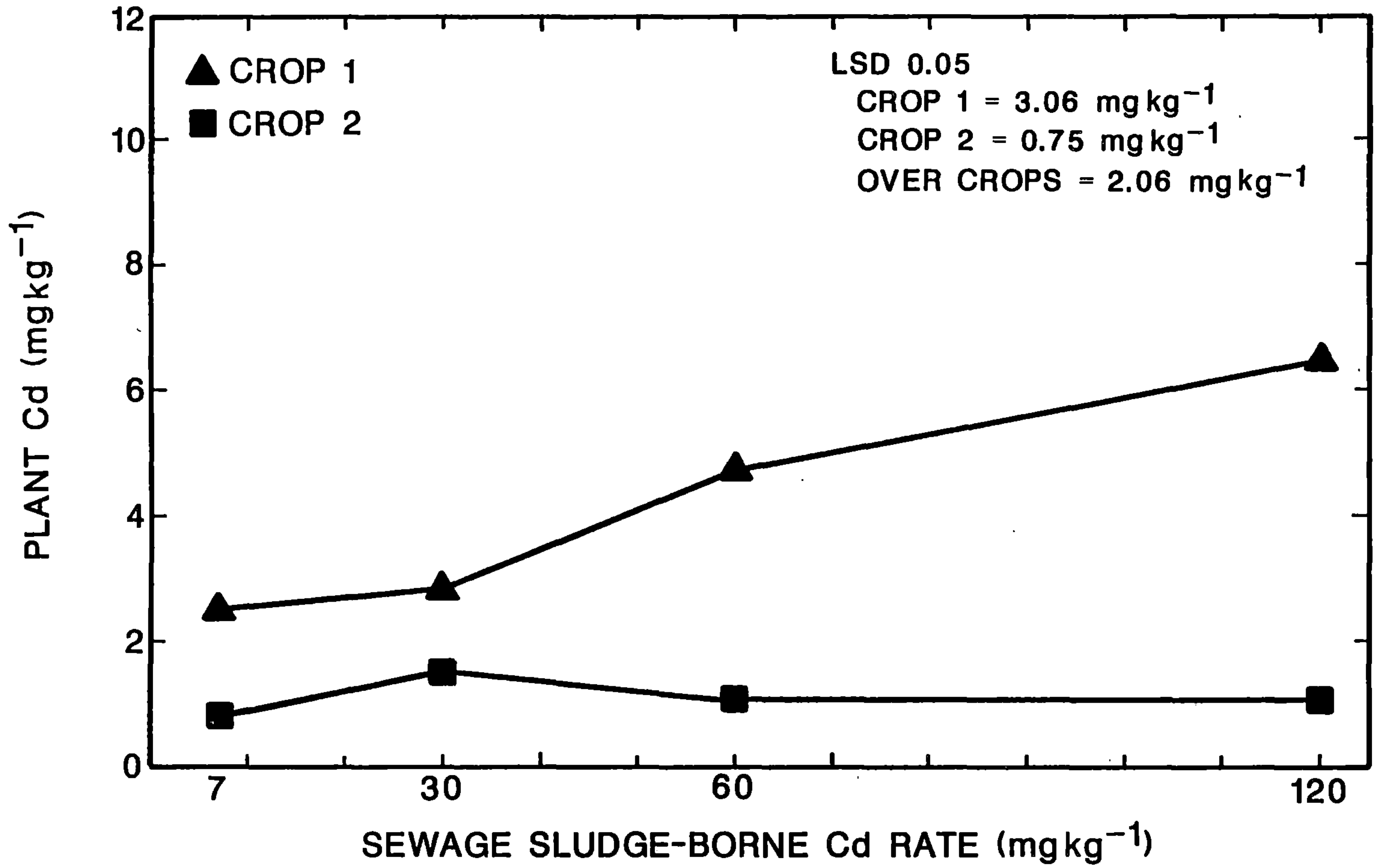

Figure 16. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (0-15 cm) on Cd Uptake by Two Successive Crops of Soybean Plants on Teller Sandy Loam Soil

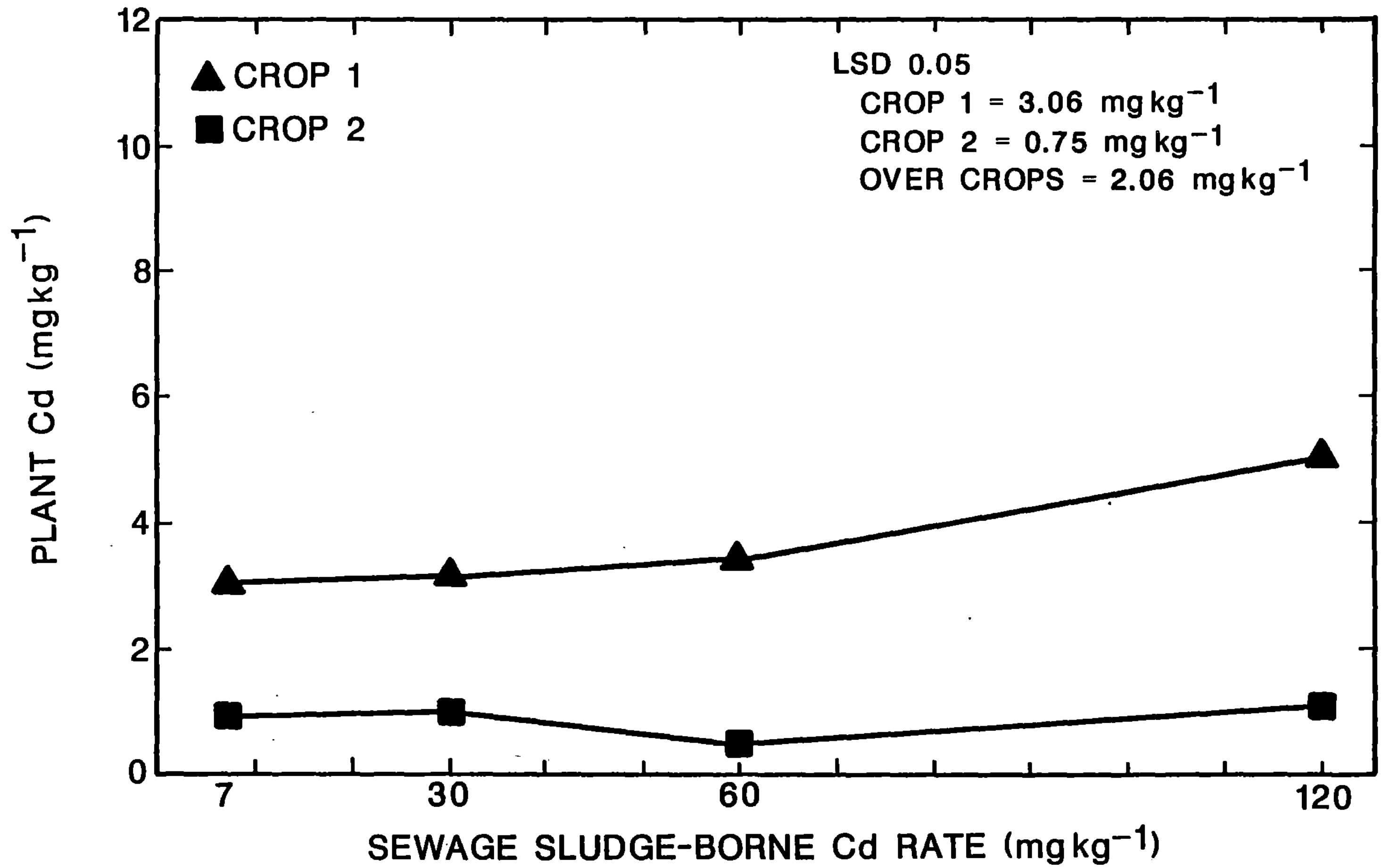

Figure 17. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (15-30 cm) on Cd Uptake by Two Successive Crops of Soybean Plants on Teller Sandy Loam Soil

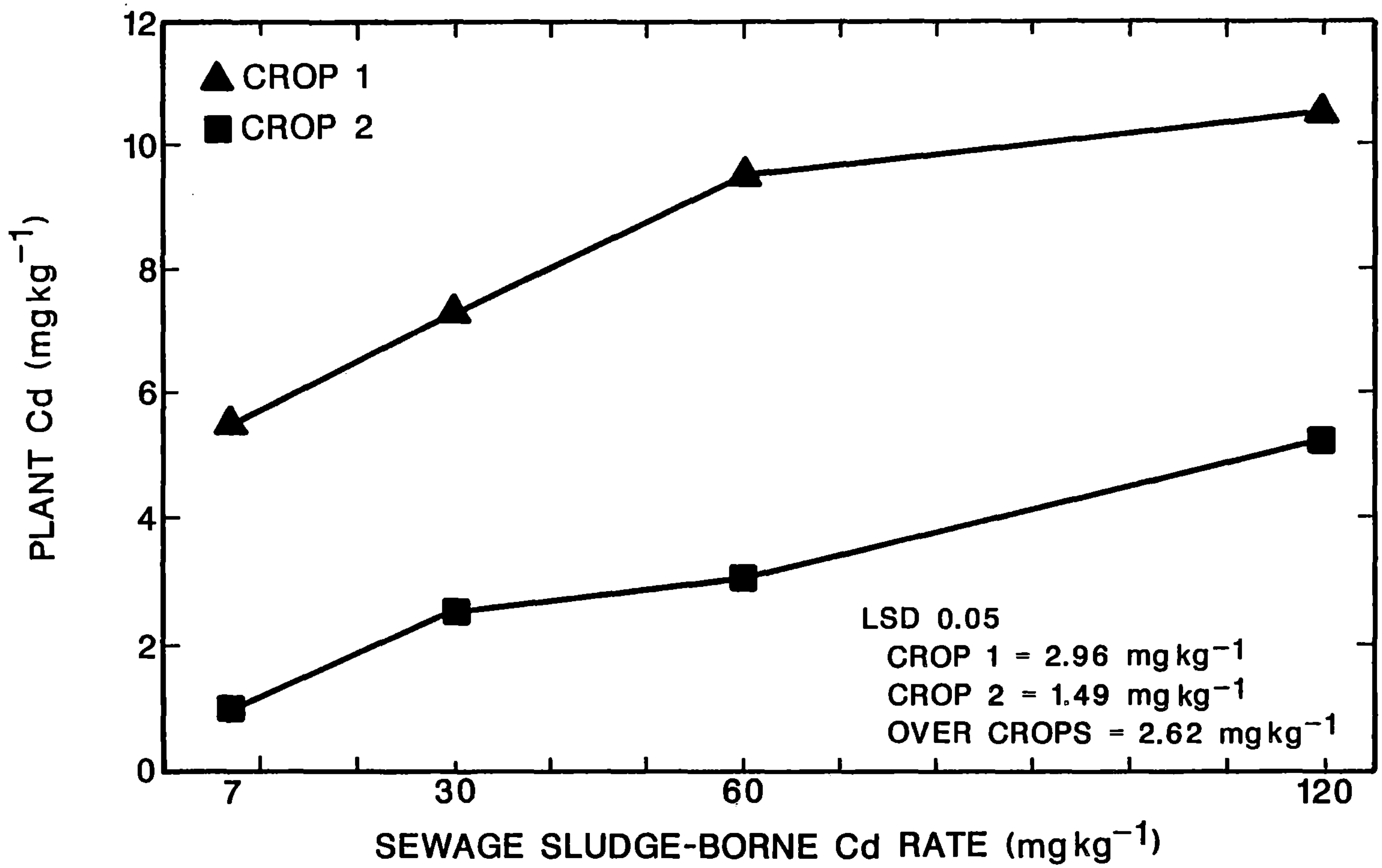

Figure 18. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (0-15 cm) on Cd Uptake by Two Successive Crops of Sorghum Plants on Teller Sandy Loam Soil

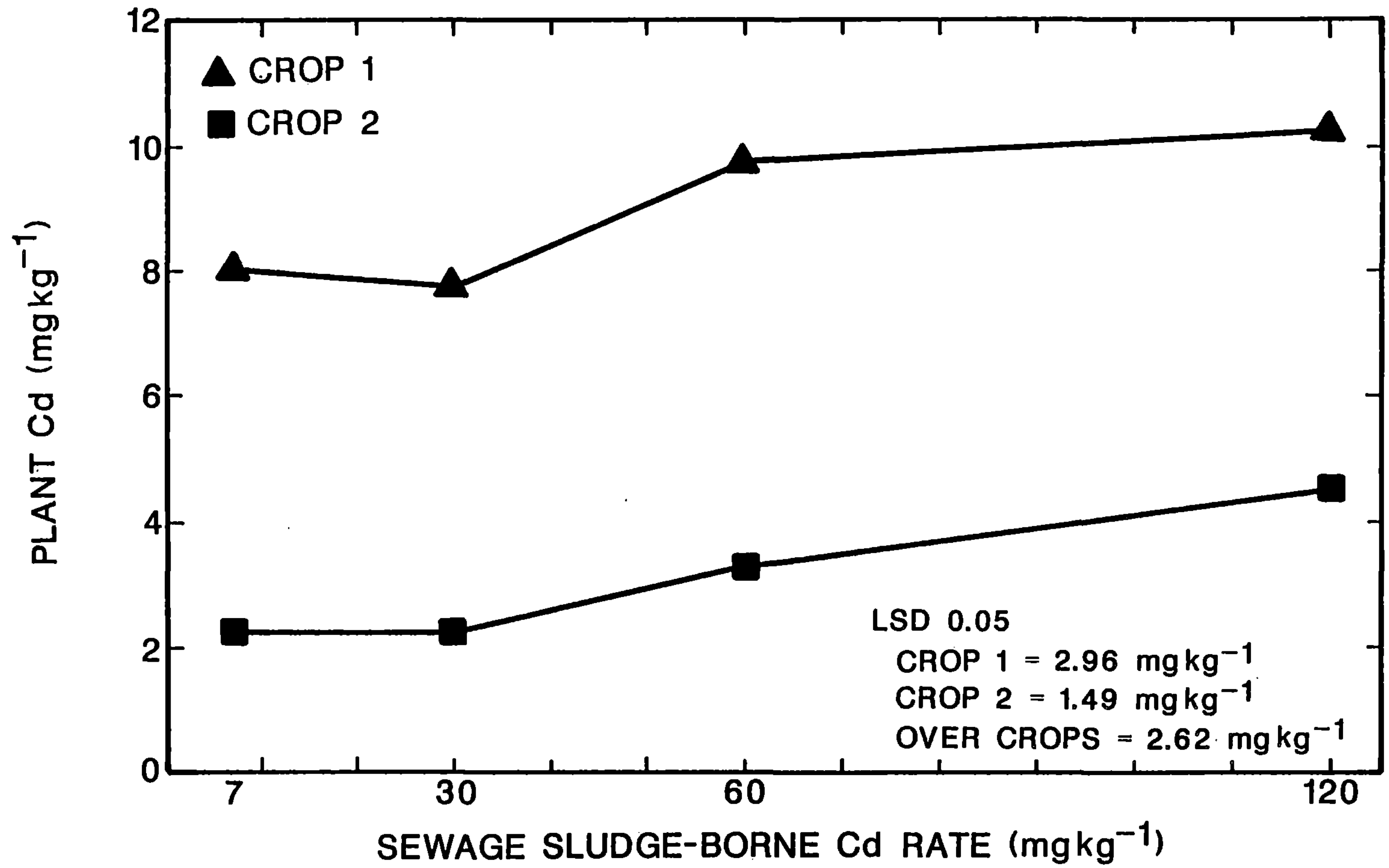

Figure 19. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (15-30 cm) on Cd Uptake by Two Successive Crops of Sorghum Plants on Teller Sandy Loam Soil

not be ignored. This possibility is supported by the finding that an increase in temperature (Haghiri, 1974) and photoperiod (Leonard and Martin,1963) could increase Cd uptake and plant growth, respectively.

A similar trend in Cd uptake by the two plant species was noticed with Norge loam soil, but no significance was observed among Cd treatments of crop two of sorghum with depth of application one in Teller sandy loam soil (Figures 16 and 18).

Plant uptake by both plant species in Norge loam soil was lower than that in Teller sandy loam soil, a probable result of the effects of soil texture (Appendix, Figures 52 to 55). This is suggested by the finding that the increase in clay content increases element retention in the soil (Kamprath and Watson, 1980; John, 1972a; Kiekens et al., 1984).

In general, Cd uptake by sorghum plants was significantly higher than that by soybean, a difference suspected of being due to genetic difference between the two plant species (Page et al., 1972; John, 1973; Turner, 1973; Lutrick et al., 1982).

While the increase in Cd level applied to the soil as a sewage sludge increased the soil content of Zn and Cd in the same direction, available Fe increased but its increase was not affected by the concentration of Cd-containing sewage sludge. This may be explained on the basis that Stillwater sludge had four times as much Fe as Tulsa sludge (Table

III), and the amount mixed with Tulsa sludge to obtain the desired Cd-concentration in the sludge mixture was higher at all concentrations used. The amounts of Stillwater sludge used ranged from 36.86 to 60 in the total 60 g sludge mixture (44 mt ha^{-1}) (Table IV). This increase in available metals did not have any significant effect on elements uptake by plants. This may have been caused by the relatively high soil pH values which are known to decrease the availability of heavy metals (Williams and David, 1976; Wallace et al., 1977; Oklahoma State Dept. of Health, 1983). Also, there is a possibility that application of sewage sludge which increased the organic matter content of soil (Figures 24 to 27; Appendix, Figures 60 to 63) with subsequent increase in the CEC and the number of chelating groups, resulted in fixation of the heavy metals (Leeper, 1972; Haghiri, 1974; Singh and Sekhon, 1977).

Soil Analysis

The soil analysis, for the two plant species, with depth is shown in Tables X and XI. The summary of the analysis of variance for Teller sandy loam soil and Norge loam soil is shown in Tables XII and XIII, respectively.

Soil pH

The original soil pH for Teller soil was 6.2. An addition of 2.2 mt ha^{-1} (one ton/acre) of ECCE was made to raise the soil pH to a value of 6.8 or above. The final soil pH

TABLE X

FINAL SOIL ANALYSIS IN TELLER SANDY LOAM AND NORGE LOAM SOILS OF SOYBEAN EXPERIMENT

							Available (mg kg^{-1})		
OBS	*DS	ST	DA	CdL	pH	OM%	Fe	Zn	Cd
1	1	0	0	0	7.17	1.26	13.56	5.57	0.39
2	1	0	0	1	7.27	1.11	11.46	6.35	0.69
3	1	0	0	2	7.27	0.95	19.55	8.15	1.08
4	1	0	0	3	7.22	1.49	22.85	9.48	1.62
5	1	0	1	0	7.03	0.83	14.97	1.39	0.40
6	1	0	1	1	7.38	0.96	19.65	2.47	0.27
7	1	0	1	2	7.37	1.06	10.82	2.38	0.39
8	1	0	1	3	7.24	0.79	15.32	1.51	0.35
9	1	1	0	0	7.37	1.26	41.84	5.29	0.87
10	1	1	0	1	7.37	1.34	39.19	5.46	0.84
11	1	1	0	2	7.56	1.42	34.38	1.59	0.93
12	1	1	0	3	7.40	1.85	51.64	8.49	2.26
13	1	1	1	0	7.59	1.19	42.02	1.25	0.69
14	1	1	1	1	7.63	1.28	39.35	1.08	0.53
15	1	1	1	2	7.64	1.04	45.61	2.12	0.52
16	1	1	1	3	7.57	1.38	35.67	1.72	0.65
17	2	0	0	0	6.95	0.80	9.88	1.25	0.52
18	2	0	0	1	6.96	0.95	12.18	0.64	0.15
19	2	0	0	2	7.04	0.82	19.13	1.35	0.27
20	2	0	0	3	6.93	0.89	15.58	2.39	0.50
21	2	0	1	0	6.66	1.18	19.35	6.65	0.54
22	2	0	1	1	6.84	1.40	22.56	7.90	0.60
23	2	0	1	2	6.81	1.26	18.36	7.79	1.17
24	2	0	1	3	6.83	1.25	17.27	8.65	2.01
25	2	1	0	0	7.32	1.40	47.44	2.06	0.82

TABLE X (Continued)

							Available (mg kg^{-1})		
OBS	*DS	ST	DA	CdL	pH	OM%	Fe	Zn	Cd
26	2	1	0	1	7.33	1.09	52.42	2.63	0.60
27	2	1	0	2	7.38	1.42	11.26	2.71	0.86
28	2	1	0	3	7.35	1.36	13.14	2.38	0.64
29	2	1	1	0	7.36	1.54	14.07	4.97	0.77
30	2	1	1	1	7.40	1.50	13.47	4.68	0.72
31	2	1	1	2	7.27	1.51	18.48	7.02	1.27
32	2	1	1	3	7.37	1.54	14.05	7.64	2.14
33	3	0	0	0	7.04	0.82	9.26	0.26	0.25
34	3	0	0	1	6.98	0.89	9.59	1.52	0.35
35	3	0	0	2	7.17	0.92	12.72	2.29	0.31
36	3	0	0	3	7.01	0.84	10.17	0.78	0.35
37	3	0	1	0	7.00	1.13	20.40	6.41	0.47
38	3	0	1	1	7.04	1.29	19.26	5.70	0.49
39	3	0	1	2	7.00	1.26	19.19	7.90	1.13
40	3	0	1	3	6.96	1.14	19.91	8.87	1.70
41	3	1	0	0	7.27	1.31	9.54	1.25	0.62
42	3	1	0	1	7.20	1.08	8.27	0.42	0.60
43	3	1	0	2	7.38	1.30	10.30	2.33	0.69
44	3	1	0	3	7.37	1.00	7.86	0.00	0.24
45	3	1	1	0	7.27	1.74	15.17	6.32	0.97
46	3	1	1	1	7.33	1.55	14.26	5.46	0.60
47	3	1	1	2	7.29	1.72	14.76	4.85	1.12
48	3	1	1	3	7.40	1.48	12.90	7.21	1.76

*DS = Depth of sampling
1 = 0 - 7.5 cm
2 = 7.5 - 15 cm
3 = 15 - 30 cm

ST = Soil type
0 = Teller sandy loam
1 = Norge loam

DA = Depth of application
0 = 1 - 15 cm
1 = 15 - 30 cm

CdL = Sewage sludge-borne Cd
0 = 7 mg kg^{-1}
1 = 30 mg kg^{-1}
2 = 60 mg kg^{-1}
3 = 120 mg kg^{-1}

TABLE XI

FINAL SOIL ANALYSIS IN TELLER SANDY LOAM AND NORGE LOAM SOILS OF SORGHUM EXPERIMENT

							Available (mg kg^{-1})		
OBS	*DS	ST	DA	CdL	pH	OM%	Fe	Zn	Cd
1	1	0	0	0	7.31	1.20	13.53	5.67	0.43
2	1	0	0	1	7.19	1.19	13.97	7.02	0.42
3	1	0	0	2	7.25	1.13	16.47	9.70	0.80
4	1	0	0	3	7.07	1.16	14.63	10.35	1.12
5	1	0	1	0	7.41	0.73	7.64	1.88	0.30
6	1	0	1	1	7.30	0.82	10.14	3.29	0.40
7	1	0	1	2	7.33	0.82	5.91	1.79	0.30
8	1	0	1	3	7.29	0.82	6.96	1.93	0.31
9	1	1	0	0	7.51	1.61	9.26	4.77	0.41
10	1	1	0	1	7.56	1.68	13.76	7.27	0.66
11	1	1	0	2	7.61	1.50	8.89	7.39	0.93
12	1	1	0	3	7.56	1.80	10.15	9.77	1.40
13	1	1	1	0	7.86	1.13	2.25	0.00	0.37
14	1	1	1	1	7.58	1.25	5.97	1.81	0.57
15	1	1	1	2	7.68	1.34	5.03	1.97	0.67
16	1	1	1	3	7.70	1.19	3.99	1.38	0.57
17	2	0	0	0	7.13	0.78	8.01	2.84	0.44
18	2	0	0	1	7.03	0.76	6.84	1.20	0.31
19	2	0	0	2	7.11	0.79	8.48	0.95	0.26
20	2	0	0	3	6.98	0.80	5.73	2.36	0.56
21	2	0	1	0	7.03	1.13	15.02	7.03	0.41
22	2	0	1	1	7.01	1.35	17.71	8.00	0.56
23	2	0	1	2	6.93	1.27	16.05	9.17	0.68
24	2	0	1	3	6.98	1.41	18.14	11.19	1.33
25	2	1	0	0	7.54	1.20	5.37	0.93	0.43

TABLE XI (Continued)

OBS	*DS	ST	DA	CdL	pH	OM%	Available (mg kg^{-1}) Fe	Zn	Cd
26	2	1	0	1	7.57	1.23	3.38	0.70	0.53
27	2	1	0	2	7.50	1.09	4.70	1.76	0.57
28	2	1	0	3	7.56	1.24	3.10	1.19	0.49
29	2	1	1	0	7.56	1.70	11.19	5.89	0.53
30	2	1	1	1	7.44	1.33	8.62	3.86	0.52
31	2	1	1	2	7.44	1.55	10.29	6.82	0.81
32	2	1	1	3	7.52	1.42	8.38	8.24	1.35
33	3	0	0	0	7.22	0.86	6.82	0.91	0.60
34	3	0	0	1	7.11	0.88	6.49	1.76	0.28
35	3	0	0	2	7.19	0.59	8.30	1.25	0.36
36	3	0	0	3	7.15	0.81	4.03	0.92	0.42
37	3	0	1	0	7.00	1.26	13.09	6.12	0.35
38	3	0	1	1	7.13	1.12	12.58	7.11	0.50
39	3	0	1	2	6.94	1.15	15.48	7.68	0.62
40	3	0	1	3	6.94	1.55	17.72	12.73	1.68
41	3	1	0	0	7.48	1.20	5.07	0.85	0.50
42	3	1	0	1	7.60	1.18	1.54	0.24	0.52
43	3	1	0	2	7.47	1.08	3.79	0.85	0.52
44	3	1	0	3	7.60	1.25	1.68	0.01	0.35
45	3	1	1	0	7.51	1.54	10.97	5.48	0.70
46	3	1	1	1	7.39	1.72	10.23	6.61	0.57
47	3	1	1	2	7.45	1.74	10.37	5.74	0.94
48	3	1	1	3	7.43	1.62	8.79	8.11	1.17

*DS = Depth of sampling
1 = 0 - 7.5 cm
2 = 7.5 - 15 cm
3 = 15 - 30 cm

ST = Soil type
0 = Teller sandy loam
1 = Norge loam

DA = Depth of application
0 = 1 - 15 cm
1 = 15 - 30 cm

CdL = Sewage sludge-borne Cd
0 = 7 mg kg^{-1}
1 = 30 mg kg^{-1}
2 = 60 mg kg^{-1}
3 = 120 mg kg^{-1}

TABLE XII

SUMMARY OF ANALYSIS OF VARIANCE FOR THE FINAL SOIL ANALYSIS IN TELLER SANDY LOAM AND NORGE LOAM SOILS FOR SOYBEAN EXPERIMENT

Variable		ST* F	ST* OSL	DA F	DA OSL	ST*DA F	ST*DA OSL	CdL F	CdL OSL	ST*CdL F	ST*CdL OSL	DA*CdL F	DA*CdL OSL	St*DA*CdL F	St*DA*CdL OSL	EMS	DF
	DS1	29.22	0.0001**	4.72	0.0378	3.01	0.929	20.39	0.0999	0.78	0.5158	0.040	0.753	0.64	0.592	0.0268	30
pH	DS2	167.24	0.0001**	6.42	0.0167*	7.68	0.0095**	0.62	0.6104	0.74	0.5356	1.05	0.03834	0.50	0.684	0.014	30
	DS3	82.45	0.0001**	6.37	0.5501	1.24	0.2735	1.21	0.3223	1.55	0.02231	20.37	0.0903	0.03	0.9930	0.0107	30
	DS1	22.91	0.0001**	21.87	0.0001**	0.20	0.6605	4.41	0.0111**	10.33	0.02819	3.73	0.0217*	20.39	0.0888	0.0391	30
Om	DS2	250.19	0.0001**	20.76	0.0001**	2.50	0.1241	0.04	0.9871	10.44	0.02509	0.037	0.7719	0.025	0.8581	0.0533	30
	DS3	22.06	0.0001**	29.05	0.0001**	0.73	0.4005	1.17	0.03373	10.012	0.03578	0.04	0.9898	0.02	0.9954	0.0630	30
	DS1	4.74	0.0374	74.15	0.0001**	0.78	0.3847	0.50	0.6839	1.07	0.03769	0.98	0.0426	0.69	0.564	8.533	30
Fe	DS2	20.95	0.0001**	79.27	0.0001**	27.32	0.0001**	0.56	0.645	30.019	0.0377*	0.45	0.7193	2.76	0.0596	6.747	30
	DS3	26.83	0.0001**	132.57	0.0001**	10.76	0.0026**	1.28	0.02989	0.53	0.6648	1.02	0.03981	0.032	0.8105	4.707	30
	DS1	6.09	0.0195*	83.89	0.0001**	3.49	0.0716	3.12	0.0405*	20.35	0.0918	40.011	0.0148*	20.018	0.01116	2.925	30
Zn	DS2	0.48	0.04923	132.03	0.0001**	10.53	0.0029**	2.65	0.0669	0.024	0.8679	0.69	0.5657	1.06	0.03794	20.227	30
	DS3	20.19	00.01493	129.75	0.0001**	1.21	0.2792	1.12	0.03559	0.87	0.04688	2.01	0.0566*	0.67	0.5781	2.753	30
	DS1	12.49	0.0014**	72.81	0.0001**	0.05	0.8229	18.09	0.0001**	2.39	0.0888	17.01	0.0001**	0.95	0.4300	0.0603	30
Cd	DS2	4.85	0.0355*	29.53	0.0001**	1.07	0.309	10.10	0.0001**	0.17	0.9157	8.89	0.0002**	0.25	0.8620	0.147	30
	DS3	5.03	0.0325*	54.60	0.0001**	0.11	0.7377	7.97	0.0005**	1.30	0.2942	13.71	0.0001**	0.58	0.6352	0.0792	30

*ST = Soil type
DA = Depth of application
CdL = Soil-applied cadmium
EMS = Error mean square

DF = Degree of freedom
OSL = Observed Statistical Level
* Significance at 0.05 level
** Significance at 0.01 level

TABLE XIII

SUMMARY OF ANALYSIS OF VARIANCE FOR THE FINAL SOIL ANALYSIS IN TELLER SANDY LOAM AND NORGE LOAM SOILS FOR SORGHUM EXPERIMENT

Variable		ST*		DA		ST*DA		CdL		ST*CdL		DA*CdL		ST*DA*CdL		EMS	DF
		F	OSL	F	OSL	F	OSL	F	OSL	F	OSL	F	OSL	F	OSL		
	DS1	114.73	0.0001**	16.32	0.0003**	0.09	0.7617	2.62	0.0686	0.74	0.5391	1.31	0.2890	1.42	0.2546	0.014	30
pH	DS2	378.27	0.0001**	9.19	0.0050**	0.86	0.3618	1.18	0.333	1.73	0.1825	1.84	0.1607	2.29	0.0980	0.0073	30
	DS3	216.45	0.0001**	14.61	0.0006**	0.42	0.5212	1.72	0.1833	0.77	0.5219	0.94	0.4313	2.92	0.0501	0.010	30
	DS1	96.55	0.0001**	72.74	0.0001**	0.21	0.647	0.58	0.6353	0,21	0.8920	1.41	0.2590	0.83	0.4903	0.0258	30
OM	DS2	34.46	0.0001**	62.18	0.0001**	3.62	0.066	0.21	0.891	1.49	0.2384	0.22	0.879	2.14	0.1156	0.032	30
	DS3	50.29	0.0001**	77.07	0.0001**	0.00	0.994	1.50	0.235	1.41	0.2597	1.17	0.3381	1.68	0.1921	0.036	30
	DS1	36.94	0.0001**	114.79	0.0001**	0.41	0.5282	3.71	0.0222*	0.84	0.4825	0.25	0.8641	3.39	0.0308	4.549	30
Fe	DS2	92.27	0.0001**	196.93	0.0001**	13.96	0.0008**	1.01	0.4019	1.81	0.1658*	1.22	0.3201	1.80	0.1691	3.405	30
	DS3	34.30	0.0001**	126.12	0.0001**	0.82	0.373	1.43	0.253	1.38	0.2693	1.90	0.1512	1.97	0.1400	5.62	30
	DS1	7.75	0.0092**	267.94	0.0001**	0.17	0.6820	12.30	0.0001**	0.70	0.5601	5.71	0.0033**	1.93	0.1463	1.675	30
Zn	DS2	16.08	0.0001**	210.54	0.0001**	5.54	0.0254*	5.41	0.0043**	0.68	0.5733	3.49	0.027*	1.41	0.258	2.074	30
	DS3	5.65	0.0241*	140.40	0.0001**	1.16	0.289	2.63	0.0684	0.85	0.4794	4.16	0.0141	0.78	0.5142	3.722	30
	DS1	28.15	0.0014**	91.96	0.0001**	0.71	0.0405	34.25	0.0001**	2.69	0.0638	25.72	0.0001**	1.02	0.3987	0.0147	30
Cd	DS2	2.58	0.1190*	38.94	0.0001**	0.30	0.589	18.05	0.0001**	1.00	0.405	11.13	0.0001**	0.85	0.475	0.32	30
	DS3	0.47	0.499*	19.29	0.0001**	0.00	0.9817	5.13	0.0055**	1.98	0.1379	7.78	0.0005*	1.28	0.2977	0.086	30

*ST=Soil type
DA=Depth of application
CdL=Soil applied Cadmium
EMS=Error mean square
DF=Degree of freedom

*Significance at 0.05 level
**Significance at 0.01 level

was found to be 7.0 ± 0.4. For both plant species, the application of sewage sludge containing Cd did not affect soil pH except at sampling depth one (0 to 7.5 cm) (Tables XII and XIII) where the pH value was significantly higher than that at sampling depth two (Figures 20 to 23). The decomposition of organic matter (OM) by the micro-organisms could have been more active at the surface than in the subsurface with a possible release of some cations such as Ca, Mg, and K, which, in turn, could have resulted in the observed increase in the soil pH (Kirkham, 1980). There was no significant difference among the pH values of the three depths of sampling in the four treatments of Cd in either surface or subsurface applications.

When Norge loam soil was investigated with both plant species, the final soil pH was found to be directly related to the soil type (Tables XII and XIII). The same soil pH result was obtained for Norge loam soil as was found for Teller sandy loam, except the pH was slightly higher for the Norge soil (Figures 20 to 23 and Appendix, Figures 56 to 59).

Organic Matter

For both plant species, the OM% , which increased at the end of the experiment in Teller soil in the zone of sewage sludge application, was affected by depth of application (Tables XII and XIII and Figures 24 to 27). The OM% increased in sampling depth one (0 to 7.5 cm) when sludge

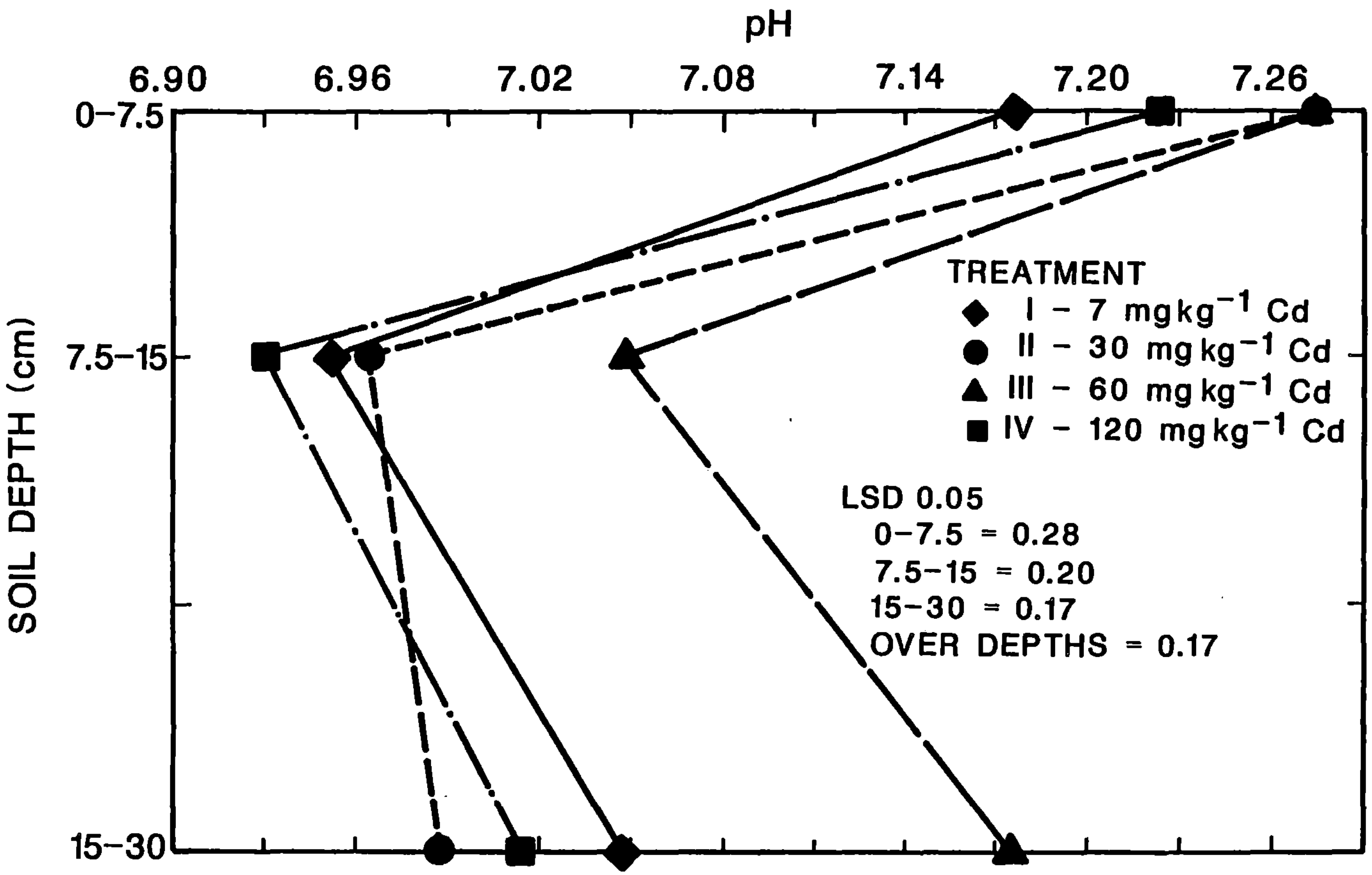

Figure 20. Soybean Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Surface Depth of Application (0-15 cm) on Final Soil pH of Teller Sandy Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

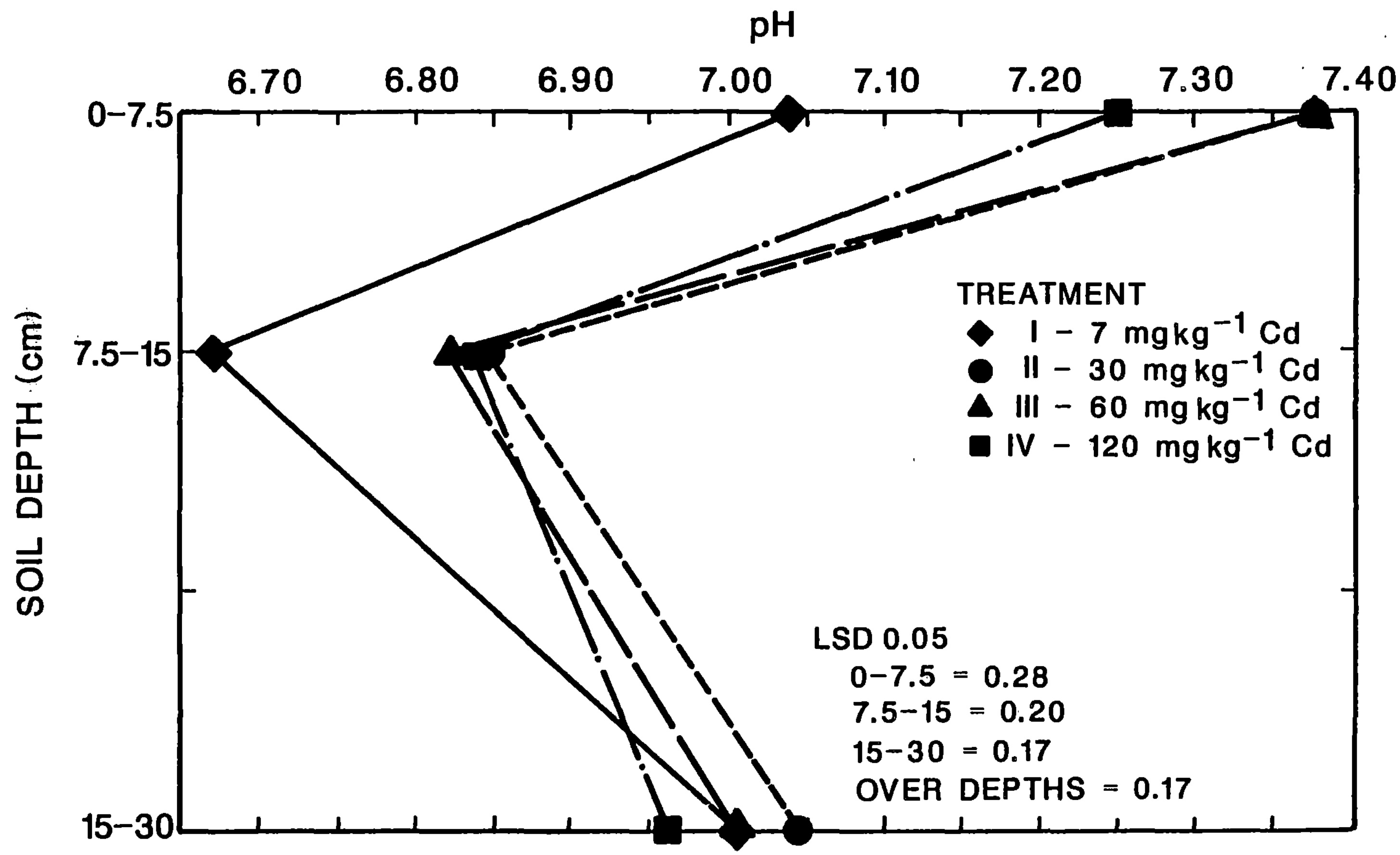

Figure 21. Soybean Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Subsurface Depth of Application (15-30 cm) on Final Soil pH of Teller Sandy Loam soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

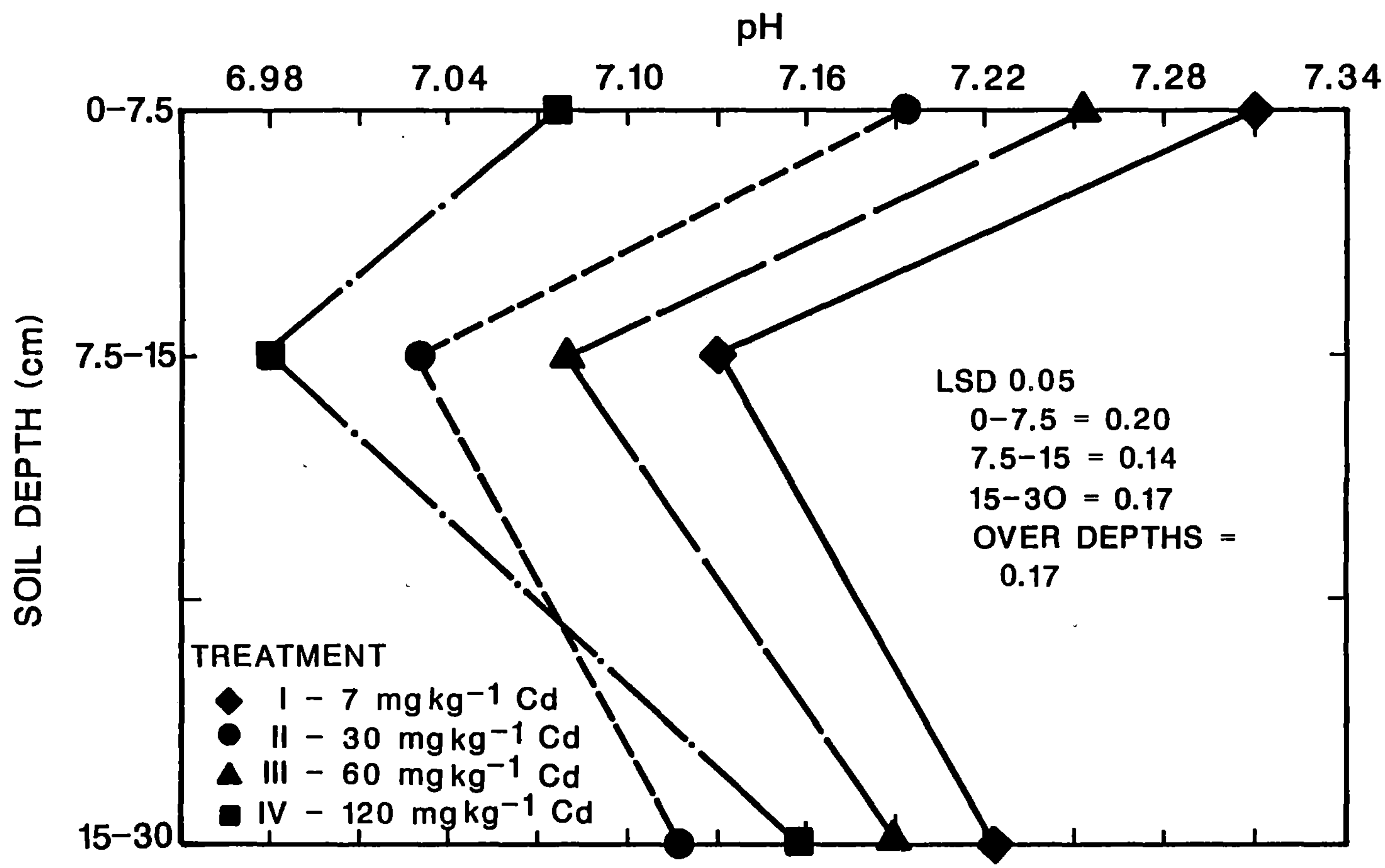

Figure 22. Sorghum Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Surface Depth of Application (0-15 cm) on Final Soil pH of Teller Sandy Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha $^{-1}$ for all Treatments)

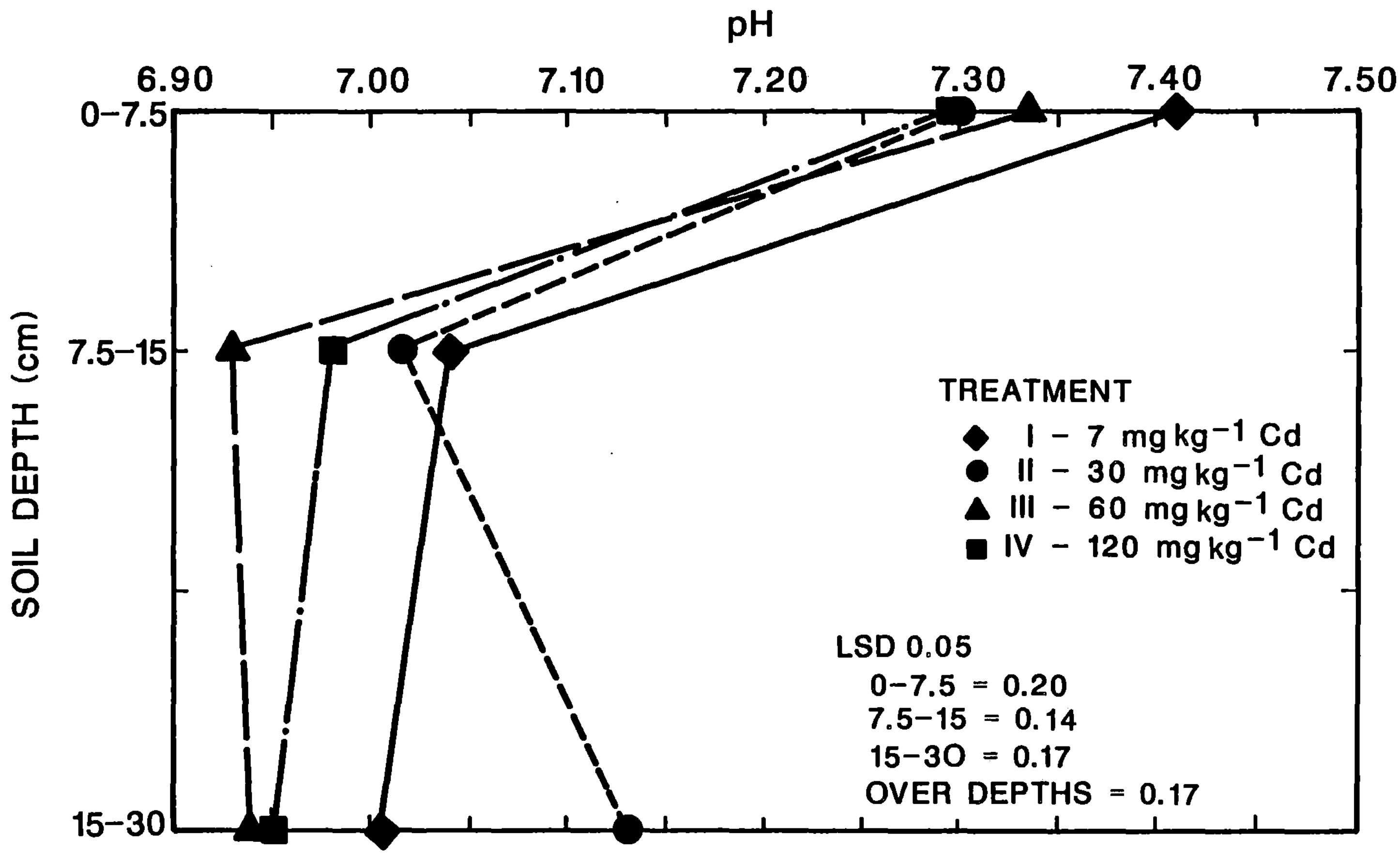

Figure 23. Sorghum Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Subsurface Depth of Application (15 to 30 cm) on Final Soil pH of Teller Sandy Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge RAte was 44 mt ha^{-1} for all Treatments)

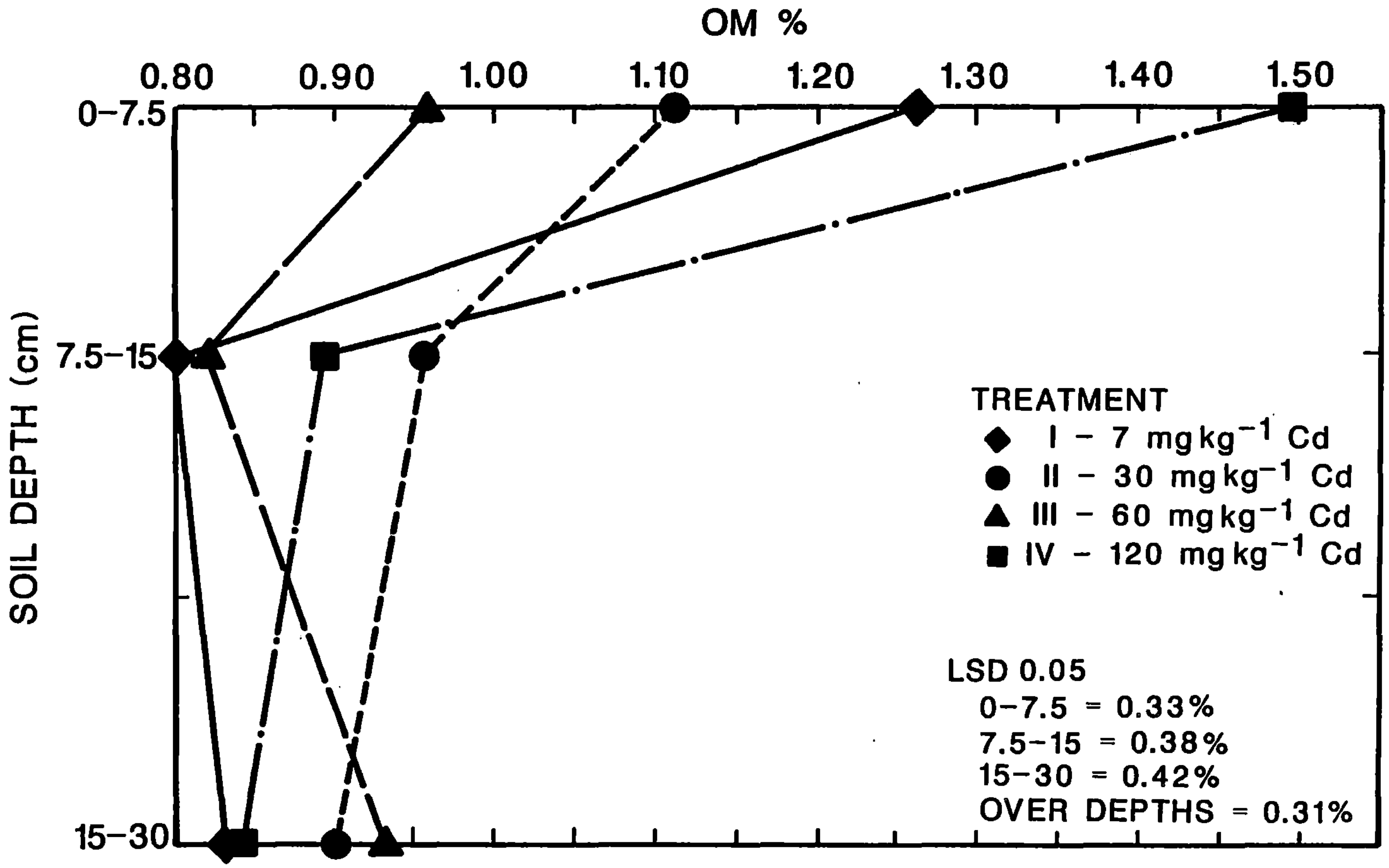

Figure 24. Soybean Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Surface Depth of Application (0-15 cm) on Final OM% of Teller Sandy Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

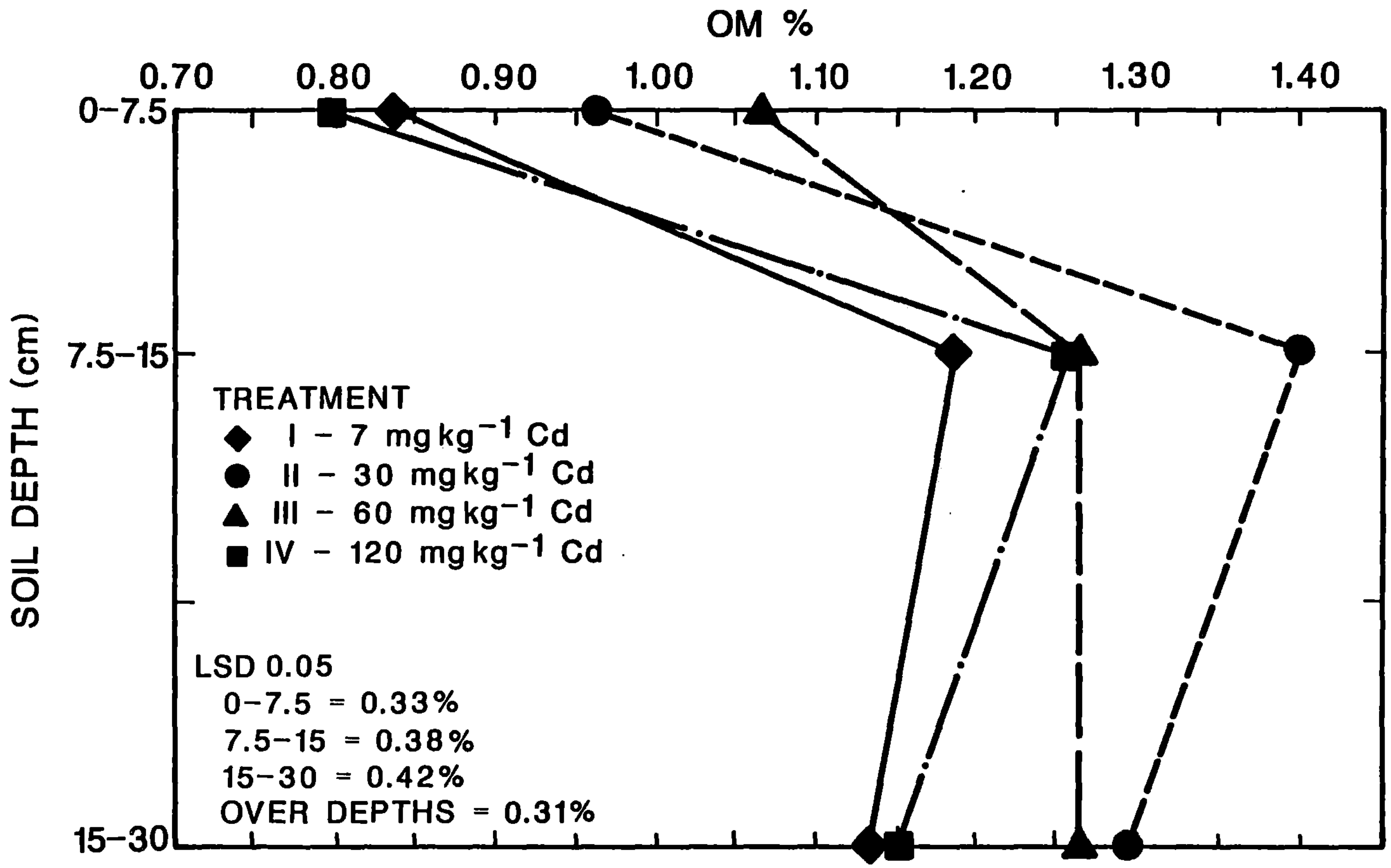

Figure 25. Soybean Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Subsurface Depth of Application (15-30 cm) on Final OM% of Teller Sandy Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

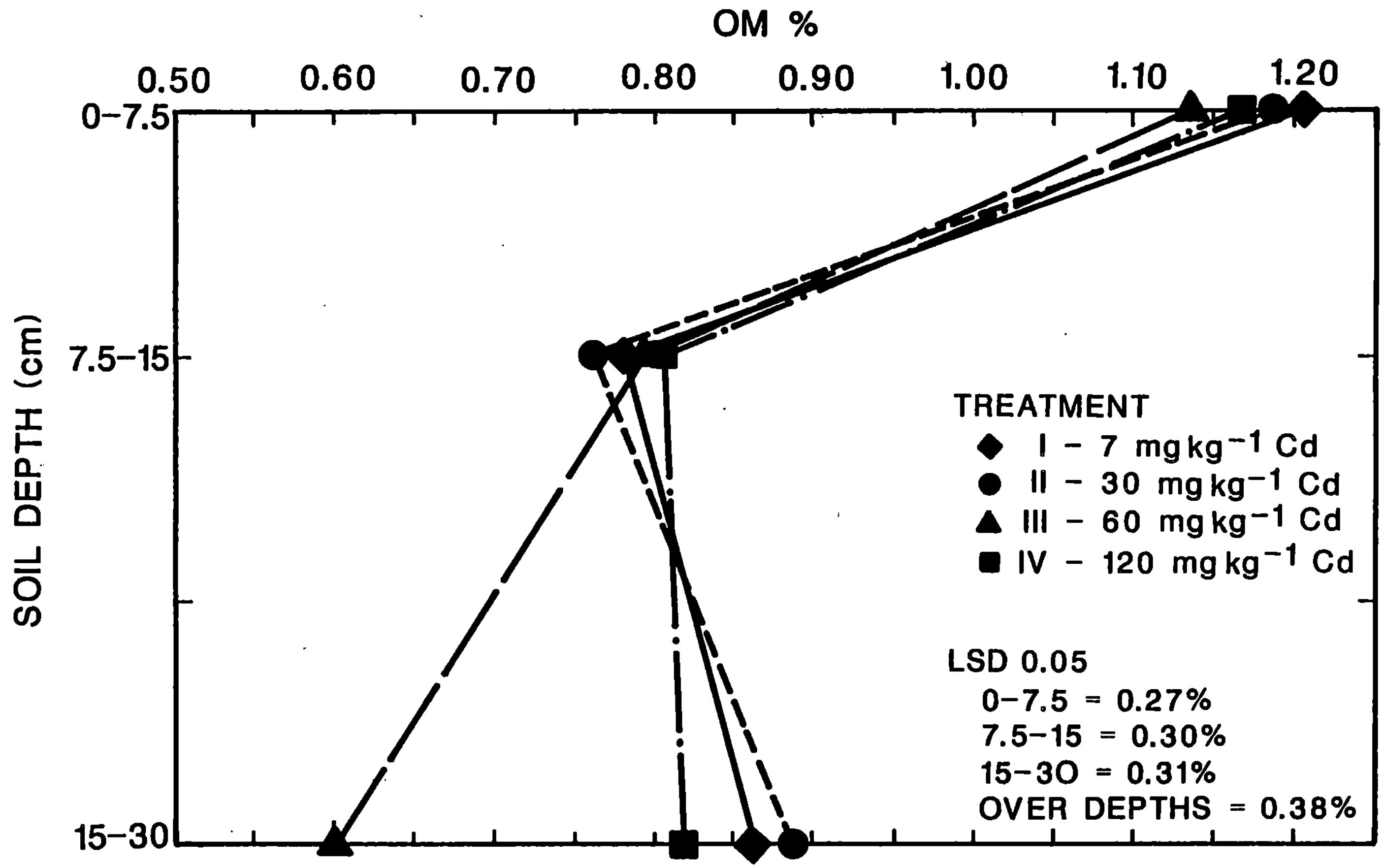

Figure 26. Sorghum Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Surface Depth of Application (0-15 cm) on Final OM% of Teller Sandy Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

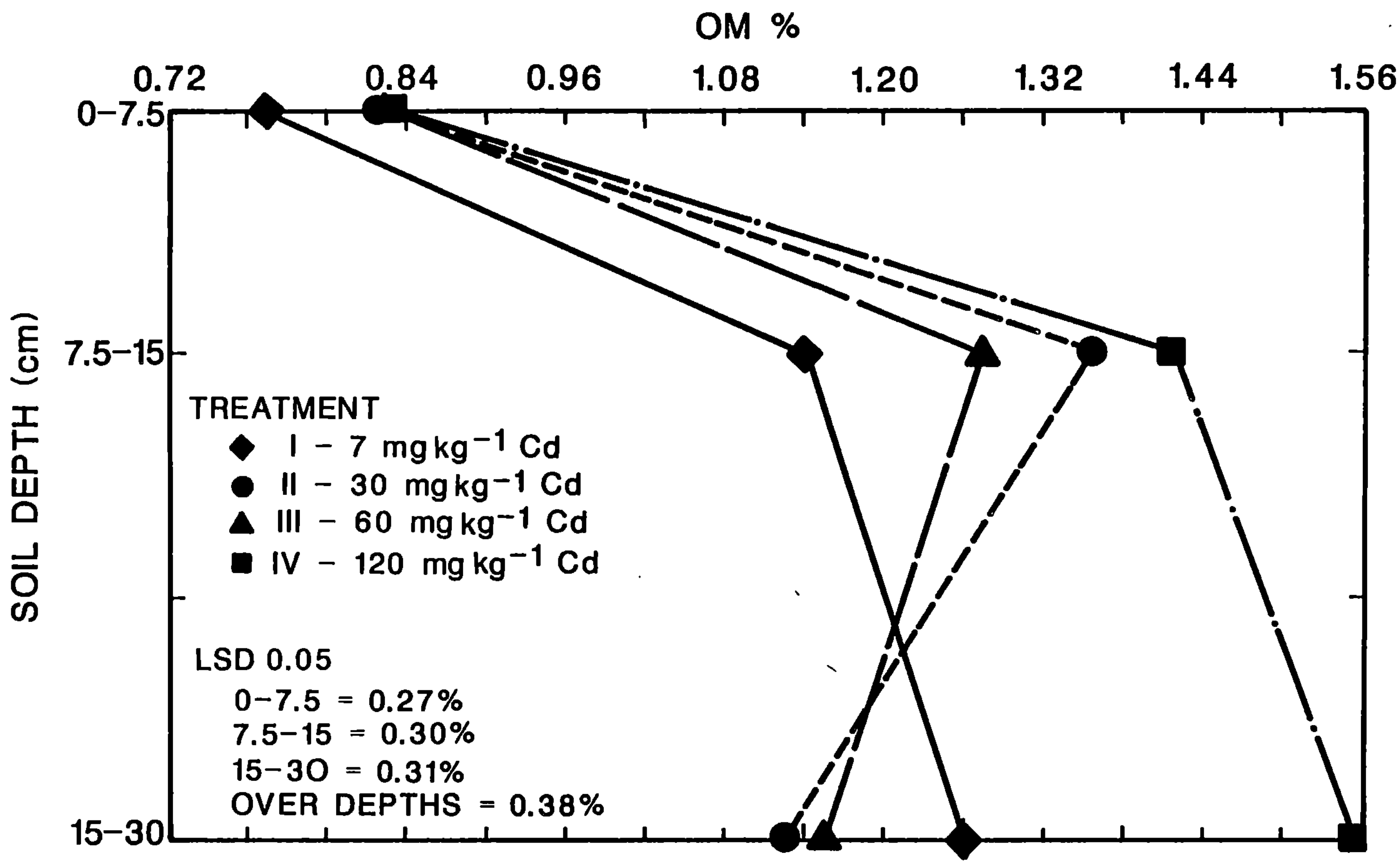

Figure 27. Sorghum Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Subsurface Depth of Application (15-30 cm) on Final OM% of Teller Sandy Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

was incorporated in the surface soil (0 to 15 cm) (Figures 24 and 26) and in sampling depth two (7.5 to 15 cm) when sludge was introduced into the subsurface soil (15 to 30 cm) (Figures 25 and 27). The increase in OM in both cases is probably due to a high density of root growth promoted by the incorporated sludges (Kirkham, 1980; Lund, 1978). This increase seems to have been an additive effect of the two successive crops. Of the four treatments, treatment IV (120 mg kg^{-1} Cd) had the highest OM content in sampling depth one (0 to 7.5 cm) of surface soil (0 to 15 cm) (Figures 24 and 26). The higher concentration of Cd in this treatment may have reduced the micro organisms decomposing activity at the surface. However, no significant differences were observed among the four treatments when sewage sludge was applied to the subsurface (Tables XII and XIII). The OM% was higher in Norge loam soil than in Teller sandy loam soil (Appendix, Figures 60 to 63; Figures 24 to 27). This difference may have been due to a higher original OM% of the Norge loam soil as compared to the Teller sandy loam soil (Table II).

Distribution and Movement of Elements

The availability (DTPA extractable) of Zn and Cd increased significantly with the increase in the concentration of Cd-containing sewage sludge (Tables XII and XIII). Available Fe increased in the soil as a result of sludge application but its increase in the soil was not affected by level of Cd-containing sewage sludge. The availability of the three elements was affected by soil type and depth of application (Tables XII and XIII). The direction of movement of Zn, Cd, and Fe, in the soil, whether sludge was applied in the surface or the subsurface, was always upwards with no downward movement observed. The pattern of distribution of Fe, Zn, and Cd was identical to that of organic matter. In the following, the results corresponding to each element will be presented, followed by a discussion of the findings reported.

Available Fe

For the two plant species, available Fe in the soil was significantly affected by soil type and depth of application but not by the concentration of Cd-containing sewage sludge (Tables XII and XIII). The higher concentration of Fe in Teller soil was detected in sampling depth one (0 to 7.5 cm) for the surface depth of application (0 to 15 cm) (Figures 28 and 29), and in sampling depth two (7.5 to 15 cm) for the subsurface depth of application 15 to 30 cm (Figures 30 and 31). The availability of Fe was not affected by the concentration of Cd-containing sewage sludge. This is not surprising because Stillwater sludge had four times as much Fe as Tulsa sludge (Table III), and the amount mixed with Tulsa sludge to obtain the desired Cd-concentration in the sludge mixture was higher at all concentrations used.

Available Fe was less in Norge loam soil (Appendix, Figures 64 to 67) than in Teller sandy loam soil (Figures 28

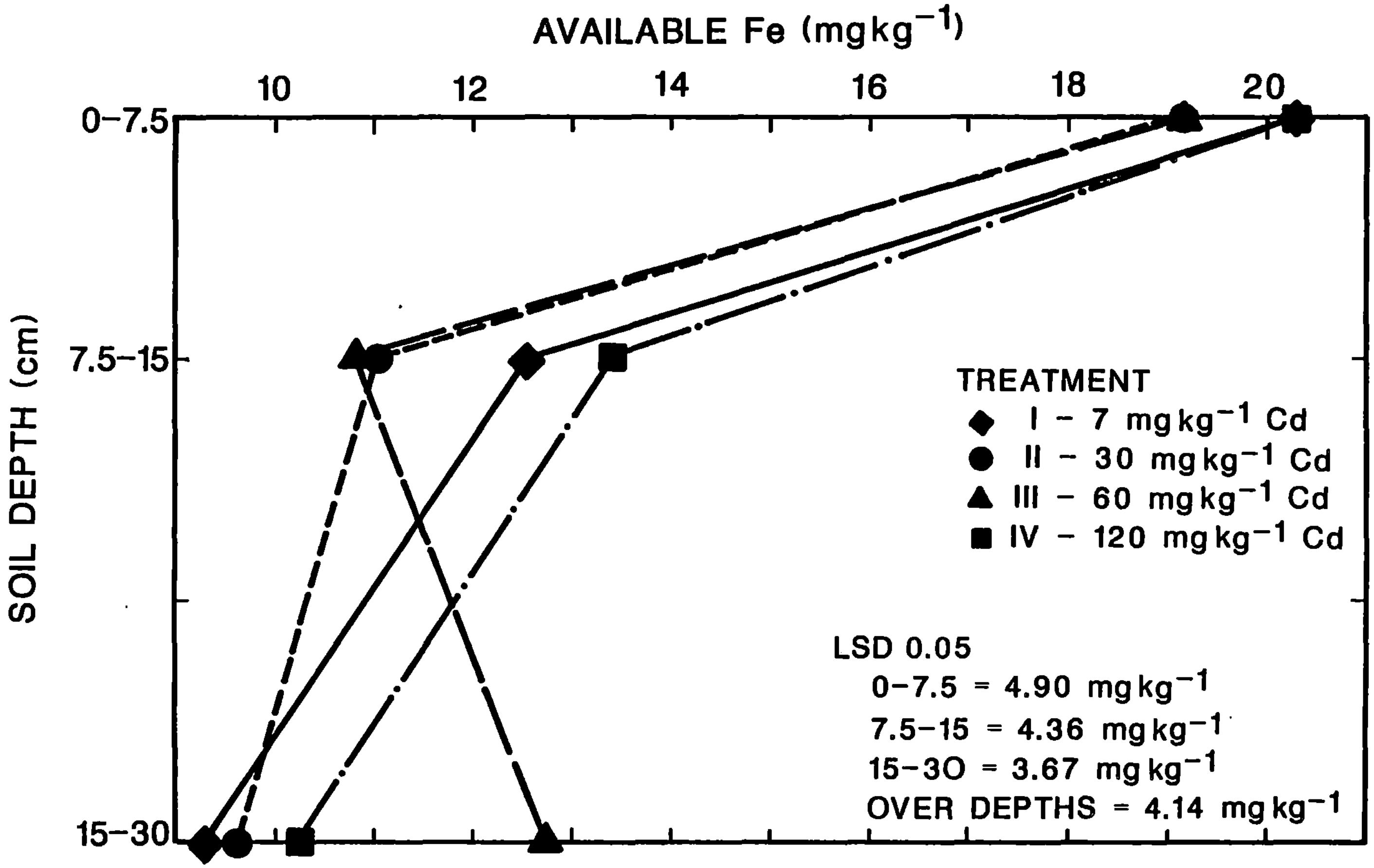

Figure 28. Soybean Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Surface Depth of Application (0-15 cm) on Available Fe of Teller Sandy Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

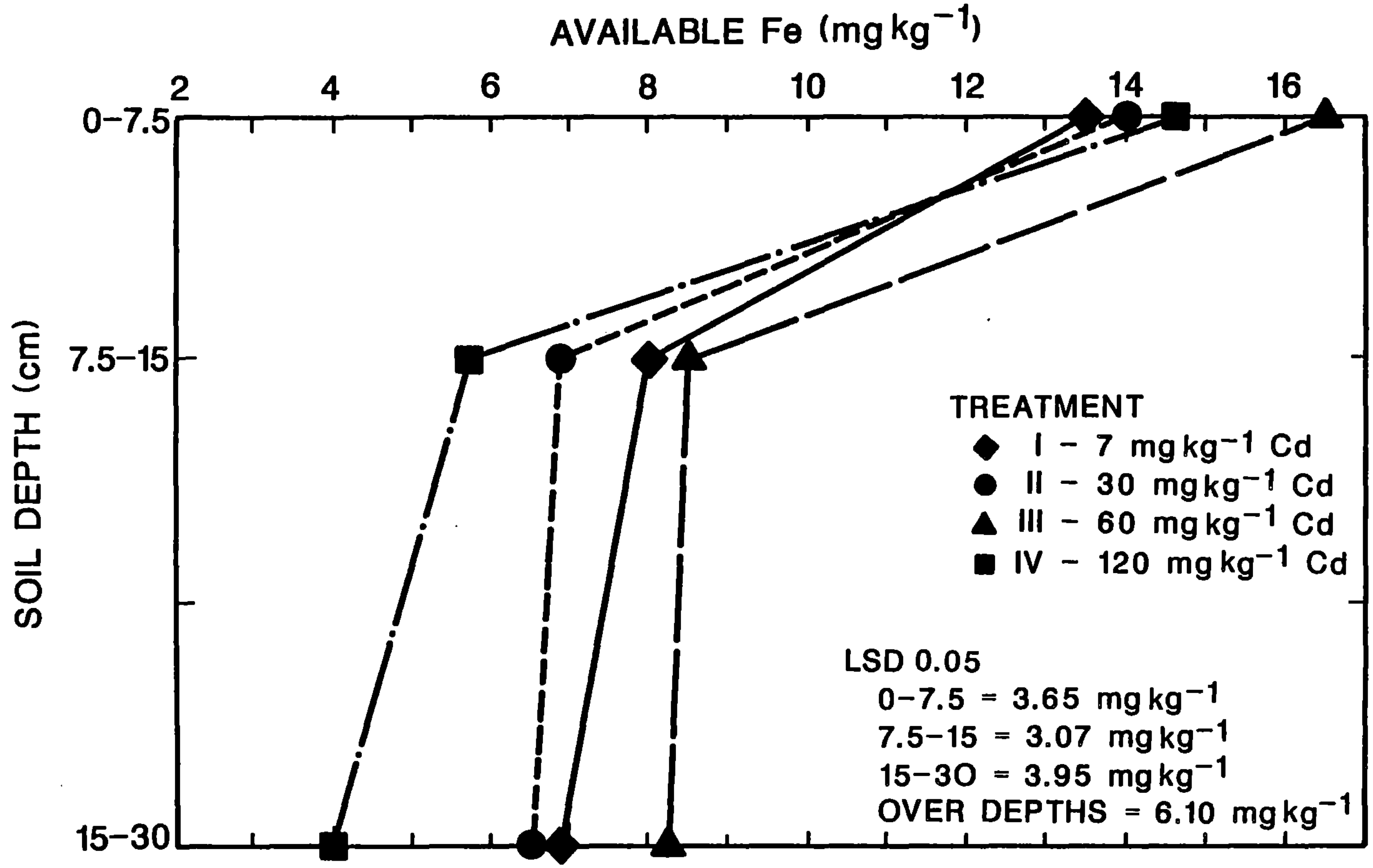

Figure 29. Sorghum Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Surface Depth of Application (0-15 cm) on Available Fe of Teller Sandy loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

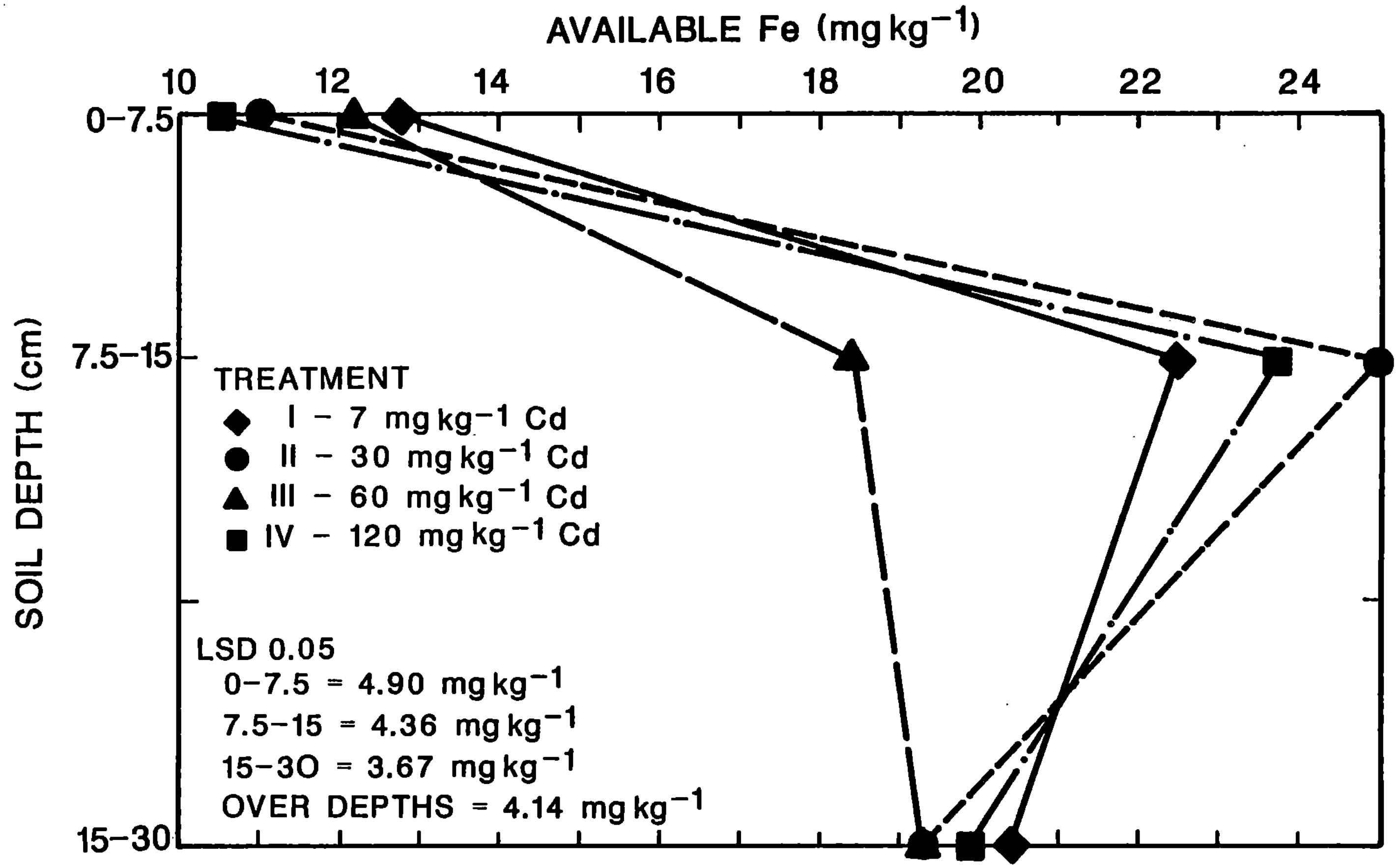

Figure 30. Soybean Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Subsurface Depth of Application (15-30 cm) on Available Fe of Teller Sandy Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

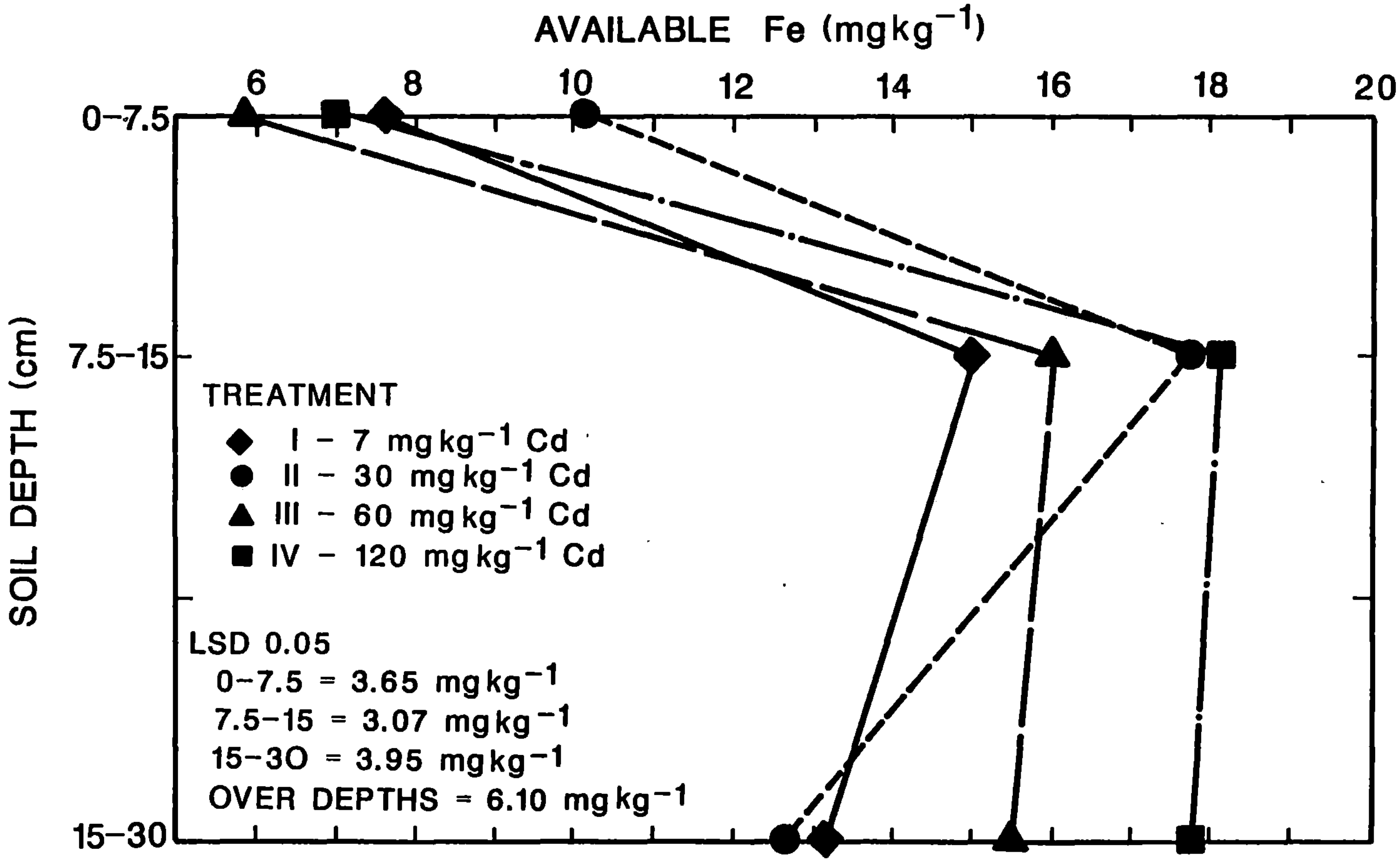

Figure 31. Sorghum Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Subsurface Depth of Application (15-30 cm) on Available Fe of Teller Sandy Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

to 31). The fact that available Fe determined for both soils at the conclusion of the experiment was less when sorghum was grown (Figures 29 and 31; Appendix, Figures 66 and 67) than when soybean were grown (Figures 28 and 30; Appendix, Figures 64 and 65) and that was accompanied by an increase in Fe content of sorghum (Figures 10 and 11; Appendix, Figures 46 and 47) compared to soybean (Figures 8 and 9; Appendix, Figures 44 and 45) is of interest. This may suggest that sorghum is more active than soybean in the uptake of heavy metals and translocating them into the shoot system.

Available Zn

Available Zn was affected by depth of application for both plant species in all three sampling depths, and was affected by the interaction between depth of application and Cd level in sampling depth one (0 to 7.5 cm) for soybean (Table XII) and in the three sampling depths for sorghum (Table XIII) at probability level 0.05. The availability of Zn in Teller soil was highly affected by the concentration of sewage sludge-borne Cd. Zinc increased with the increase in the Cd content of the four treatments (7, 30, 60, and 120 mg kg^{-1}) in the two depths of application (Figures 32 to 35). The observed relationship between Zn availability and Cd level can be explained when the high content of both Cd and Zn in Tulsa sludge as compared to that of Stillwater sludge is considered (Table III). Similar results were

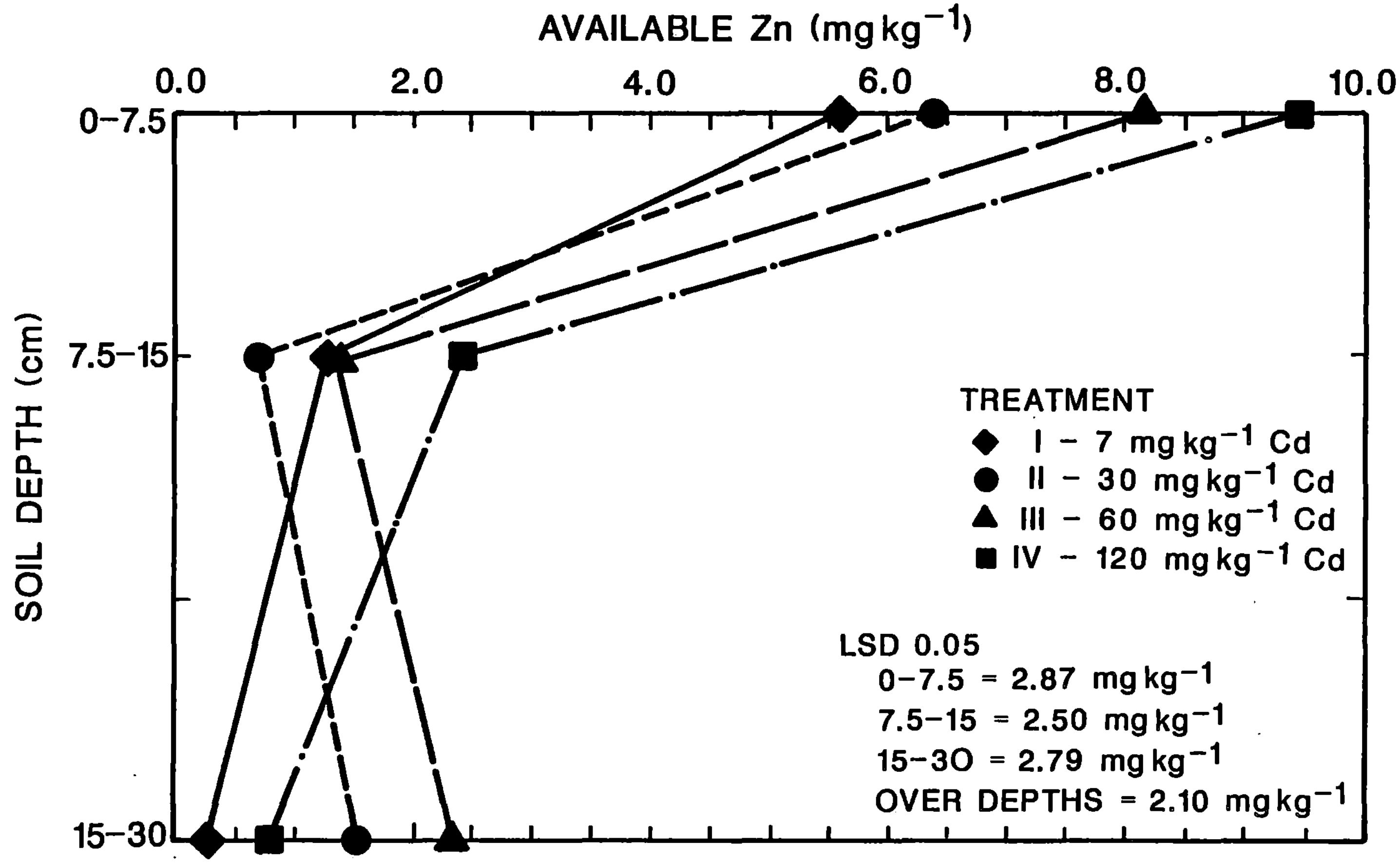

Figure 32. Soybean Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Surface Depth of Application (0-15 cm) on Available Zn of Teller Sandy Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

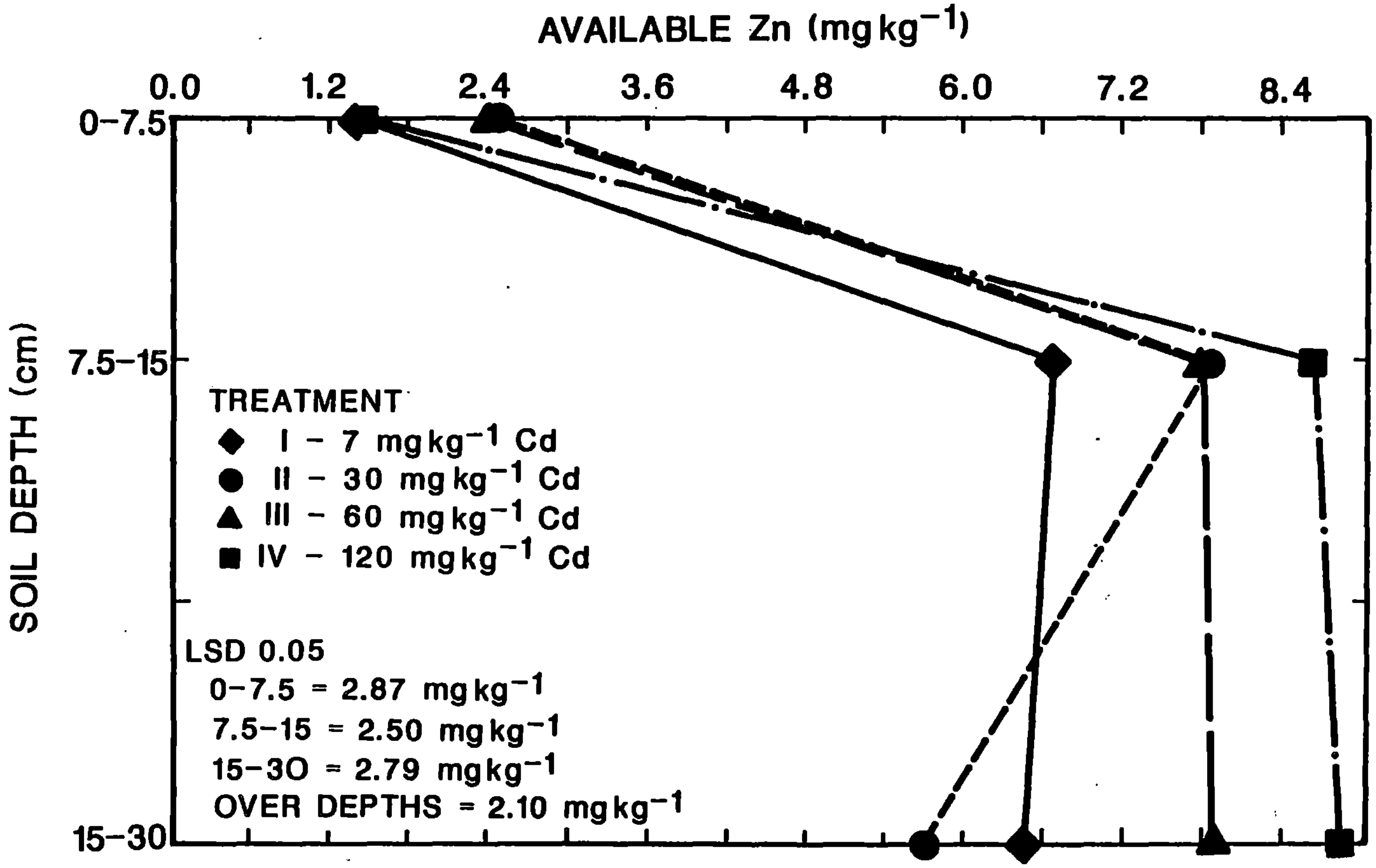

Figure 33. Soybean Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Subsurface Depth of Application (15-30 cm) on Available Zn of Teller Sandy Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

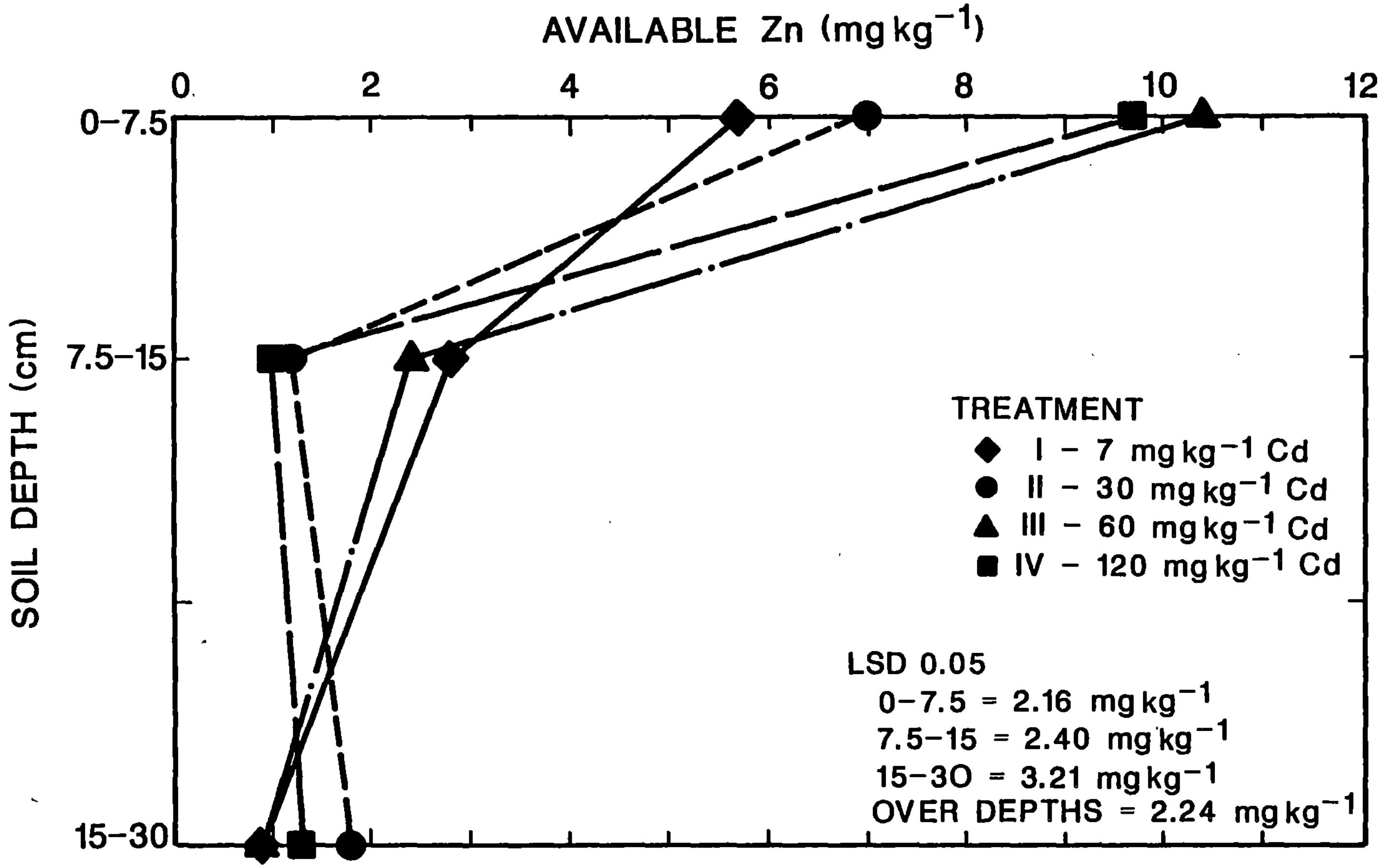

Figure 34. Sorghum Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Surface Depth of Application (0-15 cm) on Available Zn of Teller Sandy Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

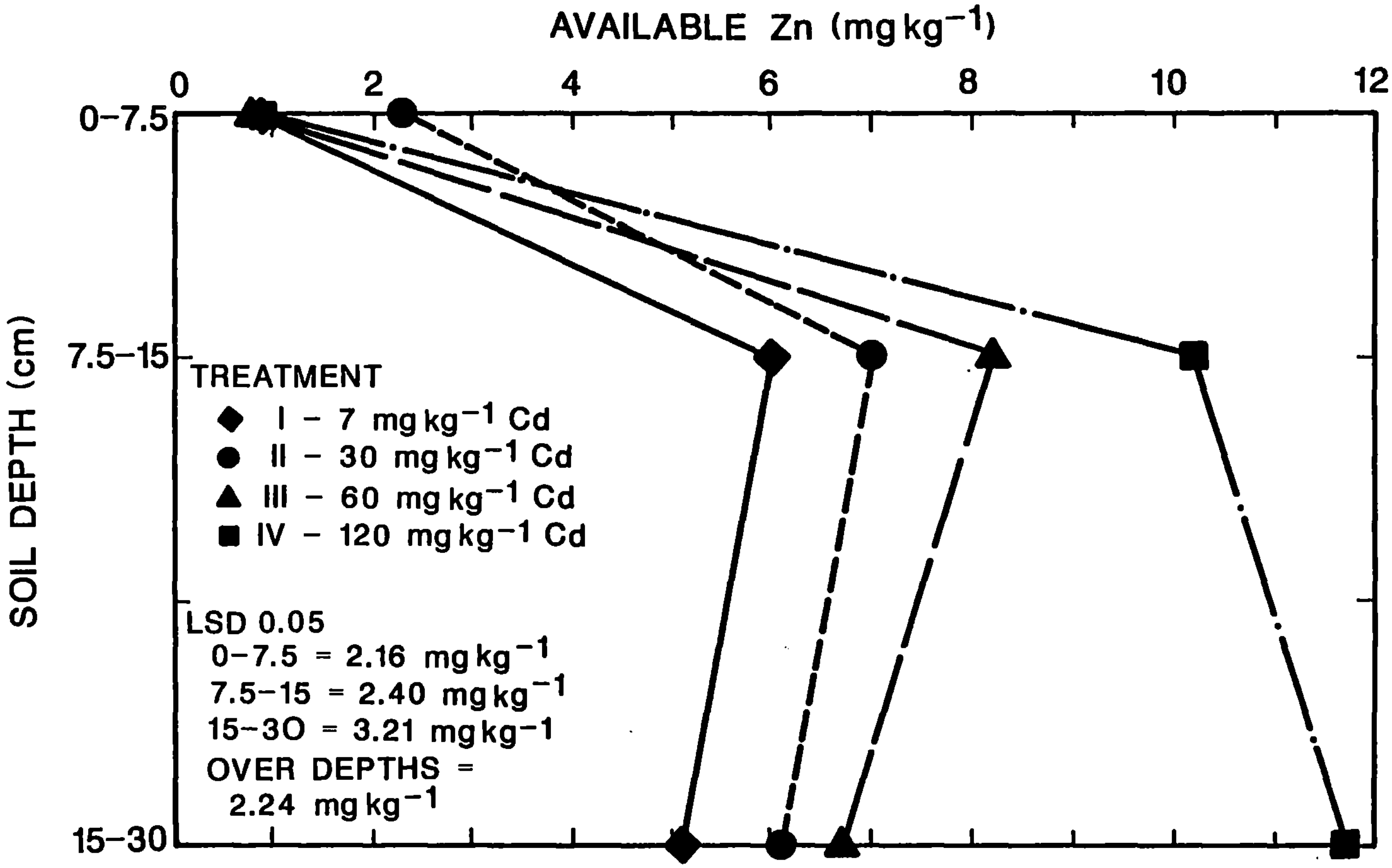

Figure 35. Sorghum Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Subsurface Depth of Application (15-30 cm) on Available Zn of Teller Sandy Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

obtained with Norge loam soil (Appendix, Figures 68 to 71). This relationship is frequently encountered in sewage sludges, and the association between Zn and Cd in nature is well documented (Chizhikov, 1966; Fleischer et al., 1974). The available Zn after growth of soybean did not differ from that in soils after growth of sorghum and was associated with almost equal Zn uptake by both plant species (Figures 12 to 15; Appendix, Figures 48 to 51).

Available Cd

The cadmium level in both soybean and sorghum soils and the interaction between the depth of application and Cd level was significant at 0.01 probability level (Tables XII and XIII). Similar to Zn, Cd availability in Teller soil, for both plant species significantly increased with the increase in the concentration of Cd-containing sewage sludge with depth of application (Figures 36 to 39). When the availability in Teller sandy loam soil was compared with that in Norge loam soil, it appeared that Cd availability is affected by soil type with Teller soil having a higher Cd availability (Appendix, Figures 72 to 75). The availability of Cd and Zn was lower in the Norge loam soil than in the Teller sandy loam soil. This difference is likely to be due to the differences in soil texture (clay content) (John, 1972a), OM% (Leeper, 1972; Singh Sekhon, 1977), and pH (Williams and David, 1976) between these two types of soil (Tables I and II). As was the case for Fe, available Cd in

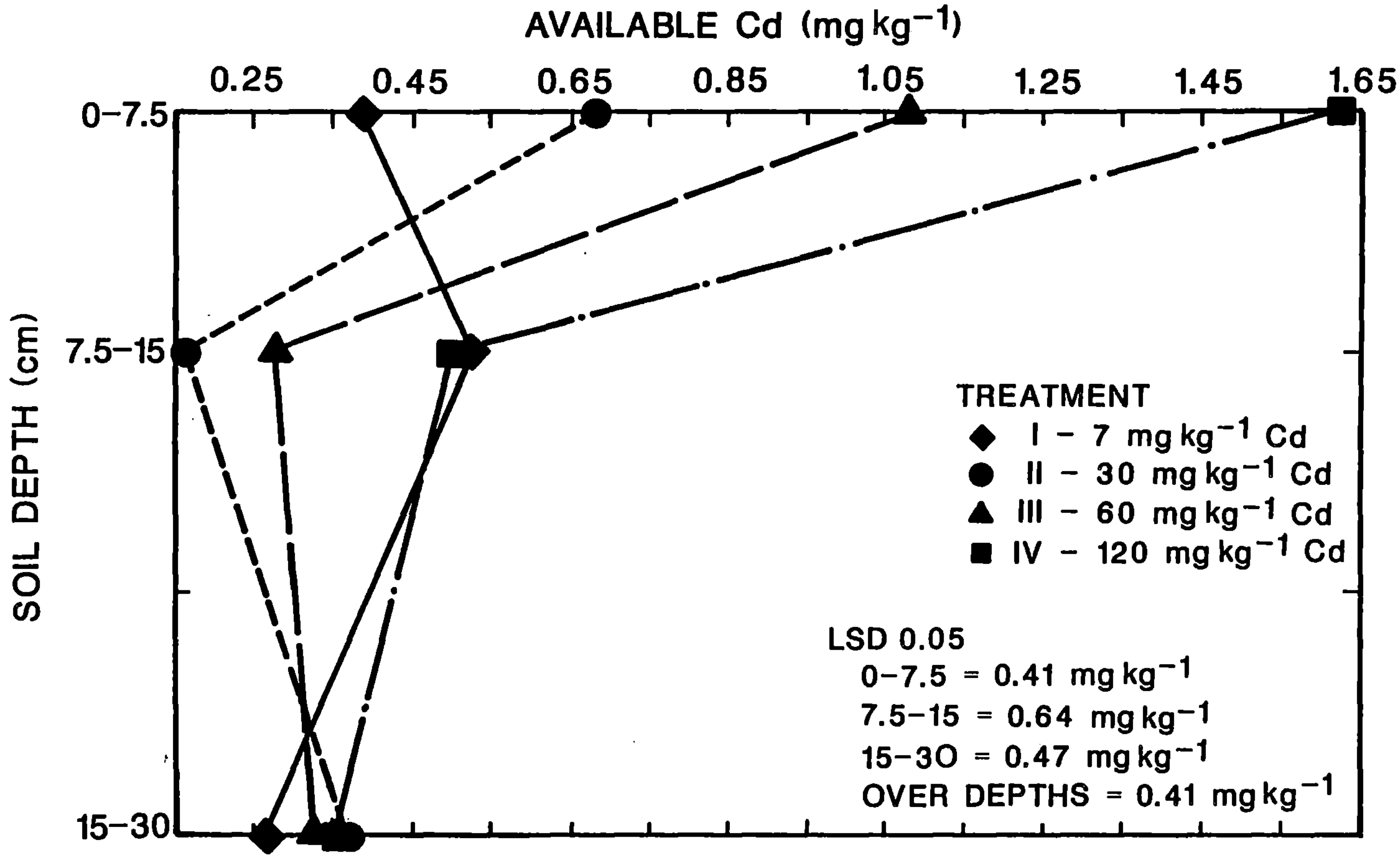

Figure 36. Soybean Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Surface Depth of Application (0-15 cm) on Available Cd of Teller Sandy Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

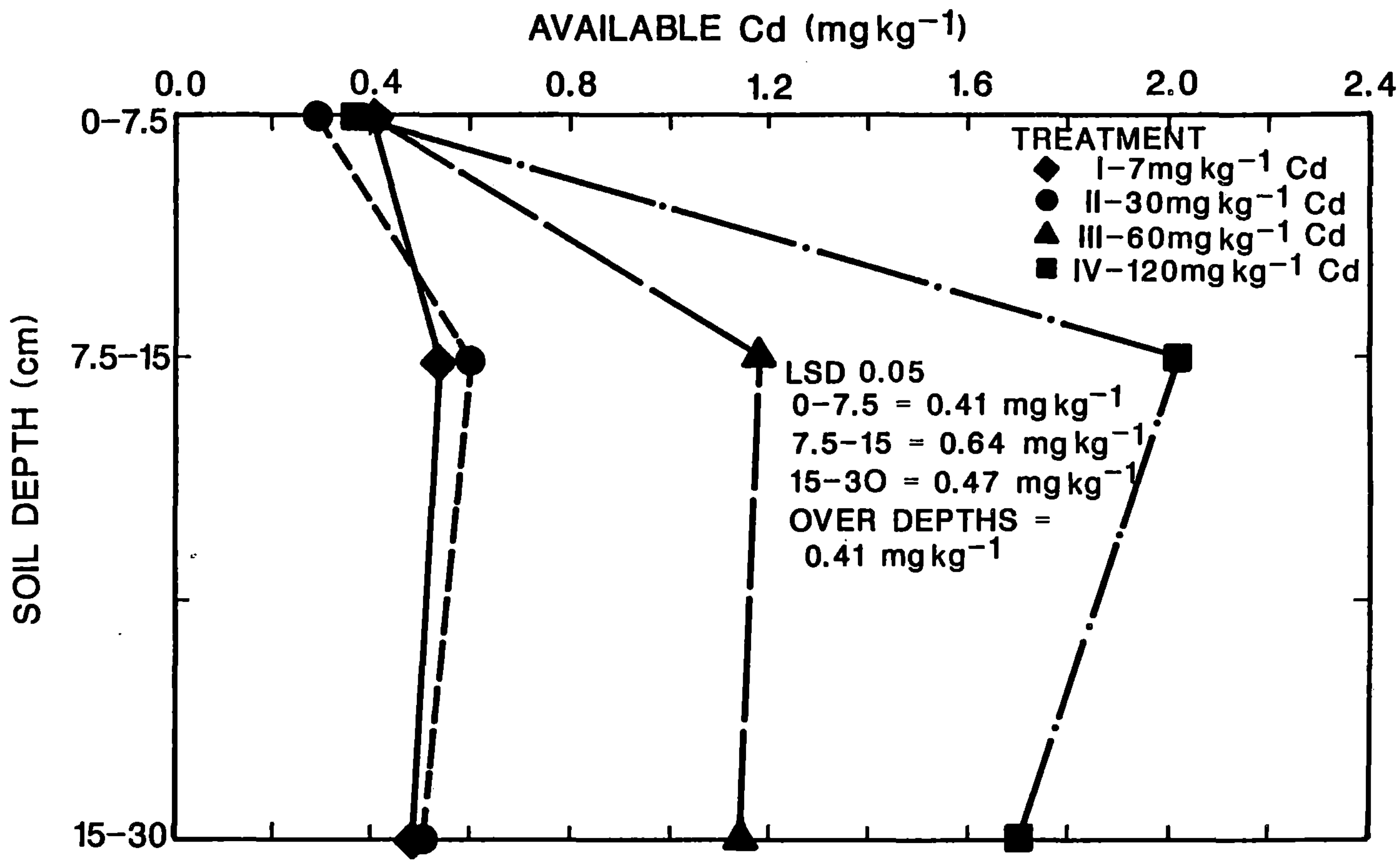

Figure 37. Soybean Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Subsurface Depth of Application (15-30 cm) on Available Cd of Teller Sandy Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

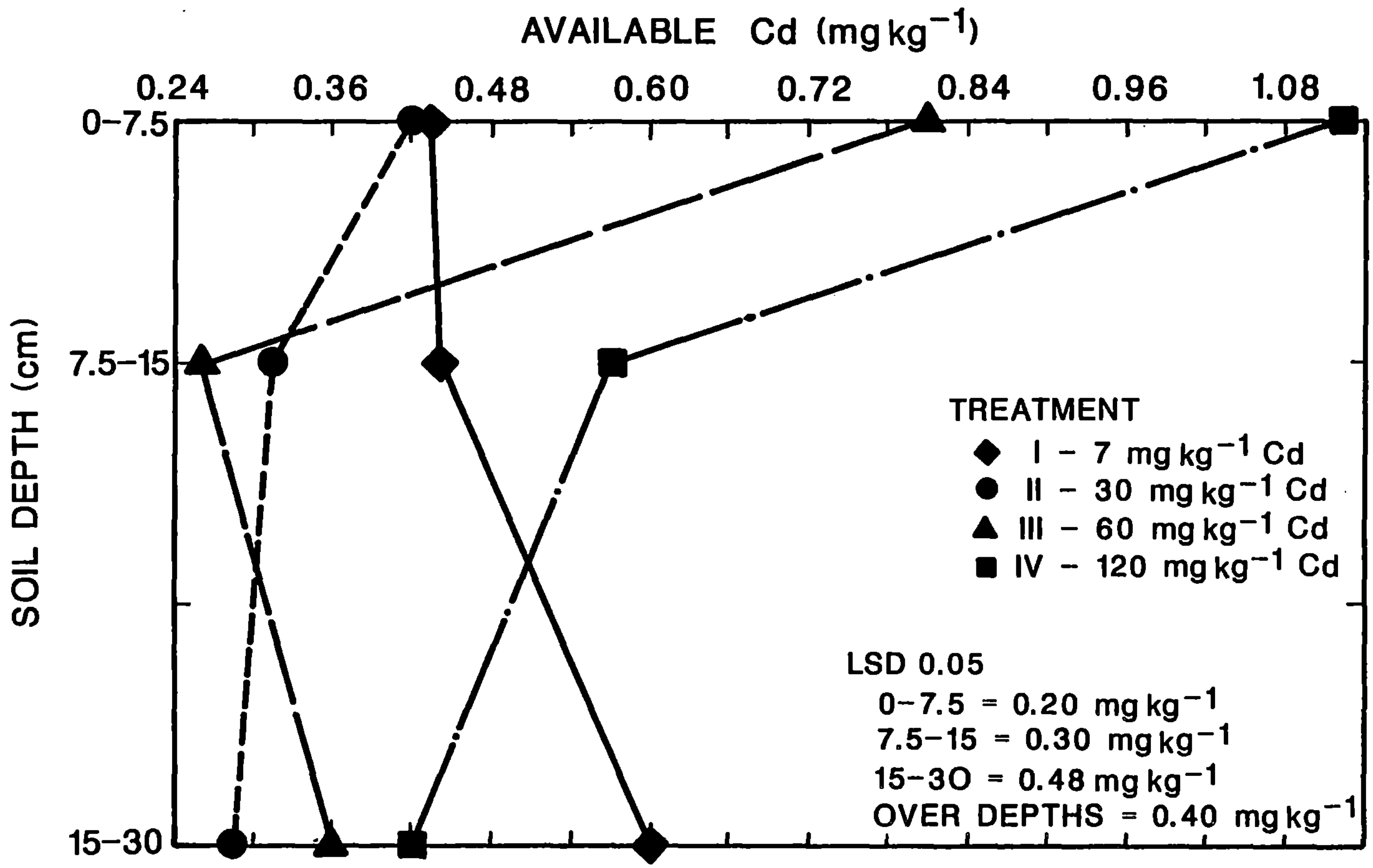

Figure 38. Sorghum Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Surface Depth of Application (0-15 cm) on Available Cd of Teller Sandy Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

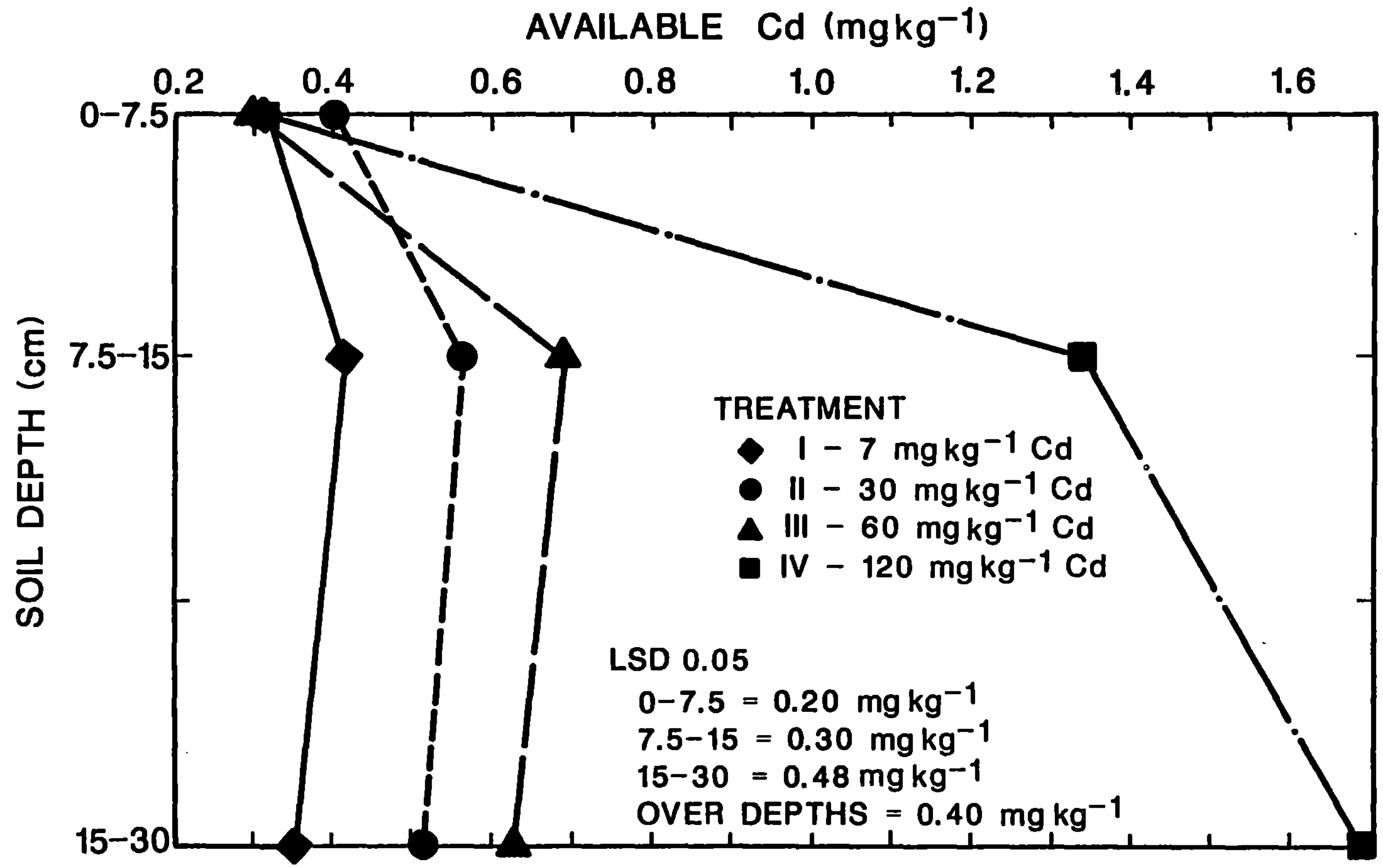

Figure 39. Sorghum Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Subsurface Depth of Application (15-30 cm) on Available Cd of Teller Sandy Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

both types of soils was lower after sorghum growth (Figures 38 and 39; Appendix, Figures 74 and 75) than after soybean growth (Figures 36 and 37; Appendix, Figures 72 and 73). This may be attributed to the high Cd uptake by sorghum plants as compared to the soybean plants (Figures 16 to 19; Appendix, Figures 52 to 55).

The direction of movement of the above three elements, Fe, Zn, and Cd was always upward with no downward movement observed. The upward movement occurred whether the sludge was incorporated into the surface or the subsurface, as reported for the organic matter. When sludge was incorporated in the 0 to 15 cm soil depth, these elements increased in the region between 0 and 7.5 cm, whereas, when it was applied in the 15 to 30 cm soil depth they accumulated in the region between 7.0 and 15 cm. The result reported here on the upward movement of these elements are in agreement with those of other investigations using sewage sludge (Kirkham, 1980), inorganic fertilizers (Alston, 1976), or dairy-cattle manure (Lund, 1978). The increase obtained in the concentrations of Fe, Zn, and Cd in the specified regions may have been the result of a high root growth density promoted by the incorporated sewage sludge within the root zone (Kirkham, 1980; Lund, 1978). This high density of root growth was apparently associated with a considerable increase in absorption and accumulation of these elements and the subsequent upward movement through the root system (Wallace et al., 1977; Wallace and Romney, 1977; Kirkham, 1980). The availability of Fe, Zn, and Cd was dependent on soil type or soil conditions as they were slightly higher in Teller sandy loam soil than in Norge loam soil. This may have been due to the high clay and OM contents of Norge loam soil (Tables I and II) as shown in earlier studies (John, 1972a; Williams and David, 1976).

CHAPTER V

SUMMARY AND CONCLUSIONS

Two greenhouse experiments including grain sorghum (Sorghum bicolor) and soybean (Glycine max) were initiated in the summer of 1984. The two experiments involved applications of four rates (7, 30, 60, and 120 mg Cd kg^{-1} sludge) of sewage sludge-borne Cd, and two types of soil, Teller sandy loam and Norge loam soils, in which the two plant species were grown, each in two successive crops.

The objectives of the study were to evaluate the effect of the concentration and placement of Cd-containing sewage sludge in the different soil types on the growth and the uptake of Fe, Zn, and Cd in the plant species and to study the pattern of accumulation or movement of these elements along with organic matter as a function of the same variables.

Data from the plant analysis and the observations made throughout the experiment showed that the two successive crops of soybean and sorghum were growing with no sign of any phytotoxic effect due to the sewage sludge-borne Cd at all concentrations used, even though application of Cd-containing sewage sludge significantly increased the available Cd in the soil. The absence of any symptoms of Cd phytotoxicity may be due to the relatively high soil pH values of the two soil types used, which has been reported earlier

(Okla. State Dept. of Health, 1983, and Williams and David, 1976), the decreased toxic effect of Cd bound to the sewage sludge as compared to inorganic Cd salts which exhibit high toxicity to plants (Singh, 1981), or the fixation of Cd ions by the chelating groups and of the high CEC of the soil organic matter (Leeper, 1972; Haghiri, 174)), that increased with continued sludge decomposition in the soil.

The dry matter yield of crop one was higher than that in crop two for both plant species. The significantly higher dry matter yield of the first crop over that of the second is attributed to the addition of 112 Kg ha^{-1} nitrogen fertilizer to the soil (Giordano and Mortvedt, 1975), to the release of nutritive elements from the decomposition of sewage sludge in the soil during the incubation period that preceded crop one, as suggested by Hinesly et al. (1976), and to the difference in the environmental conditions of crops one and two in terms of temperature (Mack et al., 1966) and light intensity (day length) (Leonard and Martin, 1963) contributed to the difference observed in yield. When the dry matter of the two plant species was compared, sorghum had a higher yield than soybean, apparently a reflection of differences in the genetic makeup of the two plant species.

Cadmium and Fe uptake by Crop one was higher than that of Crop two in both plant species. The Cd and Fe concentrations were greater in plants growing in Teller sandy loam soil where Cd was more available than in Norge loam soil because of higher clay and organic matter content of the Norge loam soil. In general, sorghum was more efficient in absorbing and accumulating Cd than soybean, a difference that may be a reflection of genetic variability in Cd uptake and accumulation by the two plants (Page et al., 1972; John, 1973; Turner, 1973; Lutrick et al, 1982). Although Zn and Cd increased significantly in the soil with the increase in the amount of Cd-containing sewage sludge incorporated, their concentration, like Fe, in both plant species did not significantly differ with Cd treatments. It is worthwhile to mention that Cd concentration in the two crops of both plant species did increase gradually with the increase in the Cd-containing sewage sludge content, but again, the increase was not statistically significant.

Data from the final soil analysis showed that soil type dominated soil pH as Norge loam soil started with higher pH value (7.4) than the adjusted pH (7.8) of Teller sandy loam soil, but the pH value at the end of the experiment did not significantly change with soil depth in either soil type. The relatively high pH values apparently reduced the availability of Fe, Zn, and Cd to plants as indicated by the Oklahoma State Department of Health (1983).

The percentage of organic matter (OM%) and the availability of Fe, Zn, and Cd were affected by the concentration of Cd-containing sewage sludge, the depth of application, and soil type. When the sludge was incorporated in 0 to 15 cm soil depth (surface), OM% increased in the region between 0 and 7.5 cm (sampling depth one), whereas, when it was applied in the 15 to 30 cm soil depth (subsurface), OM% accumulated in the region between 7.5 and 15 cm (sampling depth two). The increase in OM% in both cases is a likely result from high root growth density promoted by the incorporated sludges. This increase seems to have been an additive effect of the two successive crops. The availability of Cd, and Zn significantly increased with the increase in the concentration of the Cd-containing sewage sludge, and the direction of movement of these elements as well as Fe in the soil was always upward with no downward movement observed. The pattern of Fe, Zn, and Cd movement was identical to the pattern of OM movement. The upward movement of Fe, Zn, and Cd is believed to be due to absorption by the root system and accumulation in the upper parts that correspond to the regions of increase as described above for OM% (Wallace et al., 1977; Kirkham, 1980). The availability of these elements in the Norge loam soil was lower than that in the Teller sandy loam soil. This difference is likely to be due to the differences in soil texture (clay content) and pH (Tables I and II) as suggested by John (1972a8) and Williams and David (1976).

In the light of the results obtained in this study it seems that application of Cd-containing sludge under the conditions used in this work does not represent any health hazards that would involve the two plant species used even though the concentration of Cd applied to the soil may be from 0.17 kg ha^{-1} (120 mg kg^{-1} sewage sludge-borne Cd) to 2.8 kg ha^{-1} (120 mg kg^{-1} sewage sludge-borne Cd), the highest rate exceeding the maximum annual Cd addition (0.5 kg ha^{-1}) recommended by the Oklahoma State Department of Health (OSDH Bulletin No. 583, 1983) by almost six times. But, since higher Cd level in the soil may represent health hazards either directly or indirectly to the other plants, animals, and human beings, no recommendation can be made to increase the maximum limit of the annual Cd addition put forward by the OSDH. The ability of plants to absorb, transfer, and accumulate Cd from lower to upper regions of the soil profile and to increase the organic matter percentage and consequently the total CEC in the upper regions of the soil profile may suggest that in a Cd polluted soil, growing plants, not for leafy vegetables, but for fiber or seed where Cd is not expected to reach these plant parts (CAST. Report No. 64, 1976) may help fixing Cd in the upper part of the soil and preventing it from leaching down the soil profile with a possibility of contamination of the ground water. For further studies, it is recommended to increase the range of Cd concentration applied to the soil as sewage sludge to determine the phytotoxic concentration of this metal for several plant species. Also, a comparative study on the effect of Cd concentrations introduced to the soil sewage sludge or inorganic salt seems justified. In such studies, it is highly advised to use two extreme soils as to texture with an intermediate texture so that the effect of soil type can be better evaluated. Further study should also include several soil pH values below 6.5 and be extended over a period of time such that the effect of declining soil pH (below 6.5) effect on Cd release can be measured and related to other soil retention factors as a function of time and soil characteristics.

There is too little information in today's literature regarding dangerous dietary Cd levels. Recognizing that total Cd intake may be more important than Cd levels in feeds or foods and that other element concentrations (Zn, Ca, Cu) can directly influence Cd accumulations in animal tissues, a cooperative study to evaluate the dangers of Cd in diets is recommended. Such a study should include biological or plant Cd sources compared with inorganic Cd additions.

BIBLIOGRAPHY

Allaway, W. H. 1968. Agronomic Controls over the Environmental Cycling of Trace Elements. Adv. Agron. 20:235-274.

Alston, A. M. 1976. Effects of Depth of Fertilizer Placement on Wheat Grown under Three Water Regimes. Aust J. Agric. Res. 27:1-10.

Anderson, A. 1976. On the Influence of Manure and Fertilizers on the Distribution and Amounts of Plant-Available Cd in Soils. Swed. J. Agric. Res. 6:27-36.

Anderson, A. and Nilsson, K. O. 1974. Influence of Lime and Soil pH on Cd Availability to Plants. Ambio 3:198-200.

Baker, D. E., Esbelman, R. M., and Leach, R. M. 1975. Cadmium in Sludge Potentially Harmful when Applied to Crops. Sci. in Agric. 22:14-15.

Bates, T. E., Haq, A., Soon, Y. K., and Moyer, J. A. 1975. Uptake of Metals from Sludge Amended Soil. Proc. Int. Conf. Heavy Metals in the Environment, Toronto, Canada.

Bingham, F. T., Page, A. L., Mahler, R. J., and Ganje, T. J. 1975. Growth and Cadmium Accumulation of Plants Grown on a Soil Treated with a Cadmium Enriched Sewage Sludge. J. Environ. Qual. 4:207-211.

Bingham, F. T., Page, A. L., and Sims, J. R. 1965. Retention of Acetate by Montmorillonite. Soil Sci. Soc. Am. Proc. 29:670-672.

Bittrell, J. E. and Miller, R. J. 1974. pH, Cd and Ca Selectivity Coefficients on a Montmorillonite, Illite and Kaolinite. J. Environ. Qual. 3:250-253.

Boyle, E. A., Schlater, F., and Edmond, J. M. 1976. On the Marine Geochemistry of Cadmium. Nature 263:42-44.

Brown, J. C., Tiffin, L. O., and Holmes, R. S. 1960. Competition between Chelating Agents and Roots as a Factor Affecting Absorption of Iron and other Ions by Plant Species. Plant Physiol. 35:878-886.

Carlson, R. W. and Bazzaz, F. A. 1977. Growth Reduction in American Sycamore (Platanus Occidentalis L.) caused by Pb-Cd Interaction. Environ. Pollut. 12:243-253.

Chang, A. C., Page, A. L., Foster, K. W., and Jones, T. E. 1982. A Comparison of Cadmium and Zinc Accumulation by Four Cultivars of Barley Grown in Sludge-Amended Soils. J. Environ. Qual. 11:409-412.

Chang, A. C., Warneke, J. E., Page, A. L., and Lund, L. J. 1984. Accumulation of Heavy Metals in Sewage Sludge-Treated Soils. J. Environ. Qual. 13:87-91.

Chaney, R. L. 1985. Personal Communication. USDA-ARS. Beltsville, MD.

Chaney, R. L. 1973. Crop and Food Chain Effects of Toxic Elements in Sludges and Effluents. J. Environ. Qual. 2:129-142.

Chaney, R. L. and Hormick, S. B. 1977. Cadmium in Vegetables, Crops and the Dietary Intake. J. Environ. Qual. 6:121-132.

Checkai, R. T. 1983. Cadmium Uptake by Plants from Amiaed-Resin Hydroponic System. Ph. D. Thesis. University of Wisconsin, Madison, WI.

Chen, K. Y., Gupta, S. K., Sycip, A. Z., Lu, J. C. S., Knezevic, M., and Choi, Won-Wook. 1976. Research Study on the Effect of Dispersion, Settling, and Resedimentation on Migration of Chemical Constituents during Open-Water Disposal of Dredged Materials. U. S. Army Engineer Waterways Experiment Station: Vicksburg, Miss.

Chizhikov, D. M. 1966. Cadmium. Pergamon, Oxford. p. 265.

Council for Agri. Sci. and Tech. (CAST). 1976. Application of Sewage Sludge to Cropland. Appraisal of Potential Hazard of Heavy Metals Uptake to Plants and Animals. CAST Rep. No. 64. Iowa State Univ., Ames.

Cropper, J. B. 1969. Greenhouse Studies on Nutrient Uptake and Growth of Corn on a Sludge Treated Soil. J. Environ. Qual. 6:322-330.

Cunningham, L. M., Collins, F. W., and Hutchinson, T. C. 1975a. Physiological and Biochemical Aspects of Cadmium Toxicity in Soybean. I: Toxicity Symptoms and Autoradiographic Distribution of Cd in Roots, Stems, and Leaves. Can. J. Bot. 51:645-649.

Cunningham, J. D., Keeney, D. R., and Ryan, J. A. 1975b. Phytotoxicity and Uptake of Metals added to Soils as Inorganic Salts or in Sewage Sludge. J. Environ. Qual. 4:460-463.

Cutler, J. M. and Rains, D. W. 1974. Characterization of Cadmium Uptake by Plant Tissue. Plant Physiol. 54:67-71.

Day, R. A. 1956. Quantitative Analysis (3rd ed), Englewood Cliffs, N. J.: Prentice-Hall, Inc.

DeGroot, A. J. and Allersma, E. 1975. Field Observations on the Transport of Heavy Metals in Sediments. Prog. Water Technol. 7:85-95.

DeKock, P. C. and Mitchell, R. L. 1957. Uptake of Chelated Metals by Plants. Soil Sci. 84:55-62.

Doyle, J. J., Pfander, W. H., Grebing, S. E., and Pierce, J. O. 1974. Effects of Dietary Cadmium on Growth, Cadmium Absorption, and Cadmium Tissue Levels in Growing Lambs. J. Nutr. 104:160.

Emmerich, W. E., Lund, L. J., Page, A. L., and Chang, A. C. 1982. Movement of Heavy Metals in Sewage Sl udge-Treated Soils. J. Environ. Qual. 11:174-178.

Fleischer, M., Savofim, A. F., Fassett, D. W., and Hammond, P. 1974. Environ. Health Perspec. 7:253-323.

Florence, T. M. and Batley, G. E. 1977. Determination of the Chemical Forms of Trace Metals in Natural Waters, with Special Reference to Copper, Lead, Cadmium, and Zinc. Talanta 24:151-158.

Frost, R. R. and Griffin, R. A. 1977. Effect of pH on Absorption of Copper, Zinc, and Cadmium from Landfill Leachates by Clay Minerals. J. Environ. Sci. Health, 412:139-156.

Fulderson, W. and Geollev, H. E. (Ed) 1973. Cadmium-the Dissipated Element. Rep. NSF-EP-21, Oak Ridge Nat. Lab. Oak Ridge, Tenn.

Gambrell, R. P., Khalid, R. A., Vevloo, M. G., and Patrick, W. H. Jr. 1977. Transformations of Heavy Metals and Plant Nutrients in Dredged Sediments as Affected by Oxidation-Reduction Potential and pH. Vol. II: Materials and Methods, Results and Discussion. U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Gardiner, J. 1974. The Chemistry of Cadmium in Natural Water. II: The Absorption of Cadmium on River Muds and Naturally Occurring Solids. Water Res. 8:157-164.

Giordano, P. M. and Mays, D. A. 1976. Effect of Land Disposal Applications of Municipal Wastes on Crop Yields and Uptake of Heavy Metals. J. Environ. Qual. 4: 394-399.

Giordano, P. M. and Mortvedt, J. J. 1975. Nitrogen Effects on Mobility and Plant Uptake of Heavy Metals in Sewage Sludge Applied to Soil Columns. J. Environ. Qual. 5:165-177.

Haghiri, F. 1974. Plant Uptake of Cadmium as Influenced by Cation Exchange Capacity, Organic Matter, Zinc, and Soil Temperature. J. Environ. Qual. 3:180-183.

Hahne, H. C. H. and Kroontje, W. 1973. Significance of pH and Chloride Concentration on Behavior of Heavy Metal Pollutants: Mercury (II), Cadmium (II), Zinc (II), and Lead (II). J. Environ. Qual. 2:444-450.

Hem, J. D. 1972. Chemistry and Occurrence of Cadmium and Zinc in Surface Water and Groundwater. Water Resour. Res. 8:661-679.

Hemphill, D. D. and Rube, J. E. 1975. pp. 77-86. Inf: Intern. conf. Heavy Metals in Environ., Toronto (T. C. Hutchinson, ed.),

Hinesly, T. D., Jones, R. L., Tyler, J. J., and Ziegler, E. L. 1976. Soybean Yield Response and Assimilation of Zn and Cd from Sewage Sludge Amended Soil. J. Water Pollut. Cont. Fed. 48:2137-2152.

Hodgson, J. F. 1963. Characterization of Cadmium Uptake by Plant Tissue. Plant Physiol. 54:67-71.

Iskander, I. K. and Keeney, D. R. 1974. Concentration of Heavy Metals in Sediment Coves from Selected Wisconsin Lakes. Environ. Sci. Technol. 8:165-170.

Jaakkola, A. and Ylaranta, T. 1976. The Role of the Quality of Soil Organic Matter in Cadmium Accumulation in Plants. J. Sci. Agric. Soc. Finl. 48:415-425.

Jackson, M. L. 1973. Soil Chemical Analysis. New Delhi, India: Prentice-Hall of India.

Jenne, E. A. 1968. Trace Inorganic Elements in Water. Advances in Chemistry Series 73. Chapter 21 in R. F. Gould (Ed) Am. Chemical Society, Washington, D. C.

Jimmy, J. S., Sabey, B. R., and Lindsay, W. L. 1978. Influence of pH, Phosphorus, Cadmium, Sewage Sludge, and Incubation Time on the Solubility and Plant Uptake of Cadmium. J. Environ. Qual. 7:286-290.

Johansen, O. J. and Carlson, D. A. 1976. Characterization of Sanitary Landfill Leachates. Water Res. 10:1129-1134.

John, M. K. 1972a. Cadmium Adsorption Maxima of Soils as Measured by the Langmuir Isotherm. Can. J. Soil Sci. 52:343-350.

John, M. K. 1972b. Uptake of Soil-Applied Cadmium and it's Distribution in Radishes. Can. J. Plant Sci. 52:715-719.

John, M. K. 1973. Cadmium Uptake by Eight Food Crops as Influenced by Various Soil levels of Cadmium. Environ. Pollut. 4:7-15.

John, M. K. 1976. Interrelationships between Plant Cadmium and Uptake of some other Elements from Culture Solutions by Oats and Lettuce. Environ. Pollut. 11:85-95.

John, M. K., VanLaerhoven, C. J., and Chuah, H. H. 1972. Factors Affecting Plant Uptake and Phytotoxicity of Cadmium added to Soils. Environ. Sci. and Technol. 6:1005-1009.

John, M. K. and VenLaerhoven, C. J. 1976. Differential Effects of Cadmium Lettuce on Varieties. Environ. Pollut. 10:163-173.

Kerfoot, W. B. and Jacobs, S. A. 1976. Cadmium Accrual in Combined Wastewater Treatment-Aguaculture Systems. Environ. Sci. Technol. 10:662.

King, L. D. and Morris, H. D. 1972. Land Disposal of Liquid Sewage Sludge: II. The Effect on Soil pH, Manganese, Zinc, and Growth and Chemical Composition of Rye. J. Environ. Qual. 1:425-429.

Khalid, R. A., Gambrell, R. A., and Patrick, W. H. Jr. 1978. Chemical Transformations of Cadmium and Zinc in Mississippi River Sediments as Influenced by pH and Redox Potential. pp. 417-433. In D. C. Adriano and I. L. Brisbin, Eds.: Environmental Chemistry and Cycling Processes. Proceedings of 2nd Mineral Cycling Symposium, Energy Research Development Administration, Oak Ridge, Tenn.

Kiekens, L., A. Cottenie, and G. VanLandschoot. 1984. Chemical Activity and Biological Effect of Sludge-Borne Heavy Metals and Inorganic Metal Salts Added to Soils. Plant and Soil. 79:89-100.

Kirkham, M. B. 1980. Characteristics of Wheat Grown with Sewage Sludge Placed at Different Soil Depths. J. Environ. Qual. 9:13-18.

Kunze, G. W. 1965. Pretreatment for Mineralogical Analysis. In C. A. Black (Ed). pp. 568-577. Method of Soil Analysis, Part I Agronomy. Amer. Soc. Agron. Madison, Wis.

Lagerwerff, J. V. 1971. Uptake of Cadmium, Lead, and Zinc by Radish from Soil and Air. Soil Sci. 111:129-133.

Lagerwerff, J. V., Biersdorf, G. T., and Brower, D. L. 1976. Retention of Metals in Sewage Sludge: I. Constituent Heavy Metals. J. Environ. Qual. 5:19-23.

Lee, G. F. and Plumb, R. H. 1974. Literature Review on Research Study for the Development of Dredged Material Disposal Criteria. U. S. Army Engineer Waterways Experiment Station, Contract Rep. D-74-1, CE, Vicksburg, Miss.

Leeper, G. W. 1972. Reactions of Heavy Metals with Soils with Special Regard to their Application in Sewage Wastes. Army Corps Engineers: Contract No. DACW73-73-C-0026.

Leonard, W. H. and Martin, J. H. 1963. Cereal Crops. p. 682. MacMillan Publishing Co., Inc., New York, NY.

Lester, J. N., Harrison, R. M., and Perry, R. 1979. The Balance of Heavy Metals through a Sewage Treatment Works. I: Lead, Cadmium, and Copper. Sci. Total Environ. 12:13.

Lutrick, M. C., Robertson, W. K., and Cornell, J. A. 1982. Heavy Applications of Liquid-Digested Sludge on Three Ultisols. II: Effects on Mineral Uptake and Crop Yield. J. Environ. Qual. 11:283-287.

Lund, Z. F. 1978. Root Development in Dairy Manure-Treated Soil. J. Environ. Qual. 7:473-477.

Mack, H. J., Sc. C. Fane, and S. B. Apple, Sr. 1966. Response of Snap Beans (phaseolus Vulgaris) to Soil Temperature and Phosphorus Fertilizer on Five Western Oregon Soils. SSSA Proc., 30:236-241.

MacLean, A. J. 1976. Cadmium in Different Plant Species and its Availability in Soils as Influenced by Organic Matter and Additions of Lime, P, Cd, and Zn. Can. J. Soil Sci. 56:129-138.

Matt, K. J., C. J. VanLaerhoven, and H. H. Chuah. 1972. Factors Affecting Plant Uptake and Phytotoxicity of Cadmium Added to Soils. Environment Science and Technology. 6:1005-1009

Miller, J. E., Hassett, J. J., and Koeppe, D. E. 1976a. Uptake of Cadmium by Soybeans as Influenced by Soil Cation Exchange Capacity, pH, and Available Phosphorus. J. Environ. Qual. 5:157-160.

Miller, J. E., Hassett, J. J., and Koeppe, D. E. 1976b. Interaction of Lead and Cadmium on Maize Root Growth and Uptake of Lead and Cadmium by Roots. Environ. Pollut. 11:297-302.

Miller, J. E., Hassett, J. J., and Koeppe, D. E. 1977. Interactions of Lead and Cadmium on Metal Uptake and Growth of Corn Plants. J. Environ. Qual. 6:18-20.

Morel, F., McDuff, R. E., and Morgan, J. J. 1973. Interactions and Chemostasis in Aquatic Chemical Systems. Role of pH, Pe, Solubility, and Complexation. pp. 157-200. In P. C. Singer (Ed), Trace Metals and Metal-Organic Interactions in Natural Waters. Ann Arbor Science Publishers, Ann Arbor, Mich.

Morrison, R. 1983. Personal Communication, Oklahoma State University, Stillwater, Oklahoma.

Mortvedt, J. J. and Giordano, P. M. 1977. Crop Uptake of Heavy Metal Contaminants in Fertilizers. J. Environ. Qual. 10:402-416.

Mulla, D. J., Page, A. L., and Ganje, T. J. 1980. Cadmium Accumulations and Bioavailability in Soils from long-term Phosphorus Fertilization. J. Environ. Qual. 9:408-412.

Nomura, M. M. and Young, R. H. F. 1974. Fate of Heavy Metals in the Sewage Treatment Process. Tech. Rep. No. 82, Water Resour. Res. Ctr, University of Hawaii.

Nriagu, J. O. 1978. Lead in the Atmosphere. pp. 137-183. In: J. O. Nriagu, (Ed). Biogeochemistry of Lead in the Environment. Part IA, Elsevier, Amsterdam.

Nriagu, J. O. 1979. The Global Copper Cycle. pp. 43-75. In J. O. Nriagu, (Ed). Copper in the Environment. Part I, Wiley, New York.

Nriagu, J. O. 1980. The Global Cadmium Cycle. pp. 1-12. In J. O. Nriagu, (Ed). Cadmium in the Environment. Part I, Wiley and Sons, Inc., New York, NY.

Oklahoma State Department of Health. 1983. Guidance Manual for the Manangement of Municipal Sewage Sludge. Okla. State Dept. of Health Bulletin No. 583. P II - 3.

Oliver, B. G. and Cosgrove, E. G. 1974. The Efficiency of Heavy Metal Removal by a Conventional Activated Sludge Treatment Plant. Water Res. 8:869.

Page, A. L. 1974. Fate and Effects of Trace Elements in Sewage Sludge when Applied to Agricultural Lands. Program Element No. IB2043, US EPA., Cincinnati, OH.

Page, A. L., Bingham, F. T., and Nelson, C. 1972. Cadmium Absorption and Growth of Various Plant Species as Influenced by Solution Cadmium Concentration. J. Environ. Qual. 1:288-291.

Parizek, J. 1957. The Destructive Effect of the Cadmium Ion on Testicular Tissue and its Prevention by Zinc. J. Endocrinology. 15:56.

Peterson, O. 1977. Differences in Cadmium Uptake Between Plant Species and Cultivars. Swed. J. Agric. Res. 7:21-24.

Raveh, A. and Avnimelech, Y. 1979. Leaching of Pollutants from Sanitary Landfill Models. J. Water Pollut. Control Fed. 51:2705-2716.

Riffaldri, R. and Levi-Minzi, R. 1975. Adsorption and Desorption of Cadmium on Humic Acid Fraction of Soils, Water Air. Soil Pollut. 4:179-184.

Robert, L. J., T. D. Hinesly, and E. L. Ziegler. 1973. Cadmium Content of Soybeans Growth in Sewage-Sludge Amended Soil. J. Enriron. Quality, 2: 351-353.

Roller, J. O. and McKaig, M. E. 1939. Some Critical Studies on the Phenodisulfonic Acid Method for the determination of Nitrate. Soil Sci. 47: 397-407.

Root, R. A., Miller, R. J., and Koeppe, D. E. 1975. Uptake of Cadmium - Its Toxicity and Effect on the Iron Ratio in Hydroponically Grown Corn. J. Environ. Qual. 4: 473-476.

Serne, R. J. and Mercer, B. W. 1975. Dredge Disposal Study, San Francisco Bay and Estuary, Appendix F: Crystalline Matrix Study. U. S. Army Engineer District, San Francisco, Calif.

Shelton, W. R. and H. J. Harper. 1941. A Rapid Method for the Determination of Total Phosphorus in soil and Plant Material. Iowa State College Journal of Sci. 15:403-413.

Sidle, R. C. and Kardos, L. T. 1977. Heavy Metal Application and Plant Uptake in a Land Disposal System of Waste Water. J. Environ. Qual. 5:97-102.

Singh, B. R. and Narwal, R. P. 1984. Plant Availability of Heavy Metals in a Sludge-Treated Soil. Metal Extractability Compared with Plant Metal Uptake. J. Environ. Qual. 3:344-349.

Singh, B. and Sekhon, G. S. 1977. Absorption, Desorption and Solubility Relationships of Lead and Cadmium in some Alkaline Soils. J. Soil Sci. 28:271-275.

Singh, S. S. 1981. Uptake of Cd by Lettuce as Influenced by its Addition to a Soil as Inorganic Forms or in Sewage Sludge. Can. J. Soil Sci. 61:19-28.

Sommers, L. E. 1976. Chemical Composition of Municipal Sewage SLudges and Evaluation of their Potential use as Fertilizers. J. Environ. Qual. 4:265-271.

Sommers, L. E. 1977. Cadmium in Sewage Sludges and Plants on Amended Soils. J. Environ. Qual. 6:225-232.

Sposito, G., Levesque, C. S., Leclaire, J. P., and Chang, A. C. 1983. Trace Metal Chemistry in Arid Zone Field Soils Amended with Sewage Sludge III. Effect of Time on the Extraction of Trace Metals. Soil Sci. Soc. Am. J. 45:898-902.

Street, J. J., Lindsay, W. L., and Sabey, B. R. 1977. Solubility and Plant Uptake of Cadmium in Soils Amended with Cadmium and Sewage Sludge. J. Envir. Qual. 6:72-77.

Tiffin, L. O., Brown, J. C., and Krauss, R. W. 1960. Differential Absorption of Metal Chelate Components by Plant Roots. Plant Physiol. 35:362-367.

Tiffin, L. O. and Brown, J. C. 1961. Selective Absorption of Iron from Iron Chelates by Soybean Plants. Plant Physiol. 36:710-714.

Turner, M. A. 1973. Effect of Cadmium Treatment on Cadmium and Zinc Uptake by Selected Vegetable Species. J. Environ. Qual. 2:118-119.

Underwood, E. J. 1977. Trace Elements in Human and Animal Nutrition. 4th Ed., Academic Press, New York, NY.

US Department of Agriculture and Interior (USDA-USDI). 1977. Development of Phosphate Resources in S.E. Idaho: Final Environmental Impact Statement. 1:52-54.

Wallace, A. and Romney, E. M. 1977. Roots of Higher Plants as a Barrier to Translocation of Some Metals to Shoots of Plants. pp. 370-379. In H. Drucke and R. E. Wildung, Chairmen, Biological Implication of Metals in the Environment. Proceeding of the Fifteenth Annual Hanford Life Science Symposium, Richland, Wash. 1975. Technical Information Center, Energy Research and Development Administration, CONF-75092.

Wallace, A. Romney, E. M., Alexander, G. V., Soufi, S. M., and Patel, P. M. 1977. Some Interactions in Plants among Cadmium, other Heavy Metals and Chelating Agents. Agron. J. 69:18-20.

Williams, C. H. and D. J. David. 1973. The Effect of Superphosphate on the Cadmium Content of Soils and Plants. Aust. J. Soil res. 11:43-56.

Williams, C. H. and D. J. David. 1976. The Accumulation in Soil of Cadmium Residues from Phosphate Fertilizers and their Effect on the Cadmium Content of Plants. Soil Sci. 121:86-93.

Williams, C. H. and D. J. David. 1977. Some Effects of the Distribution of Cadmium and Phosphate in Root Zone on the Cadmium Content of Plants. Aust. J. Soil Res. 15:59-68.

Williams, D. E., Vlannis, J., Pukite, A. H., and Covey, J. E. 1983. Metal Movement in Sludge-Treated Soils after Six Years of Sludge Addition: 1. Cadmium, Copper, Lead and Zinc. J. Environ. Qual. 12:51-58.

APPENDIXES

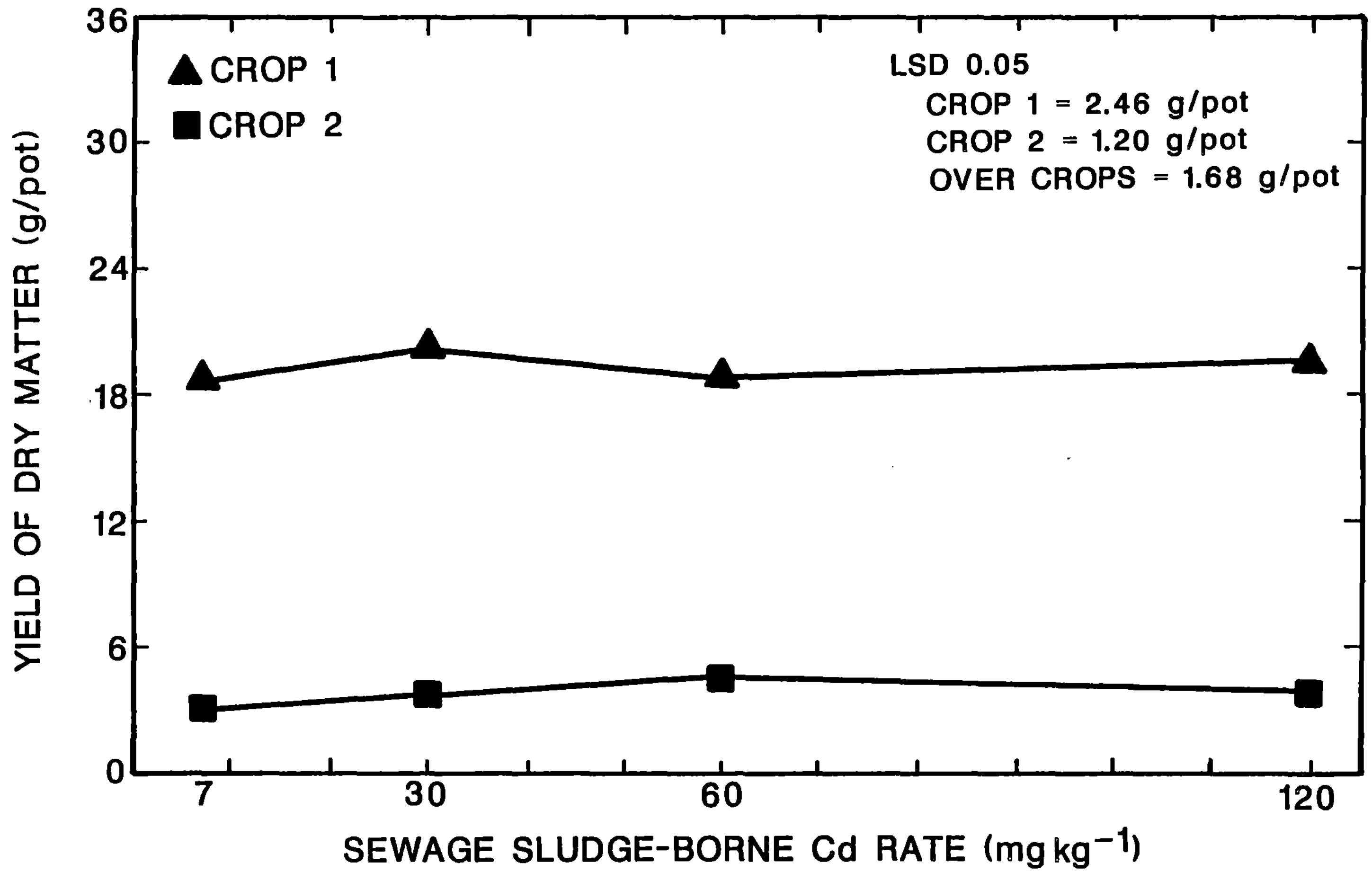

Figure 40. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (0-15 cm) on Yield of Dry Matter by Two Successive Crops of Soybean Plants on Norge Loam Soil

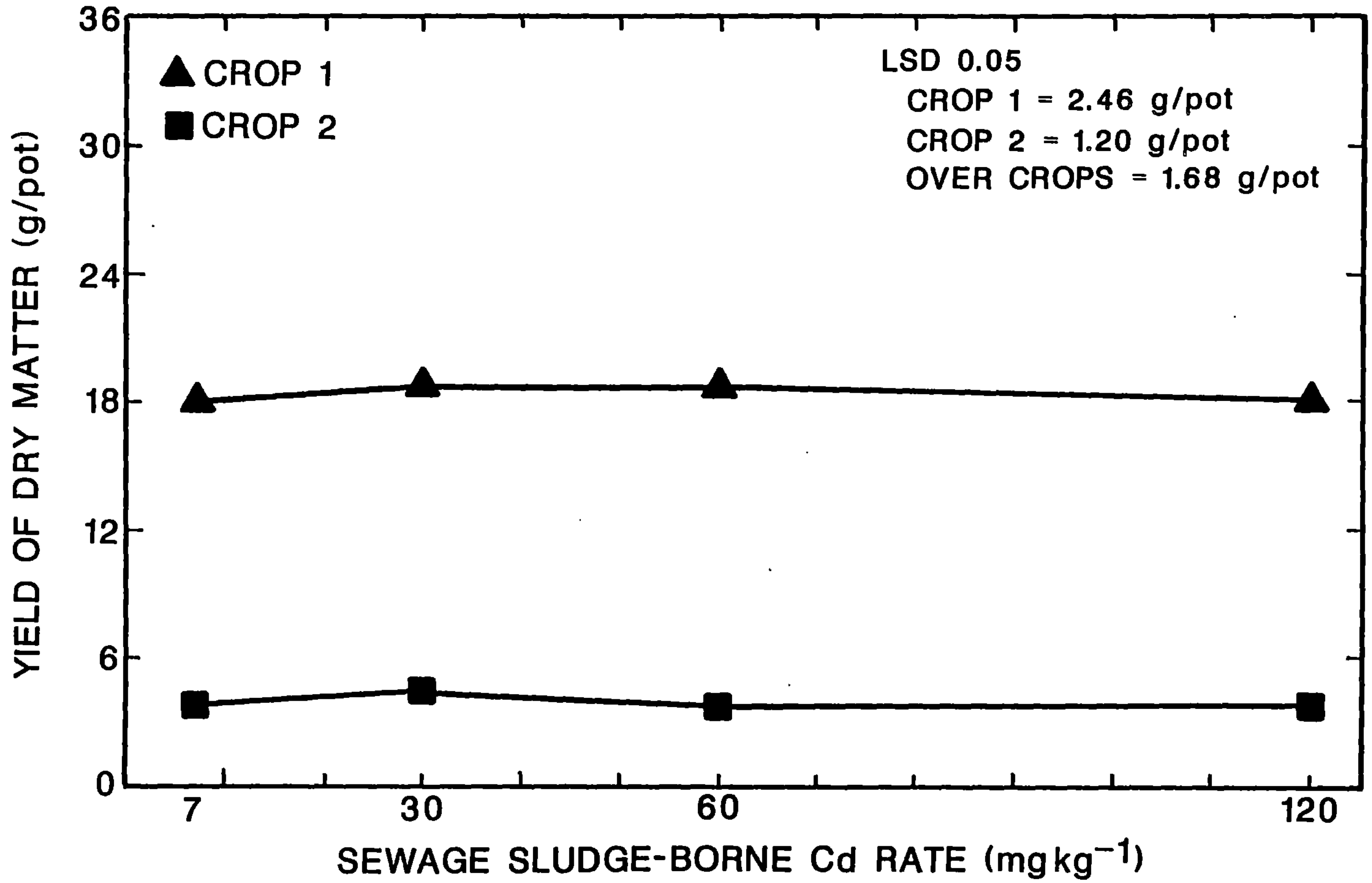

Figure 41. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (15-30 cm) on Yield of Dry Matter by Two Successive Crops of Soybean Plants on Norge Loam Soil

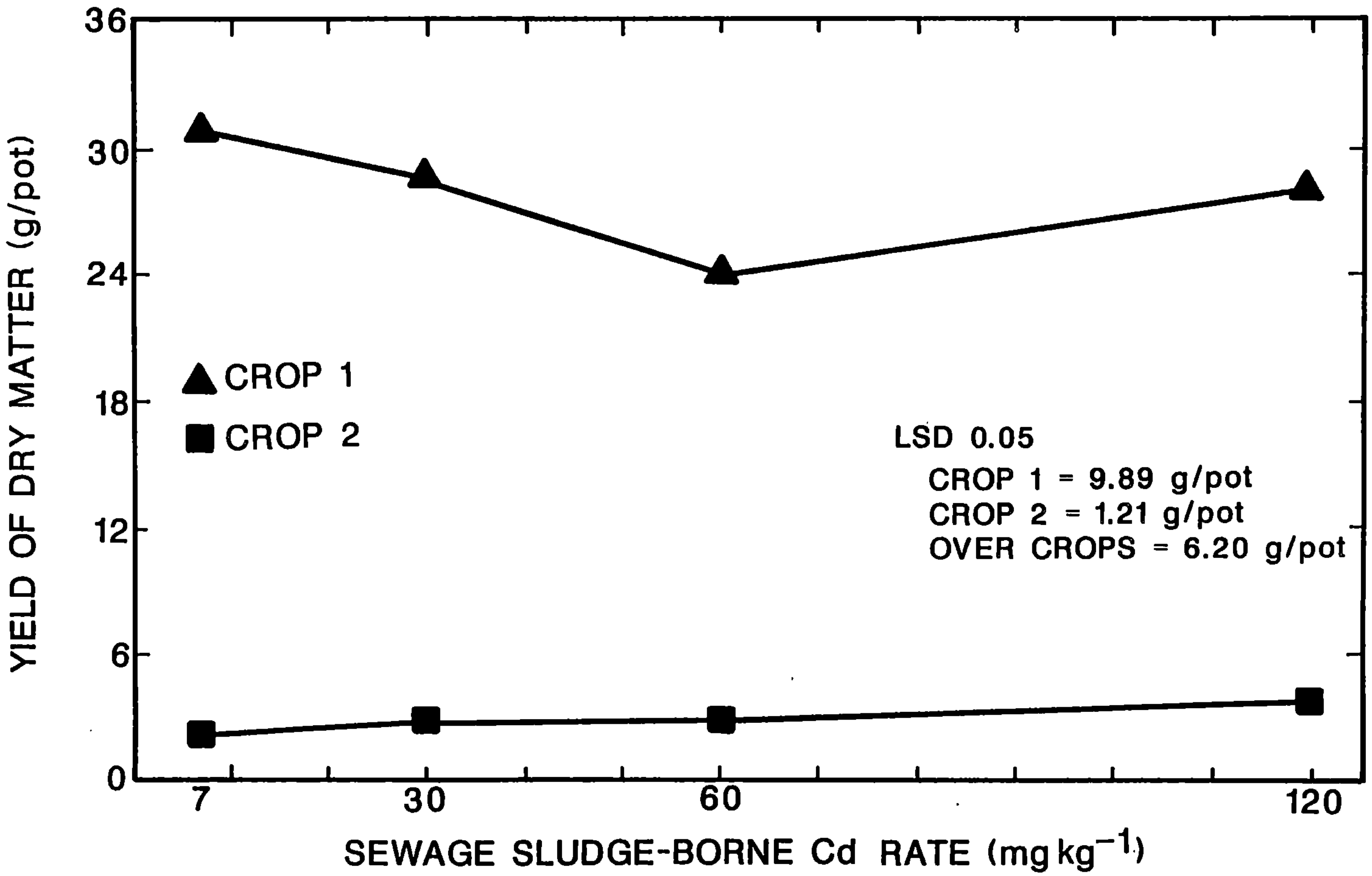

Figure 42. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (0-15 cm) on Yield of Dry Matter by Two Successive Crops of Sorghum Plants on Norge Loam Soil

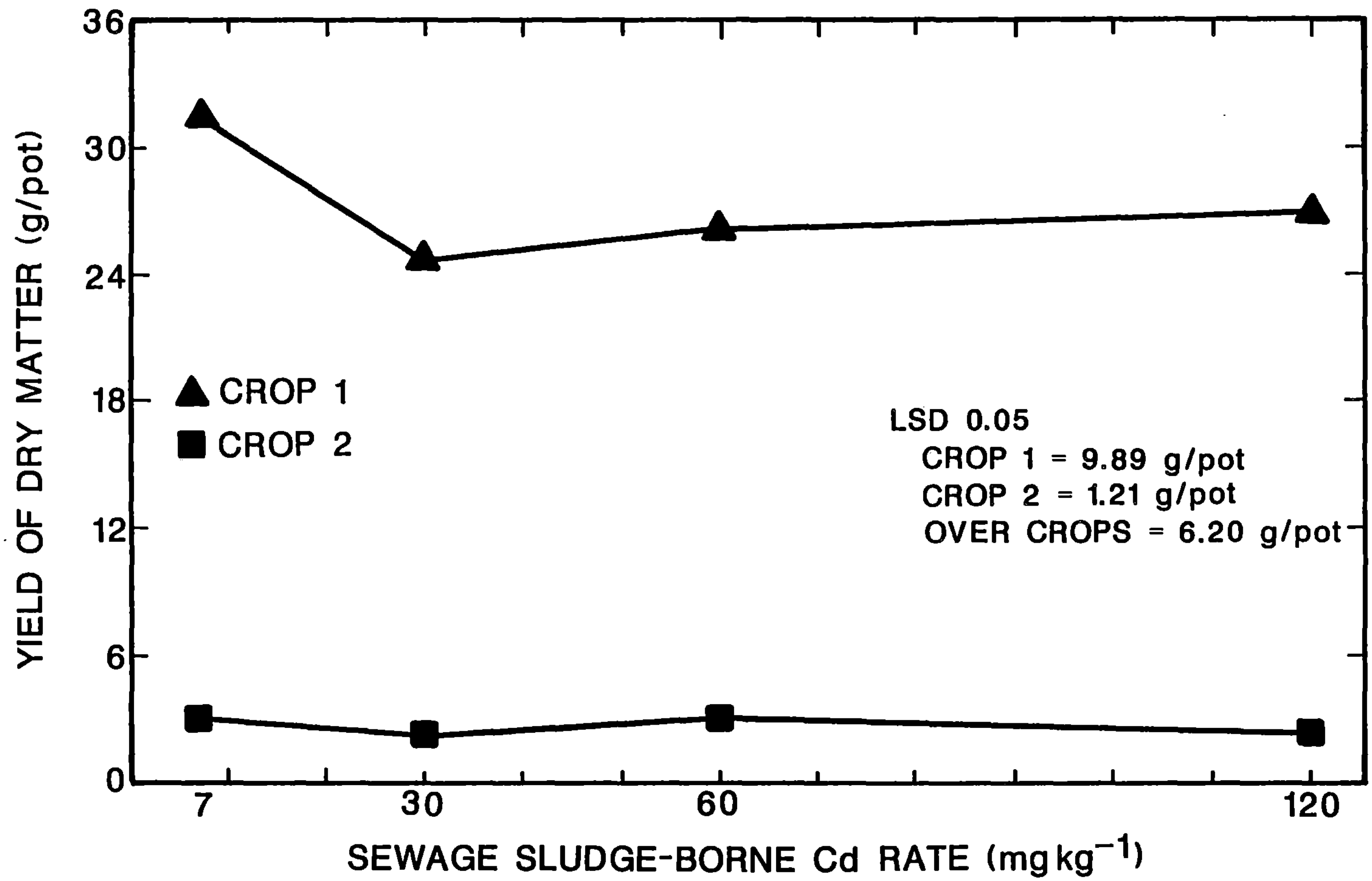

Figure 43. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (15-30 cm) on Yield of Dry Matter by Two Successive Crops of Sorghum Plants on Norge Loam Soil

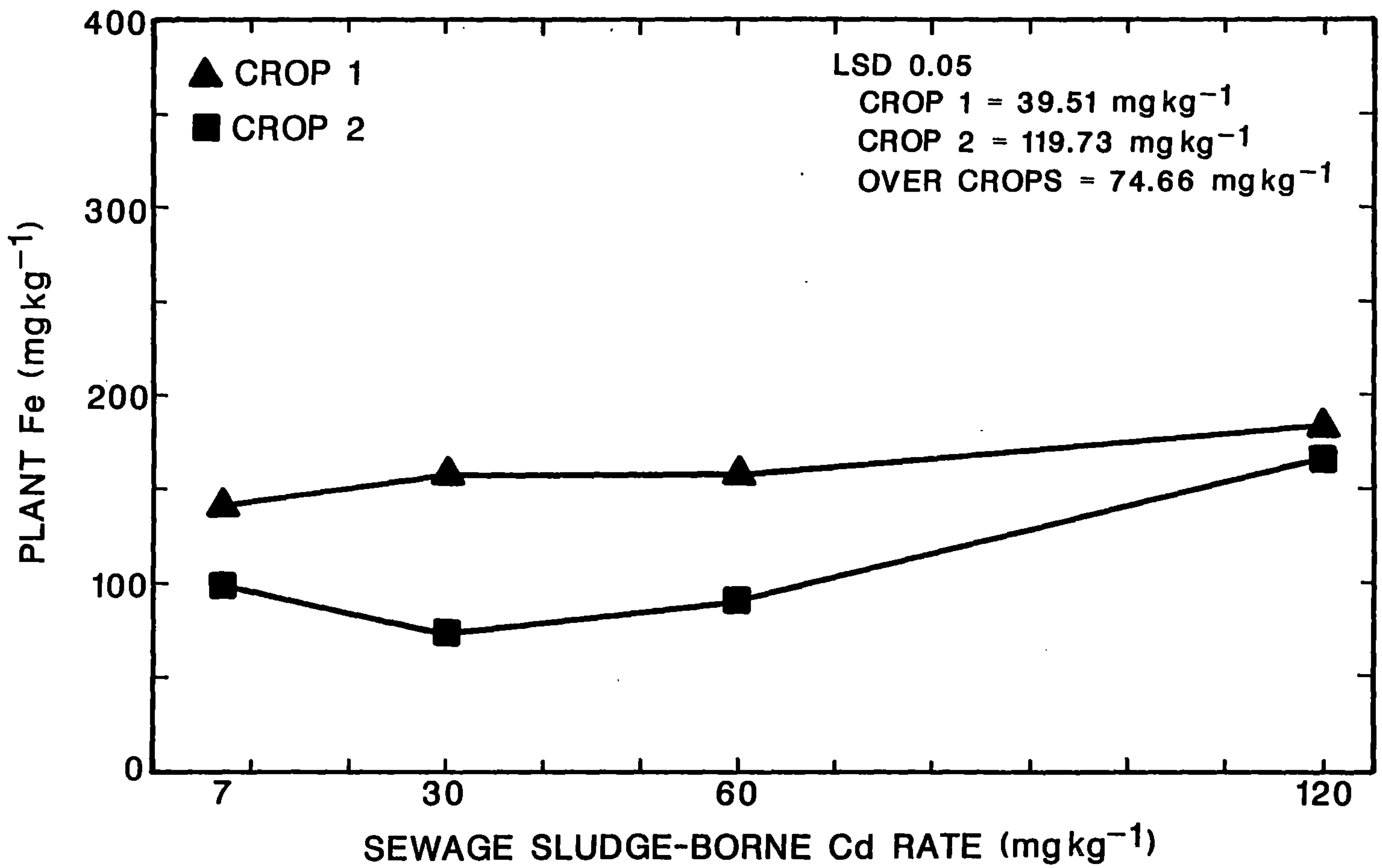

Figure 44. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (0-15 cm) on Fe Uptake by Two Successive Crops of Soybean Plants on Norge Loam Soil

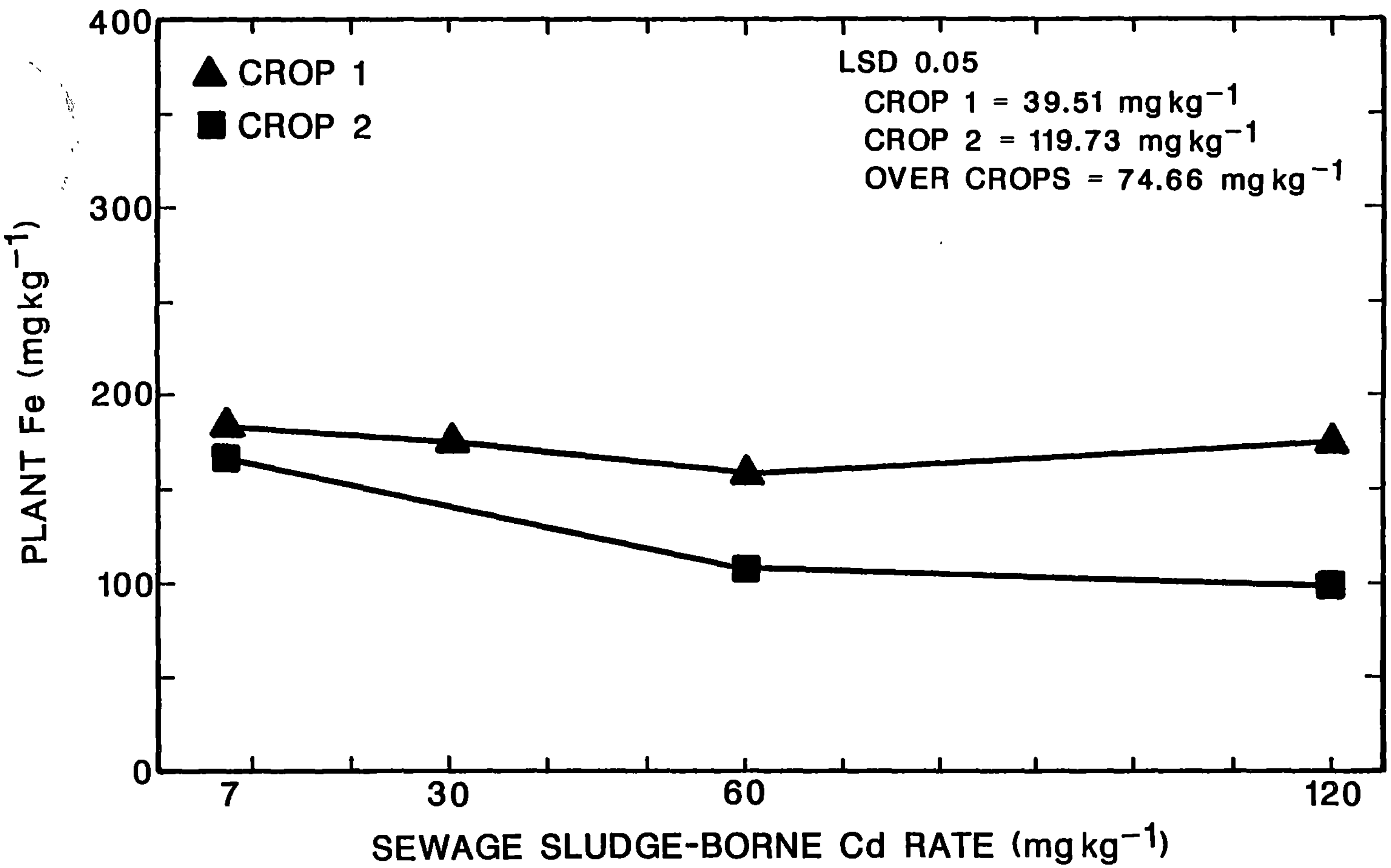

Figure 45. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (15-30 cm) on Fe Uptake by Two Successive Crops of Soybean Plants of Norge Loam Soil

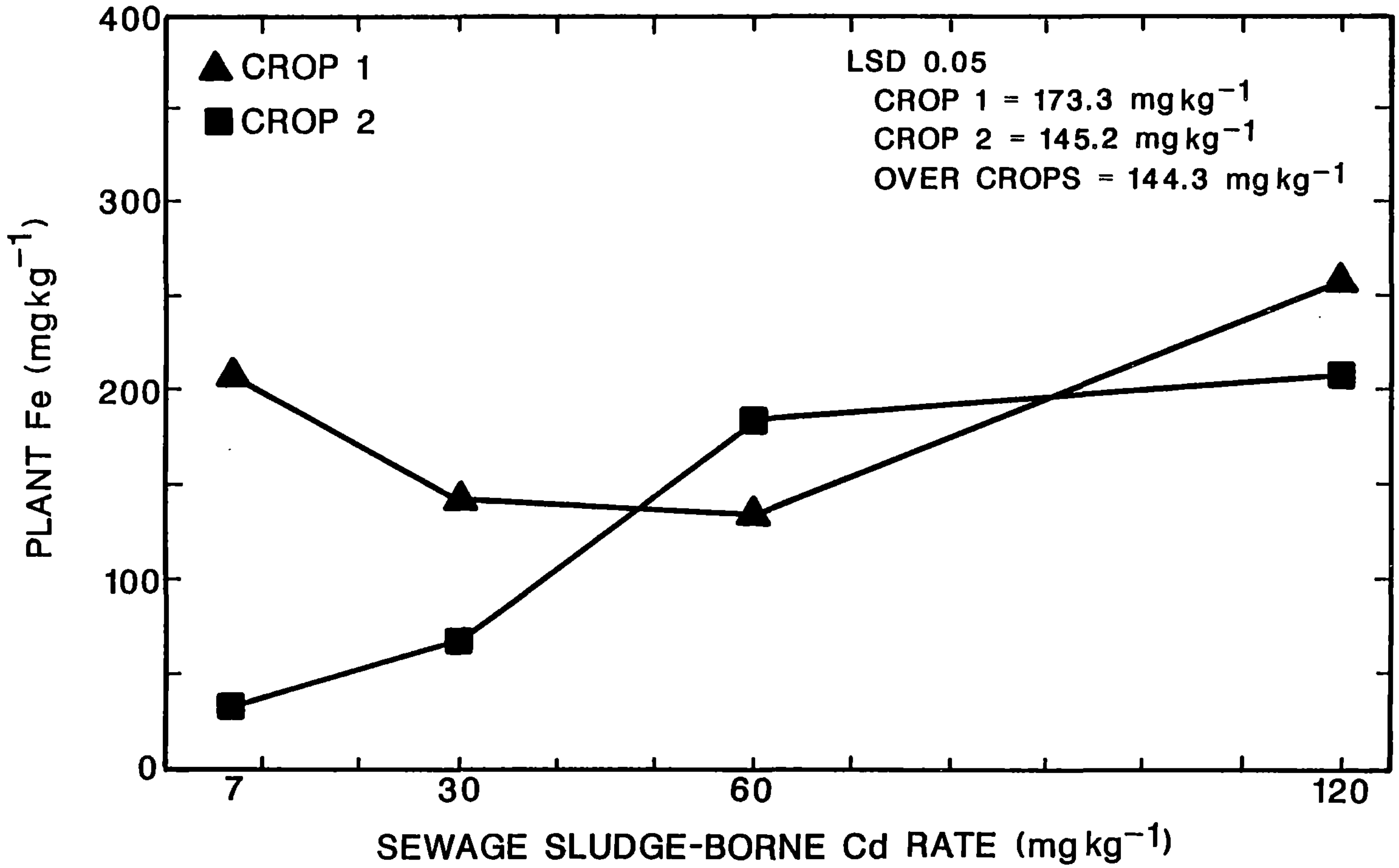

Figure 46. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (0-15 cm) on Fe Uptake by Two Successive Crops of Sorghum Plants on Norge Loam Soil

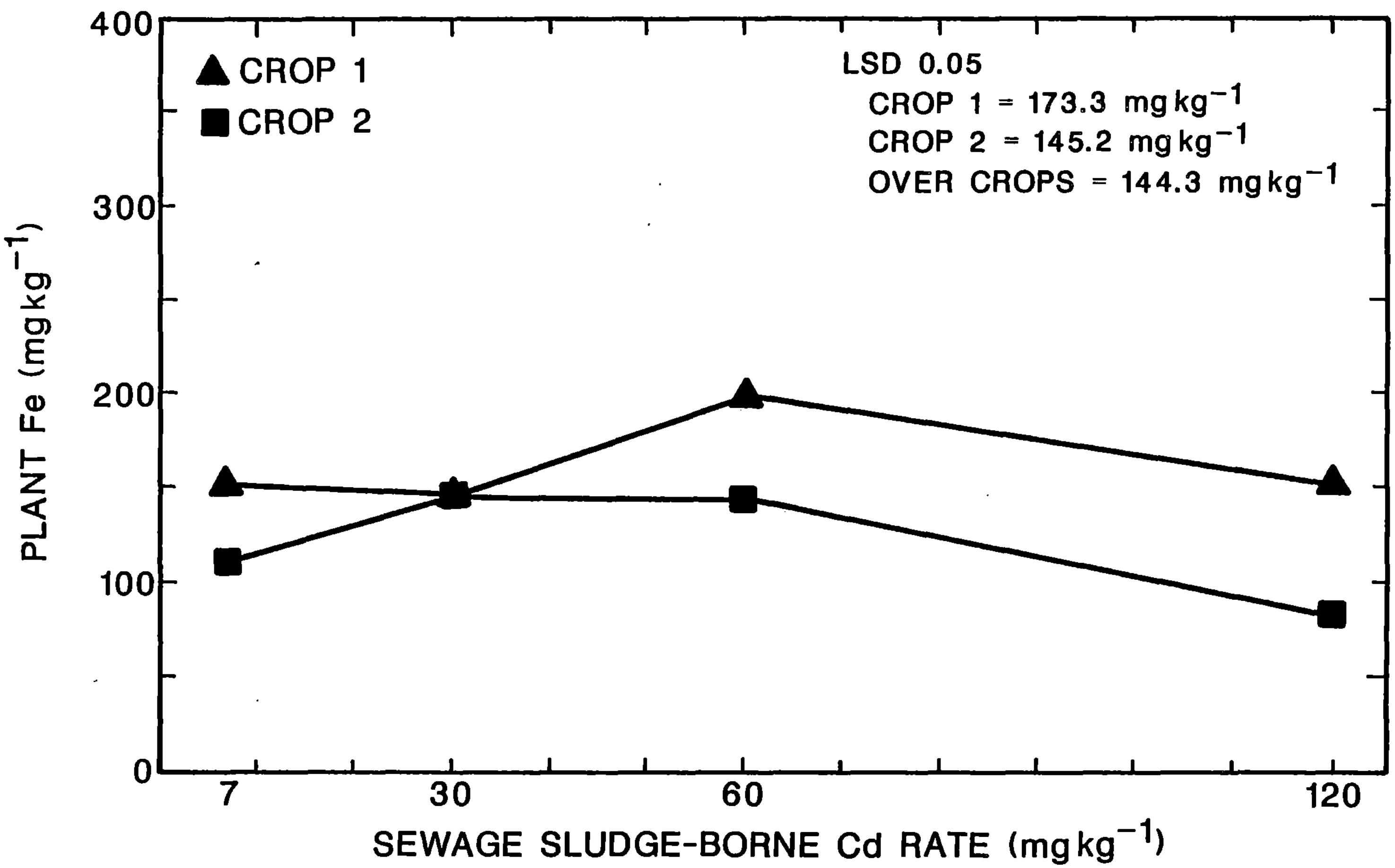

Figure 47. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (15-30 cm) on Fe Uptake by Two Successive Crops of Sorghum Plants on Norge Loam Soil

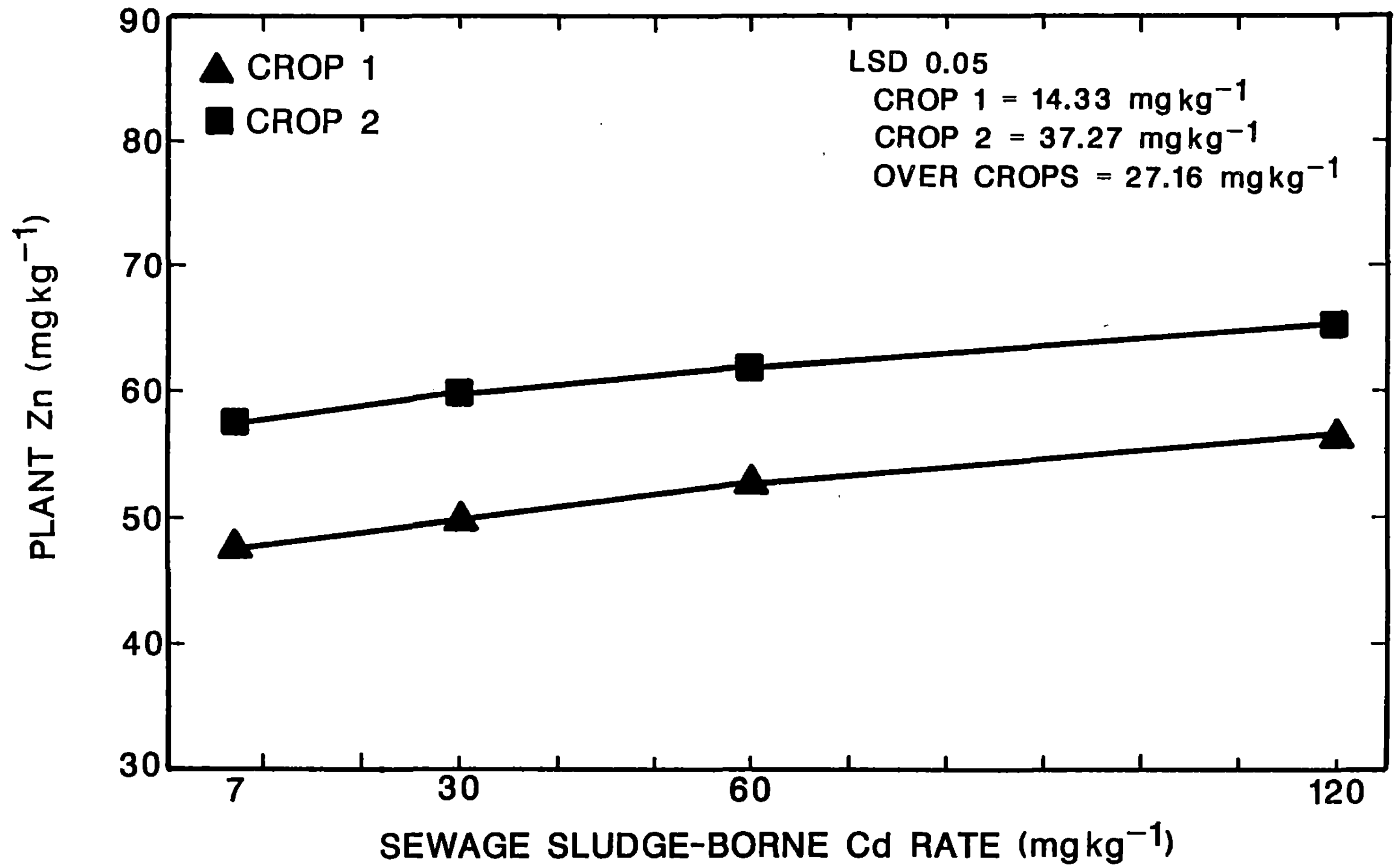

Figure 48. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (0-15 cm) on Zn Uptake by Two Successive Crops of Soybean Plants on Norge Loam Soil

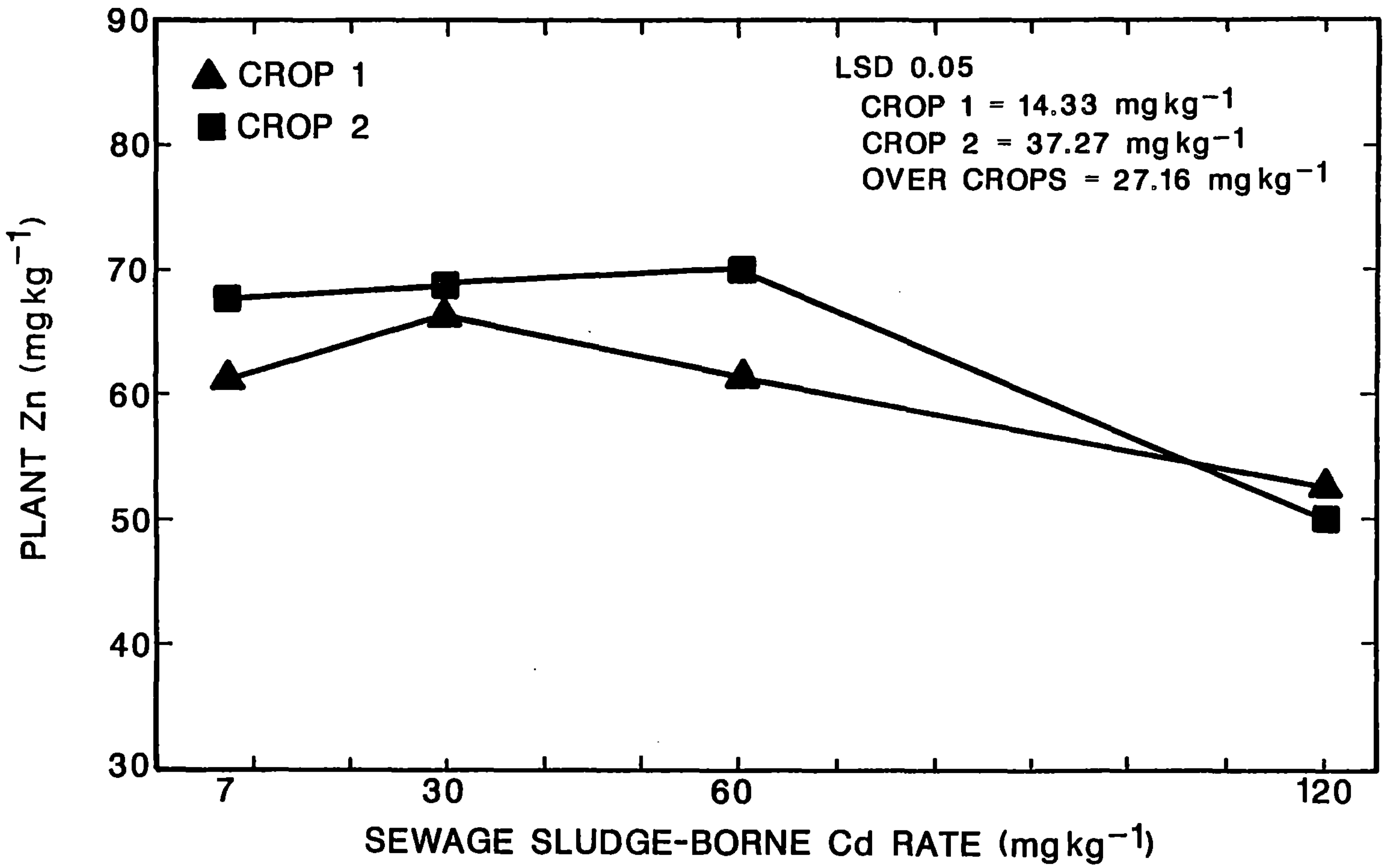

Figure 49. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (15-30 cm) on Zn Uptake by Two Successive Crops of Soybean Plants on Norge Loam Soil

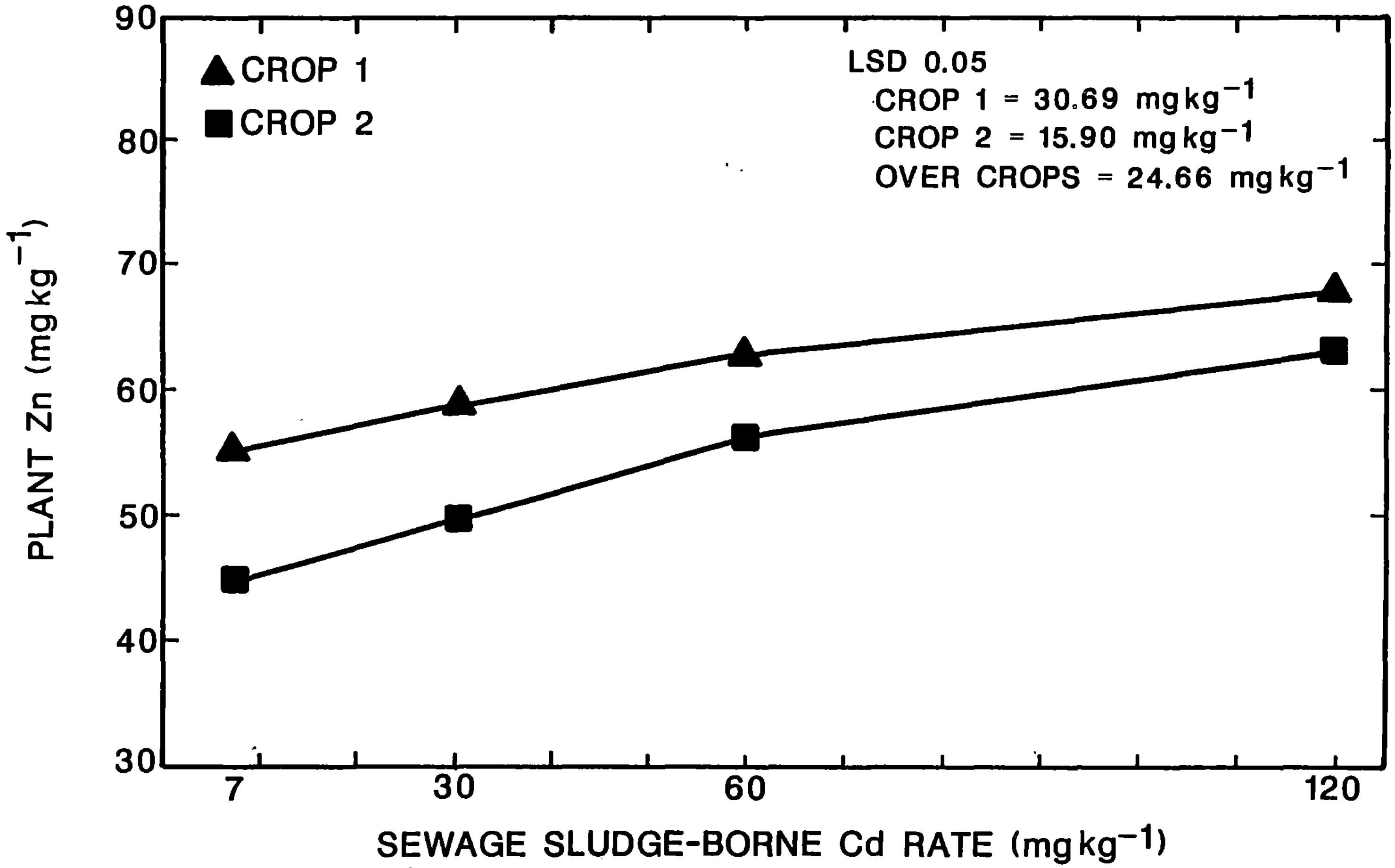

Figure 50. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (0-15 cm) on Zn Uptake by Two Successive Crops of Sorghum Plants on Norge Loam Soil

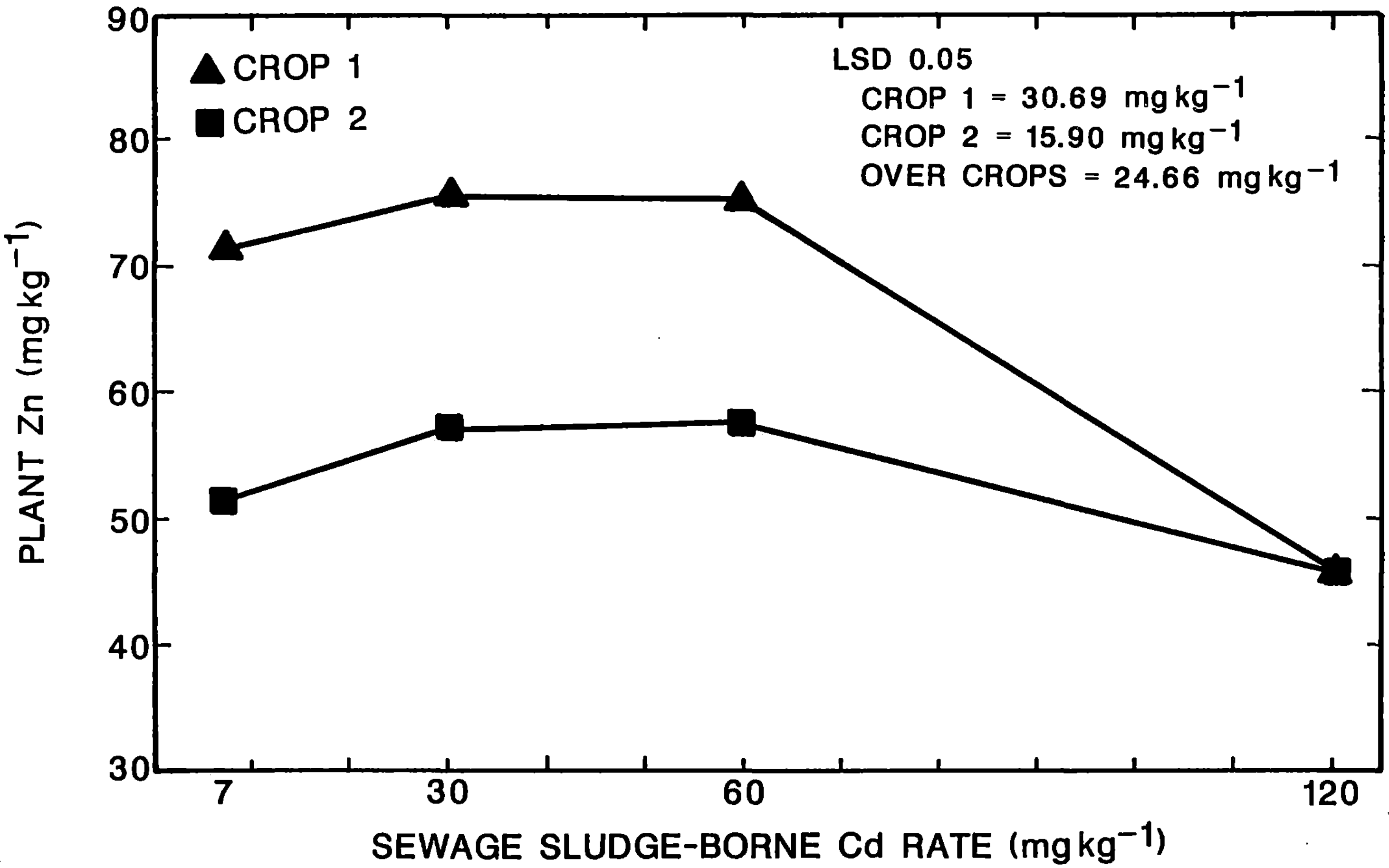

Figure 51. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (15-30 cm) on Zn Uptake by Two Successive Crops of Sorghum Plants on Norge Loam Soil

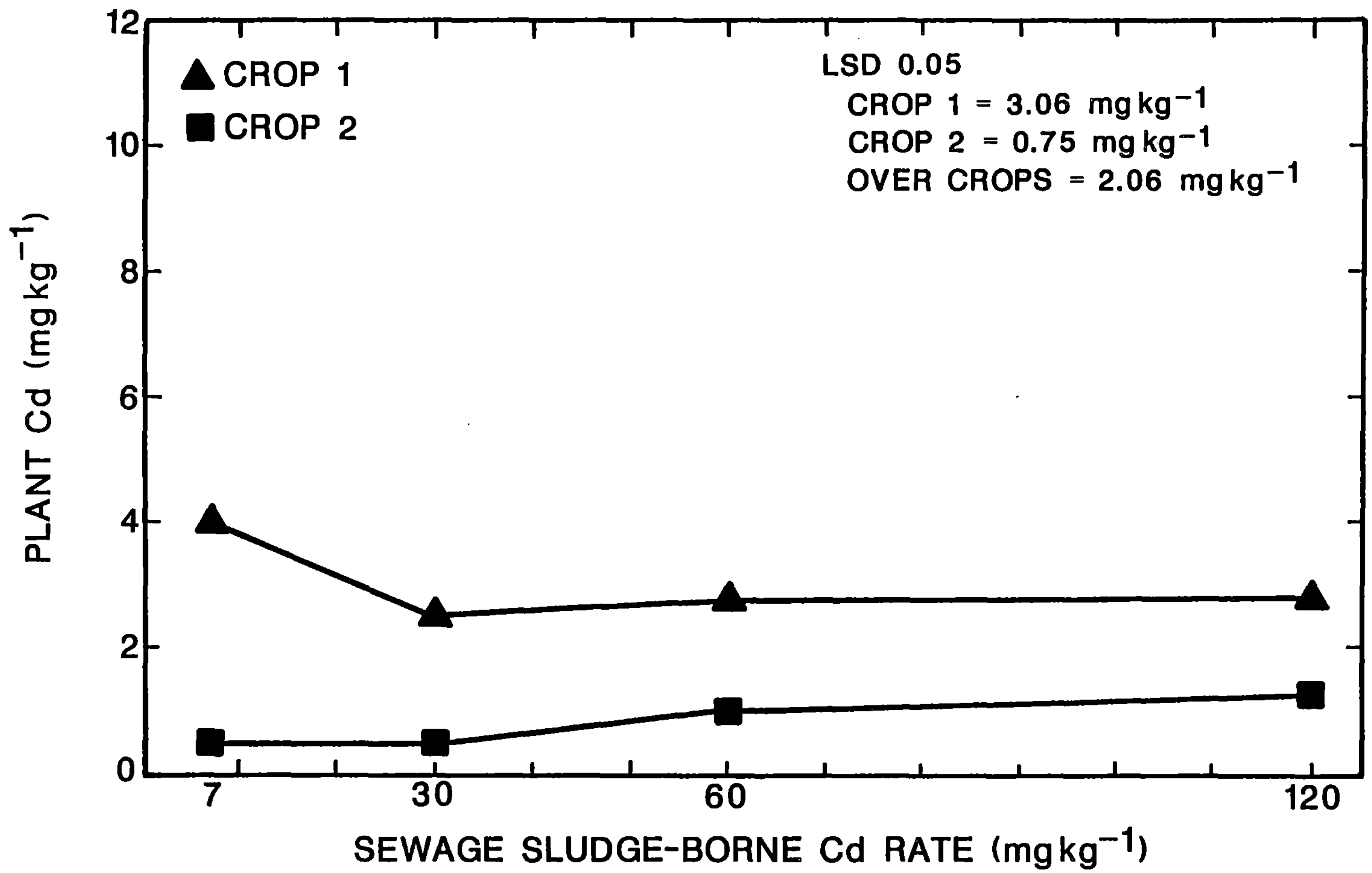

Figure 52. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (0-15 cm) on Cd Uptake by Two Successive Crops of Soybean Plants on Norge Loam Soil

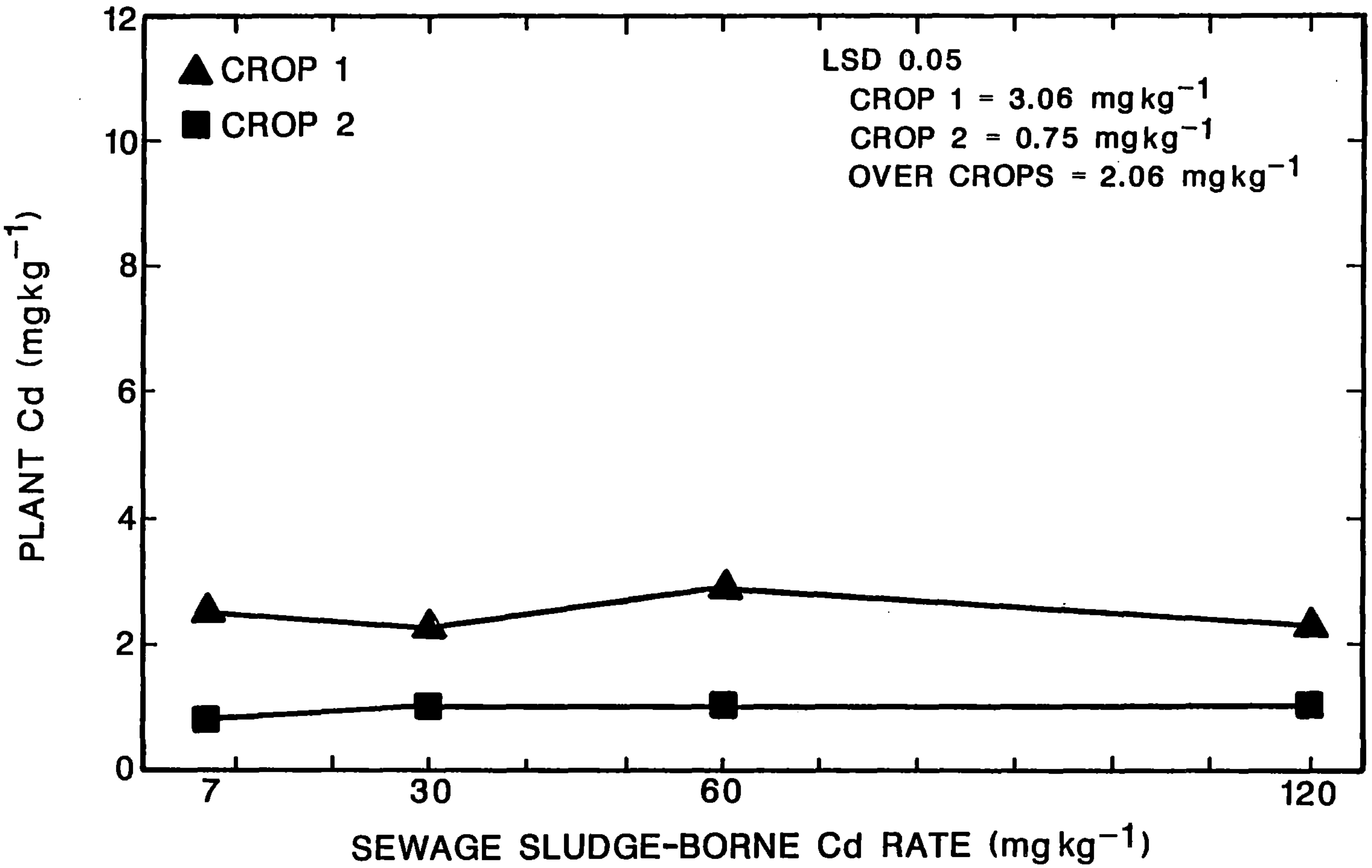

Figure 53. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (15-30 cm) on Cd Uptake by Two Successive Crops of Soybean Plants on Norge Loam Soil

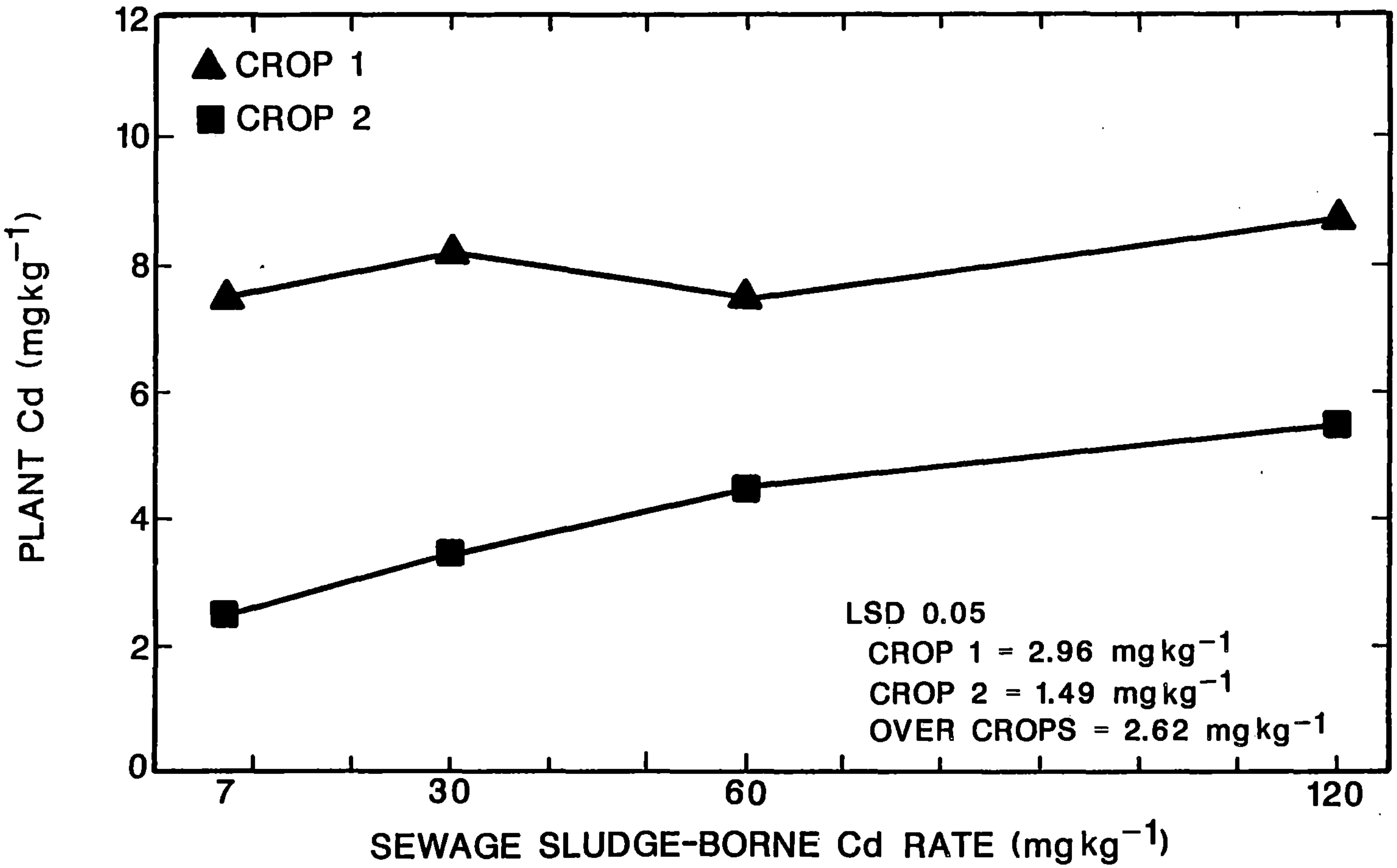

Figure 54. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (0-15 cm) on Cd Uptake by Two Successive Crops of Sorghum Plants on Norge Loam Soil

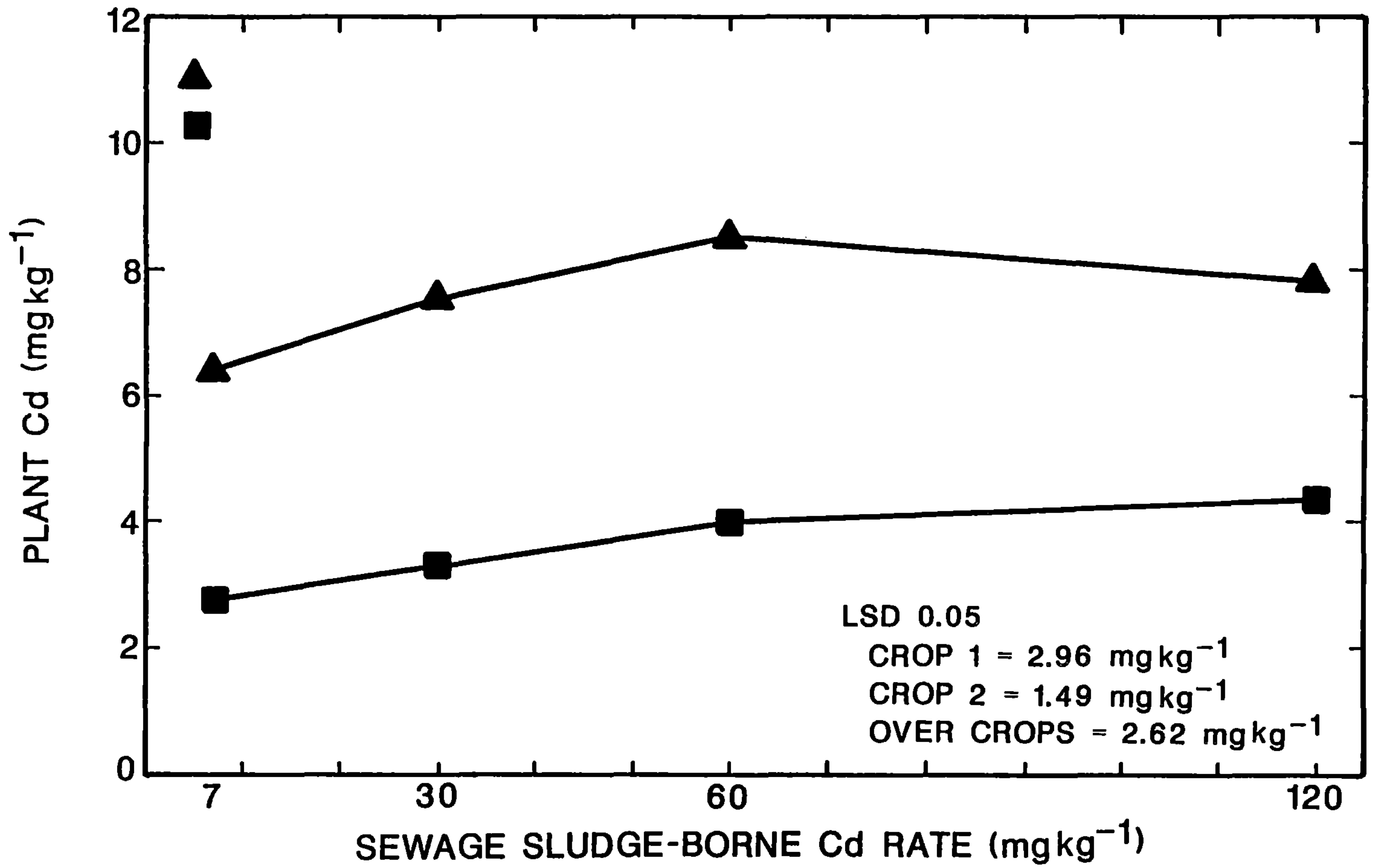

Figure 55. The Effect of Sewage Sludge-Borne Cadmium Rate (44 mt ha^{-1} Sewage Sludge) and Depth of Application (15-30 cm) on Cd Uptake by Two Successive Crops of Sorghum Plants on Norge Loam Soil

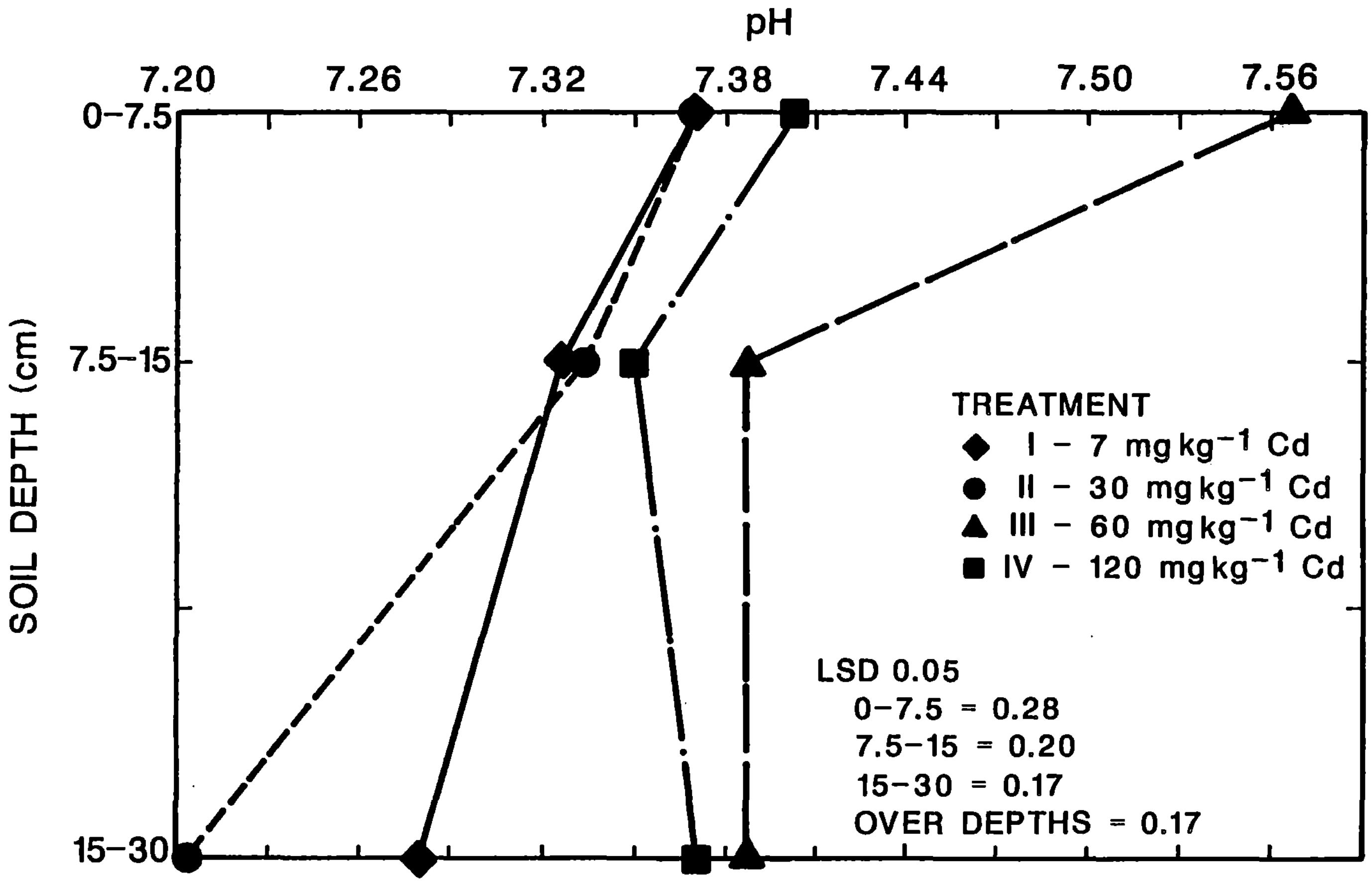

Figure 56. Soybean Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Surface Depth of Application (0-15 cm) on Final Soil pH of Norge Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

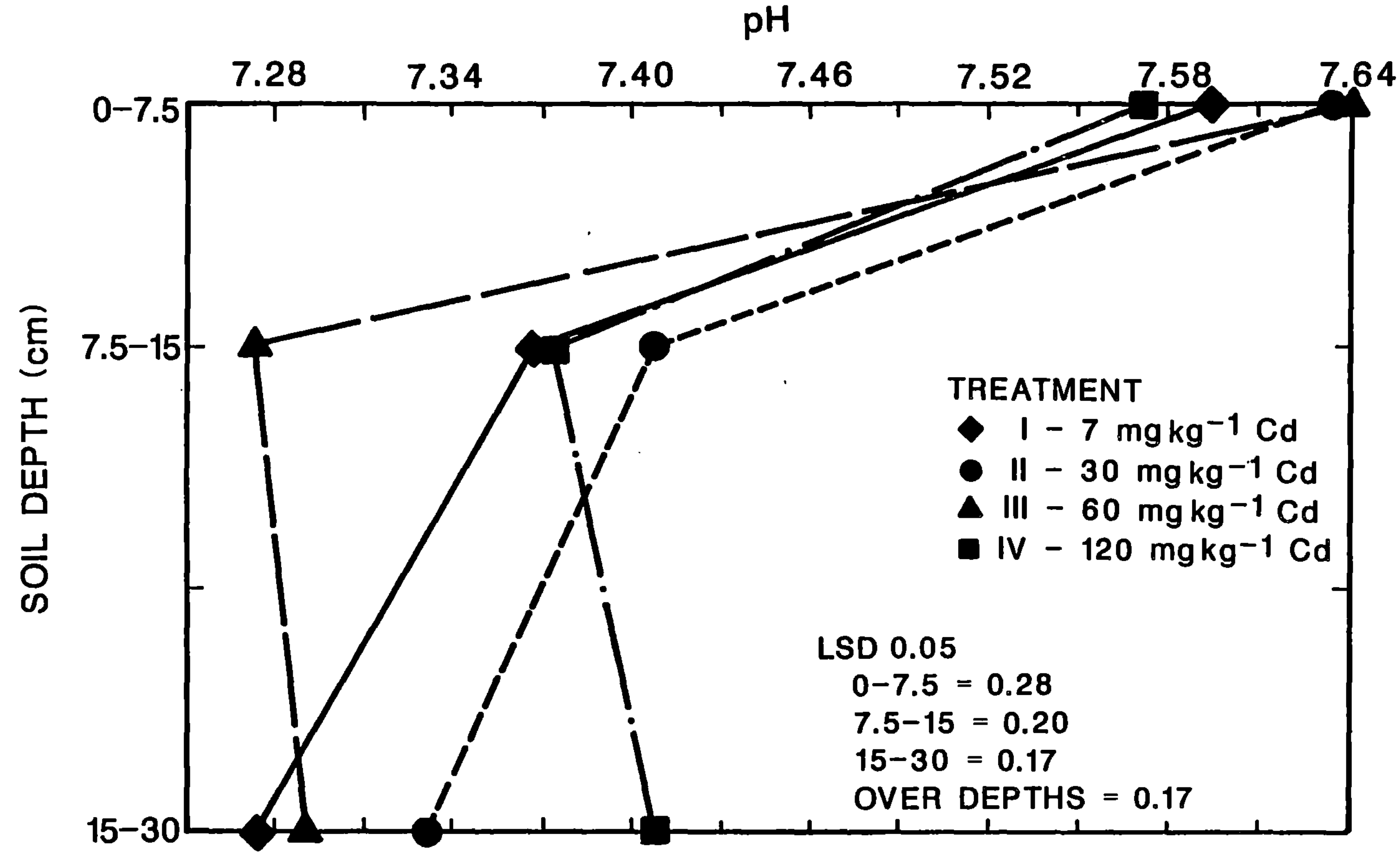

Figure 57. Soybean Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Subsurface Depth of Application (15-30 cm) on Final Soil pH of Norge Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

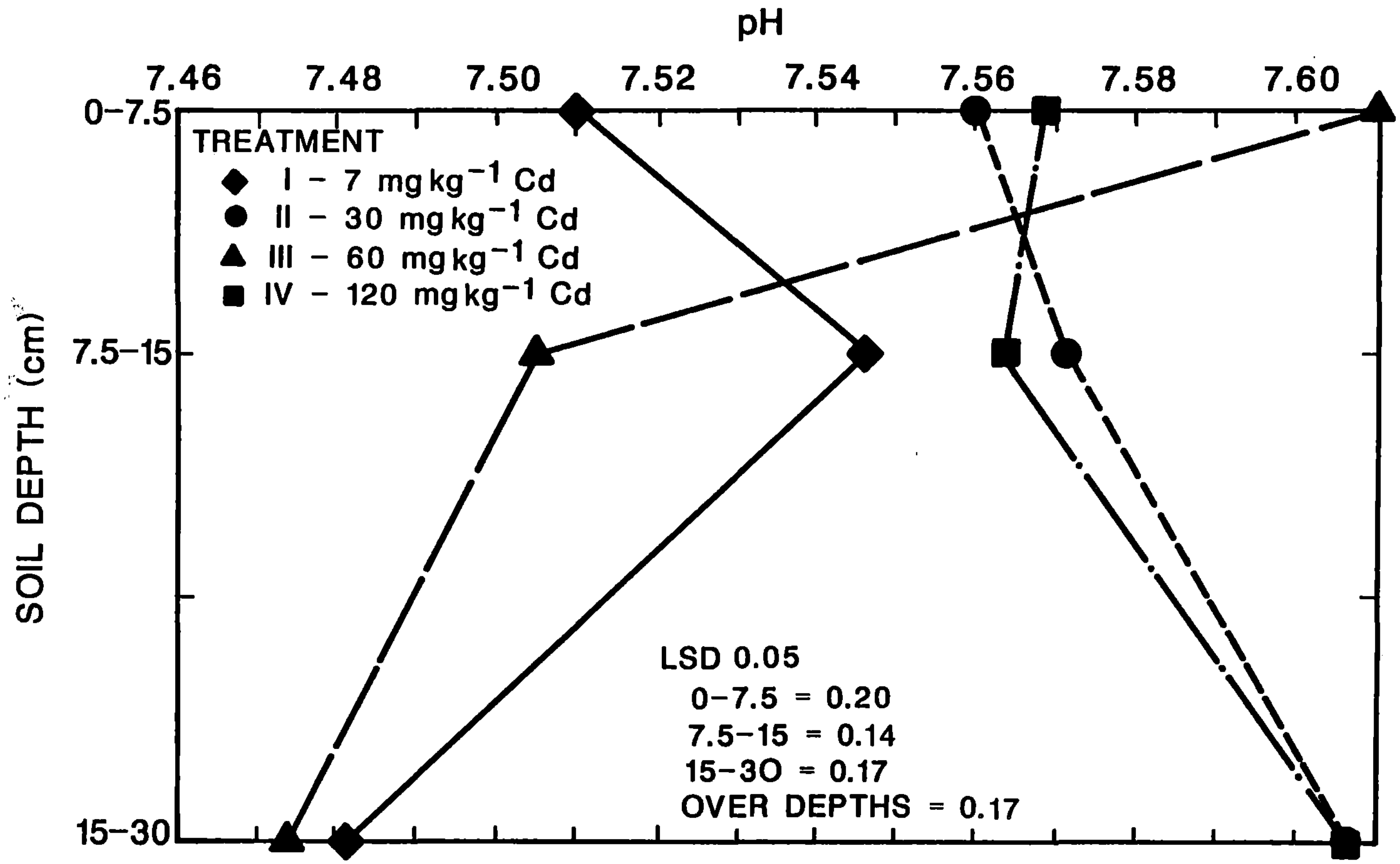

Figure 58. Sorghum Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Surface Depth of Application (0-15 cm) on Final Soil pH of Norge Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

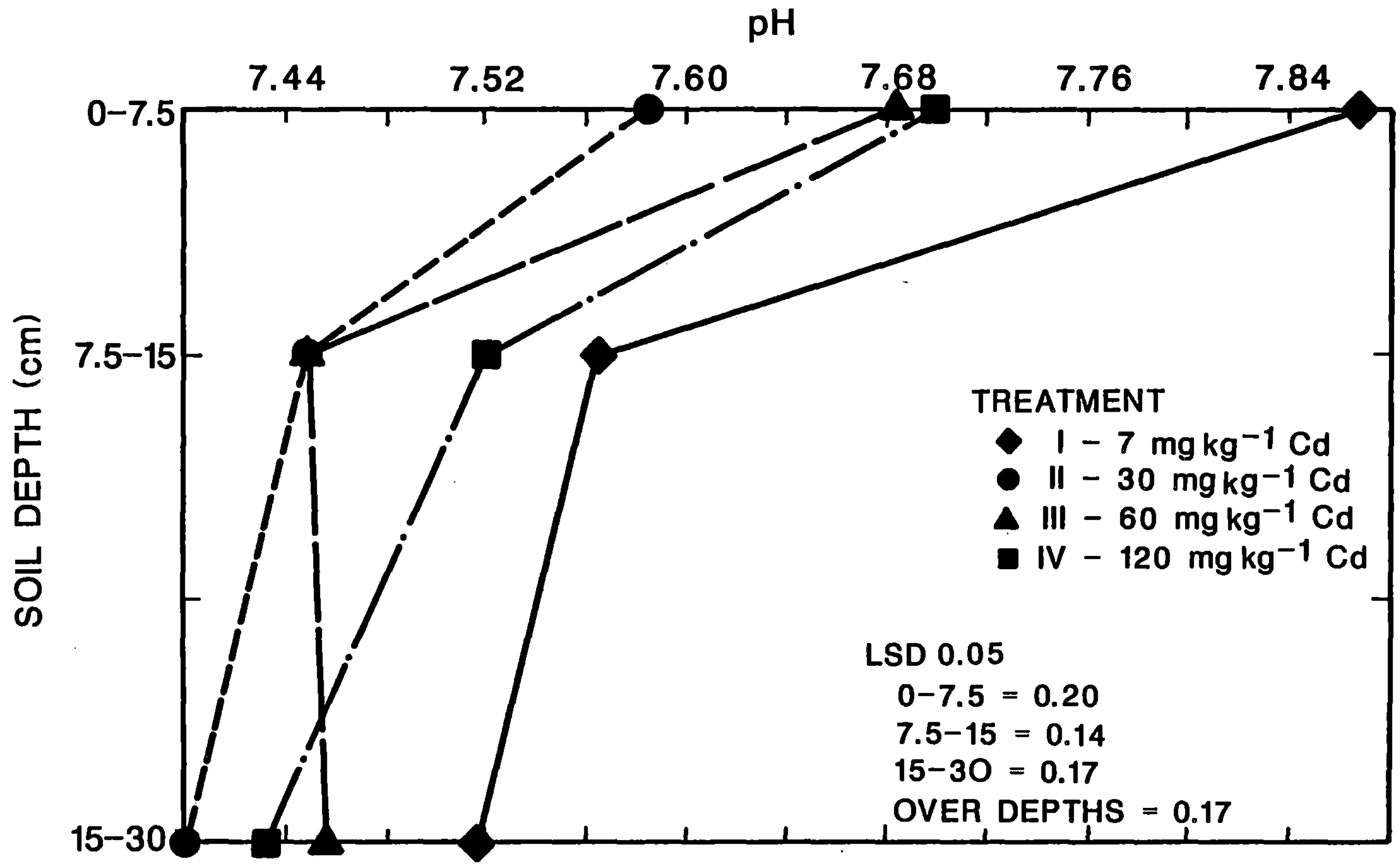

Figure 59. Sorghum Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Subsurface Depth of Application (15-30 cm) on Final Soil pH of Norge Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

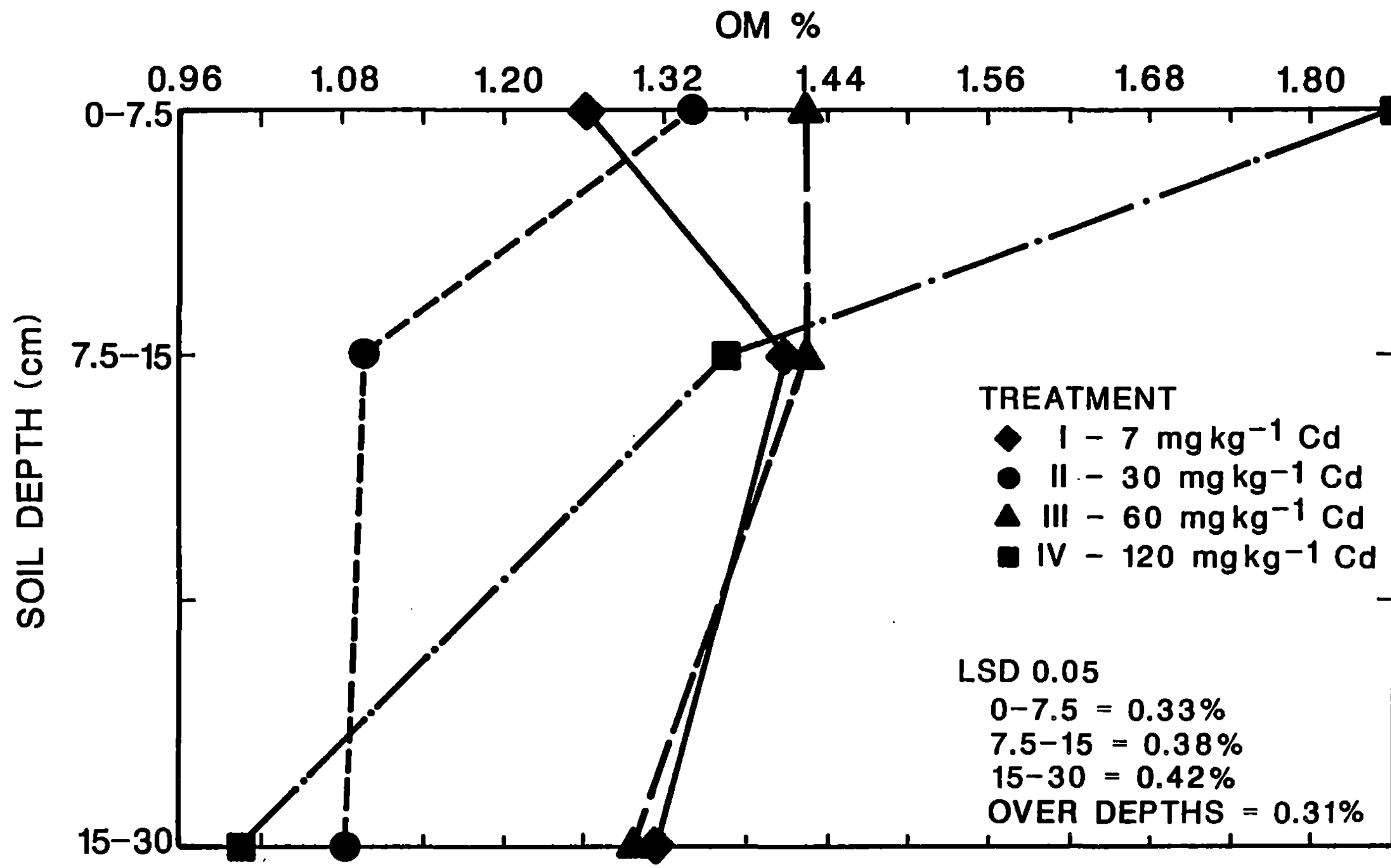

Figure 60. Soybean Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Surface Depth of Application (0-15 cm) on Final OM% of Norge Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

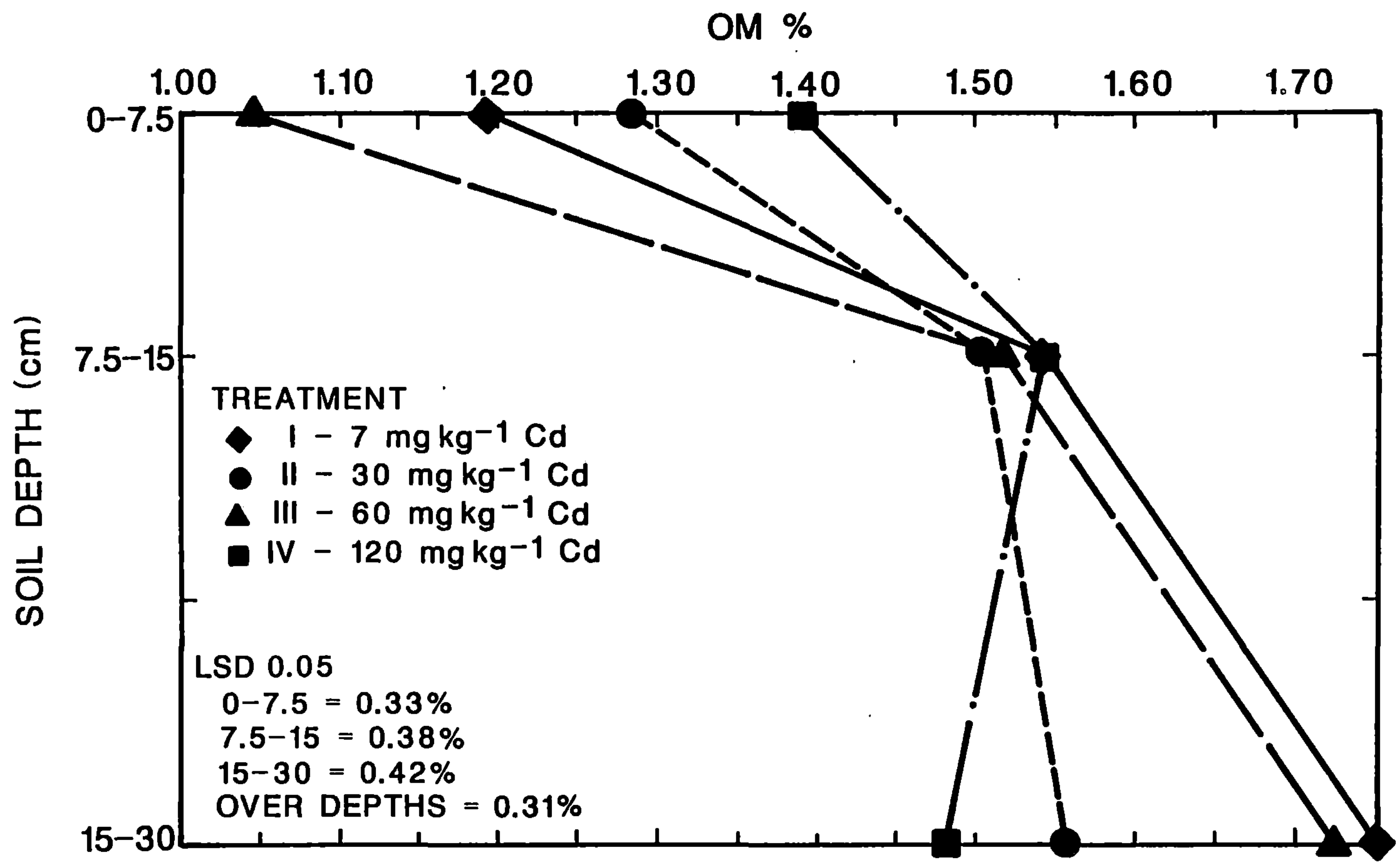

Figure 61. Soybean Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Subsurface Depth of Application (15-30 cm) on Final OM% of Norge Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

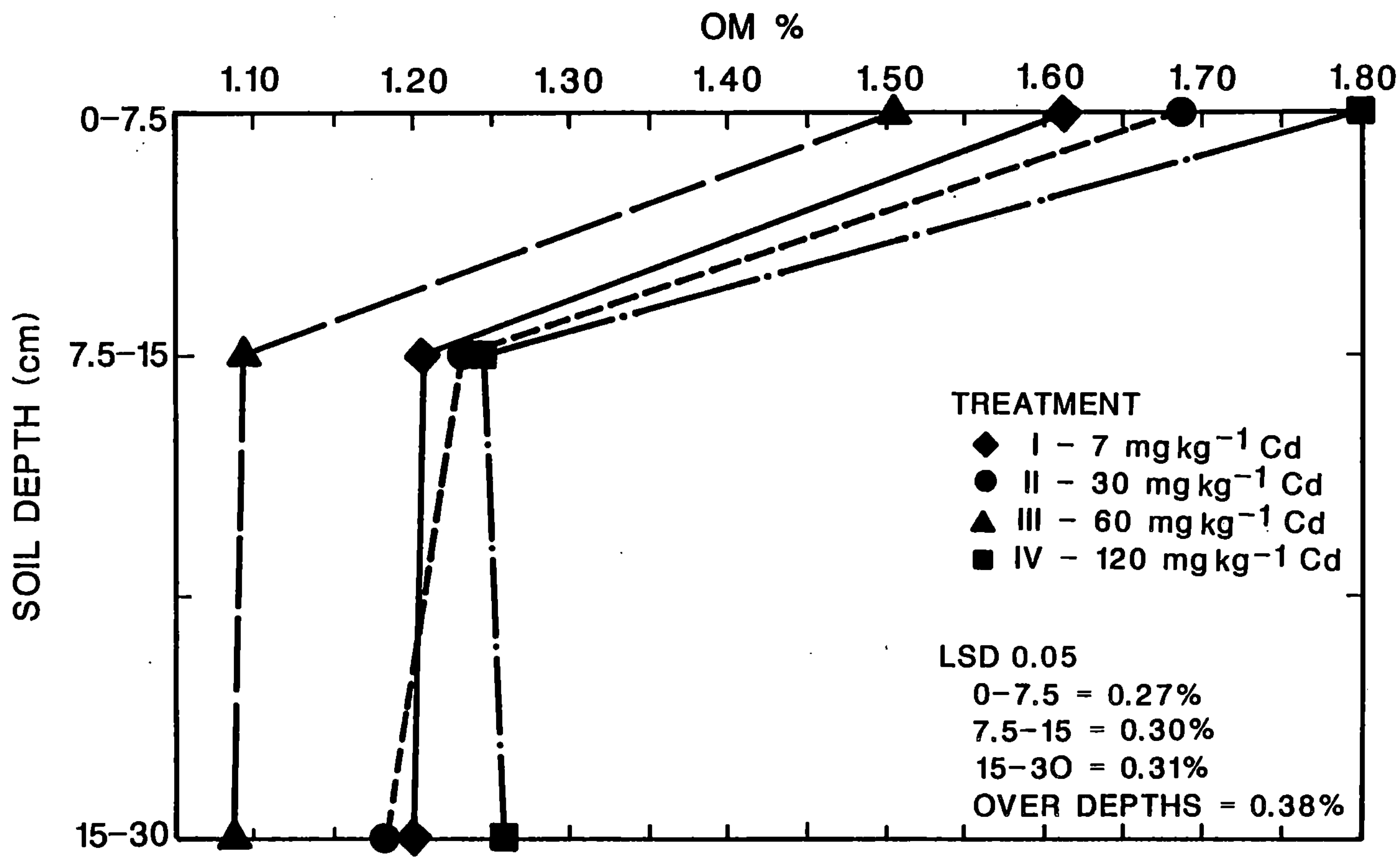

Figure 62. Sorghum Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Surface Depth of Application (0-15 cm) on Final OM% of Norge Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

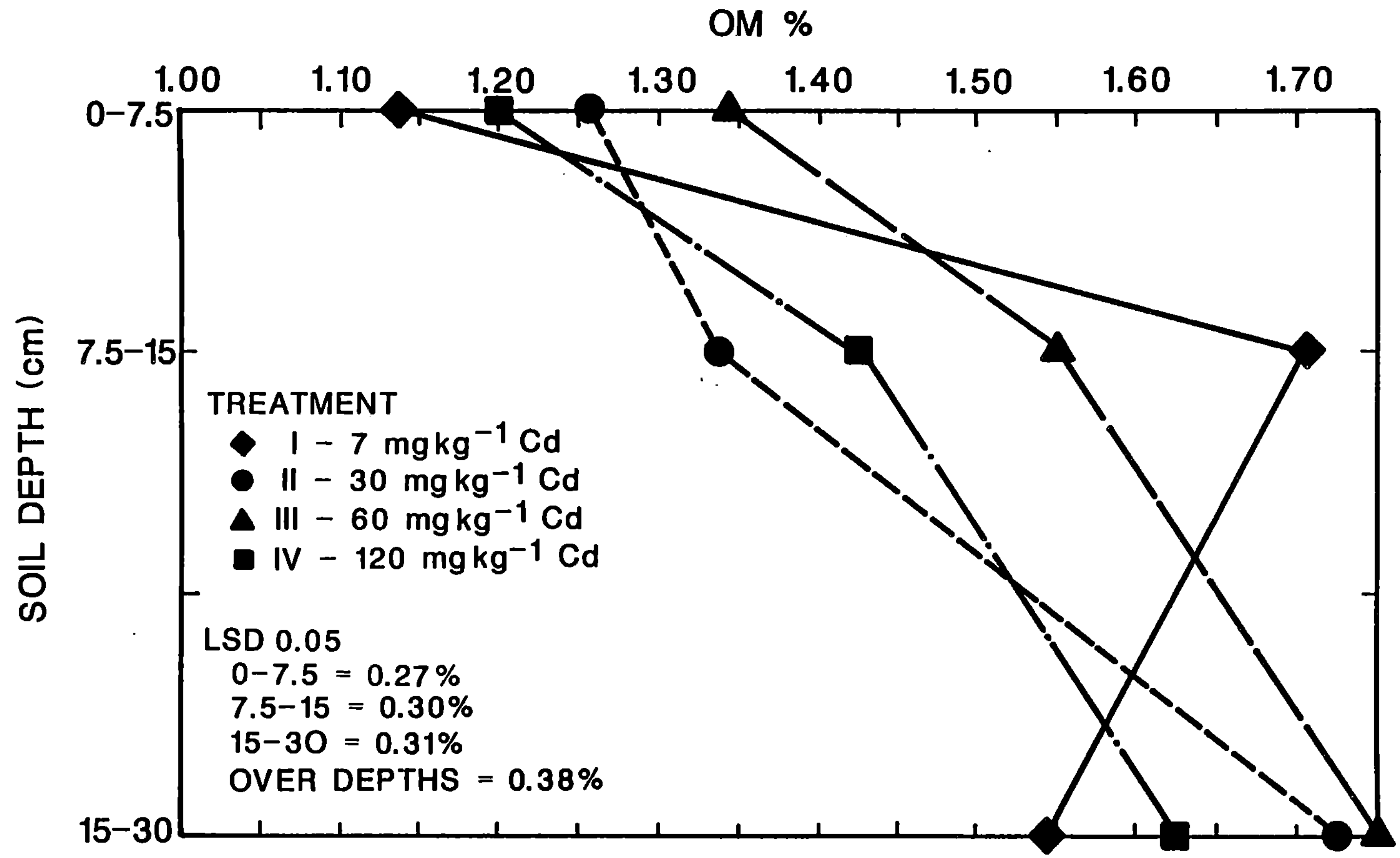

Figure 63. Sorghum Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Subsurface Depth of Application (15-30 cm) on Final OM% of Norge Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

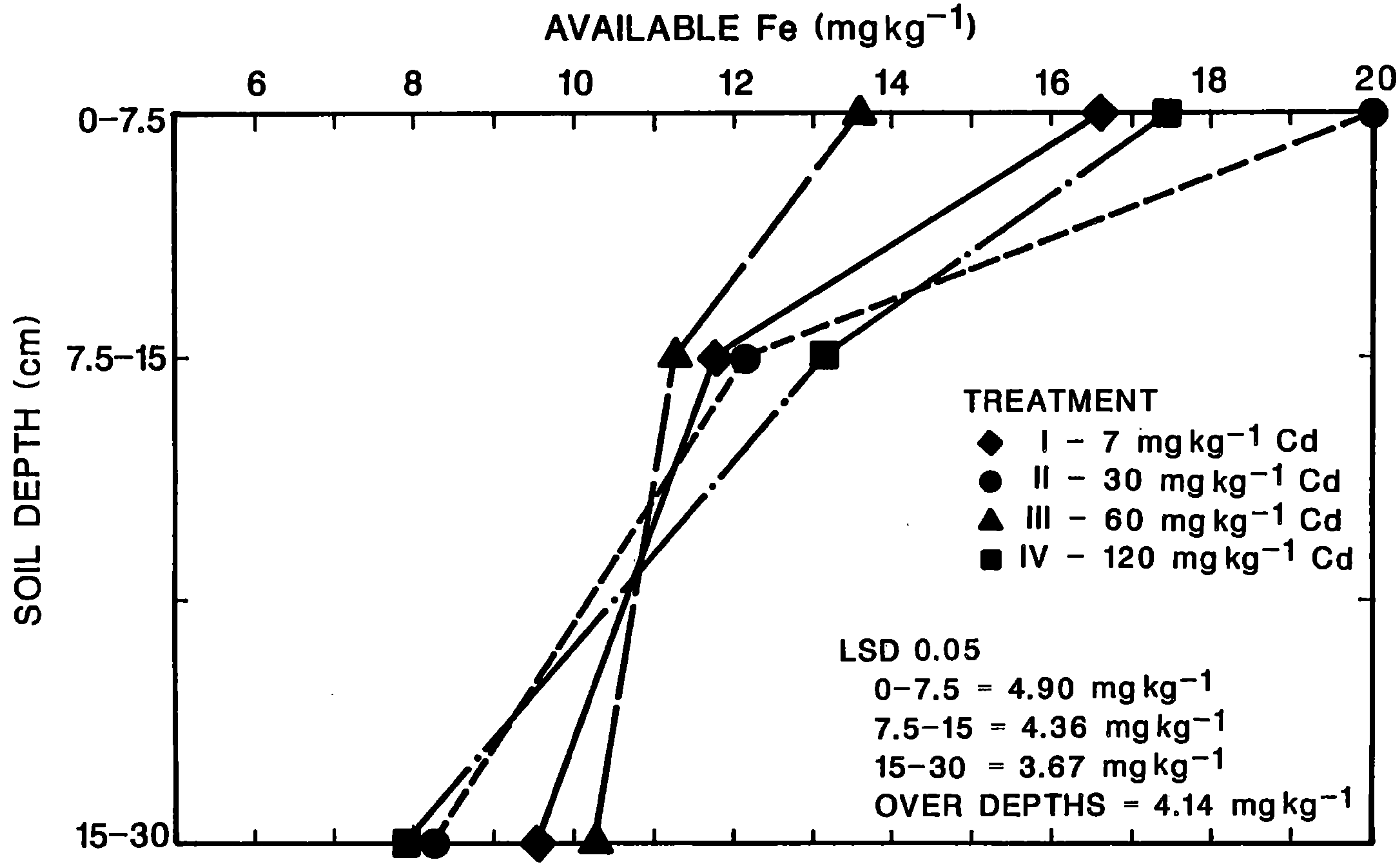

Figure 64. Soybean Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Surface Depth of Application (0-15 cm) on Available Fe of Norge Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

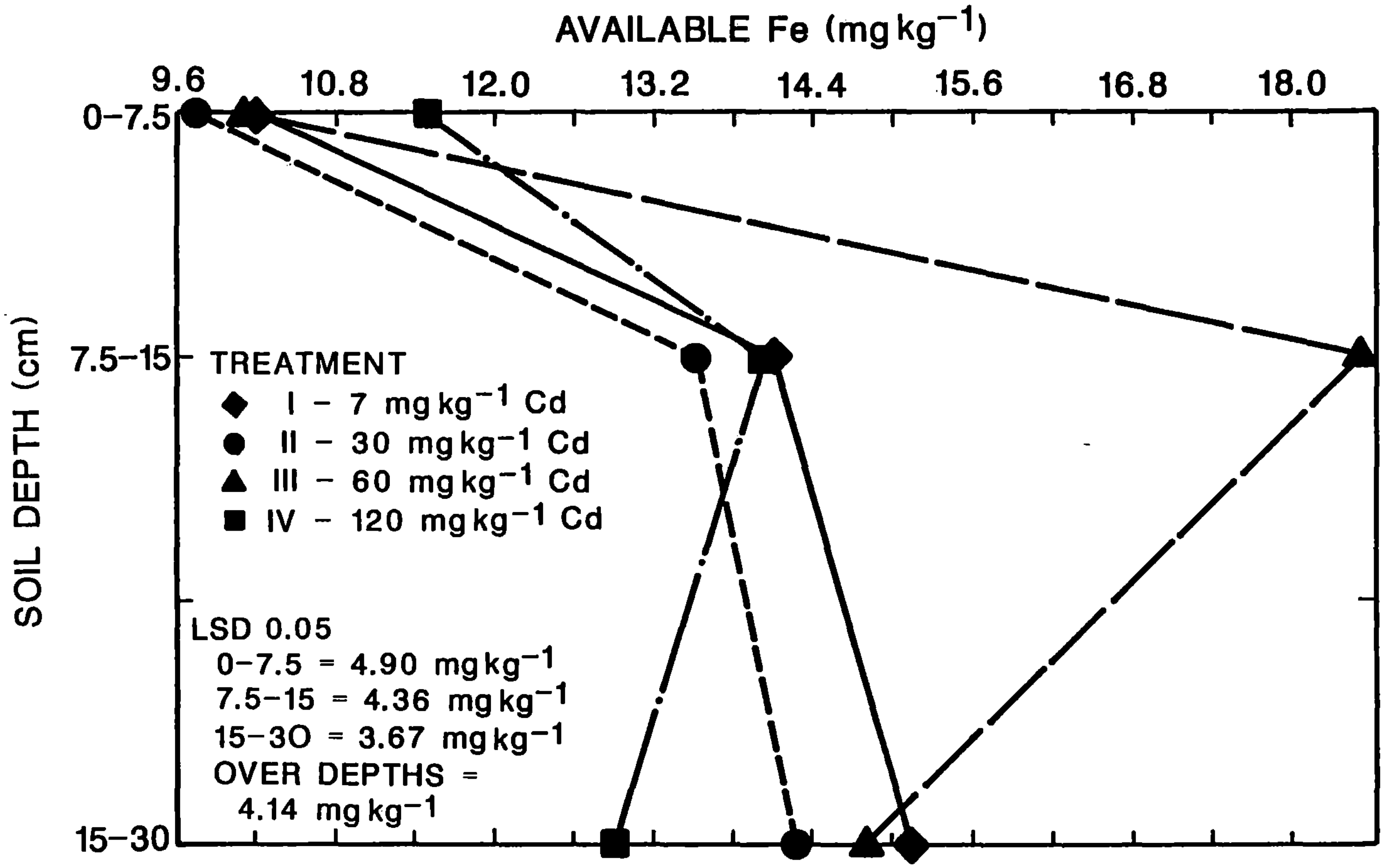

Figure 65. Soybean Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Subsurface Depth of Application (15-30 cm) on Available Fe of Norge Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

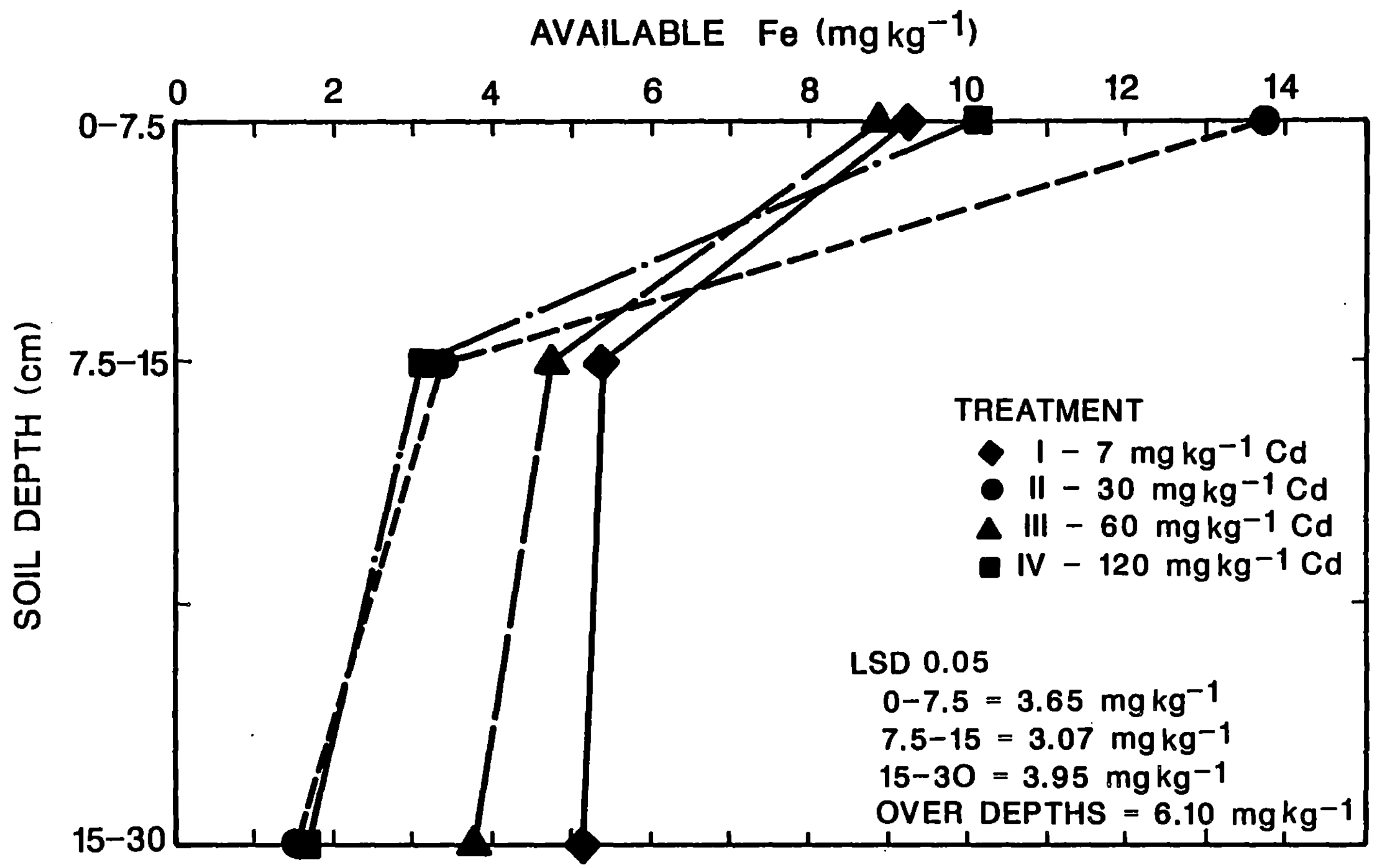

Figure 66. Sorghum Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Surface Depth of Application (0-15 cm) on Available Fe of Norge Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

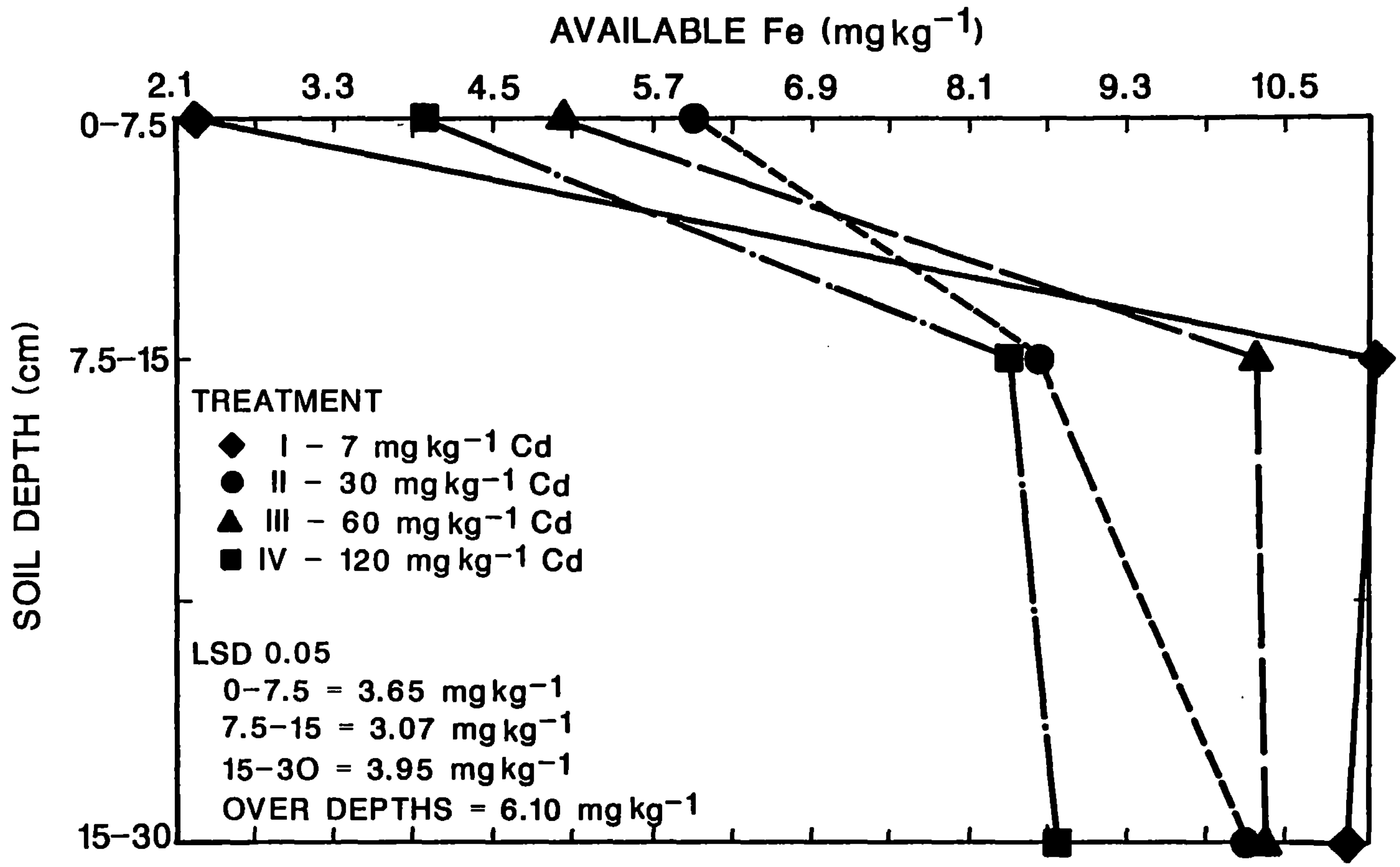

Figure 67. Sorghum Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Subsurface Depth of Application (15-30 cm) on Available Fe of Norge Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

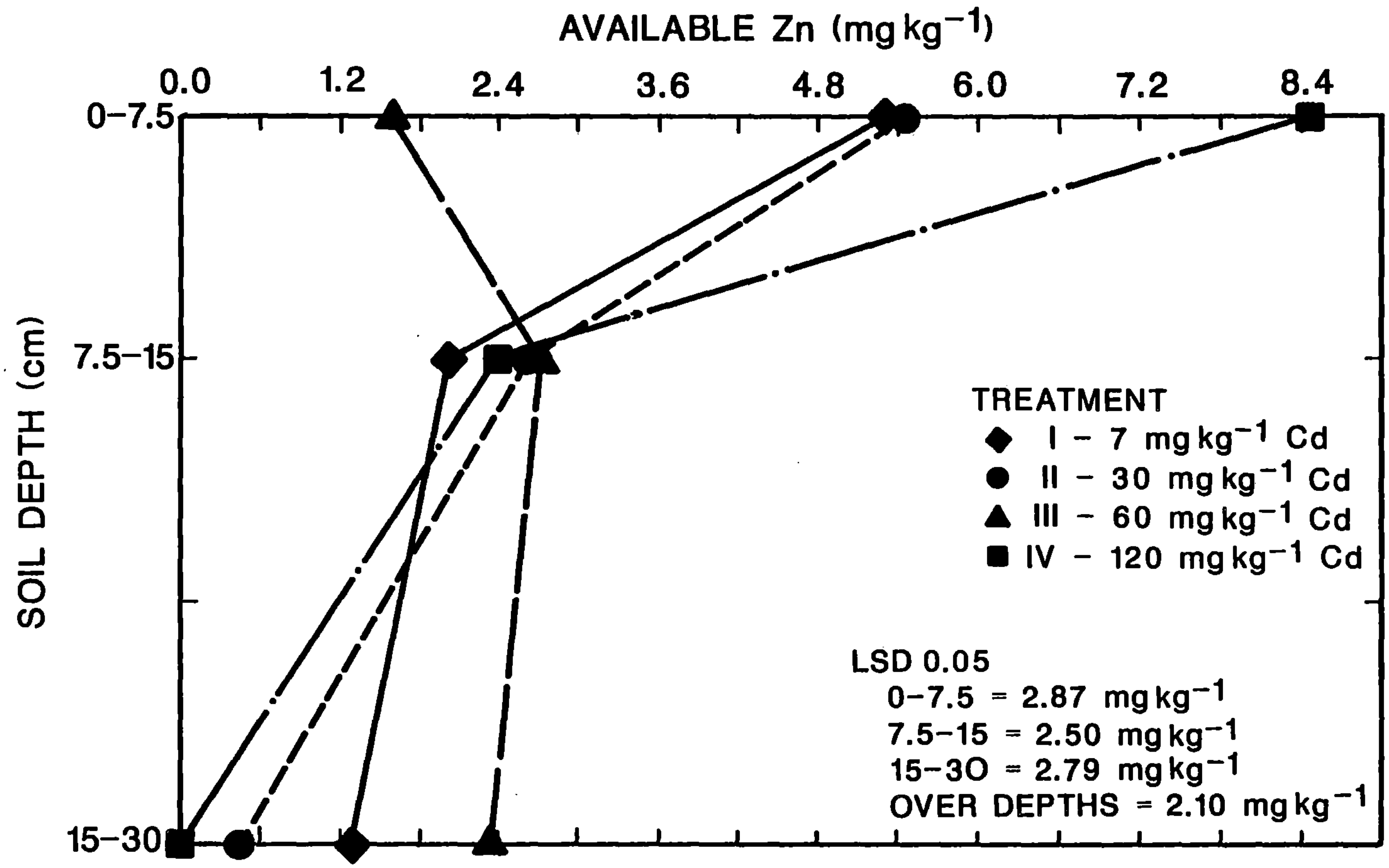

Figure 68. Soybean Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Surface Depth of Application (0-15 cm) on Available Zn of Norge Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

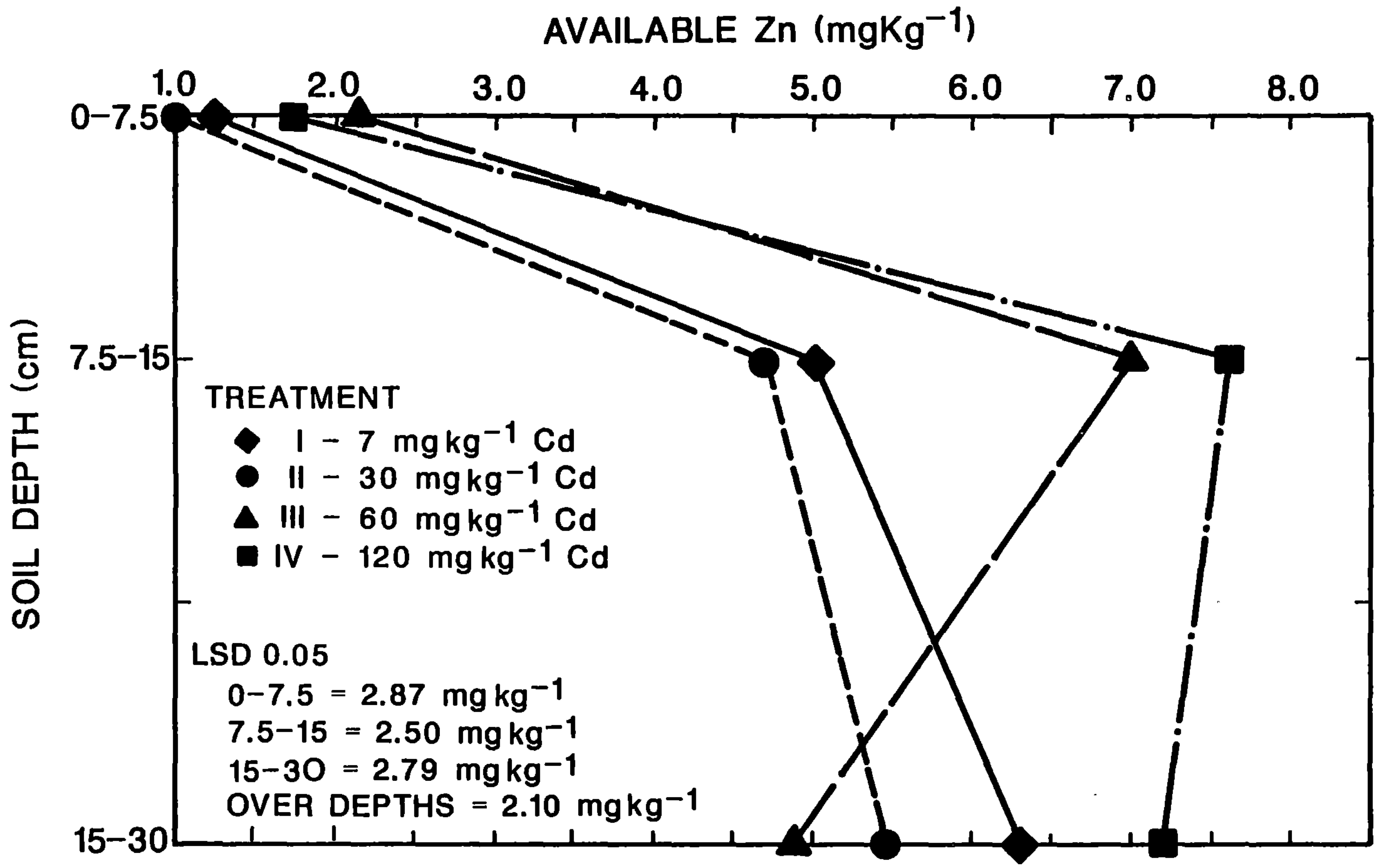

Figure 69. Soybean Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Subsurface Depth of Application (15-30 cm) on Available Zn of Norge Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

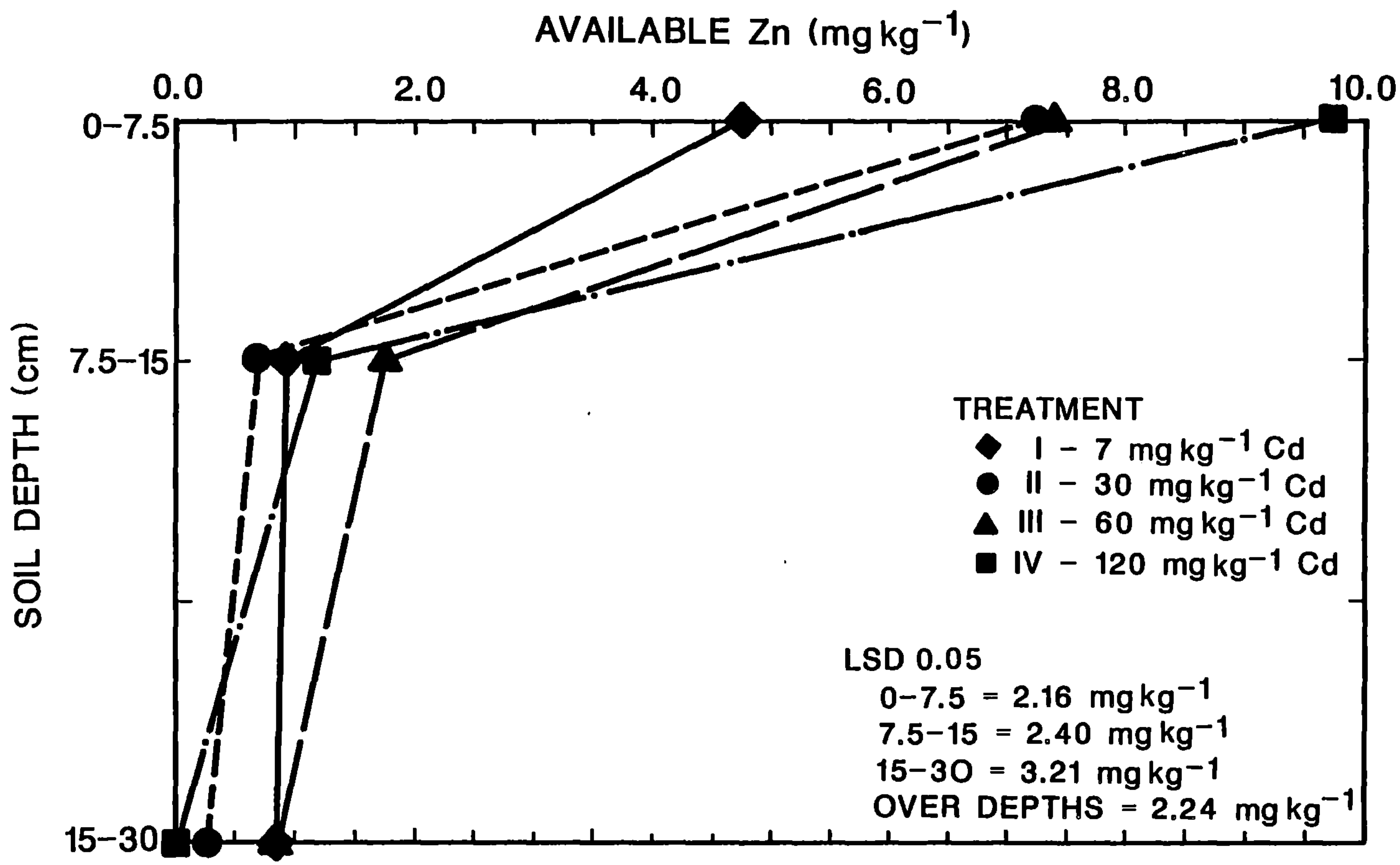

Figure 70. Sorghum Experiment: The Effect of Sewage Sludge-Borne Cadmium Cadmium Rates with Surface Depth of Application (0-15 cm) on Available Zn of Norge Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

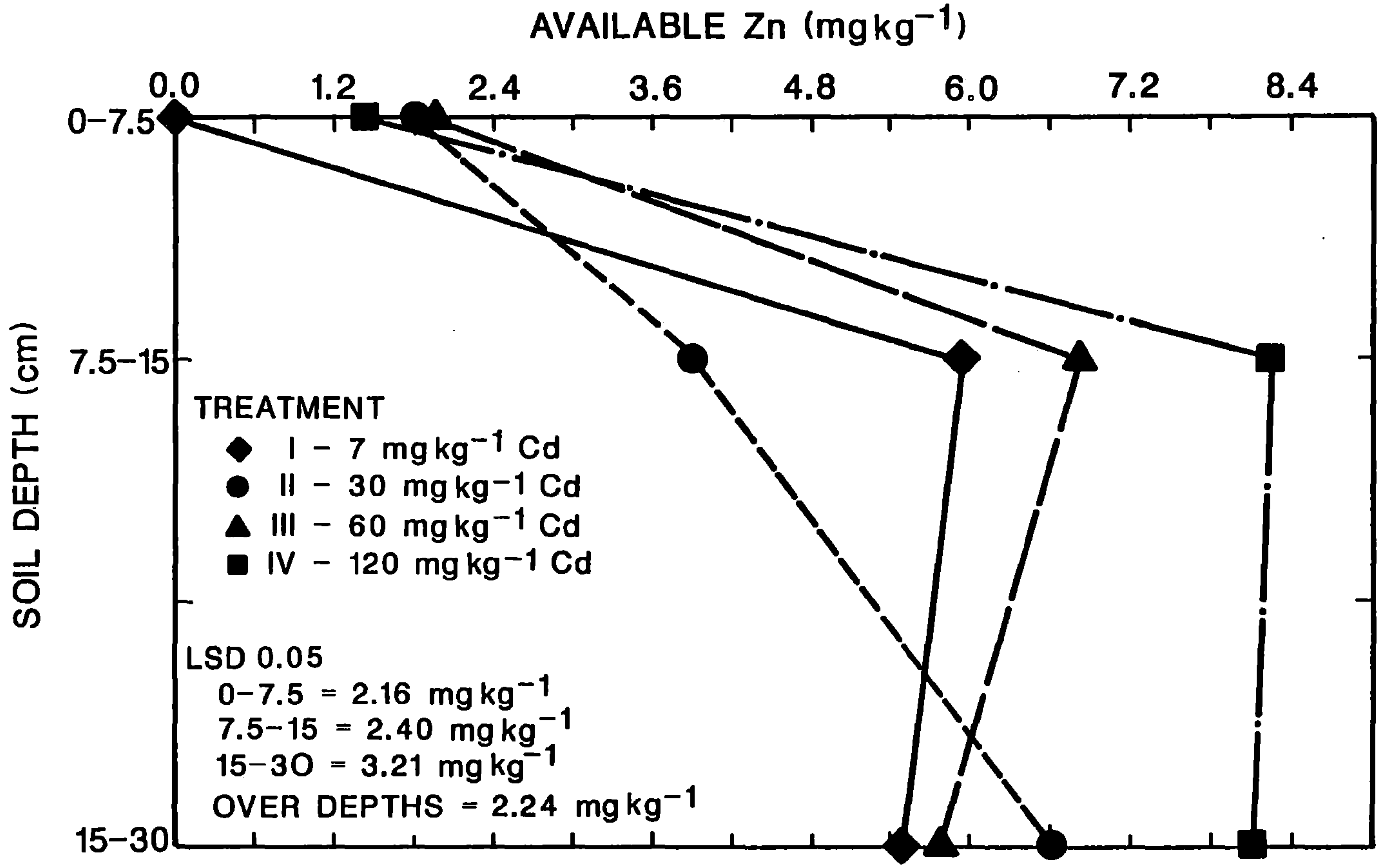

Figure 71. Sorghum Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Subsurface Depth of Application (15-30 cm) on Available Zn of Norge Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

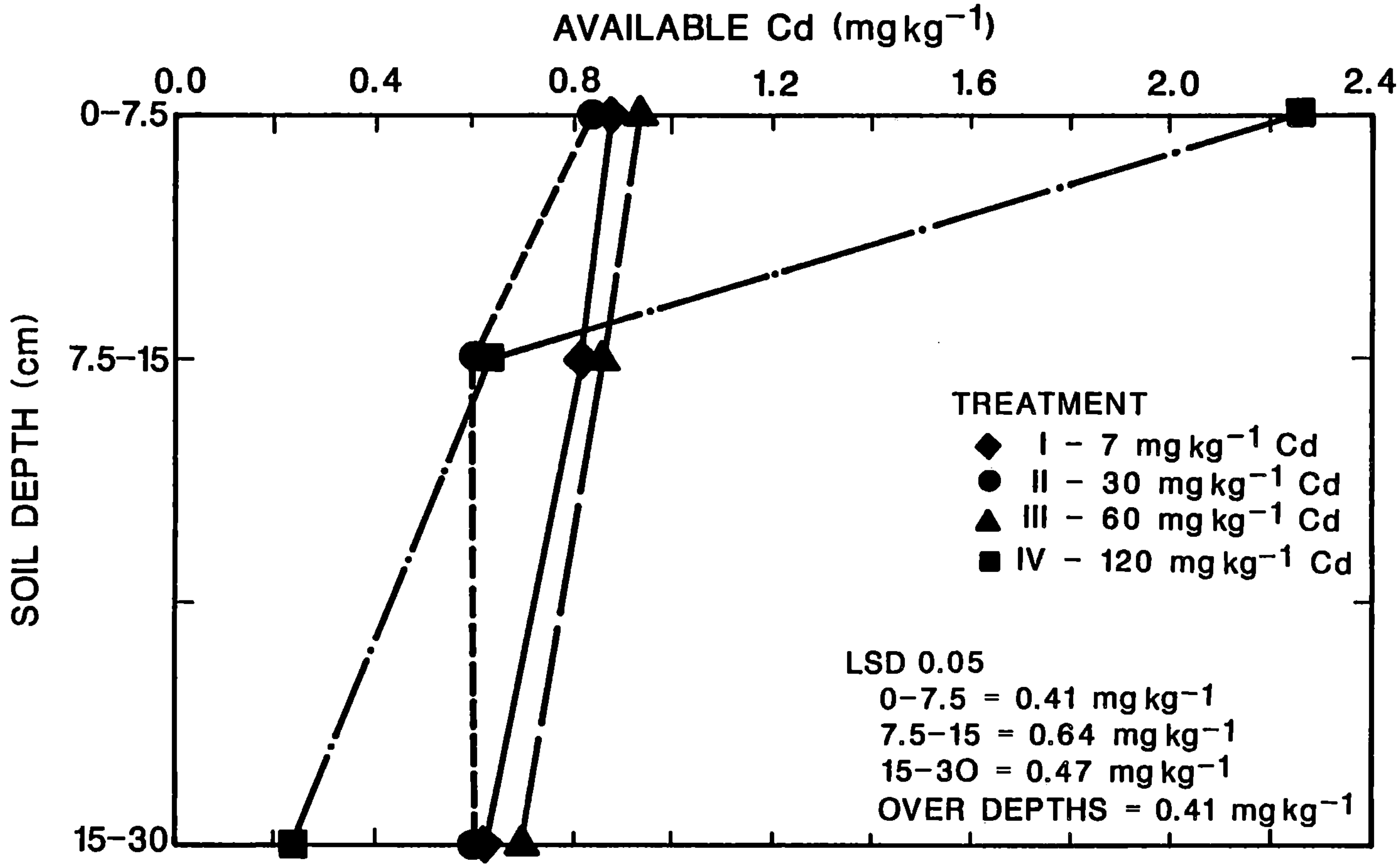

Figure 72. Soybean Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Surface Depth of Application (0-15 cm) on Available Cd of Norge Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

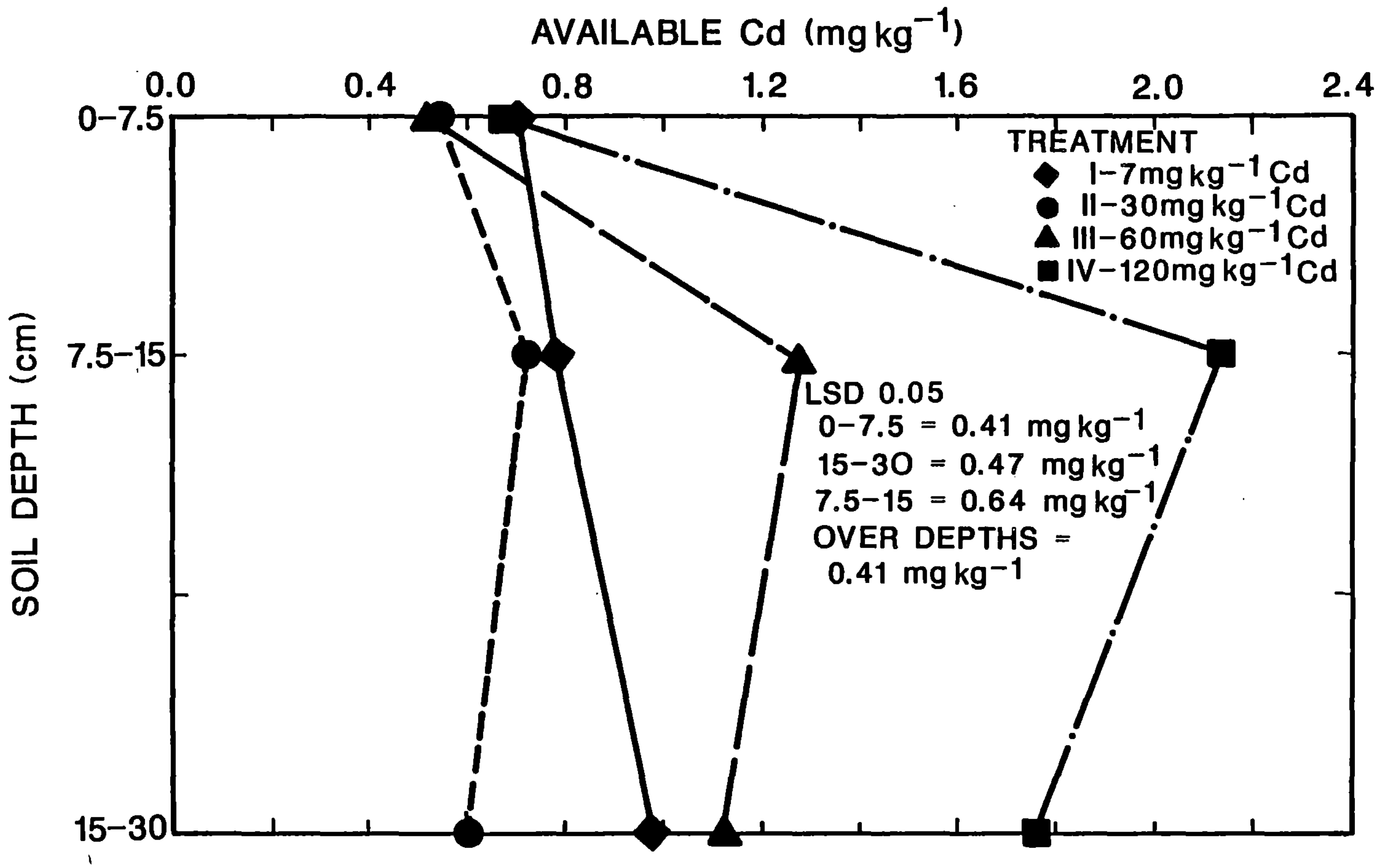

Figure 73. Soybean Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Subsurface Depth of Application (15-30 cm) on Available Cd of Norge Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

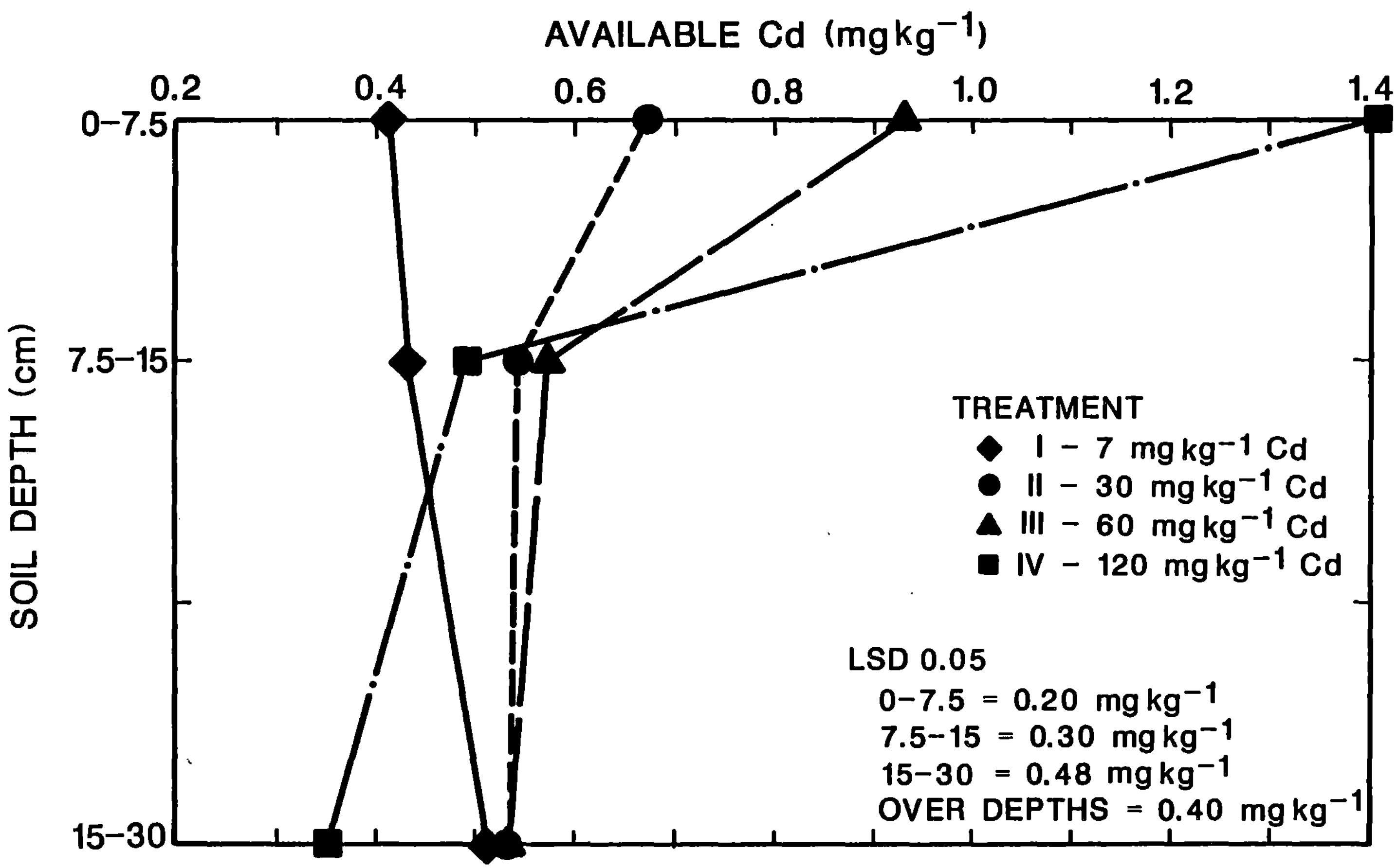

Figure 74. Sorghum Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Surface Depth of Application (0-15 cm) on Available Cd of Norge Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

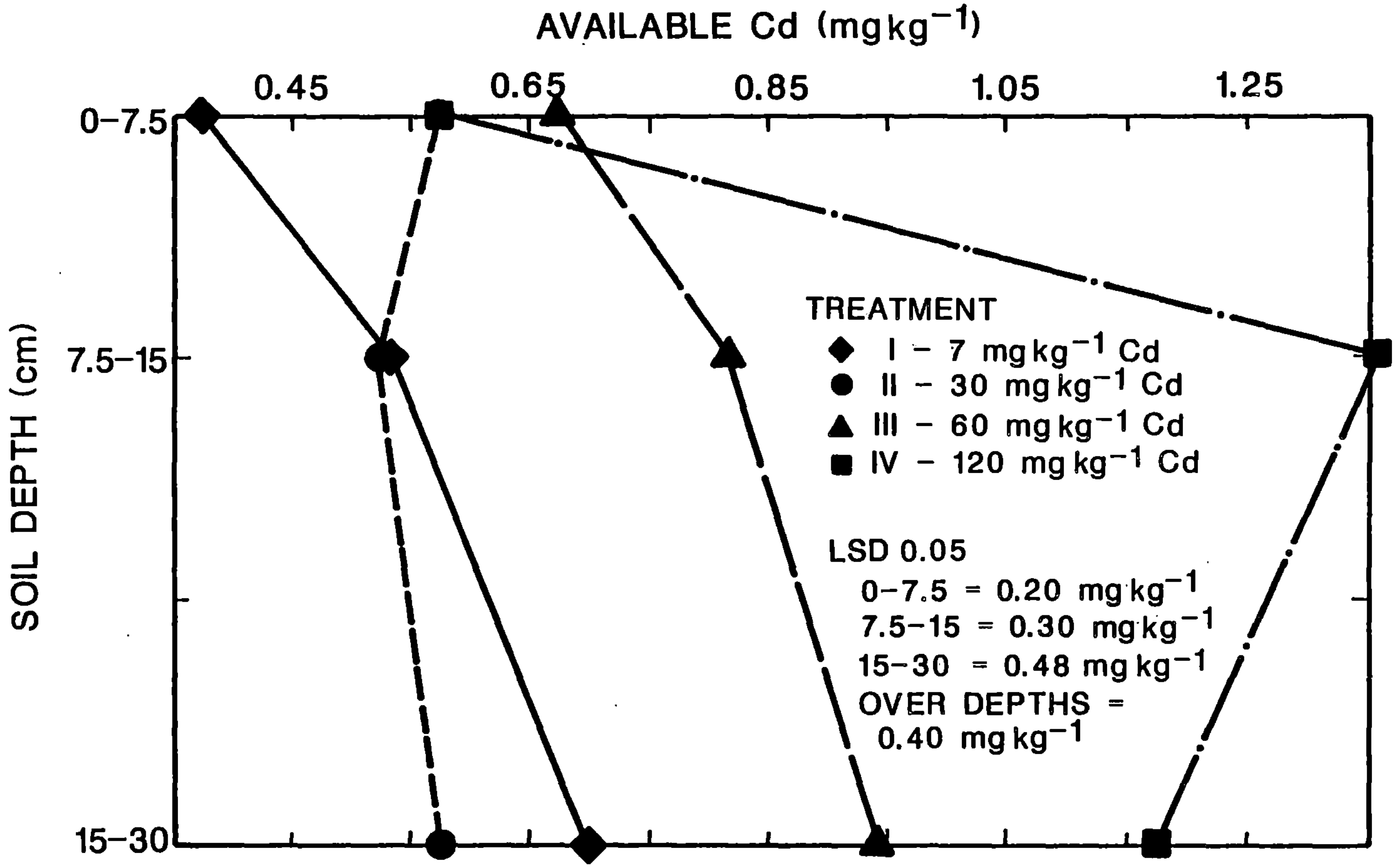

Figure 75. Sorghum Experiment: The Effect of Sewage Sludge-Borne Cadmium Rates with Subsurface Depth of Application (15-30 cm) on Available Cd of Norge Loam Soil at 0 to 7.5, 7.5 to 15, and 15 to 30 cm Depths (Sewage Sludge Rate was 44 mt ha^{-1} for all Treatments)

2

VITA

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