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ASSESSMENT OF THE TOXICITY OF ARSENIC, CADMIUM, LEAD AND ZINC IN SOIL, PLANTS, AND LIVESTOCK IN THE HELENA VALLEY OF MONTANA

for

EAST HELENA SITE (ASARCO)
EAST HELENA, MONTANA

EPA Work Assignment No. 68-8L30.0

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TABLE OF CONTENTS

LIST OF TABLES

Glossary of Units, Symbols, Acronyms and Terms

Units

kg	kilogram; kg = 10^3 g
g	gram = 10^{-3} kg
mg	milligram; mg = 10^{-3} g
ug	microgram; ug = 10^{-3} mg
ng	nanogram; ng = 10^{-3} ug
L	liter; L = 1 dm^3
ml	milliliter; ml = 10^{-3} L

Symbols

ppm	parts per million = ug/g = mg/kg
ppb	parts per billion = 10^{-3} ppm, ng/g = ug/kg
ug/g	microgram/gram
mg/kg	milligram/kilogram
mg/L	milligram/liter
ug/L	microgram/liter
ug/ml	microgram/milliliter
ng/ml	nanogram/milliliter

Acronyms

AA	Arsanilic acid
ALA-D	Delta aminolevulinic dehydratase
AAS	Atomic absorption spectrophotometry
AOAC	Association of Official Agricultural Chemists
AWT	Ash weight basis
CCM	Copper carbonate method
CEC	Cation exchange capacity
d	Day
DTPA	Diethylenetriaminepentaacetic acid
DW	Dry weight basis
EDTA	Ethylenediaminetetraacetic acid
EPA	Environmental Protection Agency
EPA CV	Environmental Protection Agency cold vapor method
ES	Emission spectrographic
FEP	Blood-free erthrotyte porphyrins
FLAAS	Flameless atomic absorption spectrophotometry
GLC	Gas liquid chromatography
INAA	Instrumental neutron activation analysis
IPAA	Instrumental photon activation analysis
LD_{20}	A dose which is lethal for 20 percent of the test subjects
MMC	Methyl mercuric chloride
MMH	Methyl mercuric hydroxide
Mo	Month
MSMA	Monosodium acid methanearsonate
MW	Mining waste
MYC	Mycorrhiza
ND	Not determined

NOAA	National Oceanic and Atmospheric Administration
NR	Not reported
NRC	National Research Council
NS	Not significant
OM	Organic Matter Content
pH	Negative logarithm, base 10, of H^+ concentration
PMA	Phenyl mercuric acetate
RNAA	Radiochemical neutron activation analysis
SCS	U.S. Soil Conservation Service
SSMS	Spark source mass spectrometry
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WW	Wet weight basis
Wks	Weeks
XRFL	X-ray fluorescence
YR	Yield reduction

Terms

acute - Sharp; poignant. Having a short and relatively severe course.

chronic - Persisting over a long period of time.

phytotoxic - Pertaining to a phytotoxin. Inhibiting the growth of plants.

toxicosis - Any disease condition due to poisoning.

criterion - A standard by which something may be judged.

1.0 INTRODUCTION

This document consists of a literature review and presents candidate hazard levels for assessment of selected environmental hazards associated with the East Helena smelter complex. A substantial amount of material was reviewed but additional material will no doubt be added to these data as the study progresses. This document has been prepared specifically for the Helena Valley, Montana area and use of this document for evaluation of other sites should be done only after appropriate consideration of site specific conditions.

1.1 Purpose

This document is a literature review from which hazard levels were developed to assess potential risk to plants and livestock from chemical element levels found in soil, plants, livestock and water present in the vicinity of the East Helena smelter. These hazard levels will enable determination of the potential danger to these agricultural resources. It is the intent of this review to assess only the potential risk to agricultural production. This document does not address any subsequent risk to the human population from consumption of these agricultural products.

1.2 Scope

The scope of this document (Volume 1) is confined to the metals arsenic, cadmium, lead and zinc present in soil, water, plants and livestock and their toxic affects to plants and livestock. In addition, a brief discussion on the toxicology mechanisms of these four metals to livestock and vegetation is included. Volume 2 presents similar data for plants and soils for the metals copper, mercury, selenium, silver and thallium.

1.3 Methods

Portions of the literature presented in this document were procured through the use of a computer search utilizing numerous data bases. Data bases utilized included AGRICOLA, BIOSIS, CAB

Abstracts, CRIS-USDA, ENVIROLINE, MEDLINE, NTIS, Pollution Abstracts, SCISEARCH and Water Resources Abstracts. A brief description of these data bases is included in section 6.3. Conventional library methods were also employed for researching abstracts, periodicals and other materials. No attempt was made to determine the relative importance of field studies versus greenhouse studies, but study settings are given in appropriate tables to enable the reader to evaluate this variable. No attempt was made to evaluate synergistic or antagonistic effects of these metals although some of these mechanisms are documented in the text. Levels of impact or an evaluation of an acceptable impact have not been determined but this data is included in appropriate tables when reported in the referenced literature.

The authors conducted a meeting to establish normal, tolerable, uncertain and toxic levels of metals in soils, plants, and livestock. At this meeting all literature was discussed followed by establishment of hazard levels based on the reviewed literature.

Background values for all parameters were generally derived directly from data in the reviewed literature and are the minimum and maximum or only value reported for normal or control parameters. The background range will no doubt expand as more data become available.

The tolerable level represent the maximum concentrations at which no toxicity has been noted. These levels were not available for many parameters.

The uncertain range represents the chemical level at which both nontoxic and toxic results have been reported by various studies. This result stems from variations in individual animal tolerances, variations in experimental designs, and by synergistic or antagonistic effects of other constituents.

Toxic concentrations have been derived from two major sources: 1) the results of individual studies and 2) criteria reported as toxic in toxicology manuals, texts, and special publications.

Data derived under conditions similar to those found in the Helena Valley merited greater consideration than other data. For example, a toxic soil level for wheat on calcareous loamy soils was more applicable than a toxic soil level for cabbage on sandy acid soils. The hazard levels presented in this document are thus site specific for crops and conditions present in the Helena Valley as much as allowed by the reviewed literature. In some cases, a site specific evaluation was not possible. Site specific conditions for the Helena Valley are presented in the following section (1.4). Once hazard levels were developed they were compared to means and ranges of soil/plant chemical levels measured in the Helena Valley and control sites.

1.4 Site Description

The Helena Valley is located in west central Montana and trends in a west northwest direction. It is 35.4 km (22.1 mi) long and 17.1 km (10.7 mi) wide. The valley is bounded on the northeast by the Big Belt Mountains, on the south by the Elkhorn Mountains and the Boulder Batholith, and on the west by mountains forming the continental divide. Lower portions of the valley are occupied by Lake Helena and Hauser Lake formed by dams on Prickly Pear Creek and the Missouri River. Elevations range from 1,113 m (3650 ft) mean sea level at Hauser Lake to 2,560 m (8,400 ft) in the surrounding mountains. Geological materials on the valley floor consist of quaternary and tertiary sediments that are consolidated or poorly consolidated. Soils are moderately calcareous and composed of silt and clay (Miesch and Huffman 1969). Typical soil series mapped in portions of the Helena Valley are the Hilger, Martinsdale, Musselshell, and Sappington series all of which contain horizons that are "strongly to violently" effervescent (Soil Conservation Service 1977b). Except for an area in the immediate vicinity of East Helena surficial soil pH values range from about 7.1 to 8.6 (EPA, 1986) Soil profiles are poorly to moderately developed on both quaternary and tertiary parent materials. The Helena Valley is semi-arid and receives less than 25.4 cm (10 in) of annual precipitation. The adjacent mountains receive up to 76.2 cm (30 in) of annual precipitation (Soil Conservation Service 1977). The climate is modified continental with an average annual temperature of 6.3°C (43.3°F) (National Oceanic and Atmospheric Administration (NOAA) 1983). Average January and July temperatures at Helena are -8°C (18.1°F) and 20°C (67.9°F) respectively (NOAA 1983). Agricultural crops in the Valley are alfalfa, small grains (usually wheat, barley and some oats) and range land.

The Helena Valley is the site for two incorporated cities: Helena and East Helena with approximate populations of 23,900 and 2,400 respectively (1980 census). The two cities are located 6.4 (4 mi) and 1 km (0.6 mi) from the smelter complex, respectively.

The valley has been the site of a lead smelter since the Helena and Livingston facility was built in East Helena in 1888. The smelter was purchased by its present owner (American Smelting and Refining Company) in 1899. The Anaconda Company built a zinc plant adjacent to the smelter in 1927 to recover zinc from waste products. In 1955 the American Chemet Company constructed a paint pigment plant utilizing zinc oxide from the zinc facility.

2.0 LITERATURE REVIEW AND HAZARD LEVELS FOR LIVESTOCK

There are three general approaches to determining the body burden of heavy metals in livestock. These are: 1) analyzing internal organ tissues; 2) analyzing accessible body fluids and materials; and 3) the in vivo determination of heavy metals utilizing radiometric analyses. A considerable amount of data has been published on background and elevated heavy metal levels in livestock organs. In most situations these organs are not available for large scale studies. Liver and bone samples may be procured through biopsy procedures. Data on blood, milk, hair, feces and urine are more limited, but sufficient in some parameters to allow their use in a livestock survey for some heavy metals. The third method offers much promise in future studies but facilities for radiometric determinations are few at this time. The following sections outline documented levels of selected heavy metals in various animal substances and their significance in determining toxicosis. All values are reported on a wet weight basis unless noted.

2.1 Arsenic

2.1.1 Arsenic literature review

Arsenic poisoning is the second most common metaloid toxin. The element is ubiquitous and has been found in all plant and animal tissues under normal background conditions (Schroeder and Balassa 1966). Several forms: arsanilic acid; sodium arsanilate; 3-nitro-4-hydroxyphenylarsonic acid, have been used as feed additives to increase weight gain and feed efficiency and to control disease in swine, poultry and other livestock.

Most documented cases of arsenic poisoning in livestock have been acute or subacute, usually from ingesting treated forage (Edwards and Clay 1979, Weaver 1962, McCulloch and St. John 1940, Selby et al. 1974, Selby et al. 1977), contaminated feed (Beregland et al. 1976, Selby et al. 1977), dipping powder and herbicides (Moxham and Coup 1968) and various refuse (McParland

and Thompson 1971, Selby et al. 1977). Very few cases of natural arsenic poisoning have been reported. Fitch et al. (1939) studied the poisoning of livestock in the Waiotapu Valley in New Zealand and attributed it to arsenic from geothermal sources. Many cases of chronic arsenic poisoning may be partially masked by the effects of other heavy metal poisoning (especially lead, copper, cadmium and zinc) usually associated with arsenic in metallurgical mining, smelting and refining industries. It has been suggested that some tolerance to arsenic is acquired by livestock with chronic exposure (McCulloch and St. John 1940).

A considerable difference exists between the effective toxicity of various forms of arsenic. Levels of total arsenic found in marine invertebrates and fish have been found to be toxic to aquatic organisms and fish when the arsenic was present as arsenic trioxide (Schroeder and Balassa 1966). Bucy et al. (1955) found differences in the toxicity of organic arsenic compounds to sheep, with 3-nitro-4-hydroxyphenylarsonic acid the least toxic. The study found arsanilic acid to be less toxic than potassium arsenite and that the latter was not very palatable to lambs. All arsenic concentrations in livestock substances have been reported as total arsenic. The arsenic hazard levels presented in this document are thus based on total arsenic.

Tables 1-4 list background and elevated arsenic levels in livestock fluids, hair and tissues. The highest concentration of arsenic in tissues has been found in the spleen, liver and kidneys (Peoples 1964, Edwards and Clay 1979, Rosiles 1977, Knapp et al. 1977). Cattle that have not been exposed to arsenic have kidney levels from 0.0 (Peoples 1964) to 0.25 ppm (wet weight) (Dickinson 1972). Doyle and Spaulding (1978) reported a value of 0.06 ppm for 100 cattle tested by the National Bureau of Standards. One hundred and ninety Australian cattle tested by Flanjak and Lee (1979) had a mean value of 0.018 ppm for kidney tissue. Normal arsenic levels in cattle kidney have been given as less than 0.5 and 0.15 to 0.4 ppm by the National Research Council (NRC, 1977) and Puls (1981), respectively. Mean background levels for sheep kidney (n=440) were found to be 0.03 ppm by Spaulding (1975) and

Table 1. Background arsenic levels in livestock fluids and hair.

Diet	Blood	Urine	Milk	Hair	n	Notes	Reference
	ppm (wet weight)			ppm (dry wt.)			
CATTLE							
				0.13-0.84	10		Orheim et al. (1974)
				0.46	10	(Mean)	Orheim et al. (1974)
	0.034 (Mean)				10		Edwards and Clay (1979)
	0.03-0.07			0.357	10		Edwards and Clay (1979)
	0.03-0.12			0.125	20	Exposed to As 1 yr prior to samples	Edwards and Clay (1979)
	0.051 (Mean)				20		Edwards and Clay (1979)
			0.028			EEC Milk	Tremaliere et al. (1975)
			0.05			UK Milk	IARC (1980)
			0.03-0.06				Underwood (1977)
				0.09-0.10	6		Riviere et al. (1981)
			0.0005-0.07				NRC (1977)
		0.17-.31			4		Lakso and Peoples (1975)
				2.7	1		Dickinson (1972)
				1.1	1		Dickinson (1972)
				0.81	1		Dickinson (1972)
			0.170			Market Milk USA	Schroeder and Vinton (1962)
			<.001		12	Market Milk UK	Hamilton et al. (1972)
			0.042-0.058			USA	Iyengar (1982)
			0.030			Alaska	Iyengar (1982)
	0.05	0.05	0.03-0.06	0.05-3.0			Puls (1981)
SHEEP							
			0.00-0.04		1		Shariatpanahi and Anderson (1984a)
		0.00-0.07	0.00-0.03		1		Shariatpanahi and Anderson (1984b)
	0.02-0.04				1		Anderson (1985)
				0.0	3		Lancaster et al. (1971)
GOATS							
			0.00-0.04		1		Shariatpanahi and Anderson (1984a)
		0.00-0.04	0.00-0.03		1		Shariatpanahi and Anderson (1984b)
	0.02-0.04				1		Anderson (1985)
			0.055				Iyengar (1982)

Table 2. Background arsenic levels in livestock tissues.

Diet	Kidney	Liver	Spleen	Heart	Brain	Pancreas	Bone	n	Notes	Reference
	ppm (wet weight)						ppm (dry wt.)			
					CATTLE					
	0.08	0.09						21		USDA (1975)
	0.018	0.013						190	Australian	Flanjak and Lee (1979)
	0.04	0.06						8		Edwards and Dooley (1980)
	<0.5	<0.5								NRC (1977)
		0.06								NRC (1977)
		0.15								NRC (1977)
	0.25	0.82			0.05	0.03(rib)		1		Dickinson (1972)
	1.1	0.7						1		Dickinson (1972)
					SHEEP					
	0.15	0.15 = $\bar{x}$						6	Lambs	Bucy et al. (1955)
	0.09-0.26	0.05-0.21						6		Bucy et al. (1955)
	<0.1	0.0								Landcaster et al. (1971)
		0.48						3		Bennett and Schwartz (1971)
	0.03	0.03						440		Spaulding (1975)

Table 3. Elevated arsenic levels in livestock fluids and hair.

Diet	Blood	Urine	Milk	Hair	n	Agent	Notes/ Response	Reference
	ppm (wet weight)			ppm (dry wt.)				
CATTLE								
			0.07-1.5			Ind. Exp.	Chronic Tox N. Zealand	Underwood (1977)
				3.7-19.0	10	Ind. Exp.	Not Noted, Smelter Polut.	Orheim et al. (1974)
				8.9	10	Ind. Exp.	Not Noted Smelter Polut.	Orheim et al. (1974)
140ppm				16.0	1	MW[F]	Subacute Emaciated	Bergeland et al. (1976)
140ppm				11.0	1	MW	Subacute Emaciated	Bergeland et al. (1976)
140ppm				6.3	1	MW	Subacute Emaciated	Bergeland et al. (1976)
140ppm				21.0	1	MW	Subacute Emaciated	Bergeland et al. (1976)
				4.0	1	MW	Unthrifty	Bergeland et al. (1976)
				5.0	1	MW	Unthrifty	Bergeland et al. (1976)
				2.4	1	MW	Unthrifty	Bergeland et al. (1976)
				4.0	1	MW	Unthrifty	Bergeland et al. (1976)
AA[D] 0.05 mg/kg		0.75			3	As acid	Non Toxic	Peoples (1964)
AA 0.25 mg/kg		2.5			3	As acid	Non Toxic	Peoples (1964)
AA 1.25 mg/kg		7.95			3	As acid	Non Toxic	Peoples (1964)
5.5ppm				0.80-3.40	4		Acute Tox	Riviere et al. (1981)
Forage Cont.			0-0.015		7	Na arsenite	Subclinical	Weaver (1962)
2.75mg/kg Na arsenate		2.45-4.86			4	Na arsenate	Non Toxic	Lakso and Peoples (1975)
1.57mg/kg $KAsO_2$		6.35			4	$KAsO_2$	Non Toxic	Lakso and Peoples (1975)
10mg/kg bwt/d, 10d				3.3	1	MSMA[C]	Fatal	Dickinson (1972)
10mg/kg bwt/d, 10d				1.4	1	MSMA[C]	Fatal	Dickinson (1972)
		16.0			1	Na arsenite	Fatal (Calf)	Weaver (1962)
HORSES								
				0-7.5	3	Ind. Exp.[E]	1 mi from smelter Response Not Noted	Lewis (1972)
				0-4.5	3	Ind. Exp.	1 mi from smelter "smoked"	Lewis (1972)
				0-4.4	11	Ind. Exp.	2.9 mi from smelter 1 fatality	Lewis (1972)
				0-2.3	5	Ind. Exp.	5.3 mi from smelter Response Not Noted	Lewis (1972)
SHEEP								
Sngl dose 10mg As/ kg bwt	14.5 [A]		0.18		2	MSMA[C]	Diarrhea	Shariatpanahi and Anderson (1984a)
10mg As/kg bwt/day	24 [B]	341.3	0.0-0.07		2	MSMA	Diarrhea	Shariatpanahi and Anderson (1984b)
1.4mg As/kg bwt/day			12.6		3	MSMA	Healthy	Lancaster et al. (1971)

Table 3. Elevated arsenic levels in livestock fluids and hair, continued.

Diet	Blood	Urine	Milk	Hair	n	Agent	Notes/ Response	Reference
	ppm (wet weight)			ppm (dry wt.)				
						GOATS		
Single Dose 10mg As/ kg bwt	17.2 [A]		0.16		2	MSMA	Diarrhea	Shariatpanahi and Anderson (1984a)
10mg As/kg bwt/day	16	218.5	0.0-0.06		2	MSMA	Diarrhea	Shariatpanahi and Anderson (1984b)

A/ Reported in ug/ml B/ Reported in mg/kg C/ Monosodium acid methanearsonate (MSMA)
D/ Arsanilic Acid E/ Industrial Exposure F/ Mining waste

Table 4. Elevated arsenic levels in livestock tissues.

Diet	Kidney	Liver	Spleen	Heart	Brain	Pancreas	Bone	n	Agent	Notes/ Response	Reference
	ppm (wet weight)						ppm (dry wt.)				
CATTLE											
	4.38	2.0						4	As Herbicide	Acute	Edwards and Clay (1979)
	3.5-5.0							4	As Herbicide	Acute	Edwards and Clay (1979)
	13.2	14.8								Acute	Rosiles (1977)
	5-35	5-29								Acute	Rosiles (1977)
	15.6	2.3						1	Wood Preserv.	Fatal	Knapp et al. (1977)
	13.3	14.0						21		Fatal	Hatch and Funnell (1969)
	1.5-37	2.1-38						21		Fatal	Hatch and Funnell (1969)
Contaminated Feed & Water	7.0	3.0						1		Fatal	Bergeland et al. (1976)
AA[A] 0.05mg/kg	0.0	0.25	0.2	0.1	0.2		0.0	3	A	Nontoxic	Peoples (1964)
AA 0.25mg/kg	0.0	0.5	0.8	0.2	0.0		0.0	3	A	Nontoxic	Peoples (1964)
AA 1.25mg/kg	0.35	1.2	2.0	0.1	0.25		0.2	3	A	Nontoxic	Peoples (1964)
5.5ppm	4.85	3.78								Acute	Riviere et al. (1981)
Forage Cont.	2.6-12.6							3	Na Arsenite	Fatal	Riviere et al. (1981)
		9.3						13		Fatal	Riviere et al. (1981)
	3.2							6		Fatal	Weaver (1962)
Poisoned	18.5	15.7						1	Lead Arsenate	Fatal	McParland and Thompson (1971)
Poisoned	31.1							1	Lead Arsenate	Fatal	McParland and Thompson (1971)
10mg/kgMSMA[D]	64.2	24.9			1.7		4.9(rib)	1	D	Fatal	Dickson (1972)
10mg/kgMSMA[D]	23.2	30.3			1.7		2.5(rib)	1	D	Fatal	Dickson (1972)
10mg/kgMSMA[D]	45.8	17.7						1	D	Fatal	Dickson (1972)
10mg/kgMSMA	3.5	1.6						1	D	Fatal	Dickson (1972)
10mg/kgMSMA[D]		7.2						1	D	Acute	Dickson (1972)
SHEEP											
1.4mg/kg 1w	3.28	2.53						3	Aquatic Veg	Healthy	Lancaster et al. (1971)
1.4mg/kg 2w	3.68	3.38						3	Aquatic Veg	Healthy	Lancaster et al. (1971)
1.4mg/kg 3w	2.76	3.07					2.21(hoof)	3	Aquatic Veg	Healthy	Lancaster et al. (1971)
22mg/kg/mo		1.33						5	Pb Arsenate 11 mo	Nontoxic	Bennett and Schwartz (1971)
44mg/kg/mo		3.57						5	Pb Arsenate 11 mo	Nontoxic	Bennett and Schwartz (1971)
88mg/kg/mo		20.71						4	Pb Arsenate 11 mo	Toxic	Bennett and Schwartz (1971)
3N[B] 0.05%	7.8	6.8						1	B	Toxic	Bucy et al. (1955)
0.1%	7.9	13.3						1	B	Toxic	Bucy et al. (1955)
0.2%	9.8	13.3						1	B	Toxic	Bucy et al. (1955)
0.4%	10.5	9.3						1	B	Toxic	Bucy et al. (1955)
AA[A] 0.05%	13.5	12.3						1	A	Toxic	Bucy et al. (1955)
0.1%	7.5	9.3						1	A	Toxic	Bucy et al. (1955)
0.2%	8.4	12.3						1	A	Toxic/Fatal	Bucy et al. (1955)
0.4%	7.1	8.3						1	A	Toxic/Fatal	Bucy et al. (1955)
KA[C] 0.05%	7.7	10.0						1	C	Toxic	Bucy et al. (1955)
0.1%	9.8	9.0						1	C	Toxic	Bucy et al. (1955)
0.2%	13.5	12.3						1	C	Toxic	Bucy et al. (1955)
0.4%	5.9	8.5						1	C	Feed Refusal Toxic	Bucy et al. (1955)

[A]/Arsanilic Acid [B]/3N-3-Nitro-4-Hydroxyphenylarsonic Acid [C]/KA-Potassium Arsenite
[D]/Monosodium Acid Methanearsonate, 10 Day Treatment

ranged from 0.09 to 0.26 ppm (mean 0.15) in six lambs analyzed by Bucy et al. (1955). Puls (1981, 1985) has given a range of 0.01 to 0.3 ppm for normal arsenic levels in sheep kidney tissue.

Arsenic levels in normal liver tissue from cattle have been reported as 0.013 ppm (n = 190) and 0.06 ppm (n = 100) by Flanjak and Lee (1979) and Doyle and Spaulding (1978), respectively. Normal ranges for cattle liver have been given as 0.03-0.40 ppm (Puls 1981) and less than 0.5 ppm (NRC 1977). Buck et al. (1976) has stated normal levels are usually less than 0.5 ppm. Background arsenic levels in sheep liver have been reported as 0.03 ppm for 440 animals tested by Spaulding (1975), and 0.05 to 0.21 ppm (mean 0.15 ppm) for six lambs studied by Bucy et al. (1955). Normal sheep liver levels given by Puls (1981) are 0.03 to 0.20 ppm. Horse liver and kidney background levels of less than 0.4 ppm have been reported by Puls (1981).

Insufficient data exist to determine background levels of arsenic in spleen tissue, but limited data suggest that in some cases elevated arsenic concentrations in the spleen may be higher than in liver or kidney tissue (Table 4).

Elevated arsenic levels in kidney, liver and spleen have been demonstrated in a number of experimental and accidental situations. Peoples (1964) found concentrations greatest in the spleen (2.0 ppm) and liver (1.2 ppm) of cattle fed 1.25 mg/kg arsenic acid for eight weeks. Bucy et al. (1955) found arsenic concentrations nearly equal in the kidneys and liver of lambs fed up to 0.4 percent of their diet as organic arsenic compounds. Levels were sharply elevated from background concentrations with diets of 500 ppm organic arsenic content. Cattle kidney levels as high as 53 ppm have been reported by Underwood (1977).

The level at which chronic poisoning occurs has not been well documented. Reduced weight gains, which are only rarely noticed, are generally the first signs of chronic arsenic poisoning. Increasing levels to 1000 ppm arsanilic acid in the diet of swine produced posterior paresis or quadriplegia in 15 days (Ledet et al. 1973). Levels of 7.5 to 7.8 and 6.8 to 12.3 ppm (wet weight) for kidneys and liver, respectively, were noted in sheep fed 0.05

percent organic arsenic compounds compared to 0.15 ppm found in the same organs of controls (Bucy et al. 1955). Buck et al. (1976) cited a level of 10 ppm in kidney and liver tissues as diagnostic of arsenic poisoning. Peoples (1964) found 0.35 ppm arsenic in the kidneys of cows receiving up to 1.25 ppm arsanilic acid diet and noted no toxic effects. A study by Bennett and Schwartz (1971) found sheep liver arsenic levels equal to or greater than 10.6 ppm in all experimental sheep that died from lead arsenate poisoning. The same study also revealed that all surviving sheep had liver concentrations of less than 3.8 ppm arsenic. Kidney and liver tissue arsenic levels associated with chronic arsenic poisoning in cattle were reported as 5.0 to 53 ppm and 7.0 to 70 ppm, respectively (Puls 1981). It should be noted however that under acute conditions, clinical toxicity has been reported in cattle exhibiting liver arsenic concentrations as low as 1.6 ppm (Dickinson 1972) and numerous clinical toxicity cases have been documented in the 1.6 to 5 ppm range (Edwards and Clay 1979, Rosiles 1977, Knapp et al. 1977, Hatch and Funnell 1969, Bergeland et al. 1976, Riviere et al. 1981). Puls (1981) reported toxic levels in horse kidney at 10.0 ppm and 7.0 to 15 ppm in liver. Bucy et al. (1955) noted arsenic levels in sheep kidney tissue decreased rapidly following removal of arsenic from the diet. Dickinson (1972) has suggested that cattle could deplete an elevated kidney arsenic content to a value less than that of diagnostic significance but still succumb to irreversible tubular damage.

The affinity of arsenic for sulfhydryl groups results in high arsenic concentrations in sulfhydryl rich keratinized tissues such as skin and hair (Riviere et al. 1981). The arsenic content of hair has been used to determine exposure of humans to this element (Bencko and Symon 1977). Normal levels found in cattle hair have been published by Riviere et al. (1981), Dickinson (1972) and Orheim et al. (1974) at values of 0.09 to 0.10 ppm 0.81 to 2.7 ppm and 0.13 to 0.84 ppm, respectively. The publication of Dickinson (1972) is not clear with respect to the sampling time for "before treatment" results which would appear to be anomalously high at

1.1 to 2.7 ppm arsenic, compared to the control animal at 0.81 ppm arsenic, therefore the 2.7 ppm value has not been included in the background range. Edwards and Clay (1979) found a range of 0.11 to 0.55 ppm (mean .36 ppm) in 10 control cows they sampled. Lewis (1972) found no arsenic in the hair of nonexposed horses he studied. Puls (1981) has reported a normal range of arsenic concentration in cattle hair of 0.5 to 3.0 ppm.

Cattle and horses exposed to industrial pollution have been found to have elevated arsenic levels in the hair. Orheim et al. (1974) reported values of 3.7 to 19.0 ppm arsenic in cattle exposed to smelter emissions. Cattle poisoned from arsenic in feed and water (mining waste) exhibited hair arsenic values of 6.3 to 21.0 ppm with a mean of 13.6 ppm (Bergeland et al. 1976). Cattle consuming 5.5 ppm arsenic in feed suffered acute toxicosis and were found to have 0.80 to 3.40 ppm arsenic in their hair (Riviere et al. 1981). Bergeland et al. (1976) reported subclinical poisoning ("unthrifty") in cattle exhibiting hair arsenic concentrations as low as 2.4 ppm.

Insufficient data exist on normal arsenic levels in wool or horse hair to properly interpret concentrations produced by chronic low level arsenic exposure. It has been shown that the amount of arsenic in human hair increases with age and that sex may have some influence on concentrations observed (Ohmori et al. 1975). To what degree these parameters affect arsenic in livestock hair is not well documented. The literature suggests that arsenic levels in hair above 3.5 ppm may indicate exposure to some arsenic source and that levels above 2 ppm are suspect. An investigation by Edwards and Clay (1979) indicated that arsenic levels in cattle hair can be expected to return to normal levels one year after exposure has ceased. Individual variations among animals may make large group analyses necessary if one assumes that the variations in arsenic levels in livestock hair are similar to those observed in humans (Bencko and Symon 1977).

Urine, blood and milk arsenic data for livestock are not commonly found in the literature. Peoples (1964) found arsenic acid was eliminated in the urine of dairy cattle in proportion to intake. Lakso and Peoples (1975) noted both trivalent and pentavalent forms of arsenic were methylated in the body and largely excreted via the urine. Urinary excretion in cattle is rapid with 54 to 98 percent of the daily intake eliminated in the urine (Peoples 1964). Normal urine arsenic levels for cattle and horses are reported as 0.5 and 0.4 ppm, respectively (Puls 1981). Lakso and Peoples (1975) found a range of 0.17 to 0.31 ppm arsenic in urine of control cattle that they tested. Selby and Dorn (1974) found 1400 ug/100 ml of arsenic in the urine of acutely poisoned steers. Puls (1981) noted urine levels of 2 to 14 ppm and 100 to 150 ppm as indicative of acute toxicosis in cattle and sheep, respectively.

Background arsenic concentrations in cattle blood have been reported as 0.03 to 0.07 ppm (Edwards and Clay 1979). Blood arsenic levels may be more insensitive to intake at low levels than are arsenic levels in urine. Peoples (1964) found no change in arsenic blood levels among cattle fed 0.0 to 1.25 mg/kg body weight arsenic acid. Shariatpanahi and Anderson (1984a, 1984b) found blood arsenic levels increased rapidly following ingestion of monosodium methanearsonate in sheep and goats. A near steady state approximately 3 orders of magnitude above background levels was observed within 10 days under daily ingestion of 10 mg/kg body weight of arsenic. These authors also reported a rapid decline in blood arsenic levels following removal of arsenic from the diet. Edwards and Clay (1979) found low concentrations of arsenic (0.03 to 0.12 ppm) in the blood of cattle exposed to toxic concentrations of arsenic in contaminated forage one year prior to sampling. The concentration range was not significantly different from non-exposed cattle. Puls (1981) has given normal blood arsenic levels as 0.05 and 0.01 ppm for cattle and swine, respectively. High blood levels for sheep were reported as 0.04 to 0.08 ppm and toxic levels were given as 0.17 to 1.0 and 5.0 ppm for cattle and sheep, respectively (Puls 1981).

Levels of arsenic in normal milk have been reported to range from 0.0005 to 0.17 ppm (NRC 1977, Iyengar 1982). Peoples (1964) found no significant correlation between arsenic in milk and arsenic in the diet of cattle. Weaver (1962) found no significant arsenic in the milk from a cow showing symptoms of arsenic poisoning. Calvert and Smith (1972) found arsenic in cattle milk increased from 0.015 to 0.026 ppm only at the highest diet level fed (3.2 mg As/kg body weight). Lesser amounts produced no increase in milk arsenic levels. Underwood (1977) has reported milk arsenic levels of 0.07 to 1.5 ppm in chronically poisoned cattle. The literature suggests that while small quantities of arsenic may appear in milk of exposed individuals, it is doubtful that any significance with respect to arsenic exposure can be attached to it.

In conclusion, arsenic concentration of the kidney, liver and possibly the spleen have been shown to correlate with arsenic intake. Elevated levels of arsenic in hair, urine and blood have also been shown to occur in exposed individuals. Due to individual variations, large groups of subjects should be used to determine the significance of hair and blood arsenic levels. Both blood and urine arsenic levels have been shown to fluctuate quickly in response to arsenic intake. Urine levels are generally about one order of magnitude greater than those found in blood and are therefore subject to less sampling and analytical error than the lower levels found in blood. It is the opinion of the authors that exposure to arsenic can be adequately determined through the use of hair and blood samples providing appropriate analytical methods can be developed for the latter. The additional accuracy provided by urine analysis would be unlikely to justify the additional expense of sample collection and urine analysis for an initial livestock survey but could be very useful for more detailed studies. The utility of milk may be of questionable value.

2.1.2 Livestock arsenic hazard levels

Background and elevated levels of arsenic have been documented in many studies (Tables 1, 2, 3 and 4). This data base has been used to select arsenic hazard levels documented in the following sections.

2.1.2.1 Toxic arsenic hazard levels for cattle

The toxic concentration of arsenic in cattle blood was reported as 0.17 - 1.0 ppm by Puls (1981) (Table 5). No other data were found in the reviewed literature on elevated arsenic levels in cattle blood. Puls (1981) reported arsenic concentrations of 2-14 ppm in cattle urine was indicative of arsenic toxicosis. Peoples (1964) found up to 7.95 ppm in the urine of cows which consumed a diet of 1.25 mg/kg "arsenic acid" without apparent toxicity. Lakso and Peoples (1975) reported total arsenic in cattle urine of 4.86 and 6.35 ppm for cows fed 2.75 mg/kg sodium arsenate and 1.75 mg/kg potassium arsenite respectively without any toxicity symptoms. The lack of cases of documented toxicity in the 2 to 8 ppm urine arsenic range suggests that a toxic hazard level of 8 to 14 ppm arsenic in cattle urine may be more appropriate but, due to the limited data base, Puls' (1981) range of 2 to 14 ppm has been recommended for this parameter.

Toxic arsenic levels 1.5 and 5 ppm in cattle kidney and liver tissue respectively have been recommended (Table 5) . All kidney arsenic levels above 1.5 ppm found in the reviewed literature were associated with toxicity. In most of these cases, poisoning was acute and therefore observed concentrations were relatively low. Kidney concentration criteria for chronic arsenic poisoning in cattle was reported as 5.0 to 53 ppm (Puls 1981). Few data were found in the review to determine the accuracy of this range. Acute arsenic toxicity was reported for cattle with liver arsenic levels as low as 1.6 ppm (Dickinson 1972), and toxicity was common in the 2 to 5 ppm range (Table 4). The highest nontoxic value for cattle liver arsenic content found in the literature was 1.2 ppm (Peoples 1964). The range from 1.6 to 5 ppm represents the range in which acute poisoning has been documented (Dickinson 1972, Rosiles 1977) but is below typical values reported for chronic poisoning (Puls 1981). Puls (1981) reported toxic cattle liver concentration ranges of 2.0 to 15 and 7.0 - 70 ppm for acute and chronic poisoning, respectively. The higher animal tissue concentrations

Table 5. Diagnostic Levels of Arsenic in Cattle.

	Background	Tolerable	Uncertain	Toxic
		(ppm, wet weight)		
Blood Hazard Levels/Source	0.03 - 0.07 Edwards and Clay (1979)	--------	-------	0.17 - 1.0 Puls (1981)
Urine Hazard Levels/Source	0.17 - 0.5 Lakso and Peoples (1975) - Puls (1981)	--------	-------	2 - 14 Puls (1981)
Kidney Hazard Levels/Source	0.018 - 1.1 Flanjak and Lee (1979) - Dickinson (1972)	0.35 Peoples (1964)	-------	>1.5 and >5 Hatch and Funnell (1969) Puls (1981)
Liver Hazard Levels/Source	0.013 - 0.82 Flanjak and Lee (1979) - Dickinson (1972)	--------	1.6 - 5. Dickinson (1972) Rosiles (1977)	>5 7 and 10 Rosiles (1977) Puls (1981) and Buck et al. (1976)
Hair Hazard Levels/Source	0.09 - 1.1 Riviere et al. (1981) - Dickinson (1972)	--------	1.4 - 3. Dickinson (1972), Bergeland et al. (1976)	>3.0 Bergeland et al. (1976) Orheim et al. (1974)
Milk Hazard Levels/Source	0.0005 - 0.17 NRC (1977) - Schroeder and Vinton (1962) - Iyengar (1982)	--------	-------	1.5 Underwood (1977)

found for many metals under chronic exposure conditions as opposed to acute poisoning are due to the fact that in acute poisoning, the animal usually dies before a large tissue metal accumulation can occur. Buck et al. (1976) suggested 10 ppm in liver and kidney tissue as diagnostic of arsenic poisoning. The 5 ppm cattle liver arsenic hazard level recommended for the Helena Valley is therefore most applicable to chronic arsenic poisoning.

The toxic hazard level for cattle hair (Table 5) was selected based on: 1) the maximum normal or background concentration reported in the reviewed literature (2.7 ppm arsenic), and 2) toxicity was observed at concentrations as low as 0.8 ppm (Riviere et al. 1981). Toxic arsenic concentrations in cattle hair tended to be low (1-3 ppm) in acute poisoning and higher (2.4 - 21.0 ppm) in prolonged or chronic exposure (Table 3). The differences in hair arsenic accumulation between acute and chronic cases has resulted in a range of values (1.4 to 3 ppm) which may be toxic in acute cases but not toxic in chronic cases. The toxic hazard level of >3 ppm in cattle hair, if statistically significant, should be an indication of excessive exposure to this element.

Milk arsenic levels remained low (<1 ppm) even under moderate exposure to arsenic (Peoples 1964). The toxic hazard level for cattle milk (1.5 ppm) was based on this level observed in a chronic toxicity case reported by Underwood (1977).

<u>2.1.2.2 Toxic arsenic hazard levels for horses</u>

Few arsenic toxicity data for horses were found in the literature. The toxic hazard levels for horse kidney and liver tissues, 10 ppm and 7-15 ppm respectively, were concentrations reported by Puls (1981) (Table 6). The toxic level for arsenic in horse hair, 4 ppm, was based on a study by Lewis (1972) of horses in the Helena Valley. Arsenic content of mane hair in affected horses ranged from 0 to 4.5 ppm. The mane hair of one horse that died of the "smoked syndrome" contained 4.4 ppm arsenic. Two out of the three affected animals had mane hair arsenic levels greater than 4 ppm. No subclinical evaluation was attempted in this study and the affected animals also exhibited high concentrations of

Table 6. Diagnostic Levels of Arsenic in Horses.

	Background	Tolerable	Uncertain	Toxic
		(ppm, wet weight)		
Blood Hazard Levels/Source	--------	--------	-------	---------
Urine Hazard Levels/Source	--------	--------	-------	---------
Kidney Hazard Levels/Source	<.4 Puls (1981)	--------	-------	10 Puls (1981)
Liver Hazard Levels/Source	<.4 Puls (1981)	--------	1.0 - 5.0 ("High") Puls (1981)	7 - 15 Puls (1981)
Hair Hazard Levels/Source	--------	--------	-------	4.[c] Lewis (1972)
Milk Hazard Levels/Source	--------	--------	-------	--------

lead and cadmium. Thus, the suggested horse hair arsenic hazard level represents a level of excessive exposure based on a very limited amount of data. It should be used with caution.

2.1.2.3 Toxic arsenic hazard levels for sheep

The toxic blood and urine arsenic concentrations for sheep were reported as >5 ppm and >100 ppm, respectively (Puls 1981) (Table 7). Values for blood and urine (14.5 ppm and 341 ppm) in two related studies by Shariatpanahi and Anderson (1984a, 1984b) generally supported the toxic concentrations reported by Puls (1981). No additional support was found in the literature.

Sheep kidney and liver toxic arsenic concentrations of >7 ppm and >8 ppm, respectively were based on data from Bucy et al. (1955). They found similar toxic effects produced by arsanilic acid, 3N-3-Nitro-4-Hydroxyphenylarsonic acid and potassium arsenite at these levels. These hazard levels were in general agreement with the toxic level of >10 ppm for both organs reported by Puls (1981).

The toxic hazard level of 0.18 ppm arsenic in sheep milk was based on one study (Shariatpanahi and Anderson 1984a). Animals in this study exhibited mild clinical symptoms of arsenic poisoning (Anderson 1985). The hazard level should be used with caution until additional data are available.

2.1.2.4 Toxic arsenic hazard levels for goats

All toxic hazard levels for goats were based on the study of Shariatpanahi and Anderson (1984b) (Table 7). These values should be used with caution until additional data are available.

2.2 Cadmium

2.2.1 Cadmium Literature Review

Most experimental data regarding cadmium toxicity have utilized dietary cadmium levels far exceeding those commonly found in nature (Hinesly et al. 1985). Hinesly et al. (1985) concluded 1 ppm (dry weight) of biologically incorporated dietary cadmium

Table 7. Diagnostic Levels of Arsenic in Sheep and Goats.

	Background	Tolerable	Uncertain	Toxic
	(ppm, wet weight)			
	SHEEP			
Blood Hazard Levels/Source	0.02 - 0.04 Anderson (1985)	--------	0.04 - 0.08 ("high") Puls (1981)	> 5 and 14.5 Puls (1981), Shariatpanahi and Anderson (1984a)
Urine Hazard Levels/Source	0.00 - 0.07 Shariatpanahi and Anderson (1984b)	--------	-------	>100 and 341 Puls (1981), Shariatpanahi and Anderson (1984b)
Kidney Hazard Levels/Source	0.03 - 0.26 Spaulding (1975) - Bucy et al. (1955)	3.6 Lancaster et al. (1971)	-------	>7 and > 10 Bucy et al. (1955), Puls (1981)
Liver Hazard Levels/Source	0.0 - 0.48 Lancaster et al. (1971) - Bennett and Schwartz (1971)	3.5 Bennett and Schwartz (1971)	4 - 8 ("High") Puls (1981)	>8 and >10 Bucy et al. (1955), Puls (1981)
Hair Hazard Levels/Source	-------	--------	-------	-------
Milk Hazard Levels/Source	0.00 - 0.04 Shariatpanahi and Anderson (1984b)	--------	-------	0.18 Shariatpanahi and Anderson (1984a)
	GOATS			
Blood Hazard Levels/Source	0.02 - 0.04 Anderson (1985)	--------	-------	>16 Shariatpanahi and Anderson (1984b)
Urine Hazard Levels/Source	0.00 - 0.04 Shariatpanahi and Anderson (1984b)	--------	-------	219 Shariatpanahi and Anderson (1984b)
Milk Hazard Levels/Source	0.00 - 0.04 Shariaptanahi and Anderson (1984b)	--------	-------	0. - 0.16 Shariatpanahi and Anderson (1984b)

"will have little if any effect on the health and performance of poultry." Exposure of livestock to excessive cadmium may result more from ingesting contaminated soils than from contaminated forage.

The liver and kidneys are the main reservoirs of cadmium in vertebrates (Tables 8-11). Concentrations in muscle tissue are always quite low (Doyle et al. 1974, Osuna et al. 1981, Mills and Dalgarno 1972), but elevated forage cadmium levels will cause slight increases in muscle concentrations as well as significant increases in liver and kidney cadmium levels (Johnson et al. 1981). All studies of elevated cadmium in diet or water referenced in Table 11 produced increased cadmium levels in liver and kidneys. Other pathogenic states or abnormalities were produced by varying additions of dietary cadmium. In studies of lambs and the Long Evans strain of laboratory rats, 5 mg/kg in the diet or drinking water caused reduced growth or hypertension (Doyle et al. 1974, Schroeder and Vinton 1962). The experimental periods were long in both examples, 163 days for lambs and 1 year for rats. Production of metallothionein by internal organs protects the animal from damage by the elevated concentration of the toxic metal until this protective mechanism is thwarted by prolonged overexposure. This mechanism is discussed more fully in Appendix section 6.1.2.

The determination of the exposure of livestock to cadmium is difficult because of the scarcity of data on cadmium in readily available samples such as hair, blood or urine. The few documents available indicate that animal hair is a controversial tool for this assessment. Limited data suggest the background range for cattle hair cadmium concentrations will be 0.6 ppm or less (Powell et al. 1964, Wright et al. 1977). Available data suggest that cadmium in animal hair will likely be significantly correlated to dietary intake at diet levels above 50 ppm. Interpretation of hair data from lower diet levels may be difficult. Hammer et al. (1971) showed a relationship between cadmium in human hair and the exposure ranking of the samples. He also found a similar relationship in East Helena, Montana (Hammer et al. 1972). The work

Table 8. Background cadmium levels in livestock fluids and hair.

Diet	Blood	Urine	Milk	Hair	n	Notes	Reference
	ppm (wet weight) unless noted			ppm (dry wt.)			
				CATTLE			
	<0.01				48		Bertrand et al. 1981)
			0.006		315	CA Milk	Bruhn and Franke (1976)
.32 ppm	<0.05			0.5	1	Calf.	Powell et al. (1964)
			0.012-0.020				Kubota et al. (1968)
			0.017-0.030			U.S. Cities	Murthy and Rhea (1968)
			0.026			U.S. Average	Murthy and Rhea (1968)
			0.020-0.037		32	Cincinnati Area	Murthy and Rhea (1968)
			0.0001-0.004		18 samples		Cornell and Pallansch (1973)
			0.004		4		Dorn et al. (1975)
			0.003		5		Dorn et al. (1975)
			0.003 A		7		Casey (1976)
		<0.15		0.6ppm (rib area)	12		Wright et al. (1977)
	0.005				91		Penumarthy et al. (1980)
	0.01				2		Lynch et al. (1976b)
				HORSES			
	0.006-0.012				20		Penumarthy et al. (1980)
		0.003-0.213 A			43		Elinder et al. (1981)
		0.0015			43		Elinder et al. (1981)
				0.2-0.6	4		Lewis (1972)
				SHEEP			
0.7ppm	0.17				4		Mills and Dalgarno (1972)
	0.02	<0.01-0.03		<1.0	2		Wright et al. (1977)
	0.007 B			0.55-0.83	6		Doyle et al. (1974)
	0.005 B			0.94	6		Doyle et al. (1974)
	0.004 B			0.74	6		Doyle et al. (1974)
	0.006 B			0.87	6		Doyle et al. (1974)
	0.006 B			0.79	6		Doyle et al. (1974)
	0.003 B				6		Doyle et al. (1974)
				GOATS			
			0.006-0.024 dw		11		Telford et al. (1984a)
			0.011-0.017 dw		2		Telford et al. (1984b)
	0.011-0.36 dw		<0.005-0.013 dw		7-9		Dowdy et al. (1983)

A/Reported in ug/liter B/Reported in ng/ml

Table 9. Background cadmium levels in livestock tissues.

Diet	Kidney	Liver	Spleen	Heart	Brain	Pancreas	Muscle	Bone	n	Notes	Reference
				ppm (wet weight) unless noted				ppm (dry wt.)			
					CATTLE						
	0.27	0.04							8		Bertrand et al. (1981)
	0.29	0.18							2	After 6 mo	Sharma et al. (1982)
0.18ppm		0.06							4		Sharma et al. (1979)
0.18ppm	0.74	0.41							4		Verma et al. (1978)
	0.55	0.21							2150		USDA (1975)
	0.34	0.10							149		Kreuzer et al. (1975)
0.07ppm	0.22	0.06							6		Munshower (1977)
0.15ppm	0.27	0.04					<0.01		8	168 Days	Bertrand et al. (1981)
		0.27 dw[A]							>100		Doyle and Spaulding (1978)
0.32ppm	<2.00 dw	4.00 dw							1		Doyle and Spaulding (1978)
1.58ppm	1.40 Cortex	0.24							1		Doyle and Spaulding (1978)
	0.48	0.24							-		Doyle and Spaulding (1978)
	1.50 Cortex	0.50							1		Doyle and Spaulding (1978)
0.1ppm	7.4 dw	1.2 dw							8	Hereford Cows	Baxter et al. (1982)
0.1ppm	3.5 dw	0.9 dw							8	Hereford Steers	Baxter et al. (1982)
0.32ppm	<2. dw	4. dw	<1 dw					0.3			Powell et al. (1964)
	0.075-2.500	0.034-0.430					0.006		85-92		Penumarthy et al. (1980)
	13.4 dw	1.06 dw							29	Range Cattle	Baxter et al. (1983)
	2.8 dw	0.74 dw							15	Dairy Cattle	Baxter et al. (1983)
	1.36 dw	0.43 dw								Angus Cows/Steers	Decker et al. (1980)
	7.4 dw								8	Hereford Cows	Baxter et al. (1983)
	3.5 dw								8	Herefore Steers	Baxter et al. (1983)
					HORSES						
	11-186 Cortex								69	Some Histo-Pathological Changes	Elinder et al. (1981)
	11.9 Cortex								1	No Pathological Changes	Elinder et al. (1981)
	2.5	3.45					0.110		20-21	Mean	Penumarthy et al. (1980)
	0.840-5.000	0.830-4.100					0.060-0.300		20-21	Range	Elinder et al. (1981)
	31.9 Cortex								5	0-4 Years old	Elinder et al. (1981)
	49.2 Cortex								13	5-9 Years old	Elinder et al. (1981)
	61.8 Cortex								16	10-14 Years old	Elinder et al. (1981)
	75.9 Cortex								15	15-19 Years old	Elinder et al. (1981)
	72.3 Cortex								18	20 + Years old	Elinder et al. (1981)
					SHEEP						
0.29ppm	2.91 dw	0.30 dw					0.02		10		Telford et al. (1982)
0.2ppm	4.42 dw	1.69 dw							6		Doyle et al. (1974)
0.7ppm		0.95 dw							4		Mills and Dalgarno (1972)
0.06ppm	0.32 dw	0.09 dw							5		Telford et al. (1984a)
0.06ppm	0.28 dw	0.09 dw							5		Telford et al. (1984a)
0.16ppm	4.42 dw	1.69 dw	0.14 dw	0.06 dw			0.025		6		Doyle and Pfander (1975)
	4.30	2.00							1		Wright et al. (1977)
		0.09 dw							1		Doyle and Pfander (1975)

Table 9. Background cadmium levels in livestock tissues, continued.

Diet	Kidney	Liver	Spleen	Heart	Brain	Pancreas	Muscle	Bone	n	Notes	Reference
	ppm (wet weight) unless noted							ppm (dry wt.)			
0.05ppm	5.4 dw	1.2 dw	0.04 dw	0.01 dw	0.01 dw		0.001-0.005	0.01	5		Hefferon et al. (1980)
0.31 ppm	1.02-2.77dw	0.-0.323 dw					<0.012		10	Range	Dalgarno (1980)
0.31ppm	1.76 dw	0.119 dw							10	Mean	Dalgarno (1980)
GOATS											
0.14ppm	1.06 dw	0.10 dw							5	Adults	Telford et al. (1984b)
0.14ppm	0.03 dw	0.05 dw							2	Kids	Telford et al. (1984b)
SWINE											
	0.01-1.00	0.01-0.30							21		USDA (1975)
	0.39	0.14							14		Munshower (1977)

[A]/ Dry weight basis

Table 10. Elevated cadmium levels in livestock fluids and hair.

Diet	Blood	Urine	Milk	Hair	n	Agent	Notes/ Response	Reference
	ppm (wet weight)			ppm (dry wt.)				
				CATTLE				
40.3ppm 12w					4	$CdCl_2$	Depressed Perf.	Powell et al. (1964)
160.3ppm 12w					4	$CdCl_2$	Depressed Perf.	Powell et al. (1964)
640.3ppm 12w	<0.05			9-11	3	$CdCl_2$	Toxic	Powell et al. (1964)
2560ppm 12w	<0.10[B]			9-13	4	$CdCl_2$	Fatal	Powell et al. (1964)
300-500ppm	0.04	0.7			2	Cadminate	Fatal	Wright et al. (1977)
50ppm				15 rib area	2	Cadminate	Inhibited Reproduction	Wright et al. (1977)
100ppm				21 rib area	2	Cadminate	Reproduction Failure	Wright et al. (1977)
200ppm				57 rib area	2	Cadminate	Toxic	Wright et al. (1977)
300ppm				63 rib area	2	Cadminate	Toxic/Fatal	Wright et al. (1977)
500ppm				88 rib area	2	Cadminate	Toxic/Fatal	Wright et al. (1977)
				HORSES				
				1.0	1	Ind. Exp.	Fatal	Lewis (1972)
				SHEEP				
3.5ppm	0.17 [B]				4	$CdSO_4$	Not Noted	Mills and Dalgarno (1972)
7.1ppm	0.17 [B]				4	$CdSO_4$	Decreased Blood Zn,Cu	Mills and Dalgarno (1972)
12.3ppm	0.19 [B]				4	$CdSO_4$	Decreased Blood Zn,Cu	Mills and Dalgarno (1972)
5ppm 163d	0.004 [A]			1.20	6	$CdCl_2$	Reduced Growth	Doyle et al. (1974)
15ppm 163d	0.003 [A]			0.84	6	$CdCl_2$	Reduced Growth	Doyle et al. (1974)
30ppm 163d	0.008 [A]			1.22	6	$CdCl_2$	Reduced Growth	Doyle et al. (1974)
60ppm 163d	0.025 [A]	26-47ug/day		0.70	6	$CdCl_2$	Reduced Growth	Doyle et al. (1974)
50-500ppm	0.1				10	Cadminate	Not Noted	Wright et al. (1977)
500ppm	0.2-2.0	1.0		>20.0	2	Cadminate	Toxic/Fatal	Wright et al. (1977)

Table 10. Elevated cadmium levels in livestock fluids and hair, continued

Diet	Blood	Urine	Milk	Hair	n	Agent	Notes Response	Reference
	ppm (wet weight)			ppm (dry wt.)				
				GOATS				
3.01ppm			0.008-0.052		19		Not Noted	Telford et al. (1984b)
				SWINE				
83ppm	No Sig. Increase 0.0						Lowered Feed Effic.	Osuna et al. (1981)

A/Reported in ng/ml B/Reported in ug/ml

Table 11. Elevated cadmium levels in livestock tissues.

Diet	Kidney	Liver	Spleen	Heart	Brain	Pancreas	Muscle	Bone	n	Agent	Notes/ Response	Reference
	ppm (wet weight) unless noted							ppm (dry wt.)				
CATTLE												
0.484												
mg/kg/bwt	19.25	3.33										
2.40ppm		0.07						0.45			Not Noted	Sharma et al. (1982)
									4		Nontoxic over	Sharma et al. (1979)
11.29ppm		2.1									12 wks.	
									4		Nontoxic over	Sharma et al. (1979)
2.40ppm	3.58	0.73									12 wks.	
11.29	8.83	3.21							4		12 wks.	Verma et al. (1978)
1.02ppm	1.59	0.51							4		12 wks.	Verma et al. (1978)
									15		Nontoxic	Rundle et al. (1984)
1.02ppm											423-451 days	
				0.09			0.05-0.09	0.32	5		Nontoxic	Rundle et al. (1984)
1.7ppm	1.67	0.34									423-451 days	
0.36ppm	0.28	0.06							9		Polluted Area	Munshower (1977)
0.78ppm	0.24	0.07					<0.01		8		168 Days	Bertrand et al. (1981)
11.5ppm(9mo)	54 dw[B]	19.4 dw					<0.01		8		168 Days	Bertrand et al. (1981)
							0.27 dw		8	Sludge	Nontoxic	Baxter et al. (1982)
10.7ppm(9mo)	57 dw	19.9 dw									Cows	
							0.43 dw		8	Sludge	Nontoxic	Baxter et al. (1982)
640ppm 12w	479-	137-	11-29 dw								Cows	
	1035 dw	1023 dw						2-5	3	$CdCl_2$	Toxic	Powell et al. (1964)
2560ppm 12w	146-	116-	9-62 dw									
	718 dw	858 dw						1-4	4	$CdCl_2$	Fatal	Powell et al. (1964)
50ppm	117.0- A	18.0-										
	228.3	34.0							2	Cadminate	Reproduction	
100ppm	210.0- A	58.8-									Inhibited	Wright et al. (1977)
	218.5 A	61.3							2	Cadminate	Reproduction	
200ppm	160.0- A	61.3-									Prevented	Wright et al. (1977)
	232.5 A	97.5							2	Cadminate	Toxic	Wright et al. (1977)
300ppm	170.0- A	41.8-										
	227.5	85.0							2	Cadminate	Toxic/Fatal	Wright et al. (1977)
500ppm	115.0-	35.5-										
	200.0	160.0							2	Cadminate	Toxic/Fatal	Wright et al. (1977)
HORSES												
Contam. Forage	228-410	80.	4.1	0.4			3.9	1.0	1	Ind. Exp.	Fatal	Lewis (1972)
SHEEP												
3.88ppm	17.84 dw	3.19 dw					0.02		10	Sludge	Slight Liver Damage	Telford et al. (1982)
50ppm	139.0-	39.5										
	227.5	147.5							2	Cadminate	Reduced Feed Efficiency	Wright et al. (1977)
100ppm	207.5-	107.5-										
	209.0	145.0							2	Cadminate	Reduced Feed Efficiency	Wright et al. (1977)
200ppm	236.5-	170-										
	389.0	240.0							2	Cadminate	Reduced Feed Efficiency	Wright et al. (1977)

Table 11. Elevated cadmium levels in livestock tissues, continued.

Diet	Kidney	Liver	Spleen	Heart	Brain	Pancreas	Muscle	Bone	n	Agent	Notes Response	Reference
	ppm (wet weight) unless noted							ppm (dry wt.)				
300ppm	52.5-118.0	462.5-492.5							2	Cadminate	Reproduction Prevented	Wright et al. (1977)
500ppm	96.5-184.5	550.0-600.0							2	Cadminate	Fatal	Wright et al. (1977)
3.5ppm		2.01 dw							4	$CdSO_4$	Not Noted	Mills and Dalgarno (1972)
7.1ppm		3.50 dw							4	$CdSO_4$	Decreased Blood Zn,Cu	Mills and Dalgarno (1972)
12.3ppm		11.20 dw							4	$CdSO_4$	Decreased Blood Zn,Cu	Mills and Dalgarno (1972)
5ppm 191d	58.85 dw	14.92 dw	0.36 dw	0.24 dw					6	$CdCl_2$	Increased organ Cd	Doyle and Pfander (1975)
15ppm 191d	187.62 dw	51.72 dw	2.15 dw	0.43 dw					6	$CdCl_2$	Increased organ Cd	Doyle and Pfander (1975)
30ppm 191d	426.81 dw	62.73 dw	7.14 dw	1.28 dw					6	$CdCl_2$	Reduced Growth	Doyle and Pfander (1975)
60ppm 191d	768.84 dw	275.94 dw	13.34 dw	2.66 dw					6	$CdCl_2$	Reduced Growth	Doyle and Pfander (1975)
0.71ppm Cd	1.22 dw	0.46 dw					0.02 dw		5		Nontoxic Rams	Telford et al. (1984a)
0.71ppm Cd	0.94 dw	0.38 dw					0.02 dw		5		Nontoxic Ewes	Telford et al. (1984a)
3.4ppm 280d	10.59-34.09 dw	2.27-7.58 dw					<0.012 dw		11	$CdSO_4$	Nontoxic Lambs	Dalgarno (1980)
6.4ppm 280d	32.6-60.1 dw	5.04-16.89 dw					<0.012 dw		11	$CdSO_4$	Nontoxic Lambs	Dalgarno (1980)
1.7ppm 274d	18.5 dw	5.8 dw	0.23 dw	0.03 dw	0.02 dw		0.01 dw	0.02 dw		C	Nontoxic Lambs	Hefferon et al. (1980)
GOATS												
3.81ppm	1.65 dw	0.39 dw					0.04 dw		3		Nontoxic Adults	Telford et al. (1984a)
3.81ppm	0.05 dw	0.07 dw					0.03 dw		3		Nontoxic Kids	Telford et al. (1984a)
SWINE												
83ppm	61.95	12.98							12	Sludge	Depressed Growth	Osuna et al. (1981)
	0.99	0.24							6	Pollution	Not Noted	Munshower (1977)

A/ Cortex B/Dry weight basis C/Sludge Grown Forage of Dorn et al. (1974) in Missouri revealed seasonal variation of cadmium concentrations in cattle hair. Elevated levels of cadmium in hair have been detected in animals exposed to dust from lead ore trucks and smelter emissions. Wright et al. (1977) found a good correlation between cadmium in cattle hair and cadmium (as cadminate) in feed for the range of 0 to 500 ppm. These authors found subclinical toxicosis associated with 15 to 21 ppm cadmium in hair resulted in reproduction problems (abnormal or dead calves). Lewis (1972) found an association between cadmium levels in horse mane hair with distance from a primary lead smelter. Diets containing 5 to 60 ppm cadmium did not produce any significant differences in cadmium levels found in sheep wool (Doyle et al. 1974). Combs et al. (1983) found cadmium in rat and goat hair was not significantly correlated to dietary cadmium at levels up to 15.9 and 18.5 mg/kg.

Typical background concentrations of cadmium in the urine of livestock are less than 0.15 ppm for cattle (Wright et al. 1977) 0.0003 to 0.0213 ppm for horses (Elinder et al. 1981) and 0.01 to 0.03 ppm for sheep (Wright et al. 1977). Urinary excretion of cadmium does not appear to increase significantly in animals until proteinuria occurs, at which time cadmium excretion increases dramatically (Friberg 1952). Thus, increased urinary cadmium is an indication of kidney damage probably caused by the metal and does not indicate the extent of subclinical cadmium exposure. However, Roels et al. (1981) found a significant relationship between the total body burden of cadmium and urine cadmium levels in humans that lacked any renal dysfunction. Background cadmium concentrations in livestock blood are 0.005 to <0.05, <0.006 to 0.012 and 0.003 to 0.17 for cattle, horses, and sheep respectively (Penumarthy et al. 1980, Powell et al. 1964, Doyle et al. 1974, Mills and Dalgarno 1972). Roels et al. (1981) found a relationship between blood cadmium levels and total body burden but the correlation coefficient was 0.45. Doyle et al. (1972) reported increased blood cadmium when lambs were fed a diet containing 60 ppm; no significant blood effects were observed at lower dietary levels. Osuna et al. (1981) found no significant increase in the blood cadmium level in swine fed 83 ppm cadmium in the diet. There were no significant differences in blood cadmium levels of lambs fed diets containing 0.7, 3.5 and 7.1 ppm cadmium (Mills and Dalgarno 1972). Similar results were obtained for goats that were fed 5.3 ppm cadmium (Dowdy et al. 1983). Cousins et al. (1973) reported that reduced hematocrit, due to induced iron deficiency, was the most sensitive indicator of cadmium toxicity in swine. Few data were found in the literature for hematocrit values and cadmium exposure relationships for other livestock species. Wright et al. (1977) reported little difference between blood cadmium concentrations in controls and cattle feed diets up to 500 ppm cadmium (clinical toxicosis). These authors found blood cadmium concentrations averaged 0.04 for all 12 of their test animals on diets of 0 to 500 ppm cadmium. Puls (1981) also reported that blood cadmium levels are not diagnostically elevated even in toxic environments. The cadmium content of cattle milk has been found to vary seasonally, generally being highest during the spring and summer (Murthy and Rhea 1968). Market milk tested by the same authors ranged from 0.017 to 0.030 ppm (mean of 0.026 ppm) and they found a range of 0.020 to 0.037 ppm in 32 individual animals tested in the Cincinnati area. Typical background values found in the literature ranged from 0.0001 ppm (Cornell and Pallansch 1973) to the 0.037 found by Murthy and Rhea (1968). Sharma et al. (1979) found no significant increase in milk cadmium levels from cattle fed up to 11.3 ppm cadmium in the diet. Levels of cadmium milk from three Holstein cows that were kept on a diet of 250-300 ppm cadmium for 2 weeks remained below the 0.1 ppm detection limit (Miller et al. 1967). Similarly, a study by Dowdy et al. (1983) found no increase in the cadmium levels in milk from goats that were fed up to 5.3 ppm cadmium.

The most reliable indicator of cadmium exposure in livestock is the determination of metal levels in the liver and/or kidney. Mean cadmium concentrations in these organs from two-year-old slaughter cattle from non-polluted areas of the Northern Great Plains were reported to be 0.06 and 0.22 ppm (wet weight), respectively (Munshower 1977). These values were lower than the levels reported by Kreuzer et al. (1975) or the U.S. Department of Agriculture (USDA 1975), but these later surveys included older animals of uncertain age and background. The maximum ranges found in the literature for cattle kidney and liver tissue were 0.075 to 4 ppm (Penumarthy et al. 1980, Baxter et al. 1983) and 0.034 to 0.84 ppm (Penumarthy et al. 1980, Doyle and Spaulding 1978) respectively. It should be noted that both maximums were converted from the reported dry weight figures using the conversions found by Munshower and Neuman (1979). The highest apparently nontoxic concentration of cadmium in cattle kidney tissue found in the reviewed literature is the 57 ppm (dry weight basis) found by Baxter et al. (1982). The effect of 19 ppm cadmium in cattle kidney tissue (Sharma et al. 1982) was not clearly stated. Penumarthy et al. (1980) found cattle background kidney and liver cadmium levels of 0.075 to 2.500 ppm and 0.034 to 0.430 ppm, respectively. Similar values for horses were given as 0.840 to 5.000 ppm and 0.830 to 4.100 ppm. Because of the difficulty and expense involved in the acquisition of liver or kidney samples from animals in the field, a survey of animal hair may be a more realistic approach to determining cadmium exposure in a large group of animals. Urine may have some future potential, but little background data are available for interpretation. Cadmium in feces may provide an estimate of dietary intake (Chaney 1980).

2.2.2 Livestock cadmium hazard levels

Documented cadmium levels in livestock fluids, tissues and hair are presented in Table 8, 9, 10 and 11. Cadmium hazard levels were derived from this data base.

2.2.2.1 Toxic cadmium hazard levels for cattle

Cadmium levels in cattle blood are not a good diagnostic indicator of cadmium toxicity (Puls 1981) (Table 12). Powell et al. (1964) found the blood cadmium level in bull calves on a diet of 2560 ppm cadmium (toxic) to be <0.10 ppm. This value was within the same order of magnitude as most background blood

Table 12. Diagnostic Levels of Cadmium in Cattle.

	Background	Tolerable	Uncertain	Toxic
	ppm wet weight			
Blood Hazard Levels/Source	0.005 - <0.05 Penumarthy et al. (1980) Powell et al. (1964)	-------	-------	0.04[A] Wright et al. (1977) Puls (1981)
Urine Hazard Levels/Source	<0.15 Wright et al. (1977)	-------	-------	0.7 Wright et al. (1977)
Kidney Hazard Levels/Source	0.075 - 1[B] Penumarthy et al. (1980) - Baxter et al. (1983)	17[B] Baxter et al. (1982)	19 Sharma et al. (1982)	44[B] Powell et al. (1964)
Liver Hazard Levels/Source	0.034 - 0.84[C] Penumarthy et al. (1980) - Doyle and Spaulding (1978), Powell et al. (1964)	4[C] Baxter et al. (1982)	-------	25[C] Powell et al. (1964) Wright et al. (1977)
Hair Hazard Levels/Source	<0.6 Wright et al. (1977)	-------		>9 Powell et al. (1964),
Milk Hazard Levels/Source	0.0001 - 0.037 Cornell and Pallansch (1973) - Murthy and Rhea (1968)	-------	-------	-------

[A] There is generally a poor correlation between cadmium intake and concentrations of cadmium in blood. Values reported for blood cadmium concentrations under observed clinical toxicosis are very similar to reported background levels, and this parameter should not be considered as a diagnostic tool.

[B] Figure converted from dry weight basis assuming kidney tissue dry matter content of 30 percent as reported by Munshower and Neuman (1979) and Spector (1956).

[C] Figure converted from dry weight basis assuming liver tissue dry matter content of 21 percent as reported by Munshower and Neuman (1979).

cadmium concentrations (0.005 to <0.05 ppm) (Table 8). The diagnostic use of cadmium in blood is not recommended.

Cadmium concentrations in cattle urine are also of limited diagnositc use. The narrow range between background values (<0.15 ppm) and the only toxic concentration reported in the reviewed literature (0.7 ppm, Wright et al. 1977) (Table 10) suggests urine may not be a reliable indicator of cadmium toxicity.

Toxic hazard levels selected for cadmium levels in cattle kidneys and liver are 44 ppm and 25 ppm respectively. The kidney hazard level is based on studies by Powell et al. (1964) and Wright et al. (1977) in which all concentrations equal or greater than 44 ppm cadmium in cattle kidneys were associated with toxicosis. Similar results were obtained by these authors for cadmium concentrations in cattle liver, meaning all values in excess of 24.4 ppm were associated with toxicity. Puls (1981) reported values of 100 to 250 ppm and 50 to 160 ppm cadmium in cattle kidneys and liver, respectively, as toxic under chronic conditions.

The recommended toxic hazard level for cadmium concentrations in cattle hair is >9 ppm cadmium. This hazard level was derived from the work of Powell et al. (1964) who found cadmium concentrations from 9 to 13 ppm in cattle hair to be associated with toxicosis. Wright et al. (1977) found levels of 15 to 21 ppm to be associated with subclinical toxicosis and levels of 57 to 88 ppm to be associated with clinical toxicosis. These authors found cadmium concentrations in cattle hair usually reached 100 ppm before death. Puls (1981) reported 40 to 100 ppm cadmium in cattle hair as toxic. The >9 ppm toxic cadmium hazard level should be an indication of possible subclinical toxicosis and should only be applied to large herds of cattle where statistically valid and representative data can be obtained. Large variations in hair cadmium concentrations between individual animals make an absolute application of this hazard level meaningless.

2.2.2.2 Toxic cadmium hazard levels for horses

Data for toxic cadmium concentrations in the tissues of horses were very limited (Table 13). The recommended toxic cadmium hazard level for horse kidneys (75 ppm) is based on the results of Elinder et al. (1981). These authors found a significant (<0.05) relationship between cadmium concentration and histopathological changes in horse kidney cortex, and noted an increase in the frequency of the histopathological changes at cortex concentrations exceeding 75 ppm.

The 80 ppm toxic hazard level for horse liver cadmium concentration is based on one sample from a horse that died from apparently being "smoked" from smelter emissions (Lewis 1972). To what extent other metals may have affected this animals is unknown. This hazard level should be used with extreme caution until additional data are obtained.

The hazard level for toxic concentrations of cadmium in horse hair is also based on the very limited data of Lewis (1972). This author reported a poor correlation between mane hair cadmium concentrations and cadmium concentrations in liver and kidney tissues. The use of this parameter is not recommended until additional support data are obtained.

2.2.2.3 Toxic cadmium hazard levels for sheep

The toxic hazard level reported for cadmium in sheep blood is 0.1 to 0.2 ppm (Puls 1981) (Table 14). This range overlaped the background range for this parameter and is not considered diagnostic.

The diagnostic level for toxic concentrations of cadmium in sheep kidney tissue (53 ppm) is based on the study of Wright et al. (1977) who found this level was associated with reproductive failure in sheep. With one exception, all sheep kidney tissue levels in excess of 53 ppm were associated with a degree of toxicity, where as all levels less than 53 ppm, with one exception, were not associated with toxicity. The 53 ppm hazard level agrees well with the 50 to 400 ppm criteria reported by Puls (1981) for toxic concentration of cadmium in sheep kidney tissue.

Table 13. Diagnostic Levels of Cadmium in Horses.

	Background	Tolerable	Uncertain	Toxic
		ppm wet weight		
Blood Hazard Levels/Source	<0.006 - 0.012 Penumarthy et al. (1980)	--------	-------	---------
Urine Hazard Levels/Source	0.0003 - 0.0213 Elinder et al. (1981)	--------	-------	---------
Kidney Hazard Levels/Source	0.84 - 5.00 Penumarthy et al. (1980)	--------	4.2 - 23 Puls (1981)	75 (Cortex), >200 Elinder et al. (1981) Puls (1981)
Liver Hazard Levels/Source	0.83 - 4.100 Penumarthy et al. (1980)	--------	22 Puls (1981)	80 Lewis (1972)
Hair Hazard Levels/Source	0.2 - 0.6 Lewis (1972)	--------	-------	0.9 - 1.0 * Lewis (1972)
Milk Hazard Levels/Source	--------	--------	-------	--------

* Not diagnostic

Table 14. Diagnostic Levels of Cadmium in Sheep and Goats.

	Background	Tolerable	Uncertain	Toxic
	ppm wet weight			
SHEEP				
Blood Hazard Levels/Source	0.003 - 0.17 Doyle et al. (1974) - Mills and Dalgarno (1972)	-------	-------	0.1 - 0.2* Puls (1981)
Urine Hazard Levels/Source	0.01 - 0.03 Wright et al. (1977)	-------	-------	-------
Kidney Hazard Levels/Source	0.084 - 4.30 Telford et al. (1982) - Wright et al. (1977)	-------	4 - 50 Puls (1981)	53 and 50 Wright et al. (1977) and Puls (1981)
Liver Hazard Levels/Source	0.019 - 2.00 Telford et al. (1984a) - Wright et al. (1977)	-------	-------	13 and 50 Doyle and Peander (1975) and Puls (1981)
Hair Criteria Levels/Source	0.55 - 0.94 Doyle et al. (1974)	-------	-------	>20 Wright et al. (1977) and Puls (1981)
GOATS				
Blood Hazard Levels/Source	0.011 - 0.036 dw Dowdy et al. (1983)	-------	-------	-------
Kidney Hazard Levels/Source	0.01 - 0.32 Telford et al. (1984b)	0.50 Telford et al. (1984b)	-------	-------
Liver Hazard Levels/Source	0.01 - 0.02 Telford et al. (1984b)	0.08 Telford et al. (1984b)	-------	-------
Milk Hazard Levels/Source	<0.005 - 0.024 dw Dowdy et al. (1983), Telford et al. (1984b)	0.008 - 0.052 Telford et al. (1984b)	-------	-------

* Not diagnostic

A sheep liver concentration of 13 ppm cadmium was selected based on the study of Doyle and Pfander (1975). These authors have reported reduced growth in lambs was associated with 13.2 ppm cadmium in liver tissue. Reduced feed efficiency and reduced growth were reported for sheep with liver cadmium concentrations in the 40 to 60 ppm range (Table 12), and Puls (1981) reported a toxic concentration of cadmium in sheep liver to be 50 to 600 ppm. The 13 ppm hazard level for this parameter should be used with caution until additional data are obtained.

The toxic hazard level (>20 ppm) of cadmium in sheep wool (hair) is based on the >20 ppm cadmium Wright et al. (1977) found in the wool of sheep fed toxic levels of cadmium (as cadminate) over a 49 week period. Doyle and Pfander (1975) noted cadmium levels of 0.7 to 1.22 ppm in the wool of sheep fed 5 to 60 ppm cadmium (as $CdCl_2$) over a 163 day period, but these levels also overlap typical background values (Table 9).

2.3 Lead

2.3.1 Lead literature review

The literature search revealed a considerable amount of data on lead levels in various animal tissues and other substances (Tables 15-18). These data suggest that lead levels in kidney and liver, which accumulate lead, and blood are good indicators of lead toxicosis. Concentrations of lead in these three tissues are elevated in all documented cases of lead toxicity. Furthermore, a considerable volume of data on background or control levels is also available (Ruhr 1984, Doyle and Younger 1984, Zmudski et al. 1983, Burrows and Borchard 1982, Schmitt et al. 1971, Dollahite et al. 1978, Buck et al. 1976). Fewer data are available on lead levels in spleen, heart, brain, pancreas, bone and hair (Tables 15-18).

Blood lead levels appear to be a good indicator of chronic toxicosis but are not as dependable for diagnosis in acute or subacute cases. This lack of diagnostic accuracy may result from an initial rapid rise of blood lead following metal ingestion and

Table 15. Background lead levels in livestock fluids and hair.

Diet*	Blood (ppm (wet weight))	Urine (ppm (wet weight))	Milk (ppm (wet weight))	Hair (ppm (dry wt.))	Feces (ppm (dry wt.))	n	Notes	Reference
				CATTLE				
0.157	0.002					4 samples		Sharma et al. (1982)
	0.01-0.21					104		Ruhr (1984)
	0.077					130		Blakley and Brockman (1976)
	0.16					20		Edwards and Clay (1977)
	0.10					92		Buck et al. (1976)
1.42ppm	0.069					4		Logner et al. (1984)
	0.127-0.226 [D]					5	Calves	Lynch et al. (1976b)
			0.040, 0.2 max			270	Market Milk	Mitchell and Aldous (1974)
			0.030-0.050			10		Lakso and Peoples (1975)
			0.420			33	Cincinati	Murthy (1974)
			0.130			8	Winter	Dorn et al. (1975)
	0.10 [B]					1	Calf	Allcroft (1951)
	0.08 [B]					1	Calf	Allcroft (1951)
			0.391			350	CA Milk	Bruhn and Franke (1976)
			0.02-0.04			3		Kehoe et al. (1940)
			0.023-0.079			59		Murthy et al. (1967)
			0.047			76		Murthy et al. (1967)
	0.02					85		Penumarthy et al. (1980)
				5.03		50	Near L.A.	USDA (1975)
	0.03					5	Calves	Zmudski et al. (1983)
	0.20					8	Calves	Edwards and Dooley (1980)
	0.129 [B]					30	Calves	Allcroft (1950)
	0.08-0.22					13	Calves	Allcroft (1950)
	0.15					2		Lynch et al. (1976b)
	0.065 [C]					12	Calves	George and Duncan (1981)
	<0.10					48		Bertrand et al. (1981)
					10.7		Beltsville MD	Chaney (1983)
			0.028-0.030			3	Near Washington D.C.	White et al. (1943)
	0.0086-0.0584					12	Calves	Logner et al (1984)
			0.0-0.12			6		Schmitt et al. (1971)
				HORSES				
	0.02-0.10					20		Penumarthy et al. (1980)
	0.04					20	Mean	Penumarthy et al. (1980)
	0.04					20		Penumarthy et al. (1980)
	0.26					1		Dollahite et al. (1978)
	0.23					1		Dollahite et al. (1978)
	0.14					1		Dollahite et al. (1978)
				1.4		4		Lewis (1972)
	0.18					2		Buck et al. (1976)
	0.051 [C]					25	Creston BC	Schmitt et al. (1971)
	0.045-0.57					25	Mean	Schmitt et al. (1971)
	0.119 [C]					40	Ottawa	Schmitt et al. (1971)
	0.06-0.21					40		Schmitt et al. (1971)
	<0.05	0.290 [A]				6		Schmitt et al. (1971)
	0.140 [B]					2		Allcroft (1950)
		0.0015				43	Sweden	Elinder et al. (1981)

Table 15. Background lead levels in livestock fluids and hair, continued.

Diet*	Blood	Urine	Milk	Hair	Feces	n	Notes	Reference
	ppm (wet weight)			ppm (dry wt.)				
SHEEP								
			0.003-0.023			8		Naplatarova et al. (1968)
			0.130			2		Blaxter (1950a)
	0.09 [E]					7		Pearl et al. (1983)
	0.09					2		Buck et al. (1976)
	0.19					4		Fick et al. (1976)
		0.07 [B]				6		Blaxter (1950a)
		0.04-0.09				Range (6)		Blaxter (1950a)
		0.04-0.06	0.11-0.15 [B]			2		Blaxter (1950a)
	0.139 [B]					12		Allcroft (1950)
	0.08-0.20					4 samples		Blaxter (1950a)
1.8-2.1 mg/day		0.07-0.09				4		Blaxter (1950a)
		0.05-0.09				1,6 samples		Blaxter (1950a)
	0.19	0.08-0.12				1,4 samples		Blaxter (1950a)
	0.15-0.20	0.04-0.05				3		Knight and Burau (1973)
GOATS								
	0.130 [B]					4		Allcroft (1950)

* mg/Kg body weight [A]/Reported as ug/liter [B]/Reported in mg/Kg [C]/Reported as mg/100g
[D]/Reported as ug/100ml [E]/Reported as ug/ml

Table 16. Background lead levels in livestock tissues.

Diet*	Kidney	Liver	Spleen	Heart	Brain	Pancreas	Bone	n	Notes	Reference
	ppm (wet weight)						ppm (dry wt.)			
CATTLE										
	≤ 1.83	≤ 0.32						8	Steers	Bertrand et al. (1981)
	1.21	1.12						92		Buck et al. (1976)
	0.63	0.54						2145,2156		USDA (1975)
	0.86				0.72			130		Blakley and Brockman (1976)
	<0.05-2.29	<0.05-0.85						190		Flanjak and Lee (1979)
.157	0.63-0.71							4	2 Animals	Sharma et al. (1982)
	3.6 dw	1.8 dw						29	Range Cattle	Baxter et al. (1983)
	1.9 dw	1.0 dw						15	Dairy Cattle	Baxter et al. (1983)
	0.19	0.11						85,92		Penumarthy et al. (1980)
	0.67-1.77	0.48-1.44						52,54		Prior (1976)
	0.11	0.13	0.08	0.07	0.05-0.10	0.07	0.22	5	Calves	Zmudski et al (1983)
	0.09-0.13	0.09-0.18	0.05-0.10	0.05-0.10		0.05-0.09	0.18-0.32	5	Calves	Zmudski et al (1983)
	0.50	0.58						8	Calves	Edwards and Dooley (1980)
1.42ppm	0.46 dw	0.17 dw			0.57 dw		0.55	4		Logner et al. (1984)
1.8ppm	1.1 dw	<0.5 dw						8	Steers	Baxter et al. (1982)
	0.4-1.0	0.4-1.0						10	Calves	Allcroft (1950)
	0.3-1.5	0.2-1.5						13	Cows/Heifers	Allcroft (1950)
1.8ppm	1.4 dw	0.6 dw						8	Cows	Baxter et al. (1982)
	3.6 dw	1.9 dw							Angus Cows/ Steers	Decker et al. (1980)
HORSES										
	0.05	0.42						20		Penumarthy et al. (1980)
	0.93	0.82						2		Buck et al. (1976)
	1.3	1.4		1.1	1.08	0.6		1		Dollahite et al. (1978)
	0.1	0.3					3.0-3.6	6		Schmitt et al. (1971)
		0.4					38.8	3	Pony	Burrows and Borchard (1982)
	5.6	1.3					1.5	3	Pony	Burrows and Borchard (1982)
	1.0	0.8						20		Eamens et al. (1984)
4ppm	<1.5 (Cortex)							45	Sweden	Elinder et al. (1981)
4ppm	0.5									
	(Medulla)	1.0					8.0	1		Willoughby et al. (1972b)
4ppm	1.0 (Cortex)							1		Willoughby et al. (1972b)
SHEEP										
	0.72	0.72						2		Buck et al. (1976)
	0.21	0.39	0.7 dw	0.2 dw	1.0 dw		9.6	4		Fick et al. (1976)
	0.3-0.8	0.6-1.2						5		Allcroft (1950)
	<1.0	<1.0						3	Lambs	Allcroft (1950)
		0.18						3		Bennett and Schwartz (1971)
SWINE										
	0.85	0.73						49,51		Prior (1976)

* mg/kg Body Weight/Day Unless Noted

Table 17. Elevated lead levels in livestock fluids and hair.

Diet*	Blood	Urine	Milk	Hair	Feces	n	Agent	Notes/ Response	Reference
	ppm (wet weight)			(dry wt.)					
CATTLE									
1.35	0.29 [A]					4	Pb Acetate	Not Noted	Sharma et al. (1982)
0.395	0.06						Pb Acetate	Not Noted	Sharma et al. (1982)
501ppm	0.54 [A]					4	$PbSO_4$	Not Noted	Logner et al. (1984)
1501ppm	0.66 [A]					4	$PbSO_4$	Clin Tox	Logner et al. (1984)
60,000ppm	1.					1	Paint	Fatal	Every (1981)
	0.98					90		Fatal	Blakley and Brockman (1976)
	0.83					12	Ind. Exp[D]	Not Noted	Edwards and Clay (1977)
	0.81							Clin Tox	Buck et al. (1976)
507			2.26			1	Pb_3O_4	Toxic	White et al. (1943)
507			0.15			1	Pb_3O_4	Mild Symptoms of Pb poisoning	White et al. (1943)
			0.028-0.030			3	Pb_3O_4	16 mo. following poisoning	White et al. (1943)
	0.59					1	Galena	Toxic	Wardrope and Graham (1982)
	1.89					1	Galena	Fatal	Wardrope and Graham (1982)
	1.93					1	Galena	Toxic	Wardrope and Graham (1982)
	2.00					1	Galena	Fatal	Wardrope and Graham (1982)
2.7	0.47					5		LD 20 @ 7 Days Calves	Zmudski et al. (1983)
5.0	1.57					11		LD 36 @ 7 Days Calves	Zmudski et al. (1983)
20.0	2.41					1		Fatal Calves	Zmudski et al. (1983)
	1.0					5		Clin Tox Calves	Buck et al. (1976)
	1.11					1		Fatal	Wardrope and Graham (1982)
	0.94					1		Clin Tox	Wardrope and Graham (1982)
	0.88					1		Clin Tox	Wardrope and Graham (1982)
1.5, 9.6w[E]	0.91 [C]					5	$PbCO_3$	Decreased Gains Calves	Lynch et al. (1976a)
3.0, 9.0w	1.36 [C]					5	$PbCO_3$	Decreased Gains Calves	Lynch et al. (1976a)
6.0, 10.8w	1.69 [C]					5	$PbCO_3$	Decreased Gains Calves	Lynch et al. (1976a)
	0.44-1.16 [C]					24		Toxic	Osweiler and Ruhr (1978)
					40.7			Ind Exp	Chaney (1983)
					28.6			Ind Exp	Chaney (1983)
Accidental	1.4					1		Acute Tox	Christian and Tryphonas (1971)
3g total over 12 days	0.7					1		Toxic	Christian and Tryphonas (1971)
20.48ppm	<.10					48		Nontoxic	Bertrand et al. (1981)
HORSES									
108 mg/kg body wt	.92					1	$PbCO_3$	Clin Tox	Willoughby et al. (1972b)
108 mg/kg body wt	.75					1	$PbCO_3$	Clin Tox	Willoughby et al. (1972b)
	.39					6		Clin Tox	Buck et al (1976)
2884	1.27-1.28					2	Pb Ace	LD_{50} @ 190 Days	Dollahite et al. (1978)
1526	1.04					1	Pb Ace	Fatal	Dollahite et al. (1978)
343	1.26					1	Pb Ace	Fatal	Dollahite et al. (1978)
2122	1.77					1	Pb Ace	Clin Tox	Dollahite et al. (1978)
3099	1.89					1	Pb Ace	Fatal	Dollahite et al. (1978)
2444	2.18					1	Pb Ace	Clin Tox	Dollahite et al. (1978)
1699	1.48					1	Pb Ace	Clin Tox	Dollahite et al. (1978)

Table 17 Elevated lead levels in livestock fluids and hair, continued.

Diet*	Blood	Urine	Milk	Hair	Feces	n	Agent	Notes/ Response	Reference
	ppm (wet weight)			(dry wt.)					
1 mi - smelter					8.1	3	Ind Exp[D]	LD_{33}	Lewis (1972)
2.9 mi - smelter					5.2	11	Ind Exp	Not Noted	Lewis (1972)
2.6 mi - smelter					18.2	2	Ind Exp	Not Noted	Lewis (1972)
5.3 mi - smelter					6.8	5	Ind Exp	Not Noted	Lewis (1972)
2.9 mi - smelter					35.1	1	Ind Exp	Not Noted	Lewis (1972)
1.9 mi - smelter					10.4	1	Ind Exp	"Smoked"	Lewis (1972)
1.0 mi - smelter					7.4	3	Ind Exp	Not Noted	Lewis (1972)
		0.0111				1	Env Exp	Histopathological	Elinder et al. (1981)
		0.0210				1	Env Exp	Changes	Elinder et al. (1981)
1.4 mi - smelter					11.8	2	Ind Exp[D]	"Stifled"	Lewis (1972)
2.3 mi - smelter					3.4	1	Ind Exp	Not Noted	Lewis (1972)
7.6 mi - smelter					7.0	2	Ind Exp	Not Noted	Lewis (1972)
3.0 mi - smelter					4.1	3	Ind Exp	Not Noted	Lewis (1972)
4.7 mi - smelter					3.2	1	Ind Exp	Not Noted	Lewis (1972)
	0.56 [B]	2.300				1	Ind Exp	Fatal Foal	Schmitt et al. (1971)
	0.35	0.340				1	Ind Exp	Clin Tox Foal	Schmitt et al. (1971)
	0.25	0.140				1	Ind Exp	Clin Tox Foal	Schmitt et al. (1971)
	0.34	1.100				1	Ind Exp	Clin Tox	Schmitt et al. (1971)
	0.20	2.100				1	Ind Exp	Clin Tox Yearling	Schmitt et al. (1971)
	0.75					1	Ind Exp	Clin Tox	Schmitt et al. (1971)
	0.16-0.75					25	Ind Exp	Partial Clin Tox	Schmitt et al. (1971)
423ppm					13.4	4	Pb Ace	Fatal Pony	Burrows and Borchard (1982)
423ppm					12.2	4	Contaminated Hay	Fatal Pony	Burrows and Borchard (1982)
				SHEEP					
13.4 ppm	0.18					4	Pb Acetate	Non Toxic	Fick et al. (1976)
103.4 ppm	0.22					4	Pb Acetate	Non Toxic	Fick et al. (1976)
503.4 ppm	0.24					4	Pb Acetate	Non Toxic	Fick et al. (1976)
1003.4 ppm	0.28					4	Pb Acetate	Toxic	Fick et al. (1976)
1000.0 ppm	1.42 [A]					6	Pb Acetate	Not Noted	Pearl et al. (1983)
150 mg	0.45-30.9	0.13-5.15				1	Pb Acetate	Fatal	Blaxter (1950a)

* mg/Kg Body Weight/day [A]/Reported in ug/ml [B]/Reported in ug/100g [C]/Reported in ug/100ml unless noted [D] Ind. Exp = Industrial exposure
E/W = week

Table 18. Elevated lead levels in livestock tissues.

Diet*	Kidney	Liver	Spleen	Heart	Brain	Pancreas	Bone	n	Agent	Notes/ Response		Reference
	ppm (wet weight) unless noted						ppm (dry wt.)					
						CATTLE						
								4	PbAcetate	Nontoxic Dairy Cows		Sharma et al. (1982)
0.395	1.24							4	PbAcetate	Nontoxic Dairy Cows		Sharma et al. (1982)
1.348	4.04							4	$PbSO_4$	NS Gain Reduction		Logner et al. (1984)
501ppm	7.27 dw	6.68 dw[A]			1.13 dw		0.77	4	$PbSO_4$	Acute Toxicity/Fatal		Logner et al. (1984)
1501ppm	21.28 dw	16.68 dw			4.28 dw		3.53	4	PcAcetate	Fatal		Doyle and Younger (1984)
6.3	97.5 dw	320.0 dw	11.9 dw	3.38 dw	3.65 dw			4	PbAcetate	Fatal		Doyle and Younger (1984)
7.8	211.9 dw	728.8 dw	27.5 dw	2.63 dw	2.63 dw			3	PbAcetate	Fatal		Doyle and Younger (1984)
9.8	135.8 dw	396.7 dw	20.8 dw	2.92 dw	2.27 dw			4	PbAcetate	Fatal		Doyle and Younger (1984)
12.2	121.9 dw	361.9 dw	25.0 dw	3.96 dw	2.94 dw							
60,000 ppm	351.							1	Paint Dust	Fatal		Every (1981)
60,000 ppm	31.3	12.8						1	Paint Dust	Fatal		Every (1981)
60,000 ppm	12.							1	Paint Dust	Fatal		Every (1981)
	88.6	17.3			1.03			90		Fatal		Blakley and Brockman (1976)
	50.3	26.4								Clin Tox		Buck et al. (1976)
		43						170		Clin Tox		Buck et al. (1976)
	137							158		Clin Tox		Buck et al. (1976)
50ppm 9 mo	4.3 dw	4.9 dw						8	Sludge	Nontoxic	Cows	Baxter et al. (1982)
50ppm 9 mo	5.2 dw	4.1 dw						8	Sludge	Nontoxic	Steers	Baxter et al. (1982)
Galena	18.6	32.9						1		Fatal		Wardrope and Graham (1982)
Galena	34.1	32.5						1		Fatal		Wardrope and Graham (1982)
Galena	16.5,	12.3,						1		Fatal		Wardrope and Graham (1982)
Galena	22.4	8.9						1		Fatal		Wardrope and Graham (1982)
2.7	49.49	19.0	0.73	0.33	0.38-0.89	3.14	49.02	5	PbAcetate	LD_{20}@7 days	Calves	Zmudski et al. (1983)
5.0	88.0	30.51	1.67	0.59	0.41-1.18	6.11	54.92	11	PbAcetate	LD_{36}@7 days	Calves	Zmudski et al. (1983)
20.0	82.92	37.11	2.52	1.64	1.41-1.43	5.66	108.52	1	PbAcetate	Fatal	Calves	Zmudski et al. (1983)
Galena	10.2	12.1						1		Fatal	Heifer	Wardrope and Graham (1982)
11.03	≤ 1.39	≤0.31						8	Sludge/ Forage	Nontoxic		Bertrand et al. (1981)
20.48ppm	≤ 0.76	≤0.49						8	Sludge/ Forage	Nontoxic		Bertrand et al. (1981)
						HORSES						
2884ppm	48.4	11.4	7.9	0.7	4.6	7.1		1	PbAcetate	Nontoxic		Dollahite et al. (1978)
2884ppm	107.5	91.5	4.7	3.7	18.0	11.4		1	PbAcetate	Fatal		Dollahite et al. (1978)
1526ppm	104.4	45.8	17.3	5.2	13.9		17.5	1	PbAcetate	Fatal		Dollahite et al. (1978)
343ppm	168.0	58.6	34.5	2.2	14.0	10.0	11.3	1	PbAcetate	Fatal		Dollahite et al. (1978)
2122ppm	188.0	70.0	12.6	2.7	16.0	27.0	11.3	1	PbAcetate	Clin Tox		Dollahite et al. (1978)
3099ppm	151.4	62.9	29.8	0.6	24.0	11.4	35.6	1	PbAcetate	Fatal		Dollahite et al. (1978)
2444ppm	230.0	78.0	115.5	7.7	35.0	14.2	15.1	1	PbAcetate	Clin Tox		Dollahite et al. (1978)
1699ppm	92.8	62.2	44.3	5.2	7.0	11.4	11.8	1	PbAcetate	Clin Tox		Dollahite et al. (1978)
	18.0	48.0					88-190	1	Ind Exp[B]	Fatal	Foal	Schmitt et al. (1971)
	4.5	16.2					43-110	1	Ind Exp	Clin Tox	Foal	Schmitt et al. (1971)
	5.1	9.6					28-80	1	Ind Exp	Clin Tox	Foal	Schmitt et al. (1971)
	20.0	9.0			1.6		119-260	1	Ind Exp	Clin Tox		Schmitt et al. (1971)
	7.7	9.7					48-55	1	Ind Exp	Clin Tox		Schmitt et al. (1971)
	13.2	15.2						1	Ind Exp	Clin Tox		Schmitt et al. (1971)
45-350ppm in forage		11.8-17.2						4	Ind Exp	Clin Tox		Knight and Burau (1973)

Table 18. Elevated lead levels in livestock tissues, continued.

Diet*	Kidney	Liver	Spleen	Heart	Brain	Pancreas	Bone	n	Agent	Notes/ Response		Reference
			ppm (wet weight) unless noted				ppm (dry wt.)					
						HORSES - Continued						
423ppm	35.3	50.2	6	0.	2.6		63.2	4	Contaminated Feed	Fatal	Ponies	Burrows and Borchard (1982)
423ppm	21.7	82.2	17.7		4.6		202	4	PbAcetate	Fatal	Ponies	Burrows and Borchard (1982)
	8.0	10.0						1	Ind Exp	Clin Tox		Eamens et al. (1984)
800ppm	20-25	20-33					200-210	2	$PbCO_3$	Fatal		Willoughby et al. (1972b)
						SHEEP						
400mg	110.0	75.6			2.0			1	PbAcetate	Fatal		Blaxter (1950a)
40 mg	195.8	37.9			2.1			1	PbAcetate	Fatal		Blaxter (1950a)
22mg/ kg/mo		1.62						5	Pb Arsenate	Nontoxic		Bennett and Schwartz (1971)
44mg/ kg/mo		2.62						5	Pb Arsenate	Nontoxic		Bennett and Schwartz (1971)
88mg/ kg/mo		4.20						4	Pb Arsenate	Not Noted		Bennett and Schwartz (1971)
13.4ppm	2.0	1.8	0.7	0.1	1.3		15.4	4	PbAcetate	Nontoxic		Fick et al. (1976)
103.4ppm	9.4	5.3	1.0	0.2	2.0		33.6	4	PbAcetate	Nontoxic		Fick et al. (1976)
503.4ppm	25.1	11.6	1.9	0.4	4.1		89.6	4	PbAcetate	Nontoxic		Fick et al. (1976)
1003.4ppm	230.6	14.4	2.6	0.8	5.4		121.3	4	PbAcetate	Reduced Feed Intake		Fick et al. (1976)

* mg/kg Body Weight/Day Unless Noted   A/ dw - dry weight basis   B/ Industrial exposure

a moderate decline within a few hours. Allcroft (1951) found blood lead levels in calves up to 4 ppm within 12 hours of ingestion, a value which fell to 1 to 1.5 ppm in the following 48 to 72 hours, but remained elevated above background levels for one to two months. Zmudski et al. (1983) found that maximum blood lead levels in calves occurred six hours after intake of the metal. After 12 hours only about one half of the peak concentration remained, but this level was still in excess of 10 times background. Sheep blood lead levels were shown to peak 4 hours following ingestion of lead acetate (Blaxter, 1950b). Buck et al. (1976) suggested that bovine blood levels from 0.10 to 0.35 ppm were significant as a primary etiological agent or as a predisposing or contributory factor in lead toxicity. Background blood lead levels up to 0.21 ppm in cattle have been reported by Ruhr (1984). Similar background levels for horses range from 0.04 to 0.26 ppm. These values compare favorably with those reported for cattle (0.02 to 0.20 ppm), horses (0.04 to 0.25 ppm) and sheep (0.02 to 0.25 ppm) by Puls (1981).

Burrows et al. (1981) found blood lead concentrations of 0.35 ppm or greater in nine percent of 118 horses and ponies he sampled in the North Idaho silver/lead belt. Two of these horses had blood lead levels of 0.7 ppm, but none of the horses exhibited signs of clinical toxicosis. It has been shown that high to toxic levels of zinc intake will prevent clinical signs of lead toxicosis in horses. This may help explain observed cases of high blood lead levels where no signs of clinical toxicosis were observed (Willoughby et al. 1972b). Several horses investigated by Schmitt et al. (1971) displayed symptoms of advanced lead toxicosis at blood lead levels ranging from 0.20 to 0.34 ppm. It is evident from the literature that a great deal of variation exists in individual animal absorption, excretion or metabolism of lead (Dollahite et al. 1978, Zmudski et al. 1983). Attempts to use more specific blood parameters such as delta-aminolevulinic dehydratase (ALA-D) and blood-free erythrocyte porphyrins (FEP) to determine the level of blood lead have met with limited success. Osweiler and Ruhr (1978) found a good correlation (r = 0.9) of FEP with blood lead levels in calves, but poor correlation of ALA-D with blood lead or with FEP. A study by George and Duncan (1981) found levels of FEP in blood of experimental calves to be more uniform than blood lead levels and that FEP levels continued to rise 3 months following deletion of lead from the diet. These authors suggested the FEP test could be more sensitive than blood lead levels for subclinical lead exposure. Ruhr (1984) found no significant correlation of FEP or ALA-D with blood lead levels in normal cattle. This may have been due to the low blood lead levels in the nonexposed cattle he sampled. Blumenthal et al. 1972 found a correlation coefficient (r) of 0.11 between the ALA-D test and blood lead levels in children. These authors calculated that the ALA-D test would miss 33 percent of the positive cases. Furthermore, there are too few data to establish lead dose and ALA-D response in cattle (Bratton and Zmudski 1984).

Lead levels in kidney and liver tissues, both background and elevated levels, are well defined for most livestock. Background levels for cattle kidneys range from 0.11 ppm (calves) to 1.77 ppm (Zmudski et al. 1983, Prior 1976). Similar levels for cattle liver range from 0.11 ppm (Penumarthy et al. 1980) to 1.44 ppm (Prior 1976). Background levels reported for horses range from 0.03 ppm to 1.3 ppm and 0.08 ppm to 1.4 ppm (Penumarthy et al. 1980) for kidney and liver tissues, respectively (Table 16). Puls (1981) has reported normal lead levels for horse kidney and liver at 0.5 ppm (wet weight). The tissue lead levels which are diagnostically significant for lead poisoning have been reported by numerous authors. Fenstermacher et al. (1946) concluded that 10 ppm (dry weight) in liver tissue was a likely indication of lead toxicosis. Buck et al. (1976) stated that kidney or liver levels equal to or greater than 10 ppm (wet weight) were diagnostically significant for ruminants. Lead levels of 3.0 to 5.0 ppm and 5.0 to 140 ppm (wet weight) in kidney tissue have been considered an indication of lead exposure or chronic lead toxicity, respectively, in horses (Puls 1981). Acute lead poisoning has been characterized in cattle by kidney cortex levels above 25 ppm (dry weight) (Todd 1962, Garner and Papworth 1967), whole kidney levels of 10 to 700 ppm (wet weight) (Puls 1981) and liver levels of 5 to 300 ppm (wet weight) (Puls 1981). Chronic lead exposure may produce kidney and liver lead levels 50 ppm (wet weight) (Table 18). Kidney tissues with 12 ppm lead have been reported in cattle killed from lead toxicosis (Every 1981) and levels as low as 4.5 ppm in foal kidney have been associated with chronic lead poisoning (Schmitt et al. 1971). Levels of lead have been reported for spleen, heart, brain, bone, pancreas, hair and milk for several species (Tables 15-18). These values are generally an order of magnitude less than corresponding levels in kidney and liver tissues and are thus, subject to greater analytical error in determining the degree of lead toxicosis. Elevated lead levels in hair have been associated with chronic lead toxicosis in horses (Lewis 1972). A study of elements in cattle hair has determined that there are large variations in elemental concentrations among individuals within the same group and that lead levels in cattle hair show only a slight correlation to other metals (Ronneau et al. 1983). Significant correlations ($p = 0.01$) between hair and liver concentrations of cattle were found by Russell and Schoberl (1970). Dorn et al. (1974) found one to two orders of magnitude increase in lead concentrations in hair of cows exposed to industrial pollution when compared to controls.

Levels of lead in milk are generally low, but have been used to estimate the degree of chronic lead poisoning. Milk lead levels are usually about two orders of magnitude less than kidney and liver samples and thus milk samples are less sensitive and more prone to contamination. Murthy et al. (1967) reported background levels of lead in milk from cattle ranged from 0.023 to 0.079 ppm with a mean of 0.047 ppm. Hammond and Aronson (1964) reported a mean and range of 0.009 and 0.006 to 0.013, respectively, in 8 animals. Lead levels in cattle milk indicative of toxicosis have been given as 0.10 to 0.25 ppm (Puls 1981). This author also indicated that a dietary intake of 100 ppm lead was associated with lead toxicosis.

In summary, it appears that kidney and liver tissues offer the best indication of lead toxicosis. Because of the expense and limited opportunity to obtain these samples, the analysis of blood may provide a good alternative. Blood lead levels are moderately well defined in the literature and sampling and analysis are relatively simple. The specific blood parameters of ALA-D and FEP may provide a means of determining lead intoxication in the future, but at the present, insufficient data exist to fully utilize these parameters for livestock toxicological evaluation. Hair samples may be used to indicate long term chronic lead exposure if a sufficiently large sample base is obtained. A hair lead content of 10 ppm has been reported as indicative of excessive lead exposure (Puls 1981). More detailed studies could make use of biopsy tissues of liver and bone, and feces can be analyzed to determine dietary exposure (Decker et al. 1980).

2.3.2 Livestock lead hazard level

The data contained in Table 15, 16, 17, and 18 and other publications were used to develop lead hazard levels in the following sections.

2.3.2.1 Toxic lead hazard levels for cattle

The 0.35 ppm toxic blood level selected for cattle is based on several publications (Table 19). Buck et al. (1976) suggested the level was indicative of probable clinical toxicosis. Buck (1975) stated "Concentrations >0.35 ppm in cattle should be considered as evidence of unusual exposure." That statement was based on the observation of 142 animals, of which 52 exhibited symptoms of clinical lead toxicosis and had blood lead levels ranging from 0.19 to 3.80 ppm, with a mean of 0.81 ppm lead. Hammond and Aronson (1964) observed that, in acute lead poisoning in cattle, blood lead levels were never less than 0.35 mg/l. The 0.35 ppm blood lead concentration was reported by Puls (1981) as indicative of toxicosis in cattle. The value is supported by other data from the reviewed literature (Tables 15 and 17). The highest concentration of lead in cattle blood at which toxicosis has not been noted is the 0.29 ppm reported by Sharma et al. (1982).

Table 19. Diagnostic Levels of Lead in Cattle.

	Background	Tolerable	Uncertain	Toxic
	ppm wet weight			
Blood Hazard Levels/Source	0.002 - 0.21 Sharma et al. (1982) - Ruhr (1984)	0.29 Sharma et al. (1982)		0.35 Buck (1975), Buck (1976 Puls (1981), Hammond an Aronson (1964)
Urine Hazard Levels/Source	--------	--------	-------	---------
Kidney Hazard Levels/Source	< 0.05 - 2.29 Flanjak and Lee (1979)	4.04 Sharma et al. (1982)	-------	6 - 10 Logner et al. (1984), Sharm et al. (1982), Buck et al. (1976) and Puls (1981)
Liver Hazard Levels/Source	< 0.05 - 1.44 Flanjak and Lee (1979) - Prior (1976)	--------	3.5[A] - 5 Logner et al. (1984)	5 - 12 Puls (1981), Zmudski et a (1983), Buck et al. (1976) Wardrope and Grahm (1982) and Every (1981)
Hair Hazard Levels/Source	0.5 - 5.0 Puls (1981)	5.00 USDA (1975)	-------	10 Puls (1981)
Milk Hazard Levels/Source	0.02 - 0.420 Kehoe et al. (1940) - Murthy (1974)	--------	-------	0.15 and 0.10 - 0.25 White et al. (1943) Puls (1981)

[A] Value converted from dry weight basis utilizing conversion factor reported by Munshower and Neuman (1979).

Background concentrations for lead in cattle kidney tissue range from <0.05 ppm to 2.29 ppm (Flanjak and Lee 1979). The highest nontoxic value reported for this parameter was 4.04 ppm found in the kidneys of dairy cattle fed lead acetate (Sharma et al. 1982). The toxic lead hazard level of 6 ppm for cattle kidney tissue is based on the study of Logner et al. (1984). These authors fed elevated lead (as lead sulfate) to calves for 7 weeks and noted acute toxicity symptoms and one fatality in the 4 calves receiving a diet with 1501 ppm lead. The surviving calves exhibited a mean kidney lead concentration of 6.38 ppm. This level agrees with other data in the reviewed literature in that all levels >6 ppm were associated with toxicity and all levels <6 ppm were nontoxic. A 10 ppm lead concentration in cattle kidney tissue was reported as toxic by Puls (1981) and Buck (1976).

Background lead concentrations in cattle liver tissue range from <0.05 to 1.44 ppm (Flanjak and Lee 1979, Prior 1976). The toxic lead hazard level for liver tissue of 5-12 ppm is based on the 5 to 300 ppm criteria reported by Puls (1981). All cattle liver lead levels in excess of 5 ppm reported in the reviewed literature were associated with toxicosis. All values less than the 5 ppm, with the exception of a 3.5 ppm value reported by Logner et al. (1984), were nontoxic. Buck et al. (1976) stated that liver levels >10 ppm lead were diagnostically significant for ruminants.

The typical background range for lead in cattle hair has been reported as 0.5 to 5.0 ppm (Puls 1981) and apparently may average close to 5 ppm near highly developed areas such as Los Angeles (USDA 1975). The toxic hazard level of 10 ppm lead in cattle hair is the value given by Puls (1981). No other data were found in the reviewed literature to substantiate this hazard level.

Background values for lead in cattle milk range from 0.02 to 0.420 ppm (Keheo et al. 1940, Murthy 1974). The toxic hazard level for cattle milk (0.15 ppm) is based on the work of White et al. (1943) who noted mild lead poisoning symptoms associated with this level. The 0.15 ppm level is in agreement with the toxic level of 0.10 to 0.25 ppm lead reported by Puls (1981) for cattle milk.

2.3.2.2 Toxic lead hazard level for horses

The basis of the toxic hazard level for lead in horse blood (>0.34 ppm) is, in part, the report of Schmitt et al. (1971) (Table 20). These authors found toxicosis in horses with blood lead levels that ranged from 0.20 to 0.75 ppm. Some of the observed toxicity symptoms in this study were likely due to zinc contamination. Burrows and Borchard (1982) noted that after feeding contaminated hay containing lead acetate (423 ppm) for 5 to 6 weeks, ponies exhibited blood levels consistently ≥0.3 ppm. These authors found that blood lead concentrations "did not increase consistently at onset of clinical toxicologic signs or just before death". Blood lead levels in four ponies fed lead acetate did not decrease below 0.39 ppm after clinical toxicosis was noted and most concentrations were ≥0.5 ppm (Burrows and Borchard, 1982). The 0.34 ppm level is the lowest toxic value found in the reviewed literature that is still above maximum background values. Puls (1981) reported a toxic range of 0.33 to 0.50 ppm for this parameter.

The toxic hazard level for lead in horse urine (0.50-5.0 ppm) is the range noted by Puls (1981). Few data were found from the literature to substantiate this range but it was generally supported by the report of Schmitt et al. (1971).

The selected lead hazard value of 10 ppm for horse kidney tissue is based on the findings of Buck et al. (1976) and Schmitt et al. (1971). Schmitt et al. (1971) observed toxicity in foals with kidney levels ranging from 4.5 to 20 ppm. The apparent toxicity in this study was likely due in part to high levels of zinc. Eamens et al. (1984) reported one case of clinical toxicity with a kidney tissue level of 8 ppm lead. Puls (1981) noted toxicity ranges for horse kidney tissue of 5.0 to 140 ppm and 20 to 200 ppm for chronic and acute poisoning, respectively. Buck et al. (1976) suggested 10 ppm in kidney tissue as diagnostic criteria for lead poisoning.

Table 20. Diagnostic Levels of Lead in Horses.

	Background	Tolerable	Uncertain	Toxic
		ppm wet weight		
Blood Hazard Levels/Source	0.02 - 0.26 Penumarthy et al. (1980) - Dollahite et al. (1978)	--------	0.20 - 0.26 Schmitt et al. (1971) Dollahite et al. (1978)	>0.34 Schmitt et al. (1971)
Urine Hazard Levels/Source	0.04 - 0.20 Puls (1981)	0.29 Schmitt et al. (1971)	-------	0.50 - 5.0 Puls (1981)
Kidney Hazard Levels/Source	0.03 - 1.3 Penumarthy et al. (1980) - Schmitt et al. (1971)	--------	-------	10, 5.0 - 140 Schmitt et al. (1971) Buck et al. (1976) Puls (1981)
Liver Hazard Levels/Source	0.08 - 1.4 Penumarthy et al. (1980) - Schmitt et al. (1971)	--------	-------	10, 4.0 - 50 Eamens et al. (1984) Buck et al. (1976) Puls (1981)
Hair Hazard Levels/Source	0.07 - 2.5 Lewis (1972)	--------	-------	10 - 12 Lewis (1972), Burrows and Boarchard (1982)
Milk Hazard Levels/Source	0.006 - 0.013 Puls (1981)	--------	-------	0.28 - 0.54 Puls (1981)

The 10 ppm toxic hazard level for horse liver tissue is based on Schmitt et al. (1971), Eamens et al. (1984) and Buck et al. (1976). Schmitt et al. (1971) found a range of 9.0 to 48 ppm lead in horse liver tissue of animals exposed to industrial pollution near Trail, British Columbia. Eamens et al. (1984) found 10.0 ppm lead in liver tissue of a horse exhibiting clinical toxicity symptoms. Similar levels (11.8-17.2 ppm) were found associated with clinical toxicity by Knight and Burau (1973). With the exception of one horse with a liver tissue lead concentration of 11.4 ppm (Dollahite et al. 1978), all horse liver tissue samples with >10 ppm lead were associated with toxicity. Puls (1981) gave ranges of 4 to 50 ppm and 10 to 500 ppm in horse liver tissue as indicative of chronic and acute toxicosis, respectively Buck et al. (1976) indicated that the 10 ppm lead concentration in liver tissues was diagnostic of lead poisoning.

The reports of Lewis (1972) and Burrows and Borchard (1982) are the basis of the toxic hazard level for horse hair. Lewis (1972) found elevated lead concentrations (9.6 to 25.8 ppm) in 3 of 4 affected horses studied in the Helena Valley. The effects of the interaction of elevated levels of other metals on the apparent toxicity noted in this study were not documented. Burrows and Borchard (1982) studied ponies on diets of contaminated hay (from the Coeur d'Alene River Basin, Idaho) and on diets with added lead acetate and found hair lead concentrations of 12.2 and 13.4 ppm for the two groups respectively. These authors suggested that the interaction of cadmium in the contaminated hay "markedly increased...the severity and rapidity of development of the clinical toxicologic signs and hematologic changes".

No elevated horse milk data were found in the reviewed literature (Table 17). The toxic hazard level is the level published by Puls (1981).

2.3.2.3 Toxic lead hazard levels for sheep

Fick et al. (1976) found concentrations of lead in sheep blood from 0.18 to 0.28 were nontoxic. Blaxter (1950a) noted sheep blood lead levels of $\geq$ 0.45 ppm were associated with toxicosis, which was the basis of the toxic hazard level for this parameter (Table 21). Puls (1981) reported sheep blood lead levels in the range of 1.0 to 5.0 ppm were toxic.

Toxic lead concentrations in sheep urine were noted by Blaxter (1950a) and ranged from 0.28 to 0.81 ppm. The 0.28 to 0.32 ppm toxic hazard level for lead in sheep urine should be used with caution until more data are available.

Toxic lead levels in sheep kidney and liver tissues were reported as 5 to 200 ppm and 10 to 100 ppm respectively (Puls 1981). With minor exceptions, data in the reviewed literature tended to support these ranges.

The toxic hazard level for lead concentrations in sheep wool (25 ppm) was reported by Puls (1981). No data were found in this review to substantiate this value.

2.4 Zinc

2.4.1 Zinc literature review

Zinc is an essential element and most animals can tolerate relatively high dietary levels. Few cases of natural zinc poisoning of livestock have been reported in the literature. Most episodes of poisoning involve contamination of livestock feed (Allen 1968, Grimmett et al. 1937, Sampson et al. 1942, Davies et al. 1977). Experimental zinc toxicosis in livestock has been studied and described in several reports and much of these data are reviewed here.

The uptake of toxic amounts of zinc affects many organs directly or interferes with the metabolism of several other elements, notably iron, copper, calcium and cadmium. Cadmium acts synergisticly with high levels of zinc, enhancing the toxic effects of zinc (Thawley et al. 1977). Cadmium also tends to reduce the absorption and retention of zinc (Miller 1969). Zinc absorption is higher in young animals than in older animals, making them more susceptible to zinc poisoning (Davies et al. 1977). The degree to which the diet composition affects this relationship remains unresolved. Diets containing 200-400 ppm zinc have been shown to produce clinical copper deficiency in diets

Table 21 . Diagnostic Levels of Lead in Sheep and Goats.

	Background	Tolerable	Uncertain	Toxic
	ppm wet weight			
	SHEEP			
Blood Hazard Levels/Source	0.08 - 0.20 Blaxter (1950a)	--------	-------	0.45 Blaxter (1950a)
Urine Hazard Levels/Source	0.04 - 0.12 Blaxter (1950a)	--------	-------	0.28 - 0.32 Blaxter (1950a)
Kidney Hazard Levels/Source	0.21 - 1.0 Fick et al. (1976) - Allcroft (1950)	--------	-------	5 - 200 and 231 Puls (1981) and Fick et al. (1976)
Liver Hazard Levels/Source	0.18 - 1.2 Bennett and Schwartz (1971) - Allcroft (1950)	11.6 Fick et al. (1976)	-------	10 - 100 and 14 Puls (1981) and Fick et al. (1976)
Hair Hazard Levels/Source	4 - 7 Puls (1981)	--------	12 - 18 Puls (1981)	25 Puls (1981)
Milk Hazard Levels/Source	0.003 - 0.15 Naplatarova et al. (1968) - Blaxter (1950a)	--------	-------	-------
	GOATS			
Blood Hazard Levels/Source	0.130 Allcroft (1950)	--------	-------	-------

with low copper content (Hill and Matrone 1970). Campbell and Mills (1979) produced a severe copper deficiency in pregnant ewes on diets of 750 ppm zinc.

The form of zinc is another important factor in zinc toxicity. Smith (1977) found that zinc sulfate was more rapidly excreted in the urine of sheep than was zinc oxide. Zinc sulfate has also been shown to accumulate less in tissues when given at the same concentration as zinc oxide (Miller et al. 1970). The sex of beef cattle has been shown to affect the amount of zinc accumulated in tissues, but the threshold level of zinc (900 ppm Zn diet) necessary to produce toxicosis was found to be similar for both heifers and steers (Ott et al. 1966b).

It is apparent from this discussion that a given amount of zinc, within limits, may or may not produce toxicosis. Many studies have attempted to determine threshold toxic levels of zinc in various animals. These studies are summarized in Tables 22-25.

Excessive absorption of zinc is controlled up to a certain dietary level by the body's homeostatic mechanisms. In lambs, this system is effective up to a dietary concentraction of approximately 1000 ppm (Ott et al. 1966c). For calves, the level is somewhat lower, as large increases in tissue zinc content have been observed at dietary levels of 638 ppm (Miller et al. 1971). Higher levels of zinc overwhelm the homeostatic mechanisms and significant increases of zinc have been observed in liver, kidney, pancreas and blood serum (Tables 24 and 25). Miller et al. (1971) found that zinc levels in whole blood did not correlate with dietary zinc levels up to 638 ppm. Similarly, normal skeletal muscle has been shown to be highly insensitive to dietary zinc. These two livestock tissues would be of little use in monitoring zinc exposure. Zinc levels in blood serum, liver, kidney and pancreas have been shown to correlate with dietary levels of the element. These three organs tend to accumulate similar metal levels and are about two orders of magnitude greater than levels found in serum. Allen et al. (1983) found that the pancreas is the only organ consistently affected by zinc toxicosis and suggested that pathological changes observed in the pancreas could

Table 22. Background zinc levels in livestock fluids and hair.

Diet	Serum (ppm, wet weight)	Urine (ppm, wet weight)	Milk (ppm, wet weight)	Hair ppm (dry wt.)	n	Notes/ Response	Reference
CATTLE							
18.0-20.9	0.98-1.93			122-220	150	Hereford Steers	Beeson et al. (1977)
44ppm	Plasma 2.1		4.2		6	Dairy Cows	Miller et al. (1965a)
				79.2-135.5	5-24	Calves	Miller et al. (1965b)
33ppm	1.47			116.4	4	Calves	Miller et al. (1970)
100ppm 5 wks	1.9				4	Calves	Ott et al. (1966d)
100ppm 5 wks	1.2-1.7			137-142	10	Heifers and Steers	Ott et al. (1966d)
			3.840 [B]		18		Parkash and Jenness (1967)
			4.780 [B]		14		Parkash and Jenness (1967)
			3.438		8		Dorn et al. (1975)
			2.800		8		Dorn et al. (1975)
			3.980 [B]		7		Casey (1976)
27.49ppm	3.74 whole blood				48		Bertrand et al. (1981)
.1g/kg=100ppm	1.02-2.32 whole blood mean 1.63				4	Calves	Miller et al. (1968)
	0.67-1.51 Plasma mean 1.26				4	Calves	Miller et al. (1968)
HORSES							
Normal				140-230	4		Lewis (1972)
			3.500		10		Ullrey et al. (1974)
			2.400		10		Ullrey et al. (1974)
			6.400		8	Colostrum	Ullrey et al. (1974)
			3.600		10	Transitional	Ullrey et al. (1974)
	Plasma 1.08				16		Eamens et al. (1984)
SHEEP							
	0.95 [A]			97	6	Lambs	Ott et al. (1966c)
	1.36			110	10	Lambs	Ott et al. (1966c)
43ppm	1.11-1.24 [A]				8		Bremner et al. (1976)
			7.200		6	UK	Ashton et al. (1977)
			7.500		6	UK	Ashton et al. (1977)
			0.930-1.900		8	BUL	Naplatarova et al. (1968)
GOATS							
			22.0		-		Dittrich (1974)
			3.0		5	India	Handa and Johri (1972)
			4.01		10	Nigeria	Akinsoyinu et al. (1979)
	0.46-1.00 (x=0.66)				3		Miller et al. (1968)
	1.25-2.16 (x=1.76) (whole blood)				3		Miller et al. (1968)

[A]/Reported in ug/ml [B]/Reported in ug/liter

Table 23. Background zinc levels in livestock tissues.

Diet	Kidney	Liver	Spleen	Heart	Brain	Pancreas	Bone	n	Notes	Reference
	ppm (wet weight) unless noted						ppm (dry wt.)			
CATTLE										
	12.9-31.6	13.4-99.2						190	New South Wales	Flanjak and Lee (1979)
44ppm 5-6 mo	73 dw[A]	187 dw				146 dw	69-85	-	Calves	Miller et al. (1969)
38ppm 21d	73 dw	101 dw					71-85	-	Calves	"
33ppm 15d	92.1 dw	118.4 dw		79.4 dw		100.8 dw	69.2-73.5	4	Calves	Miller et al. (1970)
38ppm 21d	61.8 dw	88.2 dw				71.9 dw		3	Calves	"
100ppm 5 wks	22.-24	41.	24.-25	20.-21		49.	70.-74	4	Calves	Ott et al. (1966d)
	88.4 dw	132 dw						29	Range Cattle	Baxter et al. (1983)
	96. dw	118 dw						15	Dairy Cattle	"
	22.08	38.48						8	Steers	Bertrand et al. (1981)
	76. dw	99 dw							Angus Cows/Steers	Decker et al. (1980)
100ppm 5 wks		48						2	Steer Calves	Ott et al. (1966d)
100ppm 5 wks		35						2	Heifer Calves	"
	82.2 dw	102.2 dw	63.8 dw	69.5 dw	41.5 dw			4	2-3 Yr Old Cows and 1 Steer	Doyle and Younger (1984)
HORSES										
	0.45	0.88						49		Eamens et al. (1984)
	35.7 (Cortex)							5	0-4 Years Old	Elinder et al. (1981)
	45.4 (Cortex)							13	5-9 Years Old	"
	46.9 (Cortex)							16	10-14 Years Old	"
	50.0 (Cortex)							15	15-19 Years Old	"
	49.3 (Cortex)							18	20 + Years Old	"
SHEEP										
	1.93 dw	0.35 dw							Lambs	Lee and Jones (1976)
	17	35	24	17	11	15	75	6	Lambs	Ott et al. (1966c)
	136 dw Cortex							1	Lambs	Davies et al. (1977)
	123-167 dw	159-176 dw				84-97 dw		3		Allen et al. (1983)
		31.3						8		Bremner et al. (1976)
		148. dw						5		Allen and Masters (1983)
		128. dw				74. dw		4		
	3271 dw	1523 dw	102 dw	54 dw	53 dw		625	5		Hefferon et al. (1983)
19ppm	111.8 dw	125.0 dw	113.75 dw	69.83 dw				6	Male Lambs	Doyle and Pfander (1975)

A/ Dry weight basis

Table 24. Elevated zinc levels in livestock fluids and hair.

Diet	Serum	Urine	Milk	Hair	n	Agent	Notes/ Response	Reference
	ppm (wet weight)			ppm (dry wt.)				
CATTLE								
372 ppm	Plasma 3.2		6.7		6	Zn Oxide	Dairy Cows Nontoxic	Miller at al. (1965a)
319.4ppm	Serum 1.93-2.57			154-176	8	Zn Oxide	Hereford Steers Nontoxic	Beeson et al. (1977)
639.4ppm	Serum 4.77-4.03			195-199	8	Zn Oxide	Hereford Steers Nontoxic	Beeson et al. (1977)
692ppm	Plasma 4.0		8.0		6	Zn Oxide	Dairy Cows Nontoxic	Miller et al. (1965a)
1279ppm	Plasma 7.5		8.4		6	Zn Oxide	Dairy Cows Slight Reduction in Milk Production	Miller et al. (1965a)
233ppm	1.89			134.0	4	Zn Oxide	Calves Nontoxic	Miller et al. (1970)
633ppm	3.61			157.9	4	Zn Oxide	Calves	Miller et al. (1970)
633ppm	3.59			149.8	4	Zn Sulfate	Calves	Miller et al. (1970)
238ppm	1.26				3	Zn Oxide	Calves Nontoxic	Miller et al. (1971)
638ppm	2.42				3	Zn Oxide	Calves Nontoxic	Miller et al. (1971)
1100ppm 5 wks.	15.6				4	Zn Oxide	Nontoxic	Ott et al. (1966d)
2100ppm 5 wks.	14.7				4	Zn Oxide	Reduced Gains	Ott et al. (1966d)
3100ppm 5 wks.	15.4				4	Zn Oxide	Toxic	Ott et al. (1966d)
500ppm 5 wks.	3.0			156	4	Zn Oxide	Nontoxic	Ott et al. (1966d)
900ppm 5 wks.	7.6			158	4	Zn Oxide	Nontoxic	Ott et al. (1966d)
1300ppm 5 wks.	12.7			154	4	Zn Oxide	Toxic	Ott et al. (1966d)
1700ppm 5 wks.	14.1			162	4	Zn Oxide	Toxic	Ott et al. (1966d)
2100ppm 5 wks.	14.6			173	4	Zn Oxide	Toxic	Ott et al. (1966d)
HORSES								
Contaminated Forage				230	3	Ind. Exp.[B]	Not Noted	Lewis (1972)
"				280	11	" "	1 Fatality	Lewis (1972)
"				300	2	" "	Not Noted	Lewis (1972)
"				190	5	" "	Not Noted	Lewis (1972)
"				200	1	" "	Not Noted	Lewis (1972)
"				210	1	" "	"Smoked"	Lewis (1972)
"				220	3	" "	Not Noted	Lewis (1972)
"				220	2	" "	"Stifled"	Lewis (1972)
"				200	1	Ind. Exp.[B]	Not Noted	Lewis (1972)
"				230	2	Ind. Exp.	Not Noted	Lewis (1972)
"				210	3	Ind. Exp.	Not Noted	Lewis (1972)
"				220	1	Ind. Exp.	Not Noted	Lewis (1972)
"	Plasma 1.759 [2]				1	Ind. Exp.	Toxic	Eamens et al. (1984)
SHEEP								
500ppm 6-10 wks.	1.22			95	6	Zn Oxide	Not Noted	Ott et al. (1966c)
1000ppm 6-10 wks.	1.96			101	6	Zn Oxide	Not Noted	Ott et al. (1966c)
2000ppm 6-10 wks.	7.08			102	6	Zn Oxide	Toxic	Ott et al. (1966c)
4000ppm 6-10 wks.	17.76			115	6	Zn Oxide	Toxic	Ott et al. (1966c)

Table 24. Elevated zinc levels in livestock fluids and hair, continued.

Diet	Serum	Urine	Milk	Hair	n	Agent	Notes/ Response	Reference
	ppm (wet weight)			ppm (dry wt.)				
500ppm 7 wks	1.41			115	10	Zn Oxide	Not Noted	Ott et al. (1966c)
1000ppm 7 wks	2.87			126	10	Zn Oxide	Not Noted	Ott et al. (1966c)
1500ppm 7 wks	5.24			122	10	Zn Oxide	Red. Feed. Ef.	Ott et al. (1966c)
2000ppm 7 wks	7.97			152	10	Zn Oxide	Red. Feed. Ef.	Ott et al. (1966c)
2500ppm 7 wks	6.54			132	10	Zn Oxide	Red. Feed. Ef.	Ott et al. (1966c)
3000ppm 7 wks	8.40			145	10	Zn Oxide	Toxic/Fatal	Ott et al. (1966c)
3500ppm 7 wks	8.67			134	10	Zn Oxide	Toxic/Fatal	Ott et al. (1966c)
1000ppm 11d	1.7				2	$ZnSO_4 \cdot 7H_2O$	Not Noted	Ott et al. (1966c)
1000ppm+2g/d	3.9				2	"	Red. Feed. Ef.	Ott et al. (1966c)
1000ppm+4g/d	27.8				2	"	Red. Feed. Ef.	Ott et al. (1966c)
1000ppm+6g/d	43.8				2	"	Fatal/Toxic	Ott et al. (1966c)
220ppm 24w	1.13 [A]				8	"	29ppm cu diet Nontoxic	Bremner et al. (1976)
440ppm 24w	1.29 [A]				8	"	29ppm cu diet Nontoxic	Bremner et al. (1976)

[A]/Reported in ug/ml [B]/Industrial Exposure

Table 25. Elevated zinc levels in livestock tissues.

Diet	Kidney	Liver	Spleen	Heart	Brain	Pancreas	Bone	n	Agent	Notes/ Response	Reference
	ppm (wet weight) unless noted						ppm (dry wt.)				
CATTLE											
233ppm 15d	104.8 dw[a]	212.7 dw		81.4 dw		228.1 dw	76.8-97.2	4	Zn Oxide	Calves Nontoxic	Miller et al. (1970)
633ppm 15d	614.6 dw	870.5 dw		88.4 dw		1887.2 dw	84.0-125.2	4	Zn Oxide	Calves Nontoxic	Miller et al. (1970)
633ppm 15d	648.4 dw	887.4 dw		91.7 dw		1084.8 dw	83.0-119.0	4	Zn Sulfate	Calves Nontoxic	Miller et al. (1970)
238ppm 21d	79.1 dw	163.1 dw				139.9 dw		3	Zn Oxide	Calves Nontoxic	Miller et al. (1971)
638ppm 21d	725.8 dw	735.1 dw				1424.8 dw		3	Zn Oxide	Calves Nontoxic	Miller et al. (1971)
	140	410-660				745		1-3	Nat. Zn	Calves Fatal	Allen et al. (1983)
500ppm 5 wks.	76	86	26	21		186	72	4	Zn Oxide	Calves Nontoxic	Ott et al. (1966d)
900ppm 5 wks.	291	159	27	30		249	108	4	Zn Oxide	Calves Nontoxic	Ott et al. (1966d)
1300ppm 5 wks.	470	298	27	45		181	150	4	Zn Oxide	Calves Toxic	Ott et al. (1966d)
1700ppm 5 wks.	412	136	30	42		381	172	4	Zn Oxide	Calves Toxic	Ott et al. (1966d)
2100ppm	479	326	29	55		249	198	4	Zn Oxide	Calves Toxic	Ott et al. (1966d)
HORSES											
	652	6687						1		Clin Tox	Eamens et al. (1984)
	598	5716						1		Clin Tox	Eamens et al. (1984)
SHEEP											
500ppm 6-10 wks.	24	38	24	17	11	18	39	6	Zn Oxide	Lambs Not Noted	Ott et al. (1966c)
1000ppm 6-10 wks.	71	91	23	16	12	41	96	6	Zn Oxide	Lambs Not Noted	Ott et al. (1966c)
2000ppm 6-10 wks	448	427	25	18	12	333	199	6	Zn Oxide	Lambs Toxic	Ott et al. (1966c)
4000ppm 6-10 wks.	325	398	24	18	19	518	158	6	Zn Oxide	Lambs Toxic	Ott et al. (1966c)
500ppm 7 wks.	25	45	23	19	14	26	117	10	Zn Oxide	Lambs Not Noted	Ott et al. (1966c)
1000ppm 7 wks.	154	120	24	18	16	147	113	10	Zn Oxide	Lambs Not Noted	Ott et al. (1966c)
1500ppm 7 wks.	596	268	26	22	16	361	182	10	Zn Oxide	Lambs Reduced Feed Efficiency	Ott et al. (1966c)
2000ppm 7 wks.	642	418	26	19	15	382	162	10	Zn Oxide	Lambs Reduced Feed Efficiency	Ott et al. (1966c)
2500ppm 7 wks.	491	442	28	20	16	238	168	10	Zn Oxide	Lambs Reduced Feed Efficiency	Ott et al. (1966c)
3000ppm 7 wks.	407	440	24	18	16	483	166	10	Zn Oxide	Lambs Toxic/Fatal	Ott et al. (1966c)

Table 25. Elevated zinc levels in livestock tissues, continued

Diet	Kidney	Liver	Spleen	Heart	Brain	Pancreas	Bone	n	Agent		Notes/ Response	Reference
	ppm (wet weight) unless noted						ppm (dry wt.)					
SHEEP - Continued												
3500ppm 7 wks.	568	386	29	20	16	203	168	10	Zn Oxide	Lambs	Toxic/Fatal	Ott et al. (1966c)
1000ppm 11d	46	86	25	19	14	33	93	2	Zn Oxide + $ZnSO_4 \cdot 7H_2O$	Lambs	Nontoxic	Ott et al. (1966c)
3000ppm 11d	195	384	26	16	16	215	133	2	"	Lambs	Decreased Gains	Ott et al. (1966c)
5000ppm 11d	389	346	32	24	19	457	152	2	"	Lambs	Toxic	Ott et al. (1966c)
7000ppm 11d	185	325	55	41	24	616	166	2	"	Lambs	Fatal	Ott et al. (1966c)
840ppm 33d	4750 dw[A] Medulla	2664 dw						1	"	Lamb	Toxic	Dalgarno (1978)
840ppm 33d	3220 dw	2133 dw						1	"	Lamb	Toxic	Dalgarno (1978)
840ppm	4790 dw[A]	2311 dw						1	$ZnSO_4 \cdot 7H_2O$	Lamb	Toxic	Davies et al. (1977)
	145-460	60-750				135-1565		1-10	Natural		Toxic	Allen et al. (1983)
220ppm 24w		38.7-43.4						8	$ZnSO_4 \cdot 7H_2O$		Nontoxic	Bremner et al. (1976)
420ppm 24w		43.1-52.7						8	$ZnSO_4 . 7H_2O$		Nontoxic	Bremner et al. (1976)
2g/d 13d	2050- dw 3225	1080- dw 1205				1000- dw 2795		3	$ZnSO_4 . 7H_2O$		Mild Clin Tox	Allen et al. (1983)
1.2g/d 49-72d	1150- dw 3111	1550 dw 1792				1121- dw 1760		2	Zn Oxide		Mild Clin Tox	Allen et al. (1983)
1.5g/d		348 dw				339 dw		4	$ZnSO_4 \cdot 7H_2O$		Toxic	Allen and Masters (1980)
2.0g/d		510 dw				833 dw		4	$ZnSO_4 . 7H_2O$		Toxic	Allen and Masters (1980)
729ppm, 225d	2153 dw	729 dw						10	-		Nontoxic	Telford et al. (1982)
735ppm, 225d	2155 dw	832 dw						10	Silage from Sludge		Nontoxic	Telford et al. (1982)

A/ Dry weight basis

be of use in determining the period of exposure. Very high levels of pancreatic zinc (1887 and 2795 ppm dry weight) have been observed by Allen et al. (1983) and Miller et al. (1970). Maximum levels for kidney accumulation of zinc appear to be in the 2000 to 3000 ppm (dry weight) range with liver levels usually somewhat less. Insufficient data exist to compare organ accumulation among different species at high intake levels. Although the pancreas, liver and kidney of livestock provide an excellent means of determining zinc exposure, they are rarely available on a large scale. Blood serum levels provide an alternative and have shown a good correlation to dietary zinc up to 1500 to 2000 ppm. Zinc intake above this level does not produce corresponding increases in serum zinc (Ott et al. 1966c, 1966d).

Zinc levels in hair have been used with some success for determining zinc exposure. A number of factors, including age, species, color and sex may affect the zinc content of hair (Miller et al. 1965b). These investigators also found considerable variation in hair zinc content among animals otherwise similar in age, color, breed and sex. Ronneau et al. (1983) found that the concentrations of the essential elements Na, K, Se, and Zn in hair were nearly constant with age but the accumulation of certain metals was primarily a characteristic of each individual. Elemental concentrations in cattle hair studied by Ronneau et al. (1983) also demonstrated a good correlation ($r = 0.69$) of inter-elemental ratios such as iron to zinc. These authors suggested that such ratios may be more useful as a "fingerprint" of contamination.

A study of horse mane hair in an area with heavy metal contamination found that high zinc levels were associated with the highest concentrations of lead and cadmium (Lewis 1972). Individual variations at some sites studied by Lewis (1972) were also large, but there was no attempt to compensate for age, color of hair or other factors. Ronneau et al. (1983) concluded that absolute concentrations of heavy metals in hair are of limited usefulness but they may be useful for large-scale determination of pollution.

The zinc content of milk may indicate relative dietary zinc exposure. Miller et al. (1965a) found a good correlation of blood serum zinc and zinc levels in milk up to 1000 ppm dietary zinc. Diet levels above 1000 ppm did not produce any significant increase in milk zinc concentrations. The mammary glands apparently selectively exclude zinc at higher levels. Puls (1981) has reported criteria on zinc levels in milk for cattle, horses and pigs. Few studies have been completed on the effects of varying amount of heavy metals in diets on metal concentrations in milk for horses, swine or sheep.

In summary, both milk and hair may give a gross, regional indication of zinc exposure. More specific information may be obtained through analyses of pancreas, kidney, liver and blood serum, the latter being the most available and probably the easiest to obtain. Existing experimental data should be sufficient to interpret the significance of observed zinc levels in serum.

2.4.2 Livestock zinc hazard levels

Studies reporting zinc concentrations in livestock fluids, tissue and hair are listed in Tables 22, 23, 24 and 25. This data base was used to determine zinc hazard levels in the following sections.

2.4.2.1 Toxic zinc hazard levels for cattle

Background cattle serum zinc levels range from the 0.7 to 1.4 ppm reported as normal by Puls (1981) up to the 1.9 ppm reported by Ott et al. (1966d). There is apparently a range (5.2 to 7.6 ppm) which may be both toxic and nontoxic or in which toxicosis may be subclinical such as the slight reduction in milk production observed by Miller et al. (1965a). The toxic level of zinc in the blood serum of cattle was reported as 5.2 to 7.5 ppm (Puls 1981) (Table 26). Data found in the reviewed literature generally support this range. All values <7.6 ppm zinc in cattle blood serum were reported to be nontoxic (Table 24). All values in excess of 7.6 ppm were associated with toxicity. Background

Table 26. Diagnostic Levels of Zinc in Cattle.

	Background	Tolerable	Uncertain	Toxic
		ppm wet weight		
Serum Hazard Levels/Source	0.7 - 1.9 Puls (1981) - Ott et al. (1966d)	--------	5.2 - 7.6 Puls (1981) Ott et al. (1966d)	5.2 - 7.5 and 12.7 Puls (1981) and Ott et al. (1966d)
Blood Hazard Levels/Source	1.02 - 3.74 Miller et al. (1968) - Bertrand et al. (1981)	--------	-------	-------
Kidney Hazard Levels/Source	12.9-31.6 Flanjak and Lee (1979)	76 Ott et al. (1966d)	-------	130 and 140 Puls (1981) and Allen et al. (1983)
Liver Hazard Levels/Source	13.4 - 99.2 Flanjak and Lee (1979)	86 Ott et al. (1966d)	136 - 300 Ott et al. (1966d) Miller et al. (1971) Miller et al. (1970)	300 Ott et al. (1966d)
Hair Hazard Levels/Source	79 - 142 Miller et al. (1965b) - Ott et al. (1966d)	--------	-------	154 Ott et al. (1966d)
Milk Hazard Levels/Source	2.8 - 4.780 Dorn et al. (1975) - Parkash and Jenness (1967)	--------	-------	8.4 Puls (1981)

values for zinc in whole blood are apparently slightly higher than respective values for serum. The background range for zinc in whole blood is 1.02 to 3.74 ppm (Miller et al. 1968, Bertrand et al. 1981).

The background range for zinc in cattle kidney tissue reported by Flanjak and Lee (1979) (12.9 to 31.6 ppm) encompasses all other background values found in the literature. The highest reported nontoxic value for this parameter was 76 ppm (Ott et al. 1966d). The toxic hazard level suggested for zinc concentrations in cattle kidney tissue is 130 to 140 ppm. This range is based on the 130 ppm level reported to be toxic by Puls (1981) and the 140 ppm found to be toxic by Allen et al. (1983).

Flanjak and Lee (1979) reported the maximum background range (13.4 to 99.2 ppm) of zinc in cattle liver tissue and Ott et al. (1966d) noted that 86 and 159 ppm in calf liver tissue were nontoxic but also noted that 136 ppm was toxic. The 86 ppm tolerable level for this parameter is thus based on the highest nontoxic value below the lowest reported toxic value. The toxic hazard level of 300 ppm for cattle liver tissue is based on the work of Ott et al. (1966d). These authors reported toxicity at liver zinc concentrations of 136 to 326 ppm. Several authors reported nontoxic liver zinc levels in the interval of 136 to 186 ppm. All values derived from the literature which exceeded 300 ppm were associated with zinc toxicity. Puls (1981) reported a value of >500 ppm as the toxic concentration of zinc in cattle liver tissue.

Background values of zinc in cattle hair have been reported to range from 79.2 ppm (Miller et al. 1965b) to 142 ppm (Ott et al. 1966d). Zinc concentrations in cattle hair associated with toxicity ranged from 154 to 173 ppm (Table 24). With one exception (158 ppm), all values which exceeded the suggested 154 ppm hazard level were toxic. Puls (1981) reported a range of 100 to 150 ppm zinc in cattle hair as high ("levels elevated well above normal but not necessarily toxic"). No other data were found in the reviewed literature for this parameter.

The range of background concentrations of zinc in cattle milk is 2.8 to 4.780 ppm (Dorn et al. 1975, Parkash and Jenness 1967). The toxic hazard level of 8.4 ppm zinc in cattle milk is the level reported by Puls (1981) as indicative of toxicosis. This value was derived from Miller et al. (1965a) who noted a slight reduction in milk production at that level but no other apparent toxicity to the 24 dairy cows used in the study.

2.4.2.2 Toxic zinc hazard levels for horses

The hazard level for toxic zinc concentrations in horse blood is based on only one study provided by Eamens et al. (1984) (Table 27). This hazard level should be used with care. The suggested hazard level for toxic concentrations of zinc in whole blood of horses (5-15 ppm) is the range reported by Puls (1981). No additional support data were found in the reviewed literature.

Diagnostic levels for zinc in horse kidney and liver tissues were reported between 295 to 580 ppm and 1300 to 1900 ppm, respectively (Puls 1981). The limited data of Eamens et al. (1984) suggested ranges of 180 to 580 ppm and 1200 to 1900 ppm zinc in horse kidney and liver tissue respectively may be more appropriate.

The hazard level for the toxic concentration of zinc in horse hair (280 ppm) is based on the very limited data of Lewis (1972). The 280 ppm level was the concentration found in a single horse that subsequently died. The hair of other horses in the study ranged from 140 to 430 ppm zinc. Toxicity was not noted in a number of horses with hair zinc levels above 280 ppm. This level should best be considered as an indication of possible excessive exposure to zinc and as with most hair data, sufficient numbers of animals should be sampled to provide a meaningful statistical confidence.

2.4.2.3 Toxic zinc hazard levels for sheep and goats

The toxic hazard level reported for zinc in sheep serum is 7.1 to 44 ppm (Table 28). This range was derived from data reported by Ott et al. (1966c). These authors reported reduced

Table 27. Diagnostic Levels of Zinc in Horses.

	Background	Tolerable	Uncertain	Toxic
		ppm wet weight		
Serum Hazard Levels/Source	1.08 (Plasma) Eamens et al. (1984)	--------	-------	1.76 Eamens et al. (1984)
Blood Hazard Levels/Source	2. - 5. Puls (1981)	--------	-------	6 - 15 Puls (1981)
Kidney Hazard Levels/Source	20 -45 Puls (1981) - Eamens et al. (1984)	--------	-------	180 and 295 - 580 Eamens et al. (1984) Puls (1980)
Liver Hazard Levels/Source	40 - 88 Puls (1981) - Eamens et al. (1984)	--------	-------	1300 - 1900 Puls (1981)
Hair Hazard Levels/Source	140 - 230 Lewis (1972)	--------	210 - 280 Lewis (1972)	280 Lewis (1972)
Milk Hazard Levels/Source	2.4 - 3.5 Ullrey et al. (1974)	--------	-------	-------

Table 28 Diagnostic Levels of Zinc in Sheep.

	Background	Tolerable	Uncertain	Toxic
		ppm wet weight		
Serum Hazard Levels/Source	0.95 - 1.36 Ott et al. (1966c)	--------	4 - 5 ("High") Ott et al. (1966c), Puls (1981)	7.1 - 44 and 30 - 50 Ott et al. (1966c) and Puls (1981)
Blood Hazard Levels/Source	-------	--------	-------	-------
Kidney Hazard Levels/Source	17 - 50 Ott et al. (1966c) - Allen et al. (1983)	--------	145 - 645 Allen et al. (1983), Telford et al. (1982)	185 - 325 Ott et al. (1966c)
Liver Hazard Levels/Source	28 - 75 Allen et al. (1980) - Puls (1981)	--------	73 - 175 Allen and Masters (1980), Telford et al. (1982)	400 Ott et al. (1966c)
Hair Hazard Levels/Source	<110 Ott et al. (1966c)	--------	102 - 115 Ott et al. (1966c)	-------
Milk Hazard Levels/Source	0.9 - 7.5 Naplatarova et al. (1968) - Ashton et al. (1977)	--------	-------	-------

feed efficiency in sheep with serum zinc concentrations as low as 5.24 ppm. All serum values in excess of 7.1 ppm, found in the reviewed literature, were associated with severe toxicity. Puls (1981) reported a 30 to 50 ppm toxic range for this parameter.

The toxic hazard level for zinc concentrations in sheep kidney, 185 to 325 ppm, is based in part on the publication of Ott et al. (1966c). Data for sheep liver zinc concentrations indicated most values above 185 ppm were associated with toxicity (Table 25). The only exception was a value of 2153 ppm (dry weight) reported by Telford et al. (1982). Puls (1981) reported a toxic concentration for zinc in sheep kidney tissue as 1000 ppm. This concentration would appear too high based on the reviewed literature.

The 400 ppm toxic hazard level for zinc in sheep liver tissue has been derived largely from the work of Ott et al. (1966c) who found that concentrations near or above this level were associated with toxicosis. Data from the reviewed literature suggest toxicity is not uncommon in the 200 to 400 ppm range for this parameter. All sheep liver zinc levels in excess of 400 ppm, were toxic. No zinc toxicity data for goats were found in the literature reviewed (Table 29).

Table 29. Diagnostic Levels of Zinc in Goats.

	Background	Tolerable	Uncertain	Toxic
		ppm wet weight		
Serum Hazard Levels/Source	0.46 - 1.00 Miller et al. (1968)	--------	-------	-------
Blood Hazard Levels/Source	1.25 - 2.16 Miller et al. (1968)	--------	-------	-------
Kidney Hazard Levels/Source	23.4 Miller et al. (1968)	--------	-------	-------
Liver Hazard Levels/Source	19.3 Miller et al. (1968)	--------	-------	-------
Hair Hazard Levels/Source	-------	--------	-------	-------
Milk Hazard Levels/Source	3.0 - 22.0 Handa and Johri (1972) - Dittrich (1974)	--------	-------	-------

3.0 LITERATURE REVIEW AND HAZARD LEVELS FOR SOILS AND PLANTS

Heavy metal levels in soils and plants are of concern for two primary reasons: 1) decreased crop and livestock production; and 2) the introduction of certain toxic metals into the food chain and their consumption by humans. The "soil-plant barrier" (Chaney 1983) reduces the risk from exposure to certain elements which are either not translocated to plant foliage (lead) or produce phytotoxicity in the plant at concentrations safe for animals (zinc, arsenic). Of the selected four metals evaluated in this manuscript (arsenic, cadmium, lead and zinc) only cadmium readily passes the soil-plant barrier. It should be noted, that ingestion of soil and dust by livestock or humans bypasses the soil plant barrier and increases the risk of exposure to toxic concentrations of all pollutants.

It has been shown that extractable soil levels of lead, cadmium and zinc generally show better correlations with plant uptake than do total soil levels (Neuman and Gavlak, 1984). Chelating agents such as EDTA and DTPA have been extensively used to evaluate agronomic characteristics of soils and overburden materials in western states. The correlation of total or extractable arsenic levels with vegetation uptake has been more difficult to define and a special discussion has been included for a review of this problem.

Numerous technical problems present themselves when universal phytotoxic hazard levels for soils and plants are to be defined. Some of the more important of these are: the toxic element, soil pH, soil organic matter content, soil cation exchange capacity (CEC), soil texture and the plant species involved. In general, there is an inverse relationship between microelement availability to plants and the soil pH (Logan and Chaney 1983). Molybdenum and selenium are the only notable exceptions, both of which become more available at higher pH. The Soil Survey of Broadwater County Area, Montana includes a portion of the Helena Valley study area and all background sites. All mapped soil units, except small areas which are poorly drained, exhibit calcareous to strongly calcareous conditions (U.S. Soil Conservation Service, 1977). Mean pH values of surface soils (0-4 inch) for the background sites and the project area are 8.0 and 7.2 respectively. The pH values in the project area ranged from 4.7 to 8.2 and, except for an area in and near the City of East Helena, were generally >6.5 (EPA, 1986). A pH level of ≥6.5 is considered to be effective in reducing the availability of metals (Chaney 1973, CAST 1976). The selected phytotoxic soil criteria are generally based on soil pH levels greater than 6.5 when these data were available. Other parameters are discussed in the following sections on specific element levels.

All elemental levels for plants and soils are reported in parts per million (ppm) dry weight basis unless otherwise noted.

3.1 Arsenic in soils and plants

3.1.1 Arsenic literature review

Arsenic is present in all soils, with typical values ranging from 0.1 to 40 ppm total arsenic. In plants, background concentrations vary from 0.01 to 5 ppm (Kabata-Pendias and Pendias 1984). Natural elevated soil values of up to 8000 ppm have been noted in a few rare cases (Kabata-Pendias and Pendias 1984). However, such excessive levels are usually due to soil application of arsenic-containing pesticides, or less frequently, from smelting operations. Inorganic arsenate of low solubility makes up the largest fraction of soil arsenic. The availability of this arsenic to plants and the potential for plant toxicity is dependent upon many factors, some of the major ones being: soil pH, texture, and fertility level; and plant species (Wauchope 1983). The interactions possible from these factors complicate the interpretation of phytotoxic soil and plant arsenic levels. In general, soils with higher levels of easily soluble arsenic will increase the risk of reducing plant growth (Walsh et al. 1977). The results of a number of studies regarding toxic levels of arsenic in soils and plants are summarized in Tables 30, 31 and 32.

Table 30. Phytotoxicity of total arsenic in soils.

Soil Type	Soil Concentration (ppm)	Soil pH	Chemical Form Applied	Type of Experiment	Plant Species/ Part	Hazard Response	Significance Level	Reference
Hagerstown Silty Clay Loam	1000	5.5	Na_2HAsO_4	Greenhouse/Soil Pots	Oats/Shoots	100 % YR	0.05	Woolson et al. (1973)
Hagerstown Silty Clay Loam	1000	5.5	Na_2HAsO_4	Greenhouse/Soil Pots	Corn/Shoots	90 % YR	0.05	Woolson et al. (1973)
Lakeland Loamy Sand	1000	6.2	Na_2HAsO_4	Greenhouse/Soil Pots	Corn/Shoots	100 % YR	0.05	Woolson et al. (1973)
Lakeland Loamy Sand	1000	6.2	Na_2HAsO_4	Greenhouse/Soil Pots	Oats/Shoots	100 % YR	0.05	Woolson et al. (1973)
Burnt Fork Cobbly Loam	315	6.1	Smelter Contamination	Field	Corn/Shoots	28 % YR	NR	Woolson et al. (1971)
Hagerstown Silty Clay Loam	100	5.5	Na_2HAsO_4	Greenhouse/Soil Pots	Corn/Shoots	4 % YR (N.S.)	0.05	Woolson et al. (1973)
Lakeland Loamy Sand	100	6.2	Na_2HAsO_4	Greenhouse/Soil Pots	Corn/Shoots	45 % YR	0.05	Woolson et al. (1973)
Hagerstown Silty Clay Loam	100	5.5	Na_2HAsO_4	Greenhouse/Soil Pots	Oats/Shoots	81 % YR	0.05	Woolson et al. (1973)
Lakeland Loamy Sand	100	6.2	Na_2HAsO_4	Greenhouse/Soil Pots	Oats/Shoots	98 % YR	0.05	Woolson et al. (1973)
Plainfield Sand	100	5.5	$NaAsO_2$	Field	Peas/Seeds	94.9 % YR	0.01	Steevens et al. (1972)
Plainfield Sand	100	5.5	$NaAsO_2$	Field	Potatoes/Tubers	75.2 % YR	0.01	Steevens et al. (1972)
Houston Black Clay	90	7.6	As_2O_3	Field Pots	Bermuda Grass/Leaves	Sig. Growth Reduction (50 %)	NR	Weaver et al. (1984)
Weswood Black Clay	90	7.7	As_2O_3	Field Pots	Bermuda Grass/Leaves	Growth Prevented	NR	Weaver et al. (1984)
Arenosa Fine Sand	90	4.7	As_2O_3	Field Pots	Bermuda Grass/Leaves	Growth Prevented	NR	Weaver et al. (1984)
Avg. 13 Soils	85	NR	NR	NR	Corn	Level of Sig YR	NR	Walsh et al. (1977)
Plainfield Loamy Sand	68	NR	NR	NR	Potato	Level of Sig YR	NR	Walsh et al. (1977)
Plainfield Loamy Sand	68	NR	NR	NR	Sweet Corn	Level of Sig YR	NR	Walsh et al. (1977)
Plainfield Sand	45.0	5.5	$NaAsO_2$	Field	Peas/Seed	39.9 % YR	0.10	Steevens et al. (1972)
Plainfield Sand	45.0	5.5	$NaAsO_2$	Field	Potatoes/Tubers	17.1 % YR	0.10	Steevens et al. (1972)
Houston Black Clay	45	7.6	As_2O_3	Field Pots	Bermuda Grass/Leaves	Slight YR (10 %)	NR	Weaver et al. (1984)
Weswood Silt Loam	45	7.7	As_2O_3	Field Pots	Bermuda Grass/Leaves	80 % YR	NR	Weaver et al. (1984)
Arenosa Fine Sand	45	4.7	As_2O_3	Field Pots	Bermuda Grass/Leaves	No YR	NR	Weaver et al. (1984)
Colton Loamy Sand	44	NR	NR	NR	Blueberry	Level of Sig YR	NR	Walsh et al. (1977)
Plainfield Sand	27	5.5	$NaAsO_2$	Field	Peas/Seed	2.8 % Yield Increase (N.S.)	0.10	Steevens et al. (1972)
Plainfield Sand	27	5.5	$NaAsO_2$	Field	Potatoes/Tuber	0.6 % YR (N.S.)	0.10	Steevens et al. (1972)
Plainfield Loamy Sand	25	NR	NR	NR	Snap Beans and Peas	Level of Sig YR	NR	Walsh et al. (1977)
Plainfield Sand	14.1	5.5	$NaAsO_2$	Field	Peas/Seed	15.0 % Yield Increase (N.S.)	0.10	Steevens et al. (1972)
Plainfield Sand	14.1	5.5	$NaAsO_2$	Field	Potatoes/Tubers	1.7 % YR (N.S.)	0.10	Steevens et al. (1972)
Hagerstown Silty Clay Loam	10	5.5	Na_2HAsO_4	Greenhouse/Soil Pots	Corn/Shoots	Yield Increase (N.S.)	0.05	Woolson et al. (1973)
Lakeland Loamy Sand	10	6.2	Na_2HAsO_4	Greenhouse/Soil Pots	Corn/Shoots	3 % YR (N.S.)	0.35	Woolson et al. (1973)
Hagerstown Silty Clay Loam	10	5.5	Na_2HAsO_4	Greenhouse/Soil Pots	Oats/Shoots	22 % YR	0.05	Woolson et al. (1973)
Lakeland Loamy Sand	10	6.2	Na_2HAsO_4	Greenhouse/Soil Pots	Oats/Shoots	6 % YR	0.35	Woolson et al. (1973)

Table 30. Phytotoxicity of total arsenic in soils, continued.

Soil Type	Soil Concentration (ppm)	Soil pH	Chemical Form Applied	Type of Experiment	Plant Species/ Part	Hazard Response	Significance Level	Reference
Houston Black Clay	10	7.6	As_2O_3	Field Pots	Bermuda Grass/Leaves	No YR	NR	Weaver et al. (1984)
Weswood Silt Loam	10	7.7	As_2O_3	Field Pots	Bermuda Grass/Leaves	No YR	NR	Weaver et al. (1984)
Arenosa Fine Sand	10	4.7	As_2O_3	Field Pots	Bermuda Grass/Leaves	No YR	NR	Weaver et al. (1984)
Helena Valley	6	NR	None	Field	NA	Background	NA	Miesch and Huffman (1972)
NA	5.8	NR	NR	Field	NA	Background	NA	Shacklette and Boerngen (1984)
Helena Valley		8.0	NA	Field	NA	Background	NA	EPA (1986)
Weswood Silt Loam	5.6	7.7	None	Field	NA	Background	NA	Weaver et al. (1984)
Houston Black Clay	4.0	7.6	None	Field	NA	Background	NA	Weaver et al. (1984)
Plainfield Sand	3.6	5.5	None	Field	NA	Background	NA	Steevens et al. (1972)
Arenosa Fine Sand	1.2	4.7	None	Field	NA	Background	NA	Weaver et al. (1984)
NR	1.02 ± 0.5 Wet Weight	NR	None	Field	Vegetables	Background	NA	Anderson et al. (1978)

Table 31. Phytotoxicity of extractable arsenic in soils.

Soil Type	Soil Concentration (ppm)	Soil pH	Chemical Form Applied	Type of Experiment	Plant Species/ Part	Hazard Response	Extractant	Significance Level	Reference
Plainfield Sand	60	5.5	Na Arsenite	Field	Potatoes/Tubers	75.6 % YR	Bray P-1[A]	0.10	Jacobs et al. (1970)
Plainfield Sand	53	5.5	Na Arsenite	Field	Peas/Seed	94.9 % YR	Bray P-1	0.10	Jacobs et al. (1970)
Plainfield Sand	53	5.5	Na Arsenite	Field	Sweet Corn/Ears	100 % YR	Bray P-1	0.10	Jacobs et al. (1970)
Plainfield Sand	53	5.5	Na Arsenite	Field	Snap Beans/Pods-Seed	100 % YR	Bray P-1	0.10	Jacobs et al. (1970)
Clay Loam to Loamy Sand	40.3	4.4-6.2	Na_2HAsO_4	Greenhouse/Soil Pots	Cabbage/Heads	50 % YR (Calc)	0.05N H_2SO_4 and 0.025N HCl	r = 0.80	Woolson (1973)
Houston Black Clay	20	NR	NR	NR	Cotton	Sig YR	H_2O	NR	Walsh et al. (1977)
Clay Loam to Loamy Sand	25.4	4.4-6.2	Na_2HAsO_4	Greenhouse/Soil Pots	Tomato/Fruit	50 % YR (Calc)	0.05N H_2 and 0.025N HCl	r = 0.87	Woolson (1973)
Silt Loam to Fine Sandy Loam	25.0	NR	As_2O_3	Greenhouse/Soil Pots	Barley	"Plant Barley Survived"	0.1N NH_4Ac	NR	Vandecaveye et.al (1936)
Plainfield Sand	23	5.5	$NaAsO_2$	Field	Potatoes/Tubers	21.3 % YR (N.S.)	Bray P-1	0.10	Jacobs et al. (1970)
Plainfield Loamy Sand	22	NR	NR	NR	Sweet Corn	Sig YR	Bray P-1	NR	Walsh and Keeney (1975)
Plainfield Loamy Sand	22	NR	NR	NR	Potato	Sig YR	Bray P-1	NR	Walsh and Keeney (1975)
Plainfield Sand	20	5.5	$NaAsO_2$	Field	Peas/Seed	54.1 % YR	Bray P-1	0.10	Jacobs et al. (1970)
Plainfield Sand	20	5.5	$NaAsO_2$	Field	Sweet Corn/Ears	53.5 % YR	Bray P-1	0.10	Jacobs et al. (1970)
Plainfield Sand	20	5.5	$NaAsO_2$	Field	Snap Beans/Pods-Seed	70.4 % YR	Bray P-1	0.10	Jacobs et al. (1970)
Clay Loam to Loamy Sand	19	4.4-6.2	Na_2HAsO_4	Greenhouse/Soil Pots	Radish/Tubers	50 % YR (Calc)	0.05N H_2 and 0.025N HCl	r = 0.81	Woolson (1973)
Houston Black Clay	12	NR	NR	NR	Soybean	Sig YR	H_2O	NR	Walsh et al. (1977)
Clay Loam to Loamy Sand	10.9	4.4-6.2	Na_2HAsO_4	Greenhouse/Soil Pots	Lima Beans/Seed-Pods	50 % YR (Calc)	0.05N H_2 and 0.025N HCl	r = 0.83	Woolson (1973)
Clay Loam to Loamy Sand	10.6	4.4-6.2	Na_2HAsO_4	Greenhouse/Soil Pots	Spinach/Leaves	50 % YR (Calc)	0.05N H_2 and 0.025N HCl	r = 0.91	Woolson (1973)
Ave. 13 Soils	10	NR	NR	NR	Corn	Sig YR	0.05N H_2 and 0.025N HCl	NR	Walsh and Keeney (1975)
Plainfield Loamy Sand	10	5.5	$NaAsO_2$	Field	Snap Beans/Pods-Seed	54.4 % YR (N.S.)	Bray P-1	0.10	Jacobs et al. (1970)
Plainfield Loamy Sand	10	5.5	$NaAsO_2$	Field	Peas/Seed	9.2 % YR (N.S.)	Bray P-1	0.10	Jacobs et al. (1970)
NR	9	NR	NR	NR	Peas-Beans	"Necessary to Cause Injury"	NR	NR	Patson (1974)
Silt Loam to Fine Sandy Loam	8.2	NR	Arsenical Sprays	Field	Oats/Alfalfa	Very Poor Condition	[illegible] $(NH_4)_2CO_3$	NR	Vandecaveye et.al (1936)
[illegible]	3	NR	NR	NR	Cotton	[illegible]	[illegible]	NS	Walsh et al. (1977)
[illegible]	6.32	8.0	None	Field	Range/Forage	Background	12.3M HCl	NA	EPA (1986)

Table 31. Phytotoxicity of extractable arsenic in soils, continued.

Soil Type	Soil Concentration (ppm)	Soil pH	Chemical Form Applied	Type of Experiment	Plant Species/ Part	Hazard Response	Extractant	Significance Level	Reference
Clay Loam to Loamy Sand	6.2	4.4-6.2	Na_2HAsO_4	Greenhouse/Soil Pots	Green Beans	50 % YR (Calc)	0.05N H_2 and 0.025N HCl	r = 0.89	Woolson (1973)
Colton Loamy Sand	6	NR	NR	NR	Blueberry	Sig YR	H_2O	NR	Walsh et al. (1977)
Silt Loam To Fine Sandy Loam	5	NR	As_2O_3	Greenhouse/Soil Pots	Barley	Stunted Growth	0.1N NH_4Ac	NR	Vandecaveye et.al (1936)
Plainfield Loamy Sand	4.9	5.5	$NaAsO_2$	Field	Peas/Seed	9.5 % YR (N.S.)	Bray P-1	0.10	Jacobs et al. (1970)
Plainfield Loamy Sand	4.9	5.5	$NaAsO_2$	Field	Snap Beans/Pods-Seed	11.1 % YR (N.S.)	Bray P-1	0.10	Jacobs et al. (1970)
Plainfield Loamy Sand	4.9	5.5	$NaAsO_2$	Field	Sweet Corn/Ears	Yield Increase	Bray P-1	0.10	Jacobs et al. (1970)
Amarillo Fine Sandy Clay	3	NR	NR	NR	Soybean	Sig YR	H_2O	NR	Walsh et al. (1977)
Silt Loam to Fine Sandy Loam	3	NR	Arsenical Sprays	Field	Barley/Alfalfa	Severe Injury and Death	0.1N$(NH_4)_2CO_3$	NR	Vandecaveye et.al (1936)
NR	2	NR	NR	NR	Barley	"Necessary to Cause Injury"	NR	NR	Ratsch (1974)
Silt Loam - Fine Sandy Loam	1.9	NR	Arsenical Sprays	Field	Alfalfa	Good Condition	0.1N$(NH_4)_2CO_3$	NR	Vandecaveye et.al (1936)
Silt Loam - Fine Sandy Loam	1.5	NR	Arsenical Sprays	Field	Barley/Alfalfa	Fair Condition	0.1N$(NH_4)_2CO_3$	NR	Vandecaveye et.al (1936)
Silt Loam - Fine Sandy Loam	0.6	NR	Arsenical Sprays	Field	Barley/Alfalfa	Good Condition	0.1N$(NH_4)_2CO_3$	NR	Vandecaveye et.al (1936)
Silt Loam - Fine Sandy Loam	0.1-1.1	NR	Arsenical Sprays	Field	Alfalfa	Good Condition	0.1N$(NH_4)_2CO_3$	NR	Vandecaveye et.al (1936)
Silt Loam - Fine Sandy Loam	Trace	NR	Arsenical Sprays	Field	Barley/Alfalfa	Very Good Condition	0.1N$(NH_4)_2CO_3$	NR	Vandecaveye et.al (1936)

A/ Bray P-1 = 0.25N HCl + 0.3N NH,F

Table 32. Phytotoxicity of arsenic in vegetation.

Plant/Tissue	Tissue Concentration	Type of Experiment	Chemical Form Applied	Hazard Response	Significance Level	Reference
Cotton/Plant	81	Greenhouse/Solution Culture	As_2O_3	Phytotoxic		Marcus - Wyner and Rains (1982)
Radish/Tuber	76.0	Greenhouse/Soil Pots	Na_2HAsO_4 $7H_2O$	50 % YR (Calc)	r = 0.90	Woolson (1973
Radish/Whole Plant	43.8	Greenhouse/Soil Pots	Na_2HAsO_4 $7H_2O$	50 % YR (Calc)	r = 0.88	Woolson (1973)
Bermuda Grass/Leaves	20	Field/Soil Pots	As_2O_3	Reduced Growth	NR	Weaver et al. (1984)
Barley/Shoots	20	Greenhouse/Sand Culture	Na_2HAsO_4 $7H_2O$	10 % YR	0.05	Davis et al. (1978)
Barley/Shoots	11-26	Greenhouse/Sand Culture	Na_2HAsO_4 $7H_2O$	10 % YR	0.05	Davis et al. (1978)
Spinach/Whole Plant	10	Greenhouse/Soil Pots	Na_2HAsO_4 $7H_2O$	50 % YR (Calc)		Woolson (1973)
Bermuda Grass/Whole Plant	10	Field/Soil Pots	As_2O_3	No YR in Clay Soil	NR	Weaver et al. (1984)
Tomato/Whole Plant	4.5	Greenhouse/Soil Pots	Na_2HAsO_4 $7H_2O$	50 % YR (Calc)	r = 0.80	Woolson (1973)
Cotton	4.4		As_2O_3	Sig YR		Deuel and Swoboda (1972)
Green Bean/Whole Plant	3.7	Greenhouse/Soil Pots	Na_2HAsO_4 $7H_2O$	50 % YR (Calc)	r = 0.93	Woolson (1973)
Cabbage/Whole Plant	3.4	Greenhouse/Soil Pots	Na_2HAsO_4 $7H_2O$	50 % YR (Calc)	r = 0.77	Woolson (1973)
Lima Beans/Whole Plant	1.7	Greenhouse/Soil Pots	Na_2HAsO_4 $7H_2O$	50 % YR (Calc)	r = 0.49	Woolson (1973)
Soybean/Plant	1		As_2O_3	Sig YR	-	Deuel and Swoboda (1972)
Tomato/Fruit	0.7	Greenhouse/Soil Pots	Na_2HAsO_4 $7H_2O$	50 % YR (Calc)	r = 0.29	Woolson (1973)
Wheat	0.05	NR	None	Background	NA	Kabata - Pendias and Pendias (1984)

It has been noted by investigators that chemical analysis of the total soil arsenic is not a reliable indicator of potentially phytotoxic levels in vegetation (Albert and Arndt 1931, Vandecaveye et al. 1936, Woolson et al. 1971b). This has led to attempts to develop soil tests for plant-available soil arsenic that can be correlated with symptoms of plant toxicity. A greenhouse study by Benson and Reisenauer (1951) found no satisfactory correlation between soil extractable arsenic and plant growth by four different extracting solutions (NaCl, NaOAc + CH_3COOH, H_2SO_4, NH_4F+HCL) Vandecaveye et al. (1936) believed that the condition of field crops in the state of Washington was closely related to the amount of readily soluble arsenic. However, others have noted that such easily soluble arsenic is best used as an indicator only for those soils that have had recent arsenic applications (Carrow et al. 1975, Jacobs et al. 1970).

Johnston and Barnard (1979) evaluated 14 different arsenic extracting solutions on four New York soils. The arsenic extraction ability for the 14 solutions was (in increasing order): water = 1N NH_4Cl = 0.5M CH_3COONH_4 = 0.5M NH_4NO_3 < 0.5M $(NH_4)_2SO_4$ < 0.5N NH_4F = 0.5M $NaHCO_3$ < 0.5M $(NH_4)_2CO_3$ < 0.5N HCl + .025N H_2SO_4 < 0.5N HCl = 0.5M Na_2CO_3 = 0.5M KH_2PO_4 < 0.5N H_2SO_4 = 0.1N NaOH. They made no specific recommendations for the use of any particular solution, but noted that basic solutions were more effective in arsenic extraction than were neutral solutions, and that phosphorus and arsenic reacted similarly to solutions containing bicarbonate or hydrogen ions.

The soil chemistry of arsenic is similar to that of phosphorus; its principle chemical form is that of arsenate (AsO_4^{-3}) which has been occluded or adsorbed on hydrous aluminum and iron oxides (Ganje and Rains 1982). Like phosphorus, it is also often present as precipitates of slightly soluble compounds of Al, Fe, Ca and Mg. Lesser amounts of arsenic are associated with soil clays and organic matter. This similarity between arsenic and phosphorus has led to the use of phosphorus extracting solutions for the determination of plant-available arsenic. Perhaps the two most commonly used extractants for phosphorus that have been subsequently applied to arsenic extraction are: $NaHCO_3$ (developed for use primarily on alkaline soils); and a mixture of 0.05N HCl and 0.025N H_2SO_4 (used for neutral and acidic soils).

In a study by Woolson et al. (1971a) these two methods ($NaHCO_3$, $HCl+H_2SO_4$) and four others were evaluated for determining arsenic availability to corn on 28 different soils from different areas of the United States. Most of the soils were from the east and only five had an alkaline pH, the highest being 7.50. The $NaHCO_3$ and mixed dilute acid solutions were both recommended for use, because of their relative simplicity and for their good correlations of available arsenic with reduced plant growth.

A later study by these same researchers (Woolson et al. 1973) revealed the complexity of determining plant-available arsenic in the soil. They found that plants growing on different soils that contained the same extractable arsenic levels experienced varying degrees of arsenic toxicity. This was attributed to the variability in the chemical and physical properties of the soils (texture, organic matter and pH). Jacobs and Keeney (1970) also noted the influence of soil texture on arsenic phytotoxicity, with arsenic being more toxic on sandy soils than on finer-textured soils. Such findings suggest that the general application of extractable soil arsenic levels to estimating phytotoxicity in field situations is limited. Ganje and Rains (1982), in their review of methods of analysis for soil-arsenic, state that when selecting an extracting solution to determine plant-available arsenic, no single extractant can be used as a universal indicator of arsenic availability and that each soil type or soil area must be treated independently.

The literature indicates that the selection of a soil-arsenic extracting solution is a complicated decision. Present methods have been shown to have limited applicability to field situations where an interpretation of phytotoxic levels is desired. For the Helena Valley study area a decision was made to employ a method for determination of soil extractable arsenic that has been developed and applied successfully to problems of arsenic-contaminated soils of this region.

Heilman and Ekuan (1977) investigated soil extractable arsenic levels around the ASARCO smelter near Tacoma, Washington. They extracted soil arsenic with concentrated HCl in a 1:5 soil to acid ratio; the same method was used for the Helena Valley investigation. These investigators determined a significant correlation (r = .625) between extractable soil arsenic and the arsenic levels present in above ground garden biomass. The correlation was also significant (r = .475) between extractable soil arsenic and below ground garden biomass (roots). These results suggest determination of extractable soil arsenic with concentrated HCl is indicative of the soil arsenic level that the plant can absorb. Therefore this method has merit for the determination of plant available arsenic in soils.

As a check between soil test levels obtained from this method and the $NaHCO_3$ method (which may be considered a more standard method), duplicate samples from two soils (one with high and one with low arsenic levels) were extracted with both solutions, and analyzed for arsenic (Table 33). All work was performed by the Soil, Plant, and Irrigation Water Testing Laboratory at Montana State University, Bozeman, MT.

Table 33. Comparison between concentrated HCl and $NaHCO_3$ for determination of extractable soil arsenic (ppm).

Sample	Concentrated HCl	$NaHCO_3$
2518	40.46	36.34
2518-2	37.31	No Data
STD-C	3.01	2.67
STD-C-2	1.98	1.50

The samples designated STD-C are in-house laboratory standards used for quality control. The close agreement in soil-arsenic levels provided by the two extracting solutions suggests that the concentrated HCl method provides results similar to the $NaHCO_3$ method for these soils.

The analytical method and accompanying interpretive guide was developed by N.R. Benson (Benson and Reisenauer 1951, Benson 1968) primarily through many years of field experience in diagnosing arsenic toxicity problems in orchard vegetation in central and eastern Washington (A.R. Halvorson, personal communication 1985). Soil arsenic is extracted with concentrated HCl (12.3M) in a 1:5 soil to acid ratio for a period of one hour, and standard instrumentation methods are used to determine actual concentrations. Interpretation of the results of the analysis in terms of potential phytotoxicity can be made by refering to Table 34.

Benson and Reisenauer (1951) rated the relative tolerance of crops to arsenic (Table 35). Crops such as those found in the Helena Valley (e.g. barley, wheat, alfalfa) were considered not tolerant to soil arsenic. The tolerance of wheat to soil arsenic was compared to peach and apricot fruit trees. The interpretation is that grain and forage crops will do poorly when the concentrated HCl extractable soil arsenic exceeds 50 ppm (Tables 34 and 35).

This result compliments other investigations of the effect of soil extractable arsenic on crops (Table 32). These investigators found significant yield reduction of vegetable crop when extractable arsenic was in the range of 6 to 48 ppm.

3.1.2 Arsenic in soils

3.1.2.1 Total arsenic in soils

The phytotoxic and tolerable levels of total arsenic in soils of the Helena Valley are 100 and 25 ppm, respectively (Table 30). The 100 ppm concentration has been selected primarily based on data of Woolson et al. (1973) and Steevens et al. (1972) who noted large yield reductions in oats, corn, peas and potatoes at 100 ppm total soil arsenic. All total soil arsenic values equal or greater than 100 ppm in the reviewed literature were associated with phytotoxicity. Soil characteristics, especially texture and organic matter content, strongly influence the relative toxicity of arsenic. Weaver et al. (1984) reported phytotoxicity of

Table 34. Interpretive guide for concentrated HCl soil extractable arsenic

Soil Depth feet	As Level ppm	Interpretation
0-3	Below 25 ppm	As is probably not a problem.
0-1 1-3	25-50 ppm Below 25 ppm	May reduce growth of sensitive trees, such as apricot and peach. Should not seriously affect growth of apple, pear, and cherry.
0-3	25-50 ppm	Symptoms of As toxicity may appear on apricot and peach during hot summer. Newly planted apple, pear, and cherry may be reduced in growth, but should still grow well.
0-1 1-3	50-100 ppm Below 25 ppm	Survival of apricot and peach doubtful unless planted with As-free soil. Symptoms of As toxicity should be severe on established apricot and peach. May limit growth of newly planted apple, pear, and cherry.
0-3	50-100 ppm	Significant reduction in growth of any newly planted trees should be anticipated. Avoid planting stone fruits.
0-1 1-3	Above 100 ppm Above 50 ppm	Hazardous to plant any new trees under these conditions.

A (Washington State Cooperative Extension Service, 1975).

Table 35. Relative tolerance of crops to arsenic[A]

Tolerant	Moderately Tolerant	Not Tolerant
	Tree Fruit and Berry Crops	
Apples	Cherries	Peaches
Pears	Strawberries	Apricots
Grapes		
Raspberries		
Dewberries		
	Field and Truck Crops	
Rye	Beets	Barley
Mint	Corn	Oats
Asparagus	Squash	Wheat
Cabbage	Turnips	Beans
Carrots		Cucumbers
Parsnips		Onions
Potatoes		Peas
Swiss chard		
Tomatoes		
	Forage Crops	
Bluegrass	Crested wheat grass	Alfalfa
Italian rye grass	Timothy	Alsike clover
Kentucky bluegrass		Ladino clover
Meadow fescue		Strawberry clover
Orchard grass		Sweet clover
Red Top		White clover
		Vetch
		Smooth brome
		Sudan grass

[A]Benson and Reisenauer, 1951.

bermuda grass at concentrations which ranged from 45 to 90 ppm in sand and clay soils respectively. Phytotoxic criteria reported in the literature for total arsenic in soils ranged from 15 to 50 ppm (Kitagishi and Yamane 1981, Kloke 1979, Linzon 1978 and El-Bassam and Tietjen 1977). Numerous cases of phytotoxicity were reported in the 45 to 100 ppm range (Table 30). For many situations, a phytotoxic level of 50 ppm would appear appropriate. A tolerable level of 25 ppm total soil arsenic is based on the low or no yield reductions that have been reported at or below this level (Table 30). The only important exception is the 22 percent yield reduction for oats at a 10 ppm total soil arsenic concentration that was noted by Woolson et al. (1973).

3.1.2.2 Extractable soil arsenic

It is highly probable that extractable arsenic soil concentrations greater than the 50 ppm hazard level suggested for the Helena Valley will be phytotoxic (Table 31). Jacobs et al. (1970) reported 100 percent yield reductions (no growth) for snap beans and peas at the 100 ppm extractable (Bray P-1) arsenic level. Considerable phytotoxicity was noted at levels less than 50 ppm extractable (various methods) soil arsenic (Table 31) and a phytotoxic concentration as low as 10 ppm may be an appropriate hazard level in some circumstances. It is apparent from the reviewed data that soil factors have much less influence on phytotoxic extractable arsenic levels as compared to phytotoxic total arsenic levels in soils (Tables 30, 31).

The tolerable extractable soil arsenic concentration of 2 ppm is based on the limited work of Vandecaveye et al. (1936), who noted no toxicity in barley and alfalfa at or below that level, and the observations of Walsh et al. (1977), who reported phytotoxicity to soybeans at an extractable arsenic level of 3 ppm (Table 31).

3.1.3 Arsenic in plants

Phytotoxic arsenic levels in plant tissues have been reported from 5 to 20 ppm (Table 32). The suggested 20 ppm hazard concentration is based on two publications, Davis et al. (1978) and Weaver et al. (1984). Davis et al. (1978) reported arsenic concentrations in the shoots of barley were toxic in a range of 11 to 26 ppm and determined a level of 20 ppm was the "upper critical level" at which a 10 percent yield reduction could be expected. Bermuda grass leaves containing 20 ppm arsenic were associated with plants exhibiting reduced growth (Weaver et al. 1984). These authors found bermuda grass leaves, stems and roots often exceeded 15, 25, and 200 ppm respectively in plants grown in soils containing 45 ppm arsenic. All plant tissue arsenic concentrations >20 ppm found in the reviewed literature were associated with phytotoxicity. Kabata-Pendias and Pendias (1984) reported a phytotoxic range of 5 to 20 ppm for arsenic in unspecified plant tissue.

Numerous references reported "intermediate range" arsenic levels (those values between traces and toxicity). Typical values for plant tops of alfalfa, red clover, and oats were reported as 0.05, 0.37, and 0.62 ppm respectively (Liebig, 1966). This source reported high range (elevated but not showing toxicity symptoms) values for alfalfa, red clover and barley as 3.15 to 14 ppm, 6.26 ppm and 12.3 ppm, respectively. Data from the reviewed literature indicated that no cereal and forage crops or edible vegetable portions contained a concentration of arsenic greater than the 3 ppm tolerable level suggested for the Helena Valley. Woolson (1973) calculated, through the use of regression equations, the phytotoxic tissue levels producing a yield reduction of 50 percent in 6 vegetables. This study indicated only lima beans, an arsenic sensitive crop, had a tolerance level less than 3 ppm for the calculated yield reductions.

3.2 Cadmium in soils and plants

3.2.1 Cadmium literature review

Cadmium levels in plants and soils rarely exceed 1 ppm (Kabata-Pendias and Pendias 1984). Areas with naturally occurring high levels of cadmium in soils have been documented to have up to 22 ppm total cadmium, with soil parent material up to 33 ppm total cadmium (Lund et al. 1981). In areas where soils have been contaminated, soil concentrations may approach 1000 ppm, and plants may accumulate cadmium to levels in excess to 200 ppm, (dry weight), depending on the species (Kabata-Pendias and Pendias 1984). In contaminated soils the highest cadmium concentrations are found in surface layers and decrease rapidly with depth, due to the low mobility of this element. Total soil cadmium levels are not good indices of the availability of the element to the plant, as much of the total cadmium in soil may be bound in compounds of low solubility (Pickering 1980).

Cadmium, like many metals, is more mobile and thus more available to plants in soils of low pH (4.5 to 5.5). Alkaline soils exhibit low cadmium mobility, and decrease the risk of plant toxicity even in heavily contaminated soils (Kabata-Pendias and Pensias 1984). It has been shown, however, that whereas the availability of cadmium for plant uptake is decreased by liming, cadmium added to the soil does result in increased uptake by plants (Baker et al. 1979).

Chang et al. (1982) found that the uptake of cadmium and zinc in barley cultivars was more influenced by the soil type (and pH) than by the specific barley cultivar. Similar findings by White and Chaney (1980) indicated that soil types strongly influence zinc, cadmium and manganese uptake in soybeans and that organic matter was more effective than hydrous oxides of iron and manganese in moderating the uptake of excessive soil heavy metals. A study by Haghiri (1974) suggested that the soil cation exchange capacity (CEC) largely determined the uptake of cadmium in oat shoots and that organic matter had little effect on the uptake of this element other than increasing the CEC. The study found that the concentration of cadmium in soybean shoots increased with increasing soil temperature. Chaney et al. (1976) revealed that increased levels of soil zinc increased cadmium uptake by soybeans. Boggess et al. (1978) reported that significant differences existed in the susceptibility of soybeans to cadmium among several varieties tested. These authors found that the observed susceptibility was due more to plant uptake characteristics than to the tolerance of plants to cadmium. Considerable variation in cadmium accumulation has been demonstrated for many vegetable and grain crops grown on the same soil (Davis 1984).

In recent years interest in cadmium in soils and plants has intensified because of its presence in sewage sludge. This aspect has been the subject of much research and several reviews (Hansen and Chaney 1984, Logan and Chaney 1983, Sommers 1980, Singh 1981, Standish 1981, Webber et al. 1983, Williams 1982, Rundle et al. 1984, Page 1974, Page et al. 1983, and Lutrick et al. 1982). Land application of sludge may potentially cause phytotoxicity problems, but of greater concern is the high potential for introduction of cadmium into the food chain, where it may create health hazards (Nriagu 1980). A summary of many scientific studies of plant uptake of soil cadmium is presented in Tables 36, 37 and 38.

3.2.2 Cadmium in soils

3.2.2.1 Total cadmium in soil

A total soil cadmium hazard level of 100 ppm was selected for the Helena Valley based on two major factors: 1) all total soil cadmium concentrations greater than 100 ppm found in the reviewed literature were associated with yield reductions regardless of plant type, and 2) the lack of and variability of data, especially with respect to higher pH levels (6-7), in the total soil cadmium range of 40 to 100 ppm (Table 36). Other phytotoxic total soil cadmium criteria reported in the literature ranged from 3 to 8 ppm (Melsted 1973, Linzon 1978). However, nonsignificant or no yield reductions were reported for several plant species at 40 ppm total soil cadmium (John 1973). Data of Khan and Frankland (1984) suggested highly significant yield reductions occur in the biomass of wheat, oat and radish roots at 50 ppm total soil cadmium.

Available data may support a lower (50 ppm) total soil cadmium phytotoxic hazard level than the 100 ppm level selected for the Helena Valley (Table 36). It is imperative that persons applying this hazard level be cognizant of the high concentrations

Table 36. Phytotoxicity of total cadmium in soils.

Soil Type	Soil Concentration (ppm)	Soil pH	Chemical Form Applied	Type of Experiment	Plant Species/ Part	Hazard Response	Significance Level	Reference
Domino Silt Loam	>640	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Rice/Grain	25 % YR	NR	Bingham et al. (1975)
Merrimac Fine Sandy Loam	250	6.9	$Cd(NO_3)_2\ 4H_2O$	Greenhouse/Soil Pots	Alfalfa/Tops	46.5 % YR (N.S.)	0.01	Taylor and Allinson (1981)
Merrimac Fine Sandy Loam	250	6.9	$Cd(NO_3)_2\ 4H_2O$	Greenhouse/Soil Pots	Alfalfa/Tops - 2nd cutting	71.9 % YR	0.01	Taylor and Allinson (1981)
Paxton Fine Sandy Loam	250	6.9	$CdSO_4$	Greenhouse/Soil Pots	Alfalfa/Tops	21 % YR	NR	Taylor and Allinson (1981)
Merrimac Fine Sandy Loam	250	6.9	$CdSO_4$	Greenhouse/Soil Pots	Alfalfa/Tops	62.1 % YR	NR	Taylor and Allinson (1981)
Paxton Fine Sandy Loam	250	6.9	$CdSO_4$	Greenhouse/Soil Pots	Alfalfa/Tops - 2nd cutting	29.0 % YR	NR	Taylor and Allinson (1981)
Merrimac Fine Sandy Loam	250	6.9	$CdSO_4$	Greenhouse/Soil Pots	Alfalfa/Tops - 2nd cutting	67.4 % YR	NR	Taylor and Allinson (1981)
Hazelwood Silt Loam	200	5.1	$CdCl_2$	Greenhouse/Soil Pots	Oats/Grain	56.8 % YR	0.05	John (1973)
Hazelwood Silt Loam	200	5.1	$CdCl_2$	Greenhouse/Soil Pots	Oats/Leaves	10.2 % YR (N.S.)	0.05	John (1973)
Hazelwood Silt Loam	200	5.1	$CdCl_2$	Greenhouse/Soil Pots	Oats/Stalks	22.1 % YR (N.S.)	0.05	John (1973)
Hazelwood Silt Loam	200	5.1	$CdCl_2$	Greenhouse/Soil Pots	Carrots/Tubers	96.4 % YR	0.05	John (1973)
Hazelwood Silt Loam	200	5.1	$CdCl_2$	Greenhouse/Soil Pots	Radish/Tubers	93.2 % YR	0.05	John (1973)
Hazelwood Silt Loam	200	5.1	$CdCl_2$	Greenhouse/Soil Pots	Peas/Pods	92.1 % YR	0.05	John (1973)
Hazelwood Silt Loam	200	5.1	$CdCl_2$	Greenhouse/Soil Pots	Peas/Seed	99.2 % YR	0.05	John (1973)
Hazelwood Silt Loam	200	5.1	$CdCl_2$	Greenhouse/Soil Pots	Cauliflower/Leaves	96.9 % YR	0.05	John (1973)
Hazelwood Silt Loam	200	5.1	$CdCl_2$	Greenhouse/Soil Pots	Broccoli/Leaves	63.3 % YR	0.05	John (1973)
Hazelwood Silt Loam	200	5.1	$CdCl_2$	Greenhouse/Soil Pots	Spinach/Leaves	98.5 % YR	0.05	John (1973)
Hazelwood Silt Loam	200	5.1	$CdCl_2$	Greenhouse/Soil Pots	Leaf Lettuce/Leaves	91.1 % YR	0.05	John (1973)
Domino Silt Loam	170	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Cabbage/Head	25 % YR	NR	Bingham et al. (1975)
Domino Silt Loam	160	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Bermuda Grass/Tops	25 % YR	NR	Bingham et al. (1976)
Domino Silt Loam	160	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Tomato/Ripe Fruit	25 % YR	NR	Bingham et al. (1975)
Domino Silt Loam	160	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Zucchini/Fruit	25 % YR	NR	Bingham et al. (1975)
Domino Silt Loam	160	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Sudan Grass/Tops	90 % YR	NR	Bingham et al. (1976)
Domino Silt Loam	160	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	White Clover/Tops	59 % YR	NR	Bingham et al. (1976)
Domino Silt Loam	160	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Alfalfa/Tops	56 % YR	NR	Bingham et al. (1976)
Domino Silt Loam	160	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Tall Fescue/Tops	30 % YR	NR	Bingham et al. (1976)
Redding Fine Sandy Loam	125	5.7	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Lettuce/Shoots	25 % YR	0.05	Mitchell et al. (1978)
Merrimac Fine Sandy Loam	125	6.9	$Cd(NO_3)_2\ 4H_2O$	Greenhouse/Soil Pots	Alfalfa/Tops	15.8 % YR (N.S.)	0.01	Taylor and Allinson (1981)
Merrimac Fine Sandy Loam	125	6.9	$Cd(NO_3)_2\ 4H_2O$	Greenhouse/Soil Pots	Alfalfa/Tops - 2nd cutting	56.2 % YR	0.01	Taylor and Allinson (1981)
Paxton Fine Sandy Loam	125	6.9	$CdSO_4$	Greenhouse/Soil Pots	Alfalfa/Tops	0.7 % Yield Increase	NR	Taylor and Allinson (1981)
Merrimac Fine Sandy Loam	125	6.9	$CdSO_4$	Greenhouse/Soil Pots	Alfalfa/Tops	23.6 % YR	NR	Taylor and Allinson (1981)
Paxton Fine Sandy Loam	125	6.9	$CdSO_4$	Greenhouse/Soil Pots	Alfalfa/Tops - 2nd cutting	13.0 % YR	NR	Taylor and Allinson (1981)
Merrimac Fine Sandy Loam	125	6.9	$CdSO_4$	Greenhouse/Soil Pots	Alfalfa/Tops - 2nd cutting	31.2 % YR	NR	Taylor and Allinson (1981)
Plainfield Sand	[illegible]	[illegible]	$CdCl_2$	Greenhouse/Soil Pots	7 Species [illegible] Plants	Almost Total Mortality	NR	Miles and Parker (1979)
[illegible] Silt, Clay Loam	100	6.7	$CdCl_2$	Greenhouse/Soil Pots	Wheat/Tops	73.0 % YR	NR	Haghiri (1973)
[illegible] Silt, Clay Loam	100	6.7	$CdCl_2$	Greenhouse/Soil Pots	Soybeans/Tops	85.6 % YR	NR	Haghiri (1973)
Weald Park Brown Earth	[illegible]	NR	[illegible]	Greenhouse/Soil Pots	Wheat/Roots	[illegible]	0.01	Khan and Frankland (1984)
[illegible]	[illegible]	NR	[illegible]	Greenhouse/Soil Pots	Wheat/Roots	13.8? % YR	0.05	Khan and Frankland (1984)
Weald Park Brown Earth	100	NR	$CdSO_4$	Greenhouse/Soil Pots	Wheat/Roots	67.7 % YR	0.01	Khan and Frankland (1984)
Weald Park Brown Earth	100	NR	$CdCl_2$	Greenhouse/Soil Pots	Radish/Roots	42.6 % YR	0.01	Khan and Frankland (1984)
Weald Park Brown Earth	100	NR	$CdCl_2$	Greenhouse/Soil Pots	Wheat/Roots	67.7 % YR	0.01	Khan and Frankland (1984)
Dytchleys Brown Earth	100	NR	$CdCl_2$	Greenhouse/Soil Pots	Oats/Roots	76.7 % YR	0.01	Khan and Frankland (1984)
Domino Silt Loam	96	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Radish/Tuber	25 % YR	NR	Bingham et al. (1975)
Domino Silt Loam	80	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Sudan Grass/Tops	59 % YR	NR	Bingham et al. (1976)
Domino Silt Loam	80	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	White Clover/Tops	43 % YR	NR	Bingham et al. (1976)
Domino Silt Loam	80	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Alfalfa/Tops	40 % YR	NR	Bingham et al. (1976)
Domino Silt Loam	80	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Tall Fescue/Tops	24 % YR	NR	Bingham et al. (1976)
Domino Silt Loam	80	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Bermuda Grass/Tops	12 % YR	NR	Bingham et al. (1976)

Table 36. Phytotoxicity of total cadmium in soils, continued.

Soil Type	Soil Concentration (ppm)	Soil pH	Chemical Form Applied	Type of Experiment	Plant Species/Part	Hazard Response	Significance Level	Reference
Redding Fine Sandy Loam	60	5.7	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Wheat/Leaves	25 % YR	0.05	Mitchell et al. (1978)
Paxton Fine Sandy Loam	50	6.9	$CdSO_4$	Greenhouse/Soil Pots	Alfalfa/Tops	9.8 % Yield Increase	NR	Taylor and Allinson (1981)
Merrimac Fine Sandy Loam	50	6.9	$CdSO_4$	Greenhouse/Soil Pots	Alfala/Tops	3.6 % YR	NR	Taylor and Allinson (1981)
Paxton Fine Sandy Loam	50	6.9	$CdSO_4$	Greenhouse/Soil Pots	Alfalfa/Tops - 2nd cutting	3.5 % Yield Increase	NR	Taylor and Allinson (1981)
Merrimac Fine Sandy Loam	50	6.9	$CdSO_4$	Greenhouse/Soil Pots	Alfalfa/Tops - 2nd cutting	4.3 % Yield Increase	NR	Taylor and Allinson (1981)
Weald Park Brown Earth	50	NR	$CdCl_2$	Greenhouse/Soil Pots	Radish/Roots	31.9 % YR	0.01	Khan and Frankland (1984)
Weald Park Brown Earth	50	NR	$CdCl_2$	Greenhouse/Soil Pots	Wheat/Roots	61.3 % YR	0.01	Khan and Frankland (1984)
Dytchleys Brown Earth	50	NR	$CdCl_2$	Greenhouse/Soil Pots	Oats/Roots	64.5 % YR	0.01	Khan and Frankland (1984)
Domino Silt Loam	50	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Wheat/Grain	25 % YR	NR	Bingham et al. (1975)
Merrimac Fine Sandy Loam	50	6.9	$Cd(NO_3)_2 \cdot 4H_2O$	Greenhouse/Soil Pots	Alfalfa/Tops	1 % Yield Increase (N.S.)	0.01	Taylor and Allinson (1981)
Merrimac Fine Sandy Loam	50	6.9	$Cd(NO_3)_2 \cdot 4H_2O$	Greenhouse/Soil Pots	Alfalfa/Tops - 2nd cutting	27.3 % YR	0.01	Taylor and Allinson (1981)
Flanagan Silt Loam	50	7.3	$CdCl_2$	Greenhouse/Soil Pots	Soybeans/Shoots	9.3 % YR	0.01	Boggess et al. (1978)
Marengo Silty Clay Loam	50	6.7	$CdCl_2$	Greenhouse/Soil Pots	Wheat/Tops	49.8 % YR	NR	Maghiri (1973)
Marengo Silty Clay Loam	50	6.7	$CdCl_2$	Greenhouse/Soil Pots	Soybeans/Tops	85.3 % YR	NR	Maghiri (1973)
Hazelwood Silt Loam	40	5.1	$CdCl_2$	Greenhouse/Soil Pots	Oats/Grain	36.3 % YR	0.05	John (1973)
Hazelwood Silt Loam	40	5.1	$CdCl_2$	Greenhouse/Soil Pots	Oats/Leaves	No YR	0.05	John (1973)
Hazelwood Silt Loam	40	5.1	$CdCl_2$	Greenhouse/Soil Pots	Oats/Stalks	No YR	0.05	John (1973)
Hazelwood Silt Loam	40	5.1	$CdCl_2$	Greenhouse/Soil Pots	Carrots/Tubers	8.3 % YR (N.S.)	0.05	John (1973)
Hazelwood Silt Loam	40	5.1	$CdCl_2$	Greenhouse/Soil Pots	Radish/Tubers	27.9 % YR (N.S.)	0.05	John (1973)
Hazelwood Silt Loam	40	5.1	$CdCl_2$	Greenhouse/Soil Pots	Peas/Pods	29.7 % YR (N.S.)	0.05	John (1973)
Hazelwood Silt Loam	40	5.1	$CdCl_2$	Greenhouse/Soil Pots	Peas/Seed	38.1 % YR	0.05	John (1973)
Hazelwood Silt Loam	40	5.1	$CdCl_2$	Greenhouse/Soil Pots	Cauliflower/Leaves	2.7 % YR (N.S.)	0.05	John (1973)
Hazelwood Silt Loam	40	5.1	$CdCl_2$	Greenhouse/Soil Pots	Broccoli/Leaves	No YR	0.05	John (1973)
Hazelwood Silt Loam	40	5.1	$CdCl_2$	Greenhouse/Soil Pots	Spinach/Leaves	96 % YR	0.05	John (1973)
Hazelwood Silt Loam	40	5.1	$CdCl_2$	Greenhouse/Soil Pots	Leaf Lettuce/Leaves	No YR	0.05	John (1973)
Domino Silt Loam	40	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Field Bean/Dry Bean	25 % YR	NR	Bingham et al. (1975)
Domino Silt Loam	40	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Sudan Grass/Tops	43 % YR	NR	Bingham et al. (1976)
Domino Silt Loam	40	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Alfalfa/Tops	29 % YR	NR	Bingham et al. (1976)
Domino Silt Loam	40	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	White Clover/Tops	21 % YR	NR	Bingham et al. (1976)
Domino Silt Loam	40	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Tall Fescue/Tops	19 % YR	NR	Bingham et al. (1976)
Domino Silt Loam	40	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Bermuda Grass/Tops	12 % YR	NR	Bingham et al. (1976)
Marengo Silty Clay Loam	40	6.7	$CdCl_2$	Greenhouse/Soil Pots	Wheat/Tops	49.8 % YR	NR	Maghiri (1973)
Marengo Silty Clay Loam	40	6.7	$CdCl_2$	Greenhouse/Soil Pots	Soybeans/Tops	84.8 % YR	NR	Maghiri (1973)
Plainfield Sand	30.3	4.8	$CdCl_2$	Greenhouse/Soil Pots	Kentucky Bluegrass/Shoots	90.1 % YR	NR	Miles and Parker (1979)
Plainfield Sand	30.3	4.8	$CdCl_2$	Greenhouse/Soil Pots	Little Bluestem/Shoots	10.1 % YR	NR	Miles and Parker (1979)
Plainfield Sand	30.3	4.8	$CdCl_2$	Greenhouse/Soil Pots	Rough Blazing Star/Shoots	80.5 % YR	NR	Miles and Parker (1979)
Plainfield Sand	30.3	4.8	$CdCl_2$	Greenhouse/Soil Pots	Poison Ivy/Shoots	63.3 % YR	NR	Miles and Parker (1979)
Plainfield Sand	30.3	4.8	$CdCl_2$	Greenhouse/Soil Pots	Black-eyed Susan/Shoots	98.5 % YR	NR	Miles and Parker (1979)
Plainfield Sand	30.3	4.8	$CdCl_2$	Greenhouse/Soil Pots	Wild Bergamot/Shoots	67.9 % YR	NR	Miles and Parker (1979)
Plainfield Sand	30.3	4.8	$CdCl_2$	Greenhouse/Soil Pots	Long-Fruited Thimble Weed/Shoots	30.4 % YR	NR	Miles and Parker (1979)
Marengo Silty Clay Loam	30	6.7	$CdCl_2$	Greenhouse/Soil Pots	Wheat/Tops		NR	Maghiri (1973)
Marengo Silty Clay Loam	30	6.7	$CdCl_2$	Greenhouse/Soil Pots	Soybeans/Tops		NR	Maghiri (1973)
Domino Silt Loam	20	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Turnip/Tuber	25 % YR	NR	Bingham et al. (1975)
Flanagan Silt Loam	25	7.3	$CdCl_2$	Greenhouse/Soil Pots	Soybeans/Shoots	9.8 % YR	0.01	Boggess et al. (1978)
Domino Silt Loam	20	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Carrots/Tuber	25 % YR	NR	Bingham et al. (1975)
Dytchleys Brown Earth	20	NR	$CdCl_2$	Greenhouse/Soil Pots	Oats/Roots	54.7 % YR	0.01	Khan and Frankland (1984)
Marengo Silty Clay Loam	20	6.7	$CdCl_2$	Greenhouse/Soil Pots	Wheat/Tops		NR	Maghiri (1973)
Marengo Silty Clay Loam	20	6.7	$CdCl_2$	Greenhouse/Soil Pots	Soybean/Tops		NR	Maghiri (1973)
Domino Silt Loam	18	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Corn/Kernel	25 % YR	NR	Bingham et al. (1975)
Marengo Silty Clay Loam	15	6.7	$CdCl_2$	Greenhouse/Soil Pots	Wheat/Tops	34.8 % YR	NR	Maghiri (1973)
Marengo Silty Clay Loam	15	6.7	$CdCl_2$	Greenhouse/Soil Pots	Soybean/Tops	65.2 % YR	NR	Maghiri (1973)
Domino Silt Loam	13	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Lettuce/Head	25 % YR	NR	Bingham et al. (1975)
Loams	10.8	5-8.1		Field	Potato/Tuber	"Satisfactory Yields"	NR	Chumbley and Unwin (1982)

Table 36. Phytotoxicity of total cadmium in soils, continued.

Soil Type	Soil Concentration (ppm)	Soil pH	Chemical Form Applied	Type of Experiment	Plant Species/Part	Hazard Response	Significance Level	Reference
Plainfield Sand	10.3	4.8	$CdCl_2$	Greenhouse/Soil Pots	Kentucy Bluegrass/Shoots	18.7 % YR	NR	Miles and Parker (1979)
Plainfield Sand	10.3	4.8	$CdCl_2$	Greenhouse/Soil Pots	Little Bluestem/Shoots	21.1 % YR	NR	Miles and Parker (1979)
Plainfield Sand	10.3	4.8	$CdCl_2$	Greenhouse/Soil Pots	Rough Blazing Star/Shoots	29.6 % YR	NR	Miles and Parker (1979)
Plainfield Sand	10.3	4.8	$CdCl_2$	Greenhouse/Soil Pots	Poison Ivy/Shoots	28.9 % Yield Increase	NR	Miles and Parker (1979)
Plainfield Sand	10.3	4.8	$CdCl_2$	Greenhouse/Soil Pots	Black-Eyed Susan/Shoots	78.5 % YR	NR	Miles and Parker (1979)
Plainfield Sand	10.3	4.8	$CdCl_2$	Greenhouse/Soil Pots	Wild Bergamot/Shoots	23.3 % YR	NR	Miles and Parker (1979)
Plainfield Sand	10.3	4.8	$CdCl_2$	Greenhouse/Soil Pots	Long-Fruited Thimble Weed/Shoots	8.7 % YR	NR	Miles and Parker (1979)
Dytchleys Brown Earth	10	NR	$CdCl_2$	Greenhouse/Soil Pots	Oats/Roots	24.5 % YR	0.01	Khan and Frankland (1984)
Domino Silt Loam	10	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	White Clover/Tops	23 % YR	NR	Bingham et al. (1976)
Domino Silt Loam	10	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Sudan Grass/Tops	20 % YR	NR	Bingham et al. (1976)
Domino Silt Loam	10	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Alfalfa/Tops	17 % YR	NR	Bingham et al. (1976)
Domino Silt Loam	10	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Bermuda Grass/Tops	6 % YR	NR	Bingham et al. (1976)
Domino Silt Loam	10	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Tall Fescue/Tops	2 % YR	NR	Bingham et al. (1976)
Flanagan Silt Loam	10	7.3	$CdCl_2$	Greenhouse/Soil Pots	Soybean/Shoots	4.3 % YR	0.01	Boggess et al. (1978)
Marengo Silty Clay Loam	10	6.7	$CdCl_2$	Greenhouse/Soil Pots	Wheat/Tops	28.4 % YR	NR	Haghiri (1973)
Marengo Silty Clay Loam	10	6.7	$CdCl_2$	Greenhouse/Soil Pots	Soybeans/Tops	49.2 % YR	NR	Haghiri (1973)
Loams	9.3	5.-8.1	Sludge	Field	Spring Greens/Leaves	"Satisfactory Yields"	NR	Chumbley and Unwin (1982)
Loams	7.8	5.-8.1	Sludge	Field	Lettuce/Leaf	"Satisfactory Yields"	NR	Chumbley and Unwin (1982)
Loams	7.8	5.-8.1	Sludge	Field	Sweet Corn/Grain	"Satisfactory Yields"	NR	Chumbley and Unwin (1982)
Loams	6.5	5.-8.1	Sludge	Field	Beet Root/Tuber	"Satisfactory Yields"	NR	Chumbley and Unwin (1982)
Grenville Loam 0-15 cm	5.6	6.6	$CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	7.5 % YR (N.S.)	0.05	Singh (1981)
Grenville Loam 0-15 cm	5.6	6.5	$CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	13.9 % YR (N.S.)	0.05	Singh (1981)
Grenville Loam 0-15 cm	5.6	6.5	Fe Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	8.8 % YR (N.S.)	0.05	Singh (1981)
Grenville Loam 0-15 cm	5.6	6.5	Fe Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	21.9 % YR	0.05	Singh (1981)
Grenville Loam 0-15 cm	5.6	6.7	Al Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	12.7 % YR (N.S.)	0.05	Singh (1981)
Grenville Loam 0-15 cm	5.6	6.6	Al Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	15.2 % YR	0.05	Singh (1981)
Grenville Loam 0-15 cm	5.6	6.6	Mn Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	5.7 % YR (N.S.)	0.05	Singh (1981)
Grenville Loam 0-15 cm	5.6	6.7	Mn Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	18.5 % YR	0.05	Singh (1981)
Grenville Loam 0-15 cm	5.6	7.1	$CaCO_3$ + $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	16.6 % YR	0.05	Singh (1981)
Grenville Loam 0-15 cm	5.6	7.1	$CaCO_3$ + $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	27.2 % YR	0.05	Singh (1981)
Grenville Loam 0-15 cm	5.6	7.0	$CdCl_2$ + $CaCO_3$	Greenhouse/Soil Pots	Lettuce/Tops	14.6 % YR	0.05	Singh (1981)
Grenville Loam 0-15 cm	5.6	6.9	$CdCl_2$ + $CaCO_3$	Greenhouse/Soil Pots	Lettuce/Tops	23.2 % YR	0.05	Singh (1981)
Grenville Loam 0-15 cm	5.6	6.8	Sludge	Greenhouse/Soil Pots	Lettuce/Tops	29.3 % YR	0.05	Singh (1981)
Grenville Loam 0-15 cm	5.6	6.7	Sludge	Greenhouse/Soil Pots	Lettuce/Tops	52.3 % Yield Increase	0.05	Singh (1981)
Grenville Loam 0-15 cm	5.6	7.0	Sludge	Greenhouse/Soil Pots	Lettuce/Tops	19.1 % YR	0.05	Singh (1981)
Grenville Loam 0-15 cm	5.6	7.0	Sludge	Greenhouse/Soil Pots	Lettuce/Tops	55.0 % Yield Increase	0.05	Singh (1981)
Grenville Sandy Loam 0-15 cm	5.60	7.4	$CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	9.7 % YR	NR	MacLean (1976)
Romona Sandy Loam	5.57	6.0	Sludge	Greenhouse/Soil Pots	Barley-Barsoy/Tops	15 % YR (N.S.)	0.01	Chang et al. (1982)
Romona Sandy Loam	5.57	6.0	Sludge	Greenhouse/Soil Pots	Barley-Briggs/Tops	27 % YR (N.S.)	0.01	Chang et al. (1982)
Romona Sandy Loam	5.57	6.0	Sludge	Greenhouse/Soil Pots	Barley-Floride 103/Tops	14 % Yield Increase	0.01	Chang et al. (1982)
Romona Sandy Loam	5.57	6.0	Sludge	Greenhouse/Soil Pots	Barley-Larker/Tops	11 % Yield Increase	0.01	Chang et al. (1982)
Uplands Sand 0-15 cm	5.50	5.5	$CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	5.0 % YR	NR	MacLean (1976)
Uplands Sand 0-15 cm	5.50	7.0	$CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	9.9 % YR	NR	MacLean (1976)
Rideau Clay 0-15 cm	5.50	6.1	$CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	0.4 % Yield Increase	NR	MacLean (1976)
Rideau Clay 0-15 cm	5.50	6.8	$CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	7.6 % YR	NR	MacLean (1976)
Granby Sandy Loam 0-15 cm	5.45	6.7	$CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	4.1 % YR	NR	MacLean (1976)
Uplands Sand 15-30 cm	5.30	5.2	$CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	31.3 % YR	NR	MacLean (1976)
Uplands Sand 15-30 cm	5.30	6.8	$CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	26.4 % YR	NR	MacLean (1976)
Marengo Silty Clay Loam	5	6.7	$CdCl_2$	Greenhouse/Soil Pots	Wheat/Tops	27.9 % YR	NR	Haghiri (1973)
Marengo Silty Clay Loam	5	6.7	$CdCl_2$	Greenhouse/Soil Pots	Soybeans/Tops	18.3 % YR	NR	Haghiri (1973)
Merrimac Fine Sandy Loam	5	6.9	$Cd(NO_3)_2 \cdot 4H_2O$	Greenhouse/Soil Pots	Alfalfa/Tops	25.7 % YR (N.S.)	0.01	Taylor and Allinson
Merrimac Fine Sandy Loam	5	6.9	$Cd(NO_3)_2 \cdot 4H_2O$	Greenhouse/Soil Pots	Alfalfa/Tops	16.5 % YR	0.01	Taylor and Allinson

Table 36. Phytotoxocity of total cadmium in soils, continued.

Soil Type	Soil Concentration (ppm)	Soil pH	Chemical Form Applied	Type of Experiment	Plant Species/ Part	Hazard Response	Significance Level	Reference
Domino Silt Loam	5	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Soybean/Dry Bean	25 % YR	NR	Bingham et al. (1975)
Domino Silt Loam	5	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Sudan Grass/Tops	10 % YR	NR	Bingham et al. (1976)
Domino Silt Loam	5	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Alfalfa/Tops	8 % YR	NR	Bingham et al. (1976)
Domino Silt Loam	5	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Tall Fescue/Tops	6 % YR	NR	Bingham et al. (1976)
Domino Silt Loam	5	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Bermuda Grass/Tops	2 % YR	NR	Bingham et al. (1976)
Domino Silt Loam	5	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	White Clover/Tops	6 % Yield Increase	NR	Bingham et al. (1976)
Paxton Fine Sandy Loam	5	6.9	$CdSO_4$	Greenhouse/Soil Pots	Alfalfa/Tops	20.3 % Yield Increase	NR	Taylor and Allinson (1981)
Merrimac Fine Sandy Loam	5	6.9	$CdSO_4$	Greenhouse/Soil Pots	Alfalfa/Tops	13.6 % YR	NR	Taylor and Allinson (1981)
Paxton Fine Sandy Loam	5	6.9	$CdSO_4$	Greenhouse/Soil Pots	Alfalfa/Tops - 2nd cutting	3 % Yield Increase	NR	Taylor and Allinson (1981)
Merrimac Fine Sandy Loam	5	6.9	$CdSO_4$	Greenhouse/Soil Pots	Alfalfa/Tops - 2nd cutting	1.4 % YR	NR	Taylor and Allinson (1981)
Bloomfield Loamy Sand	5	6.0	$CdSO_4$	Greenhouse/Soil Pots	Corn/Shoots	46.8 % YR	0.01	Miller et al. (1977)
Loams	4.8	5.-8.1	Sludge	Field	Salad Onions/Bulb	"Satisfactory Yields"	NR	Chumbley and Unwin (1982)
Loams	4.6	5.-8.1	Sludge	Field	Spinach/Leaves	"Satisfactory Yields"	NR	Chumbley and Unwin (1982)
Loams	4.4	5.-8.1	Sludge	Field	Cabbage/Heads	"Satisfactory Yields"	NR	Chumbley and Unwin (1982)
Domino Silt Loam	4	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Spinach/Shoot	25 % YR	NR	Bingham et al. (1975)
Loams	3.5	5.-8.1	Sludge	Field	Cauliflower	"Satisfactory Yield"	NR	Chumbley and Unwin (1982)
Grenville Loam 0-15 cm	3.1	6.5	$CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	20.5 % YR	0.05	Singh (1981)
Grenville Loam 0-15 cm	3.1	6.6	$CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	1 % YR (N.S.)	0.05	Singh (1981)
Grenville Loam 0-15 cm	3.1	6.6	Fe Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	1 % YR (N.S.)	0.05	Singh (1981)
Grenville Loam 0-15 cm	3.1	6.6	Fe Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	23.2 % YR	0.05	Singh (1981)
Grenville Loam 0-15 cm	3.1	6.6	Al Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	5.7 % YR (N.S.)	0.05	Singh (1981)
Grenville Loam 0-15 cm	3.1	6.5	Al Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	11.9 % YR (N.S.)	0.05	Singh (1981)
Grenville Loam 0-15 cm	3.1	6.5	Mn Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	0.6 % YR (N.S.)	0.05	Singh (1981)
Grenville Loam 0-15 cm	3.1	6.6	Mn Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	3.3 % YR (N.S.)	0.05	Singh (1981)
Grenville Loam 0-15 cm	3.1	7.0	$CaCO_3$ + $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	1.9 % YR (N.S.)	0.05	Singh (1981)
Grenville Loam 0-15 cm	3.1	7.1	$CaCO_3$ + $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	17.2 % YR	0.05	Singh (1981)
Grenville Loam 0-15 cm	3.1	7.0	$CdCl_2$ + $CaCO_3$	Greenhouse/Soil Pots	Lettuce/Tops	4.4 % YR (N.S.)	0.05	Singh (1981)
Grenville Loam 0-15 cm	3.1	7.0	$CdCl_2$ + $CaCO_3$	Greenhouse/Soil Pots	Lettuce/Tops	21.2 % YR	0.05	Singh (1981)
Grenville Loam 0-15 cm	3.1	6.7	Sludge	Greenhouse/Soil Pots	Lettuce/Tops	24.2 Yield Increase	0.05	Singh (1981)
Grenville Loam 0-15 cm	3.1	6.6	Sludge	Greenhouse/Soil Pots	Lettuce/Tops	11.9 % YR (N.S.)	0.05	Singh (1981)
Grenville Loam 0-15 cm	3.1	6.9	Sludge	Greenhouse/Soil Pots	Lettuce/Tops	10.2 % Yield Increase(N.S.)	0.05	Singh (1981)
Grenville Loam 0-15 cm	3.1	6.9	Sludge	Greenhouse/Soil Pots	Lettuce/Tops	3.3 % Yield Increase (N.S.)	0.05	Singh (1981)
Loams	3.1	5.-8.1	Sludge	Field	Leeks/Bulb	"Satisfactory Yield"	NR	Chumbley and Unwin (1982)
Loams	2.7	5.-8.1	Sludge	Field	Radish/Tuber	"Satisfactory Yield"	NR	Chumbley and Unwin (1982)
Marengo Silty Clay Loam	2.5	6.7	$CdCl_2$	Greenhouse/Soil Pots	Wheat/Tops	19.1 % YR	NR	Haghiri (1973)
Marengo Silty Clay Loam	2.5	6.7	$CdCl_2$	Greenhouse/Soil Pots	Soybeans/Tops	10.6 % YR	NR	Haghiri (1973)
Domino Silt Loam	2.5	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	White Clover/Tops	11 % YR	NR	Bingham et al. (1976)
Domino Silt Loam	2.5	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Sudan Grass/Tops	6 % YR	NR	Bingham et al. (1976)
Domino Silt Loam	2.5	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Alfalfa/Tops	2 % YR	NR	Bingham et al. (1976)
Domino Silt Loam	2.5	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Tall Fescue/Tops	No YR	NR	Bingham et al. (1976)
Domino Silt Loam	2.5	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Bermuda Grass/Tops	No YR	NR	Bingham et al. (1976)
Bloomfield Loamy Sand	2.0	6.0	$CdCl_2$	Greenhouse/Soil Pots	Corn/Shoots	28.2 % YR	0.01	Miller et al. (1977)
Bloomfield Loamy Sand	2.0	5.5	$CdCl_2$	Greenhouse/Soil Pots	Soybeans/Shoots	37.8 % YR from 0.5 ppm Soil Level	0.01	Boggess et al. (1978)
Plainfield Loamy Sand	2.0	6.5	$CdCl_2$	Greenhouse/Soil Pots	Soybeans/Shoots	27.2 % YR from 0.5 ppm Soil Level	0.01	Boggess et al. (1978)
Romona Sandy Loam	1.57	6.0	Sludge	Greenhouse/Soil Pots	Barley-Barsoy/Tops	4 % YR (N.S.)	0.01	Chang et al. (1982)
Pomona Sandy Loam	1.57	6.0	Sludge	Greenhouse/Soil Pots	Barley-Briggs/Tops	23 % YR (N.S.)	0.01	Chang et al. (1982)
Romona Sandy Loam	1.57	6.0	Sludge	Greenhouse/Soil Pots	Barley-Florida 103/ Tops	2 % Yield Increase	0.01	Chang et al. (1982)
Romona Sandy Loam	1.57	6.0	Sludge	Greenhouse/Soil Pots	Barley-Larker/Tops	11 % Yield Increase (N.S.)	0.01	Chang et al. (1982)

Table 36. Phytotoxicity of total cadmium in soils, continued.

Soil Type	Soil Concentration (ppm)	Soil pH	Chemical Form Applied	Type of Experiment	Plant Species/ Part	Hazard Response	Significance Level	Reference
Bloomfield Loamy Sand	1.0	5.5	$CdCl_2$	Greenhouse/Soil Pots	Soybeans/Shoots	10.6 % YR from 0.5 ppm Soil Level	0.01	Boggess et al. (1978)
33 Fraser Valley Ag. Soils	0.88		None	Field	Farmland	Background	NR	John et al. (1972)
Helena Valley Soils	0.8	NR	None	Field	NA	Background	NA	Miesch and Huffman (1972)
Grenville Loam 0-15 cm	0.60	6.7	None	Greenhouse/Soil Pots	Lettuce	Background	NR	Singh (1981)
U.S. Soils	0.1-0.8	NR	None	Field	NA	Background	NA	Meyer et al. (1982)
16 Minn. Surface Soils	0.39	5.3-8.2	None	Field	NR	Background	NA	Pierce et al. (1982)
Plainfield Sand	0.33	4.8	None	Field	"Uncontaminated Site"	Background	NA	Miles and Parker (1982)
Domino Silt Loam	0.3	7.8	None	Field	Crop Land	Background	NR	Chang et al. (1982)
Helena Valley Soils	0.24	8.0	None	Field	Forage/Range	Background	NA	EPA (1986)
16 Minn. Subsoils	0.23	5.3-8.2	None	Field	NR	Background	NA	Pierce et al. (1982)
Greenfield Sandy Loam	0.1	7.1	None	Field	Crop Land	Background	NR	Chang et al. (1982)
Romona Sandy Loam	0.1	6.0	None	Field	Crop Land	Background	NR	Chang et al. (1982)

Table 37. Phytotoxicity of extractable cadmium in soils.

Soil Type	Soil Concentration (ppm)	Soil pH	Chemical Form Applied	Type of Experiment	Plant Species/ Part	Hazard Response	Extractant	Significant Level	Reference
Redding Fine Sandy Loam	524	5.7	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Wheat/Grain	94 % YR	DTPA-TEA	0.05	Mitchell et al. (1978)
Redding Fine Sandy Loam	524	5.7	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Lettuce/Tops	97 % YR	DTPA-TEA	0.05	Mitchell et al. (1978)
Domino Silt Loam	416	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Wheat/Grain	95 % YR	DTPA-TEA	0.05	Mitchell et al. (1978)
Domino Silt Loam	>384.0	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Rice/Grain	25 % YR	DTPA	NR	Bingham et al. (1975)
Domino Silt Loam	208	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Wheat/Grain	91 % YR	DTPA-TEA	0.05	Mitchell et al. (1978)
Domino Silt Loam	208	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Lettuce/Tops	82 % YR	DTPA-TEA	0.05	Mitchell et al. (1978)
Redding Fine Sandy Loam	168	5.7	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Wheat/Grain	82 % YR	DTPA-TEA	0.05	Mitchell et al. (1978)
Redding Fine Sandy Loam	168	5.7	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Lettuce/Tops	60 % YR	DTPA-TEA	0.05	Mitchell et al. (1978)
Redding Fine Sandy Loam	122	5.7	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Wheat/Grain	66 % YR	DTPA-TEA	0.05	Mitchell et al. (1978)
Redding Fine Sandy Loam	122	5.7	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Lettuce/Tops	50 % YR	DTPA-TEA	0.05	Mitchell et al. (1978)
Domino Silt Loam	107	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Bermuda Grass/Tops	25 % YR	DTPA	NR	Bingham et al. (1976)
Domino Silt Loam	102.0	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Cabbage/Head	25 % YR	DTPA	NR	Bingham et al. (1975)
Domino Silt Loam	96.0	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Zucchini/Fruit	25 % YR	DTPA	NR	Bingham et al. (1975)
Domino Silt Loam	96.0	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Tomato/Ripe Fruit	25 % YR	DTPA	NR	Bingham et al. (1975)
Domino Silt Loam	96.0	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Wheat/Grain	70 % YR	DTPA-TEA	0.05	Mitchell et al. (1978)
Domino Silt Loam	96.0	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Lettuce/Tops	64 % YR	DTPA-TEA	0.05	Mitchell et al. (1978)
Domino Silt Loam	71	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Tall Fescue/Tops	25 % YR	DTPA	NR	Bingham et al. (1976)
Redding Fine Sandy Loam	58	5.7	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Wheat/Grain	42 % YR	DTPA-TEA	0.05	Mitchell et al. (1978)
Redding Fine Sandy Loam	58	5.7	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Lettuce/Tops	20 % YR	DTPA-TEA	0.05	Mitchell et al. (1978)
Domino Silt Loam	57.6	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Radish/Tuber	25 % YR	DTPA	NR	Bingham et al. (1975)
Domino Silt Loam	49	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Wheat/Grain	61 % YR	DTPA-TEA	0.05	Mitchell et al. (1978)
Domino Silt Loam	49	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Lettuce/Tops	61 % YR	DTPA-TEA	0.05	Mitchell et al. (1978)
Redding Fine Sandy Loam	31	5.7	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Wheat/Grain	18 % YR	DTPA-TEA	0.05	Mitchell et al. (1978)
Redding Fine Sandy Loam	31	5.7	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Lettuce/Tops	10 % YR	DTPA-TEA	0.05	Mitchell et al. (1978)
Domino Silt Loam	30.0	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Wheat/Grain	25 % YR	DTPA	NR	Bingham et al. (1975)
Domino Silt Loam	29	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	White Clover	25 % YR	DTPA	NR	Bingham et al. (1976)
Domino Silt Loam	24.0	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Field Bean/Dry Bean	25 % YR	DTPA	NR	Bingham et al. (1975)
Domino Silt Loam	23	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Wheat/Grain	22 % YR	DTPA-TEA	0.05	Mitchell et al. (1978)
Domino Silt Loam	23	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Lettuce/Tops	49 % YR	DTPA-TEA	0.05	Mitchell et al. (1978)
Domino Silt Loam	22	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Alfalfa/Tops	25 % YR	DTPA	NR	Bingham et al. (1976)
Redding Fine Sandy Loam	17	5.7	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Wheat/Grain	5 % Yield Increase (N.S.)	DTPA-TEA	0.05	Mitchell et al. (1978)
Redding Fine Sandy Loam	17	5.7	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Lettuce/Tops	7 % YR (N.S.)	DTPA-TEA	0.05	Mitchell et al. (1978)
Domino Silt Loam	16.0	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Turnip/Tuber	25 % YR	DTPA	NR	Bingham et al. (1975)
Domino Silt Loam	13	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Wheat/Grain	10 % Yield Increase (N.S.)	DTPA-TEA	0.05	Mitchell et al. (1978)
Domino Silt Loam	13	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Lettuce/Tops	12 % YR	DTPA-TEA	0.05	Mitchell et al. (1978)
Domino Silt Loam	12.0	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Carrot/Tuber	25 % YR	DTPA	NR	Bingham et al. (1975)
Domino Silt Loam	11	7.5	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Sudan Grass/Tops	25 % YR	DTPA	NR	Bingham et al. (1976)
Domino Silt Loam	10.8	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Corn/Kernal	25 % YR	DTPA	NR	Bingham et al. (1975)

Table 37. Phytotoxicity of extractable cadmium in soils, continued.

Soil Type	Soil Concentration (ppm)	Soil pH	Chemical Form Applied	Type of Experiment	Plant Species/ Part	Hazard Response	Extractant	Significance Level	Reference
Domino Silt Loam	7.8	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Lettuce/Head	25 % YR	DTPA	NR	Bingham et al. (1975)
Domino Silt Loam	4.8	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Curly Cress/Shoots	25 % YR	DTPA	NR	Bingham et al. (1975)
Market Garden Soil	4.6	7.0	Sludge	Field/Mini Plots	Linseed/Tops	No YR	EDTA	NR	DeVries and Merry (1980)
Market Garden Soil	4.6	7.0	Sludge	Field/Mini Plots	Rapeseed/Tops	No YR	EDTA	NR	DeVries and Merry (1980)
Market Garden Soil	4.6	7.0	Sludge	Field/Mini Plots	Safflower/Tops	No YR	EDTA	NR	DeVries and Merry (1980)
Market Garden Soil	4.6	7.0	Sludge	Field/Mini Plots	Radish/Roots	No YR	EDTA	NR	DeVries and Merry (1980)
Market Garden Soil	4.6	7.0	Sludge	Field/Mini Plots	Carrot/Roots	No YR	EDTA	NR	DeVries and Merry (1980)
Market Garden Soil	4.6	7.0	Sludge	Field/Mini Plots	Silverbeet/Roots	No YR	EDTA	NR	DeVries and Merry (1980)
Grenville Loam 0-15 cm	3.76	6.7	Al Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	12.7 % YR (N.S.)	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	3.60	6.6	$CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	7.5 % YR (N.S.)	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	3.54	7.1	$CaCO_3$ + $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	16.6 % YR	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	3.44	7.0	$CdCl_2$ + $CaCO_3$	Greenhouse/Soil Pots	Lettuce/Tops	14.6 % YR	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	3.32	6.6	Al Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	15.2 % YR	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	3.26	6.5	$CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	13.9 % YR (N.S.)	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	3.22	6.5	Fe Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	8.9 % YR (N.S.)	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	3.15	7.1	$CaCO_3$ + $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	27.2 % YR	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	3.06	6.9	$CdCl_2$ + $CaCO_3$	Greenhouse/Soil Pots	Lettuce/Tops	23.2 % YR	DTPA	0.05	Singh (1981)
Domino Silt Loam	3.00	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Soybean/Dry Bean	25 % YR	DTPA	NR	Bingham et al. (1975)
Grenville Loam 0-15 cm	2.98	6.6	Mn Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	5.7 % YR (N.S.)	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	2.92	6.5	Fe Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	21.9 % YR	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	2.89	6.7	Mn Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	18.5 % YR	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	2.60	6.8	Sludge	Greenhouse/Soil Pots	Lettuce/Tops	29.3 % Yield Increase	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	2.59	6.7	Sludge	Greenhouse/Soil Pots	Lettuce/Tops	52.3 % Yield Increase	DTPA	0.05	Singh (1981)
Domino Silt Loam	2.40	7.5-7.8	Sludge/$CdSO_4$	Greenhouse/Soil Pots	Spinach/Shoot	25 % YR	DTPA	NR	Bingham et al. (1975)
Grenville Loam 0-15 cm	2.33	7.0	Sludge	Greenhouse/Soil Pots	Lettuce/Tops	19 % Yield Increase	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	2.22	7.0	Sludge	Greenhouse/Soil Pots	Lettuce/Tops	55 % Yield Increase	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	2.00	6.6	$CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	1 % YR (N.S.)	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	1.88	7.0	$CaCO_3$ + $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	1.9 % YR (N.S.)	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	1.76	6.6	Al Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	5.7 % YR (N.S.)	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	1.75	7.0	$CdCl_2$ + $CaCO_3$	Greenhouse/Soil Pots	Lettuce/Tops	4.4 % YR (N.S.)	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	1.66	6.6	Fe Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	1 % YR (N.S.)	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	1.63	6.5	Al Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	11.9 % YR (N.S.)	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	1.60	6.5	Mn Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	0.6 % YR (N.S.)	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	1.60	6.5	$CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	20.5 % YR	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	1.60	7.1	$CaCO_3$ + $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	17.2 % YR	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	1.60	7.0	$CdCl_2$ + $CaCO_3$	Greenhouse/Soil Pots	Lettuce/Tops	21.2 % YR	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	1.52	6.6	Sludge	Greenhouse/Soil Pots	Lettuce/Tops	11.9 % YR (N.S.)	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	1.46	6.6	Fe Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	23.2 % YR	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	1.46	6.6	Mn Precip $CdCl_2$	Greenhouse/Soil Pots	Lettuce/Tops	3.3 % YR (N.S.)	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	1.38	6.7	Sludge	Greenhouse/Soil Pots	Lettuce/Tops	24.2 % Yield Increase	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	1.32	6.9	Sludge	Greenhouse/Soil Pots	Lettuce/Tops	10.2 % Yield Increase (N.S.)	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	1.32	6.9	Sludge	Greenhouse/Soil Pots	Lettuce/Tops	3.3 % Yield Increase (N.S.)	DTPA	0.05	Singh (1981)

Table 37. Phytotoxicity of extractable cadmium in soils, continued.

Soil Type	Soil Concentration (ppm)	Soil pH	Chemical Form Applied	Type of Experiment	Plant Species/ Part	Hazard Response	Extractant	Significance Level	Reference
1305 N. Ireland Soil Samples	0.17	NR	None	Field	NR	Background	EDTA, pH 7.0	NR	Dickson and Stevens (1983)
Paxton Fine Sandy Loam	<0.1	6.9	None	Greenhouse/Soil Pots	Alfalfa/Tops	Background	NH_4OAc-pH 4.8	NR	Taylor and Allinson (1981)
Merrimac Fine Sandy Loam	<0.1	6.9	None	Greenhouse/Soil Pots	Alfalfa/Tops	Background	NH_4OAc-pH 4.8	NR	Taylor and Allinson (1981)
Domino Silt Loam	<0.1	7.5	None	Greenhouse/Soil Pots	Lettuce-Wheat/Leaves	Background	DTPA	NA	Mitchell et al. (1978)
Redding Fine Sandy Loam	<0.1	5.7	None	Greenhouse/Soil Pots	Lettuce-Wheat/Leaves	Background	DTPA	NA	Mitchell et al. (1978)
A - Horizon NGP[A]	0.1	6.2-8.2	None	Field	Native Vegetation	Background	EDTA	NR	Severson et al. (1977)
A - Horizon NGP	0.1	6.2-8.2	None	Field	Native Vegetation	Background	DTPA	NR	Severson et al. (1977)
Grenville Loam 0-15 cm	0.10	6.6	None	Greenhouse/Soil Pots	Lettuce/Tops	Background	DTPA	0.05	Singh (1981)
Grenville Loam 0-15 cm	0.07	6.5	None	Greenhouse/Soil Pots	Lettuce/Tops	Background	DTPA	0.05	Singh (1981)
Sassafras Silt Loam	0.07	5.4	None	Field	Uncultivated Field	Background	DTPA	NR	White and Chaney (1980)
Helena Valley Soils	0.02	8.0	None	Field	Forage/Range	Background	DTPA	NR	EPA (1986)
C - Horizon NGP	0.03	7.0-8.9	None	Field	Native Vegetation	Background	EDTA	NR	Severson et al. (1977)
A - Horizon NGP	0.03	6.2-8.2	None	Field	Native Vegetation	Background	NH_4OAc	NR	Severson et al. (1977)
C - Horizon NGP	0.02	7.0-8.9	None	Field	Native Vegetation	Background	DTPA	NR	Severson et al. (1977)
C - Horizon NGP	0.01	7.0-8.9	None	Field	Native Vegetation	Background	NH_4OAc	NR	Severson et al. (1977)
Pocomoke Silt Loam	0.01	4.3	None	Field	Forest	Background	DTPA	NR	White and Chaney (1980)

A/ Northern Great Plains

Table 38. Phytotoxicity of cadmium in vegetation.

Plant/Tissue	Tissue Concentration (ppm)	Type of Experiment	Chemical Form Applied	Hazard Response	Soil pH	Significant Level	Reference
Alfalfa/Tops	3378.2	Greenhouse/Soil Pots	$CdSO_4$	29% YR	6.9	NR	Taylor and Allinson (1981)
Alfalfa/Tops	1960.0	Greenhouse/Soil Pots	$CdSO_4$	21.0 % YR	6.9	NR	Taylor and Allinson (1981,
Alfalfa/Tops	1813.5	Greenhouse/Soil Pots	$Cd(NO_3)_2 \cdot 4H_2O$	46.5 % YR (N.S.)	6.9	0.01	Taylor and Allinson (1981)
Lettuce/Roots	1620	Greenhouse/Soil Pots	$CdCl_2$	60 % YR	5.1	0.05	John (1973)
Cabbage/Leaf	800	Greenhouse/Solution Culture	$CdSO_4$	50 % YR	5.0-5.5	NR	Page et al. (1972)
Lettuce/Shoots	695	Greenhouse/Soil Pots	$CdSO_4$/Sludge	96 % YR	5.7	0.05	Mitchell et al. (1978)
Lettuce/Leaves	667.7	Greenhouse/Soil Pots	$CdCl_2$	91 % YR	5.1	0.05	John (1973)
Lettuce/Shoots	593	Greenhouse/Soil Pots	$CdSO_4$/Sludge	50 % YR	5.7	0.05	Mitchell et al. (1978)
Tomato/Leaf	570	Greenhouse/Solution Culture	$CdSO_4$	50 % YR	5.0-5.5	NR	Page et al. (1972)
Turnip/Leaf	469	Greenhouse/Solution Culture	$CdSO_4$	73 % YR	5.0-5.5	NR	Page et al. (1972)
Lettuce/Shoots	413	Greenhouse/Soil Pots	$CdSO_4$/Sludge	82 % YR	7.5	0.05	Mitchell et al. (1978)
Radish/Tops	398	Greenhouse/Soil Pots	$CdCl_2$	82 % YR	5.1	0.05	John (1973)
Turnip/Leaf	394	Greenhouse/Solution Culture	$CdSO_4$	71 % YR	5.0-5.5	NR	Page et al. (1972)
Lettuce/Leaf	384	Greenhouse/Solution Culture	$CdSO_4$	84 % YR	5.0-5.5	NR	Page et al. (1972)
Alfalfa/Tops	365	Greenhouse/Soil Pots	$CdSO_4$	62.1 % YR	6.9	NR	Taylor and Allinson (1981)
Plantain/Shoots	350	Greenhouse/Soil Pots	Cd Salts	50 % YR	4.4	NR	Dijkshoorn et al. (1979)
Lettuce/Shoots	343	Greenhouse/Soil Pots	$CdSO_4$/Sludge	64 % YR	7.5	0.05	Mitchell et al. (1978)
Beet/Leaf	326	Greenhouse/Solution Culture	$CdSO_4$	76 % YR	5.0-5.5	NR	Page et al. (1972)
Beet/Leaf	321	Greenhouse/Solution Culture	$CdSO_4$	62 % YR	5.0-5.5	NR	Page et al. (1972)
Lettuce/Leaf	320	Greenhouse/Solution Culture	$CdSO_4$	50 % YR	5.0-5.5	NR	Page et al. (1972)
Beet/Leaf	295	Greenhouse/Solution Culture	$CdSO_4$	73 % YR	5.0-5.5	NR	Page et al. (1972)
Carrot/Tops	294.4	Greenhouse/Soil Pots	$CdCl_2$	92 % YR	5.1	0.05	John (1973)
Red Beet/Leaf	290	Greenhouse/Solution Culture	$CdSO_4$	50 % YR	5.0-5.5	NR	Page et al. (1972)
Red Beet/Leaf	280	Greenhouse/Solution Culture	$CdSO_4$	45.5 % YR	5.0-5.5	NR	Page et al. (1972)
Alfalfa/Tops	279.1	Greenhouse/Soil Pots	$Cd(NO_3)_2 \cdot 4H_2O$	71.9 % YR	6.9	0.01	Taylor and Allinson (1981)
Turnip/Leaf	270	Greenhouse/Solution Culture	$CdSO_4$	56 % YR	5.0-5.5	NR	Page et al. (1972)
Broccoli/Leaves	268.5	Greenhouse/Soil Pots	$CdCl_2$	63 % YR	5.1	0.05	John (1973)
Radish/Tops	264.7	Greenhouse/Soil Pots	$CdCl_2$	24 % YR	5.1	0.05	John (1973)
Corn/Shoots	264	Greenhouse/Solution Culture	$CdCl_2$	66 % YR	5.5	NR	Iwai et al. (1975)
Lettuce/Shoots	240	Greenhouse/Soil Pots	$CdSO_4$/Sludge	18 % YR	5.7	0.05	Mitchell et al. (1978)
Spinach/Leaves	239.3	Greenhouse/Soil Pots	$CdCl_2$	99 % YR	5.1	0.05	John (1973)
Sweet Corn/Leaf	234	Greenhouse/Solution Culture	$CdSO_4$	17 % YR	5.0-5.5	NR	Page et al. (1972)
Sweet Corn/Leaf	230	Greenhouse/Solution Culture	$CdSO_4$	50 % YR	5.0-5.5	NR	Page et al. (1972)
Sweet Corn/Leaf	227	Greenhouse/Solution Culture	$CdSO_4$	45.5 % YR	5.0-5.5	NR	Page et al. (1972)
Lettuce/Shoots	226	Greenhouse/Soil Pots	$CdSO_4$/Sludge	61 % YR	7.5	0.05	Mitchell et al. (1978)
Cabbage/Leaf	212	Greenhouse/Solution Culture	$CdSO_4$	53.5 % YR	5.0-5.5	NR	Page et al. (1972)
Spinach/Leaves	207.5	Greenhouse/Soil Pots	$CdCl_2$	96 % YR	5.1	0.05	John (1973)
Cauliflower/Leaves	198.6	Greenhouse/Soil Pots	$CdCl_2$	97 % YR	5.1	0.05	John (1973)
Oats/Stalks	177	Greenhouse/Soil Pots	$CdCl_2$	10 % YR (N.S.)	5.1	0.05	John (1973)
Tomato/Leaf	174	Greenhouse/Solution Culture	$CdSO_4$	63 % YR	5.0-5.5	NR	Page et al. (1972)
Alfalfa/Tops	171.6	Greenhouse/Soil Pots	$Cd(NO_3)_2 \cdot 4H_2O$	15.8 % YR (N.S.)	6.9	0.01	Taylor and Allinson (1981)
Sweet Corn/Leaf	165	Greenhouse/Solution Culture	$CdSO_4$	33.5 % YR	5.0-5.5	NR	Page et al. (1972)
Cabbage/Most Recent Enclosed Leaf	160	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham (1979)

Table 38. Phytotoxicity of cadmium in vegetation, continued.

Plant/Tissue	Tissue Concentration (ppm)	Type of Experiment	Chemical Form Supplied	Hazard Response	Soil pH	Significant Level	Reference
Pepper/Leaf	160	Greenhouse/Solution Culture	$CdSO_4$	50 % YR	5.0-5.5	NR	Page et al. (1972)
Turnip/Leaf	160	Greenhouse/Solution Culture	$CdSO_4$	22 % YR	5.0-5.5	NR	Page et al. (1972)
Lettuce/Shoots	153	Greenhouse/Soil Pots	$CdSO_4$/Sludge	49 % YR	7.5	0.05	Mitchell et al. (1978)
Swiss Chard/Leaves	153	Greenhouse/Soil Pots	Sludge/$CdSO_4$	56.7 % YR	7.5	NR	Mahler et al. (1980)
Swiss Chard/Shoots	150	Greenhouse/Soil Pots	$CdSO_4$/Sludge	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Lettuce/Shoots	147	Greenhouse/Soil Pots	$CdSO_4$/Sludge	18 % YR	5.7	0.05	Mitchell et al. (1978)
Tomato/Leaf	138	Greenhouse/Solution Culture	$CdSO_4$	50 % YR	5.0-5.5	NR	Page et al. (1972)
Tomato/Leaf	125	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Radish/Tubers	123.3	Greenhouse/Soil Pots	$CdCl_2$	93 % YR	5.1	0.05	John (1973)
Turnip/Leaf	121	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Barley/Leaf	120	Greenhouse/Solution Culture	$CdSO_4$	50 % YR	5.0-5.5	NR	Page et al. (1972)
Lettuce/Shoots	118	Greenhouse/Soil Pots	$CdSO_4$/Sludge	45 % YR	7.5	0.05	Mitchell et al. (1978)
Peas-Perf/Vine	116.9	Greenhouse/Soil Pots	$CdCl_2$	87 % YR	5.1	0.05	John (1973)
Oats/Stalk	116.5	Greenhouse/Soil Pots	$CdCl_2$	22 % YR (N.S.)	5.1	0.05	John (1973)
Corn/Lower Leaves	116	Greenhouse/Solution Culture	$CdCl_2$	41 % YR	5.0	NR	Iwai et al. (1975)
Tomato/Leaf	115	Greenhouse/Solution Culture	$CdSO_4$	41 % YR	5.0-5.5	NR	Page et al. (1972)
Green Pepper/Leaf	104	Greenhouse/Solution Culture	$CdSO_4$	58 % YR	5.0-5.5	NR	Page et al. (1972)
Corn/Upper Leaves	99	Greenhouse/Solution Culture	$CdCl_2$	41 % YR	5.0	NR	Iwai et al. (1975)
Wheat/Grain	95	Greenhouse/Soil Pots	$CdSO_4$/Sludge	82 % YR	5.7	0.05	Mitchell et al. (1978)
Sweet Corn/Leaf	90	Greenhouse/Solution Culture	$CdSO_4$	6.5 % YR	5.0-5.5	NR	Page et al. (1972)
Wheat/Grain	87	Greenhouse/Soil Pots	$CdSO_4$/Sludge	66 % YR	5.7	0.05	Mitchell et al. (1978)
Corn/Shoots	85	Greenhouse/Solution Culture	$CdCl_2$	23 % YR	5.5	NR	Iwai et al. (1975)
Curlycress/Edible	80	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Carrot/Tops	79.3	Greenhouse/Soil Pots	$CdCl_2$	11 % YR (N.S.)	5.1	0.05	John (1973)
Barley/Leaf	75	Greenhouse/Solution Culture	$CdSO_4$	68.5 % YR	5.0-5.5	NR	Page et al. (1972)
Radish/Leaf	75	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Spinach/Shoot	75	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Curlycress/Leaf	70	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Lettuce/Head	70	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Zucchini/Leaf	68	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Lettuce/Shoots	68	Greenhouse/Soil Pots	$CdSO_4$/Sludge	23 % YR (N.S.)	7.5	0.05	Mitchell et al. (1978)
Bermuda Grass/Tops	67	Greenhouse/Soil Pots	Sludge/$CdSO_4$	68 % YR	7.5	NR	Bingham et al. (1976)
Corn/Lower Leaves	60	Greenhouse/Solution Culture	$CdCl_2$	18 % YR	5.0	NR	Iwai et al. (1975)
Tomato/Leaf	58	Greenhouse/Solution Culture	$CdSO_4$	28 % YR	5.0-5.5	NR	Page et al. (1972)
Alfalfa/Tops	57.6	Greenhouse/Soil Pots	$CdSO_4$	0.7 % Yield Increase	6.9	NR	Taylor and Allinson (1981)
Radish/Tubers	54.6	Greenhouse/Soil Pots	$CdCl_2$	28 % YR (N.S.)	5.1	0.05	John (1973)
Lettuce/Tops	52.0	Greenhouse/Soil Pots	Al Precip/$CdCl_2$	12.7 % YR (N.S.)	6.7	0.05	Singh (1981)
Lettuce/Tops	51.5	Greenhouse/Soil Pots	$CaCO_3$ + $CdCl_2$	16.6 % YR	7.1	0.05	Singh (1981)
Lettuce/Leaves	51.1	Greenhouse/Soil Pots	$CdCl_2$	7.5 % Yield Increase			
Lettuce/Tops	49.7	Greenhouse/Soil Pots	Fe Precip/$CdCl_2$	8.9 % YR (N.S.)	6.5	0.05	Singh (1981)
Lettuce/Tops	48.7	Greenhouse/Soil Pots	$CdCl_2$ + $CaCO_3$	14.6 % YR	7.0	0.05	Singh (1981)
Lettuce/Leaf	48	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)

Table 38. Phytotoxicity of cadmium in vegetation, continued.

Plant/Tissue	Tissue Concentration (ppm)	Type of Experiment	Chemical Form Applied	Hazard Response	Soil pH	Significant Level	Reference
Oats/Stalk	47.4	Greenhouse/Soil Pots	$CdCl_2$	31 % Yield Increase (N.S.)	5.1	0.05	John (1973)
Lettuce/Tops	46.4	Greenhouse/Soil Pots	$CdCl_2$	7.5 % YR (N.S.)	6.6	0.05	Singh (1981)
Oats/Leaves	45.4	Greenhouse/Soil Pots	$CdCl_2$	3.1 % YR (N.S.)	5.1	0.05	John (1973)
Alfalfa/Tops	45	Greenhouse/Soil Pots	Sludge/$CdSO_4$	56 % YR	7.5	NR	Bingham et al. (1976)
Corn-High Accum/Stover	44.4	Field	Sludge	16 % YR	7.4	0.05	Hinesly et al. (1982)
Bermuda Grass/Leaf	43	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5	NR	Bingham et al. (1976)
Tall Fescue/Tops	42	Greenhouse/Soil Pots	Sludge/$CdSO_4$	30 % YR	7.5	NR	Bingham et al. (1976)
Alfalfa/Tops	40.3	Greenhouse/Soil Pots	$Cd(NO_3)_2 \cdot 4H_2O$	1 % Yield Increase (N.S.)	6.9	0.01	Taylor and Allinson (1981)
Tall Fescue/Tops	40	Greenhouse/Soil Pots	Sludge/$CdSO_4$	24 % YR	7.5	NR	Bingham et al. (1976)
Ryegrass/Shoots	40	Greenhouse/Soil Pots	Cd Salts	50 % YR	4.4	NR	Dijkshoorn et al. (1979)
Wheat/Grain	39	Greenhouse/Soil Pots	$CdSO_4$/Sludge	42 % YR	5.7	0.05	Mitchell et al. (1978)
Corn/Shoots	39	Greenhouse/Solution Culture	$CdCl_2$	10 % YR	5.5	NR	Iwai et al. (1975)
Lettuce/Tops	38.5	Greenhouse/Soil Pots	Mn Precip/$CdCl_2$	5.7 % YR (N.S.)	6.6	0.05	Singh (1981)
Peas-Perf/Vine	37.2	Greenhouse/Soil Pots	$CdCl_2$	27 % YR (N.S.)	5.1	0.05	John (1973)
Tall Fescue/Leaf	37	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5	NR	Bingham et al. (1976)
Corn/Upper Leaves	37	Greenhouse/Solution Culture	$CdCl_2$	10 % YR	5.0	NR	Iwai et al. (1975)
Bermuda Grass/Tops	36	Greenhouse/Soil Pots	Sludge/$CdSO_4$	12 % YR	7.5	NR	Bingham et al. (1976)
Alfalfa/Tops	36	Greenhouse/Soil Pots	$CdSO_4$	23.6 % YR	6.9	NR	Taylor and Allinson (1981)
Broccoli/Leaves	36	Greenhouse/Soil Pots	$CdCl_2$	28 % Yield Increase (N.S.)	5.1	0.05	John (1973)
White Clover/Shoots	36	Greenhouse/Soil Pots	Cd Salts	50 % YR	4.54	NR	Dijkshoorn et al. (1979)
Alfalfa Tops	36	Greenhouse/Soil Pots	Sludge/$CdSO_4$	40 % YR	7.5	NR	Bingham et al. (1976)
Corn/Leaf	35	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Field Bean/Leaf	35	Greenhouse/Soil Pots	$CdSO_4$	85 % YR	5.0-5.5	NR	Page et al. (1972)
Alfalfa/Tops	34.9	Greenhouse/Soil Pots	$CdSO_4$	67.4 % YR	6.9	NR	Taylor and Allinson (1981)
Corn-High Accum/Stover	34.7	Field	Sludge	10.6 % Yield Increase (N.S.)	7.4	0.05	Hinesly et al. (1982)
Field Bean/Leaf	34	Greenhouse/Solution Culture	$CdSO_4$	79 % YR	5.0-5.5	NR	Page et al. (1972)
Oats/Grain	33.6	Greenhouse/Soil Pots	$CdCl_2$	57 % YR	5.1	0.05	John (1973)
Wheat/Leaf	33	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Carrot/Leaf	32	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Wheat/Grain	31	Greenhouse/Soil Pots	$CdSO_4$/Sludge	95 % YR	7.5	0.05	Mitchell et al. (1978)
Lettuce/Tops	30.2	Greenhouse/Soil Pots	$CaCO_3$ + $CdCl_2$	27.2 % YR	7.1	0.05	Singh (1981)
Tall Fescue/Tops	30	Greenhouse/Soil Pots	Sludge/$CdSO_4$	19 % YR	7.5	NR	Bingham et al. (1976)
Carrot/Tubers	29.8	Greenhouse/Soil Pots	$CdCl_2$	96 % YR	5.1	0.05	John (1973)
Alfalfa/Tops	29.5	Greenhouse/Soil Pots	$CdSO_4$	31.2 % YR	6.9	0.01	Taylor and Allinson (1981)
Wheat/Grain	29	Greenhouse/Soil Pots	$CdSO_4$/Sludge	91 % YR	7.5	0.05	Mitchell et al. (1978)
Lettuce/Tops	28.3	Greenhouse/Soil Pots	$CdCl_2$ + $CaCO_3$	23.2 % YR	6.9	0.05	Singh (1981)
Lettuce/Tops	28.3	Greenhouse/Soil Pots	$CaCO_3$ + $CdCl_2$	2 % YR (N.S.)	7.0	0.05	Singh (1981)
Peas-Perf/Pod	28.2	Greenhouse/Soil Pots	$CdCl_2$	92 % YR	5.1	0.05	John (1973)
Bermuda Grass/Tops	28	Greenhouse/Soil Pots	Sludge/$CdSO_4$	12 % YR	7.5	NR	Bingham et al. (1976)
Wheat/Grain	28	Greenhouse/Soil Pots	$CdSO_4$/Sludge	70 % YR	7.5	0.05	Mitchell et al. (1978)
Lettuce/Tops	27.5	Greenhouse/Soil Pots	Al Precip/$CdCl_2$	6 % YR (N.S.)	6.6	0.05	Singh (1981)
Lettuce/Tops	27.1	Greenhouse/Soil Pots	Al Precip/$CdCl_2$	15.2 % YR	6.6	0.05	Singh (1981)
Alfalfa/Tops	27	Greenhouse/Soil Pots	Sludge/$CdSO_4$	28 % YR	7.5	NR	Bingham et al. (1976)

Table 38. Phytotoxicity of cadmium in vegetation, continued.

Plant/Tissue	Tissue Concentration (ppm)	Type of Experiment	Chemical Form Applied	Hazard Response	Soil pH	Significant Level	Reference
Field Bean/Leaf	27	Greenhouse/Solution Culture	$CdSO_4$	66 % YR	5.0-5.5	NR	Page et al. (1972)
Carrot/Tubers	26.8	Greenhouse/Soil Pots	$CdCl_2$	8.2 % YR (N.S.)	5.1	0.05	John (1973)
Tall Fescue/Tops	26	Greenhouse/Soil Pots	Sludge/$CdSO_4$	2 % YR	7.5	NR	Bingham et al. (1976)
Lettuce/Tops	25.7	Greenhouse/Soil Pots	Fe Precip/$CdCl_2$	1.3 % YR (N.S.)	6.6	0.05	Singh (1981)
Lettuce/Tops	25.6	Greenhouse/Soil Pots	$CdCl_2$	1.3 % YR (N.S.)	6.6	0.05	Singh (1981)
Lettuce/Tops	25.4	Greenhouse/Soil Pots	Fe Precip/$CdCl_2$	21.9 % YR	6.5	0.05	Singh (1981)
Wheat/Grain	25	Greenhouse/Soil Pots	$CdSO_4$/Sludge	18 % YR	5.7	0.05	Mitchell et al. (1978)
Corn-High Accum/Stover	24.9	Field	Sludge	27 % YR	7.4	0.05	Hinesly et al. (1982)
Corn-High Accum/Stover	24.6	Field	Sludge	9.8 % YR (N.S.)	7.4	0.05	Hinesly et al. (1982)
Lettuce/Tops	24.6	Greenhouse/Soil Pots	$CdCl_2$	13.9 % YR (N.S.)	6.5	0.05	Singh (1981)
Lettuce/Tops	24.4	Greenhouse/Soil Pots	$CdCl_2$ + $CaCO_3$	4.4 % YR (N.S.)	7.0	0.05	Singh (1981)
Alfalfa/Tops	24	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5	NR	Bingham et al. (1976)
Corn-High Accum/Stover	23.9	Field	Sludge	5.6 % YR (N.S.)	7.4	0.05	Hinesly et al. (1982)
Lettuce/Tops	23.6	Greenhouse/Soil Pots	Mn Precip/$CdCl_2$	1 % YR (N.S.)	6.5	0.05	Singh (1981)
White Clover/Tops	22.5	Greenhouse/Soil Pots	Sludge/$CdSO_4$	58 % YR	7.5	NR	Bingham et al. (1976)
Field Beans/Leaf	22	Greenhouse/Solution Culture	$CdSO_4$	50 % YR	5.0-5.5	NR	Page et al. (1972)
Corn/Lower Leaves	22	Greenhouse/Solution Culture	$CdCl_2$	2 % YR	5.0	UP	Iwai et al. (1975)
Alfalfa/Tops	21.7	Greenhouse/Soil Pots	$Cd(NO_3)_2 \cdot 4H_2O$	56.2 % YR	6.9	0.01	Taylor and Allinson (1981
White Clover/Tops	21.5	Greenhouse/Soil Pots	Sludge/$CdSO_4$	44 % YR	7.5	NR	Bingham et al. (1976)
Radish/Tuber	21	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Oats/Grain	20.8	Greenhouse/Soil Pots	$CdCl_2$	36 % YR	5.1	0.05	John (1973)
Lettuce/Tops	20.4	Greenhouse/Soil Pots	Mn Precip/$CdCl_2$	18.5 % YR	6.7	0.05	Singh (1981)
Bermuda Grass/Tops	20	Greenhouse/Soil Pots	Sludge/$CdSO_4$	5 % YR	7.5	NR	Bingham et al. (1976)
Corn/Leaf - Shoot	20	Greenhouse/Solution Culture	$CdCl_2$	Onset YR	5.5	NR	Iwai et al. (1975)
Alfalfa/Tops	19.9	Greenhouse/Soil Pots	$CdSO_4$	3.6 % YR	6.9	NR	Taylor and Allinson (1981
Peas-Perf/Seed	19.7	Greenhouse/Soil Pots	$CdCl_2$	99 % YR	5.1	0.05	John (1973)
Corn/Kernal	19	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham (1979)
Carrot/Tuber	19	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Wheat/Grain	19	Greenhouse/Soil Pots	$CdSO_4$/Sludge	61 % YR	7.5	0.05	Mitchell et al. (1978)
Cauliflower/Leaves	18.5	Greenhouse/Soil Pots	$CdCl_2$	2.7 % YR (N.S.)	5.1	0.05	John (1973)
Sudan Grass/Tops	18	Greenhouse/Soil Pots	Sludge/$CdSO_4$	58 % YR	7.5	NR	Bingham et al. (1976)
Corn/Upper Leaves	17	Greenhouse/Solution Culture	$CdCl_2$	2 % YR	5.0	NR	Iwai et al. (1975)
White Clover/Leaf	17	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5	NR	Bingham et al. (1976)
Alfalfa/Tops	17	Greenhouse/Soil Pots	Sludge/$CdSO_4$	20 % YR	7.5	NR	Bingham et al. (1976)
Alfalfa/Tops	16.1	Greenhouse/Soil Pots	$CdSO_4$	13.0 % YR	6.9	NR	Taylor and Allinson (1981
Corn/Shoots	16	Greenhouse/Solution Culture	$CdCl_2$	10 % YR	5.5	NR	Iwai et al. (1975)
Lettuce/Tops	15.5	Greenhouse/Soil Pots	$CaCO_3$ + $CdCl_2$	17.2 % YR	7.1	0.05	Singh (1981)
Turnip/Tuber	15	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Tall Fescue/Tops	15	Greenhouse/Soil Pots	Sludge/$CdSO_4$	1 % YR	7.5	NR	Bingham et al. (1976)
Field Bean/Leaf	15	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Lettuce/Tops	15	Greenhouse/Soil Pots	$CdCl_2$ + $CaCO_3$	21.2 % YR	7.0	0.05	Singh (1981)
Barley-Julia/Shoots	15	Greenhouse/Sand Culture	$CdSO_4$	10 % YR	NR	NR	Davis et al. (1978)
Corn-High Accum/Stover	14.2	Field	Sludge	32 % YR	7.4	0.05	Hinesly et al. (1982)
Lettuce/Tops	14.1	Greenhouse/Soil Pots	Sludge	29.3 % YR	6.8	0.05	Singh (1981)
Wheat/Grain	14	Greenhouse/Soil Pots	$CdSO_4$/Sludge	22 % YR	7.5	0.05	Mitchell et al. (1978)
Tomato/Tops	13.6	Greenhouse/Soil Pots	High Metal Sludge	84 % YR	6.2	0.01	Sterrett et al. (1982)
Tomato/Tops	13.4	Greenhouse/Soil Pots	High Metal Sludge	64 % YR	6.2	0.01	Sterrett et al. (1982)

Table 38. Phytotoxicity of cadmium in vegetation, continued.

Plant/Tissue	Tissue Concentration ppm	Type of Experiment	Chemical Form Applied	Hazard Response	Soil pH	Significant Level	Reference
Corn-Low Accum/Stover	13.2	Field	Sludge	3.9 % Yield Increase (N.S.)	7.4	0.05	Hinesly et al. (1982)
Sudan Grass/Tops	12.5	Greenhouse/Soil Pots	Sludge/$CdSO_4$	43 % YR	7.5	NR	Bingham et al. (1976)
Lettuce/Tops	12.5	Greenhouse/Soil Pots	Fe Precip/$CdCl_2$	23.2 % YR	6.6	0.05	Singh (1981)
Lettuce/Tops	11.8	Greenhouse/Soil Pots	Al Precip/$CdCl_2$	11.9 % YR (N.S.)	6.5	0.05	Singh (1981)
Corn-Low Accum/Stover	11.5	Field	Sludge	8 % Yield Increase (N.S.)	7.4	0.05	Hinesly et al. (1982)
Wheat/Grain	11.5	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Cabbage/Head	11	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Lettuce/Tops	11	Greenhouse/Soil Pots	$CdCl_2$	20.5 % YR	6.5	0.05	Singh (1981)
Corn-High Accum/Stover	10.8	Field	Sludge	38 % YR (N.S.)	7.4	0.05	Hinesly et al. (1982)
Alfalfa/Tops	10.4	Greenhouse/Soil Pots	Mn Percip/$CdCl_2$	3.3 % YR (N.S.)	6.6	0.05	Singh (1981)
Corn-High Accum/Stover	10.3	Field	Sludge	11.8 % YR (N.S.)	7.4	0.05	Hinesly et al. (1982)
Alfalfa/Tops	10.3	Greenhouse/Soil Pots	$Cd(NO_3)_2\ 4H_2O$	27.3 % YR	6.9	0.01	Taylor and Allinson (1981)
Peas-Perf/Seed	10.1	Greenhouse/Soil Pots	$CdCl_2$	10.1 % YR	5.1	0.05	John (1973)
White Clover/Tops	10	Greenhouse/Soil Pots	Sludge/$CdSO_4$	15 % YR	7.5	NR	Bingham et al. (1976)
Alfalfa/Tops	10	Greenhouse/Soil Pots	$CdSO_4$	9.8 % Yield Increase	6.9	NR	Taylor and Allinson (1981)
Zucchini/Fruit	10	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Peas-Perf/Pod	9.5	Greenhouse/Soil Pots	$CdCl_2$	30 % YR (N.S.)	5.1	0.05	John (1973)
Sudan Grass/Tops	9	Greenhouse/Soil Pots	Sludge/$CdSO_4$	30 % YR	7.5	NR	Bingham et al. (1976)
Sudan Grass/Leaf	9	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5	NR	Bingham et al. (1976)
Bermuda Grass/Tops	9	Greenhouse/Soil Pots	Sludge/$CdSO_4$	4 % YR	7.5	NR	Bingham et al. (1976)
Bean/Leaf	9	Greenhouse/Solution Culture	$CdSO_4$	27.5 % YR	5.0-5.5	NR	Page et al. (1972)
Alfalfa/Tops	8.5	Greenhouse/Soil Pots	$CdSO_4$	4.3 % Yield Increase	6.9	NR	Taylor and Allinson (1981)
Corn-Low Accum/Stover	8.48	Field	Sludge	0.7 % YR (N.S.)	7.4	0.05	Hinesly et al. (1982)
Barley-Julia/Shoots	8	Greenhouse/Sand Culture	$CdSO_4$	Upper Critical Level	NR	NR	Beckett and David (1977)
Alfalfa/Tops	8	Greenhouse/Soil Pots	Sludge/$CdSO_4$	16 % YR	7.5	NR	Bingham et al. (1976)
Cabbage/Tops	7.18	Greenhouse/Soil Pots	High Metal Sludge	65 % YR	6.2	0.01	Sterrett et al. (1982)
Cabbage/Tops	7.17	Greenhouse/Soil Pots	High Metal Sludge	67 % YR	6.2	0.01	Sterrett et al. (1982)
Alfalfa/Tops	7.1	Greenhouse/Soil Pots	$CdSO_4$	3.5 % Yield Increase	6.9	NR	Taylor and Allinson (1981)
Tomato/Ripe Fruit	7	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Soybean/Leaf	7	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5	NR	Bingham et al. (1979)
Tall Fescue/Tops	7	Greenhouse/Soil Pots	Sludge/$CdSO_4$	6 % YR	7.5	NR	Bingham et al. (1976)
Soybean/Dry Bean	7	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Lettuce/Tops	7	Greenhouse/Soil Pots	Sludge	19 % YR	7.0	0.05	Singh (1981)
Lettuce/Tops	6.6	Greenhouse/Soil Pots	Sludge	52.3 % Yield Increase	6.7	0.05	Singh (1981)
Sudan Grass/Tops	6	Greenhouse/Soil Pots	Sludge/$CdSO_4$	18 % YR	7.5	NR	Bingham et al. (1976)
Tall Fescue/Tops	6	Greenhouse/Soil Pots	Sludge/$CdSO_4$	1 % YR	7.5	NR	Bingham et al. (1976)
Alfalfa/Tops	5.9	Greenhouse/Soil Pots	$CdSO_4$	20.3 % Yield Increase	6.9	NR	Taylor and Allinson (1981)
Corn-High Accum/Stover	5.78	Field	Sludge	22 % YR (N.S.)	7.4	0.05	Hinesly et al. (1982)
White Clover/Tops	5.5	Greenhouse/Soil Pots	Sludge/$CdSO_4$	20 % YR	7.5	NR	Bingham et al. (1976)
Lettuce/Tops	5.3	Greenhouse/Soil Pots	Sludge	24 % Yield Increase	6.7	0.05	Singh (1981)
Alfalfa/Tops	5	Greenhouse/Soil Pots	Sludge/$CdSO_4$	8 % YR	7.5	NR	Bingham et al. (1975)

Table 38. Phytotoxicity of cadmium in vegetation, continued.

Plant/Tissue	Tissue Concentration (ppm)	Type of Experiment	Chemical Form Applied	Hazard Response	Soil pH	Significant Level	Reference
Barley-Larker/Straw	4.57	Greenhouse/Soil Pots	Sludge	11 % Yield Increase	6.0	0.01	Chang et al. (1982)
Corn-Low Accum/Stover	4.18	Field	Sludge	11.3 % Yield Increase (N.S.)	7.4	0.05	Hinesly et al. (1982)
Bermuda Grass/Tops	4	Greenhouse/Soil Pots	Sludge/$CdSO_4$	1 % YR	7.5	NR	Bingham et al. (1976)
Lettuce/Tops	3.8	Greenhouse/Soil Pots	Sludge	11.9 % YR	6.6	0.05	Singh (1981)
Corn-Low Accum/Stover	3.53	Field	Sludge	2.2 % Yield Increase (N.S.)	7.4	0.05	Hinesly et al. (1982)
Alfalfa/Tops	3.4	Greenhouse/Soil Pots	$Cd(NO_3)_2$ $4H_2O$	25.7 % YR (N.S.)	6.9	0.01	Taylor and Allinson (1981
Lettuce/Tops	3.2	Greenhouse/Soil Pots	Sludge	10 % Yield Increase	6.9	0.05	Singh (1981)
Alfalfa/Tops	3.1	Greenhouse/Soil Pots	None	Background	6.9	NR	Taylor and Allinson (1981
Rice/Leaf	3	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Corn-Low Accum/Stover	2.83	Field	Sludge	2.9 % Yield Increase (N.S.)	7.4	0.05	Hinesly et al. (1982)
Lettuce/Tops	2.8	Greenhouse/Soil Pots	Sludge	55 % Yield Increase	7.0	0.05	Singh (1981)
Alfalfa/Tops	2.6	Greenhouse/Soil Pots	$CdSO_4$	13.6 % YR	6.9	NR	Taylor and Allinson (1981
Sudan Grass/Tops	2.5	Greenhouse/Soil Pots	Sludge/$CdSO_4$	8 % YR	7.5	NR	Bingham et al. (1976)
White Clover/Tops	2.5	Greenhouse/Soil Pots	Sludge/$CdSO_4$	5 % Yield Increase	7.5	NR	Bingham et al. (1976)
Barley-Barsoy/Straw	2.45	Greenhouse/Soil Pots	Sludge	15 % YR (N.S.)	6.0	0.01	Chang et al. (1982)
Lettuce/Tops	2.4	Greenhouse/Soil Pots	Sludge	3.3 % Yield Increase (N.S.)	6.9	0.05	Singh (1981)
Alfalfa/Tops	2.4	Greenhouse/Soil Pots	$Cd(NO_3)_2 \cdot 4H_2O$	16.5 % YR	6.9	0.01	Taylor and Allinson (1981
Barley-Briggs/Straw	2.30	Greenhouse/Soil Pots	Sludge	27 % YR (N.S.)	6.0	0.01	Chang et al. (1982)
Alfalfa/Tops	2.3	Greenhouse/Soil Pots	None	Background	6.9	NR	Taylor and Allinson (1981
Alfalfa/Tops	2.2	Greenhouse/Soil Pots	$CdSO_4$	1.4 % YR	6.9	NR	Taylor and Allinson (1981
Barley-Florida/Straw	2.19	Greenhouse/Soil Pots	Sludge	14 % Yield Increase	6.0	0.01	Chang et al. (1982)
Alfalfa/Tops	2.1	Greenhouse/Soil Pots	$CdSO_4$	3.0 % Yield Increase	6.9	NR	Taylor and Allinson (1981
Rice/Grain	2	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Corn/Kernal	2	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Alfalfa/Tops	2	Greenhouse/Soil Pots	Sludge/$CdSO_4$	2 % YR	7.5	NR	Bingham et al. (1976)
Sudan Grass/Tops	2	Greenhouse/Soil Pots	Sludge/$CdSO_4$	8 % YR	7.5	NR	Bingham et al. (1976)
Corn-Low Accum/Stover	1.87	Field	Sludge	16 % YR (N.S.)	7.4	0.05	Hinesly et al. (1982)
Corn-High Accum/Grain	1.83	Field	Sludge	14 % YR (N.S.)	7.4	0.05	Hinesly et al. (1982)
Corn-Low Accum/Stover	1.82	Field	Sludge	0.9 % Yield Increase (N.S.)	7.4	0.05	Hinesly et al. (1982)
Corn/High Accum/Grain	1.70	Field	Sludge	11.5 % YR (N.S.)	7.4	0.01	Hinesly et al. (1982)
Field Bean/Dry Bean	1.7	Greenhouse/Soil Pots	Sludge/$CdSO_4$	25 % YR	7.5-7.8	NR	Bingham et al. (1975)
Corn-Low Accum/Stover	1.66	Field	Sludge	11.7 % YR (N.S.)	7.4	0.05	Hinesly et al. (1982)
Lettuce/Shoots	1.6	Greenhouse/Soil Pots	None	Background	5.7 & 7.5	0.05	Mitchell et al. (1978)
Lettuce/Tops	1.6	Greenhouse/Soil Pots	None	Background	6.6	0.05	Singh (1981)
Corn-High Accum/Grain	1.48	Field	Sludge	6 % YR (N.S.)	7.4	0.05	Hinesly et al. (1982)
Corn-High Accum/Stover	1.45	Field	None	Background	7.4	0.01	Hinesly et al. (1982)
Barley-Larker/Leaf	1.27	Greenhouse/Soil Pots	Sludge	11 % Yield Increase	6.0	0.01	Chang et al. (1982)
Corn-High Accum/Stover	1.22	Field	None	Background	7.4	0.01	Hinesly et al. (1982)
Lettuce/Leaves cv Bibb	1.18	Field	None	Background	4.6	NR	Giordano et al. (1979)
Corn-High Accum/Grain	1.12	Field	Sludge	5 % YR (N.S.)	7.4	0.05	Hinesly et al. (1982)
Tomato/Foliage	1.11	Field	None	Background	4.7	NR	Giordano et al. (1979)

Table 38. Phytotoxicity of cadmium in vegetation, continued.

Plant/Tissue	Tissue Concentration (ppm)	Type of Experiment	Chemical Form Applied	Hazard Response	Soil pH	Significant Level	Reference
Oats/Straw	0.48	Field	None	Background	6.5	0.05	Dudas and Pawluk (1977)
Tomato/Tops	0.46	Greenhouse/Soil Pots	Low Metal Sludge	26 % YR	7.1	0.01	Sterrett et al. (1982)
Tomato/Tops	0.45	Greenhouse/Soil Pots	Low Metal Sludge	16 % YR	7.1	0.01	Sterrett et al. (1982)
Cabbage/Tops	0.45	Greenhouse/Soil Pots	None	Background	NR	0.01	Sterrett et al. (1982)
Barley-Barsoy/Grain	0.40	Greenhouse/Soil Pots	Sludge	15 % YR (N.S.)	6.0	0.01	Chang et al. (1982)
Barley-Larker/Grain	0.40	Greenhouse/Soil Pots	Sludge	11 % Yield Increase	6.0	0.01	Chang et al. (1982)
Barley/Straw	0.35	Field	None	Background	6.9	0.05	Dudas and Pawluk (1977)
Oats/Straw	0.31	Field	None	Background	7.4	0.05	Dudas and Pawluk (1977)
Barley/Straw	0.30	Field	None	Background	6.2	0.05	Dudas and Pawluk (1977)
Silver Sagebrush	0.30	Field	None	Background	6.2	NR	Severson et al. (1977)
Lettuce/Leaves cv Great Lakes	0.30	Field	None	Background	5.1	NR	Giordano et al. (1979)
Sweet Corn/Foliage	0.29	Field	None	Background	5.1	NR	Giordano et al. (1979)
Barley-Barsoy/Leaf	0.28	Greenhouse/Soil Pots	Sludge	15 % YR (N.S.)	6.0	0.01	Chang et al. (1982)
Corn-Low Accum/Stover	0.271	Field	None	Background	7.4	0.01	Hinesly et al. (1982)
Broccoli/Flowers	0.27	Field	None	Background	4.7	NR	Giordano et al. (1979)
Wheat/Straw	0.26	Field	None	Background	5.7	0.05	Dudas and Pawluk (1977)
Corn-Low Accum/Stover	0.258	Field	None	Background	7.4	0.01	Hinesly et al. (1982)
Barley-Briggs/Straw	0.25	Greenhouse/Soil Pots	Sludge	2 % Yield Increase	6.0	0.01	Chang et al. (1982)
Wheat/Straw	0.25	Field	None	Background	6.2	0.05	Dudas and Pawluk (1977)
Barley/Straw	0.25	Field	None	Background	6.4	0.05	Dudas and Pawluk (1977)
Pepper/Fruit	0.25	Field	None	Background	5.1	NR	Giordano et al. (1979)
Pepper/Fruit	0.24	Field	None	Background	4.6	NR	Giordano et al. (1979)
Barley/Straw	0.24	Field	None	Background	7.4	0.05	Dudas and Pawluk (1977)
Barley/Straw	0.22	Field	None	Background	6.5	0.05	Dudas and Pawluk (1977)
Wheat/Straw	0.22	Field	None	Background	6.9	0.05	Dudas and Pawluk (1977)
Tomato/Tops	0.21	Greenhouse/Soil Pots	None	Background	NR	0.01	Sterrett et al. (1982)
Cantaloupe/Mellon	0.21	Field	None	Background	4.6	NR	Giordano et al. (1979)
Cantaloupe/Mellon	0.21	Field	None	Background	6.3	NR	Giordano et al. (1979)
Wheat Straw	0.21	Field	None	Background	6.4	0.05	Dudas and Pawluk (1977)
Corn-Low Accum/Leaves	0.198	Field	None	Background	7.4	0.01	Hinesly et al. (1982)
Cabbage/Heads	0.19	Field	None	Background	4.6	NR	Giordano et al. (1979)
Pepper/Fruit	0.19	Field	None	Background	6.3	NR	Giordano et al. (1979)
Barley-Briggs/Leaf	0.19	Greenhouse/Soil Pots	Sludge	15 % YR (N.S.)	6.0	0.01	Chang et al. (1982)
Barley-Briggs/Grain	0.19	Greenhouse/Soil Pots	Sludge	27 % YR (N.S.)	6.0	0.01	Chang et al. (1982)
Corn-Low Accum/Leaves	0.180	Field	None	Background	7.4	0.31	Hinesly et al. (1982)
Corn-Low Accum/Stover	0.165	Field	None	Background	7.4	0.01	Hinesly et al. (1982)
Cabbage/Heads	0.16	Field	None	Background	6.3	NR	Giordano et al. (1979)
Bean/Foliage	0.16	Field	None	Background	5.1	NR	Giordano et al. (1979)
Squash/Fruit	0.15	Field	None	Background	5.1	NR	Giordano et al. (1979)
Squash/Foliage	0.15	Field	None	Background	5.1	NR	Giordano et al. (1979)
Beans/Pods Only	0.14	Field	None	Background	5.1	NR	Giordano et al. (1979)
Barley-Barsoy/Grain	0.14	Greenhouse/Soil Pots	Sludge	4 % YR (N.S.)	6.0	0.01	Chang et al. (1982)
Barley-Larker/Grain	0.14	Greenhouse/Soil Pots	Sludge	11 % Yield Increase	6.0	0.01	Chang et al. (1982)
Corn-Low Accum/Grain	0.131	Field	Sludge	2.3 % YR (N.S.)	7.4	0.01	Hinesly et al. (1982)
Wheat/Seed	0.120	Field	None	Background	6.5	0.35	Dudas and Pawluk (1977)

Table 38. Phytotoxicity of cadmium in vegetation, continued.

Plant/Tissue	Tissue Concentration (ppm)	Type of Experiment	Chemical Form Applied	Hazard Response	Soil pH	Significant Level	Reference
Corn-High Accum/Grain	1.10	Field	Sludge	20 % YR	7.4	0.01	Hinesly et al. (1982)
Alfalfa/Tops	1.0	Greenhouse/Soil Pots	None	Background	6.9	0.01	Taylor and Allinson (1981)
White Clover/Tops	1.	Greenhouse/Soil Pots	Sludge/$CdSO_4$	10 % YR	7.5	NR	Bingham et al. (1976)
Corn-High Accum/Leaves	0.981	Field	None	Background	7.4	0.05	Hinesly et al. (1982)
Corn-High Accum/Grain	0.974	Field	Sludge	1 % Yield Increase (N.S.)	7.4	0.05	Hinesly et al. (1982)
Carrot/Root	0.96	Field	None	Background	4.6	NR	Giordano et al. (1979)
Lettuce/Leaves cv Boston	0.95	Field	None	Background	4.6	NR	Giordano et al. (1979)
Corn-High Accum/Grain	0.943	Field	Sludge	11 % Yield Increase (N.S.)	7.4	0.05	Hinesly et al. (1982)
Barley-Larker/Straw	0.94	Greenhouse/Soil Pots	Sludge	11 % Yield Increase	6.0	0.01	Chang et al. (1982)
Corn-High Accum/Leaves	0.927	Field	None	Background	7.4	0.05	Hinesly et al. (1982)
Pepper/Foliage	0.90	Field	None	Background	5.1	NR	Giordano et al. (1979)
Lettuce/Leaves cv Boston	0.90	Field	None	Background	6.3	NR	Giordano et al. (1979)
Cabbage/Tops	0.89	Greenhouse/Soil Pots	Low Metal Sludge	19 % Yield Increase	7.1	0.01	Sterrett et al. (1982)
Lettuce/Leaves cv Romaine	0.88	Field	None	Background	4.6	NR	Giordano et al. (1979)
Lettuce/Leaves cv Great Lakes	0.86	Field	None	Background	4.7	NR	Giordano et al. (1979)
Corn-High Accum/Leaves	0.852	Field	None	Background	7.4	0.01	Hinesly et al. (1982)
Cabbage/Tops	0.85	Greenhouse/Soil Pots	Low Metal Sludge-Peat Moss	9.6 YR	7.1	0.01	Sterrett et al. (1982)
Eggplant/Foliage	0.81	Field	None	Background	4.7	NR	Giordano et al. (1979)
Potato/Foliage	0.80	Field	None	Background	4.7	NR	Giordano et al. (1979)
Lettuce/Tops	0.8	Greenhouse/Soil Pots	None	Background	6.5	0.05	Singh (1981)
Lettuce/Leaves cv Romaine	0.78	Field	None	Background	6.3	NR	Giordano et al. (1979)
Lettuce/Leaves cv Bibb	0.78	Field	None	Background	6.3	NR	Giordano et al. (1979)
Corn-High Accum/Stover	0.753	Field	None	Background	7.4	0.01	Hinesly et al. (1982)
Carrot/Root	0.71	Field	None	Background	6.3	NR	Giordano et al. (1979)
Barley/Straw	0.70	Field	None	Background	6.5	0.05	Dudas and Pawluk (1977)
Barley/Straw	0.67	Field	None	Background	6.4	0.05	Dudas and Pawluk (1977)
Wheat/Straw	0.64	Field	None	Background	7.2	0.05	Dudas and Pawluk (1977)
Corn/Grain-High Accum	0.626	Field	Sludge	24 % YR	7.4	0.01	Hinesly et al. (1982)
Wheat/Straw	0.62	Field	None	Background	6.5	0.05	Dudas and Pawluk (1977)
Barley-Barsoy/Straw	0.62	Greenhouse/Soil Pots	Sludge	4 % YR (N.S.)	6.0	0.01	Chang et al. (1982)
Barley/Straw	0.61	Field	None	Background	5.7	0.05	Dudas and Pawluk (1977)
Alfalfa/Tops	0.60	Greenhouse/Soil Pots	None	Background	6.9	0.01	Taylor and Allinson (1981
Corn-High Accum/Grain	0.568	Field	Sludge	9 % Yield Increase (N.S.)	7.4	0.01	Hinesly et al. (1982)
Barley-Florida/Straw	0.56	Greenhouse/Soil Pots	Sludge	2 % Yield Increase	6.0	0.01	Chang et al. (1982)
Eggplant/Fruit	0.54	Field	None	Background	4.7	NR	Giordano et al. (1979)
Barley-Florida/Grain	0.53	Greenhouse/Soil Pots	Sludge	14 % Yield Increase	6.0	0.01	Chang et al. (1982)
Tomato/Fruit	0.52	Field	None	Background	4.7	0.05	Giordano et al. (1979)
Barley-Florida/Leaf	0.51	Greenhouse/Soil Pots	Sludge	14 % Yield Increase	6.0	0.01	Chang et al. (1982)
Barley/Straw	0.51	Field	None	Background	7.2	0.05	Dudas and Pawluk (1977)
Wheat/Leaves	0.50	Greenhouse/Soil Pots	None	Background	5.7	0.05	Mitchell et al. (1978)
Wheat/Straw	0.50	Field	None	Background	6.4	0.05	Dudas and Pawluk (1977)

Table 38. Phytotoxicity of cadmium in vegetation, continued.

Plant/Tissue	Tissue Concentration (ppm)	Type of Experiment	Chemical Form Applied	Hazard Response	Soil pH	Significant Level	Reference
Barley-Larker/Straw	0.12	Greenhouse/Soil Pots	None	Background	6.0	0.01	Chang et al. (1982)
Barley-Larker/Leaf	0.11	Greenhouse/Soil Pots	Sludge	11 % Yield Increase	6.0	0.01	Chang et al. (1982)
Potato/Tuber	0.11	Field	None	Background	4.7	NR	Giordano et al. (1979)
Barley-Barsoy/Leaf	0.10	Greenhouse/Soil Pots	Sludge	4 % YR (N.S.)	6.0	0.01	Chang et al. (1982)
Sweet Corn/Seed	0.10	Field	None	Background	5.1	NR	Giordano et al. (1979)
Corn-Low Accum/Grain	0.109	Field	Sludge	18 % Yield Increase	7.4	0.05	Hinesly et al. (1982)
Wheat/Leaves	<0.1	Greenhouse/Soil Pots	None	Background	7.5	0.05	Mitchell et al. (1978)
Wheat/Grain	<0.1	Greenhouse/Soil Pots	None	Background	5.7-7.5	0.05	Mitchell et al. (1978)
Corn-Low Accum/Grain	0.095	Field	Sludge	7.9 % YR (N.S.)	7.4	0.05	Hinesly et al. (1982)
Corn-High Accum/Grain	0.090	Field	None	Background	7.4	0.01	Hinesly et al. (1982)
Barley-Florida/Leaf	0.09	Greenhouse/Soil Pots	Sludge	2 % Yield Increase	6.0	0.01	Chang et al. (1982)
Barley-Florida/Grain	0.09	Greenhouse/Soil Pots	Sludge	2 % Yield Increase	6.0	0.01	Chang et al. (1982)
Corn-High Accum/Grain	0.084	Field	None	Background	7.4	0.01	Hinesly et al. (1982)
Barley-Larker/Leaf	0.08	Greenhouse/Soil Pots	None	Background	6.0	0.01	Chang et al. (1982)
Wheat/Seed	0.072	Field	None	Background	6.4	0.05	Dudas and Pawluk (1977)
Beans/Seed	0.07	Field	None	Background	5.1	0.05	Giordano et al. (1979)
Barley-Briggs/Straw	0.07	Greenhouse/Soil Pots	None	Background	6.0	0.01	Chang et al. (1982)
Barley/Seed	0.062	Field	None	Background	6.4	0.05	Dudas and Pawluk (1977)
Corn-Low Accum/Grain	<0.062	Field	Sludge	30 % YR	7.4	0.01	Hinesly et al. (1982)
Corn-Low Accum/Grain	<0.062	Field	Sludge	24 % YR	7.4	0.01	Hinesly et al. (1982)
Corn-Low Accum/Grain	<0.062	Field	Sludge	6.4 % Yield Increase (N.S.)	7.4	0.05	Hinesly et al. (1982)
Corn-Low Accum/Grain	<0.062	Field	Sludge	16.5 % Yield Increase (N.S.)	7.4	0.05	Hinesly et al. (1982)
Corn-Low Accum/Grain	<0.062	Field	Sludge	1.0 % YR (N.S.)	7.4	0.05	Hinesly et al. (1982)
Corn-Low Accum/Grain	<0.062	Field	Sludge	6.1 % YR (N.S.)	7.4	0.05	Hinesly et al. (1982)
Corn-Low Accum/Grain	<0.062	Field	None	Background	7.4	0.01	Hinesly et al. (1982)
Wheat/Seed	0.061	Field	None	Background	6.2	0.05	Dudas and Pawluk (1977)
Barley-Florida/Straw	0.06	Greenhouse/Soil Pots	None	Background	6.0	0.01	Chang et al. (1982)
Oats/Seed	0.060	Field	None	Background	6.5	0.05	Dudas and Pawluk (1977)
Barley-Barsoy/Straw	0.06	Greenhouse/Soil Pots	None	Background	6.0	0.01	Chang et al. (1982)
Barley-Briggs/Grain	0.06	Greenhouse/Soil Pots	Sludge	23 % YR (N.S.)	6.0	0.01	Chang et al. (1982)
Corn-Low Accum/Leaves	0.059	Field	None	Background	7.4	0.01	Hinesly et al. (1982)
Barley/Seed	0.058	Field	None	Background	6.5	0.05	Dudas and Pawluk (1977)
Corn-High Acum/Grain	0.056	Field	None	Background	7.4	0.01	Hinesly et al. (1982)
Barley/Seed	0.052	Field	None	Background	5.7	0.05	Dudas and Pawluk (1977)
Wheat/Seed	0.051	Field	None	Background	5.7	0.05	Dudas and Pawluk (1977)
Barley-Barsoy/Leaf	0.05	Greenhouse/Soil Pots	None	Background	6.0	0.01	Chang et al. (1982)
Barley/Seed	0.044	Field	None	Background	6.2	0.05	Dudas and Pawluk (1977)
Barley/Seed	0.044	Field	None	Background	7.4	0.05	Dudas and Pawluk (1977)
Wheat/Kernel	0.043	Field	None	Background	NR	NR	Wolnik et al. (1983)
Oats/Seed	0.041	Field	None	Background	7.4	0.05	Dudas and Pawluk (1977)
Barley/Seed	0.041	Field	None	Background	6.9	0.05	Dudas and Pawluk (1977)

Table 38. Phytotoxicity of cadmium in vegetation, continued.

Plant/Tissue	Tissue Concentration (ppm)	Type of Experiment	Chemical Form Applied	Hazard Response	Soil pH	Significant Level	Reference
Barley-Florida/Grain	0.04	Greenhouse/Soil Pots	None	Background	6.0	0.01	Chang et al. (1982)
Barley-Larker/Grain	0.04	Greenhouse/Soil Pots	None	Background	6.0	0.01	Chang et al. (1982)
Barley-Briggs/Leaf	<0.04	Greenhouse/Soil Pots	Sludge	23 % YR (W.S.)	6.0	0.01	Chang et al. (1982)
Barley-Florida/Leaf	<0.04	Greenhouse/Soil Pots	None	Background	6.0	0.01	Chang et al. (1982)
Barley-Briggs/Leaf	<0.04	Greenhouse/Soil Pots	None	Background	6.0	0.01	Chang et al. (1982)
Barley-Barsoy/Grain	<0.04	Greenhouse/Soil Pots	None	Background	6.0	0.01	Chang et al. (1982)
Barley-Briggs/Grain	<0.04	Greenhouse/Soil Pots	None	Background	6.0	0.01	Chang et al. (1982)
Barley/Seed	0.039	Field	None	Background	7.2	0.05	Dudas and Pawluk (1977)
Wheat/Seed	0.039	Field	None	Background	7.2	0.05	Dudas and Pawluk (1977)
Barley/Seed	0.039	Field	None	Background	6.4	0.05	Dudas and Pawluk (1977)
Wheat/Seed	0.038	Field	None	Background	6.4	0.05	Dudas and Pawluk (1977)
Barley/Seed	0.035	Field	None	Background	6.5	0.05	Dudas and Pawluk (1977)
Silver Sage Brush	0.03	Field	None	Background	6.2-8.2	NR	Severson et al. (1977)
Western Wheatgrass/Tops	0.03	Field	None	Background	6.2-8.2	NR	Severson et al. (1977)
Wheat/Seed	0.030	Field	None	Background	6.9	0.05	Dudas and Pawluk (1977)

of cadmium that may enter the food chain at either 100 or 50 ppm total soil cadmium concentration.

The total soil cadmium tolerable concentration of 4 ppm was selected for the Helena Valley based on the generally small or nonsignificant yield reductions reported below this level, compared to the higher yield reductions (up to 46.8% for corn shoots) noted at the 5 ppm total soil cadmium level.

3.2.2.2 Extractable soil cadmium

The DTPA extractable soil cadmium phytotoxic and tolerable concentrations selected for the Helena Valley were 30 and 2 ppm, respectively (Table 37). All extractable cadmium concentrations, found in the reviewed literature, that were in excess of 30 ppm were phytotoxic. The hazard level was based on the 25 percent yield reductions that were noted for wheat grain and white clover at concentrations of 30 and 29 ppm, respectively (Bingham et al. 1975). Numerous occurrences of phytotoxicity were noted for a number of species in the 4.8 to 30 ppm extractable cadmium range (Table 37). Of particular interest were the 22 and 25 percent yield reductions for alfalfa and wheat grain at extractable soil cadmium levels of 22 and 23 ppm respectively (Bingham et al. 1976, Mitchell et al. 1978). Extractable soil cadmium concentrations between 2 and 4.8 ppm were associated with both yield increases and yield decreases. Concentrations less than the suggested 2 ppm tolerable level were not generally significantly phytotoxic except under specific experimental conditions (Table 37).

3.2.3 Cadmium in plants

The phytotoxic concentration of cadmium in plant tissues (50 ppm) selected for the Helena Valley was based on the literature in which most concentrations greater than 50 ppm were associated with phytotoxicity. The only exceptions were slight yield increases noted for lettuce and alfalfa at levels of 51.1 and 57.6 ppm, respectively (Table 38). Large yield reductions in ryegrass and wheat grain (50 and 42 percent, respectively) were reported at tissue cadmium levels at or near 40 ppm, (Dijkshoorn et al. 1979, Mitchell et al. 1978) and very large yield reductions for field beans, peas, carrots and wheat grain were noted in the 27 to 40 ppm range (Table 38). Davis et al. (1978) found barley shoot cadmium concentrations of 14 to 16 ppm to be phytotoxic. These authors noted that 15 ppm cadmium in barley shoots was associated with 10 percent yield reduction. It is clear that the 50 ppm phytotoxic hazard level for cadmium concentrations in plant tissue will be associated with phytotoxicity in nearly all cases and that phytotoxicity may occur in many species at notably lower concentrations. All of the above cadmium concentrations far exceed recommended levels for forage and will likely increase the probability of high levels of cadmium entering the food chain.

A tolerable plant tissue cadmium level of 10 ppm was suggested based on the generally low yield reductions that were noted in the literature below this concentration (Table 38). The alfalfa study of Taylor and Allinson (1981) was of particular importance in that these authors reported several cases of increased production up to the 10 ppm cadmium concentration in alfalfa tops. Again, the 10 ppm tolerable level selected for the Helena Valley will allow much higher cadmium concentrations in forages than the maximum recommended level (0.5 ppm) (NRC 1980).

3.3 Lead in soils and plants

3.3.1 Lead literature review

Mean values for total lead concentration in soil range from 10 to 67 ppm, while common levels in plants range from 0.5 to 4 ppm (Kabata-Pendias and Pendias 1984). Meyer et al. (1982) found that background soil lead levels ranged from 3 to 23 ppm (mean of 12 ppm) for 290 locations in the United States. In urban areas soil lead values may be considerably higher due to contamination from automobile exhaust and industrial activity. Lead is not an essential plant element, and is apparently taken up passively from the soil. While plant toxicity to lead has been noted, it is extremely rare even when excessive amounts of lead are added to the soil (Cannon 1976). This is because lead is one of the least mobile of the heavy metals, resulting in generally low lead levels in the soil solution and minimal plant uptake. Chumbley and Unwin (1982) determined that there was no significant correlation between total soil lead and plant lead levels. The low mobility of lead is governed primarily by soil pH, texture, cation exchange capacity and organic matter content (Zimdahl and Arvik 1973, Pepper et al. 1983).

Little specific research has been directed toward the determination of plant and soil lead toxicity levels. Rather, concern has centered around the introduction of lead into the human food chain from plants (either from lead taken up from the soil or from aerially deposited lead on plant surfaces), or from ingestion of lead that is in soil or dust. Tables 39, 40 and 41 summarize the limited number of studies where the phytotoxic concentration of lead in soil and plant tissue has been documented.

3.3.2 Lead in soils

3.3.2.1 Total lead in soils

The suggested total soil lead hazard concentration for the Helena Valley is 1000 ppm. Phytotoxic levels of total soil lead were reported by many authors (Table 39). Values ranged from 100 ppm to 1000 ppm. It must be noted that considerable crop damage may occur to sensitive crops or other crops grown in soils with higher available lead content (i.e. lower pH) at levels considerably lower than the selected hazard level (Table 39). The above problem was exemplified in the following reviewed literature.

McLean et al. (1969) noted significant reductions in alfalfa yields at total soil lead levels of 100 to 1000 ppm in soils with a pH range of 4.9 to 5.7. These authors reported nonsignificant yield reductions at 1000 ppm total soil lead at a pH of 6.3 and no yield reductions at a pH of 7.5. Similar results were reported by these authors for oats: the only significant yield reduction occurred at 1000 ppm total lead at a pH of 5.2. John and VanLaerhoven (1972) found a 30 percent yield reduction in lettuce but no effect to oat yield at a total soil lead level of 1000 ppm and a

Table 39. Phytotoxicity of total lead in soils.

Soil Type	Soil Concentration (ppm)	Soil pH	Chemical Form Applied	Type of Experiment	Plant Species/ Part	Hazard Response	Significance Level	Reference
Drummer Silt Loam	1400 (Calc)	5.9	Pb Acetate	Field	Corn/Stover-Grain	No Effect	NR	Baumhardt and Welch (1972)
Hjorth Silty Clay Loam	1000	3.8	$PbCl_2$	Greenhouse/Soil Pots	Lettuce/Leaf	35.5 % YR	0.05	John and Van Laerhoven (1972)
Hjorth Silty Clay Loam	1000	3.8	$Pb(NO_3)_2$	Greenhouse/Soil Pots	Lettuce/Leaf	25.0 % YR	0.05	John and Van Laerhoven (1972)
Hjorth Silty Clay Loam	1000	3.8	$PbCO_3$	Greenhouse/Soil Pots	Lettuce/Leaf	17.1 % YR	0.05	John and Van Laerhoven (1972)
Hjorth Silty Clay Loam	1000	3.8	$PbCl_2$	Greenhouse/Soil Pots	Oats/Tops	No Effect	0.05	John and Van Laerhoven (1972)
Hjorth Silty Clay Loam	1000	3.8	$Pb(NO_3)_2$	Greenhouse/Soil Pots	Oats/Tops	No Effect	0.05	John and Van Laerhoven (1972)
Hjorth Silty Clay Loam	1000	3.8	$PbCO_3$	Greenhouse/Soil Pots	Oats/Tops	No Effect	0.05	John and Van Laerhoven (1972)
Yolo Loam	1000	4.0	$Pb(NO_3)_2$	Greenhouse/Soil Pots	Barley/Tops	33.3 % YR	0.05	Patel et al. (1977)
Yolo Loam	1000	6.0	$Pb(NO_3)_2$	Greenhouse/Soil Pots	Barley/Tops	17.3 % YR	0.05	Patel et al. (1977)
Yolo Loam	1000	7.0	$Pb(NO_3)_2$	Greenhouse/Soil Pots	Barley/Tops	1.9 % YR (N.S.)	0.05	Patel et al. (1977)
Yolo Loam	1000	8.5	$Pb(NO_3)_2$	Greenhouse/Soil Pots	Barley/Tops	No Effect	0.05	Patel et al. (1977)
Dytchleys Brown Earth	1000	NR	$PbCl_2$	Greenhouse/Soil Pots	Oats/Roots	42.9 % YR	0.01	Khan and Frankland (1984)
Heald Park Brown Earth	1000	NR	PbO	Greenhouse/Soil Pots	Wheat/Roots	6.7 % YR (N.S.)	0.05	Khan and Frankland (1984)
Heald Park Brown Earth	1000	NR	$PbCO_3$	Greenhouse/Soil Pots	Wheat/Roots	12.8 % YR	0.05	Khan and Frankland (1984)
Heald Park Brown Earth	1000	NR	$PbSO_4$	Greenhouse/Soil Pots	Wheat/Roots	7.4 % YR (N.S.)	0.05	Khan and Frankland (1984)
Heald Park Brown Earth	1000	NR	$PbCl_2$	Greenhouse/Soil Pots	Wheat Roots	33.7 % YR	0.01	Khan and Frankland (1984)
Heald Park Brown Earth	1000	NR	$PbCl_2/PbO$	Greenhouse/Soil Pots	Radish/Roots	19.8 % YR	0.01	Khan and Frankland (1984)
Dytchleys Brown Earth	500	NR	$PbCl_2$	Greenhouse/Soil Pots	Oat/Roots	36.8 % YR	0.01	Khan and Frankland (1984)
Heald Park Brown Earth	500	NR	$PbCl_2$	Greenhouse/Soil Pots	Wheat/Roots	14.8 % YR	0.01	Khan and Frankland (1984)
Heald Park Brown Earth	500	NR	$PbCl_2/PbO$	Greenhouse/Soil Pots	Radish/Roots	4.6 % YR (N.S.)	0.05	Khan and Frankland (1984)
	400				Oats	No YR		Pruves (1977)
	400				Lettuce	No YR		Pruves (1977)
	400				Clover	No YR		Pruves (1977)
Paxton Fine Sandy Loam	250	4.5-6.4	$Pb(NO_3)_2$	Greenhouse/Soil Pots	Ryegrass/Tops	No YR	0.01	Allinson and Dziaco (1981)
Paxton Fine Sandy Loam	250	4.5-6.4	$Pb(NO_3)_2$	Greenhouse/Soil Pots	Oats/Seed	No YR	0.01	Allinson and Dziaco (1981)
Merrimac Fine Sandy Loam	250	6.9	$Pb(NO_3)_2$	Greenhouse/Soil Pots	Alfalfa/Tops	17.9 % YR (N.S.)	0.01	Taylor and Allinson (1981)
Paxton Fine Sandy Loam	250	6.9	$Pb(NO_3)_2$	Greenhouse/Soil Pots	Alfalfa/Tops	6.7 % YR (N.S.)	0.01	Taylor and Allinson (1981)
Bloomfield Loamy Sand	250	6.0	$PbCl_2$	Greenhouse/Soil Pots	Corn/Shoots	41.7 % YR	0.01	Miller et al. (1977)

Table 39. Phytotoxicity of total lead in soils, continued.

Soil Type	Soil Concentration (ppm)	Soil pH	Chemical Form Applied	Type of Experiment	Plant Species/ Part	Hazard Response	Significance Level	Reference
ght Textured	214	5.-8.1	Sludge	Field	Spring Greens	Satisfactory Yields	NA	Shumbley and Unwin (1982)
ester Silt Loam	212	5.2	$PbCl_2$	Greenhouse/Soil Pots	Corn/Tops	2.1 % YR (N.S.)	0.05	Lagerwerff et al. (1973)
ester Silt Loam	212	7.2	$PbCl_2$	Greenhouse/Soil Pots	Alfalfa/Tops	12.1 % YR (N.S.)	0.05	Lagerwerff et al. (1973)
ester Silt Loam	212	5.2	$PbCl_2$	Greenhouse/Soil Pots	Alfalfa/Tops	2.0 % YR (N.S.)	0.05	Lagerwerff et al. (1973)
ester Silt Loam	212	7.2	$PbCl_2$	Greenhouse/Soil Pots	Alfalfa/Tops	17.5 % Yield Increase	0.05	Lagerwerff et al. (1973)
ngo Silt	106	5.6	Sludge	Field	Corn/Grain	No YR	0.05	Giordano et al. (1975)
ght Textured	176	5.-8.1	Sludge	Field	Potato (Tuber)	Satisfactory Yields	NA	Chumbley and Unwin (1982)
ght Textured	156	5.-8.1	Sludge	Field	Sweet Corn (Edible POR)	Satisfactory Yields	NA	Chumbley and Unwin (1982)
ght Textured	155	5.-8.1	Sludge	Field	Lettuce (Edible POR)	Satisfactory Yields	NA	Chumbley and Unwin (1982)
oomfield Loamy Sand	125	6.0	$PbCl_2$	Greenhouse/Soil Pots	Corn/Shoots	13.5 % YR (N.S.)	0.01	Miller et al. (1977)
ght Textured	117	5.-8.1	Sludge	Field	Cabbage	Satisfactory Yields	NA	Chumbley and Unwin (1982)
ester Silt Loam	113	5.2	$PbCl_2$	Greenhouse/Soil Pots	Corn/Tops	7.8 % Yield Increase	0.05	Lagerwerff et al. (1973)
ester Silt Loam	113	7.2	$PbCl_2$	Greenhouse/Soil Pots	Corn/Tops	13.0 % YR (N.S.)	0.05	Lagerwerff et al. (1973)
ester Silt Loam	113	5.2-7.2	$PbCl_2$	Greenhouse/Soil Pots	Alfalfa/Tops	No Effect	0.05	Lagerwerff et al. (1973)
bow Loam	109	7.7	$PbCl_2$	Greenhouse/Soil Pots	Bromegrass/Tops	7.9 % YR from 29 ppm (N.S.)	0.05	Karamanos et al. (1976)
bow Loam	109	7.7	$PbCl_2$	Greenhouse/Soil Pots	Alfalfa/Tops	24.5% YR from 29 ppm	0.05	Karamanos et al. (1976)
itville Loam	108	6.3	$PbCl_2$	Greenhouse/Soil Pots	Alfalfa/Tops	0.09 % YR from 28 ppm (N.S.)	0.05	Karamanos et al. (1976)
quith Fine Sandy Loam	106	6.6	$PbCl_2$	Greenhouse/Soil Pots	Alfalfa/Tops	10.7 % YR from 26 ppm (N.S.)	0.05	Karamanos et al. (1976)
quith Fine Sandy Loam	106	6.6	$PbCl_2$	Greenhouse/Soil Pots	Bromegrass/Tops	17.8 % Yield Increase 26 ppm (N.S.)	0.05	Karamanos et al. (1976)
tchleys Brown Earth	100	NR	$PbCl_2$	Greenhouse/Soil Pots	Oats/Roots	15.9 % Yr (N.S.)	0.05	Khan and Frankland (1984)
rface Soils 0-10 cm	15	NR	None	Field	NR	Background Helena Valley	NA	Miesch and Huffman (1972)
rface Soils 0-10 cm	11.6	8.0	None	Field	Range/Forage	Background Helena Valley	NA	EPA (1986)
bow Loam	9	7.7	None	Field	NR	Background	NA	Karamanos et al. (1976)
itville Loam	8	6.3	None	Field	NR	Background	NA	Karamanos et al. (1976)
squith Fine Sandy Loam	6	6.6	None	Field	NR	Background	NA	Karamanos et al. (1976)

Table 40. Phytotoxicity of extractable lead in soils.

Soil Type	Soil Concentration (ppm)	Soil pH	Chemical Form Applied	Type of Experiment	Plant Species/ Part	Hazard Response	Extractant	Significance Level	Reference
Uplands Sand 15-30 cm	367	5.2	$PbCl_2$	Greenhouse/Soil Pots	Oats/Grain	Yield Increase	1N NH_4OAc	NR	MacLean et al. (1969)
Uplands Sand 15-30 cm	367	5.2	$PbCl_2$	Greenhouse/Soil Pots	Oats/Straw	13.3 % YR	1N NH_4OAc	NR	MacLean et al. (1969)
Uplands Sand 15-30 cm	367	5.2	$PbCl_2$	Greenhouse/Soil Pots	Alfalfa/Tops	71.4 % YR	1N NH_4OAc	NR	MacLean et al. (1969)
Grenville Sandy Loam	356	7.4	$PbCl_2$	Greenhouse/Soil Pots	Oats/Grain	Yield Increase	1N NH_4OAc	NR	MacLean et al. (1969)
Grenville Sandy Loam	356	7.4	$PbCl_2$	Greenhouse/Soil Pots	Oats/Straw	Yield Increase	1N NH_4OAc	NR	MacLean et al. (1969)
Grenville Sandy Loam	356	7.4	$PbCl_2$	Greenhouse/Soil Pots	Alfalfa/Tops	No Effect	1N NH_4OAc	NR	MacLean et al. (1969)
Uplands Sand 0-15 cm	283	4.9	$PbCl_2$	Greenhouse/Soil Pots	Oats/Grain	Yield Increase	1N NH_4OAc	NR	MacLean et al. (1969)
Uplands Sand 0-15 cm	283	4.9	$PbCl_2$	Greenhouse/Soil Pots	Oats/Straw	1.1 % YR	1N NH_4OAc	NR	MacLean et al. (1969)
Uplands Sand 0-15 cm	283	4.9	$PbCl_2$	Greenhouse/Soil Pots	Alfalfa/Tops	42.3 % YR	1N NH_4OAc	NR	MacLean et al. (1969)
Chester Silt Loam	212	5.2	$PbCl_2$	Greenhouse/Soil Pots	Corn/Tassel	Yield Increase	1N HCl	0.05	Lagerwerff et al. (1973)
Chester Silt Loam	212	5.2	$PbCl_2$	Greenhouse/Soil Pots	Corn/Leaves	Yield Increase	1N HCl	0.05	Lagerwerff et al. (1973)
Chester Silt Loam	212	5.2	$PbCl_2$	Greenhouse/Soil Pots	Corn/Stalks	12.9 % YR (N.S.)	1N HCl	0.05	Lagerwerff et al. (1973)
Chester Silt Loam	212	7.2	$PbCl_2$	Greenhouse/Soil Pots	Corn/Tassel	Yield Increase	1N HCl	0.05	Lagerwerff et al. (1973)
Chester Silt Loam	212	7.2	$PbCl_2$	Greenhouse/Soil Pots	Corn/Leaves	No Effect	1N HCl	0.05	Lagerwerff et al. (1973)
Chester Silt Loam	212	7.2	$PbCl_2$	Greenhouse/Soil Pots	Corn/Stalks	12.3 % YR (N.S.)	1N HCl	0.05	Lagerwerff et al. (1973)
Chester Silt Loam	212	5.2	$PbCl_2$	Greenhouse/Soil Pots	Alfalfa/Tops	2.9 % YR (N.S.)	1N HCl	0.05	Lagerwerff et al. (1973)
Chester Silt Loam	212	7.2	$PbCl_2$	Greenhouse/Soil Pots	Alfalfa/Tops	Yield Increase	1N HCl	0.05	Lagerwerff et al. (1973)
Gramby Sandy Loam	124	5.8	$PbCl_2$	Greenhouse/Soil Pots	Oats/Grain	Yield Increase	1N NH_4OAc	NR	MacLean et al. (1969)
Gramby Sandy Loam	124	5.8	$PbCl_2$	Greenhouse/Soil Pots	Oats/Straw	3.8 % YR	1N NH_4OAc	NR	MacLean et al. (1969)
Gramby Sandy Loam	124	5.8	$PbCl_2$	Greenhouse/Soil Pots	Alfalfa/Tops	Yield Increase	1N NH_4OAc	NR	MacLean et al. (1969)
Gramby Sandy Loam	7.0	6.1	$PbCl_2$	Greenhouse/Soil Pots	Oat/Straw and Grain	Yield Increase	1N NH_4OAc	NR	MacLean et al. (1969)
					Alfalfa/Tops	No Effect	1N NH_4OAc	NR	MacLean et al. (1969)
Uplands Sand 0-30	7.0	5.2-5.7	$PbCl_2$	Greenhouse/Soil Pots	Alfalfa/Tops	9.6 % Yield Increase to 4.8 % YR	1N NH_4OAc	NR	MacLean et al. (1969)
Uplands Sand 0-30	7.0	5.2-5.7	$PbCl_2$	Greenhouse/Soil Pots	Oats/Straw and Grain				
Gramby Sandy Loam	4.2	6.1	None	Greenhouse/Soil Pots	Oats - Alfalfa	Background	1N NH_4OAc	NR	MacLean et al. (1969)
A - Horizon NGP[A]	2.	6.2-8.2	None	Field	Native Vegetation	Background	EDTA	NR	Severson et al. (1977)
Helena Valley Soils	1.89	8.0	None	Field	Forage/Range	Background	DTPA	NA	EPA (1986)
Grenville Sandy Loam	1.4	7.6	None	Greenhouse/Soil Pots	Oats - Alfalfa	Background	1N NH_4OAc	NR	MacLean et al. (1969)
C - horizon NGP	1.	7.0-8.9	None	Field	Native Vegetation	Background	EDTA	NR	Severson et al. (1977)
A - Horizon NGP	0.6	6.2-8.2	None	Field	Native Vegetation	Background	DTPA	NR	Severson et al. (1977)
Merrimac Fine Sandy Loam	0.5	6.9	None	Greenhouse/Soil Pots	Alfalfa	Background	NH_4OAc	NR	Taylor and Allinson (1981)
C - horizon NGP	0.3	7.0-8.9	None	Field	Native Vegetation	Background	DTPA	NR	Severson et al. (1977)
A - Horizon NGP	0.3	6.2-8.2	None	Field	Native Vegetation	Background	NH_4OAc	NR	Severson et al. (1977)
C - Horizon NGP	0.1	7.0-8.9	None	Field	Native Vegetation	Background	NH_4OAc	NR	Severson et al. (1977)

A Northern Great Plains

Table 41. Phytotoxicity of lead in vegetation.

Plant/Tissue	Tissue Concentration (ppm)	Type of Experiment	Chemical Form Applies	Hazard Response	Significance Level	Reference
Alfalfa/Tops	357.8	Greenhouse/Soil Pots	$PbCl_2$	57.7 % YR	Prob 0.05 - NR	MacLean et al. (1969)
Oat/Straw	202	Greenhouse/Soil Pots	$PbCl_2$	No Effect	Prob 0.05 - NR	MacLean et al. (1969)
Corn/Middle Leaves	148	Greenhouse/Soil Pots	$PbCl_2$	No Sig YR	0.05	Lagerwerff et al. (1973)
Corn/Middle Leaves	141	Greenhouse/Soil Pots	$PbCl_2$	No Sig YR	0.05	Lagerwerff et al. (1973)
Lettuce/Leaves	140.6	Greenhouse/Soil Pots	$Pb(NO_3)_2$	25 % YR	0.05	John and VanLaerhoven (1972)
Lettuce/Leaves	138.9	Greenhouse/Soil Pots	$PbCl_2$	36 % YR	0.05	John and VanLaerhoven (1972)
Lettuce/Leaves	126.0	Greenhouse/Soil Pots	$PbCO_3$	17 % YR	0.05	John and VanLaerhoven (1972)
Alfalfa/Tops	65.0	Greenhouse/Soil Pots	$Pb(NO_3)_2$	No Effect	0.01	Taylor and Allinson (1981)
Alfalfa/Tops	57.5	Greenhouse/Soil Pots	$PbSO_4$	37 % YR	0.01	Taylor and Allinson (1981)
Alfalfa/Tops	56.8	Greenhouse/Soil Pots	$PbSO_4$	10 % YR	0.01	Taylor and Allinson (1981)
Alfalfa	54.8	Greenhouse/Soil Pots	$PbCl_2$	No Effect	NR	MacLean et al. (1969)
Lettuce/Leaves	50.0	Greenhouse/Soil Pots	None	Background	NA	John and VanLaerhoven (1972)
Alfalfa/Tops	45.2	Greenhouse/Soil Pots	$PbCl_2$	15 % YR		MacLean et al. (1969)
Corn/Tops	37.8	Field	Pb Acetate	No Effect	0.01	Baumhardt and Welch (1972)
Oat/Tops	37.1	Greenhouse/Soil Pots	$PbCl_2$	No Effect	0.05	John and VanLaerhoven (1972)
Oat/Tops	35.7	Greenhouse/Soil Pots	$Pb(NO_3)_2$	No Effect	0.05	John and VanLaerhoven (1972)
Barley Seedlings	35.	Greenhouse/Sand Culture	$Pb(NO_3)_2$	10 % YR	0.05	Davis et al. (1978)
Oat/Tops	28.6	Greenhouse/Soil Pots	$PbCO_3$	No Effect	0.05	John and VanLaerhoven (1972)
Barley Seedlings/Tops	25	Greenhouse/Sand Culture	$Pb(NO_3)_2$	Onset of Growth Reduction		Davis et al. (1978)
Oat/Grain	23.1	Greenhouse/Soil Pots	$PbCl_2$	No Sig YR		MacLean et al. (1969)
Oat/Roots	20.3	Greenhouse/Soil Pots		Background		John and VanLaerhoven (1972)
Alfalfa	14-17.1	Greenhouse/Soil Pots	$PbCl_2$	No Effect	0.05	Lagerwerff et al. (1973)
Alfalfa/Tops	11.8	Greenhouse/Soil Pots	$PbCl_2$	No Sig YR		Karamanos et al. (1976)
Alfalfa/Tops	10.8	Greenhouse/Soil Pots	$PbCl_2$	25 % YR		Karamanos et al. (1976)
Alfalfa/Tops	8.1	Greenhouse/Soil Pots	$PbCl_2$	No Sig YR		Karamanos et al. (1976)
Oat/Tops	4.4	Greenhouse/Soil Pots				John and VanLaerhoven (1972)
Silver Sagebrush	1.1	Field	None	Background		Severson et al. (1977)
Western Wheatgrass	.63	Field	None	Background		Severson et al (1977)
Corn/Grain	0.5	Field	Pb Acetate 3200 kg/ha	No Sig YR	0.01	Baumhardt and Welch (1972)

pH of 3.8. Total soil lead levels in the range of 250 ppm to 400 ppm had no effect on alfalfa, clover, oats, ryegrass and lettuce (Allinson and Dzialo 1981, Pruves 1977, Taylor and Allinson 1981). Miller et al. (1977) reported the stunting of corn seedlings grown in a silty clay loam with a pH of 6.0 at a total lead level of 125 ppm. The reason for the phytotoxicity of this anomalously low value was not resolved although this study was designed to evaluate the interaction of lead on the uptake of cadmium. Yields of barley grown in loam soil containing 1000 ppm total lead and a pH range of 4.0 to 8.5 were significantly reduced at pH values of 4.0 and 6.0 and not affected at pH values of 7.8 and 8.5 (Patel et al. 1977).

The above discussion suggests the 1000 ppm total soil lead level is a level at which significant yield reductions may occur in alfalfa, barley and oats in soils with pH values $\leq$6.0. It is also the level at which a 30 percent yield reduction has been observed in lettuce. The lead content of some vegetation growing on a soil containing 1000 ppm total lead may exceed the 30 ppm maximum recommended forage limit (NRC 1980). by a considerable amount without any apparent toxicity to the plant (John and VanLaerhoven 1972, Patel et al. 1977).

A tolerable plant lead level of 250 ppm is based on the observed "no effect" to alfalfa, oats and ryegrass at this level (Allinson and Dzials 1981, Taylor and Allinson 1979). With the exception of one publication (Miller et al. 1977) which reported the stunting of corn seedlings at 125 ppm total soil lead, no phytotoxicity was noted in the reviewed literature for total soil lead values less than 250 ppm.

3.3.2.2 Extractable soil lead

Extractable soil lead data were relatively less abundant in the literature than were data for total soil lead (Table 40). All elevated extractable soil lead data were derived from the publications of MacLean et al. (1969) and Lagerwerff et al. (1973). The 500 ppm hazard level concentration has been estimated based on the mixed experimental results at 367 ppm 1N NH_4OAc extractable soil lead (MacLean et al. 1969). These authors noted a 71.4 percent reduction in alfalfa yield at this level but stated that the observed yield reduction may have been due to excess chloride rather than high lead in the soil pots. MacLean et al. (1969) reported 1N NH_4OAc extractable soil lead levels were in accord with concentrations found in plants which suggested extractable soil lead concentrations reflected soil characteristics. The 200 ppm tolerable extractable lead level has been selected based on data reported by Lagerwerff et al. (1973) who found no significant yield reductions for corn and alfalfa at a concentration of 212 ppm 1N HCl extractable soil lead. Only one occurrence of a yield reduction was noted at levels less than 200 ppm extractable soil lead (3.8 percent for alfalfa at a concentration of 124 ppm 1N NH_4OAc extractable soil lead (Table 40).

3.3.3 Lead in plants

There is a wide range of values, 4 to 300 ppm, reported for the phytotoxic level of lead in plant tissues (Table 41). Plant tissues vary considerably in their tendency to accumulate lead. High lead levels were observed in the roots of many plants. Alloway (1968) noted 500 ppm lead in the roots of apparently healthy radish plants, and Keaton (1937) reported 808 ppm lead in the roots of barley plants which contained only 3.08 ppm lead in plant tops. Alfalfa plants, grown in pots with 1000 ppm total soil lead and amended with lime and phosphate, were shown to accumulate up to 730 ppm in plant top tissue without apparent phytotoxicity (MacLean et al. 1969). Taylor and Allinson (1981) noted 65 ppm lead in alfalfa plant tissues without yield reductions. Davis et al. (1978) found the critical level (10 percent yield reduction) of lead in barley shoots was 35 ppm. The tolerable level of 25 ppm lead in vegetative tissue was selected based on two factors: 1) it was within the range which Davis et al. (1978) noted the "onset of growth reduction" in barley seedlings (20 to 35 ppm) and 2) it was below the 35 ppm concentration these authors found to be associated with a 10 percent yield reduction.

3.4 Zinc in soils and plants

3.4.1 Zinc literature review

Zinc is an essential plant nutrient normally present in soils at a concentration of 10 to 300 ppm and averages 54 ppm in U.S. soils (Connor and Shacklette 1975). Typical levels in vegetation range from 25 to 150 ppm (dry wt.). Most research concerning zinc in soils and plants has examined the phenomenom of zinc deficiency. Zinc toxicity is rare, usually only occurring in contaminated areas or in extremely acid soils. High levels of soil calcium and phosphorus, and alkaline soil conditions reduce zinc availability to plants, lowering the risk of plant toxicity even in zinc-contaminated soils (Kabata-Pendias and Pendias 1984). Plant uptake of zinc is also influenced by the organic matter content of the soil, presence of chelating compounds, and overall soil fertility (Shuman 1980). Plant species vary widely in their tolerance to zinc which further complicates efforts to determine specific levels of phytotoxicity (Taylor et al. 1982). Studies examining the relationship between zinc concentrations in soil and plant tissue with zinc phytotoxicity are summarized in Tables 42, 43 and 44.

3.4.2 Zinc in soils

3.4.2.1 Total zinc in soils

Total soil zinc concentrations in excess of 600 ppm were generally associated with yield reductions greater than 25 percent in most crop species (Table 42). The only exception found in the reviewed literature was the sludge study by Hinesly et al. (1982) which noted no yield reductions for corn at a total soil zinc concentration of 606 ppm. The application of sludge study results should be used with extreme caution due to the ameliorating effect of sludge. Yield reductions in the 500 to 600 ppm total soil zinc range were between 8 percent found for peas and potatoes (Boawn and Rasmussen 1971) and 72 percent found for soybeans (White and

Table 42. Phytotoxicity of total zinc in soils.

Soil Type	Soil Concentration (ppm)	Soil pH	Chemical Form Applied	Type of Experiment	Plant Species/ Part	Hazard Response	Significance Level	Reference
Hartsells Fine Sandy Loam	960	5.5	$ZnSO_4$	Greenhouse/Soil Pots	Corn/Forage	98.2 % YR	NR	Mortvedt and Giordano (1975)
Hartsells Fine Sandy Loam	960	6.0	$ZnSO_4$	Greenhouse/Soil Pots	Corn/Forage	96.7 % YR	NR	Mortvedt and Giordano (1975)
Hartsells Fine Sandy Loam	960	6.5	$ZnSO_4$	Greenhouse/Soil Pots	Corn/Forage	96.7 % YR	NR	Mortvedt and Giordano (1975)
Hartsells Fine Sandy Loam	960	7.0	$ZnSO_4$	Greenhouse/Soil Pots	Corn/Forage	86.7 % YR	NR	Mortvedt and Giordano (1975)
Domino Silt Loam	660	7.5	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Wheat/Grain	75 % YR	NR	Mitchell et al. (1978)
Domino Silt Loam	660	7.5	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Lettuce/Tops	53 % YR	NR	Mitchell et al. (1978)
Redding Fine Sandy Loam	660	5.7	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Wheat/Grain	27 % YR	NR	Mitchell et al. (1978)
Redding Fine Sandy Loam	660	5.7	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Lettuce/Tops	81 % YR	NR	Mitchell et al. (1978)
Blount Silt Loam	606	7.4	Sludge	Field	Corn/Stover	No YR	0.05	Hinesly et al. (1982)
Blount Silt Loam	606	7.4	Sludge	Field	Corn/Grain	No YR	0.05	Hinesly et al. (1982)
Redding Fine Sandy Loam	580	5.7	Sludge/$ZnSO_4$	Greenhouse/Soil Pots	Wheat/Grain	25 % YR	0.05	Mitchell et al. (1978)
Sassafras Silt Loam	524	6.3	$ZnSO_4$ $7H_2O$	Greenhouse/Soil Pots	Soybeans/Leaf	72.4 % YR	NR	White and Chaney (1980)
Pocomoke Silt Loam	524	6.3	$ZnSO_4$ $7H_2O$	Greenhouse/Soil Pots	Soybeans/Leaf	26.2 % YR	NR	White and Chaney (1980)
Shano Silt Loam 15-30 cm	>500	7.0	$Zn(NO_3)_2$ $6H_2O$	Greenhouse/Soil Pots	Pea/Tops	8 % YR	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	>500	7.0	$Zn(NO_3)_2$ $6H_2O$	Greenhouse/Soil Pots	Clover/Tops	9 % YR	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	>500	7.0	$Zn(NO_3)_2$ $6H_2O$	Greenhouse/Soil Pots	Potato/Tops	8 % YR	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	500	7.0	$Zn(NO_3)_2$ $6H_2O$	Greenhouse/Soil Pots	Tomato/Tops	26 % YR	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	500	7.0	$Zn(NO_3)_2$ $6H_2O$	Greenhouse/Soil Pots	Lettuce/Tops	31 % YR	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	400	7.1	$Zn(NO_3)_2$ $6H_2O$	Greenhouse/Soil Pots	Alfalfa/Tops	17 % YR	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	400	7.1	$Zn(NO_3)_2$ $6H_2O$	Greenhouse/Soil Pots	Field Corn/Tops	26 % YR	0.05	Boawn and Rasmussen (1971)
Sassafras Silt Loam	393	6.3	$ZnSO_4$ $7H_2O$	Greenhouse/Soil Pots	Soybeans/Leaf	33.3 % YR	NR	White and Chaney (1980)
Pocomoke Silt Loam	393	6.3	$ZnSO_4$ $7H_2O$	Greenhouse/Soil Pots	Soybeans/Leaf	15.9 % YR	NR	White and Chaney (1980)
Domino Silt Loam	340	7.5	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Wheat/Grain	29 % YR	NR	Mitchell et al. (1978)
Domino Silt Loam	340	7.5	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Lettuce/Tops	12 % YR	NR	Mitchell et al. (1978)
Redding Fine Sandy Loam	340	5.7	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Wheat/Grain	12 % YR	NR	Mitchell et al. (1978)
Redding Fine Sandy Loam	340	5.7	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Lettuce/Tops	55 % YR	NR	Mitchell et al. (1978)
Lakeland Sand	300	NR	$ZnSO_4$	Greenhouse/Soil Pots	Slash Pine Seedling/ Shoots	59.6 % YR	NR	VanLear and Smith (1972)
Shano Silt Loam 15-30 cm	300	7.3	$Zn(NO_3)_2$ $6H_2O$	Greenhouse/Soil Pots	Wheat/Tops	18 % YR	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	300	7.3	$Zn(NO_3)_2$ $6H_2O$	Greenhouse/Soil Pots	Sweet Corn/Tops	32 % YR	0.05	Boawn and Rasmussen (1971)
Sassafras Silt Loam	262	6.3	$ZnSO_4$ $7H_2O$	Greenhouse/Soil Pots	Soybeans	10.3 % YR	NR	White and Chaney (1980)
Pocomoke Silt Loam	262	6.3	$ZnSO_4$ $7H_2O$	Greenhouse/Soil Pots	Soybeans	22.1 % YR	NR	White and Chaney (1980)
Hartsells Fine Sandy Loam	240	5.9	Sludge	Greenhouse/Soil Pots	Corn/Forage	Yield Increase	NR	Mortvedt and Giordano (1975)
Hartsells Fine Sandy Loam	240	5.5	$ZnSO_4$	Greenhouse/Soil Pots	Corn/Forage	49.1 % YR	NR	Mortvedt and Giordano (1975)
Hartsells Fine Sandy Loam	240	6.0	$ZnSO_4$	Greenhouse/Soil Pots	Corn/Forage	35.0 % YR	NR	Mortvedt and Giordano (1975)
Hartsells Fine Sandy Loam	240	6.5	$ZnSO_4$	Greenhouse/Soil Pots	Corn/Forage	8.3 % YR	NR	Mortvedt and Giordano (1975)
Hartsells Fine Sandy Loam	240	7.0	$ZnSO_4$	Greenhouse/Soil Pots	Corn/Forage	5.0 % YR	NR	Mortvedt and Giordano (1975)
Shano Silt Loam 15-30 cm	200	7.5	$Zn(NO_3)_2$ $6H_2O$	Greenhouse/Soil Pots	Barley/Tops	16 % YR	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	200	7.5	$Zn(NO_3)_2$ $6H_2O$	Greenhouse/Soil Pots	Sorghum/Tops	30 % YR	0.05	Boawn and Rasmussen (1971)

Table 42. Phytotoxicity of total zinc in soils, continued.

Soil Type	Soil Concentration (ppm)	Soil pH	Chemical Form Applied	Type of Experiment	Plant Species/ Part	Hazard Response	Significance Level	Reference
Sassafras Silt Loam	196	5.5	$ZnSO_4$ $7H_2O$	Greenhouse/Soil Pots	Soybeans/Leaf	81.6 % YR	NR	White and Chaney (1980)
Sassafras Silt Loam	196	6.3	$ZnSO_4$ $7H_2O$	Greenhouse/Soil Pots	Soybeans/Leaf	0.6 % YR	NR	White and Chaney (1980)
Pocomoke Silt Loam	196	5.5	$ZnSO_4$ $7H_2O$	Greenhouse/Soil Pots	Soybeans/Leaf	6.4 % YR	NR	White and Chaney (1980)
Pocomoke Silt Loam	196	6.3	$ZnSO_4$ $7H_2O$	Greenhouse/Soil Pots	Soybeans/Leaf	13.8 % YR	NR	White and Chaney (1980)
Domino Silt Loam	180	7.5	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Wheat/Grain	12 % YR	NR	Mitchell et al. (1978)
Domino Silt Loam	180	7.5	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Lettuce/Tops	No YR	NR	Mitchell et al. (1978)
Redding Fine Sandy Loam	180	5.7	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Wheat/Grain	9 % YR	NR	Mitchell et al. (1978)
Redding Fine Sandy Loam	180	5.7	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Lettuce/Tops	32 % YR	NR	Mitchell et al. (1978)
Sassafras Silt Loam	131	5.5	$ZnSO_4$ $7H_2O$	Greenhouse/Soil Pots	Soybeans/Leaf	28.1 % YR	NR	White and Chaney (1980)
Sassafras Silt Loam	131	6.3	$ZnSO_4$ $7H_2O$	Greenhouse/Soil Pots	Soybeans/Leaf	19.9 % Yield Increase	NR	White and Chaney (1980)
Pocomoke Silt Loam	131	5.5	$ZnSO_4$ $7H_2O$	Greenhouse/Soil Pots	Soybeans/Leaf	10.1 % YR	NR	White and Chaney (1980)
Pocomoke Silt Loam	131	6.3	$ZnSO_4$ $7H_2O$	Greenhouse/Soil Pots	Soybeans/Leaf	0.7 % YR	NR	White and Chaney (1980)
Redding Fine Sandy Loam	130	5.7	Sludge/$ZnSO_4$	Greenhouse/Soil Pots	Lettuce/Shoots	25 % YR	0.05	Mitchell et al. (1978)
Domino Silt Loam	100	7.5	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Wheat/Grain	14 % YR	NR	Mitchell et al. (1978)
Domino Silt Loam	100	7.5	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Lettuce/Tops	4 % Yield Increase	NR	Mitchell et al. (1978)
Redding Fine Sandy Loam	100	5.7	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Wheat/Grain	3 % YR	NR	Mitchell et al. (1978)
Redding Fine Sandy Loam	100	5.7	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Lettuce/Tops	13 % YR	NR	Mitchell et al. (1978)
Sassafras Silt Loam	65	5.5	$ZnSO_4$ $7H_2O$	Greenhouse/Soil Pots	Soybeans/Leaf	8.2 % Yield Increase	NR	White and Chaney (1980)
Sassafras Silt Loam	65	6.3	$ZnSO_4$ $7H_2O$	Greenhouse/Soil Pots	Soybeans/Leaf	10.3 % Yield Increase	NR	White and Chaney (1980)
Pocomoke Silt Loam	65	-5.5	$ZnSO_4$ $7H_2O$	Greenhouse/Soil Pots	Soybeans/Leaf	0.6 % YR	NR	White and Chaney (1980)
Pocomoke Silt Loam	65	6.3	$ZnSO_4$ $7H_2O$	Greenhouse/Soil Pots	Soybeans/Leaf	10.3 % YR	NR	White and Chaney (1980)
16 Minn. Surface Soils	60	5.3-8.2	None	Field	NR	Background	NA	Pierce et al. (1982)
Hartsells Fine Sandy Loam	60	5.5	Sludge	Greenhouse/Soil Pots	Corn/Forage	Yield Increase	NR	Mortvedt and Giordano (1975)
Hartsells Fine Sandy Loam	60	5.5	$ZnSO_4$	Greenhouse/Soil Pots	Corn/Forage	No YR	NR	Mortvedt and Giordano (1975)
Hartsells Fine Sandy Loam	60	6.0	$ZnSO_4$	Greenhouse/Soil Pots	Corn/Forage	5 % YR	NR	Mortvedt and Giordano (1975)
Hartsells Fine Sandy Loam	60	6.5	$ZnSO_4$	Greenhouse/Soil Pots	Corn/Forage	Yield Increase	NR	Mortvedt and Giordano (1975)
Hartsells Fine Sandy Loam	60	7.0	$ZnSO_4$	Greenhouse/Soil Pots	Corn/Forage	Yield Increase	NR	Mortvedt and Giordano (1975)
Lakeland Sand	60	NR	$ZnSO_4$	Greenhouse/Soil Pots	Slash Pine Seedlings/ Shoots	42.9 % YR	NR	VanLear and Smith (1972)
Domino Silt Loam	60	7.5	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Wheat/Grain	6 % YR	NR	Mitchell et al. (1978)
Domino Silt Loam	60	7.5	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Lettuce/Tops	10 % Yield Increase	NR	Mitchell et al. (1978)
Redding Fine Sandy Loam	60	5.7	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Wheat/Grain	6 % Yield Increase	NR	Mitchell et al. (1978)
Redding Fine Sandy Loam	60	5.7	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Lettuce/Tops	2 % YR	NR	Mitchell et al. (1978)
16 Minn. Soils Series - All Depths	54	5.3-8.2	None	Field	NR	Background	NR	Pierce et al. (1982)
16 Minn. Soils Parent Material	52	5.3-8.2	None	Field	NR	Background	NR	Pierce et al. (1982)
16 Minn. Subsoils	49	5.3-8.2	None	Field	NR	Background	NR	Pierce et al. (1982)
Helena Valley Soils	46.9	8.0	None	Field	Forage/Range	Background	NR	EPA ([illegible])

Table 42. Phytotoxicity of total zinc in soils, continued.

Soil Type	Soil Concentration (ppm)	Soil pH	Chemical Form Applied	Type of Experiment	Plant Species/ Part	Hazard Response	Significance Level	Reference
13 Laden Fine Sandy Loam	41.3	NR	None	Greenhouse/Soil Pots	Slash Pine Seedlings/ Shoots	Background	NR	VanLear and Smith (1972)
Domino Silt Loam	40	7.5	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Wheat/Grain	6 % YR	NR	Mitchell et al. (1978)
Domino Silt Loam	40	7.5	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Lettuce/Tops	4 % YR	NR	Mitchell et al. (1978)
Redding Fine Sandy Loam	40	5.7	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Wheat/Grain	2 % YR	NR	Mitchell et al. (1978)
Redding Fine Sandy Loam	40	5.7	$ZnSO_4$/Sludge	Greenhouse/Soil Pots	Lettuce/Tops	No YR	NR	Mitchell et al. (1978)
Leon Fine Sand	37.5	NR	None	Greenhouse/Soil Pots	Slash Pine Seedlings/ Shoots	Background	NR	VanLear and Smith (1972)
Sassafras Silt Loam	33	5.5	$ZnSO_4$ $7H_2O$	Greenhouse/Soil Pots	Soybeans/Leaf	9.7 % Yield Increase	NR	White and Chaney (1980)
Pocomoke Silt Loam	33	5.5	$ZnSO_4$ $7H_2O$	Greenhouse/Soil Pots	Soybeans/Leaf	9.5 % YR	NR	White and Chaney (1980)
Lakeland Sand	30	NR	$ZnSO_4$	Greenhouse/Soil Pots	Slash Pine Seedlings/ Shoots	11.8 % YR	NR	VanLear and Smith (1972)
Lakeland Sand	30	NR	None	Greenhouse/Soil Pots	Slash Pine Seedlings/ Shoots	Background	NR	VanLear and Smith (1972)

Table 43. Phytotoxicity of extractable zinc in soils.

Soil Type	Soil Concentration (ppm)	Soil pH	Chemical Form Applied	Type of Experiment	Plant Species/ Part	Hazard Response	Extractant	Significant Level	Reference
Shano Silt Loam 15-30 cm	246	7.0	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Clover/Tops	9 % YR (N.S.)	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	246	7.0	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Alfalfa/Tops	22 % YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	246	7.0	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Barley/Tops	76 % YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	246	7.0	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Wheat/Tops	45 % YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	246	7.0	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Field Beans/Tops	10 % YR (N.S.)	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	246	7.0	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Pea-Alaska/Tops	30 % YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	246	7.0	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Lettuce/Tops	31 % YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	246	7.0	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Spinach/Tops	32 % YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	246	7.0	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Tomato/Tops	26 % YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	195	7.1	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Clover/Tops	No YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	195	7.1	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Alfalfa/Tops	17 % YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	195	7.1	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Barley/Tops	59 % YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	195	7.1	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Wheat/Tops	30 % YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	195	7.1	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Field Beans/Tops	No YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	195	7.1	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Pea-Alaska/Tops	10 % YR (N.S.)	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	195	7.1	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Lettuce/Tops	18 % YR (N.S.)	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	195	7.1	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Spinach/Tops	19 % YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	195	7.1	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Tomato/Tops	10 % YR (N.S.)	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	146	7.3	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Clover/Tops	7 % YR (N.S.)	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	146	7.3	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Alfalfa/Tops	No YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	146	7.3	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Barley/Tops	42 % YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	146	7.3	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Wheat/Tops	18 % YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	146	7.3	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Field Beans/Tops	No YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	146	7.3	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Pea-Alaska/Tops	9 % YR (N.S.)	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	146	7.3	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Lettuce/Tops	21 % YR (N.S.)	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	146	7.3	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Spinach/Tops	12 % YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	146	7.3	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Tomato/Tops	8 % YR (N.S.)	DTPA	0.05	Boawn and Rasmussen (1971)
Warden Fine Sandy Loam	118	6.1	$ZnSO_4\ H_2O$	Field	Letuce/Plant or Head	Normal	DTPA	NR	Boawn (1971)
Warden Fine Sandy Loam	118	6.1	$ZnSO_4\ H_2O$	Field	Swiss Chard/Plant	"Stunted"	DTPA	NR	Boawn (1971)
Warden Fine Sandy Loam	118	6.1	$ZnSO_4\ H_2O$	Field	Spinach/Plant	"Stunted"	DTPA	NR	Boawn (1971)
Warden Fine Sandy Loam	118	6.1	$ZnSO_4\ H_2O$	Field	Cabbage/Heads	Normal	DTPA	NR	Boawn (1971)
Warden Fine Sandy Loam	118	6.1	$ZnSO_4\ H_2O$	Field	Brussel Sprouts/Heads	Normal	DTPA	NR	Boawn (1971)
Fatepur Loamy Sand	97	NR	$ZnSO_4$	Soil Pots	Corn/Tops	Toxic Symptoms	DTPA	NR	Takkar and Mann (1970)
Shano Silt Loam 15-30 cm	88	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Clover/Tops	2 % YR (N.S.)	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	88	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Alfalfa/Tops	3 % YR (N.S.)	DPTA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	88	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Barley/Tops	16 % YR	DPTA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	88	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Wheat/Tops	*3 % YR (N.S.)	DPTA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	88	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Field Beans/Tops	No YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	[illegible]	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Pea-Alaska/Tops	[illegible]	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	88	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Lettuce/Tops	4 % YR (N.S.)	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	88	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Spinach/Tops	1 % YR (N.S.)	DTPA	0.25	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	[illegible]	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Tomato/Tops	5 % YR (N.S.)	DTPA	0.05	Boawn and Rasmussen (1971)
Warden Fine Sandy Loam	54.9	6.1	$ZnSO_4\ H_2O$	Field	12 Leafy Vegetables	Normal	DTPA	NR	Boawn and Rasmussen (1971)
Plainfield Loamy Sand	[illegible]	6.7	$ZnSO_4$	Field	Snap Beans Pod	56 [illegible]	DTPA	0.10	Boawn (1971)
Shano Silt Loam 15-30 cm	[illegible]	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Clover/Tops	[illegible]	DTPA	0.05	Walsh et al. (1972)
Shano Silt Loam 15-30 cm	[illegible]	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Alfalfa/Tops	[illegible]	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	46	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Barley/Tops	[illegible] (N.S.)	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	46	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Wheat/Tops	1 % YR (N.S.)	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	46	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Field Beans/Tops	No YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	46	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Pea-Alaska/Tops	No YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	46	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Lettuce/Tops	18 % YR (N.S.)	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	46	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Spinach/Tops	No YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	46	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Tomato/Tops	No YR	DTPA	0.05	Boawn and Rasmussen (1971)
Plainfield Loamy Sand	33.8	6.7	$ZnSO_4$	Field	Cucumbers/Fruit	9 % YR (N.S.)	0.1N HCl	0.10	Walsh et al. (1972)
Plainfield Loamy Sand	29.2	6.7	$ZnSO_4$	Field	Corn/Grain	4 % Yield Increase	0.1N HCl	0.10	Walsh et al. (1972)

Table 43. Phytotoxicity of extractable zinc in soils, continued.

Soil Type	Soil Concentration (ppm)	Soil pH	Chemical Form Applied	Type of Experiment	Plant Species/ Part	Hazard Response	Extractant	Significant Level	Reference
Alberta Gray Soil (Poorly Drained)	26	7.4	None	Field	Grain/Seed	Background	1N HCl	NA	Dudas and Pawluk (1977)
Domino Silt Loam	19	7.5	None	Greenhouse/Soil Pots	Wheat-Lettuce	Background	DTPA	NA	Mitchell et al. (1978)
Alberta Black Soil (Solonetz)	19	5.7	None	Field	Grain/Seed	Background	1N HCl	NA	Dudas and Pawluk (1977)
Alberta Black Soil (Poorly Drained)	19	6.9	None	Field	Grain/Seed	Background	1N HCl	NA	Dudas and Pawluk (1977)
Redding Fine Sand, Loam	13	5.7	None	Greenhouse/Soil Pots	Wheat-Lettuce	Background	DTPA	NA	Mitchell et al. (1978)
Alberta Black Soil (Well Drained)	13	6.4	None	Field	Grain/Seed	Background	1N HCl	NA	Dudas and Pawluk (1977)
Alberta Brown Soil (Poorly Drained)	13	6.5	None	Field	Grain/Seed	Background	1N HCl	NA	Dudas and Pawluk (1977)
Alberta Gray Soil (Well Drained)	11	6.5	None	Field	Grain/Seed	Background	1N HCl	NA	Dudas and Pawluk (1977)
Fatepur Loamy Sand	11	NR	$ZnSO_4$	Soil Pots	Corn/Tops	Initial YR	DTPA	NR	Takkar and Mann (1978)
Alberta Brown Soil (Solonetz)	10	6.4	None	Field	Grain/Seed	Background	1N HCl	NA	Dudas and Pawluk (1977)
Alberta Gray Soil (Solonetz)	9.2	6.2	None	Field	Grain/Seed	Background	1N HCl	NA	Dudas and Pawluk (1977)
Fatepur Loamy Sand	7	NR	$ZnSO_4$	Soil Pots	Wheat/Tops	Initial YR	DTPA	NR	Takkar and Mann (1978)
Alberta Brown Soil (Well Drained)	5.7	7.2	None	Field	Grain/Seed	Background	1N HCl	NA	Dudas and Pawluk (1977)
Shano Silt Loam 15-30 cm	5	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Clover/Tops	No YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	5	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Alfalfa/Tops	No YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	5	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Barley/Tops	No YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	5	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Wheat/Tops	No YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	5	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Field Beans/Tops	No YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	5	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Pea-Alaska/Tops	No YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	5	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Lettuce/Tops	No YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	5	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Spinach/Tops	No YR	DTPA	0.05	Boawn and Rasmussen (1971)
Shano Silt Loam 15-30 cm	5	7.5	$Zn(NO_3)_2\ 6H_2O$	Greenhouse/Soil Pots	Tomato/Tops	No YR	DTPA	0.05	Boawn and Rasmussen (1971)
Northern Great Plains (A Hor.)	2	6.2-8.2	None	Field	Native Vegetation	Background	NH_4OAC	NR	Severson et al. (1977)
Northern Great Plains (A Hor.)	1.6	6.2-8.2	None	Field	Native Vegetation	Background	EDTA	NR	Severson et al. (1977)
Northern Great Plains (A Hor.)	0.6	6.2-8.2	None	Field	Native Vegetation	Background	DTPA	NR	Severson et al. (1977)
Northern Great Plains (C Hor.)	0.3	7.0-8.9	None	Field	Native Vegetation	Background	EDTA	NR	Severson et al. (1977)
[illegible]	0.2	[illegible]	[illegible]	[illegible]	[illegible]	Background	NH_4OAC	NR	Severson et al. (1977)
[illegible]	0.05	7.0-8.9	None	Field	[illegible]	Background	DTPA	NR	Severson et al. (1977)
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Background	[illegible]	[illegible]	[illegible]

Table 44. Phytotoxicity of zinc in vegetation.

Plant/Tissue	Tissue Concentration (ppm)	Type of Experiment	Chemical Form Applied	Hazard Response	Soil pH	Significance Level	Reference
Corn/Forage	8624	Greenhouse/Soil Pots	$ZnSO_4$	96 % YR	6.0	0.05	Mortvedt and Giordano (1975)
Corn/Forage	8237	Greenhouse/Soil Pots	$ZnSO_4$	96 % YR	6.5	0.05	Mortvedt and Giordano (1975)
Corn/Forage	5622	Greenhouse/Soil Pots	$ZnSO_4$	85 % YR	7.0	0.05	Mortvedt and Giordano (1975)
Corn/Forage	3067	Greenhouse/Soil Pots	$ZnSO_4$	45 % YR	4.6	0.05	Mortvedt and Giordano (1975)
Corn/Forage	2302	Greenhouse/Soil Pots	$ZnSO_4$	51 % YR	5.5	0.05	Mortvedt and Giordano (1975)
Barley/Tops	2112	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	76 % YR	7.0	0.05	Boawn and Rasmussen (1971)
Wheat/Straw	1850	Soil Pots	$ZnSO_4$	81 % YR	NR	NR	Takkar and Mann (1978)
Corn/Forage	1640	Greenhouse/Soil Pots	$ZnSO_4$	3 % YR (N.S.)	4.8	0.05	Mortvedt and Giordano (1975)
Wheat/Straw	1600	Soil Pots	$ZnSO_4$	63 % YR	NR	NR	Takkar and Mann (1978)
Lettuce/Shoot	1585	Greenhouse/Soil Pots	Sludge/$ZnSO_4$	55 % YR	5.7	0.05	Mitchell et al. (1978)
Corn/Forage	1575	Greenhouse/Soil Pots	$ZnSO_4$	29 % YR	6.0	NR	Mortvedt and Giordano (1975)
Lettuce/Shoot	1265	Greenhouse/Soil Pots	Sludge/$ZnSO_4$	55 % YR	7.5	0.05	Mitchell et al. (1978)
Barley/Tops	1237	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	59 % YR	7.1	0.05	Boawn and Rasmussen (1971)
Sorghum/Tops	1140	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	70 % YR	7.0	0.05	Boawn and Rasmussen (1971)
Sugar Beet/Tops	1067	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	40 % YR	7.0	0.05	Boawn and Rasmussen (1971)
Lettuce/Shoot	1058	Greenhouse/Soil Pots	Sludge/$ZnSO_4$	25 % YR	5.7	0.05	Mitchell et al. (1978)
Sorghum/Tops	1029	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	80 % YR	7.0	0.05	Boawn and Rasmussen (1971)
Corn/Forage	1025	Field	$ZnSO_4$	58 % YR	4.9	0.05	Giordano et al. (1975)
Ryegrass/Shoots	1000	Greenhouse/Soil Pots	Zn Salts	50 % YR	4.3	NR	Dijkshoorn et al. (1979)
Sorghum	975	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	66 % YR	7.1	0.05	Boawn and Rasmussen (1971)
Spinach/Tops	945	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	32 % YR	7.0	0.05	Boawn and Rasmussen (1971)
Sorghum/Tops	917	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	62 % YR	7.1	0.05	Boawn and Rasmussen (1971)
Barley/Tops	910	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	42 % YR	7.3	0.05	Boawn and Rasmussen (1971)
Wheat/Tops	909	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	45 % YR	7.3	0.05	Boawn and Rasmussen (1971)
Corn/Forage	884	Field	$ZnSO_4$	47 % YR	4.9	0.05	Giordano et al. (1975)
Corn/Tops	870	Soil Pots	$ZnSO_4$	70 % YR	NR	NR	Takkar and Mann (1978)
Swiss Chard/Plant Tops	862	Field	$ZnSO_4\ H_2O$	Stunted	6.1	NR	Boawn (1971)
Plantain/Shoots	800	Greenhouse/Soil Pots	Zn Salts	50 % YR	4.3	NR	Dijkshoorn et al. (1979)
Spinach/Tops	775	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	19 % YR	7.1	0.05	Boawn and Rasmussen (1971)
Field Corn/Tops	763	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	42 % YR	7.0	0.05	Boawn and Rasmussen (1971)
Sorghum/Tops	748	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	43 % YR	7.3	0.05	Boawn and Rasmussen (1971)
Sweet Corn/Tops	713	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	48 % YR	7.0	0.05	Boawn and Rasmussen (1971)
Sweet Corn/Tops	695	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	55 % YR	7.1	0.05	Boawn and Rasmussen (1971)
Wheat/Tops	682	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	30 % YR	7.1	0.05	Boawn and Rasmussen (1971)
Sugar Beet/Tops	670	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	20 % YR	7.2	0.05	Boawn and Rasmussen (1971)
Lettuce/Tops	665	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	31 % YR	7.0	0.05	Boawn and Rasmussen (1971)
Wheat/Leaf	655	Greenhouse/Soil Pots	Sludge/$ZnSO_4$	25 % YR	5.7	0.05	Mitchell et al. (1978)
Sorghum/Tops	646	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	50 % YR	7.3	0.05	Boawn and Rasmussen (1971)
Spinach/Tops	640	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	12 % YR	7.3	0.05	Boawn and Rasmussen (1971)
Corn/Tops	605	Soil Pots	$ZnSO_4$	50 % YR	NR	NR	Takkar and Mann (1978)
Rye/Tops	632	Greenhouse/Soil Pots	Sludge	YR	6.8	0.05	Cunningham et al. (1975)
Swiss Chard	620	Greenhouse/Soil Pots	Sludge	No Sig YR	4.6-6.3	0.05	Valdares et al. (1983)
Corn/Tops	567	Greenhouse/Soil Pots	Sludge	YR	6.8	0.05	Cunningham et al. (1975)
Bush Bean/Vine	[illegible]	Field	$ZnSO_4$	90 % YR	4.9	0.05	Giordano et al. (1975)

Table 44. Phytotoxicity of zinc in vegetation, continued.

Plant Tissue	Tissue Concentration (ppm)	Type of Experiment	Chemical Form Applied	Hazard Response	Soil pH	Significant Level	Reference
ield Corn/Tops	576	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	26 % YR	7.1	0.05	Boawn and Rasmussen (1971)
orghum/Tops	571	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	11 % YR (N.S.)	7.5	0.05	Boawn and Rasmussen (1971)
heat-Gaines/Tops	560	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	20 % YR	7.2	0.05	Boawn and Rasmussen (1971)
lover/Shoots	550	Greenhouse/Soil Pots	Zn Salts	50 % YR	4.3	NR	Dijkshoorn et al. (1979)
arley-Trail/Tops	540	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	20 % YR	7.5	0.05	Boawn and Rasmussen (1971)
arley/Tops	530	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	16 % YR	7.5	0.05	Boawn and Rasmussen (1971)
ettuce/Shoot	527	Greenhouse/Soil Pots	Sludge/$ZnSO_4$	No Sig YR	5.7	0.05	Mitchell et al. (1978)
heat/Tops	522	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	18 % YR	7.3	0.05	Boawn and Rasmussen (1971)
ea-Alaska/Tops	522	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	30 % YR	7.0	0.05	Boawn and Rasmussen (1971)
omato/Tops	514	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	26 % YR	7.0	0.05	Boawn and Rasmussen (1971)
orn/Forage	508	Greenhouse/Soil Pots	Sludge	No Sig YR	5.5	0.05	Mortvedt and Giordano (1975)
orghum/Tops	506	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	30 % YR	7.5	0.05	Boawn and Rasmussen (1971)
ea-Perf/Tops	489	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	8 % YR (N.S.)	7.0	0.05	Boawn and Rasmussen (1971)
ield Corn/Tops	484	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	20 % YR (N.S.)	7.3	0.05	Boawn and Rasmussen (1971)
orghum-NK-125/Tops	475	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	20 % YR	7.5	0.05	Boawn and Rasmussen (1971)
weet Corn/Tops	475	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	32 % YR	7.3	0.05	Boawn and Rasmussen (1971)
orn/Forage	472	Field	$ZnSO_4$	56 % YR	4.9	0.05	Giordano et al. (1975)
orn/Forage	462	Greenhouse/Soil Pots	$ZnSO_4$	5 % YR	7.0	0.05	Mortvedt and Giordano (1975)
ield Corn/Forage	460	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	20 % YR	7.1	0.05	Boawn and Rasmussen (1971)
pinach/Tops	452	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	1 % YR (N.S.)	7.5	0.05	Boawn and Rasmussen (1971)
omato-Royal Ace/Tops	450	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	20 % YR	7.0	0.05	Boawn and Rasmussen (1971)
nap Beans/Leaf	444	Field	$ZnSO_4$	5 % Yield Increase	6.7	0.10	Walsh et al. (1972)
arsley	438	Field	$ZnSO_4\ H_2O$	No Apparent YR	6.1	NR	Boawn (1971)
orn/Forage	438	Greenhouse/Soil Pots	$ZnSO_4$	No Sig YR	5.5	0.05	Mortvedt and Giordano (1975)
ettuce-NY/Tops	430	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	20 % YR	7.1	0.05	Boawn and Rasmussen (1971)
ea-Alaska/Tops	420	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	20 % YR	7.1	0.05	Boawn and Rasmussen (1971)
heat/Leaf	412	Greenhouse/Soil Pots	Sludge/$ZnSO_4$	85 % YR	7.5	0.05	Mitchell et al. (1978)
heat/Leaf	406	Greenhouse/Soil Pots	Sludge/$ZnSO_4$	No Sig YR	5.7	0.05	Mitchell et al. (1978)
weet Corn/Tops	400	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	20 % YR	7.4	0.05	Boawn and Rasmussen (1971)
wiss Chard/Tops	≤400	Greenhouse/Soil Pots	Sludge	No Sig YR	5.2-7.2	0.001	Valdares et al. (1983)
ucumbers	394	Field	$ZnSO_4$	9 % YR (N.S.)	6.7	0.10	Walsh et al. (1972)
ettuce/Tops	390	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	18 % YR (N.S.)	7.1	0.05	Boawn and Rasmussen (1971)
abbage-Chinese/Heads	389	Field	$ZnSO_4\ H_2O$	No Apparent YR	6.1	NR	Boawn (1971)
heat/Grain	382	Greenhouse/Soil Pots	Sludge/$ZnSO_4$	30 % YR	5.7	0.05	Mitchell et al. (1978)
omato Tops	381	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	18 % YR (N.S.)	7.1	0.05	Boawn and Rasmussen (1971)
ettuce Shoot	380	Greenhouse/Soil Pots	Sludge/$ZnSO_4$	15 % YR	7.5	0.05	Mitchell et al. (1978)
orghum Tops	380	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	10 % YR (N.S.)	7.5	0.05	Boawn and Rasmussen (1971)
Pea-Alaska/Tops	379	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	10 % YR (N.S.)	7.1	0.05	Boawn and Rasmussen (1971)
Sweet Corn/Tops	367	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	12 % YR (N.S.)	7.5	0.05	Boawn and Rasmussen (1971)
Pea-Perf/Tops	367	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	7 % YR (N.S.)	7.1	0.05	Boawn and Rasmussen (1971)
Collard/Young Leaves	366	Field	$ZnSO_4\ H_2O$	No Apparent YR	6.1	NR	Boawn (1971)
Corn/Forage	365	Greenhouse/Soil Pots	$ZnSO_4$	8 % YR	6.5	0.05	Mortvedt and Giordano (1975)
Mustard	364	Field	$ZnSO_4\ H_2O$	No Apparent YR	6.1	NR	Boawn (1971)
Wheat/Straw	360	Soil Pots	$ZnSO_4$	45 % YR	NR	NR	Takkar and Mann (1978)

Table 44. Phytotoxicity of zinc in vegetation, continued.

Plant/Tissue	Tissue Concentration (ppm)	Type of Experiment	Chemical Form Applied	Hazard Response	Soil pH	Significant Level	Reference
Sorghum/Tops	357	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	7 % YR (N.S.)	7.5	0.05	Boawn and Rasmussen (1971)
Snap Beans/Leaf	350	Field	$ZnSO_4$	66 % YR	6.7	0.10	Walsh et al. (1972)
Wheat/Tops	345	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	3 % YR (N.S.)	7.5	0.05	Boawn and Rasmussen (1971)
Alfalfa/Tops	345	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	22 % YR	7.0	0.05	Boawn and Rasmussen (1971)
Endive/Plant Tops	343	Field	$ZnSO_4\ H_2O$	No Apparent YR	6.1	NR	Boawn (1971)
Spinach/Plant Tops	340	Field	$ZnSO_4\ H_2O$	Stunted	6.1	NR	Boawn (1971)
Spinach	338	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	No YR	7.5	0.05	Boawn and Rasmussen (1971)
Wheat/Grain	325	Soil Pots	$ZnSO_4$	94 % YR	NR	NR	Takkar and Mann (1978)
Tomato/Tops	316	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	8 % YR (N.S.)	7.3	0.05	Boawn and Rasmussen (1971)
Field Corn/Tops	314	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	13 % YR (N.S.)	7.5	0.05	Boawn and Rasmussen (1971)
Bush Bean/Vine	305	Field	$ZnSO_4$	55 % YR	4.9	0.05	Giordano et al. (1975)
Alfalfa/Tops	295	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	20 % YR	7.0	0.05	Boawn and Rasmussen (1971)
Barley-Julia/Shoots	290	Greenhouse/Sand Culture	$ZnSO_4$	10 % YR	NR	NR	Davis et al. (1978)
Pea-Perf/Tops	285	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	6 % YR (N.S.)	7.3	0.05	Boawn and Rasmussen (1971)
Leaf Lettuce/Leaves	269	Field	$ZnSO_4\ H_2O$	No Apparent YR	6.1	NR	Boawn (1971)
Wheat/Grain	266	Greenhouse/Soil Pots	Sludge/$ZnSO_4$	No Sig YR	5.7	0.05	Mitchell et al. (1978)
Wheat/Grain	260	Soil Pots	$ZnSO_4$	76 % YR	NR	NR	Takkar and Mann (1978)
Bush Bean/Vine	259	Field	$ZnSO_4$	23 % YR	4.9	0.05	Giordano et al. (1975)
Field Beans/Tops	257	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	10 % YR (N.S.)	7.0	0.05	Boawn and Rasmussen (1971)
Tomato/Tops	257	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	5 % YR (N.S.)	7.5	0.05	Boawn and Rasmussen (1971)
Sweet Corn/Tops	255	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	8 % YR (N.S.)	7.5	0.05	Boawn and Rasmussen (1971)
Clover/Tops	252	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	9 % YR (N.S.)	7.0	0.05	Boawn and Rasmussen (1971)
Lettuce/Tops	250	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	21 % YR (N.S.)	7.3	0.05	Boawn and Rasmussen (1971)
Snap Beans/Leaf	249	Field	$ZnSO_4$	24.5 % YR (N.S.)	6.7	0.10	Walsh et al. (1972)
Head Lettuce/Heads	248	Field	$ZnSO_4\ H_2O$	No Apparent YR	6.1	NR	Boawn (1971)
Corn/Forage	241	Field	Sludge	No YR	5.3	0.05	Giordano et al. (1975)
Peas-Alaska/Tops	236	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	9 % YR (N.S.)	7.3	0.05	Boawn and Rasmussen (1971)
Alfalfa/Tops	232	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	17 % YR	7.1	0.05	Boawn and Rasmussen (1971)
Ryegrass/Seedlings	221	Greenhouse/Sand Culture	$ZnSO_4$	Upper Critical Level	NR	NR	Davis and Beckett (1978)
Barley/Tops	220	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	10 % YR (N.S.)	7.5	0.05	Boawn and Rasmussen (1971)
Corn/Tops	220	Soil Pots	$ZnSO_4$	32 % YR	NR	NR	Takkar and Mann (1978)
Field Beans/Tops	213	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	No YR	7.1	0.05	Boawn and Rasmussen (1971)
Snap Beans/Tops	213	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	12 % YR (N.S.)	7.0	0.05	Boawn and Rasmussen (1971)
Bush Bean/Vine	211	Field	Sludge	No Sig YR	5.6	0.05	Giordano et al. (1975)
Barley Seedlings	210	Greenhouse/Sand Culture	$ZnSO_4$	Upper Critical Level	NR	NR	Davis and Beckett (1978)
Field Corn/Tops	205	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	No YR	7.5	0.05	Boawn and Rasmussen (1971)
Barley-Barsoy/Straw	204	Greenhouse/Soil Pots	Sludge	15 % YR (N.S.)	6.0	0.01	Chang et al. (1982)
Corn/Stover	204	Field	Sludge	No Zn YR	5.5	NR	Hinesly et al. (1982)
Clover/Tops	202	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	No YR	7.1	0.05	Boawn and Rasmussen (1971)
Barley-Julia/Seedlings	199	Greenhouse/Sand Culture	$ZnSO_4$	NR	NR	NR	Beckett and Davis (1979)
Pea-Perf/Tops	197	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	4 % YR (N.S.)	7.5	0.05	Boawn and Rasmussen (1971)
Lettuce/Shoot	190	Greenhouse/Soil Pots	Sludge/$ZnSO_4$	No Sig YR	7.5	0.05	Mitchell et al. (1978)
Wheat/Leaf	189	Greenhouse/Soil Pots	Sludge/$ZnSO_4$	35 % YR	7.5	0.05	Mitchell et al. (1978)
Wheat/Tops	185	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	1 % YR (N.S.)	7.5	0.05	Boawn and Rasmussen (1971)
Barley-Briggs/Straw	184	Greenhouse/Soil Pots	Sludge	27 % YR (N.S.)	6.0	0.01	Chang et al. (1982)
Wheat/Grain	183	Greenhouse/Soil Pots	Sludge/$ZnSO_4$	85 % YR	7.5	0.05	Mitchell et al. (1978)
Wheat/Grain	180	Soil Pots	$ZnSO_4$	74 % YR	NR	NR	Takkar and Mann (1978)

Table 44. Phytotoxicity of zinc in vegetation, continued.

Plant/Tissue	Tissue Concentration (ppm)	Type of Experiment	Chemical Form Applied	Hazard Response	Soil pH	Significant Level	Reference
Lettuce/Leaves	179	Field	$ZnSO_4$ H_2O	No Apparent YR	6.1	NR	Boawn (1971)
Swiss Chard	170	Greenhouse/Soil Pots	Sludge	No Sig YR	6.9-7.6	0.001	Valdares et al. (1983)
Pea-Alaska/Tops	166	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	1 % YR (N.S.)	7.5	0.05	Boawn and Rasmussen (1971)
Clover/Tops	161	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	7 % YR (N.S.)	7.3	0.05	Boawn and Rasmussen (1971)
Corn/Grain	160	Field	$ZnSO_4$	4 % Yield Increase	6.7	0.10	Walsh et al. (1972)
Lettuce/Tops	152	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	4 % YR (N.S.)	7.5	0.05	Boawn and Rasmussen (1971)
Tomato/Tops	150	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	No YR	7.5	0.05	Boawn and Rasmussen (1971)
Wheat/Grain	149	Greenhouse/Soil Pots	Sludge/$ZnSO_4$	35 % YR	7.5	0.05	Mitchell et al. (1978)
Snap Beans/Tops	142	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	14 % YR (N.S.)	7.1	0.05	Boawn and Rasmussen (1971)
Alfalfa/Tops	142	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	No YR	7.3	0.05	Boawn and Rasmussen (1971)
Lettuce/Shoots	139	Greenhouse/Soil Pots	None	Background	7.5	0.05	Mitchell et al. (1978)
Peas-Perf/Tops	132	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	No YR	7.5	0.05	Boawn and Rasmussen (1971)
Wheat/Grain	129	Greenhouse/Soil Pots	Sludge/$ZnSO_4$	No Sig YR	7.5	0.05	Mitchell et al. (1978)
Snap Beans/Leaf	129	Field	$ZnSO_4$	12.4 % YR (N.S.)	6.7	0.10	Walsh et al. (1972)
Barley-Florida/Straw	126	Greenhouse/Soil Pots	Sludge	14 % Yield Increase	6.0	0.01	Chang et al. (1982)
Barley-Larker/Straw	126	Greenhouse/Soil Pots	Sludge	11 % Yield Increase	6.0	0.01	Chang et al. (1982)
Lettuce-Romaine/Heads	122	Field	$ZnSO_4$ H_2O	No Apparent YR	6.1	NR	Boawn (1971)
Barley-Florida/Leaf	121	Greenhouse/Soil Pots	Sludge	14 % Yield Increase	6.0	0.01	Chang et al. (1982)
Wheat/Grain	117	Greenhouse/Soil Pots	None	Background	5.7	0.05	Mitchell et al. (1978)
Cabbage-Chinese/Young Plant	114	Field	$ZnSO_4$ H_2O	No Apparent YR	6.1	NR	Boawn (1971)
Snap Beans/Tops	111	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	8 % YR (N.S.)	7.3	0.05	Boawn and Rasmussen (1971)
Clover/Tops	109	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	2 % YR (N.S.)	7.5	0.05	Boawn and Rasmussen (1971)
Wheat/Leaf	108	Greenhouse/Soil Pots	Sludge/$ZnSO_4$	No Sig YR	7.5	0.05	Mitchell et al. (1978)
Bush Bean/Pod	105	Field	$ZnSO_4$	51 % YR	4.9	0.05	Giordano et al. (1975)
Corn/Forage	104	Greenhouse/Soil Pots	$ZnSO_4$	6 % Yield Increase	4.8	0.05	Mortvedt and Giordano (1975)
Peas-Alaska/Tops	104	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	No YR	7.5	0.05	Boawn and Rasmussen (1971)
Bush Bean/Pod	101	Field	Sludge	60 % YR	5.6	0.05	Giordano et al. (1975)
Corn/Tops	100	Soil Pots	$ZnSO_4$	9 % YR	NR	NR	Takkar and Mann (1978)
Barley-Briggs/Grain	100	Greenhouse/Soil Pots	Sludge	27 % YR (N.S.)	6.0	0.01	Chang et al. (1982)
Wheat/Grain	100	Soil Pots	$ZnSO_4$	10 % YR	NR	NR	Takkar and Mann (1978)
Barley-Florida/Grain	99	Greenhouse/Soil Pots	Sludge	14 % Yield Increase	6.0	0.01	Chang et al. (1982)
Alfalfa/Tops	97	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	3 % YR (N.S.)	7.5	0.05	Boawn and Rasmussen (1971)
Lettuce/Tops	96	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	18 % YR (N.S.)	7.5	0.05	Boawn and Rasmussen (1971)
Barley-Larker/Grain	94	Greenhouse/Soil Pots	Sludge	11 % Yield Increase	6.0	0.01	Chang et al. (1982)
Bush Bean/Pod	90	Field	Sludge	No Sig YR	5.3	0.05	Giordano et al. (1975)
Bush Bean/Pod	90	Field	Sludge	29 % YR	5.3	0.05	Giordano et al. (1975)
Broccoli/Flower	87	Field	None	Background	4.7	NR	Giordano et al. (1979)
Bush Bean/Pod	87	Field	$ZnSO_4$	32 % YR	4.9	0.05	Giordano et al. (1975)
Snap Beans/Leaf	84.5	Field	$ZnSO_4$	18.4 % YR (N.S.)	6.7	0.10	Walsh et al. (1972)
Lettuce/Shoots	82	Greenhouse/Soil Pots	None	Background	5.7	0.05	Mitchell et al. (1978)
Barley/Leaf	81.9	Field	Sludge	No Inhibition	6.3-7.0	0.01	Chang et al. (1982)
Clover/Tops	81	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	No YR	7.5	0.05	Boawn and Rasmussen (1971)
Corn/Tops	81	Soil Pots	$ZnSO_4$	Maximum Yield	NR	NR	Takkar and Mann (1978)
Brussel Sprouts/Heads	79	Field	$ZnSO_4$ H_2O	No Apparent YR	6.1	NR	Boawn (1971)
Wheat/Grain	75	Soil Pots	$ZnSO_4$	Maximum Yield	NR	NR	Takkar and Mann (1978)

Table 44. Phytotoxicity of zinc in vegetation, continued.

Plant/Tissue	Tissue Concentration (ppm)	Type of Experiment	Chemical Form Applied	Hazard Response	Soil pH	Significant Level	Reference
Barley-Barsoy/Grain	73	Greenhouse/Soil Pots	Sludge	15 % YR (N.S.)	6.0	0.01	Chang et al. (1982)
Cabbage/Heads	73	Field	$ZnSO_4$ H_2O	No Apparent YR	6.1	NR	Boawn (1971)
Wheat/Grain	73	Greenhouse/Soil Pots	None	Background	7.5	0.05	Mitchell et al. (1978)
Barley-Larker/Grain	73	Greenhouse/Soil Pots	Sludge	11 % Yield Increase	6.0	0.01	Chang et al. (1982)
Barley-Briggs/Straw	72	Greenhouse/Soil Pots	Sludge	23 % YR (N.S.)	6.0	0.01	Chang et al. (1982)
Alfalfa	71	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	No YR	7.5	0.05	Boawn and Rasmussen (1971)
Pepper/Foliage	71	Field	None	Background	5.1	0.05	Giordano et al. (1979)
Wheat/Straw	70	Soil Pots	$ZnSO_4$	29 % YR	NR	NR	Takkar and Mann (1978)
Barley/Tops	70	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	No YR	7.5	0.05	Boawn and Rasmussen (1971)
Snap Beans/Tops	69	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	8 % YR (N.S.)	7.5	0.05	Boawn and Rasmussen (1971)
Barley-Florida/Grain	67	Greenhouse/Soil Pots	Sludge	2 % Yield Increase	6.0	0.01	Chang et al. (1982)
Barley-Larker/Leaf	67	Greenhouse/Soil Pots	Sludge	11 % Yield Increase	6.0	0.01	Chang et al. (1982)
Wheat/Grain	66	Soil Pots	$ZnSO_4$	Maximum Yield	NR	NR	Takkar and Mann (1978)
Barley-Barsoy/Grain	65	Greenhouse/Soil Pots	Sludge	4 % YR (N.S.)	6.0	0.01	Chang et al. (1982)
Bean/Seed	64	Field	None	Background	5.1	0.05	Giordano et al. (1979)
Barley-Briggs/Grain	64	Greenhouse/Soil Pots	Sludge	23 % YR (N.S.)	6.0	0.01	Chang et al. (1982)
Wheat/Leaves	63	Greenhouse/Soil Pots	None	Background	7.5	0.05	Mitchell et al. (1978)
Bush Bean/Vine	63	Field	Sludge	No Sig. YR	5.3	0.05	Giordano et al. (1975)
Wheat/Grain	62	Field	None	Background	5.7	NR	Dudas and Pawluk (1977)
Barley-Briggs/Leaf	61	Greenhouse/Soil Pots	Sludge	27 % YR (N.S.)	6.0	0.01	Chang et al. (1982)
Barley-Julia/Seedlings	60	Greenhouse/Sand Culture	$ZnSO_4$	"Normal"	NR	NR	Beckett and Davis (1979)
Barley-Barsoy/Straw	59	Greenhouse/Soil Pots	Sludge	4 % YR (N.S.)	6.0	0.01	Chang et al. (1982)
Wheat/Leaves	58	Greenhouse/Soil Pots	None	Background	7.5	0.05	Mitchell et al. (1978)
Lettuce/Leaves CV Great Lakes	54	Field	None	Background	5.1	0.05	Giordano et al. (1979)
Barley-Barsoy/Leaf	52	Greenhouse/Soil Pots	Sludge	15 % YR (N.S.)	6.0	0.01	Chang et al. (1982)
Sweet Corn/Foliage	52	Field	None	Background	5.1	0.05	Giordano et al. (1979)
Barley-Larker/Straw	52	Greenhouse/Soil Pots	Sludge	11 % Yield Increase	6.0	0.01	Chang et al. (1982)
Barley-Florida/Leaf	51	Greenhouse/Soil Pots	Sludge	2 % Yield Increase	6.0	0.01	Chang et al. (1982)
Wheat/Tops	51	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	No YR	7.5	0.05	Boawn and Rasmussen (1971)
Barley-Florida/Straw	50	Greenhouse/Soil Pots	Sludge	2 % Yield Increase	6.0	0.01	Chang et al. (1982)
Ryegrass/Seedlings	50	Greenhouse/Sand Culture	$ZnSO_4$	"Normal"	NR	NR	Davis and Beckett (1978)
Wheat/Grain	49	Field	None	Background	6.5	NR	Dudas and Pawluk (1977)
Barley-Briggs/Straw	49	Greenhouse/Soil Pots	None	Background	6.0	0.01	Chang et al. (1982)
Lettuce/Leaves CV Great Lakes	48	Field	None	Background	4.7	0.05	Giordano et al. (1979)
Squash/Foliage	48	Field	None	Background	5.1	0.05	Giordano et al. (1979)
Cabbage/Heads	48	Field	None	Background	4.6	0.05	Giordano et al. (1979)
Barley/Grain	48	Field	None	Background	5.7	NR	Dudas and Pawluk (1977)
Lettuce/Leaves CV Bibb	46	Field	None	Background	4.6	0.05	Giordano et al. (1975)
Snap Beans/Tops	46	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	11 % YR (N.S.)	7.5	0.05	Boawn and Rasmussen (1971)
Barley/Grain	45	Field	None	Background	6.5	NR	Dudas and Pawluk (1977)
Wheat/Straw	45	Soil Pots	$ZnSO_4$	Maximum Yield	NR	NR	Takkar and Mann (1978)
Barley-Larker/Grain	45	Greenhouse/Soil Pots	None	Background	6.0	0.01	Chang et al. (1982)
Lettuce/Leaves CV Bibb	43	Field	None	Background	6.3	0.05	Giordano et al. (1975)

Table 44. Phytotoxicity of zinc in vegetation, continued.

Plant/Tissue	Tissue Concentration (ppm)	Type of Experiment	Chemical Form Applied	Plant Response	Soil pH	Significant Level	Reference
Barley/Grain	27	Field	None	Background	7.2	NR	Dudas and Pawluk (1977)
Barley/Grain	27	Field	None	Background	7.4	NR	Dudas and Pawluk (1977)
Potato/Foliage	27	Field	None	Background	4.7	0.05	Giordano et al. (1979)
Tomato/Fruit	26	Field	None	Background	4.7	0.05	Giordano et al. (1979)
Barley-Larker/Leaf	26	Greenhouse/Soil Pots	None	Background	6.0	0.01	Chang et al. (1982)
Sweet Corn/Seed	25	Field	None	Background	5.1	0.05	Giordano et al. (1979)
Wheat/Grain	25	Field	None	Background	6.2	NR	Dudas and Pawluk (1977)
Oats/Grain	24	Field	None	Background	7.4	NR	Dudas and Pawluk (1977)
Pepper/Fruit	24	Field	None	Background	6.3	0.05	Giordano et al. (1979)
Barley/Straw	24	Field	None	Background	5.7	NR	Dudas and Pawluk (1977)
Barley Briggs/Leaf	24	Greenhouse/Soil Pots	None	Background	6.0	0.01	Chang et al. (1982)
Barley-Florida/Straw	23	Greenhouse/Soil Pots	None	Background	6.0	0.01	Chang et al. (1982)
Oats/Grain	22	Field	None	Background	6.5	NR	Dudas and Pawluk (1977)
Carrot/Root	22	Field	None	Background	6.3	0.05	Giordano et al. (1979)
Snap Beans/Tops	21	Greenhouse/Soil Pots	$Zn(NO_3)_2\ 6H_2O$	No YR	7.5	0.05	Boawn and Rasmussen (1971)
Eggplant/Foliage	21	Field	None	Background	4.7	0.05	Giordano et al. (1979)
Squash/Fruit	19	Field	None	Background	5.1	0.05	Giordano et al. (1979)
Cantaloupe/Fruit	18	Field	None	Background	6.3	0.05	Giordano et al. (1979)
Cantaloupe/Fruit	18	Field	None	Background	4.6	0.05	Giordano et al. (1979)
Potato/Tuber	16	Field	None	Background	4.7	0.05	Giordano et al. (1979)
Barley/Straw	16	Field	None	Background	6.5	NR	Dudas and Pawluk (1977)
Western Wheatgrass	5.7-34 (15)	Field	None	Background	6.2-8.2	NR	Severson et al. (1977)
Eggplant/Fruit	15	Field	None	Background	4.7	0.05	Giordano et al. (1979)
Wheat/Straw	15	Field	None	Background	5.7	NR	Dudas and Pawluk (1977)
Wheat/Straw	14	Field	None	Background	6.5	NR	Dudas and Pawluk (1977)
Corn/Tops	14	Greenhouse/Soil Pots	None	Background	4.9	0.05	Mortvedt and Giordano (1975)
Wheat/Straw	9.1	Field	None	Background	6.4	NR	Dudas and Pawluk (1977)
Wheat/Straw	8.5	Field	None	Background	6.9	NR	Dudas and Pawluk (1977)
Barley/Straw	6.4	Field	None	Background	6.2	NR	Dudas and Pawluk (1977)
Barley/Straw	6.3	Field	None	Background	6.4	NR	Dudas and Pawluk (1977)
Barley/Straw	8.3	Field	None	Background	6.5	NR	Dudas and Pawluk (1977)
Barley/Straw	6.9	Field	None	Background	6.9	NR	Dudas and Pawluk (1977)
Barley/Straw	6.6	Field	None	Background	6.4	NR	Dudas and Pawluk (1977)
Barley/Straw	6.4	Field	None	Background	7.4	NR	Dudas and Pawluk (1977)
Wheat/Straw	6.3	Field	None	Background	6.2	NR	Dudas and Pawluk (1977)
Oats/Straw	6.0	Field	None	Background	7.4	NR	Dudas and Pawluk (1977)
Wheat/Straw	5.8	Field	None	Background	7.2	NR	Dudas and Pawluk (1977)
Barley/Straw	5.4	Field	None	Background	7.2	NR	Dudas and Pawluk (1977)
Wheat/Straw	5.2	Field	None	Background	6.4	NR	Dudas and Pawluk (1977)
Oats/Straw	4.9	Field	None	Background	6.5	NR	Dudas and Pawluk (1977)

Table 44. Phytotoxicity of zinc in vegetation, continued.

Plant/Tissue	Tissue Concentration ppm	Type of Experiment	Chemical Form Applied	Hazard Response	Soil pH	Significant Level	Reference
Corn/Grain	42.8	Field	Sludge	No Zn YR	5.5	0.01	Hinesly et al. (1982)
Barley-Briggs/Grain	42	Greenhouse/Soil Pots	None	Background	6.0	0.01	Chang et al. (1982)
Sweet Corn/Tops	41	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	No YR	7.5	0.05	Boawn and Rasmussen (1971)
Barley-Barsoy/Leaf	41	Greenhouse/Soil Pots	Sludge	4 % YR (N.S.)	6.0	0.01	Chang et al. (1982)
Barley-Florida/Grain	40	Greenhouse/Soil Pots	None	Background	6.0	0.01	Chang et al. (1982)
Barley/Grain	40	Field	None	Background	6.9	NR	Dudas and Pawluk (1977)
Carrot/Root	39	Field	None	Background	4.6	0.05	Giordano et al. (1979)
Wheat/Grain	39	Field	None	Background	6.4	NR	Dudas and Pawluk (1977)
Tomato/Foliage	38	Field	None	Background	4.7	0.05	Giordano et al. (1979)
Barley-Barsoy/Grain	37	Greenhouse/Soil Pots	None	Background	6.0	0.01	Chang et al. (1982)
Field Corn/Tops	37	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	No YR	7.5	0.05	Boawn and Rasmussen (1971)
Barley/Grain	37	Field	None	Background	6.4	NR	Dudas and Pawluk (1977)
Bean/Foliage	37	Field	None	Background	5.1	0.05	Giordano et al. (1979)
Wheat/Grain	37	Field	None	Background	6.9	NR	Dudas and Pawluk (1977)
Pepper/Fruit	36	Field	None	Background	5.1	0.05	Giordano et al. (1979)
Barley/Grain	36	Field	None	Background	6.2	NR	Dudas and Pawluk (1977)
Barley/Grain	36	Field	None	Background	6.5	NR	Dudas and Pawluk (1977)
Barley-Larker/Leaf	35	Greenhouse/Soil Pots	Sludge	11 % Yield Increase	6.0	0.01	Chang et al. (1982)
Lettuce/Leaves CV Romaine	35	Field	None	Background	4.6	0.05	Giordano et al. (1979)
Barley/Grain	35	Field	None	Background	6.4	NR	Dudas and Pawluk (1977)
Silver Sagebrush	19-64 (34)	Field	None	Background	6.2-8.2	NR	Severson et al. (1977)
Sorghum/Tops	34	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	No YR	7.5	0.05	Boawn and Rasmussen (1971)
Lettuce/Tops	34	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	No YR	7.5	0.05	Boawn and Rasmussen (1971)
Sorghum/Tops	32	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	No YR	7.5	0.05	Boawn and Rasmussen (1971)
Wheat/Grain	32	Field	None	Background	6.4	NR	Dudas and Pawluk (1977)
Barley-Briggs/Leaf	31	Greenhouse/Soil Pots	Sludge	23 % YR (N.S.)	6.0	0.01	Chang et al. (1982)
Beans/Pod Only	31	Field	None	Background	5.1	0.05	Giordano et al. (1979)
Lettuce/Leaves CV Romaine	31	Field	None	Background	6.3	0.05	Giordano et al. (1979)
Lettuce/Leaves CV Boston	31	Field	None	Background	6.3	0.05	Giordano et al. (1979)
Wheat/Grain	31	Field	None	Background	7.2	NA	Dudas and Pawluk (1977)
Barley-Larker/Straw	30	Greenhouse/Soil Pots	None	Background	6.0	0.01	Chang et al. (1982)
Barley-Barsoy/Leaf	30	Greenhouse/Soil Pots	None	Background	6.9	0.01	Chang et al. (1982)
Barley-Florida/Leaf	29	Greenhouse/Soil Pots	None	Background	6.0	0.01	Chang et al. (1982)
Lettuce/Leaves CV Boston	29	Field	None	Background	4.6	0.05	Giordano et al. (1979)
Pepper/Fruit	29	Field	None	Background	4.6	0.05	Giordano et al. (1979)
Cabbage/Heads	29	Field	None	Background	6.3	0.05	Giordano et al. (1979)
Hard Wheat	28	NR	None	Background	NR	NR	Kabata - Pendias and Pendias (1984)
Barley-Barsoy/Straw	27	Greenhouse/Soil Pots	None	Background	6.0	0.01	Chang et al. (1982)
Alfalfa/Tops	27	Greenhouse/Soil Pots	$Zn(NO_3)_2$ $6H_2O$	No YR	7.5	0:35	Boawn and Rasmussen (1971)

Chaney 1980). Typical phytotoxic criteria for total soil zinc were reported by various authors as 250 to 500 ppm (Kitagishi and Yamane 1981, Chapman 1960, El-Bassam and Tietjen 1977, Linzon 1978, Kabata-Pendias 1979, Kloke 1979, Melsted 1973, Chaney et al. 1978). The suggested 500 ppm hazard level for the Helena Valley is also the level suggested by Chaney et al. (1978) and has been selected because it best fit data from the reviewed literature (Table 42).

The tolerable total soil zinc concentration (200 ppm) is based on the observation that reductions in yields of most species, with the exception of soybeans, were generally low at concentrations less than 200 ppm while levels greater than 200 ppm were shown to result in yield reductions for many crops. Vegetative yields for two of the specific crops of interest for the Helena Valley, barley and wheat, were reported to be decreased by 16 percent and 18 percent at total soil zinc concentrations of 200 ppm and 300 ppm respectively (Boawn and Rasmussen 1971). Mitchell et al. (1978) noted reductions in wheat grain yields of 3 to 14 percent in the 100 to 180 ppm total soil zinc range and 12 to 29 percent at 340 ppm total soil zinc. No data were found in the reviewed literature relating alfalfa yields and total soil zinc levels below 200 ppm.

3.4.2.2 Extractable soil zinc

The 60 ppm phytotoxic extractable soil zinc hazard level has been selected utilizing data reported by Boawn (1971), Boawn and Rasmussen (1971) and Walsh et al. (1972) (Table 43). Boawn (1971) reported normal yields for 12 leafy vegetables at a DTPA extractable soil zinc concentration of 55 ppm. Boawn and Rasmussen (1971) noted a 16 percent reduction in the vegetative yield of barley at 88 ppm DTPA extractable soil zinc and Walsh et al. (1972) reported a 66 percent yield reduction of snap bean pods at 47 ppm DTPA extractable soil zinc. The 5 ppm DTPA extractable soil zinc tolerable level is based on the observations of Boawn and Rasmussen (1971) who noted no yield reductions for a number of crops, including wheat, barley and alfalfa, at or below this level.

An argument can be made to revise both the phytotoxic and tolerable extractable zinc levels upward to 125 ppm and 40 ppm respectively. The 60 ppm phytotoxic hazard level was selected based on two phytotoxic occurrences noted above (Table 43). Significant yield reductions for most crops were rare at DTPA extractable zinc concentrations less than 146 ppm. The first significant yield reductions for wheat and alfalfa were reported at DTPA extractable soil zinc concentrations of 146 ppm and 195 ppm, respectively (Boawn and Rasmussen 1971). Some yield reductions may occur in barley at DTPA extractable soil zinc concentrations less than 125 ppm but the level appears more appropriate for wheat, alfalfa and clover which are grown extensively in the Helena Valley.

No significant yield reductions were noted in the reviewed literature for any crops at DTPA extractable soil zinc concentrations less than 40 ppm. The maximum background extractable (1N HCl) zinc concentration found in the reviewed literature was 26 ppm (Dudas and Pawluk 1977) and Walsh et al. (1972) noted a yield increase for corn grain at a 29 ppm 0.1 NHCl extractable soil zinc concentration. The maximum yield of rye was noted at 40 ppm 0.1N $MgSO_4$ extractable zinc (Chapman 1966).

3.4.3 Zinc in plants

There is a wide range of zinc phytotoxic levels reported among some plant species, different plant types and for different parts of plants (Table 44). Reported phytotoxic zinc levels range from 60 ppm for wheat plants (Takkar and Mann 1978) to values greater than 800 ppm for swiss chard (Boawn 1971) (Table 44). Most values for crops of concern (cereal grains and forages) fall within the range of 189 ppm to 560 ppm (35 and 20 percent yield reductions, respectively) found by Mitchell et al. (1978) and Boawn and Rasmussen (1971). Boawn and Rasmussen (1971) reported 20 percent yield reductions for barley, wheat and alfalfa at above ground plant tissue levels of 540 ppm, 560 ppm and 295 ppm, respectively. Zinc phytotoxicity to barley seedlings was reported in the range of 160 to 320 ppm (Davis et al. 1978). It is apparent that the suggested plant tissue phytotoxic level of 500 ppm zinc will produce phytotoxicity in most plants. Only two values in excess of the suggested 500 ppm plant tissue phytotoxic level were found not to be phytotoxic (508 ppm for corn forage and 527 ppm for lettuce shoots) (Mortvedt and Giordano 1975, Mitchell et al. 1978). Phytotoxic criteria levels reported in the literature ranged from 100 to 400 ppm zinc (Kabata-Pendias and Pendias 1984).

The suggested 50 ppm tolerable zinc level in vegetation is based on the lowest phytotoxic tissue level found for crops of interest (barley, oats, wheat, alfalfa and other forage crops). The value 51 ppm was reported for a 20 percent yield reduction in wheat (Boawn and Rasmussen 1971). These authors also reported a 20 percent yield reduction for sweet corn and sorghum at zinc tissue levels of 41 and 34 ppm respectively. These values were the only occurrences of phytotoxicity found in the reviewed literature at levels less than the 50 ppm suggested tolerable concentration.

4.0 HAZARD LEVELS FOR WATER

A large number of factors influence the suitability of water for livestock consumption and for irrigation purposes. Some of these are discussed in the following sections. A computer literature review was not conducted for this subject.

4.1 Water Quality Levels for Livestock

A number of factors, including animal tolerance, water consumption and forage ingestion, are involved in the determination of the suitability of a water source for livestock. Water consumption by livestock is influenced by the species, the age, the condition of the animals and climatic factors. Temperature changes have been shown to vary water consumption in cattle by a factor of three (Rittenhouse and Sneva 1973). The moisture content of forage affects water consumption and some species such as sheep have been shown to subsist entirely on dew or snow (Butcher 1973). Water consumption by domestic livestock varies between 1 and 4 gallons per day for sheep or goats and 10 to 16 gallons per day for dairy cattle (Federal Water Pollution Control Administration 1968). It is clear that any given amount of heavy metal in water will likely affect individual animals in a slightly different manner.

The heavy metal content of forage and soil is another factor which influences the allowable amount of heavy metals in livestock drinking water. Contaminated water will only exacerbate toxicosis produced from ingesting contaminated forage. Mayland et al. (1975) estimated cattle ingested soil in the amount of 100 to 1500 g/animal/day. In areas with high levels of heavy metals in soils, this source may represent a considerable fraction of the total heavy metal intake in some animals.

Several organizations have established suitability criteria levels for most constitutents found in water. Criteria for arsenic, cadmium, lead and zinc are reviewed in Table 45.

Table 45. Water quality criteria for arsenic, cadmium, lead and zinc.

Use	As	Cd	Pb	Zn	Reference
	mg/L				
DRINKING WATER	0.05	0.01	0.05	5	EPA 1983, USPHS 1962
LIVESTOCK WATER	0.2	0.05	0.1	25	NRC 1974
LIVESTOCK WATER	0.5	0.05	0.1	50	Dyer and Johnson 1975
LIVESTOCK WATER	0.05	0.01	0.05	--	Federal Water Pollution Control Administration 1968 (FWPCA)

Standards for arsenic have been based on total arsenic and are usually reported on the toxicity of arsenic trioxide (Peoples 1983). Methylated forms have been shown to be one hundred times less toxic than inorganic forms. With the exception of rats, arsenic is rapidly eliminated from the bodies of most animals (Peoples 1964). Chronic toxicity in livestock has been demonstrated at levels of 50 mg/kg forage (NRC 1980). Problems may occur on the most contaminated soils (greater than 100 ppm arsenic) if livestock ingest considerable quantities of the soil. A survey of water quality in the Helena Valley in 1972 found no arsenic values greater than 0.03 mg/L (Soukup 1972). Dyer and Johnson (1975) suggested 0.5 mg/L may be a more appropriate maximum level for arsenic in livestock water but, given the possibility of intake from other sources, the 0.2 mg/L level may provide a better margin of safety. Arsenic toxicosis may still occur in very extreme cases in which ingestion of soil by livestock is the major contributing factor.

Both lead and cadmium tend to accumulate in animal tissues and therefore are more prone to cause toxicosis in chronic poisoning cases. Allcroft (1951) found that both soluble and insoluble (lead acetate and lead carbonate respectively) forms of lead were absorbed at about the same rate. Puls (1981) has given dietary intake levels of >100 ppm lead as toxic to cattle. Soukup (1972) found a maximum lead value of 0.044 mg/L in Helena Valley water, well below the permissible criteria of 0.1 mg/L. The possibility of high levels of lead in forage and soil, suggests that the drinking water criteria of 0.05 ppm lead may be most appropriate for the Helena Valley.

The most appropriated hazard level for cadmium concentrations in livestock water of the Helena Valley will depend on cadmium levels found in forage and soils under background conditions. The 0.5 ppm criteria reported by the NRC (1974) may be the most applicable. Chaney (1984) and NRC (1980) have given a value of 0.5 mg/kg cadmium in forage as the chronic toxicosis tolerance level. However data discussed by Hansen and Chaney (1984) showed that the 0.5 mg/kg cadmium value was based upon conservative estimates for cadmium accumulation in animal livers. They felt that when the Cd:Zn ratio is <1.0%, cadmium in feed may reach 5 ppm with little accumulation in liver and kidney tissues of animals. However, the drinking water standard and the FWPCA livestock criteria of 0.01 mg/L may be insufficient to prevent cadmium toxicosis under conditions of heavy contamination.

Zinc tolerence is high in animals and dietary intake exceeding 2000 ppm may be required to produce zinc toxicosis (Puls 1981). The 1972 study of the Helena Valley indicated a maximum forage content of 232.0 ppm (dry wt.) zinc (Hindawi and Neely 1972). Soils sampled in the same study contained a maximum of 5200 ppm zinc and the mean for sites 0.67 to 10 miles from the smelter was found to be 79 ppm (Miesch and Huffman 1972). It is apparent that the recommend zinc limit of 25 mg/L for livestock water will provide a sufficient margin of safety except in areas with very high soil contamination.

No data were found that would document the heavy metal content of snowmelt runoff and its consumption by livestock.

4.2 Water Quality Levels for Irrigation

Water quality criteria for irrigation must take into consideration the nature of the specific water constituent, soil characteristics, plant species and climatic variables. Irrigation methods can also influence the relative toxicity of some elements. Sprinkler irrigation can result in foliar absorption or adsorption of minerals at levels detrimental to plant growth if the water contains excessive levels of some constituents (Federal Water Pollution Control Administration 1968). Ground application of the same water may not produce any adverse effects due to soil chemical and physical properties that may reduce some elements to insoluble forms and adsorption of elements by soil constituents with high cation exchange capacity. Helena Valley waters analyzed by Soukup (1972) contained no levels above the more restrictive irrigation criteria for all soils for arsenic, cadmium, lead and zinc (Table 46).

Table 46. Irrigation water criteria for arsenic, cadmium, lead, and zinc.

Use	As	Cd	Pb	Zn	Reference
	mg/L				
Irrigation All Soils	0.1	0.01	5	2	NRC 1972
Irrigation Fine Textured Soils	2.0	0.05	10	10	NRC 1972

The use of contaminated surface runoff, waters receiving industrial effluent or polluted ground water could result in waters exceeding existing irrigation guidelines.

5.0 REGULATORY CRITERIA FROM OTHER TECHNOLOGIES

Several state, provincial and national regulatory agencies have attempted to set limits for metal contaminants in soils and/or to define metal hazard levels in waste materials. These hazard levels have been developed from different technologies and view soils from different perspectives. Much of the criteria come from four sources: (1) sewage sludge amendment of agricultural soils; (2) coal overburden materials used as rooting zone material in revegetation attempts; (3) defining hazardous materials using various extraction techniques; and (4) setting limits for metal contaminants in soil based on the intended future use of the soil. The criteria presented in this section are provided for a comparison to hazard levels suggested in this document for the Helena Valley. These criteria were not used to determine the Helena Valley hazard levels. Tables 47 to 51 summarize this regulatory information.

5.1 Criteria from Land Application of Sewage Sludge

Metals commonly present in sludge have been classified (CAST, 1978) as those that are likely to pose little hazard (manganese, iron, aluminum, chromium, arsenic, selenium, antimony, mercury and lead) for land application and those which pose significant hazard (cadmium, copper, molybdenium, nickel and zinc). Many national regulatory agencies have set maximum cumulative loading levels of these elements for agricultural lands (Table 47). These loading levels have been set to prevent toxicity to humans or animals from crops grown on treated agricultural lands. It is of interest to note that Norway and Sweden prescribe very low cumulative loading levels while the United Kindom and United States allow significantly higher levels. Cumulative loading levels are given in kg of metal/ha. Conversion to mg of metal/kg of soil is based on a one acre furrow slice (6 to 7" depth) weighing two million pounds.

Table 47. Maximum permissible cumulative metal loadings from sewage sludge to agricultural lands.

Element	Medium	Use	Criteria[1]		Hazard[1] Response	Receptor[5]	Method	Enforcement Code	Ref.
As	Soil	Vegetation; Crops	15kg/ha	6.7mg/kg			Total	British Columbia	British Columbia 1982, EPS 1984
As	Soil	Vegetation; Crops	14kg/ha	6.2mg/kg			Total	Ontario	OMAF/OMOE 1981
As	Soil	Vegetation; Crops	15kg/ha	6.7mg/kg			Total	Canada	EPS 1984, Standish 1981
As	Soil	Vegetation; Crops	2kg/ha	0.9mg/kg			Total	Netherlands	EPS 1984, Webber et al. 1983
As	Soil	Vegetation; Crops	10kg/ha	4.5mg/kg			Total	United Kingdom	EPS 1984, Webber et al. 1983
Cd	Soil	Vegetation; Crops	0.8-1.5 kg/ha	0.4-0.7 mg/kg			Total	Alberta	Alberta Environment 1982, EPS 1984
Cd	Soil	Vegetation; Crops	4kg/ha	1.8mg/kg			Total	British Columbia	British Columbia 1982, EPS 1984
Cd	Soil	Vegetation; Crops	1.6kg/ha	0.7mg/kg			Total	Ontario	EPS 1984, OMAF/OMOE 1981
Cd	Soil	Vegetation; Crops	4kg/ha	1.8mg/kg			Total	Canada	EPS 1984, Standish 1981
Cd	Soil	Vegetation; Crops	0.2kg/ha	0.09mg/g			Total	Denmark	EPS 1984, Webber et al. 1983
Cd	Soil	Vegetation; Crops	0.1kg/ha	0.05mg/kg			Total	Finland	EPS 1984, Webber et al. 1983

Table 47. Continued.

Element	Medium	Use	Criteria		Hazard Response[4]	Receptor[5]	Method	Enforcement Code	Ref.
Cd	Soil	Vegetation; Crops	5.4kg/ha	2.4mg/kg			Total	France	EPS 1984, Webber et al. 1983
Cd	Soil	Vegetation; Crops	8.4kg/ha	3.7mg/kg			Total	Germany	EPS 1984, Webber et al. 1983
Cd	Soil	Vegetation; Crops	2.0kg/ha	0.9mg/kg			Total	Netherlands	EPS 1984, Webber et al. 1983
Cd	Soil	Vegetation; Crops	0.2kg/ha	0.09mg/kg			Total	Norway	EPS 1984, Webber et al. 1983
Cd	Soil	Vegetation; Crops	0.075 kg/ha	0.033 mg/kg			Total	Sweden[2]	EPS 1984, Webber et al. 1983
Cd	Soil	Vegetation; Crops	5kg/ha	2.2mg/kg			Total	United Kingdom	EPS 1984, Webber et al. 1983
Cd	Soil	Vegetation; Crops	5-20[3] kg/ha	2.2-8.9 mg/kg			Total	United States	EPS 1984, Webber et al. 1983
Pb	Soil	Vegetation; Crops	50-100 kg/ha	22.3-44.6 mg/kg			Total	Alberta	Alberta Environment 1982, EPS 1984
Pb	Soil	Vegetation; Crops	100kg/ha	44.6mg/kg			Total	British Columbia	British Columbia 1982, EPS 1984
Pb	Soil	Vegetation; Crops	90kg/ha	40.1mg/kg			Total	Ontario	EPS 1984, OMAF/OMOE 1981
Pb	Soil	Vegetation; Crops	100kg/ha	44.6mg/kg			Total	Canada	EPS 1984, Webber et al. 1983
Pb	Soil	Vegetation; Crops	210kg/ha	93.8mg/kg			Total	France	EPS 1984, Webber et al. 1983
Pb	Soil	Vegetation; Crops	210kg/ha	93.8mg/kg			Total	Germany	EPS 1984, Webber et al. 1983

Table 47. Continued.

Element	Medium	Use	Criteria[1]		Hazard Response[4]	Receptor[5]	Method	Enforcement Code	Ref.
Pb	Soil	Vegetation; Crops	100kg/ha	44.6mg/kg			Total	Netherlands	EPS 1984, Webber et al. 1983
Pb	Soil	Vegetation; Crops	6kg/ha	2.7mg/kg			Total	Norway	EPS 1984, Webber et al. 1983
Pb	Soil	Vegetation; Crops	1.5kg/ha	0.7mg/kg			Total	Sweden[2]	EPS 1984, Webber et al. 1983
Pb	Soil	Vegetation; Crops	1000 kg/ha	446.7mg/kg			Total	United Kingdom	EPS 1984, Webber et al. 1983
Pb	Soil	Vegetation; Crops	500-2000[3] kg/ha	223.3-893.3 mg/kg			Total	United States	EPS 1984, Webber et al. 1983
Zn	Soil	Vegetation; Crops	150-300 kg/ha	67.0-134.0 mg/kg			Total	Alberta	Alberta Environment 1983, EPS 1984
Zn	Soil	Vegetation; Crops	370kg/ha	165.3mg/kg			Total	British Columbia	British Columbia 1982 EPS 1984
Zn	Soil	Vegetation; Crops	330kg/ha	147.4mg/kg			Total	Ontario	EPS 1984, Webber et al. 1983
Zn	Soil	Vegetation; Crops	370kg/ha	165.3mg/kg			Total	Canada	EPS 1984, Webber et al. 1983
Zn	Soil	Vegetation; Crops	750kg/ha	335.0mg/kg			Total	France	EPS 1984, Webber et al. 1983
Zn	Soil	Vegetation; Crops	750kg/ha	335.0mg/kg			Total	Germany	EPS 1984, Webber et al. 1983
Zn	Soil	Vegetation; Crops	400kg/ha	178.7mg/kg			Total	Netherlands	EPS 1984, Webber et al. 1983

Table 47. Continued.

Element	Medium	Use	Criteria[1]	Hazard Response[4]	Receptor[5]	Method	Enforcement Code	Ref.
Zn	Soil	Vegetation; Crops	60kg/ha 26.8mg/kg			Total	Norway	EPS 1984, Webber et al. 1983
Zn	Soil	Vegetation; Crops	50kg/ha 22.3mg/kg			Total	Sweden [2]	EPS 1984, Webber et al. 1983
Zn	Soil	Vegetation; Crops	560kg/ha 250.1mg/kg			Total	United Kingdom	EPS 1984, Webber et al. 1983
Zn	Soil	Vegetation;	250-1000[3]kg/ha 111.7-446.7 mg/kg			Total	United States	EPS 1984, Webber et al. 1983

1 Criteria is given in Kg/ha. Conversions were made to mg/Kg of soil based on a soil of $2x10^6$lbs/acre furrow slice (plow depth of 6-7").

2 Sweden's values are for a 5 year loading; can be repeated.

3 Levels are related to cation exchange capacity. Low limit given is for soils with a CEC of <5 meg/100g high limit is for soil with CEC > 15 meg/100g

4 Plant uptake from sludge ammended soil, bioaccumulation.

5 Plants, and bioaccumulation in humans from ingestion of crops.

5.2 Criteria from Coal Overburden Suitability for Root Zone Material

Because strip mining for coal in the western United States increased significantly in the 1970s several state regulatory agencies established guidelines for the analysis of soils and overburden materials to determine their suitability as root zone materials in revegetation attempts. Suitability guidelines and suspect levels were set by some states and are shown in Table 48. The levels for cadmium, lead and zinc established by Montana as being suspect, have been rescinded, but not yet replaced. New proposed guidelines are under consideration.

5.3 Criteria for Defining Hazardous Wastes

The Resource Conservation and Recovery Act (RCRA) set criteria for determining if a waste is hazardous. Part of this act defines the EP Toxicity Test (40 CFR) 261.24, 19 May 1980). The levels of arsenic, cadmium and lead that are defined as the concentration of contaminants which will produce characteristic EP Toxicity are shown in Table 49. The state of California has also taken a similiar approach to defining hazardous materials by using two criteria; soluble threshold limit concentration (STLC), and total threshold limit concentraction (TTLC). These criteria are given in Table 50.

5.4 Criteria for Metal Contaminants Based on Land Use

The British Department of Environment has set draft guidelines for the concentration of contaminants in soils based on land use. These criteria are given in Table 51.

5.5 Summary

Table 52 summarizes the hazard criteria for arsenic, cadmium, lead and zinc concentrations. These data are a synthesis of information from state, provincial and national regulatory agencies. Heavy emphasis is given to maximum cumulative loadings of sludge to agricultural soils.

Table 48. Suitability criteria for soil overburden used as root zone materials.

Element	Medium	Use	Criteria	Hazard Response	Exposure Pathway	Receptor	Duration	Method	Enforcement Code	Ref.
As	Overburden	Root Zone Material	2.0ppm	Suitability Guideline	Uptake from Soil	Plants		PH<6.5, (.04N HCl&.025N H_2SO_4) PH>6.5, (.4N $NaHCO_3$)	Draft Regulation	Wyoming Dept. of Environmental Quality (WDEQ) 1983
Pb	Overburden	Root Zone Material	10ppm	Suitability Guideline	Uptake from Soil	Plants		PH>6.0, (DTPA) pH<6.0, (.04N HCl& .025N H_2SO_4)	Draft Regulation	WDEQ 1983
Pb	Overburden Soils	Root Zone Material	10-15ppm (pH<6); 15-20ppm (pH>6)	Suspect Level	Uptake from Soil	Plants		DTPA	Guideline[1]	Montana Department of State Lands (MDSL) 1977
Cd	Overburden Soils	Root Zone Material	0.1-1.0ppm	Suspect Level	Uptake from Soil	Plants		DTPA	Guideline[1]	MDSL 1977
Zn	Overburden Soils	Root Zone Material	40ppm	Suspect Level	Uptake from Soil	Plants		DTPA	Guideline[1]	MDSL 1977

[1] These guidelines have been rescinded, with proposed guidelines under review.

Table 49. EP toxicity testing for hazardous materials.

Element	Medium	Use	Criteria	Hazard Respose	Exposure Pathway	Receptor	Duration	Method	Enforcement	Ref.
As	Soil/Waste	Removal Disposal	5.0mg/L	EP Toxicity				EP Toxicity Test	Federal Standard	Resource Conservation and Recovery Act (RCRA, 1980
Cd	Soil/Waste	Removal/ Disposal	1.0mg/L	EP Toxicity				EP Toxicity Test	Federal Standard	RCRA 1980
Pb	Soil/Waste	Removal/ Disposal	5.0mg/L	EP Toxicity				EP Toxicity Test	Federal Standard	RCRA 1980

Table 50. Identification of hazardous wastes (California).

Element	Medium	Use	Criteria	Hazard Response	Exposure Pathway	Receptor	Duration	Method	Enforcement Code	Ref.
As	Soil/Waste	Removal/ disposal	5mg/kg wet weight	Soluble threshold limit concentration				0.2M Sodium citrate (pH 5.0) extraction	Draft Regulation (California)	California Administrative Code (CAC) 1983
As	Soil/Waste	Removal/ disposal	500mg/kg wet weight	Total threshold limit concentration				Total	Same as above	CAC 1983
Cd	Soil/Waste	Removal/ disposal	1.0mg/kg wet weight	Soluble threshold limit concentration				0.2M Sodium citrate (pH 5.0) extraction	Same as above	CAC 1983
Cd	Soil/Waste	Removal/ Disposal	100mg/kg wet weight	Total threshold limit concentration				Total	Same as above	CAC 1983
Pb	Soil/Waste	Removal/ Disposal	5mg/kg wet weight	Soluble threshold limit concentration				0.2M Sodium citrate (pH 5.0) extraction	Same as above	CAC 1983
Pb	Soil/Waste	Removal/ Disposal	1000mg/kg wet weight	Total threshold limit concentration				Total	Same as above	CAC 1983
Zn	Soil/Waste	Removal/ Disposal	250mg/kg wet weight	Soluble threshold limit concentraction				0.2M Sodium citrate (pH 5.0) extraction	Same as above	CAC 1983
Zn	Soil/Waste	Removal/ Disposal	5000mg/kg wet weight	Total threshold limit concentration				Total	Same as above	CAC 1983

Table 51. Acceptable concentration of contaminants in soils (United Kingdom).

Element	Medium	Use	Criteria	Hazard Response	Exposure Pathway	Receptor	Duration	Method	Enforcement Code	Ref.
As	Soil	Small gardens [1]	20mg/kg dry soil	Threshold for no significant hazard	Ingestion of soil, crops; dermal contact, inhalation	Humans		Total As in top 450mm of soil	Tentative guidelines (UK)	Smith 1981
As	Soil	Large gardens [1]	10mg/kg dry soil	As above	Ingestion of soil, crops; dermal contact inhalation	Humans		As above	As above	Smith 1981
As	Soil	Amenity Grass [3]	40mg/kg dry soil	As above	Ingestion of soil, dermal contact, inhalation	Humans		As above	As above	Smith 1981
As	Soil	Public open space [4]	40mg/kg dry soil	As above	As above	Humans		As above	As above	Smith 1981
Cd	Soil	Small gardens [1]	5mg/kg dry soil	As above	Ingestion of soil, crops; dermal contact, inhalation	Humans		Total Cd in top 450mm of soil	As above	Smith 1981
Cd	Soil	Large gardens [2]	3mg/kg dry soil	As above	As above	Humans		As above	As above	Smith 1981
Cd	Soil	Amenity grass [3]	12mg/kg dry soil	As above	Ingestion of soil, dermal contact, inhalation	Human		As above	As above	Smith 1981

Table 51. Continued.

Element	Medium	Use	Criteria	Hazard Response	Exposure Pathway	Receptor	Duration	Method	Enforcement Code	Ref.
Cd	Soil	Public open space [4]	15mg/kg dry soil	Threshold for no significant hazard	Ingestion of soil, dermal contact, inhalation	Humans		Total Cd in top 450mm of soil	Tentative guidelines (UK)	Smith 1981
Pb	Soil	Small [1] gardens	550mg/kg dry soil	As above	Ingestion of soil, crops; dermal contact, inhalation	Humans		Total Pb in top 450mm of soil	As above	Smith 1981
Pb	Soil	Large [2] gardens	550mg/kg	As above	As above	Humans		As above	As above	Smith 1981
Pb	Soil	Amenity grass [3]	1500mg/kg dry soil	As above	Ingestion of soil; dermal contact, inhalation	Humans		As above	As above	Smith 1981
Pb	Soil	Public open space [4]	2000mg/kg dry soil	As above	As above	Humans		As above	As above	Smith 1981
Zn	Soil	Small [1] gardens	280mg/kg dry soil	As above	Ingestion of soil, crops; dermal contact, inhalation	Humans		0.05M EDTA extractable Zn in top 450mm of soil	As above	Smith 1981
Zn	Soil	Large [2] gardens	280mg/kg dry soil	As above	As above	Humans		As above	As above	Smith 1981

Table 51. Continued.

Element	Medium	Use	Criteria	Hazard Response	Exposure Pathway	Receptor	Duration	Method	Enforcement Code	Ref.
Zn	Soil	Amenity grass [3]	280-560 mg/kg dry soil	Threshold for no significant hazard	Ingestion of soil, dermal contact, inhalation	Humans		0.05M EDTA extractable Zn in top 450mm	Tentative Guidelines (UK)	Smith 1981
Zn	Soil	Public open space [4]	280-560 mg/kg dry soil	As above	As above	Humans		As above	As above	Smith 1981
Zn	Soil	Vegeta-tion	130mg/kg dry soil	Phytotixic guideline	Uptake from soil	Plants		0.05M EDTA Extractable Zn	As above	Smith 1981

1 Small garden is less than $75m^2$.
2 Large garden $\geq 75m^2$.
3 Amenity grass includes schools, play areas etc.
4 Public open space includes parkland, playing fields.

Table 52. Suggested hazard criteria for soil based on regulatory agency data.

	Arsenic	Cadmium	Lead	Zinc
	mg/kg			
Soil, Total level	6-10	1.5-2.0	1000	150-300
Soil, Extractable[A] level	2-5	1.0	20	40-130

[A]/DPTA extractant for Pb, Cd and Zn; HCl extractant for As.

6.0 APPENDIX

6.1 Toxicology Mechanisms of Metals for Livestock

6.1.1 Arsenic toxicology

Arsenic is second only to lead for heavy metal poisoning of domestic livestock (Sahli 1982, Buck et al. 1976). Arsenic intoxication can occur through inhalation or ingestion of arsenic bearing compounds. The trivalent forms of arsenic are generally more toxic than are pentavalent forms (Franke and Moxon 1936) and inorganic compounds are generally more toxic than organic forms (Savchuck et al. 1960). The most common means of arsenic poisoning is through ingestion of contaminated food and the most affected livestock are cattle, sheep, and horses (Sahli 1982, Selby et al. 1977). Arsenic poisoning in livestock by inhalation of arsenic compounds is not well documented.

Absorption of arsenic is dependent upon the means of exposure (inhalation or ingestion), the form of arsenic, the species of animal, and the condition of the animal. Soluble forms such as sodium arsenite are readily absorbed by all body surfaces but less soluble forms such as arsenic trioxide are not as well absorbed and are partially eliminated by excretion in the feces (Buck et al. 1976). Less than 10 percent of the usually soluble forms appear in the feces (NRC 1980). Absorbed arsenic is transported via the blood to most body tissues. In peracute, acute, or subacute poisoning, arsenic tends to accumulate in the liver and kidneys, with levels of 2 to 100 ppm (wet weight) found in these organs in dying animals. High levels have also been observed in skin tissues, hair, and spleen. Absorbed arsenic compounds are generally excreted via urine, with lesser amounts in milk and feces (Peoples 1964, Lakso and Peoples 1975, Shariatpanahi and Anderson 1984a). Bennett and Schwartz (1971) found that a considerable portion of arsenic from lead arsenate fed to sheep was excreted in feces within 3 to 7 days. Phenylarsonic compounds are generally excreted rapidly by the urinary system in domestic animals, with 50 to 75 percent excreted within one day and the remaining 25 percent excreted in 8 to 10 days (NRC 1977). Shariatpanahi and Anderson (1984a) found that the half life of arsenic in blood of sheep and goats was 3.2 and 2.1 days, respectively after monosodium methanearsonate was removed from the diet. Dehydrated animals and those in poor condition are more susceptible to poisoning, probably due to reduced excretion via the kidneys. Some ingested inorganic arsenate and arsenite have been shown to be methylated in vivo by both ruminants and nonruminants (Lakso and Peoples 1975, Tsukamoto et al. 1983). The action is apparently endogenous and the result of intestinal microflora (Penrose 1975). This action may reduce the toxicity of these compounds.

The toxicosis of arsenic is generally attributed to the trivalent form (Buck et al. 1976). Arsenic reacts with sulfhydryl groups in cells inhibiting sulfhydryl enzyme systems such as pyruvate oxidase, which is essential for proper fat and carbohydrate metabolism in the cell. Arsenic also uncouples oxidative phosphorylation by substituting for phosphorus; labile arsenylated oxidation products are substituted for stable phosphorylated intermediates (Riviere et al. 1981). Tissues most affected are the alimentary tract, kidney, liver, lung and epidermis (Buck et al. 1976). Capillary damage, especially in the splanchnic area, results in transudation of plasma into the intestinal tract and sharply reduced blood volume. Blood pressure falls to shock levels, the heart muscle becomes depressed, and general circulatory failure occurs. The capillary transudation of plasma in vesicles results in edema of the gastrointestinal mucosa, eventually leading to epithelial sloughing and the discharge of plasma into the gastrointestinal tract (Radeleff 1970).

Chronic arsenic poisoning through faulty diets containing phenylarsonic feed additives are well documented (NRC 1977). Toxicosis by phenylarsonic compounds apparently involves peripheral nerve degeneration and symptoms include incoordination, inability to control body and limb movements, and ataxia. The condition may progress to quadriplegia (Ledet et al. 1973)

The rapid excretion of arsenic from the system in sublethal doses prevents any large bioaccumulation of arsenic in livestock. Selby (1974) recommended a 14 day market withholding time for a single dose of arsenic and a 6 week period for multiple arsenic exposure. These authors suggested that arsenic intoxicated cattle "...usually will represent a minimal hazard to man as a food source."

Although epidemiological studies have implicated arsenic as a carcinogen in humans, no literature was found indicating similar implications in domestic livestock. The average elapsed time from the beginning of skin treatments with arsenic compounds (Fowler's solution) to the development of ephitheliomatous growth in humans has averaged 18 years (NRC 1977). It is thus likely that similar occurrences in livestock would not have sufficient time to develop, and possible metabolic differences such as exhibited by rats, may produce a different syndrome.

6.1.2 Cadmium toxicology

Uptake of cadmium by domestic livestock is generally restricted to ingestion via contaminated food supplies or soil. Natural inhalation of cadmium at levels necessary to produce toxicosis in livestock is poorly documented. Cadmium poisoning through inhalation has been limited to human subjects, usually associated with industrial exposure. Cadmium contamination of livestock food sources may occur from airborne fallout, which accumulates on or in forage, or from excessive levels in forage grown on contaminated soils. Two of the major sources of cadmium contamination are from the land disposal of sewage sludge high in heavy metals and from mining and smelting operations. It is likely that most instances of cadmium poisoning in domestic livestock (ruminants and horses) are the result of the ingestion of contaminated feed.

Absorption of cadmium is apparently not controlled by a homeostatic mechanism and therefore accumulation of cadmium in the body will occur regardless of the existing body burden or level of intake (NRC 1980). Absorption through the gastrointestinal tract has been shown to range from 0.3 percent to 5 percent in various animals (Doyle et al. 1974, Moore et al. 1973, Miller et al. 1967) and is similar to the 2.7 percent absorption found for humans (Newton et al. 1984). Data suggest diets deficient in protein and calcium may increase cadmium absorption or retention (Larsson and Piscator 1971, Suzuki et al. 1969). Elevated concentrations of zinc, copper, iron, selenium or ascorbic acid tend to reduce the deleterious effects of this element (Pond and Walker 1972, Hill et al. 1963, Gunn et al. 1968). Cadmium retained by the gastrointestinal tract appears to represent the fraction most rapidly cleared from the body, usually within 4 to 12 days for cows and goats (NRC 1980). Lesser amounts of absorbed cadmium are excreted via bile, intestinal tract wall and urine. Very small amounts (.002 ppm) of cadmium have been detected in milk from Holstein cows which suggests milk is not an important factor in the excretion of cadmium from the body (Miller et al. 1967). Excretion of cadmium via the urine increases markedly following renal damage but prior to tissue damage, urine is an erratic indicator of cadmium exposure.

The most common signs of cadmium poisoning in livestock are reduced growth rates in young animals, anemia, infertility, abortions and deformed young. Sheep fed cadmium have lost the crimp in their wool, a characteristic of copper deficiency (NRC 1980).

The physiological action of cadmium within the body is intimately associated with zinc metabolism. Cadmium apparently leaves the blood rapidly following absorption and accumulates to some extent in most organs in the body. Both zinc and cadmium are known to induce the synthesis of the protein thionein to which the metals become bound (Cousins 1979). Cadmium metallothionein eventually accumulates in the liver and kidneys; kidneys have the highest concentration. The degradation of metallothionein has been shown to follow the order thionein < zinc metallothionein < cadmium metallothionein. When cadmium metallothionein is degraded, the released cadmium ions are quickly incorporated into nascent chains of thionein and retained within the body (Cousins

1979). The cadmium metallothionein is thus maintained in the kidneys. Cadmium then interferes with zinc in enzymes necessary for reabsorption and catabolism of proteins, producing tubular proteinuria. Development of proteinuria in humans takes a number of years of chronic exposure (more than 10). High concentrations of cadmium in kidneys of livestock fed cadmium in their diet suggests that this condition will occur in domestic animals if the exposure time is of sufficient duration. However, with the possible exception of horses, it is unlikely that animals would be maintained for such long periods, especially in large commercial operations.

Cadmium has been shown to decrease uptake of calcium by bone in rats and chronic exposure via water and food in the presence of a calcium deficient diet has been implicated in the development of the Itai-Itai disease in humans. Osteoporosis has been observed in horses and foals near a zinc smelter and has been attributed to direct cadmium poisoning or "the result of a conditioned copper deficiency associated with high intakes of zinc and cadmium" (Gunson et al. 1982).

Studies of the effect of cadmium on the reproduction of livestock strongly indicate a high incidence of abortions and deformed offspring. A diet of 50 ppm cadmium succinate produced dead and abnormal calves and lambs (Wright et al. 1977). Goats on a diet of 75 ppm experienced 50 percent abortions, with no normal young (Anke et al. 1970).

The tendency of cadmium to accumulate in the kidney and liver of livestock and the low rate of elimination from the body make bioaccumulation of cadmium very important as a means of introducing this element into the human food chain. There is less danger, however, from consumption of livestock muscle tissues which accumulate very little cadmium (Table 12).

Available data strongly suggests carcinogenic effects of cadmium on humans. Many studies involving subcutaneous injections of cadmium chloride or other cadmium salts in rats have produced sarcoma. Similar studies with oral ingestion of cadmium in rats and mice did not suggest cadmium was carcinogenic in the doses given (Friberg et al. 1974). Only a small amount of literature exists concerning the long-term carcinogenic effects of low level chronic cadmium poisoning in domestic livestock.

Zinc is antagonistic to cadmium and the effects of cadmium poisoning have been somewhat attenuated by increasing zinc in the diet. The antagonistic nature of zinc has reduced the risk of exposure to cadmium in some areas polluted by smelters. Similarly, supplemental calcium, iron, copper, selenium and ascorbic acid in the diet has decreased the effects of cadmium toxicity. Lead appears to be synergistic and increases cadmium toxicity.

6.1.3 Lead toxicology

Lead poisoning is the most common form of heavy metal poisoning in livestock and has been the subject of many reports and literature reviews (Amnerman et al. 1977, Aronson 1972, Buck 1970). Ingestion and subsequent absorption of lead in the gastrointestinal tract is the primary mode of absorption in domestic animals although Dogra et al. (1984) found bovine lungs with lead concentrations up to 4268 ppm in industrial areas. Sources of lead include contaminated feed, forage, and soils, along with lead-bearing debris (storage batteries, used crankcase oil, paint, leaded gasoline, etc.). Lead compounds are generally insoluble and some soluble forms (lead acetate) develop insoluble compounds (lead sulfate) in the gastrointestinal tract. Ruminants and nonruminants absorb less than three percent and about 10 percent of ingested lead, respectively (National Research Council (NRC) 1972). Research has shown that excessive dietary calcium and phosphorus decrease lead absorption in rats and lambs (NRC 1980). High zinc intake has a beneficial effect on lead toxicity in horses (Schmitt et al. 1971, Willoughby et al. 1972) and swine (Hsu et al. 1975). Horses may be more prone to lead poisoning than ruminants, but the higher number of incidents reported for horses may be partially the result of ingestion of higher levels of contaminated soils (Buck et al. 1976). Swine, sheep, goats, and chickens are apparently somewhat resistant to lead intoxication (Damron et al. 1969, Staples 1975, NRC 1980).

Excretion of lead occurs through urine, feces, milk, and hair. Studies with rats (Castellino et al. 1966) and sheep (Blaxter and Cowie 1946, Pearl et al. 1983, Bennett and Schwartz 1971) suggest that fecal excretion, via bile and by secretion of lead and epithelial exfoliation in the gastrointestinal tract, may be greater than or equal to urinary excretion. Fecal excretion of ingested lead has been reported to range from 82 to 99 percent for sheep (Bennett and Schwartz 1971, Pearl et al. 1983, Blaxter 1950, Fick et al 1976) and high lead levels were found in feces of experimental horses (Willoughby et al. 1972). Chronic exposure to low levels of lead have been shown to produce a near steady state in adult humans, sheep (Pearl et al. 1983), and cattle (Allcroft 1951) where metabolic excretion of lead approximately equals lead absorption.

The estimated minimal cumulative fatal dosage of lead in cattle is 6 to 7 mg/kg body weight per day (Buck et al. 1976). Allcroft (1951) fed lead as lead acetate to an experimental steer at a dose of 5 to 6 mg/kg body weight per day for 33 months before any signs of clinical toxicosis occurred. Hammond and Aronson (1964) observed no effects in cattle consuming 3.0 to 3.5 mg lead/kg body weight per day for several months. Cattle fed 6.25 mg lead/kg body weight lead per day died within 24 days (Doyle and Younger 1984), and calves on milk diets containing lead levels of 2.7 mg/kg body weight per day died within 20 days (Zmudski et al. 1983). Horses have been reported to be poisoned at lead levels of 1.7 mg/kg body weight per day. Evidence clearly indicates that livestock can be poisoned by moderately low chronic lead levels.

Clinical signs of lead poisoning include anorexia, excessive salivation, diarrhea, blindness, muscle twitching, hyperirritability, depression, convulsions, grinding teeth, ataxia, circling, bellowing ("roaring in horses") and incoordination. Lack of muscular control of lips and the rectal sphincter has been observed in ponies (Burrows and Borchard 1982).

Absorbed lead is initially distributed to soft tissues via the blood. Some of the lead is later redeposited in bone where it accumulates and forms the bulk of the body's lead burden. Lead affects all major body organs and has been found concentrated in kidneys, liver, spleen, heart and brain. Circulating lead combines with erythrocytes and results in increased fragility of red blood cells and their subsequent premature destruction. Lead also depresses bone marrow and as a result fewer red blood cells are produced. The above effects of blood result in the development of microcytic hypochronic anemia in some animals species. Lead causes rupture of lysosomes and release of acid phosphatase that is required for energy production and protein synthesis. Lead disrupts heme synthesis by interfering with several enzymes and blocks metabolism of aminolevulinic acid which causes abnormally large amounts of deltaminolevulinic acid to appear in plasma and urine. Chronic lead poisoning causes degeneration of kidney and liver tissues with necrosis of the renal tubule cells. Acute poisoning produces necrosis of the gastrointestinal mucosa. The central nervous system is affected by decreased blood supply due to capillary damage which produces edema or collapse of small arteries. Extensive brain lesions have been noted in both chronic and acute lead poisoning in cattle (Christian and Tryphonas 1971). These lesions involve the cerebral cortex, thalamus, hypothalamus, medulla oblongata and proximal cervical spinal cord. Pharyngeal or buccal paralysis in cattle and laryngeal and pharyngeal paralysis in horses may be produced by damage to either cranial nerves or the brain stem nuclei. Incoordination and degeneration of muscle control occurs through segmental demyelination of peripheral nerves.

Lead has been shown to adversely affect reproduction in several animal species, including humans. Sheep grazing in lead mining areas have exhibited high rates of abortions and failures to conceive. Pregnant goats on lead-supplemented diets (lead acetate, 50 to 6,400 mg Pb/kg/day) aborted 6 to 8 days after starting the lead diets (Dollahite et al. 1975). There is evidence that lead can cross the placenta and affect fetal development (Barltrop 1969).

The large accumulation of lead in livestock organs and bone represents a potentially significant source of lead in the human diet.

No documentation has been found relating chronic exposure of livestock to lead and the subsequent development of cancer. Studies of rats and mice subjected to rather high doses of lead compounds via oral or parenteral administrations exhibited malignant and benign renal neoplasms (Environmental Protection Agency 1977).

The synergistic effects of lead and cadmium have been documented for ponies and calves (Burrows and Borchard 1982, Lynch et al. 1976b). Zinc appears to be antagonistic to lead and inhibits symptoms of lead toxicity in young horses (Willoughby et al. 1972b). These authors found that, in the presence of toxic amounts of lead and zinc, the symptoms and tissue lead accumulation normally associated with lead toxicity were suppressed and that the clinical symptoms were those associated with zinc toxicity. Willoughby et al. (1972b) found that dietary doses of lead and zinc necessary to experimentally produce clinical toxicity in foals were considerably higher than lead and zinc levels in diets associated with natural toxicosis, thus suggesting interaction with unknown additional elements occurred in the natural poisoning cases. Lead has been shown to also disrupt tissue levels of iron, copper and manganese in cattle (Doyle and Younger 1984). There is conflicting data concerning the effect of calcium on the absorption and excretion of lead (Pearl et al. 1983, Willoughby et al. 1972).

6.1.4 Zinc toxicology

Animals have high tolerances for zinc, and only under large, excessive exposures have toxic effects been documented. Diets with 3,000 ppm have been required to induce zinc toxicosis experimentally, and 1,000 ppm zinc has not produced adverse effects if there has been an adequate amount of copper and iron in the diet. Ott et al. (1966a) has shown that 1000 to 2000 ppm zinc is necessary to adversely affect the performance of lambs. Zinc is an essential element, and all body tissues contain some zinc. Metabolic problems with zinc generally involve a zinc deficiency.

Although inhalation of industrial dust has resulted in deposition of up to 13,311 ppm zinc in bovine lungs (Dogra et al. 1984) the normal route of zinc absorption is through the gastrointestinal tract. The approximate minimum requirement of zinc in the diet is 40 to 100 ppm for young domestic animals (NRC 1980). Absorption of zinc is controlled by homeostatic mechanisms when zinc ingestion is within normal ranges. These mechanisms have been shown to become markedly less effective at higher (600 ppm) levels of zinc intake in calves (Miller et al. 1970, 1971). Zinc absorption in humans has been reported to range from 16 to 77 percent of the total amount ingested (EPA 1977). Sheep absorbed 13 percent of a 39 mg per day zinc diet (Doyle et al. 1974). Zinc deficiency and underweight conditions increase absorption while excessive dietary calcium with phytate decreases zinc absorption. Zinc is primarily excreted in the feces, with lesser amounts in urine. Small amounts are also found in milk, saliva, sweat and hair, the latter is commonly used as an indicator of body zinc levels (Miller et al. 1965b).

Manifestations of excess dietary zinc include reduced weight gains, anemia, reduced bone ash, decreased iron, copper and manganese in tissues, and diminished utilization of calcium and phosphorus (Ott et al. 1966 c,d). Lameness has been observed in horses receiving up to 186 mg/kg body weight zinc, and severe bone and cartilage abnormalities have been observed in swine receiving 268 ppm dietary zinc. Diets with 2,000 to 4,000 ppm zinc have produced an arthritis-like syndrome, internal hemorrhaging and 33 to 50 percent mortality in swine (Brink 1959).

Absorbed zinc binds to sulfyhdryl, amino, imidazole and phosphate groups. Zinc is necessary for several zinc metalloenzyme and metalloprotein systems, including carbonic anhydrase, carboxypeptidases A and B, alcohol dehydrogenase, glutamic dehydrogenase, D-glyceraldehyde-3-phosphate dehydrogenase, lactic dehydrogenase, malic dehydrogenase, alkaline phosphatase, aldolase, superoxide dismutase, ribonnuclease and DNA polymerase

(Riordan and Vallee 1976, Chesters 1978). The toxic effects of excessive zinc include disrupting bone mineralization (by depressing calcium and phosphorus levels and by decreasing the calcium:phosphorus ratio), interference with copper metabolism (lessened activity of cytochrome oxidase and catalase), and reduced iron concentrations in some tissues (iron deficiency anemia and reduced hepatic iron stores) (NRC 1979).

Zinc chloride has been shown to induce testicular tumors when injected into the active gonads of some fowl, but there is no evidence that zinc is carcinogenic when ingested. Some studies suggest zinc supplements may inhibit tumor growth.

Zinc is antagonistic to cadmium and can reduce many of the adverse effects produced by cadmium when the diet is supplemented with zinc. Animals receiving both zinc and lead exhibit lower lead in bones but higher levels of lead in kidneys and liver. The neurologic dysfunction associated with high lead intake has been absent in the presence of supplemented zinc in the diet. Zinc is antagonistic to copper and may produce copper deficiencies at elevated levels (Eamens et al. 1984). Zinc also disrupts levels of calcium, phosphorus and iron, as indicated above.

6.2 Toxicology Mechanisms of Metals for Plants

The toxicology of metals in plants may involve different biochemical mechanisms in different species and varieties (Foy et al. 1978). Numerous other factors also influence the toxicity of heavy metals. These factors and plant toxicology mechanisms are presented in the following sections.

6.2.1 Arsenic toxicology

While elemental arsenic is not toxic, many of its compounds are toxic. Chief among these are arsenate (AsO_4^{-3}) and arsenite (AsO_2^{-2}). Other common forms are methanearsenate and dimethylarsenate, which are commercially prepared as post-emergence herbicides, but may also be synthesized in trace amounts in the soil by microorganisms. Plants take up relatively small amounts of arsenic from soils and the arsenic levels in natural soils are rarely high enough to cause phytotoxicity. Aerial deposition of arsenic from smelters, or long-term application of arsenical pesticides may elevate soil values to phytotoxic levels. Plant toxicity to arsenic occurs when: 1) abnormally high arsenic levels are produced in soil, either deliberately or accidentally by man's activities; 2) a change in soil chemistry increases arsenic availability; and 3) plant foliage is sprayed with arsenical compounds (Wauchope 1983). Symptoms of arsenic toxicity include wilting of new-cycle leaves, followed by retardation of root and top growth (Liebig 1966).

Arsenite is 4 to 100 times more toxic and its compounds are more available to plants than arsenate (Wauchope 1983). However, in most cases arsenite is rapidly oxidized to arsenate in the soil. Arsenic phytotoxicity is a four-stage process: 1) absorption onto plant surfaces; 2) movement to the plant interior; 3) translocation to the site of action; and 4) a biochemical reaction that is toxic (Wauchope 1983). Both arsenate and arsenite are rapidly and intensely adsorbed to plant roots, resulting in very high concentrations in the root vicinity (Machlis 1974). Because of its extremely high toxicity to cell membranes, very limited translocation of arsenite occurs once the chemical has penetrated the cuticle and entered the apoplast phase of the plant system. Membrane degradation is the result of arsenite oxidation by sulfhydryl groups, causing cessation of root functions and foliar necrosis upon contact (Speer 1973). Internal injury of this type is manifested as wilting due to loss of turgor.

Arsenate is less toxic and therefore is more readily translocated. If sub-lethal concentrations are present in the soil, substantial accumulation may occur in foliage (Liebig 1966). Translocation occurs both intra- and extracellularly, including xylem and phloem transport. Arsenate does not react with sulfhydryl groups, nor does it degrade cell membranes like arsenite. Its main toxic effects are apparently due to its disturbance of phosphorus metabolism in plants. Studies have shown that the chemistry of arsenate and phosphate is very similar and they tend to replace one another chemically, but not functionally. Such substitution of arsenate for phosphate may cause decoupling of oxidative phosphorylation in mitochondria and inhibit leaf uptake of chemicals. Further, as arsenate is translocated throughout the plant it may interfere with cell organelles such as chloroplasts in which phosphorus plays an important role (NRC 1977). Porter and Sheridan (1981) noted reduction in the nitrogen fixing activity at low levels (1 mg/L of added arsenic) and inhibition of photosynthesis and respiration at very high levels (100 mg/L).

6.2.2 Cadmium toxicology

Cadmium is an element serving no apparent essential biological function, yet it is often readily taken up, translocated and accumulated by plants. It is found in very low concentrations in natural soils and generally only reaches phytotoxic levels due to anthropogenic activities. Plant uptake occurs both through roots and leaves. Uptake of soil-cadmium is influenced by several factors including pH, CEC, plant species and varieties and age (Jastrow and Koeppe 1980, Boggess et al. 1978). Recently, added chloride was shown to increase the level of soluble soil-cadmium (Bingham et al. 1984). A study of cadmium uptake and translocation from solution has shown most of the cadmium to be retained in plant roots (Jarvis et al. 1976). Symptoms of cadmium toxicity include stunting and chlorosis. While much is known about the toxicological effects of cadmium, little has been discovered concerning the biochemical basis for plant toxicity.

Cadmium is chemically allied with zinc and often substitutes for zinc in plant metabolic activities; this substitution may be a reason for its phytotoxicity. Vallee and Ulmer (1972) proposed that cadmium toxicity is in part due to the replacement of zinc by cadmium at certain enzyme sites. Root et al. (1975) stated that excess cadmium may cause chlorosis in corn leaves due to decreased zinc uptake and subsequent changes in the Fe:Zn ratios. Cadmium interference with zinc uptake and translocation in beans was documented by Hawf and Schmid (1967). In contrast, added cadmium levels significantly increased the zinc concentration of tomato leaf tissue (Smith and Brennan 1983). Other researchers have reported both interference and enhancement of zinc uptake by cadmium in different plants and at varying levels of cadmium concentration (Hinesly et al. 1982, Pepper et al. 1983, Chaney et al. 1976). Gerritse et al. (1983) found that increasing zinc in the soil solution apparently increased cadmium uptake at high solution concentrations of cadmium and decreased uptake at low solution concentractions. Air pollution (as ozone) may interact synergistically with cadmium to reduce crop yields, causing ozone toxicity symptoms to develop at cadmium levels that normally would be harmless (Czuba and Ormrod 1974). Hovmand et al. (1983) reported that atmospheric cadmium accounted for 20 to 60 percent of the total amount of cadmium in some agricultural crops in Denmark.

More than 70 percent of the total amount of cadmium in tree leaves near a zinc smelter was found to be associated with the cell wall. The remaining cadmium was distributed among the cytosol, vacuole sap and cell organelles (Ernst, 1980). Such a compartmentalization of cadmium in cell walls may protect the more susceptible metabolic sites of the cell. Cadmium content in cell organelles is related to their function and potential for ion uptake. For example, chloroplasts will accumulate much more cadmium than mitochondria.

Lee et al. (1976) found that cadmium may either stimulate or inhibit a large number of plant enzyme systems, which may cause subsequent biochemical chain reactions. Enzyme inhibition has been shown to be the result of cadmium affinity for sulfhydryl groups. Such disruption of enzyme systems has been shown to affect nitrate uptake in corn seedlings and amino group catalysis and nitrogen fixation by legumes (Mathys 1975, Volk and Jackson 1973, Huang et al. 1974).

Cadmium may also negatively affect photosynthesis. It has often been associated with reduced chlorophyll content, possibly due to interference with the biosynthesis of photosynthetic pigments and biomembranes. Enzymes needed for catalytic activity may also be inactivated by cadmium because cadmium will bind with sulfhydryl groups. Reduced carbon dioxide fixation may result from cadmium substitution for zinc in zinc metalloenzymes and substitution for manganese may cause inhibition of electron flow in plant photosystems (Ernst 1980).

Plant respiration may be enhanced or inhibited depending upon species-specific carbohydrate metabolism. Cadmium has been shown to cause pronounced swelling of mitochondria, with a resultant decrease in respiration rate (Bittell and Miller 1974). Like numerous other metals, cadmium may have a strong effect on the properties of DNA. It has been demonstrated that cadmium may decrease cell viability, increase single-strand breakage of DNA and inhibit cell division (Mitra and Bernstein 1978).

6.2.3 Lead toxicology

Lead is considered a nonessential element for plant growth. Lead uptake from soils is dependent on many factors, including soil pH, cation exchange capacity (CEC), organic matter, calcium content, plant species and the soluble metal concentration. Climatic conditions such as precipitation, temperature and the length of daylight also influence lead uptake.

Lead uptake is enhanced by low pH conditions and by soils with little organic matter. Organic matter is known to have a high CEC and tends to adsorb or bind most metal cations. Thus, high CEC or organic matter content renders soil lead less available to plants. Low pH conditions enhance the solubility of most metals, including lead, making them more available for plant uptake. The addition of phosphate and liming have been shown to reduce lead uptake by plants by forming low solubility compounds such as lead hydroxide, carbonate and phosphate (Demayo et al. 1982). Plant species also differ in their lead uptake. Lead tends to collect in the top layer of soil and, therefore, shallow rooted plants such as annual grasses take up more lead than deep rooted perennials such as alfalfa.

Absorption of lead by plants is both by root uptake and absorption through foliage of airborne lead fallout. Most of the literature indicates that uptake by roots is the primary means of lead absorption (Zimdahl and Arvik, 1973). Translocation of lead from the root system to other parts of the plant is poor, with roots generally accumulating the highest lead concentration. The translocation is predominantly apoplastic in nature (Holl and Hampp 1975). Indirect evidence suggests transport is via sieve tubes which are part of the phloem (food) transport system in plants. Some lead may be precipitated in root dictyosomes, possibly due to phosphatase enzymes (Haque and Subramanian 1982). The dictyosome vesicles contain cell wall precursors and as the dictyosomes move to the cell walls and fuse to it, the lead may be bound at that site. Translocation of lead is apparently enhanced when the soil solution is deficient in other nutrients. Many researchers have found increased lead levels in all plant tissues growing in a nutrient solution containing lead. The fruiting and flowering parts of plants have been found to accumulate the least amount of lead (NRC 1972).

The toxicosis of lead in plants is expressed by reduced growth and vital processes such as photosynthesis, mitosis and water absorption. Lead accumulates in tissues with high mitotic activity and appears to be bound to polyuronic acids of the cell walls (Holl and Hampp, 1975). High concentrations of lead are found in organelles such as mitochondria, chloroplasts and also in nuclei. The lead is apparently bound to certain phosphate groups in cells.

Roots that are in contact with lead degenerate because of a decrease in cell division in root meristems. The photosynthetic process is hindered by diminished CO_2 fixation by chloroplasts and by the disturbance that lead causes in the transport of electron between the site of primary electron donor and water oxidation (Holl and Hampp 1975). The activity of many enzymes is inhibited due to blocking by lead of sulfhydryl groups in proteins due to changes in the phosphate levels of living cells.

6.2.4 Zinc toxicology

Zinc is an essential element in plant metabolism. Zinc deficiency in crops is the most common micronutrient deficiency in the United States (NRC 1979). Zinc phytotoxicity exists naturally in only isolated instances with most toxicity problems related to anthropogenic sources such as in metal mining, smelting and refining.

Zinc uptake by plants is influenced by the soil pH, soil composition, CEC, organic matter, phosphorus levels, and soluble zinc concentrations. Uptake is also influenced by the form of zinc. Zinc oxides, carbonates, phosphates and sulfides are generally less soluble and therefore less toxic than similar concentrations of soluble zinc salts. Zinc availability to plants is enhanced in low pH in soils where the solubility of many metals is increased. The potential for zinc toxicosis is reduced in soils high in calcium and magnesium and the increase of soil pH from the liming of agricultural soils reduced zinc toxicosis (Lee and Page 1967). The fixation of zinc through microbial activity also reduces zinc available for plant uptake. Studies suggest plants remove 1 to 3 percent of the zinc added to a soil (Taylor et al. 1982).

Absorption of zinc is influenced by copper, phosphorus, and iron levels. Copper and zinc are antagonistic and the absorption of one usually depresses absorption of the other. Phosphorus in excessive amounts can reduce zinc uptake and, conversely, excessive zinc apparently depresses phosphorus metabolism. Excess iron tends to intensify a zinc deficiency. Translocation of zinc occurs through the xylem (water transports system) and a small amount may be redistributed via the phloem (food transport system). Normal zinc concentrations in plants range from 15 to 150 ppm (dry matter) with zinc toxicosis commonly occurring at levels of 400 ppm (dry matter) (Gough et al. 1979). The susceptibility of plants to zinc toxicity varies among species. Boawn and Rasmussen (1971) have shown that monocotyledonous species (corn, sorghum, barley and wheat) were more sensitive to excess zinc than were dicotuledmons species (beans, peas, some leafy vegetables and clover). Symptoms of zinc toxicity include stunted growth, reduced yields, reduced size of leaves, necrosis of leaf tips and shoot apices, a reddish tint near the basal part of leaves and curling and distortion of foliage.

Zinc is an enzyme cofactor and binds pyridine nucleotides to the protein portion of enzymes. Zinc atoms also stabilize the structure of yeast alcohol dehydrogenase and are an essential component in a variety of dehydrogenases, proteinases, peptidases and zinc metalloenzyme carbonic anhydrase (NRC 1979). Lack of zinc, therefore, produces a general failure in the metabolic system; RNA doesn't form, resulting in lowered protein formation, less total nitrogen and DNA lesions.

6.3 Computerized Data Base Utilized

The following data bases have been computer searched for this document. Descriptions are quoted directly from Dialog database catalog for 1985.

AGRICOLA **File 10, 110**

1970-present, 2,826,000 records, monthly updates (National Agricultural Library, Beltsville, MD).

AGRICOLA (formerly CAIN) is the cataloging and indexing database of the National Agricultural Library (NAL). This massive file provides comprehensive coverage of worldwide journal and monographic literature on agriculture and related subjects. Since AGRICOLA represents the actual holdings of the National Agricultural Library, there is substantial coverage of all subject matter normally contained in a very large library. File 110 contains the citations for the years 1980-1978. File 10 contains citations from 1979 to the present. Both files have similar format and identical coverage and pricing.

BIOSIS PREVIEWS **Files 5, 55, 255**

1969-present, 4,566,000 records, biweekly updates (BioSciences Information Service, Philadelphia, PA).

BIOSIS PREVIEWS contains citations from both Biological Abstracts and Biological Abstracts/RRM (formerly entitled Bio-research Index), the major publications of BioSciences Information

Service of Biological Abstracts. Together, these publications constitute the major English language service providing comprehensive worldwide coverage of research in the life sciences. Over 9,000 primary journals and monographs as well as symposia, reviews, preliminary reports, semi-popular journals, selected institutional and government reports, research communications, and other secondary sources provide citations on all aspects of the biosciences and medical research. Searchable abstracts are available for Biological Abstracts records from July 1976 to the present. File 5 contains all the citations from 1981 through the present. The citations for the years from 1977 through 1980 are available in File 55, and citations for the years 1969-1976 are available in File 255.

CAB ABSTRACTS **File 50**

1972-present, 1,760,000 records, monthly updates (Commonwealth Agricultural Bureaux, Farnham Royal, Slough, England).

CAB ABSTRACTS is a comprehensive file of agricultural and biological information containing all records in the 26 main abstract journals published by Commonwealth Agricultural Bureaux. Over 8,500 journals in 37 languages are scanned, as well as books, reports, and other publications. In some instances less accessible literature is abstracted by scientists working in other countries. About 130,000 items are selected for publication yearly; significant papers are abstracted, while less important works are reported with bibliographic details only.

The following journals are included in CAB ABSTRACTS: Agricultural Engineering Abstracts; Animals Breeding Abstracts; Apicultural Abstracts; Arid Lands Abstracts; Dairy Science Abstracts; Field Crop Abstracts; Forest Products Abstracts; Forestry Abstracts; Helminthological Abstracts (A & B); Herbage Abstracts; Horticultural Abstracts; Index Veterinarius; Nutrition Abstracts and Reviews (A & B); Plant Breeding Abstracts; Protozoological Abstracts; Review of Applied Entomology (A & B); Review of Medical and Veterinary Mycology; Review of Plant Pathology;

Rural Development Abstracts; Rural Extension, Education and Training Abstracts; Leisure, Recreation and Tourism Abstracts; Rural Sociology Abstracts; Soils and Fertilizers; Veterinary Bulletin; Weed Abstracts; and World Agricultural Economics.

CRIS/USDA **File 60**

Last two years, 35,700 records, monthly updates (U.S. Department of Agriculture, Beltsville, MD).

CRIS (Current Research Information System) is a valuable current-awareness database for agriculturally related research projects. The projects described in CRIS cover current research in agriculture and related sciences, sponsored or conducted by USDA research agencies, state agricultural experiment stations, state forestry schools, and other cooperating state institutions. Currently active and recently completed projects within the last two years are included.

The subject coverage of CRIS encompasses the following disciplines: biological, physical, social and behavioral sciences related to agriculture in its broadest applications, including natural resource conservation and management; marketing and economics; food and nutrition; consumer health and safety; family life, housing, and rural development; environmental protection; forestry; outdoor recreation; and community, area, and regional development.

ENVIROLINE **File 40**

1971-present, 115,500 records, monthly updates (EIC/Intelligence, New York, NY).

ENVIRONLINE, produced by the Environment Information Center, covers the world's environmental information. Its comprehensive, interdisciplinary approach provides indexing and abstracting coverage of more than 5,000 international primary and secondary source publications reporting on all aspects of the environment. Included are such fields as: management, technology, planning, law, political science, economics, geology, biology, and chemistry as they relate to environmental issues. Literature covered includes periodicals, government documents, industry reports, proceedings of meetings, newspaper articles, films and monographs. Also included are rulings from the Federal Register and patents from the Official Gazette.

MEDLINE **Files 152, 153, 154**

1966-present, 4,687,000 records, monthly updates (U.S. National Library of Medicine, Bethesda, MD).

MEDLINE (MEDLARS onLINE), produced by the U.S. National Library of Medicine, is one of the major sources for biomedical literature. MEDLINE corresponds to three printed indexes: Index Medicus, Index to Dental Literature, and International Nursing Index. MEDLINE covers virtually every subject in the broad field of biomedicine. MEDLINE indexes articles from over 3000 international journals published in the United States and 70 countries. Citations to chapters or articles from selected monographs are also included.

MEDLINE is indexed using NLM's controlled vocabulary MeSH (Medical Subject Headings). Over 40% of records added since 1975 contain author abstracts taken directly from the published articles. Over 250,000 records are added per year, of which over 70% are English language.

NTIS **File 6**

1964-present, 1,122,000 records, biweekly updates (National Technical Information Service, [NTIS], U.S. Department of Commerce, Springfield, VA).

The NTIS database consists of government-sponsored research, development, and engineering plus analyses prepared by federal agencies, their contractors or grantees. It is the means through which unclassified, publicly available unlimited distribution reports are made available for sale from such agencies as NASA, DDC, DOE, HHS (Formerly HEW), HUD, DOT, Department of Commerce, and some 240 other units. State and local government agencies are now beginning to contribute their reports to the file.

The NTIS database includes material from both the hard and soft sciences, including substantial materials on technological applications, business procedures, and regulatory matters. Many topics of immediate broad interest are included, such as environmental pollution and control, energy conversion, technology transfer, behavioral/societal problems, urban and regional planning.

POLLUTION ABSTRACTS **File 41**

1970-present, 110,000 records, bimonthly updates (Cambridge Scientific Abstracts, Bethesda, MD).

POLLUTION ABSTRACTS is a leading resource for references to environmentally related literature on pollution, its sources, and its control. The following subjects are covered by the POLLUTION ABSTRACTS database: Air Pollution, Environmental Quality, Noise Pollution; Pesticides, Radiation, Solid Wastes, and Water Pollution.

SCISEARCH **Files 34, 87, 94, 186**

1974-present, 6,189,000 records, biweekly updates (Institute for Scientific Information, Philadelphia, PA)

SCISEARCH is a multidisciplinary index to the literature of science and technology prepared by the Institute for Scientific Information (ISI). It contains all the records published in Science Citation Index (SCI) and additional records from the Current Contents series of publications that are not included in the printed version of SCI. SCISEARCH is distinguished by two important and unique characteristics. First, journals indexed are carefully selected on the basis of several criteria, including citation analysis, resulting in the inclusion of 90 percent of the world's significant scientific and technical literature. Second, citation indexing is provided, which allows retrieval of newly published articles through the subject relationships established by an author's reference to prior articles. SCISEARCH covers every area of the pure and applied sciences.

The ISI staff indexes all significant items (articles, reports of meetings, letter, editorials, correction notices, etc.) from about 2600 major scientific and technical journals. In addition, the SCISEARCH file for 1974-75 includes approximately 38,000 items from Current Contents--Clinical Practice. Beginning January 1, 1976, all items from Current Contents--Engineering, Technology, and Applied Science and Current Contents--Agriculture, Biology, and Environmental Sciences that are not presently covered in the printed SCI are included each month. This expanded coverage adds approximately 58,000 items per year to the SCISEARCH file.

WATER RESOURCES ABSTRACTS **File 117**

1968-present, 176,000 records, monthly updates (U.S. Dept. of the Interior, Washington, D.C.).

Water Resources Abstracts is prepared from materials collected by over 50 water research centers and institutes in the United States. The file covers a wide range of water resource topics including water resource economics, ground and surface water hydrology, metropolitan water resources planning and management, and water-related aspects of nuclear radiation and safety. The collection is particularly strong in the literature on water planning (demand, economics, cost allocations), water cycle (precipitation, snow, groundwater, lakes, erosion, etc), and water quality (pollution, waste treatment). WRA covers predominantly English-language material and includes monographs, journal articles, reports, patents and conference proceedings.

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