Lead, Mercury, Cadmium and Arsenic in the Environment
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CHAPTER 10

Cadmium Levels in Soils and Crops in the United States

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ABSTRACT

The concentrations of cadmium in agricultural soils depend upon the amounts present in the parent rocks from which the soils form, the amounts added in the form of fertilizers and soil amendments, the amounts deposited onto soils from the atmosphere, and the amounts removed by harvested crops and by leaching. On average, sedimentary rocks contain greater concentrations of Cd than either igneous or metamorphic rocks, and therefore, recent soils derived from sedimentary rock should contain greater concentrations of Cd than those derived from igneous or metamorphic rocks. Among the commercial fertilizers, phosphorus fertilizers contain somewhat elevated levels of Cd. Results show that the long-term use of phosphorus fertilizers will slightly increase the concentration of Cd in surface soils. Due to the combustion of fossil fuels and to the smelting and processing of ores, air in rural regions contains Cd. Results show that the amounts of Cd added to soils via aerial deposition in rural agricultural regions is of the order of a few grams per hectare per year and approximately equal to that added to soil from normal phosphorus fertilization operations. All crops contain Cd, and the harvested portion will serve to remove some Cd from soil. Amounts removed from soil in harvested crops, however, are quite small compared with the amounts present. Cadmium is reasonably immobile in soils, and the available data suggest that the amounts removed by leaching are also small compared with amounts present.

The concentrations of Cd in non-contaminated agricultural soils in the United States range from about 0.1 to 1.0 mg/kg. Except for a limited number of soils derived from parent materials unusually high in Cd, organic soils (Histosols) tend to contain the highest total Cd concentrations, and highly weathered soils (Ultisols and Alfisols) the lowest. Other soil orders contain concentrations of Cd in amounts approximately equal to their geological abundance or from about 0.2 to 0.4 mg Cd/kg. The fact that highly weathered soils are somewhat depleted in Cd suggest that greater quantities of Cd are removed by crops and leaching than are added through fertilization and atmospheric deposition. Surface soils commonly contain higher concentrations of Cd than subsurface horizons. The higher concentrations of Cd in surface horizons are probably due to the cycling of Cd from lower depths to the surface by plants.

Concentrations of Cd in food chain crops vary substantially within and among species. Research conducted during the past has demonstrated that the variations observed are due to differences in the Cd concentrations present in the soil, differences in the growth conditions among the regions where the crops are grown, differences in the cultivars of a particular crop, and differences in soil chemical and physical properties. We have grown a number of vegetable crops in fall and spring seasons and have observed seasonal differences in the amounts of Cd which the crops accumulate. Numerous data from a number of sources have demonstrated that different cultivars of the same plant show differences in their Cd absorption characteristics. Likewise, numerous published data have demonstrated that soil chemical properties, particularly soil pH, influence the amounts of Cd absorbed by crops.

On a dry weight basis the concentration of cadmium in food chain crops grown in non-contaminated soils (except those soils unusually naturally elevated in Cd) range from 0.01 to 1.0 mg/kg. Leafy vegetables (lettuce, spinach) usually show the highest Cd concentrations, grains (wheat, oats, barley) show the lowest concentrations and root vegetables (carrot, radish, onion, potato) are intermediate between the two extremes. Concentrations of Cd in crops grown on soils elevated in Cd, either naturally or from anthropogenic sources, may accumulate substantially greater than 1.0 mg/kg. The amounts accumulated depend upon the level of Cd present in the root zone of the soil, the crop species, and the chemical properties of the soil.

INTRODUCTION

Cadmium (Cd) is regarded as one of the most toxic trace elements in the environment. The increased emissions resulting from its production, use, and disposal, combined with its persistence in the environment, and its relatively rapid uptake and accumulation by food chain crops contribute to its potential environmental hazards. Cadmium may find its way to the human population through food and beverage, drinking water, air, and cigarette smoking. Although acute Cd toxicity caused by food consumption is rare, chronic exposure to high Cd levels in food can significantly increase the accumulation of Cd in certain body organs. When the concentration in the human body reaches levels considered to be harmful (>200 μg/gm wet weight in the kidney cortex according to Kjellström and Nordberg, 1978), cadmium-induced kidney damage, skeletal disorders as well as other diseases may result.

A highly publicized episode of Cd poisoning of humans (itai-itai disease) was reported in Japan in the mid-1950s (Tsuchiya, 1978). The source of excessive Cd to the affected individuals came from rice grown on nearby paddies which had been irrigated with water from a river contaminated by zinc mining operations. The Cd concentrations of the rice, of the river sediments and of the soil in which the rice was grown were considerably greater than those found in uncontaminated regions. However, the actual Cd levels in the rice grain were not unusually high. Since the per capita dietary consumption of rice among the Japanese population is high, the impact of Cd enrichment in the rice on the indigenous population was proportionally magnified. The Japanese incident is the only documented Cd poisoning arising from human consumption of crops grown on Cd-contaminated soils.

For populations not subjected to a Cd-contaminated environment, the main source of Cd human body burden is also from food. Drinking water and ambient air contribute significantly lesser amounts to the daily intake. Concentrations of Cd in domestic water supplies seldom exceed a few μg/litre, and at a consumption of 1–2 litres of water/day the daily intake would be merely a few micrograms (Friberg *et al.*, 1974; Tsuchiya, 1978; Pahren *et al.*, 1979). Cadmium concentrations of ambient air rarely exceed 0.01 $\mu g/m^3$, and at an intake rate of 20 m^3 of air/day the daily Cd intake would not exceed 0.2 μg. Cigarette smoking, however, adds considerably to Cd input via inhalation. Friberg *et al.* (1974) estimated that a daily intake of 2 to 4 μg Cd would be expected from smoking one package of cigarettes per day. They further suggested that the daily ingestion of Cd from all sources for the world's population ranged from 25 to 75 μg/day. Based upon results of market basket surveys over a seven-year period, the US Food and Drug Administration (Mahaffey *et al.*, 1975) showed an average intake of 39 μg Cd/day for the 15 to 20 year old age group males in the United States. If the figure is adjusted according to the recommended daily caloric intake for other age groups, the average daily intake from birth to age 50 for men and women in the US would be 33 and 26 μg/day, respectively (Pahren *et al.*, 1979). These values, however, were derived with the assumption that any market basket food items analyzed contained at least 0.02 mg Cd/kg. More recent data based upon analysis of fecal excretion gave estimated figures of from 18 to 21 μg Cd/day for teenage males (Ryan *et al.*, 1982; Kowal, 1984).

The above-cited figures illustrate the importance of Cd in the food chain crops to the accumulation of Cd in the human body. The concentration of Cd in foods is, in turn, controlled by its concentration in the soil substrate and by the physical and chemical nature of this soil. In the following sections we will review concentrations of Cd in crops and soils in the United States. Sources of Cd in soils, as well as factors influencing its absorption by crops, are also discussed.

NATURAL OCCURRENCE

According to Heinrichs *et al.* (1980), the average concentration of cadmium in the lithosphere is 0.098 mg/kg. It is a rarer element than mercury and about 1/700 as abundant as zinc (whose crustal abundance averages 70 mg/kg). The ranges and mean concentrations of cadmium for some common igneous, sedimentary, and metamorphic rocks are presented in Table 10.1. There are very small differences in the overall abundance of cadmium in

Table 10.1 Abundance of cadmium in common rocks*

Rock type	Cadmium content (mg/kg)	
	Mean	Range
Igneous		
Granite	0.09	0.001–0.60
Basalt	0.13	0.006–0.60
Ultramafic	0.026	0.001–0.03
Metamorphic		
Gneisses	0.04	0.007–0.26
Schists	0.02	0.005–0.87
Ecologite	0.11	0.04–0.26
Sedimentary		
Limestone	0.065	0.001–0.50
Sandstone	0.02	0.01–0.41
Shale, clay	0.03	0.02–11.0
Red clay	0.56	
Organic mud	0.39	
Deep ocean sediments	0.5	0.05–17
Oceanic manganese oxides	8.0	<3.0–21
Phosphorites	25	<10–500
Recent sediments		
Lake sediments	0.91	0.02–6.2
Stream sediments	0.16	0.03–0.40

* Based on compilations by Fleischer *et al.* (1974), Gong *et al.* (1977), Waketa and Schmitt (1970), Horn and Adams (1966), and Marowsky and Wedepohl (1971).

mafic and granitic rocks. It tends to concentrate by sedimentation as evidenced by the high concentrations (0.001–11.0 mg/kg) in sedimentary rocks. Some shales are unusually high in Cd (Wedepohl, 1968). Along the Pacific Coast in the US, the Monterey shale formation in some locations has been found to contain as much as 90 mg Cd/kg (Lund *et al.*, 1981).

Amounts of cadmium in marine sediments in the Atlantic and Pacific Oceans range from 0.1–1.0 mg Cd/kg (Mullin and Riley, 1956). Marine manganese nodules (5.1–8.4 mg Cd/kg) and marine zinc-bearing phosphorite (60–340 mg Cd/kg) are also high in cadmium (Mullin and Riley, 1956; Goldschmidt, 1958; Auer 1977).

CADMIUM IN NON-CONTAMINATED AND CONTAMINATED SOILS

Natural Levels in Soils

Amounts of indigenous cadmium in cultivated and non-cultivated soils are determined by the quantities of Cd in the parent materials together with amounts added through atmospheric deposition, fertilizers, pesticides, and irrigation water, but minus amounts removed by leaching, erosion, and in harvested crops. Based upon Cd concentrations reported for common rocks, one would expect on the average, soils of similar age derived from igneous rocks to be lowest in total Cd, soils derived from metamorphic rocks to be intermediate, and soils derived from sedimentary rocks to contain the largest quantities of Cd.

Recently, an extensive survey was conducted to investigate Cd in surface soils in the major crop producing regions of the continental United States (Holmgren *et al.*, 1986). This survey took great care to ensure that the sites sampled were free from any known source of contamination and to ensure the utmost analytical accuracy. A total of 3305 soil samples were collected from crop-producing areas in 36 states. Concentrations of Cd ranged from 0.005 to 2.4 mg/kg, with mean and median values of 0.27 and 0.20 mg/kg, respectively. A summary of the results by geographical regions (Figure 10.1) is presented in Table 10.2. On average, Cd concentrations in soils from the Western and North Central states are greater than those from the Northeastern and Southern states.

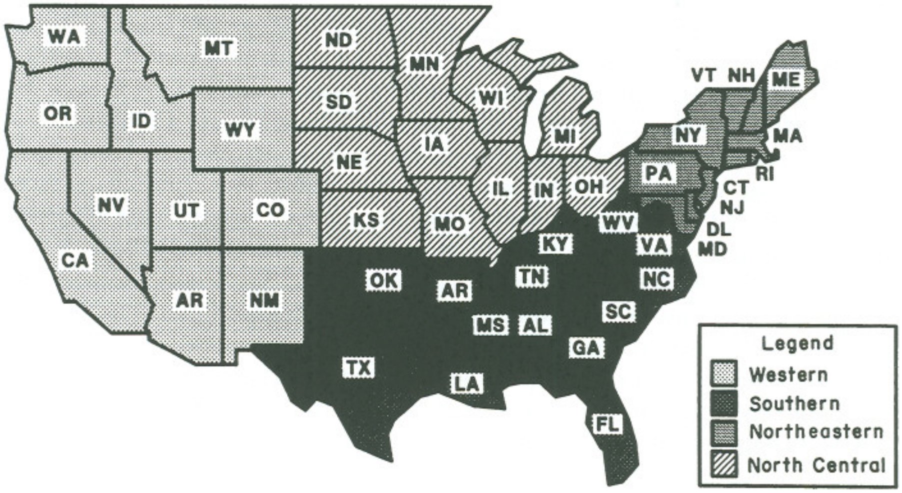

Figure 10.1 Map showing regions and states within the contiguous United States

Data from other sources are in general agreement with those published by Holmgren *et al.* (1986). Logan and Miller (1983) collected surface soils from 237 farms in six counties in Ohio and observed Cd concentrations to range

Table 10.2 Cadmium concentrations of soils from major agricultural regions in the United States

Region*	No. of samples	No. of states sampled	Cd concentration (mg/kg) Range	Cd concentration (mg/kg) Mean
Western	742	8	0.20–0.49	0.33
North Central	937	12	0.20–0.94	0.37
Northeast	293	5	0.08–0.21	0.17
Southern	1230	9	0.03–0.44	0.15

Derived from data presented by Holmgren *et al.* (1986), excluding organic soils from New York and high lead samples from West Virgina.

* See Figure 10.1.

from <0.1 to 2.9 mg/kg with a mean concentration of 0.2 mg/kg. Pierce *et al.* (1982) presented data to show the Cd concentration of soils from 16 soil series developed on seven parent materials in Minnesota varied from 0.06 to 0.74 mg/kg. The soil series sampled were considered representative of most of the crop-producing areas in Minnesota. The highest total Cd concentrations occurred in calcareous soils developed in lacustrine sediments and, generally, in soils with free carbonates. In California, soils developed from Monterey shale or alluvium from the shale frequently have elevated Cd concentrations. Burau *et al.* (1973) surveyed 177 agricultural soils developed from or near to Monterey shale deposits (Salinas Valley) and found Cd concentrations which ranged from 0.05 to 10.1 mg/kg with a mean of 1.24 mg/kg. Lund *et al.* (1981) observed highly elevated concentrations of Cd in soils developed from Monterey shale in the Malibu Canyon area in California.

A summary of the survey data for cadmium concentrations in US agricultural soils by taxonomic order is presented in Table 10.3. Excluding those soils influenced by Monterey shale deposits, the data suggest that Histosols on the average contain the highest concentrations of Cd; Mollisols, Vertisols, Entisols, and Inceptisols are intermediate, and Spodosols, Alfisols and particularly Ultisols are the lowest in total Cd concentrations. The Ultisols and to a lesser extent the Spodosols and Alfisols are more highly leached than the remaining soil orders, and less Cd in these surface soils may be the result of leaching. Organic soils (Histosols) in the United States are used rather extensively in the production of vegetable crops which require intensive phosphorus fertilization, and the elevated concentrations in this soil order, at least in part, could be due to phosphorus fertilization. The cycling of Cd from soil to plant and subsequent decomposition in soils combined with retention of Cd by organic matter may also account for elevated levels of Cd in the Histosols. Based on the data summarized in Table 10.3, most uncontaminated agricultural surface soils will contain from about 0.1 to 1.0 mg Cd/kg.

Table 10.3 Cadmium concentrations of agricultural soils in the United States*

Location	No. of samples	Taxonomic Order†	Cadmium concentration (mg/kg)				Reference
			Minimum	Maximum	Mean	(Median)	
Ohio	231	NR (Alfisol)	<0.1	2.9	0.2		Logan and Miller, 1983
	6	NR (Entisol)	0.3	0.4	0.2		
	81	NR	0.08	0.68	0.38	(0.30)	Holmgren *et al.*, 1986
Michigan	91	NR (Alfisol)	NR	NR	0.4	(0.57)	Klein, 1972
	86	NR	0.34	1.54	0.94		Holmgren *et al.*, 1985
Minnesota	21	Mollisol	NR	NR	0.48		Pierce *et al.*, 1982
	18	Alfisol	NR	NR	0.28		
	89	NR	0.12	0.18	0.30		Holmgren *et al.*, 1985
California	283	NR	0.03	0.87	0.31		Holmgren *et al.*, 1985
Soils developed on or in regions near Monterey shale deposits	105	Mollisol	0.077	15	1.54	(0.85)	Burau *et al.*, 1973 and Lund *et al.*, 1981
	39	Alfisol	0.13	6.38	1.12	(0.76)	
	18	Vertisol	0.39	2.10	1.08	(1.10)	
	17	Entisol	0.05	3.70	0.93	(0.69)	
	2	Inceptisol	12	22	17		
Excluding soils influenced by Monterey shale	7	Mollisol	0.01	0.26	0.08	(0.15)	Various sources from authors' file
	10	Alfisol	<0.1	0.6	0.25	(0.2)	
	10	Entisol	0.13	3.5	0.95	(0.75)	
	4	Aridisol	<0.1	0.3		(<0.1)	
Continental US	288	Histosol	0.36	1.44	0.72		Holmgren *et al.*, 1986
	152	Aridisol	0.17	0.71	0.35		
	256	Entisol	0.07	0.70	0.28		
	1076	Mollisol	0.08	0.68	0.28		
	256	Inceptisol	0.05	0.71	0.27		
	91	Vertisol	0.13	0.55	0.27		
	43	Spodosol	0.08	0.47	0.21		
	570	Alfisol	0.03	0.42	0.16		
	571	Ultisol	<0.01	0.30	0.08		

* Range from Holmgren *et al.* (1985) is estimated from the standard deviation (95% confidence interval).

† NR = no record; order in parentheses represent authors' estimate.

Only limited data are available pertaining to concentrations of cadmium in relation to soil depth. Pierce *et al.* (1982) showed that levels of Cd in surface horizons of Mollisols and Alfisols are greater than those found in subsurface horizons. Mean concentrations of Cd in surface horizons were 0.39 mg/kg compared with 0.23 mg/kg for subsurface horizons. The higher concentrations in surface horizons suggest that additions of Cd by atmospheric deposition, fertilizers, and plant cycling exceed losses by leaching and plant removal in the surface horizon.

Sources and Extent of Cadmium Contamination of Soils

Soils may be contaminated with cadmium by fallout from aerial sources, by application of waters, fertilizers, or pesticides which contain cadmium, or by the discharge of cadmium-containing waste materials from industrial, metallurgical or urban activities.

1. Levels Near Mining and Smelting Operations

Processing of industrial metals is an important source of atmospheric emission of trace metals including Cd. Smelting and sintering of non-ferrous metals have resulted in Cd contamination of the nearby environment. The ore-smelting furnaces in which metals enter the flue-gas stream as fine particulates or volatiles are responsible for the majority of discharge from the stack and, eventually, the deposition onto soils and vegetation. Airborne dusts and fumes from charging furnaces, transporting metal ores, and sintering and metal-reducing furnaces are also sources of metals found in and near the metallurgical operations. Soils contaminated by smelting operations exhibited the highest Cd concentrations in the upper horizons near the point of discharge in the direction of the prevailing winds. The Cd concentrations at a depth of about 30–40 cm would return to levels close to the background because of surface retention especially in organic matter and litter.

The extent to which soils in the United States have been contaminated by mining and smelting operations can be found in published reports by Fulkerson and Goeller (1973), Buchauer (1973), Munshower (1977), Ragaini *et al.* (1977), Johnson *et al.* (1975), Lagerwerff and Brower (1975) and US Environmental Protection Agency (1972). Two kilometres northeast of a lead-zinc smelter in Montana, 29 mg Cd/kg in surface soils was observed (Munshower, 1977). The Cd concentration of surface soil decreased with distance and reached near background levels 24 kilometres from the source. Likewise, within one kilometre of a zinc smelter at Palmerton, Pennsylvania, Buchauer (1973) reported concentrations of Cd in the surface organic horizon as great as 750 mg Cd/kg. The Cd concentrations of the soils decreased logarithmically with distance and levels exceeding background were observed up to 21 kilometres from the source. Recently adopted emission control measures should lessen future contamination of soils from mining and smelting. However, those soils already contaminated by past operations will remain high in Cd more or less permanently because Cd is quite immobile in soil.

The extent of contamination of soils resulting from stack emissions of coal-fired power plants varies as a result of differences in emission control devices. The rate of atmospheric discharge of Cd per ton of coal combusted ranges from 3 to 90 mg (Lyon, 1977). With 90% emission control, the annual deposition rate of Cd onto soil adjacent to a 3000 MW coal-fired power plant is 0.00002 mg/kg soil (Ondov, *et al.*, 1976). Assuming a mean Cd concentration of 0.2 mg/kg soil, the enrichment of the soil over the lifetime of the power plant (~35 years) is approximately 0.35%.

2. *Disposal/Recycling of Municipal Sewage Sludges*

Sewage sludges from municipalities are frequently applied to soils in disposal operations, as soil conditioners, or as a source of plant nutrients. The concentrations of Cd in sewage sludge always exceed those normally found in soils. Municipal sewage sludge contains in the range of approximately 2 to 3500 mg Cd/kg sludge, with medians in the order of 5 to 20 mg/kg (Page, 1974; Sommers, 1977; Logan and Chaney 1984). Application of sludge as a nitrogen fertilizer can increase the cadmium level in surface soils. A 5 tons/ha application of sludge containing 10 to 15 mg Cd/kg may result in an increase of cadmium concentration by as much as 10–15% in the surface soil (assuming background level is 0.22 mg/kg). The applied cadmium may remain available to plants for an extended period of time.

Although the use of municipal sewage sludge as a fertilizer or soil conditioner will result in increased Cd concentrations in soil, the impact of this practice on the Cd concentration of commercial crops which enter the marketing and distribution systems is expected to be minimal. This is so because less than 1.0% of the agricultural land in the United States would be affected if 50% of the sludges generated annually were to be applied to agricultural lands as a source of nitrogen (CAST, 1976). Currently, less than 20% of the sludge generated is applied to lands used to produce commercial crops. In situations where foods grown on sludged lands made up a substantial percentage of the human diet, over a number of years it is possible that consumers could accumulate Cd in amounts considered to be a health hazard.

3. *Phosphorus Fertilizers*

Phosphorus fertilizers frequently contain greater concentrations of cadmium than are typically found in soils. Depending upon the source of phosphorus, commercial fertilizers produced in the United States contain from a few to 200 mg Cd per kilogram with median values from 2 to 20 mg Cd/kg (US Environmental Protection Agency, 1978). The amounts of Cd introduced into the soil through normal phosphorus fertilization, however, are quite small. For example, the application of 50 kg P per hectare from rock phosphate [$Ca_{10}F_2(PO_4)_6$] which contained 20 mg P per kg would introduce 5.4 gm of Cd to the soil. If mixed with the surface 15 cm of a silt loam soil, this application would increase the Cd concentration of a soil containing 0.3 mg Cd/kg by about 1%.

4. Atmospheric Deposition

The extent of contamination of soil arising from deposition from air in agricultural regions of the United States, except near point emission sources, amounts to a few grams per hectare per year or less. For example, data derived from Hunt *et al.* (1971) for 77 cities in the midwestern United States show an annual deposition in residential areas of 1.2 gm Cd per hectare. Likewise, in a rural region of Tennessee, Lindberg *et al.* (1981) observed an annual deposition of 0.9 gm Cd per hectare.

Adjacent to point emission sources, concentrations of Cd in air are considerably greater. Consequently, amounts deposited onto land surfaces are also greater. Data derived from Rupp *et al.* (1978), for example, show annual depositions of Cd of 170, 89, 46, and 23 grams per hectare at distances of 1.6, 3.2, 6.4 and 12.8 kilometres, respectively, downwind from a smelter in Montana.

SOIL FACTORS INFLUENCING THE ACCUMULATION OF CADMIUM BY FOOD CHAIN CROPS

The two most important factors governing the uptake of cadmium by crops are the soil pH and the concentration of Cd in the soil. Factors of less importance include soil temperature, content of hydrous oxides of iron and manganese in soils, redox potential in soil, and interactions with other metals. To delineate Cd accumulation by crops, a wide variety of plants will be referred to by their common names in the remainder of the text. To avoid unnecessary duplication, the scientific names of these crops are summarized in Table 10.4.

Soil pH Effects

If other soil conditions remain unchanged, the cadmium concentration of plant tissue would decrease as the pH of the soil increased. Data selected

Table 10.4 Common and scientific names of listed crops

Common name	Scientific name
Apple	*Malus pumila*
Asparagus	*Asparagus officinalis*
Barley	*Hordeum vulgare*
Beans	*Phaseolus* spp.
Broccoli	*Brassica oleracea botrytis*
Cabbage	*Brassica oleracea capitata*
Cantaloupe	*Cucumis melo*
Carrot	*Daucus carota sativa*
Corn	*Zea mays*
Cucumber	*Cucumis sativus*
Eggplant	*Solanum melongena*
Grape	*Vitis* spp.
Grapefruit	*Citrus paradisi*
Lettuce	*Lactuca sativa*
Oat	*Avena sativa*
Onion	*Allium cepa*
Orange	*Citrus sinensis*
Pea	*Pisum sativum*
Peach	*Prunus persica*
Peanut	*Arachis hypogaea*
Pear	*Pyrus communis*
Pepper	*Capsicum* spp.
Plum	*Prunus americana*
Potato	*Solanum tuberosum*
Radish	*Raphanus sativus*
Rice	*Oryza sativa*
Sorghum	*Sorghum vulgare*
Soybean	*Glycine max*
Spinach	*Spinacea oleracea*
Squash	*Cucurbita* spp.
Swiss chard	*Beta vulgaris* var. *cicla*
Tomato	*Lycopersicon esculentum*
Turnip	*Brassica rapa*
Wheat	*Triticum* spp.

from results published in a report by the Council for Agricultural Science and Technology (1980) illustrate Cd accumulation by Swiss chard and oat grain in relation to soil pH (Table 10.5). The mean concentration of Cd in Swiss chard grown at control plots of four farms with soil pH values ranging from 4.9 to 5.4 was 1.98 mg Cd/kg while that of the limed control plots (soil pH values between 6.1 to 6.4) was 0.57 mg Cd/kg. Liming the same soils which were contaminated with Cd from land application of municipal sewage sludge reduced the mean Cd concentration of the Swiss chard from 40.5 to 3.01 mg/kg. Similar results reported by Chaney *et al.* (1975) showed

Table 10.5 Influence of soil pH and cadmium concentration on the cadmium concentration of Swiss chard and oat grain[*]

Treatment	Soil Cd conc. (mg/kg)	Soil pH	Cd concentration (mg/kg[†])	
			Swiss chard	Oat grain
Control				
Farm 1	0.18	4.9	3.34	0.104
Farm 2	0.10	5.3	2.65	0.076
Farm 3	0.22	5.4	1.48	0.034
Farm 4	0.07	5.9	0.44	0.051
Mean			1.98	0.066
Control plus limestone				
Farm 1	0.15	6.4	0.94	0.052
Farm 2	0.10	6.1	0.37	0.064
Farm 3	0.16	6.4	0.63	0.025
Farm 4	0.07	6.3	0.33	0.044
Mean			0.57	0.046
Sludge-treated				
Farm 1	1.66	4.9	94.80	1.960
Farm 2	9.10	5.5	54.30	2.240
Farm 3	0.98	4.9	3.24	0.209
Farm 4	3.26	5.5	9.51	0.299
Mean			40.50	1.180
Sludge-treated plus limestone				
Farm 1	2.10	6.3	2.20	0.259
Farm 2	7.02	6.2	5.34	0.277
Farm 3	0.94	6.0	0.82	0.065
Farm 4	4.50	6.2	3.68	0.193
Mean			3.01	0.198

[*] Data from paired plots on sludge utilization farms in four northeastern USA cities. Derived from data presented by Council for Agricultural Science and Technology, 1980.

[†] Dry weight basis.

a reduction in the Cd concentration of soybean leaves from 33 to 5 mg/kg when the pH of the soil on which the plants were grown was increased by liming from pH 5.3 to pH 7.0. Cadmium content of oat grain also showed a dramatic reduction as the soil pH was raised even when the pH increase was only from 4.9 to 5.3. These data and others demonstrate that one of the most effective means of minimizing the absorption of Cd by plants grown on acid soils is liming.

Under similar chemical, physical, biological and mineralogical conditions in the soil, amounts of Cd absorbed by plants tend to increase as the concentration of Cd in the soil increases (Valadares *et al.*, 1983; Chang *et al.*, 1983). However, the increased Cd concentration in plants may or may not be proportional to the increased concentration in the soil. Also repeated annual applications of fertilizers or soil conditioners which contain Cd (e.g. municipal sewage sludges), even though they increase the concentration of Cd in the soil each subsequent year, may or may not increase contents of Cd in the crop from year to year. Repeated applications alter the soil conditions and in turn the plant availability of Cd. Perhaps the factors which control the availability of Cd to the crop are not necessarily the same each year. Additional information on the availability of Cd to crops following repeated applications of Cd to soil can be obtained from Chang *et al.* (1982) and the Council for Agricultural Science and Technology (1980). These reports demonstrate that the magnitude of increased concentrations of Cd in plants is not always consistent with cumulative amounts applied to soil, and may depend upon a wide variety of environmental factors.

Although only limited data are available, it appears that crops grown on soil naturally elevated in Cd show higher concentrations of Cd than those grown on similar soils whose Cd concentrations are low. Feeney *et al.* (1984) reported results from a national survey of metals content of vegetable species. In the region where soils were naturally elevated in Cd (Salinas Valley, California) mean concentrations of Cd for lettuce, spinach, carrot, and tomato were, without exception, greater than mean concentrations for the same crops grown on soils with more or less normal Cd concentrations (Table 10.6). The Cd concentrations for the soils in the region designated as naturally elevated are not uniformly high throughout, and vary quite substantially from what would be considered normal (Table 10.3). This natural variation among the soils within the region accounts for the wide range of Cd concentrations observed for the vegetable species sampled. Studies by Lund *et al.* (1981) and our laboratory on native vegetation and crops grown on soils naturally high in Cd also show elevated Cd concentrations in plants when compared with the same plants grown on soils with normal levels of Cd. The data demonstrate that background levels for crops will vary with, in addition to pH and possibly other soil properties, the level of Cd in soil.

Both field and greenhouse experiments have been conducted to evaluate the effect of adding Cd to soil on its concentration in plants. Plants grown on Cd-enriched soils in containers in the greenhouse tend to absorb more Cd than the same plants grown on the same soil amended with identical amounts of Cd in the field (Page and Chang, 1978; DeVries and Tiller, 1978). The extension of the field plant roots beyond the contaminated layer results in less Cd absorption by roots and subsequently less accumulation in the plant tissues (Page *et al.*, 1981).

Results derived from field experiments conducted by Giordano *et al.* (1979), illustrate the relationship between the increased Cd added to soils

Table 10.6 Cadmium concentrations of vegetable crops grown in a region naturally elevated in Cd and other regions*

Crop/Region	No. of samples	Conc. in soil (mg/kg)† Range	Conc. in crop (mg/kg)‡ Range	Conc. in crop (mg/kg)‡ Mean
Lettuce				
Naturally elevated	13	0.33–5.98	0.52–24	4.63
Other	12	<0.33–1.38	0.48–1.54	0.88
Spinach				
Naturally elevated	5	0.26–1.26	2.38–3.80	3.09
Other	12	<0.33	0.38–1.98	0.85
Carrot				
Naturally elevated	8	0.16–5.97	0.39–2.79	0.98
Other	15	0.50–1.10	0.04–0.39	0.25
Tomato				
Naturally elevated	10	0.60–8.42	0.46–4.12	2.57
Other	8	NR	0.09–0.78	0.35

* Derived from Feeney *et al.* (1984).

† 0.1 *N* HCl soluble Cd, dry weight basis.

‡ Dry weight basis.

NR = Not reported.

and the corresponding Cd concentration in a variety of vegetables (Table 10.7). Increases in concentration of Cd in foliage and the edible part of all crops tested, except potato, were observed upon addition of Cd to soil at a rate equivalent to 11.2 kg/ha. Even at considerably lower Cd inputs, vegetable crops grown on soils contaminated with Cd experienced significant rises in plant tissue Cd. Four years of data from one of the authors' field experiments are tabulated as an example (Table 10.8). Although the range of plant tissue Cd concentrations for different levels of Cd treatment appeared to overlap one another, statistical analysis showed an increase of Cd in each of the five vegetables tested (carrot, lettuce, radish, Swiss chard and turnip) with increased levels of Cd inputs at $p<0.05$. There are also significant effects due to years of Cd addition and interaction between Cd treatment and years. But Cd in plant tissue did not always increase with years of Cd addition. These effects reflect the influence of plant tissue Cd concentrations by secondary factors (such as climatic conditions, soil pH changes, length of growing season, etc.) which varied from year to year and could not be controlled during the experiment. This set of data demonstrates that Cd content of plant tissue will always be elevated by introducing Cd into the soil. For a given soil, the level of elevation in plant tissue Cd, however, will depend on the level of Cd input. Due to the influence of other factors on plant growth,

Table 10.7 Influence of cadmium applications to soils on the cadmium concentrations of various vegetable crops*

		Cd concentration (μg/gm)[†] Application rate[‡]	
Crop	Tissue	0 kg/ha	11.2 kg/ha
Lettuce	Edible part	0.83	4.44
Broccoli	Edible part	0.27	0.89
Eggplant	Foliage	0.81	2.02
	Edible part	0.54	1.64
Tomato	Foliage	1.11	3.61
	Edible part	0.52	1.04
Potato	Foliage	0.80	0.69
	Edible part	0.11	0.10
Corn	Foliage	0.29	16.30
	Edible part	0.10	1.83
Squash	Foliage	0.15	1.40
	Edible part	0.15	0.27
Pepper	Foliage	0.90	7.51
	Edible part	0.24	1.08
Bean	Foliage	0.16	0.72
	Edible part	0.07	0.21
Cabbage	Edible part	0.18	0.27
Carrot	Edible part	0.84	1.77
Cantaloupe	Edible part	0.21	0.63

[*] Derived from data published by Giordano *et al.* (1979).
[†] Dry weight basis.
[‡] Cadmium was applied in the form of municipal sewage sludge.

the actual Cd content of plants grown in Cd-contaminated soils may vary from crop to crop and from season to season. Additional data on the accumulation of Cd in crops in relation to amounts applied in the form of sewage sludge are presented in a review by Sommers (1982).

The oxidation-reduction potential of soil also has a marked influence on the concentration of Cd absorbed from soil by plants. This is so because under reducing conditions Cd is substantially less soluble in soil solutions than it is under oxidizing conditions. Although the redox potential in soil influences Cd bioavailability, it is only important in the culture of rice because all other agricultural crops will not grow under reducing conditions. Bingham *et al.* (1976) have shown that the concentration of Cd in rice grown under reducing conditions (flooded) is less than that of rice grown under oxidizing

Table 10.8 Cadmium contents (d.w.) of selected vegetables grown on composted sludge-treated soils

Treatment	Cadmium contents ($\mu g/gm$)				
	Carrot	Lettuce	Radish	Swiss chard	Turnip
Control					
1976	0.44	0.60	0.13	0.24	0.11
1977	0.10	0.65	0.17	0.20	0.16
1978	0.60	0.40	0.12	0.23	0.10
1979	0.60	0.61	0.25	0.27	0.20
*1.2 kg Cd/ha/yr**					
1976	0.91	1.25	0.16	0.56	0.17
1977	0.91	1.27	0.32	0.55	0.27
1978	0.60	0.90	0.38	0.55	0.20
1979	1.40	1.00	0.68	0.90	0.30
*2.4 kg Cd/ha/yr**					
1976	1.51	2.39	0.27	0.66	0.12
1977	1.64	3.05	0.46	1.35	0.27
1978	0.80	1.25	0.56	1.65	0.30
1979	1.10	2.80	0.78	1.91	0.60

* Cd input from application of composted municipal sludge.

conditions (dry land). Similar observations have been made by Takijima *et al.*, (1973).

Although other soil factors have been reported to influence the absorption of Cd by agricultural crops, their effects are not nearly as consistent and clear-cut as those of soil pH, Cd content of soil, and redox potential. These factors include: (a) cation exchange capacity (Haghiri, 1974; Stenström and Lonsjo, 1974; Mahler *et al.*, 1978); (b) content of oxides of iron and manganese in soil (Forbes *et al.*, 1976; Chaney and Hornick, 1978; Corey *et al.*, 1981); (c) interactive effects of zinc, copper, nickel, manganese, selenium, and phosphorus (Lagerwerff and Biersdorf, 1971; John *et al.*, 1972; Francis and Rush, 1974; Haghiri, 1974; Cunningham *et al.*, 1975; Iwai *et al.*, 1975; McLean, 1976; Williams and David, 1977; Chaney and Hornick, 1978; Mitchell *et al.*, 1978; Street *et al.*, 1978; Valadares *et al.*, 1983); (d) soil temperature (Haghiri 1974; Giordano *et al.*, 1979). Effects of these soil factors are beyond the scope of this chapter. Details, however, can be obtained from the references cited.

CONCENTRATIONS OF CADMIUM IN FOOD CHAIN CROPS

Cadmium is a naturally occurring element present in all soils in at least trace quantities. For this reason, all food chain crops contain at least trace amounts of Cd. The concentrations of Cd in plants vary among species and cultivars. Different plant parts (leaves, stems, fruit, roots) accumulate different amounts of Cd (Table 10.9). The concentration of cadmium in the leaves and seeds of pea, wheat and corn (Table 10.10) are representative of results reported in the literature. The concentration of Cd in a particular plant part is also influenced by its physiological state of development (Chang *et al.*, 1984).

In the past decade numerous reports on the concentrations of Cd in agricultural crops grown in the United States have appeared in the literature. Most of these reports, however, deal with a limited number of crops grown at only one location. The recent reports of Shacklette (1980), Wolnick *et al.* (1983, 1985) and Feeney *et al.* (1984), however, are exceptions in that they deal with a survey of a variety of crops grown in a number of locations throughout the continental United States. Data reported in these surveys along with those obtained from control plots of various field experiments are presented in Table 10.9. The data pertain to situations where the soils on which the crops were grown were not known to be subject to any major external sources of Cd contamination. They represent more than one cultivar of the same plant species and a wide variety of soil types and climatic conditions. The concentrations of Cd reported for the various crops, therefore, should be representative of natural background levels.

The mean concentrations of the various crops as reported by a number of investigators vary by a factor of about 2 to 10. For example, the range of means among the various investigators for tomatoes, carrots, lettuce, barley, and field corn are, respectively, 0.08 to 0.52; 0.15 to 0.71; 0.42 to 0.88; 0.027 to 0.14 and <0.02 to 0.15 mg/kg (Table 10.9). The variations are most likely due to a combination of differences in substrate Cd concentration, soil properties such as soil pH, and different cultivars of the crop grown. It is worthwhile to single out the data reported by Wolnik *et al.* (1983, 1985). These data are derived from a national survey of the main crop production areas in the United States. The survey was jointly conducted by the US Department of Agriculture, Food and Drug Administration, and the Environmental Protection Agency. Special care was taken to insure that all sites selected were remote from sources of contamination, and care was taken in the handling, packaging and shipping of samples. All samples were analyzed in a specially equipped Food and Drug Administration laboratory. The senior author of this review (A.L. Page) served on the advisory committee for the study, and in his opinion the data are among the most reliable in existence. A summary showing maximum, minimum, mean, and median concentrations for the various crops surveyed is presented in Table 10.11. Generally, the results of others fall within the range reported by Wolnik *et al.* (1983, 1985).

The data presented in Table 10.12 are condensed by crop class (fruits,

Table 10.9 Mean concentrations of cadmium in various crops from locations throughout the United States

Crop	No. of samples	Areas represented (by state(s))	Cd conc. (mg/kg)*	Reference
Fruits				
Grapes				
American	21	MI,NY,WA	0.0110	Shacklette, 1980
European	12	CA,WA	0.0043	Shacklette, 1980
Oranges	20	AZ,CA,FL,TX	0.0050	Shacklette, 1980
Grapefruit	23	AZ,CA,FL,TX	0.0061	Shacklette, 1980
Apples	36	MI,NY,NJ,WA,CO	0.0340	Shacklette, 1980
Peaches	24	CA,CO,NY,WA	0.0110	Shacklette, 1980
Pears	38	CA,CO,MI,NY,WA	0.0057	Shacklette, 1980
Plums	16	CO,MI,NY,WA	0.0058	Shacklette, 1980
Vegetable fruits				
Peppers	2	MI	0.021	Shacklette, 1980
	–	AL	0.250	Giordano *et al.*, 1979
Cucumber	22	CA,MI,NY	0.093	Shacklette, 1980
Tomatoes	48	CA,FL,MI,WA	0.110	Shacklette, 1980
	8	CA[†],FL,GA,IL,IN,MI,TN	0.350	Feeney *et al.*, 1984
	3	MN	0.080	Dowdy and Larson, 1975
	–	AL	0.520	Giordano *et al.*, 1979
	231	CA,FL,NY,OH,PA,TX	0.270	Wolnik, *et al.*, 1985
Squash	1	AL	0.150	Giordano *et al.*, 1979
Cantaloupe	2	AL	0.210	Giordano *et al.*, 1979
Eggplant	1	AL	0.540	Giordano *et al.*, 1979
	2	MI	0.380	Shacklette, 1980
Seed vegetables				
Dry beans	35	CA,CO,ID,NY	0.110	Shacklette, 1980
Snap beans	42	ID,FL,MI,NY,NJ	0.024	Shacklette, 1980
Green beans	9	CA,FL,IL,IN,LA,NC,TX	0.130	Feeney *et al.*, 1984
Peas	1	MN	<0.030	Dowdy and Larson, 1975

Sweet corn	40	ID,FL,MI,NJ	0.026	Shacklette, 1980
	268	MD,MN,NY,OR,WA,WI	0.016	Wolnik *et al.*, 1983
Root and bulb crops				
Carrots	20	CA,TX	0.150	Shacklette, 1980
	2	AL	0.710	Giordano *et al.*, 1979
	207	FL,MI,NY,TX,WA,WI	0.250	Wolnik *et al.*, 1985
	15	CA[†],AZ,CO,FL,MI,TX	0.250	Feeney *et al.*, 1984
	6	CA	0.460	Authors' unpublished data
Radish	17	CA	0.310	Authors' unpublished data
Potatoes	40	ID,NY,NJ,WA	0.029	Shacklette, 1980
	1	AL	0.110	Giordano *et al.*, 1979
	297	AL,CA,CO,ID,ME,NC,NY, OR,TX,WA,WI,FL	0.170	Wolnik, *et al.*, 1983
Turnip	5	CA	0.170	Author's unpublished data
Onion	10	TX	0.050	Shacklette, 1980
	228	CA,CO,MI,NM,NY,OR,TX	0.100	Wolnik *et al.*, 1983
Peanuts	320	AL,GA,NC,TX	0.090	Wolnik *et al.*, 1983
Asparagus	10	CA	0.032	Shacklette, 1980
Leaf vegetables				
Cabbage	24	AR,MI,NJ,TX	0.093	Shacklette, 1980
	2	AL	0.160	Giordano *et al.*, 1979
Lettuce	40	CA,FL,NJ,TX	0.420	Shacklette, 1980
	9	MD	0.830	CAST, 1980
	8	AL	0.830	Giordano *et al.*, 1979
	150	AZ,CA,FL,NY,TX,WI	0.620	Wolnik *et al.*, 1983
	12	CA[†],IL,MO,NJ,OR,PA,TX	0.880	Feeney *et al.*, 1984
	8	CA	0.570	Author's unpublished data
Spinach	104	CA,DE,MD,NJ,TX	0.800	Wolnik *et al.*, 1985
	12	CA[†],IL,MO,NJ,OR,PA,TX	0.850	Feeney *et al.*, 1984
Swiss chard	16	CA	0.470	Authors' unpublished data
	6	MD	0.580	CAST, 1980
	7	CA,IL,NJ	0.350	Feeney *et al.*, 1984
Broccoli	1	AL	0.270	Giordano *et al.*, 1979

Table 10.9 Continued

Field crops				
Wheat	9	CA	0.055	Hyde *et al.*, 1979
	288	CO,ID,IL,KS,MT,ND, NE,OK,SD,TX,WA	0.048	Wolnik *et al.*, 1983
Barley	37	CA	0.055	Vlamis *et al.*, 1978
	29	CA	0.027	Chang *et al.*, 1979
	3	MT	0.080	Munshower, 1977
	75	AL,AZ,CA,CO,FL,IL,IN, MD,MI,MN,OH,OR,WI	0.140	‡CSRS Regional Report, 1984
Rice	166	AZ,CA,LA,TX	0.013	Wolnik *et al.*, 1985
Field corn	9	CA	0.020	Hyde *et al.*, 1979
	16	IL	0.080	CAST, 1980
	7	IL	0.150	Hinesly *et al.*, 1979
	3	MN	<0.020	Dowdy and Larson, 1975
	10	MD	0.090	CAST, 1980
	277	GA,IA,IL,IN,MN,MO, NC,NE,OH,WI	0.014	Wolnik *et al.*, 1985
Oat	6	MD	0.090	Chaney and Hornick, 1977
	6	MD	0.060	CAST, 1980
Sorghum	36	CA	0.033	Chang *et al.*, 1979
Soybeans	6	MD	0.021	Chaney and Hornick, 1977
	322	AR,GA,IA,IL,IN,LA, MN,NC	0.064	Wolnik *et al.*, 1983

AL = Alabama; AR = Arkansas; AZ = Arizona; CA = California; CO = Colorado; DE = Delaware; FL = Florida; GA = Georgia; IA = Iowa; ID = Idaho; IL = Illinois; IN = Indiana; KS = Kansas; LA = Louisiana; MD = Maryland; ME = Maine; MI = Michigan; MN = Minnesota; MO = Missouri; MT = Montana; NC = North Carolina; ND = North Dakota; NE = Nebraska; NJ = New Jersey; NM = New Mexico; NY = New York; OH = Ohio; OK = Oklahoma; OR = Oregon; PA = Pennsylvania; SD = South Dakota; TN = Tennessee; TX = Texas; WA = Washington; WI = Wisconsin.

* Oven dry basis (~70° C).

† Excluding samples from the Salinas Valley.

‡ Unpublished report of the CSRS Regional Project W-124. A.L.Page, University of California Riverside, and Lee Sommers, Purdue University, West Lafayette, Indiana, co-chairpersons.

Table 10.10 Cadmium concentrations of vegetative and reproductive tissues from plants grown on sewage sludge-amended soils in relation to species, application rate and soil pH

Cd added from sludge (kg/ha)	Soil pH	Cadmium concentrations (mg/kg)[*]					
		Pea		Wheat		Corn	
		Leaves	Seeds	Leaves	Grain	Leaves	Grain
0	4.4	0.94	0.20	0.19	0.06	0.11	0.03
2.2	4.6	4.40	0.64	0.82	0.25	1.44	0.06
4.5	5.0	3.80	1.11	1.10	0.32	1.83	0.08
9.0	5.2	6.05	1.45	0.89	0.58	3.37	0.09
0	7.8	0.43	0.14	0.14	0.04	0.07	0.01
2.2	7.6	0.43	0.17	0.18	0.12	0.14	0.02
4.5	7.4	0.42	0.18	0.25	0.23	0.41	0.03
9.0	7.3	0.48	0.30	0.33	0.34	0.92	0.03

[*] Dry weight basis.

Table 10.11 Cadmium concentrations of various crops from major producing regions throughout the United States[*]

Crop	No. of samples	Regions sampled[†]	Cadmium concentration (mg/kg)[‡]			
			Minimum	Maximum	Median	Mean
Wheat	288	NC,S,W	<0.001	0.22	0.036	0.048
Rice	166	S,W	0.001	0.25	0.005	0.013
Field corn	277	NC,S	<0.001	0.35	0.004	0.014
Sweet corn	268	NC,NE,W	<0.001	0.23	0.008	0.016
Soybeans	322	NC,S	0.002	1.20	0.045	0.064
Peanuts	320	S	0.011	0.66	0.068	0.090
Potatoes	297	NC,NE,S,W	0.009	1.00	0.140	0.170
Onions	228	NC,NE,S,W	0.011	0.34	0.090	0.100
Carrots	207	NC,NE,S,W	0.015	1.20	0.160	0.250
Tomatoes	231	NC,NE,S,W	0.045	0.79	0.220	0.270
Spinach	104	NE,S,W	0.160	1.90	0.800	0.830
Lettuce	150	NC,NE,S,W	0.034	3.80	0.440	0.620

[*] Derived from Wolnik *et al.* (1983, 1985).

[†] NC=North Central; NE=Northeast; S=Southern; W=Western; (see Figure 10.1).

[‡] Dry weight basis.

vegetables, field crops). This data show that on a dry weight basis fruits contain the lowest ($\bar{x} = 0.005$ mg/kg) and leafy vegetables contain the highest concentrations of cadmium ($\bar{x} = 0.560$ mg/kg). Seed crops (bean, sweet corn) and grains on the average, show mean concentrations of cadmium of approximately 0.03 mg/kg; root/tuber (carrots, potatoes, etc.) and fruity

Table 10.12 Concentrations of cadmium in crops and range of mean concentration by crop class*

Crop class	No. of samples	Cadmium concentration (mg/kg) Minimum	Maximum	Mean
Fruits	190	0.0043	0.012	0.005
Vegetables				
Seed	394	0.016	0.13	0.028
Root/Bulb†	878	0.029	0.71	0.208
Fruity	322	0.021	0.54	0.237
Leafy‡	297	0.093	0.88	0.560
Field Crops				
Grains	1302	0.014	0.21	0.047

* Derived from data presented in Table 10.9.
† Excluding peanuts.
‡ Excluding asparagus.

(tomatoes, cucumbers, etc.) vegetables show mean concentrations of 0.21 and 0.24 mg/kg, respectively.

SUMMARY

Concentrations of cadmium in soils from major agricultural regions throughout the United States not subject to external sources of contamination vary from about 0.1 to 1.0 mg/kg, with a median concentration of about 0.3 mg/kg. Soils from the Northeastern and Southeastern United States, on average, contain less total cadmium than do soils from the North Central and Western regions. In terms of taxonomic order classification, Histosols show the highest total cadmium concentrations; Aridisols, Entisols, Mollisols, Inceptisols, and Vertisols are intermediate; while Spodosols, Alfisols, and particularly Ultisols contain the lowest total cadmium concentrations. The lower concentrations of cadmium in the Spodosols, Alfisols and Ultisols are probably due to the more intense leaching these soil orders experience. Exceptions to the above generalizations are soils developed from parent materials unusually high in cadmium. Concentrations as high as 22 mg Cd/kg have been observed for soils developed from shales along the Pacific Coast.

Mining, smelting, and sintering of non-ferrous metals have resulted in cadmium contamination of nearby soils. In regions near these types of industrial operations, surface soils with concentrations in excess of 24 mg Cd/kg have been frequently reported. The contamination is restricted to the surface horizons; subsurface soils usually show concentrations representative of background levels for the region.

The major soil factors which influence the accumulation of cadmium by plants are soil pH and cadmium concentration. All other soil factors being equal, the accumulation of cadmium by crops increases as the pH of the soil decreases and as the concentration of cadmium in soil increases. Although fertilization and atmospheric deposition are sources of cadmium, amounts added to rural agricultural soils from these sources are small and amount to a few grams per hectare per year or less.

Concentrations of cadmium in crops vary quite substantially among species and even among cultivars of the same species. Different parts of the plant (leaves, stems, fruit, roots) accumulate different amounts of cadmium. For the above-ground parts, leaves usually contain greater concentrations of cadmium than the flowering and fruiting parts of the plant. On a dry weight basis, fruits (e.g. grapes, citrus, apples, peaches, etc.) contain the lowest concentrations of cadmium ($\bar{x} = 0.005$), and leafy vegetables (lettuce, spinach, etc.) the highest total concentration ($\bar{x} = 0.560$). Seed crops (bean, sweet corn) and grains on the average, show mean concentrations of cadmium of approximately 0.03 mg/kg; root/tuber (carrots, potatoes, etc.) and vegetable fruits (tomatoes, cucumbers, etc.) show mean concentrations of 0.21 and 0.24 mg/kg, respectively. The efficacy with which leafy crops take up Cd and transport it to the foliage suggests caution and monitoring of sewage sludge additions to land on which these crops are or might be grown.

The concentrations of crops grown in the United States vary within and among crop species. Within any particular plant species the variation in concentration of crops grown at one location to those of the same crop given another location can be as much as a factor of 600; factors ranging from 50 to 300 are common. For example, the concentration of cadmium in wheat was observed to vary from a minimum of 0.001 mg Cd/kg when grown at one location to a maximum of 0.22 mg Cd/kg when grown at another. Similarly, from one location to another the concentrations of cadmium for carrots and potatoes varied from 0.015 to 1.2 and 0.009 to 1.0 mg/kg, respectively.

Third World countries, as compared with the Western world, are less likely to be subjected to a Cd-contaminated environment. The main source of Cd human burden for those populations is food. Since the main source of Cd human burden for those populations is food, and the per capita dietary consumption of grains is high, the impact of Cd enrichment may be proportionately magnified. Food crops imported from or grown in areas high in Cd may result in a greater impact. Other factors such as the less stringent emission control and waste disposal measures for the developing industries contribute to the potential environmental hazards of Cd.

REFERENCES

Auer, C. (1977). *Cadmium in Phosphate Fertilizer Production.* US Environmental Protection Agency, Midwest Research Institute Report, Washington, DC.

Bingham, F. T., Page, A. L., Mahler, R. J., and Ganje, T. J. (1976). Cadmium availability to rice in sludge-amended soil under 'flood' and 'nonflood' culture. *Soil Sci. Soc. Am. J.*, **40**, 715–719.

Buchauer, M. J. (1973). Contamination of soil and vegetation near a zinc smelter by zinc, cadmium, copper and lead. *Environ. Sci. Technol.*, **7**, 131–135.

Burau, R. G., Kaita, K. Y., Inouye, T. S., and Miller, M. (1973). *Chemical Analysis of Soil Samples from the Salinis Valley, California for Cadmium, Zinc, and Phosphate.* Report to State Water Resources Control Board, University of California, Davis.

CAST (Council for Agricultural Science and Technology) (1976). *Application of Sewage Sludge to Cropland: Appraisal of Potential Hazards of the Heavy Metals to Plants and Animals.* Council for Agricultural Science and Technology, No. 64, Ames, Iowa, 63 pages.

CAST (Council for Agricultural Science and Technology) (1980). *Effects of Sewage Sludge on the Cadmium and Zinc Content of Crops.* Council for Agricultural Science and Technology, No. 83, Ames, Iowa, 77 pages.

Chaney, R. L., White, M. C., and Simon, P. W. (1975). Plant uptake of heavy metals from sewage sludge applied to land. In *Proceedings of Second National Conference on Municipal Sludge Management.* p. 169, Information Transfer, Inc., Rockville, MD.

Chaney, R. L., and Hornick, S. B. (1978). Accumulation and effects of cadmium on crops. In *Proceedings of First International Cadmium Conference*, p. 125, San Francisco, Metal Bulletin Ltd, London.

Chang, A. C., Page, A. L., Lund, L. J., Pratt, P. F., and Bradford, G. R. (1979). Land application of sewage sludges—a field demonstration. Final report, Regional Wastewater Solids Management Program, Los Angeles/Orange County Metropolitan Area (LA/OMA Project), 311 pages.

Chang A. C., Page, A. L., Warneke, J. E., and Johanson, J. B. (1982). Effects of sludge application on the Cd, Pb and Zn levels of selected vegetable plants. *Hilgardia*, **50**, 1–14.

Chang, A. C., Page, A. L., Warneke, J. E., Resketo, M. R., and Jones T. E. (1983). Accumulation of cadmium and zinc in barley grown in sludge-treated soils: A long–term field study. *J. Environ. Qual.* **12**, 391–397.

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.

Corey, R. B., Fujii, R., and Hendrickson, L. L. (1981). Bioavailability of heavy metals in soil-sludge. In *Conference on Application Research Practices of Municipal and Industrial Waste*, p. 449, University of Wisconsin Extension, Madison.

Cunningham, J. D., Keeney, D. R., and Ryan, J. A. (1975). Yield and metal composition of rye grown on sewage sludge-amended soil. *J. Environ. Qual.*, **4**, 448–454.

DeVries, M. P. C., and Tiller, K. G. (1978). Sewage sludge as a soil amendment with special reference to Cd, Mn, Ni, Pb and Zn comparisons of results from experiments conducted inside and outside a glasshouse. *Environ. Pollut.*, **16**, 231–240.

Dowdy, R. H., and Larson, W. E. (1975). The availability of sludge-borne metals to various vegetable crops. *J. Environ. Qual.*, **4**, 278–282.

Feeney, S., Peterson, J. R., Zenz, D. R., and Lue-Hing, C. (1984). *National Survey of the Metals Content of Seven Vegetable Species.* Dept. of Research and Development—Report No. 84-4 Metropolitan Sanitary District of Greater Chicago, Chicago, Illinois.

Fleischer, M., Sarofim, A. F., Fassett, D. W., Hammond, P., Shacklette, H. T., Nisbet,

I. C., and Epstein, S. (1974). Environmental impact of cadmium; A review by the panel on hazardous trace substances. *Environ. Health Persp.*, **7**, 253–323.

Forbes, E. A., Posner, A. M., and Quirk, J. P. (1976). The specific adsorption of divalent Cd, Co, Cu, Pb and Zn on geothite. *Soil Sci.*, **27**, 154–160.

Francis, C. W. and Rush, S. G. (1974). Factors affecting uptake and distribution of cadmium in plants. In Hemphill, D. D. (Ed.), *Trace Substances in Environmental Health VII*, p. 75, University of Missouri Press, Columbia.

Friberg, L., Piscator, M., Nordberg, G., and Kjellström, T. (1974). *Cadmium in the Environment.* 2nd ed. CRC Press, Cleveland, Ohio, 248 pages.

Fulkerson, W., and Goeller, H. E. (Eds) (1973). *Cadmium, the Dissipated Element.* Oak Ridge National Laboratory, Oak Ridge, Tennessee, ORNL/NSF/EP-21.

Giordano, P. M., Mays, D. A., and Behel, A. D-Jr. (1979). Soil temperature effects on the uptake of cadmium and zinc by vegetables grown on sludge-amended soil. *J. Environ. Qual.*, **8**, 232–236.

Goldschmidt, V. M. (1958). *Geochemistry.* Oxford University Press, London, 730 pages.

Gong, H., Rose, A. W., and Suhr, N. H. (1977). The geochemistry of cadmium in some sedimentary rocks. *Geochim. Cosmochim. Acta.*, **41**, 1687.

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.

Heinrichs, H., Schulz-Dobrick, B., and Wedepohl, K. H. (1980). Terrestrial Geochemistry of Cd, Bi, Ti, Pb, Zn and Rb. *Geochim. Cosmochim. Acta.*, **44**, 1519–1532.

Hinesly, T. D., Ziegler, E. L., and Barrett, G. L. (1979). Residual effects of irrigating corn with digested sewage sludge. *J. Environ. Qual.*, **8**, 35–38.

Holmgren, G. G. S., Meyer, M. W., Daniels, R. B., Kubota, J., and Chaney, R. L. (1986). Cadmium, lead, zinc, copper, and nickel in agricultural soils in the United States. *J. Environ. Qual.*, **16** (in press).

Horn, M. K., and Adams, J. A. S. (1966). Computer-derived geochemical balances and element abundances. *Geochim. Cosmochim. Acta.*, **30**, 279.

Hunt, W. F., Pinkerton, C., McNulty, O., and Creason, J. A. (1971). A study of trace element pollution of air in 77 midwestern cities. In Hemphill, D. D. (Ed.), *Trace Substances in Environmental Health IV*, p. 56, University of Missouri, Columbia.

Hyde, H. C., Page, A. L., Bingham, F. T., and Mahler, R. J. (1979). Effect of heavy metals in sludge on agricultural crops. *J. Water Pollut. Control Fed.*, **51**, 2475–2486.

Iwai, I., Hara, T., and Sonoda, Y. (1975). Factors affecting cadmium uptake by corn plant. *Soil Sci. Plant Nutr.*, **21**, 37–46.

John, M. K., Van Laerhoven, C. J., and Chuah, H. H. (1972). Factors affecting plant uptake and phytotoxicity of cadmium added to soils. *Environ. Sci. Technol.*, **6**, 1005–1009.

Johnson, R. D., Miller, R. J., Williams, R. E., Wai, C. M., Wies, A. C., and Mitchell, J. E. (1975). The heavy metal problem of Silver Valley, Northern Idaho. In Hutchinson, T. C. (Ed.), *Proceedings of International Conference on Heavy Metals in the Environment.* Vol. II, Part 2, p. 465, University of Toronto, Toronto, Canada.

Kjellström, T., and Nordberg, G. F. (1978). A kinetic model of cadmium metabolism in human beings. *Environ. Res.*, **16**, 248–269.

Klein, D. H. (1972). Mercury and other metals in urban soils. *Env. Sci. Technol.*, **6**, 558–559.

Kowal, N. E. (1984). An overview of public health effects. In Page, A. L., Gleason, T. L., Smith, J. E., Iskandar, I. K., and Sommers, L. E. (Eds), *Utilization of Municipal Wastewater and Sludge on Land*, p. 329. University of California Press, Riverside, California.

Lagerwerff, J. V., and Biersdorf, G. T. (1971). Interactions of zinc with uptake and translocation of cadmium in radish. In Hemphill, D. D. (Ed.), *Trace Substances in Environmental Health V*, p. 515, University of Missouri Press, Columbia, Missouri.

Lagerwerff, J. V., and Brower, D. L. (1975). Source determination of heavy metal contaminants in the soil of a mine and smelter area. In Hemphill, D. D. (Ed.), *Trace Substances in Environmental Health IX*, p. 207, University of Missouri Press, Columbia, Missouri.

Lindberg, S. E., Turner, R. R., Shriner, D. S., and Huff, D. D. (1981). Atmospheric deposition of heavy metals and their interaction with acid precipitation in a North American deciduous forest. In *Proceedings of International Conference on Heavy Metals in the Environment*, p. 306, CEP Consultants Ltd, Edinburgh, U. K.

Logan, T. J., and Miller, R. H. (1983). *Background Levels of Heavy Metals in Ohio Farm Soils.* Research Circular 275. The Ohio State University Agricultural Research and Development, Wooster, Ohio.

Logan, T. J., and Chaney, R. (1984). Metals. In Page, A. L., Gleason, T. L., Smith, J. E., Iskandar. I. K., and Sommers. L. E. (Eds), *Utilization of Municipal Wastewater and Sludge on Land*, p. 235, University of California Press, Riverside, California.

Lund, L. J., Betty, E. E., Page, A. L., and Elliott, R. A. (1981). Occurrence of high Cd levels in soil and its accumulation by vegetation. *J. Environ. Qual.*, **10**, 551–556.

Lyon, W. S. (1977). *Trace Element Measurements at the Coal-fired Power Plant.* CRC Press, Cleveland, OH, 136 pages.

Mahaffey, K. R., Corneliussen, P. E., Jelinek, C. F., and Fiorino, J. A. (1975). Heavy metal exposure from foods. *Environ. Health Perspec.*, **12**, 63–69.

Mahler, R. J., Bingham, F. T., and Page, A. L. (1978). Cadmium-enriched sewage sludge application to acid and calcareous soils: I. Effect on yield and cadmium uptake by lettuce and Swiss chard. *J. Environ. Qual.*, **7**, 274–281.

Marowsky, G., and Wedepohl, K. H. (1971). General trends in the behavior of Cd, Hg, Ti, and Bi in some major rock forming processes. *Geochim. Cosmochim. Acta.*, **35**, 1255.

McLean, 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. *Canadian J. Soil Sci.*, **56**, 129–138.

Mitchell, G. A., Bingham, F. T., Page, A. L., and Nash, P. (1978). Yield and metal composition of lettuce and wheat grown on soils amended with sewage sludge enriched with Cd, Cu, Ni and Zn. *J. Environ. Qual.*, **7**, 165–171.

Mullin, J. B., and Riley, J. P. (1956). The occurrence of cadmium in sea water and in marine organisms and sediments. *J. Marine Res.*, **15**, 103.

Munshower, F. F. (1977). Cadmium accumulation in plants and animals of polluted and nonpolluted grasslands. *J. Environ. Qual.*, **6**, 411–413.

Ondov, J. M., Regaini, R. C., Heft, R. E., Fisher, G. L., Silberman, D., and Prentice, B. A. (1976). Interlaboratory comparison of neutron activation and atomic absorption analyses of size-classified stack fly ash. *Eighth Materials Research Symposium on Methods and Standards for Environmental Measurement.* Gaithersberg, MD.

Page, A. L. (1974). *Fate and Effects of Trace Elements in Sewage Sludge When Applied* *to Agricultural Lands.* U. S. Environmental Protection Agency Special Publication EPA 670/2-74-005.

Page, A. L., and Chang, A. C. (1978). Trace elements impact on plants during cropland disposal of sewage sludges. In *Proceedings of Fifth National Conference on Acceptable Sludge Disposal Techniques*, p. 91, Information Transfer Inc., Rockville, Maryland.

Page, A. L., Bingham, F. T., and Chang, A. C. (1981). Cadmium in terrestrial plants. In Lepp, N. W.. (Ed.) *Effect of Heavy Metal Pollution on Plants.* Vol. 1. *Effects of Trace Metals on Plant Function*, p. 77, Applied Science Publishers, London, U. K.

Pahren, H. R., Lucas, J. B., Ryan, J. A., and Dotson, G. R. (1979). Health risks associated with land application of municipal sludge. *J. Water Pollut. Control Fed.*, **51**, 2588–2601.

Pierce, F. J., Dowdy, R. H., and Grigal, D. F. (1982). Concentrations of six trace metals in some major Minnesota soil series. *J. Environ. Qual.*, **11**, 416–422.

Ragaini, R. C., Ralston, H. R., and Roberts, N. (1977). Environmental trace metal contamination in Kellogg, Idaho near a lead smelting complex. *Environ. Sci. Technol.*, **11**, 773–781.

Rupp, E. M., Parzyck, D. C., Walsh, P. J., Booth, R. S., Raridon R. J., and Whitfield, B. L. (1978). Composite hazard index for assessing limiting exposures to environmental pollutants: Application through a case study. *Environ. Sci. Technol.*, **12**, 802–807.

Ryan, J. A., Pahren, H. R., and Lucas, J. B. (1982). Controlling cadmium in the human food chain: A review and rationale based on health effects. *Environ. Res.*, **28**, 251–302.

Shacklette, H. T. (1980). *Elements in Fruits and Vegetables from Areas of Commercial Production in the Conterminous United States.* Geological Survey Professional Paper No.1178. US Government Printing Office, Washington, DC. 149 pages.

Sommers, L. E. (1977). Chemical composition of sewage sludges and analysis of their potential use as fertilizers. *J. Environ. Qual.*, **6**, 225–232.

Sommers, L. E. (1982). Toxic metals in agricultural crops. In Bitton, G., Damron, B. L., Edds, G. T., and Davidson, J. M. (Eds), *Sludge-Health Risks of Land Application*, p. 105, Ann Arbor Science Publishers/The Butterworth Group, Ann Arbor, Michigan.

Stenström, T., and Lonsjo, H. (1974). Cadmium availability to wheat: a study with radioactive tracers under field conditions. *Ambio*, **3**, 87–90.

Street, J. J., 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.

Takijima, Y., Katsumi, F., and Takezawa, K. (1973). Cadmium contamination of soils and rice plants caused by zinc mining. II. Soil conditions of contaminated paddy fields which influence heavy metal contents of rice. *Soil Sci. Plant Nutr.*, **19**, 173–182.

Tsuchiya, K. (Ed). (1978). *Cadmium Studies in Japan–A Review.* Elsevier/North Holland Biomedical Press, Amsterdam.

US Environmental Protection Agency (1972). *Helena Valley, Montana Area Environmental Pollution Study.* EPA Office of Air Programs Publ. AP-91 Research Triangle Park, North Carolina.

US Environmental Protection Agency. (1978). *Cadmium additions to Agricultural Lands Via Commercial Phosphate Fertilizers—A Preliminary Assessment*, p. 35, Office of Water and Waste Management, Washington DC. Soil Waste Management Series No. SW-718.

Valadares, J. M. A. S., Gal, M., Mingelgrin, U., and Page. A. L. (1983). Some heavy metals in soils treated with sewage sludge, their effects on yield, and their uptake by plants. *J. Environ. Qual.*, **12**, 49–57.

Vlamis, J., Williams, T. E., Fong, K., and Corey, J. E. (1978). Metal uptake by barley from field plots fertilized with sludge. *Soil Sci.*, **126**, 49–55.

Waketa, H., and Schmitt, R. A. (1970). Cadmium. In Wedepohl, K. H. (Ed.), *Handbook of Geochemistry.* Springer-Verlag. New York, Chapter 48.

Wedepohl, K. H. (1968). Origin and distribution of elements. In Ahrens, L. H. (Ed). *International Symposium on the Origin and Distribution of the Elements,* p. 999, Pergamon Press, New York.

Williams, C. H., and David, D. J. (1977). Some effects of the distribution of cadmium and phosphate in the root zone on the cadmium content of plants. *Australian J. Soil Res.*, **15**, 59–68.

Wolnik, K. A., Fricke, F. L., Capar, S. G., Braude, G. L., Meyer, M. W., Satzger, R. D., and Bonnin, E. (1983). Elements in major raw agricultural crops in the United States. I. Cadmium and lead in lettuce, peanuts, potatoes, soybeans, sweet corn and wheat. *J. Agric. Food Chem.*, **31**, 1240–1244.

Wolnik, K. A., Fricke, F. L., Capar, S. G., Meyer, M. W., Satzger, R. D., Bonnin, E. and Gaston, C. M. (1985). Elements in major raw agricultural crops in the United States. III. Cadmium, lead and other elements in carrots, field corn, onion, rice, spinach and tomatoes. *J. Agric. Food Chem.*, **33**, 807–811.