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RISK EVALUATION FOR SLUDGE-BORNE ELEMENTS TO WILDLIFE FOOD CHAINS

By

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ABSTRACT

RISK EVALUATION FOR SLUDGE-BORNE ELEMENTS TO WILDLIFE FOOD CHAINS

by

David Kent Woodyard

Studies were conducted to evaluate the human and wildlife food chain risks from exposure to potentially toxic metals associated with recycling sludges to forest lands. The fate of 5 selected metals, Cd, Cr, Cu, Ni and Zn, was determined in both field and laboratory food chains exposed to sludge-borne metals. Knowledge gained on the fate of the selected metals and existing knowledge of their toxicological properties were used to complete a risk assessment.

Nonindustrial, municipal sewage sludge was applied to 5 forest types in 2 counties of northern lower Michigan. Monitoring of metals in soils, selected wildlife forages, and small mammal tissues was completed for 3 years on both replicated, control and sludge-treated plots. In addition 2 laboratory food chains were evaluated for metal fate after exposure to sludge-borne metals. One food chain was a plant-small mammal-raptor the other a soil-macroinverte-brate-vertebrate insectivore food chain.

Some metals, primarily Cd and Cr, did accumulate in wildlife forages during the first year after application but returned to background concentrations by the second growing season. Maximum metal concentrations were magnitudes less than doses suspected to elicit chronic toxicities in wildlife. Tissues collected from herbivorous and omnivorous small mammals showed no evidence of metal accumulation. Laboratory experiments support this observation. The soil macroinvertebrate-vertebrate insectivore food chain did appear as a potential pathway for metals to accumulate, as woodcock (Philohela minor) fed sludge-contaminated earthworms concentrated Cd in kidney and liver tissues. However, muscle tissues collected from the woodcock did not contain significant concentrations of the selected metals.

Results from this study suggest that at the application rates used, sludge does not present a metal toxicity problem to wildlife consuming vegetation or to higher trophic groups consuming certain small mammal species. Consequently, upland forest types, such as addressed in this investigation, can be recommended for sludge-recycling without significant health risks from metals to wildlife or humans consuming wildlife. However, monitoring sewage and forest response to sludge amendments is recommended to ensure environmental and public safety. Forest soils supporting habitat more suitable for wildlife that consume invertebrate detritivores (e.g. earthworms) require further study to determine safe application rates.

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SLUDGE-BORNE METALS IN WILDLIFE FOOD CHAINS FROM SLUDGE RECYCLING TO FORESTED LANDS

One of the residuals from waste water treatment is sewage sludge. Passage of the 1972 amendments to the Federal Water Pollution Control Act accelerated production of sewage sludges. Subsequently, regulatory agencies and waste managers realized that the existing practices of disposal were inadequate (Riordan 1983). Of the disposal alternatives, only agricultural and forest landspreading allowed for reuse of nutrients and organic matter concentrated in sewage sludges. Thus, interest in land treatment developed.

Today, for several reasons, recycling to forested lands is of particular interest in Michigan. Researchers have suggested that public exposure to health risks and food chain hazards is minimized more with recycling on forest than on agricultural lands (Zasoski et al. 1977, Brockway 1979, Zasoski 1981). In addition, forest disposal can be cost effective, as many Michigan communities are situated near public-owned, forested lands. Furthermore, studies have indicated there is generally more public acceptance for forest application than other options (Gigliotti 1983, Lagerstrom 1983).

Specific knowledge is necessary to manage sludge to maintain the quality of the forest environment. To avoid nitrate degradation of ground water quality, Brockway and Urie (1983) determined application rates for some of Michigan's sand soils. Other environmental concerns lead to adjunctive research (Harris et al. 1984, Urie et al. 1978, Urie et al. 1984); with particular emphasis placed on measuring the response of wildlife and wildlife habitat (Campa 1982, Woodyard 1982, Thomas 1983, Seon 1984).

To complete a risk-benefit analysis for forest application, it is essential to understand risks associated with sludge-borne, potentially toxic metals. As wildlife generally respond positively (Haufler and West 1986), risks from metals entering the wildlife food chain could be augmented. Concerns include possible metal accumulation in the food base of sensitive, higher trophic level species, such as raptors and in game species consumed by people.

OBJECTIVES

This study was part of a sludge-recycling project designed to determine the influence of land application upon some upland forested ecosystems. Wildlife were included in the ecosystem components examined. To identify potential problems with sludge-borne metals entering wildlife food chains, objectives included:

1. testing for concentration differences (for Cd, Cr, Cu, Ni, and Zn) between sludge-amended and control sites in soils, plants, and small mammals,
2. testing for potentially toxic metal concentrations in tissues of white-tailed deer (*Odocoileus virginianus*) collected from a sludge-amended area,
3. measuring the longevity of any metal changes produced by recycling sewage sludges.

A final objective was to complete a risk assessment based on the knowledge gained on the fate of the selected metals and existing knowledge of the toxicological properties of the metals.

STUDY AREAS

Field investigations were conducted in 2 counties of the northern lower peninsula of Michigan. In 1980 a 4-year-old jack pine clearcut, was located in Wexford County (44° 16'N, 85° 20'W) as the first research site. A year later, 4 additional forest types were located in Montmorency County (44° 59'N, 84° 10'W) and included stands of 10-year-old aspen, 70-year-old oak, 50-year- old pine, and 50-year-old mixed hardwoods.

Climate of both counties is typical of northern lower Michigan (NOAA 1981). The mean annual temperature for this region is 5.8 C with monthly extremes in January (-7.8 C) and July (19.6 C). Influenced by its proximity to Lake Michigan, 64 Km to the West, Wexford County averages a 20% greater snowfall (180.0 cm) than Montmorency (152.4 cm), but total precipitation is similar (82.1 cm and 76.7 cm). During the study period (May 1980 - December 1985), temperature and precipitation followed the average except the 1982 winter was unusually cold (NOAA 1982).

Vegetation on the Wexford study site was in an early successional stage after being clearcut in 1976. Overstory vegetation consisted of widely dispersed clumps of regenerating jack pine (Pinus banksiana) dominated by black cherry (Prunus serotina), choke cherry (P. virginiana) and pin cherry (P. pensylvanica). Brambles (Rubus) dominated the groundstory. Common groundstory species included panic grass (Panicum virgatum), orange hawkweed (Hieracium aurantiacum), and sedges (Carex). A mosaic pattern existed with clumps of cherries and brambles interspersed with gaps of no vegetation and exposed soil. Soils on this study site were sands of the Graycalm and Montcalm series (Eutric Glossoboralfs). Excessively to well drained (Corder 1979), these soils were strongly acidic (Woodyard unpubl. data). Absence of an A2 horizon suggested cultivation may have occurred within the last century.

The Montmorency County Sites were of 4 different vegetation types. Past habitat manipulation of the aspen type included repeated roller chopping and burning in an unsuccessful effort to create a wildlife opening. The result was also a mosaic pattern of clumps consisting of bigtooth aspen (_Populus grandidenta_) and trembling aspen (_P. tremuloides_) interspersed with scattered pin cherry, red maple (_Acer rubrum_), and oaks (_Quercus_) Major understory vegetation consisted of sweetfern (_Comptonia_), braken fern (_Pteridium_), sedges, panic grass, and brambles. Predominant soil types were excessively and well drained sands of the Rubicon (Eutic Haplorthod) and Montcalm series. (Nguyen and Hart 1984).

The upland oak stand supported an overstory mixture of red oak (_Q. rubra_), white oak (_Q. alba_) and red maple, and an understory of the same species along with witch hazel (_Hamamelis virginiana_) and service berry (_Amelanchier_). Common groundstory species were bracken fern, wintergreen (_Gaultheria_), and sedges. Excessively and somewhat excessively drained sands from the Grayling (Typic Udipsamment) and Rubicon series were predominate soils on the site.

The pine plantation consisted of jack pine interspersed with red pine (_P. resinosa_). A sparse midstory consisted of red oak and red maple. Dominant groundstory species were blueberry (_Vaccinium_), sweetfern, bracken fern and sedges. Soils consisted of excessively drained sands of the Garyling series (Typic Udipsamment) and a well drained coarse loam of the Montcalm series (Eutric Glossoboralf).

Sugar maple (*A. saccharum*), red maple, American beech (*Fagus grandifolia*) and American basswood (*Tilia americana*) were the important overstory species for the mixed hardwoods type. A well developed midcanopy included individuals of the overstory species and white ash (*Fraxinus americana*), eastern hophornbeam (*Ostrya virginiana*), and striped maple (*A. pensylvanicum*). The groundstory was sparse but diverse and was described by Thomas (1983). Soils were sands of the Mancelona and Menominee series (Alfic Haplorthods) with smaller areas consisting of somewhat poorly drained soils of the Kawkawlin (Aquic Eutroboralfs) and Sims (Mollic Haplaquept) series.

METHODS

Experimental Design

A completely randomized design was employed for all field experiments. Treatments were randomly replicated among plots located within each vegetation type. Plot design required modifications as land spreading techniques were different between counties.

For the jack pine clearcut, the experimental design included the location of 6, 2 ha plots (Fig. 1a). Three plots each were randomly chosen to receive sludge and to exist as controls.

For Montmorency County, the sludge application method selected by Michigan's Department of Natural Resources required application trails. As site impacts associated with the construction of application trails could be significant, this manipulation was considered a treatment. Consequently, 9 study plots, each 1.5 ha, were delineated

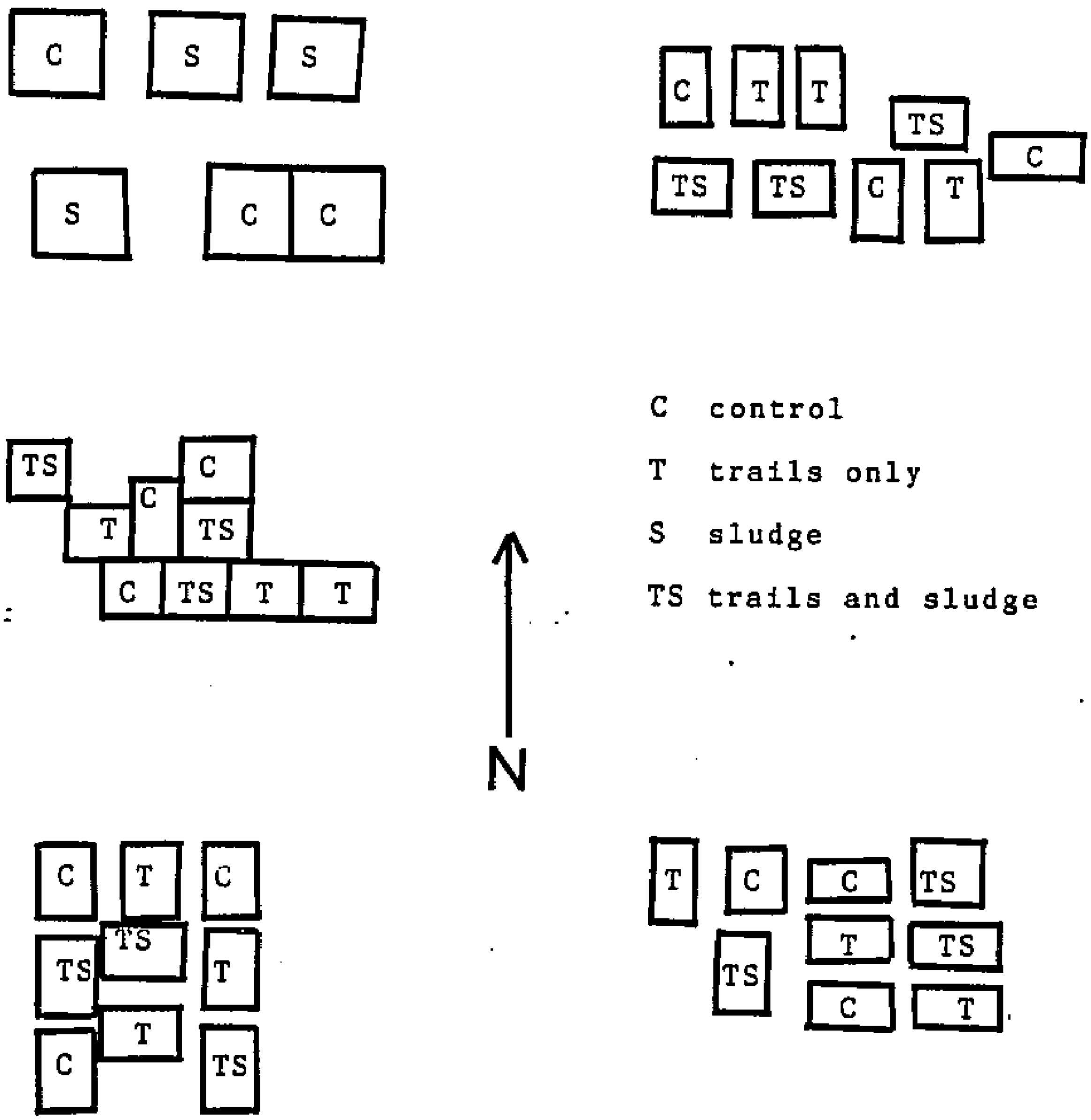

Fig. 1. Location of study plots on a) jack pine clearcut, b) jack pine/ red pine, c) oak, d) aspen, and mixed hardwoods study areas.

in each vegetation type (Figs. 1b-1e). Three plots were randomly assigned as controls with no manipulation. Three plots received the clearing of application trails but were not amended with sludge. The remaining 3 plots had application trails cut and received sludge.

Sludge Application

Digested municipal sewage sludge was obtained from water treatment facilities in Cadillac, Alpena, and Rodgers City Michigan. Sludge was transported to all sites in tanker trucks, but 2 application methods were employed. A rain cannon and portable irrigation pipe were used to distribute sludge over the jack pine clearcut. An adapted agricultural spreader, which required 5 m-wide trails for access, was used to distribute sludges in Montmorency County. These access trails were located 20 m apart and constructed in Fall 1981.

In May 1980, 1,020,000 L of Cadillac sewage sludge (6 % solids) were applied to the jack pine clearcut. A total of 1,113,000 L of Alpena sludge was used to treat the aspen site in October 1981. One month later, a total of 780,000 L, from both Alpena and Rodgers City, was recycled to the oak type. The pine plantation and mixed hardwood stand received sludge in June and July 1982, respectively. Approximately 1,113,000 L of sludge from Alpena was applied to the plantation, while Rodgers City was the source of the 674,000 L applied to the hardwoods. Application rates (L/ha) were designed so as not to exceed projected groundwater nitrate concentrations of 10 ppm.

Sludge Metal Composition

All sludge analyses were conducted by the cooperative effort of the North Central Experiment Station of the U.S. Forest Service and the Forestry Department at Michigan State University. Complete sludge descriptions are presented elsewhere (Woodyard 1982, Nguyen and Hart 1984). Concentrations of the selected metals in the applied sludges were generally within limits considered appropriate for application to agricultural lands (Table 1). Exceptions were Cd concentrations in the sludges applied to the jack pine clearcut, oak stand and pine plantation and Cu in the sludges applied to the mixed hardwoods type. There are no federal restrictions on the annual or cumulative metal accumulations in soils used for non-food chain crops. When applied to soils supporting human foods, however, sludge-borne Cd cannot exceed 0.5 kg/ha/year or a maximum cumula-

Table 1. Concentrations (ug g^{-1}) of the selected metals in the sludges applied to the 5 study areas, and limits considered appropriate (Chaney and Giordano 1977).

Metal	Maximum suggested concentration	Forest Type				
		Jack pine	Aspen	Oak	Pine	Hardwoods
Cd	50	56*	27	54	60	9
Cr	1000	154	181	106	106	64
Cu	1000	428	570	775	515	1182
Ni	200	45	43	39	43	23
Zn	2000	985	705	1145	931	942

*dry weight

tive application of 5 kg/ha (Environmental Protection Agency 1979). Loading rates for Cd ranged from 0.08 to 0.63 kg/ha in this study, with only the jack pine clearcut receiving an application > 0.5 kg/ha (Table 2).

Vegetative Tissue Sampling

Vegetative samples were collected for metal analyses during spring, summer and early winter, beginning the first season after the sludge treatment and continuing for 2 years. Three samples/ plot of common forage species (Table 3) were collected from each forest type. Samples were collected from randomly established belt transects and included tissues from many individual plants. For herbaceous species, the above ground portion of the plants was clipped, while only the current annual growth was included for woody species. Winter samples were restricted to twigs of woody species. Samples were dried at 60° C until a constant weight was maintained. Samples were then ground in a Wiley Mill to pass a 1 mm sieve and stored in Whirl Paks until analyzed.

Small Mammal Tissue Sampling

Small mammals were collected during late summer when

Table 2. Rates of metal application (kg/ha) applied to the 5 study areas.

Metal	Forest Type				
	Jack pine	Aspen	Oak	Pine	Hardwood
Cd	0.63	0.28	0.42	0.36	0.08
Cr	1.69	1.81	0.85	0.86	0.58
Cu	4.76	5.68	6.13	4.22	10.8
Ni	0.54	0.42	0.31	0.35	0.21
Zn	10.9	12.3	9.25	7.61	8.60

*dry weight

Table 3. Forage species collected for metal analysis from each forest type.

Jack pine	Aspen	Oak	Pine	Hardwood
brambles (*Rubus*)	wild strawberry (*Fragaria virginiana*)	red maple (*Acer rubrum*)	red maple	sugar maple (*A. saccharium*)
orange hawkweed (*Hieracium aurantiacum*	orange hawkweed	bracken fern (*Pterdium aquilinum*)	sedge (*Carex*)	american beech (*Fagus americana*)
panic grass (*Panicum virgatum*)	panic grass	white oak (*Quercus rubra*)	bracken fern	white ash (*Fraxinus americana*)
sedge	bigtooth aspen (*Populus gradidentata*)	red oak (*Q. rubra*)	red oak	hophornbeam (*Ostrya virginiana*)
jack pine (*Pinus banksiana*)	bracken fern			
cherries (*Prunus*)	pin cherry (*P. pensylvanica*)			
	trembling aspen (*P. tremuloides*)			

populations were highest. Species whose individual numbers were too infrequent for statistical analysis were not included. Adequately abundant species (Table 4) were obtained from all plots via Sherman live-traps baited with a mixture of oats, fat and anise extract. Specimens were identified with a number and frozen for future, metal analysis. Livers, kidneys, humeri, and muscles of the hindlegs were removed, dried at 60° C and analyzed immediately. Composite samples of tissues from 3 individuals were required for the smaller species, *Napaeozapus insignis*, *Zapus husonius* and *Peromyscus leucopus*. While all individuals collected of the genus *Peromyscus* were not identified to species through cranial examination, all examined were of the species *leucopus*.

Soil Sampling

For the Wexford County site, each plot was divided into a 6x6 matrix of 36 subplots (550 m). In October 1980, each subplot was sampled with a bucket auger at 7 depths; 0-5cm, 5-10cm, 10-15cm, 15-30cm, 30-60cm and 60-90 cm. Samples were dried at 105° C for 24 hours and passed through a 2 mm sieve before analyzing. Sampling was

Table 4. Small mammal species collected for metal analysis from each forest type.

Forest Type	Species	Treatment	samples/ year* 1	2	3
jack pine	white-footed mouse (*Peromyscus leucopus*)	control	(6)	(8)	(3)
		sludge	(6)	(8)	(3)
	13-lined ground squirrel (*Citellus tridecemlineatus*)	control	(5)	(5)	(3)
		sludge	(5)	(5)	(3)
	meadow jumping mouse (*Zapus hudsonius*)	control	(-)	(2)	(-)
		sludge	(-)	(3)	(-)
aspen	13-lined ground squirrel	control	(6)	(-)	(-)
		trails only	(6)	(-)	(-)
		sludge	(6)	(-)	(-)
	eastern meadow vole (*Microtus pennsylvanicus*)	control	(6)	(6)	(5)
		trails only	(6)	(3)	(6)
		sludge	(6)	(3)	(6)
	eastern chipmunk (*Tamias striatus*)	control	(4)	(-)	(-)
		trails only	(4)	(-)	(-)
		sludge	(4)	(-)	(-)

Table 4 cont.

	woodland jumping mouse (*Napaeozapus insignis*)	control	(3)	(3)	(3)
		trails only	(3)	(3)	(4)
		sludge	(3)	(3)	(4)
oak	white-footed	control	(6)	(6)	(9)
		trails only	(6)	(6)	(9)
		sludge	(6)	(6)	(9)
pine	eastern chipmunk	control	(-)	(5)	(-)
		trails only	(-)	(4)	(-)
		sludge	(-)	(4)	(-)
	white-footed mouse	control	(-)	(-)	(4)
		trails only	(-)	(-)	(4)
		sludge	(-)	(-)	(3)
hardwoods	white-footed mouse	control	(4)	(4)	(10)
		trails only	(6)	(6)	(10)
		sludge	(6)	(6)	(10)
	eastern chipmunk	control	(6)	(6)	(4)
		trails only	(6)	(6)	(3)
		sludge	(6)	(6)	(4)

*number of samples per treatment per year; 1, 2 and 3 are 1980, 81 and 82 for the jack pine, 1982, 83 and 84 for all study areas.

restricted to 6 subplots per plot in fall of 1981 and 1982. Metal concentrations in Montmorency County soils were obtained from cooperators of the Forestry Department at Michigan State University. Their sampling and analytical schemes, as described by Nguyen and Hart (1984), were varied but parallel with those employed for Wexford County.

Collection of Deer Samples

Three white-tailed deer does were collected while feeding among the sludge-treated plots, in the aspen study area, in November 1982. Livers, kidneys, hearts, and skeletal muscle were collected for metal analyses, as these tissues are most likely to concentrate potentially toxic metals or to be consumed by humans (Underwood 1977). Like small mammal tissues, the deer samples were frozen upon collection and stored before drying at 60° C.

Analytical Procedures

The dried organic matter was broken down in all samples by wet digestion with nitric and perchloric acids to minimize losses from volatilization and retention (Auchmody and Greweling 1979). Samples were then analyzed with a DC-argon plasma atomic emission spectrometer (Spectrametrics, Inc., Andover, MA) for Cd, Cr, Cu, Ni, and Zn.

To assure quality control, duplicate tests were conducted for at least 10% of the samples. When duplicate samples were not within 10% of the first samples 90% of the time, the analysis was repeated for all samples of that series. In addition, samples yielding spurious results were retested. To monitor for contamination, blanks (5-10% of the number of samples) were subjected to digestion and analysis with the spectrometer. Samples of a series containing contaminated blanks were reanalyzed.

Data Analysis

The power of the methods available to test for assumption violations is sensitive to small sample sizes. Since plot numbers were restricted by plot size demands, the resulting sample sizes were suspect for hypothesis testing with parametric tests (Sokal and Rohlf 1981). Therefore, all data sets were subjected to nonparametric statistical analyses. For 2 sample cases, a randomization test was used. In cases of 3 samples, a Kruskal-Wallis one-way analysis of variance was completed. A 0.1 significance level was used for all tests.

RESULTS AND DISCUSSION

Soils

The application of sludge to the jack pine clearcut did not result in the accumulation of metals below the litter layer. Samples collected at 0.5, 1.5 and 2.5 years after sludge application to the forest floor provided no evidence of metal movement through the soil column. In the first year, only 2 of 30 comparisons yielded significantly greater concentrations in soil taken from the sludge-treated plots (Table 5). Similar results were obtained in 1981 and 1982. All soil metal concentration are presented in Tables 27-31 (Appendix).

No accumulation of the sludge-borne metals in the soil profile was expected. Sludges applied at similar rates in other studies have demonstrated little influence on soil metals below a 5 cm depth for forests (Brockway 1979) or agricultural lands (Chang et al. 1984). Only after sludge

Table 5. Soil depths demonstrating a significant difference (0.1 level) in metal concentration on the jack pine clearcut.

Year	Metal	Soil Depth	ug g^{-1} (dry wt.)	
			C**	S
1980	Cd	5-10	0.38	0.66*
	Cu	10-15	0.94	0.66
		15-30	0.15	0.09
	Ni	15-30	0.00	0.23
	Zn	10-15	2.44	1.37
1981	Cd	0-5	0.42	0.77
	Cr	5-10	3.13	3.67
	Cu	0-5	2.03	2.67
	Zn	15-30	1.97	0.89
1982	Cd	0-5	0.37	0.77
	Zn	0-5	15.6	11.1
		10-15	9.77	3.56

* values were significantly different (0.1 level) from controls. **C and S are control and sludge values, respectively ** C, T, S are control, trails only, and sludge, respectively.

was repeatedly applied at high rates have metals appeared to move through soils (Hinesly et al. 1972, Lund et al. 1976, Chang et al. 1984).

Forages

While the plant species and plant parts varied in their metal content, the 5 sites examined in this study were generally similiar with respect to metal ranges. Concentrations of the 5 metals were within the normal ranges found in plants as reported by Kabata-Pendias and Pendias (1984) for the United States.

After the addition of sludge to the jack pine clear-cut, several plant species appeared to accumulate sludge-borne metals. Brambles, panic grass, and orange hawkweed were the most consistant accumulators of metals over the first year following application (Table 6). During the first year, Cd and Cr were the metals most consistantly increased in the forages as a result of sludge recycling. Orange hawkweed contained the greatest metal concentrations and exhibited the largest increase recorded (2.5x more Cu than observed for controls in summer 1982). Generally, the sludge-treated forages contained 1.5 to 2x the metal concentrations observed on controls. By the summer

Table 6. Forage species demonstrating a significant difference (0.1 level) in metal concentration on the jack pine clearcut.

Year	Season	Metal	Forage	ug g^{-1} (dry wt.) control	ug g^{-1} (dry wt.) sludge
1980	summer	Cd	Brambles	0.68	1.07
			jack pine needles	0.43	0.33
			orange hawkweed	0.73	1.59
		Cr	cherry twigs	1.04	0.74
			cherry leaves	1.08	1.74
			jack pine needles	0.72	1.20
			orange hawkweed	2.28	5.84
			panic grass	0.47	0.76
		Cu	brambles	2.30	2.99
			orange hawkweed	3.82	9.63
			panic grass	0.97	2.27
		Ni	cherry twigs	1.15	1.53
			orange hawkweed	3.74	5.44
			panic grass	0.69	1.26
		Zn	brambles	53.2	65.6
			panic grass	14.8	31.0
	winter	Cd	cherry twigs	0.25	0.51
			jack pine needles	0.24	0.45
			brambles	0.83	1.26
		Cr	brambles	1.45	2.29
		Cu	brambles	1.78	3.19
		Ni	jack pine twigs	1.72	2.31
			brambles	0.98	2.43
		Zn	brambles	56.7	78.3

table 6 cont.

1981	spring	Cd	cherry leaves	0.50	0.88
			jack pine twigs	0.91	1.34
			jack pine needles	0.35	0.60
			orange hawkweed	0.61	1.09
		Cr	cherry twigs	2.45	3.25
			jack pine twigs	1.74	2.57
			orange hawkweed	1.96	2.91
			panic grass	1.14	1.78
		Cu	brambles	1.88	2.66
			orange hawkweed	3.82	6.77
		Ni	panic grass	0.44	0.77
	summer	Cd	cherry leaves	0.51	0.29
		Cr	brambles	1.14	1.52
		Ni	jack pine twigs	1.18	1.90
	winter	Cd	brambles	0.81	0.99
			cherry twigs	0.45	0.25
982	spring	Ni	jack pine needles	0.45	1.46
	summer	Ni	orange hawkweed	2.45	4.87
	winter	Cu	jack pine twigs	2.04	3.34

* value is significantly different (0.1 level) from controls

of 1981 (14 months after application) and throughout the following year, increased metal concentrations were no longer apparent. All metal concentrations found in forages collected off the jack pine clearcut are reported in Tables 32-36 (Appendix).

Increased metal concentrations in forages were never apparent on the Montmorency County sites. Significantly greater metal concentrations in sludge-amended plants were a rare occurence during the 3 years of monitoring (Tables 7-10). The more common than expected by chance. However, recycling sludge on these sites increased annual production by both woody and herbaceous understory groups (Haufler and Woodyard 1985). Consequently, the total metal burden in forages was greater on sludge-treated plots. Expansion of plant biomass from the sludge-borne nutrients was great enough to dilute any increased availability of metals.

Two of the forages, orange hawkweed and panic grass, which accumulated metals from sludge applied to the jack pine clearcut were also monitored on the aspen study area. The metal content in control plants were similar on both the jack pine clearcut and the aspen site, as were the sludges received by both sites. However, neither orange hawkweed nor panic grass accumulated metals on the aspen

Table 7. Forage species demonstrating a significant difference (0.1 level) in metal concentration on the aspen study area.

Year	Season	Metal	Forage	(ug g^{-1} (dry wt.) C**	T	S
1982	spring	Cd	wild strawberry	1.19a*	2.32b	1.76b
			panic grass	0.25a	0.12b	0.26a
			bracken fern	0.25a	0.12b	0.26a
		Cu	bracken fern	2.42a	2.23a	3.71b
		Zn	trembling aspen	79.3a	38.8b	97.5a
	summer	Cd	panic grass	0.28a	0.26ab	0.12b
			bracken fern	0.28a	0.26ab	0.12b
1983	spring	Cd	panic grass	0.18a	0.36b	0.21ab
		Cu	panic grass	0.73ab	1.31b	0.95a
			bracken fern	3.17ab	2.93a	2.36b
		Ni	orange hawkweed	1.68a	1.80ab	2.86b
	summer	Ni	big tooth aspen	1.23a	2.42b	1.89ab
1984	winter	Zn	pin cherry	--	147a	69.7b

* values within a row with the same letter are not significantly different (0.1 level)
** C,T,S are control, trails only, and sludge, respectively

Table 8. Forage species demonstrating a significant difference (0.1 level) in metal concentration on the oak study area.

Year	Season	Metal	Forage	ug g^{-1} (dry wt.)		
				C**	T	S
1982	spring	Cr	red oak	0.64a*	0.70a	1.29b
		Cu	red oak	1.61a	1.89a	2.70b
	summer	Cr	red oak	0.72a	0.98a	0.28b
		Zn	red oak	58.6a	60.2ab	36.0b
1983	spring	Cd	white oak	1.66a	0.83b	0.77b
		Cu	red oak	1.96ab	1.49a	2.35b
		Zn	red oak	50.7a	51.6ab	74.1b
	summer	Cr	red maple	1.66a	1.13b	1.14b
		Cu	red oak	1.47a	1.81ab	2.07b
1984	winter	Cu	red maple	--	6.11a	4.28b

* values within a row with the same letter are not significantly different (0.1 level).
** C,T,S are control, trails only, and sludge, respectively

Table 9. Forage species demonstrating a significant difference (0.1 level) in metal concentration on the jack pine/ red pine study area.

Year	Season	Metal	Forage	ug g^{-1} (dry wt.)		
				C**	T	S
1982	summer	Cu	sedge	3.62a*	3.80a	2.76b
		Ni	red oak	1.62a	1.71ab	1.18b
1983	spring	Cd	bracken fern	1.27a	1.35a	1.61b
		Cu	sedge	2.96ab	3.41a	2.76b
		Zn	red oak	28.5a	40.6ab	65.1b
	summer	Cd	sedge	0.60a	0.89a	1.64b
		Cu	bracken fern	2.55a	3.80b	3.51b
		Ni	sedge	1.34a	1.06ab	1.00b
	winter	Ni	red oak	0.76a	1.84ab	1.29b

* values within a row with the same letter are not significantly different (0.1 level)
** C,T,S are control, trails only, and sludge, respectively

Table 10. Forage species demonstrating a significant difference (0.1 level) in metal concentration on the mixed hardwoods study area.

Year	Season	Metal	Forage	ug g^{-1} (dry wt.)		
				C**	T	S
1982	summer	Cd	hophornbeam	0.32a*	0.47a	0.16b
1983	spring	Cr	hophornbeam	0.46a	0.66ab	0.88b
			American beech	0.96a	0.60b	0.59b
		Cu	white ash	6.54a	8.96a	12.3b
		Zn	white ash	30.4a	42.4b	38.3b
	summer	Cd	sugar maple	0.75a	0.59b	0.56b
		Cu	white ash	7.55ab	6.62a	10.8b
		Ni	sugar maple	1.25a	1.03ab	0.81b
		Zn	hophornbeam	34.7a	77.3b	44.0ab
	winter	Cd	American beech	0.96a	0.22b	0.32b
		Ni	American beech	2.32a	1.64b	1.93b
1984	spring	Cu	American beech	--	3.76a	6.47b
	summer	Cd	white ash	--	0.66a	0.49b
			American beech	--	0.34a	0.68b
		Zn	American beech	--	70.9a	116b

* values within a row with the same letter are not significantly different (0.1 level)
** C,T,S are control, trails only, and sludge, respectively

site. All metal concentrations found for forages collected off the 4 Montmorency County sites are reported in Tables 37-56 (Appendix).

An increase in metal concentrations within the understory has commonly been observed during the first year following sludge application (Brockway 1979, Smith et al. 1979, Urie et al. 1981). However, as observed for the jack pine clearcut, by the second growing season, foliar metals returned to background concentrations. Consequently, increased metal exposure to wildlife from accumulation in the primary producers of a food chain appears restricted to the first year.

Studies of metal toxicity, such as dose response curves, are nonexistant for wildlife species. Unfortunately, only information obtained for laboratory mice and rats are available for predicting a potentially toxic exposure for small mammals. While such relationships may not be completely true for wildlife, they are the best available at this time. Diets containing as high as 5 ppm Cd, 100 ppm Cr, 500 ppm Cu, 1000 ppm Ni, and 2500 ppm Zn have not elicited chronic toxicites in laboratory rodents (Underwood 1977). Consequently, none of the metal concentrations found in forages on either sludge-treated or control sites appeared to represent a potentially chronic dose to small mammals.

Small Mammals

Metal concentrations in small mammal tissues demonstrated no consistant trend related to treatment. Significant differences in metal concentrations were rare (Tables 11-15), and were no more frequent than was expected by chance. All metal concentrations found in small mammal tissues collected from the 5 study areas are reported in Tables 57-81 (Appendix).

Differences in metal affinities for tissues were evident. For all species, liver and kidney tissues contained metals at concentrations of a magnitude greater than observed in bone or muscle. As expected the relative concentrations of the metals were Zn >> Cu > Cd, Cr and Ni.

Tissue concentrations found in this study were similar to those reported in uncontaminated small mammals by Johnson et al. (1978), Anderson et al. (1982), and Hunter and Johnson (1982). An exception was the concentration of Cd in bone and muscle which in this study was generally undetectable. Furthermore, Cd in all tissues was a magnitude below the 10 ppm fresh weight value described

Table 11. Small mammal species demonstrating a significant difference (0.1 level) in metal concentration on the jack pine clearcut.

Year	Metal	Tissue	Species	ug g^{-1} (dry wt.) C**	S
1980	Cd	kidney	13-lined ground squirrel	0.84	0.51*
	Cu	kidney	13-lined ground squirrel	7.53	4.27
1981	Cd	kidney	13-lined ground squirrel	0.60	1.37
	Cu	liver	meadow jumping mouse	3.47	7.04
	Cr	liver	meadow jumping mouse	0.10	0.17
	Ni	liver	meadow jumping mouse	0.62	0.13
	Zn	muscle	white-footed mouse	9.32	19.7
		kidney	meadow jumping mouse	62.4	91.7
1982	Cr	liver	13-lined ground squirrel	1.26	0.60
	Ni	liver	white-footed mouse	0.83	0.34
	Zn	liver	white-footed	44.6	78.9

* values were significantly different (0.1 level) from controls.
**C and S are control and sludge values, respectively

Table 12. Small mammal species demonstrating a significant difference (0.1 level) in metal concentration on the aspen study area.

Year	Metal	Tissue	Species	ug g^{-1} (dry wt.)		
				C**	T	S
1982	Cd	liver	woodland jumping mouse	0.18a*	0.07a	0.64b
		kidney	woodland jumping mouse	0.27a	0.22a	0.83b
	Cr	muscle	eastern meadow vole	2.51a	1.15b	1.63ab
1983	Cd	liver	woodland jumping mouse	0.22a	0.64b	0.47c
	Cu	bone	woodland jumping mouse	2.06ab	5.34b	3.95ab
	Zn	liver	woodland jumping mouse	74.0a	35.1b	20.0b
		bone	woodland jumping mouse	38.3a	18.7b	39.6ab
1984	Cd	liver	eastern meadow vole	0.12a	0.05b	0.03b
	Cu	muscle	eastern meadow vole	1.27a	2.31b	1.70b
	Ni	liver	woodland jumping mouse	0.34a	0.12b	0.06b
	Zn	kidney	eastern meadow vole	20.0a	39.1ab	67.4b

* values within a row with the same letter are not significantly different (0.1 level)

** C,T,S are control, trails only, and sludge, respectively

Table 13. Small mammal species demonstrating a significant difference (0.1 level) in metal concentration on the oak study area.

Year	Metal	Tissue	Species	ug g^{-1} (dry wt.)		
				C**	T	S
1983	Cd	liver	white-footed mouse	0.16a*	0.07b	0.14ab
		kidney	white-footed mouse	0.21ab	0.38b	0.20a
	Cr	kidney	white-footed mouse	1.54a	2.86b	1.88ab
	Cu	kidney	white-footed mouse	11.5a	22.8b	8.62a
	Zn	kidney	white-footed mouse	24.8a	30.4ab	47.7b

* values within a row with the same letter are not significantly different (0.1 level)
** C,T,S are control, trails only, and sludge, respectively

Table 14. Small mammal species demonstrating a significant difference (.10 level) in metal concentration on the jack pine/ red pine study area.

Year	Metal	Tissue	Species	ug g^{-1} (dry wt.)		
				C**	T	S
1983	Cu	bone	eastern chipmunk	1.41a*	1.80b	1.62ab
	Ni	liver	eastern chipmunk	0.14a	0.25b	0.19ab
	Zn	muscle	eastern chipmunk	12.9a	20.0b	28.9b
1984	Cr	bone	white-footed mouse	0.12a	0.08b	0.06b
	Cu	kidney	white-footed mouse	16.2a	13.8b	10.9c

* values within a row with the same letter are not significantly different (0.1 level)
** C,T,S are control, trails only, and sludge, respectively

Table 15. Small mammal species demonstrating a significant difference (.10 level) in metal concentration on the mixed hardwoods study area.

Year	Metal	Tissue	Species	ug g^{-1} (dry wt.)		
				C**	T	S
1982	Cd	kidney	eastern chipmunk	0.79a*	1.60b	1.73ab
	Cr	kidney	white-footed mouse	1.13a	0.69a	8.64b
	Cu	liver	eastern chipmunk	6.22a	18.4b	7.39a
1983	Cd	kidney	white-footed mouse	0.22a	0.42b	0.54b
		liver	eastern chipmunk	1.20a	0.70b	0.88b
	Cu	kidney	eastern chipmunk	8.11a	13.9b	6.71a
	Ni	liver	eastern chipmunk	0.63a	0.27b	0.13b
1984	Zn	bone	white-footed mouse	33.6a	54.7b	84.4b

* values within a row with the same letter are not significantly different (0.1 level)
** C,T,S are control, trails only, and sludge, respectively

as evidence of probable Cd contamination (Eisler 1985).

The food habits of the small mammals monitored in this study were probably a major factor in preventing metal accumulation in small mammal tissues. All of the species found in significant numbers were either herbivores or omnivores. Hunter and Johnson (1982) have demonstrated that insectivorous small mammals and not herbivores or omnivores accumulate metals from contaminated ecosystems. The upland forest types addressed in this study did not support significant populations of insectivorous small mammals (e.g. Blarina brevicauda and Sorex cinereus), probably due to insufficient production of their prey, invertebrate detritivores.

Current research at the University of Washington on the Pack Experimental Forest indicates that, of the small mammals utilizing sludge-treated sites, only the insectivores feeding upon invertebrate detritivores are accumulating sludge-borne metals (only Cd to date) (S.D. West, pers. commun.). In the Pack Forest Demonstration Project, application rates are considerably higher than those used in this study and are repeated annually (Anderson 1985).

While several laboratory studies have shown metal accumulation in animals fed sludge-grown plants (Furr et al. 1976, Hansen et al. 1976, Hinesly et al. 1976, Chaney et al. 1978a and 1978b, Williams et al. 1978), there have been no published reports of free-ranging small mammals accumulating sludge-borne metals. Anderson et al. (1982) did find meadow voles contained significantly increased Cd in liver and kidney tissue, when enclosed for 2 years on areas receiving sludge at 10x (both years) the loading rate applied in this study.

Along with food habits, duration of time spent on a sludge-treated site obviously would affect the possibility of small mammals accumulating metals. The majority of the small mammals produced on the study sites were juveniles and subadults and present for only 2 months; a duration possibly too short to allow for significant metal pick-up.

White-tailed Deer

By a magnitude, tissues obtained from deer contained greater concentrations of the selected metals than small mammals (Table 16). The metal burdens observed for deer in this study were comparable to those reported for other white-tailed deer in the Midwest (Jenkins 1980 and Woolf et al. 1982), mule deer in the West (Munshower and Neuman

Table 16. Mean (±S.E.) metal concentrations in tissues of white-tailed deer harvested from the aspen study area in November 1982.

Tissue	Metals ug g^{-1} (dry wt.)				
	Cd	Cr	Cu	Ni	Zn
muscle	1.08±0.29	1.26±0.65	9.39±0.89	1.70±0.17	399±26
heart	0.81±0.32	0.43±0.14	19.57±3.53	0.60±0.44	397±63
kidney	31.36±1.28	0.85±0.20	21.16±3.88	0.99±0.39	858±184
liver	3.13±0.32	1.59±1.00	473±71.5	1.53±0.27	688±75

1979), and black-tailed deer in the Pacific Northwest (Andersen 1985). The exceptions were slightly greater concentrations of Cd and Zn in hepatic tissues, which could be a result of such factors as local differences in geology (and metal availability), differences in analytical methods, the wide variation of metal concentrations found among individual animals, or exposure to sludge-amended lands.

None of the concentrations recorded for the selected metals approached a dose known to produce chronic toxicities in humans (Underwood 1977). With the exception of Zn none of the selected metals demonstrated an affinity for muscle tissue, which is the only part of deer likely to be consumed in large quantities by humans. Zn, while relatively abundant in muscle tissue, at the observed concentrations is not toxic but probably beneficial to humans, who are likely Zn deficient (Underwood 1977). With respect to Cd, the greatest observed concentration was less than the 10 ppm (fresh weight) used as evidence of contamination and magnitudes less than the 200 ppm fresh weight (kidney residue) considered life-threatening to vertebrates (Eisler 1985).

Summary

Results from this study suggest that at the application rates used, sludge recycling to forest lands does not present a metal toxicity problem to wildlife consuming vegetation or to higher trophic groups consuming the small mammal species studied. While some forages accumulated metals after sludge application, by the second growing season metals in tissues had returned to background concentrations. Small mammals did not appear to accumulate metals. However, the insectivorous small mammal-detritivorous soil macrofauna food chain, which has been identified as a potential pathway for sludge-borne metals, was not a major component of the communities studied. Consequently, forest soils supporting habitat more suitable for wildlife that consume invertebrate detritivores (e.g. earthworms) require further study to determine safe application rates. Hunters consuming deer harvested off sludge-treated areas would not appear to be exposed to potentially toxic doses of metals especially if internal organs were not consumed.

CONTAMINATION RISKS TO RAPTOR FOODCHAINS FROM SLUDGE-BORNE METALS

A popular conception held by both ecologists and nonecologists is that birds of prey have historically endured greater mortality and poorer reproductive success from biomagnification of xenobiotics (Cooke 1973, Stickel 1975). The degree to which reported declining raptor populations can be attributed to environmental toxicities is debatable (Barthalmus 1980). Still, their position in the food chain, long life span, and low reproductive potential make these species susceptable to environmental toxicities.

Small mammals, which are an important prey item for most hawks and owls, can respond to sludge-induced habitat changes with significantly greater densities (Haufler and West 1986). Greater concentrations of prey could concentrate raptor feeding on sludge amended sites. Metal toxicosis in wildlife has been rare with the exception of lead poisoning from shot ingestion; however, if landspreading were to become widespread, exposure to sludge-borne metals could be significant.

Low population densities, characteristic of raptors, are not conducive to field investigations. Consequently, evaluation of the potential for metal transfer between trophic groups of the raptor food chain required a laboratory study. To enhance applicability and comparability to the field, attention was given to using species representative of the field and realistic test durations.

OBJECTIVES

The purpose of this experiment was to evaluate the potential for sludge-borne metals to transfer between trophic groups of a raptor food chain when sludge was applied at a rate that prevents ground water contamination. The objective was to test for concentration differences (of Cd, Cr, Cu, Ni, and Zn) among 3 food chains at 3 trophic levels: the producer, primary consumer, and secondary consumer. Two food chains were based on producers grown on soils amended with different sludges. The third was the control, which was based on a producer grown with a commercial fertilizer.

METHODS

Sludge Description

This experiment used sludges (approximately 1000 L) obtained from the Alpena and Detroit Metro wastewater treatment facilities. The facility in Alpena was chosen to represent those used in the field evaluations. Sludge from Detroit's municipality was selected as an example of sludges produced from a more populated area. Detroit's sludge was expected to contain greater metal concentrations. However, sludges from the 2 cities were similar with respect to the metals selected for study (Table 17).

The Production of Rye-grass

In a greenhouse environment, sand soils were sewn with rye-grass (*Lolium perenne*) seed. Rye-grass was chosen to represent grasses in general, which respond dramatically to sludge amendment (Urie et *al*. 1979, Woodyard 1982, Haufler

Table 17. Concentrations (ug g^{-1}) of the selected metals in sludges obtained from Alpena and Detroit, Michigan and the inorganic fertilizer.

Metal (ug g^{-1} dry wt.)	Alpena	Detroit	12-12-12
Cd	7.5	13.0	3.2
Cr	48.8	139	24.0
Cu	1230	527	115
Ni	36.3	9.8	5.6
Zn	1125	1718	401

and West 1986). Furthermore, Anderson (1985) has recommended forest openings planted to grasses as the best sites to receive sludge for improving forage quality for wildlife.

Before germination, the Alpena and Detroit sludges were applied, with a manual pump, at rates of 584 and 739 kg N/ha, respectively. In addition, more rye-grass was grown with a 12-12-12 agricultural fertilizer applied at 600 kg N/ha. The grass leaves were harvested at 6-10 weeks.

After drying at 60° C, the rye-grass was ground to pass through a 1 mm sieve. Equal weights of soybean and corn meals were combined with the rye and bentonite (5% of the total dry weight) to make a small mammal diet with 55% dry weight as rye. Water was then added to the mixture before heating and pellet formation. The grain suppliments were added to simulate the omnivorous diet of the primary consumer. Since plants do not isolate metals to seed tissue, it was not necessary to grow the grains on sludge-amended soils.

The White-footed Mice

The white-footed mouse (*Peromyscus leucopus*) was selected as the primary consumer. Common to all of the field sites, the small mammal remains abundant following sludge application. A total of 72 white-footed mice were included in this experiment. Three adults were randomly selected from each of 26 litters (F_{4-6} generations of wild mice). The mice were reared on a commercial feed pellet and housed in individual plastic cages with stainless steel tops.

The Raptors

Both great horned owls (Bubo virginianus) and red-tailed hawks (Buteo jamaicensis) were ideal for the study since they are abundant ,widely distributed, generally nonmigratory, and feed extensively on small mammals. Having these characteristics suggest exposure to sludge-borne metals could be significant for both. Twelve individuals of each species were housed in stainless steel cages (0.7 x 1 x 1 m). Although unable to be rehabilitated due to previous injuries, the birds were otherwise healthy and exhibited consistant, daily patterns of ingestion and egestion. The birds were maintained at a constant weight on a diet of laboratory-reared small mammals for 14 months prior to the beginning of the study.

The Food Chain

The white-footed mice were randomly selected so to have 1 littermate placed on each of the 3 rye-grass diets. Over a period of 60 days, 2 littermate groups were sacrificed every 5 days. The 60-day test period was chosen to represent the 2 month period (July and August) when small mammal populations are most abundant in Michigan (Woodyard 1982, Beyer 1983, Thomas 1983, Seon 1984). By far the majority of the small mammal population has only these 2 months to feed on sludge-grown vegetation. Only during this time could a raptor concentrate its feeding on sludge amended sites. Once a trend of metal accumulation was apparent from a diet, the original plans provided for additional mice to be placed on those pellets. Ultimately, these mice were to be fed to the owls and hawks for up to 90 days. Birds were to be sacrificed at set time intervals. The number of birds and the interval length were to be dependent on whether the mice accumulated metals from 1 or both diets containing sludge-grown rye-grass.

Metal Analysis

The same analytical procedures employed for the field-collected samples were conducted to determine metal concentrations for the sludges, rye-grasses, diets, and small mammal tissues (liver, kidney, humeri and muscle from the hindleg). To be included were tissues (liver, kidney and breast muscle) collected from the owls and hawks both prior (except kidney) to the feeding trial and after their sacrifice. Biopsy techniques were developed to determine background metal burdens for each bird.

Data Analysis

Kruskal-Wallis one-way analysis of variance was used to test for concentration differences (in the selected metals) among the rye-grass treatments and among the diets. The differences in metal concentrations between littermates fed the control diet and a diet of sludge-grown rye-grass were regressed over time. The slope of the lines obtained by the linear regressions represented the metal accumulation rates from both sludge-grown diets. Student's t was used to test the hypothesis that the rate of change in metal concentrations within small mammal tissues was different from zero for both sludge-grown diets (Steel and Torrie 1980: 256).

RESULTS

The Rye-grass

Three metals, Cd, Cr and Zn, were found in significantly greater concentrations in rye-grass grown on soils treated with the sludges than with the inorganic fertilizer (Table 18). Cd and Cr concentrations were 2x greater in sludge-treated grass, while Zn was approximately 1.5x more concentrated. Rye-grass grown on the Alpena and Detroit sludges were similar in respect to metal concentration.

The metal concentrations observed in the greenhouse-grown rye-grasses were quite similar to those values found for forages collected from control and sludge-treated plots within the jack pine clearcut. Cd and Cr differences between control and treated plants were nearly identical for both the field (forages in the first growing season after sludge was applied to the jack pine clearcut) and greenhouse experiments. Zn did not exhibit a trend for

Table 18. Mean metal concentrations in rye-grass grown on sludge-treated and inorganically fertilized sand soils.

	Metal (ug g^{-1} dry wt.)				
Treatment	Cd	Cr	Cu	Ni	Zn
12-12-12	0.32a	0.47a	3.6a	1.1a	44a
Alpena	0.78b	0.91b	3.7a	1.0a	73b
Detroit	0.93b	0.95b	3.0a	1.1a	60b

* values in a column with the same letter are not significantly different (at the 0.1 level).

accumulation in the field trials.

Rye-grass pellets made with rye grown with Alpena sludge contained significantly greater concentrations of Cd, Cr and Zn than those made with rye grown on inorganically fertilized soils (Table 19). Pellets made with grass produced with Detroit sludge were significantly greater in Cd and Cr; the significantly greater Zn concentration (in rye-grass) was lost when the pellets were diluted with the grain components. Pellets containing rye-grass grown on the 2 sludge treatments were not significantly different.

The White-footed Mice

Feeding of sludge-grown rye-grass to the white-footed mice over a 2 month period did not result in a significant trend of accumulation for any of the 5 selected elements (Figs. 2-11). The metal-tissue affinities observed in the field experiments were again obvious. Cd and Ni were found almost exclusively in kidney and liver tissue. However, Cd and Zn concentrations were nearly 2x greater in the laboratory-raised mice than those observed for free-ranging small mammals.

Since the 60-day trial provided no indication of metal

Table 19. Mean metal concentrations in rye-grass pellets fed to white-footed mice.

	Metal (ug g^{-1} dry wt.)				
Treatment	Cd	Cr	Cu	Ni	Zn
12-12-12	0.183a	0.654a	3.94a	8.98a	39.4a
Alpena	0.425b	0.952b	4.34a	9.96a	54.0b
Detroit	0.471b	0.898b	4.14a	9.75a	48.2ab

* values in a column with the same letter are not significantly different (at the 0.1 level).

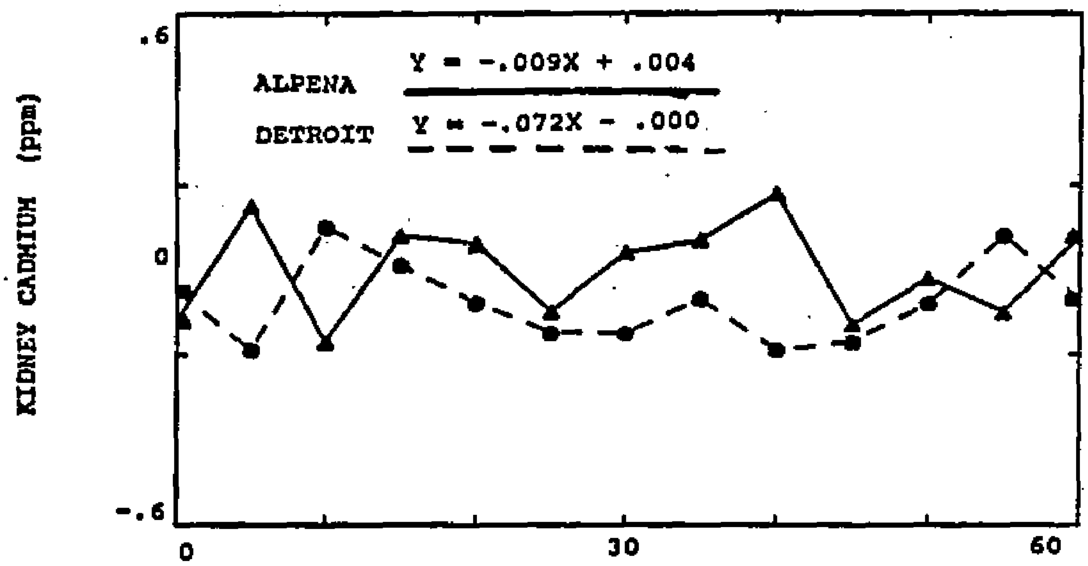

Fig. 2. Difference in kidney Cd concentrations between mice fed sludge-grown (Alpena or Detroit sludges) and inorganically fertilized rye-grass from 0 to 60 days.

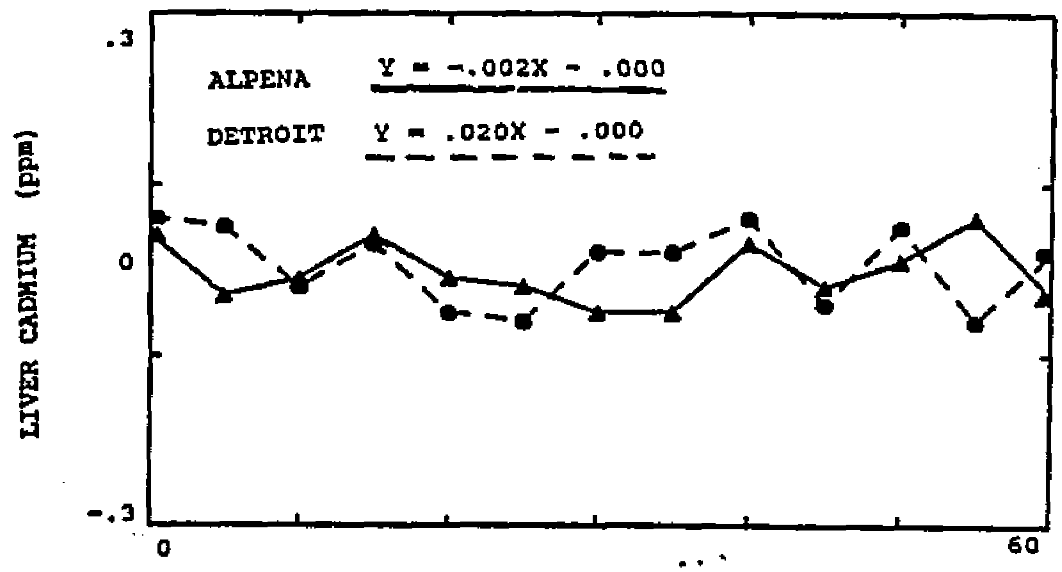

Fig. 3. Difference in liver Cd concentrations between mice fed sludge-grown (Alpena or Detroit sludges) and inorganically fertilized rye-grass from 0 to 60 days.

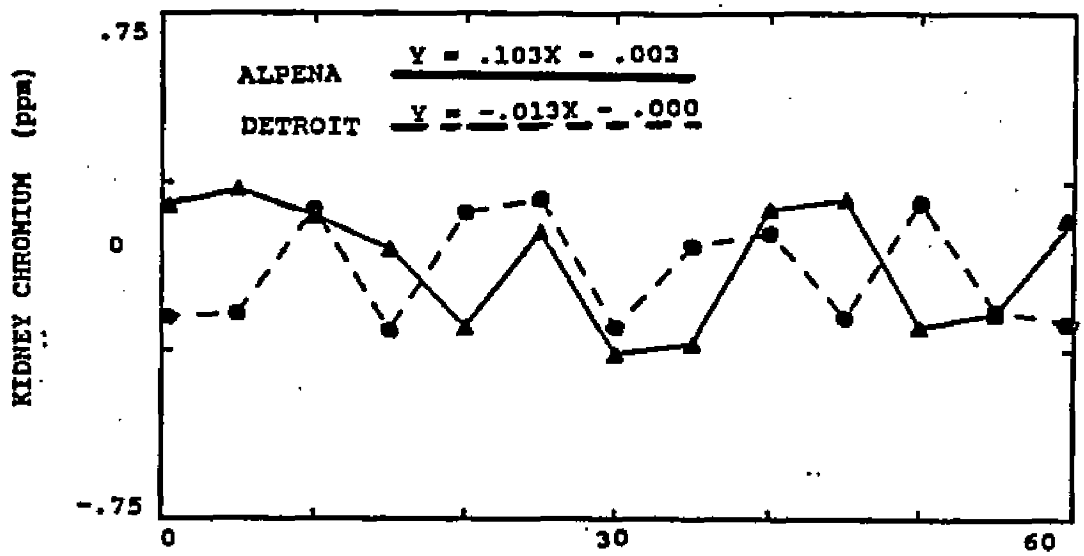

Fig. 4. Difference in kidney Cr concentrations between mice fed sludge-grown (Alpena or Detroit sludges) and inorganically fertilized rye-grass from 0 to 60 days.

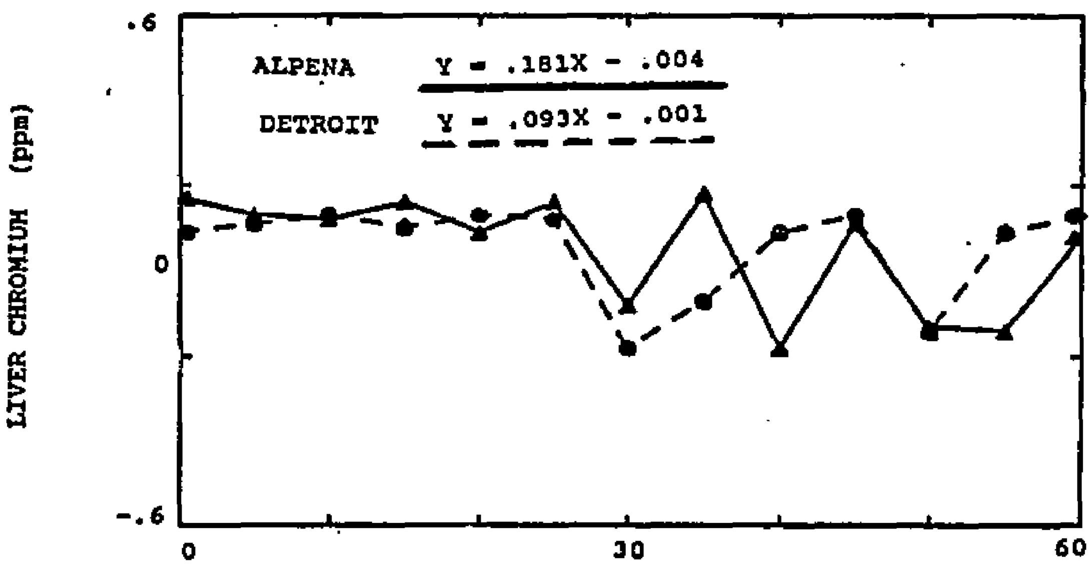

Fig. 5. Difference in liver Cr concentrations between mice fed sludge-grown (Alpena or Detroit sludges) and inorganically fertilized rye-grass from 0 to 60 days.

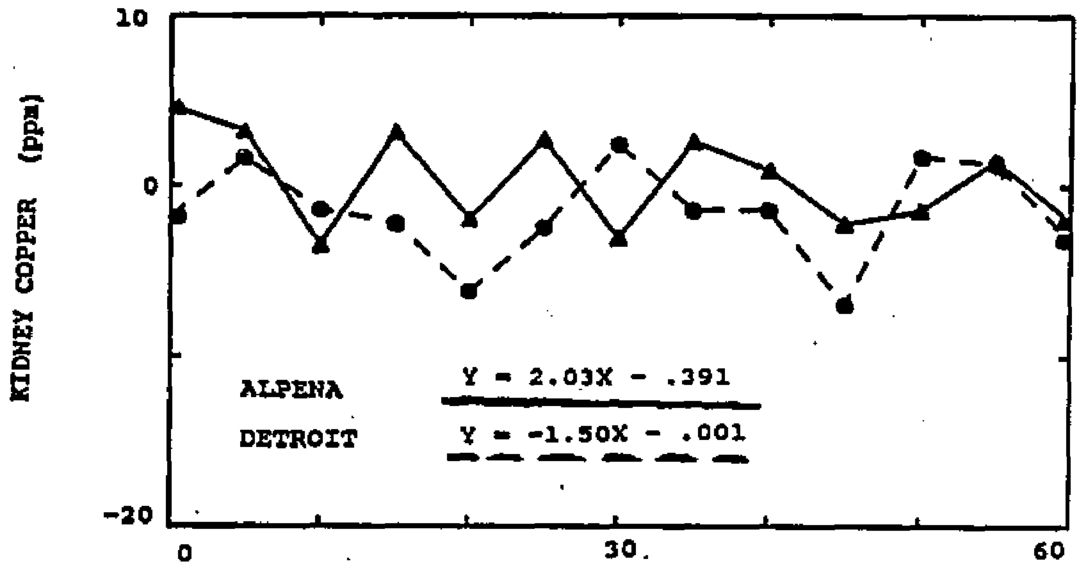

Fig. 6. Difference in kidney Cu concentrations between mice fed sludge-grown (Alpena or Detroit sludges) and inorganically fertilized rye-grass from 0 to 60 days.

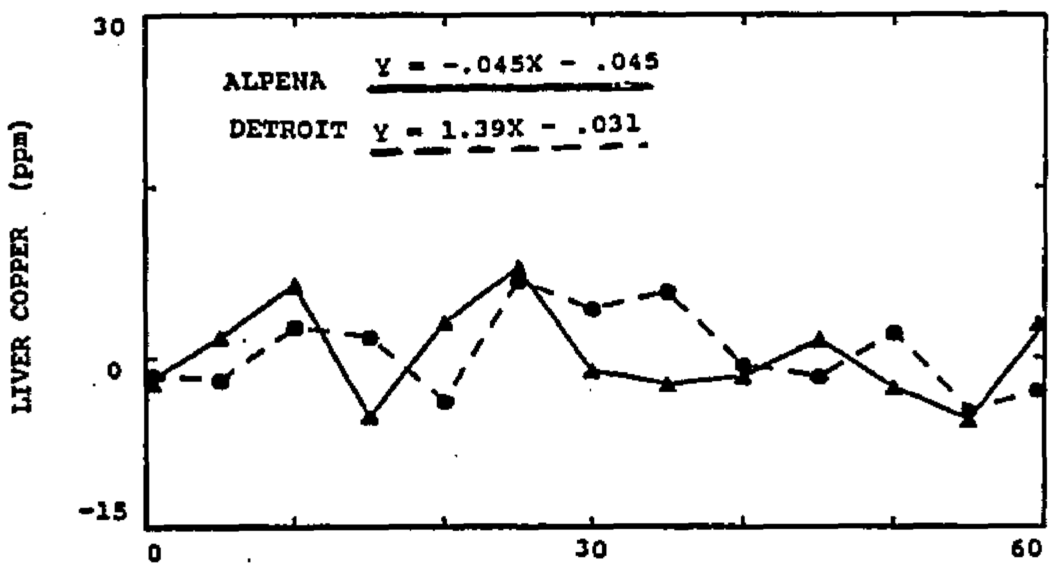

Fig. 7. Difference in liver Cu concentrations between mice fed sludge-grown (Alpena or Detroit sludges) and inorganically fertilized rye-grass from 0 to 60 days.

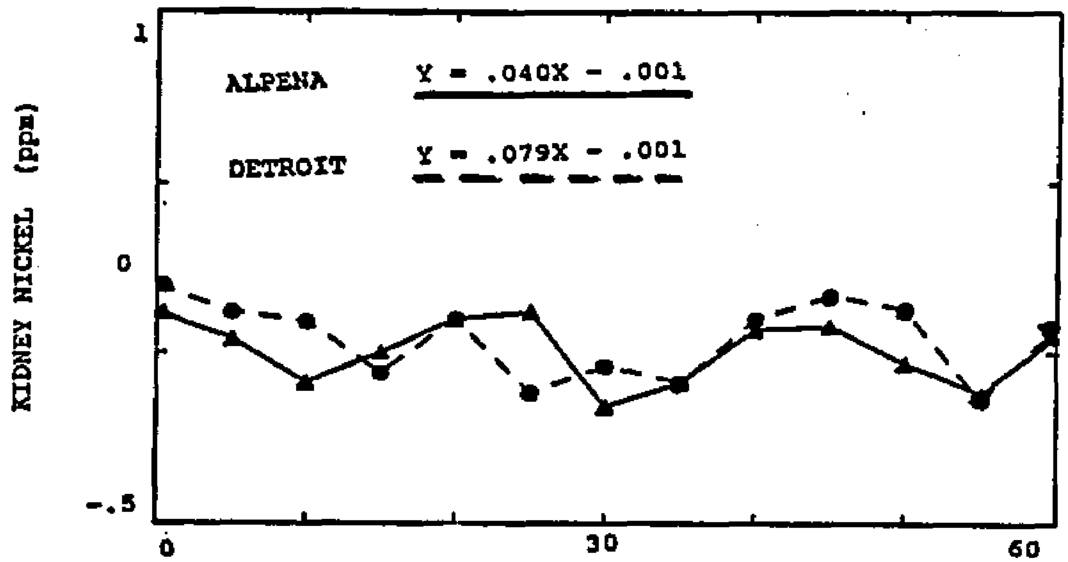

Fig. 8. Difference in kidney Ni concentrations between mice fed sludge-grown (Alpena or Detroit sludges) and inorganically fertilized rye-grass from 0 to 60 days.

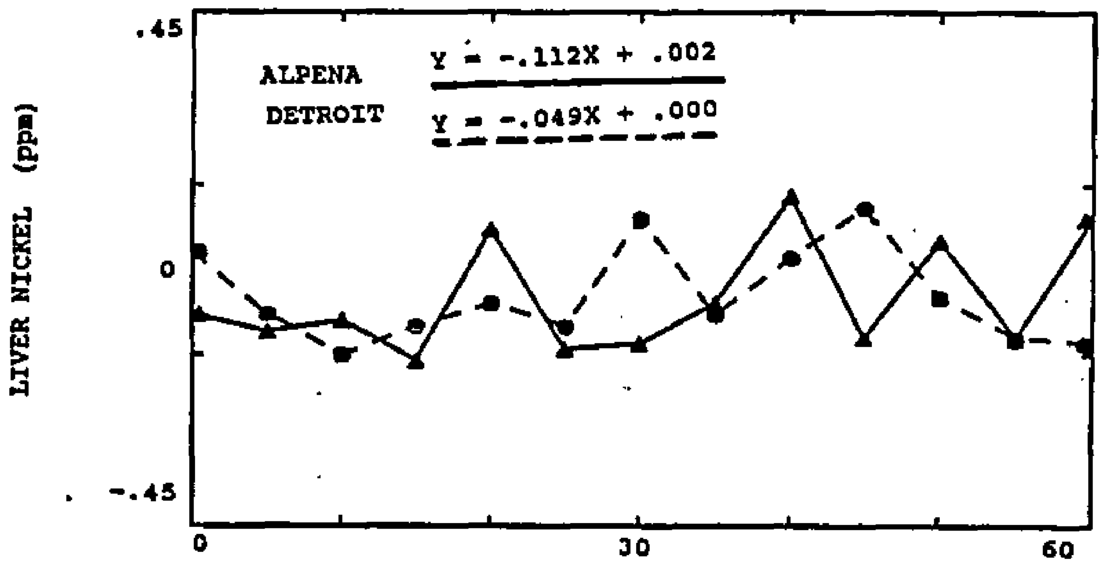

Fig. 9. Difference in liver Ni concentrations between mice fed sludge-grown (Alpena or Detroit sludges) and inorganically fertilized rye-grass from 0 to 60 days.

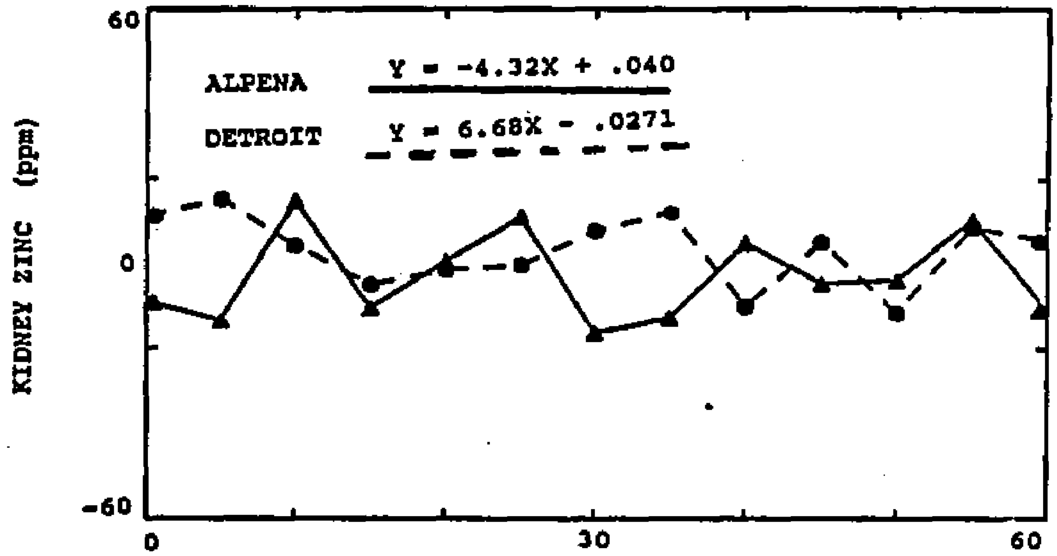

Fig.10. Difference in kidney Zn concentrations between mice fed sludge-grown (Alpena or Detroit sludges) and inorganically fertilized rye-grass from 0 to 60 days.

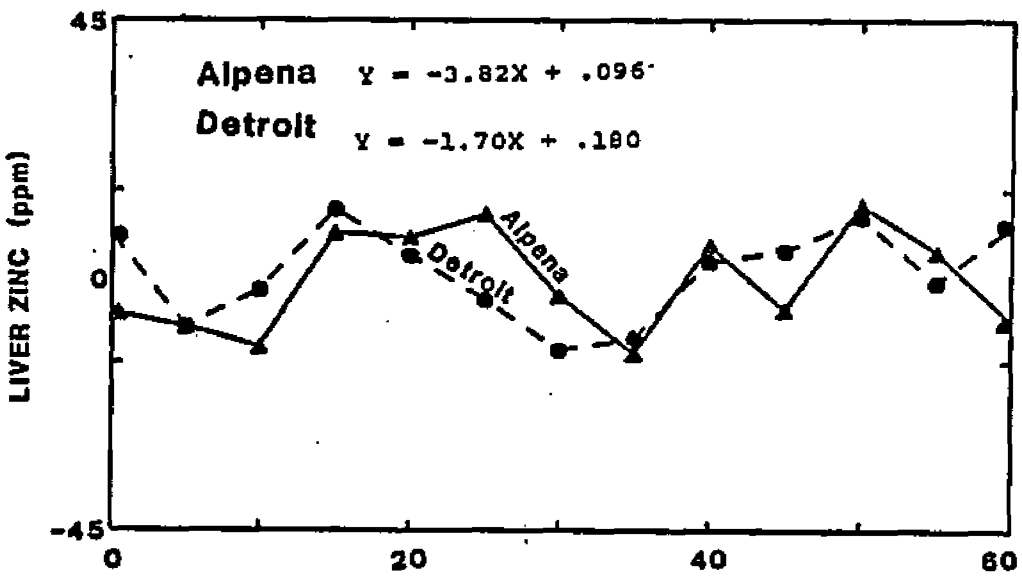

Fig.11. Difference in liver Zn concentrations between mice fed sludge-grown (Alpena or Detroit sludges) and inorganically fertilized rye-grass from 0 to 60 days.

accumulation in the rodents, the food chain was terminated without the inclusion of the owls and hawks. (With no accumulation by 60 days, the length of time required for metal accumulation to pose a threat to the raptors would have been unrealistic of the food chain observed in the field.)

DISCUSSION

Anderson et al. (1982) demonstrated that herbivorous small mammals accumulated Cd and Cu, when confined to sludge-treated lands for 2 years while still being allowed to freely choose preferred plant species. Results from the field experiments found small mammals did not accumulate metals even when forages significantly concentrated metals (first year results from the jack pine clearcut). Possible causes of the lack of metal accumulation in small mammal tissues were 1) the 2 month duration that the majority of individuals used the study sites was too short to allow for accumulation from the concentrations found in the forage tissues; 2) feeding habits of the small mammal species monitored included enough noncontaminated foods to preclude accumulation from the contaminated portion of their diet.

Results indicate that a combination of both a shortened period of exposure (2 months) and a diet containing only half contaminated material could prevent significant accumulation of sludge-borne metals in rodents, when sludge was applied at the rates employed in this study. Consequently, if sludge recycling, at the employed rates, is restricted to forest types that support small mammal food chains primarily based on energy from primary producers, raptors feeding on such sites should be protected from accumulation of sludge-borne elements. Such areas would include most well-drained sites that do not provide adequate moisture and detritus production capable of supporting significant populations of macroinvertebrate detritivores. Small mammal food chains based on soil macroinvertebrates appear to accumulate metals (Hunter and Johnson 1981) and may present a pathway for metals to move to higher trophic groups.

TRANSFER OF SLUDGE-BORNE METALS THROUGH A WOODCOCK-EARTHWORM FOOD CHAIN

Earthworms have been identified as accumulators of metals from soils near smelters (Hunter and Johnson 1982) and road sides (Gish and Christensen 1973). Van Hook (1974) has demonstrated earthworms accumulate metals from uncontaminated soils with a natural range in metal concentrations. In concurrence, earthworms have been identified as biomagnifiers of sludge-borne metals (Helmke et al. 1979, Beyer et al. 1982, Wade et al. 1982, Pietz et al. 1984). As an important link in many wildlife food chains, earthworms present a possible means for metals to transfer to vertebrate predators from sludge-amended soils.

Of particular concern, is the American woodcock (*Philohela minor*) food chain. Woodcock are a popular game species not only in Michigan but through the Eastern U.S., where over 1.5 million birds are harvested each year (Artmann 1977). Consequently, human health risks become an issue if sludge-borne metals were to transfer and accumulate in woodcock tissues.

OBJECTIVES

This experiment's purpose was to evaluate the potential for sludge-borne metals to transfer to woodcock, after consuming earthworms maintained in a sludge-soil complex. The objective was to test for concentration differences (of Cd, Cr, Cu, Ni, and Zn) among 3 food chains at 3 trophic levels: the detritus complex, detritivorous invertebrate, and vertebrate predator. Two food chains were based on a detritus complex of an organic soil with different sludges. The third was the control, which was based on an organic soil treated with an inorganic fertilizer.

METHODS

Sludge Description

As in the raptor food chain study, Alpena and Detroit sludges were used in this experiment. Each sludge was mixed with an organic top soil to make a 7:10 combination of wet sludge to soil. In the field experiments, wet sludge was applied at a depth of approximately 7 cm. Considering that woodcock cannot forage below a soil depth of 10 cm, the ratio was chosen as a realistic scenario of that portion of a sludge-amended forest floor providing earthworms to this species.

The Earthworms

Ranch-farmed earthworms (Lumbricidae) were used to avoid a gapeworm (*Syngamus trachei*) outbreak among the woodcock (Sikarskie, pers. commun.). Over 30,000 earthworms were placed in each of 3 organic media for 30-90 days. A 1 to 3 month exposure was appropriate for simulating the time intervals, April-June and late August-October, in which most earthworms are produced and are active near the soil surface (Rabe 1981). The organic media included the 2 sludge-soil mixtures and the organic soil with the 12-12-12 organic fertilizer (applied at 400 kg/ha of 5 cm deep soil).

The Woodcock

Woodcock were captured from an oldfield in northeast Roscommon County, using 300,000 candle spotlights and handheld nets. A description of the area is provided by Rabe (1977). The birds were collected during late summer of 1984. Several individuals were initially used to determine the weight of earthworms required daily by a woodcock to maintain bodyweight. Twelve birds were used in the foodchain.

The Food Chain

Three woodcock were randomly selected to be fed worms from each media, for a total of 9 birds. In addition, 3 birds were sacrificed at their initial capture to create another study control. Earthworms were fed to the birds for 30 days. While a woodcock can feed on an area for 4-5 months, 30 days (20-25%) was believed an appropriate time interval to allow for metal accumulation to become apparent. Daily consumption ranged from 250-400 worms, thus each bird consumed approximately 10,000 worms over the course of the trial. All birds were sacrificed at the end of the test and stored frozen. Ultimately, livers, kidneys, hearts, breast muscles, and femurs were separated, dried at 60° C, and analyzed for metals.

Metal Analysis

As before, the same analytical procedures were employed for measuring Cd, Cr, Cu, Ni and Zn in the earthworm and woodcock tissues. Ten samples of 10 worms were removed from each soil mixture and analyzed for the selected metals. The worms were dried at 60°C prior to wet digestion.

Data Analysis

Kruskal-Wallis one-way analysis of variance was used to test for concentration differences (in the selected metals) among the soil mixtures, earthworms, and woodcock tissues.

RESULTS

Soil-sludge and Soil-inorganic Mixtures

The Alpena soil-sludge mixture contained significantly greater concentrations of all 5 metals than the soil-inorganic fertilzer media (Table 20). Compared to the soil-inorganic fertilizer media, the Detroit soil-sludge mixture included significantly greater concentrations of Cd, Cr, Cu and Zn. In addition, Cd in the Detroit mixture was significantly greater than that recorded in the Alpena mixture.

Earthworms

Significantly greater concentrations of Cd, Cr, Cu and Zn were observed in earthworms grown in the sludge-treated soils when compared to worms grown in the inorganically fertilized soil (Table 21). Earthworms exposed to Alpena and Detroit sludges contained 2.5 to 5.4x greater concen-

Table 20. Mean metal concentrations in soil-sludge and soil-inorganic fertilizer mixtures.

Soil Treatment	Metal ($ug\ g^{-1}$ dry wt.)				
	Cd	Cr	Cu	Ni	Zn
12-12-12	1.63a	48.8a	15.2a	20.6a	78.0
Alpena	3.73b	56.5b	41.6b	24.8b	287b
Detroit	4.50c	58.0b	34.4b	19.5ab	327b

* values in a column with the same letter are not significantly different (at the .10 level).

Table 21. Mean metal concentrations in earthworms exposed to sludge-treated and inorganically fertilized soil.

Soil Treatment	Metal ($\mu g\ g^{-1}$ dry wt.)				
	Cd	Cr	Cu	Ni	Zn
12-12-12	5.0a	16.5a	9.6a	21.1a	21.0a
Alpena	19.2b	67.4b	37.9b	35.4a	85.4b
Detroit	27.4b	47.7b	24.9b	19.8a	117b

* values in a column with the same letter are not significantly different (at the 0.1 level).

trations of the selected metals than worms exposed to the inorganic fertilizer. No signifcant difference was apparent between the worms grown on soils with the 2 sludge treatments.

Cd in worm tissues was over 5x greater than the concentrations found in the soil mixtures. Ni concentrations were similar between soils and worms, while Cr, Cu and Zn were observed in greater concentrations in the soils than worms. These metal trends were similar for both the sludge and inorganic fertilizer treatments.

The Woodcock

After consuming earthworms for 30 days, woodcock fed sludge-exposed worms contained liver and kidney Cd concentrations approximately 2x greater than control birds (individuals sacrificed upon capture) and 3x greater than birds fed worms exposed to the inorganic fertilizer (Table 22). Cd concentrations were not significantly different among the treatments with respect to woodcock heart, muscle, or bone tissues.

Woodcock Cr, Cu, and Ni concentrations were not affected by differences in earthworm contamination (Tables 23-25). The only significant difference found for Zn was

Table 22. Mean Cd concentrations in tissues of woodcock fed earthworms exposed to sludge-treated and inorganically fertilized soil.

Soil Treatment	Tissue Cd (ug g^{-1} dry wt.)				
	Liver	Kidney	Heart	Muscle	Bone
Control	3.12a	17.9a	0.78a	1.25a	0.05a
12-12-12	1.81b	12.6b	0.57a	0.69a	0.02a
Alpena	7.38c	30.4c	0.61a	0.97a	0.04a
Detroit	6.21c	36.1c	0.56a	1.12a	0.02a

* values in a column with the same letter are not significantly different (at the 0.1 level).

Table 23. Mean Cr concentrations in tissues of woodcock fed earthworms exposed to sludge-treated and inorganically fertilized soil.

Soil Treatment	Liver	Tissue Cr (ug g^{-1} dry wt.) Kidney	Heart	Muscle	Bone
Control	1.31a	0.61a	0.42a	1.29a	0.50a
12-12-12	1.16a	0.45a	0.27a	1.84a	0.65a
Alpena	1.17a	0.65a	0.31a	1.52a	0.43a
Detroit	1.27a	0.42a	0.26a	1.42a	0.26a

* values in a column with the same letter are not significantly different (at the 0.1 level).

Table 24. Mean Cu concentrations in tissues of woodcock fed earthworms exposed to sludge-treated and inorganically fertilized soil.

Soil Treatment	Tissue Cu (ug g^{-1} dry wt.)				
	Liver	Kidney	Heart	Muscle	Bone
Control	310a	28.7a	12.1a	24.4a	3.16a
12-12-12	328a	24.3a	12.9a	17.8a	3.31a
Alpena	246a	21.6a	8.46a	20.2a	2.15a
Detroit	347a	35.7a	14.5a	26.5a	2.65a

* values in a column with the same letter are not significantly different (at the 0.1 level).

Table 25. Mean Ni concentrations in tissues of woodcock fed earthworms exposed to sludge-treated and inorganically fertilized soil.

Soil Treatment	Tissue Ni (ug g^{-1} dry wt.)				
	Liver	Kidney	Heart	Muscle	Bone
Control	2.14a	1.83a	0.58a	1.43a	0.06a
12-12-12	1.88a	1.54a	0.97a	1.41a	0.44a
Alpena	2.23a	1.14a	1.09a	1.74a	0.19a
Detroit	2.23a	1.65a	1.26a	1.95a	0.64a

* values in a column with the same letter are not significantly different (at the 0.1 level).

the lesser concentration present in renal tissues of birds fed worms exposed to the 12-12-12 fertilizer (Table 26).

Table 26. Mean Zn concentrations in tissues of woodcock fed earthworms exposed to sludge-treated and inorganically fertilized soil.

Soil Treatment	Tissue Zn (ug g^{-1} dry wt.)				
	Liver	Kidney	Heart	Muscle	Bone
Control	464a	982a	273a	390a	200a
12-12-12	344a	738b	306a	322a	125a
Alpena	537a	1214a	331a	276a	298a
Detroit	756a	1159a	386a	345a	219a

* values in a column with the same letter are not significantly different (at the 0.1 level).

DISCUSSION

Results from analyses of whole earthworms and liver and kidney tissues from the woodcock indicated sludge-borne metals can be mobile in a wildlife food chain based on soil macroinvertebrates. All of the selected metals appeared to accumulate in the earthworms in relation to dietary concentrations. Cd appeared not only to accumulate but concentrate in the invertebrate tissues. However, woodcock demonstrated some homeostasis for Cr, Cu, Ni and Zn to prevent their transfer between trophic groups. Only Cd appeared to transfer between trophic groups and accumulate. Greater mobility by Cd in contaminated ecosystems, as compared to other metals, has been observed by Johnson et al. (1978), Roberts and Johnson (1978), and Hunter and Johnson (1981).

Cd demonstrated an obvious affinity for liver and kidney tissues but no accumulation or concentration in woodcock muscle. The greatest Cd concentration recorded in woodcock tissues (45 ppm dry weight in renal tissue of a bird fed worms exposed to Detroit sludge) approached the 10ppm fresh weight for vertebrate kidney tissue that may indicate Cd contamination (Eisler 1985). The results from this study suggest if similar sludges were applied to forest lands supporting good woodcock feeding habitat, Cd could concentrate in woodcock tissues. At the observed rate of renal Cd accumulation, 10-20 ppm/ 30 days, and assuming a constant rate of Cd excreation, approximately 2 years of continual exposure could result in the potentially lethal kidney concentration of 200 ppm (fresh weight).

Toxic effects from renal Cd concentrations of less than 200 ppm in wildlife are not known. Therefore, at which Cd concentration does individual fitness becomes compromised and woodcock populations harmed, can not be predicted. Risks to human health, however, do not appear to be increased from sludge-borne Cd transfer to woodcock tissues. Muscle tissues are not sites of Cd deposition, and hunters usually do not consume significant quantities of the internal organs taken from upland game birds.

Because predictions can not be made with regards to acceptable Cd accumulation in woodcock populations, avoidence of contamination is the best alternative. Macroinvertebrate detritivore - vertebrate insectivore food chains are most likely restricted to soils containing well developed organic layers; sites which are the least nutrient-deficient. Consequently, by limiting sludge recycling to more nutrient-deficient, upland forest lands, such as those used in the field evaluations of this study, health risks to wildlife from sludge-borne metals should be mitigated.

RISK ASSESSMENT OF SLUDGE-BORNE CD, CR, CU, NI AND ZN TO WILDLIFE FROM RECYCLING SLUDGES UPON FORESTED LAND

Results from this investigation indicated some sludge-borne metals, primarily Cd and Cr, may be accumulated in wildlife forages during the first year after application. During the second growing season, metal concentrations return to background levels. The maximum forage concentration recorded for each metal was magnitudes less than could provide a dose Underwood (1977) reported as capable of eliciting chronic toxicities in laboratory and domestic animals.

There appeared to be no health effects associated with sludge recycling to small mammals or white-tailed deer. Use of sludge-treated sites was generally greater by both small mammals (Haufler and Woodyard 1984) and ungulates (Haufler and Campa 1984).

Tissues collected from herbivorous and omnivorous small mammals, exposed to sludge-treated forages, showed no evidence for accumulation of the sludge-borne metals.

Laboratory experiments supported this observation. Short life spans and other factors such as diets that include some uncontaminated materials prevent accumulation of sludge-borne metals by small mammals. Consequently, health risks to higher trophic species from consuming small mammals produced on sludge-treated sites does not appear significant.

The exception for small mammals may be insectivores, such as shrews, that consume macroinvertebrates that utilize soil detritus. The upland forests addressed in the field evaluations of this study did not support this type of food chain, which are restricted to sites containing considerable organic matter as a source of energy. Thus, testing insectivores as a critical pathway for sludge-borne metals was not accomplished.

The soil macroinvertebrate - vertebrate insectivore food chain investigated in the laboratory did appear as a potential pathway for sludge-borne Cd to mobilize and concentrate in a wildlife food chain. Woodcock accumulated Cd at a rate that, if continuous, could be life-threatening after 2 years of continual exposure. The applicability of this experiment to field conditions is unkown, but the results suggest a conservative recycling approach is warrented.

Human health risks from harvesting and consuming wildlife produced on sludge-treated lands appear minimal. Cd, which was the only metal to demonstrate mobility from sludge into wildlife tissues, exhibited a definite affinity for kidney and liver tissues that excluded depostion in muscular tissues. Consequently, consuming muscle tissue poses no threat. Consumption of internal organs should probably not be advised, but at the greatest concentration recorded (<50 ppm dry weight) significant human pick-up of Cd would require years of daily intake.

MANAGEMENT RECOMMENDATIONS

Results from this study suggest that at the application rates used, sludge does not present a metal toxicity problem to wildlife consuming vegetation or to higher trophic groups consuming the small mammal species studied. Consequently, upland forest types, such as addressed in this investigation, can be recommended for sludge-recycling without significant health risks from metals to wildlife or humans consuming wildlife. However, monitoring sludges and forest response to amendment is recommended to ensure environmental and public safety. Forest soils supporting habitat more suitable for wildlife that consume invertebrate detritivores (e.g. earthworms) require further study to determine safe application rates. In addition, industrial sewage sludges, with potential for higher concentrations of metals such as Cd, need additional evaluation to assess human and wildlife food chain hazards.

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APPENDIX

Table 27. Mean Cd concentrations in soils collected on the jack pine clearcut from 1980-1982.

Treatment	Year	Soil depth (cm)					
		0-5	5-10	10-15	15-30	30-60	60-90
Control	1980	0.50	0.38	0.08	0.03	0.00	0.00
Sludge		0.95	0.66*	0.14	0.06	0.00	0.00
Control	1981	0.42	0.42	0.16	0.00	0.00	0.00
Sludge		0.77*	0.34	0.09*	0.01	0.01	0.00
Control	1982	0.37	0.46	0.18	0.07	0.01	0.00
Sludge		0.77*	0.42	0.14	0.04	0.01	0.00

*value is significantly different (.10 level) from controls

Table 28. Mean Cr concentrations in soils collected on the jack pine clearcut from 1980-1982.

Treatment	Year	Soil depth (cm)					
		0-5	5-10	10-15	15-30	30-60	60-90
Control	1980	4.07	3.87	1.48	0.45	0.01	0.00
Sludge		4.08	3.99	1.67	0.46	0.00	0.00
Control	1981	4.03	3.13	1.88	0.35	0.02	0.00
Sludge		3.96	3.67*	1.88	0.13	0.00	0.00
Control	1982	3.34	3.13	1.66	0.47	0.06	0.00
Sludge		3.82	3.86	1.63	0.68	0.00	0.00

*value is significantly different (.10 level) from controls

Table 29. Mean Cu concentrations in soils collected on the jack pine clearcut from 1980-1982.

Treatment	Year	Soil depth (cm)					
		0-5	5-10	10-15	15-30	30-60	60-90
Control	1980	2.40	2.34	0.94	0.15	0.00	0.01
Sludge		2.64	2.53	0.66*	0.09*	0.00	0.00
Control	1981	2.03	2.19	0.65	0.03	0.00	0.00
Sludge		2.67*	2.30	0.58	0.00	0.00	0.00
Control	1982	2.37	2.13	0.60	0.00	0.00	0.00
Sludge		2.49	1.74	0.53	0.01	0.00	0.00

*value is significantly different (.10 level) from controls

Table 30. Mean Ni concentrations in soils collected on the jack pine clearcut from 1980-1982.

Treatment	Year	Soil depth (cm)					
		0-5	5-10	10-15	15-30	30-60	60-90
Control	1980	2.46	2.28	0.53	0.00	0.00	0.00
Sludge		2.20	2.46	1.04	0.23*	0.00	0.00
Control	1981	2.67	2.33	0.86	0.05	0.00	0.00
Sludge		2.51	2.15	0.79	0.16	0.00	0.00
Control	1982	2.12	2.13	0.95	0.13	0.01	0.00
Sludge		2.39	2.36	0.51	0.03	0.00	0.00

*value is significantly different (.10 level) from controls

Table 31. Mean Zn concentrations in soils collected on the jack pine clearcut from 1980-1982.

Treatment	Year	Soil depth (cm)					
		0-5	5-10	10-15	15-30	30-60	60-90
Control	1980	14.0	13.7	2.44	0.93	0.56	0.34
Sludge		12.3	10.9	1.37*	1.01	0.61	0.99
Control	1981	2.8	13.3	5.27	1.97	0.94	0.81
Sludge		11.3	13.2	3.18	0.89*	1.14	0.95
Control	1982	15.6	11.2	9.77	5.60	1.45	0.37
Sludge		11.1*	14.3	3.56*	2.70	1.20	0.68

*value is significantly different (.10 level) from controls

Table 32. Mean Cd concentrations in forages collected off the jack pine clearcut from 1980-1982.

Species	Treatment	Season	Year 1980	Year 1981	Year 1982
brambles	control	spring	--	1.08	0.91
	sludge		--	1.12	1.05
	control	summer	0.68	0.52	0.71
	sludge		1.07*	0.67	0.61
	control	winter	0.83	0.81	0.61
	sludge		1.26*	0.99*	0.65
cherry twigs	control	spring	--	0.65	0.68
	sludge		--	0.75	0.56
	control	summer	0.80	0.59	0.69
	sludge		0.62	0.54	0.71
	control	winter	0.21	0.45	0.26
	sludge		0.29	0.26*	0.17
cherry leaves	control	spring	--	0.50	0.66
	sludge		--	0.88*	0.39
	control	summer	0.24	0.51	0.22
	sludge		0.18	0.29*	0.21
jack pine twigs	control	spring	--	0.91	0.82
	sludge		--	1.34*	0.71
	control	summer	0.48	0.37	0.39
	sludge		0.55	0.69	0.42
	control	winter	0.91	1.20	0.96
	sludge		0.74	1.03	0.86

Table 32. cont.

jack pine needles	control	spring	--	0.35	0.38
	sludge		--	0.60*	0.50
	control	summer	0.43	0.26	0.50
	sludge		0.33*	0.33	0.57
	control	winter	0.24	0.45	0.48
	sludge		0.45*	0.31	0.38
orange hawk-weed	control	spring	--	0.61	0.86
	sludge		--	1.09*	0.84
	control	summer	0.73	--	0.90
	sludge		1.59*	--	0.83
panic grass	control	spring	--	0.60	0.39
	sludge		--	0.39	0.60
	control	summer	0.21	--	0.23
	sludge		0.29	--	0.24
sedge	control	spring	--	0.70	0.78
	sludge		--	0.90	0.84
	control	summer	0.63	--	0.69
	sludge		0.43	--	0.58

samples collected in 1980 included all cherries; 1981 and 1982 samples included only pin cherry (*P. pensylvanica*)

samples collected in 1980 included all brambles; 1981 and 1982 samples included only red raspberry (*R. idaeus*)

*value is significantly different (.10 level) from controls

Table 33. Mean Cr concentrations in forages collected off the jack pine clearcut from 1980-1982.

Species	Treatment	Season	Year 1980	1981	1982
brambles	control	spring	--	2.26	2.02
	sludge		--	2.19	1.89
	control	summer	1.47	1.14	1.37
	sludge		1.50	1.52*	1.75
	control	winter	2.29	2.13	1.69
	sludge		1.45*	1.86	1.88
cherry twigs	control	spring	--	2.45	2.69
	sludge		--	3.25*	2.68
	control	summer	1.04	0.99	1.13
	sludge		0.74*	0.91	1.12
	control	winter	2.17	2.25	2.37
	sludge		2.29	2.34	2.05
cherry leaves	control	spring	--	1.93	2.11
	sludge		--	1.95	1.84
	control	summer	1.74	1.59	0.71
	sludge		1.08*	1.93	0.95
jack pine twigs	control	spring	--	1.74	2.39
	sludge		--	2.57*	2.96
	control	summer	0.79	0.85	0.91
	sludge		0.91	0.69	1.25
	control	winter	1.54	1.69	1.85
	sludge		3.37	1.54	1.95

Table 33. cont.

jack pine needles	control	spring	--	1.40	1.28
	sludge		--	1.54	1.42
	control	summer	0.72	0.68	0.55
	sludge		1.20*	0.51	0.69
	control	winter	1.63	1.25	1.20
	sludge		1.95	1.71	1.86
orange hawk-weed	control	spring	--	1.96	1.42
	sludge		--	2.91*	2.21
	control	summer	2.28	--	2.42
	sludge		5.84*	--	3.23
panic grass	control	spring	--	1.14	1.42
	sludge		--	1.78 *	1.03
	control	summer	0.47	--	0.78
	sludge		0.76*	--	0.86
sedge	control	spring	--	0.54	0.99
	sludge		--	0.62	0.77
	control	summer	0.41	--	0.56
	sludge		0.41	--	0.42

samples collected in 1980 included all cherries; 1981 and 1982 samples included only pin cherry (P. pensylvanica)

samples collected in 1980 included all brambles; 1981 and 1982 samples included only red raspberry (R. idaeus)

*value is significantly different (.10 level) from controls

Table 34. Mean Cu concentrations in forages collected off the jack pine clearcut from 1980-1982.

Species	Treatment	Season	Year 1980	1981	1982
brambles	control	spring	--	1.88	1.96
	sludge		--	2.66*	1.61
	control	summer	2.33	2.59	2.40
	sludge		2.99*	2.13	2.64
	control	winter	1.78	1.71	1.95
	sludge		3.19*	1.72	1.61
cherry twigs	control	spring	--	3.80	3.04
	sludge		--	3.13	2.66
	control	summer	6.44	4.85	5.20
	sludge		2.71	4.31	4.55
	control	winter	8.29	5.38	3.40
	sludge		2.18	3.51	3.20
cherry leaves	control	spring	--	1.25	1.09
	sludge		--	0.88	1.03
	control	summer	1.80	1.56	1.69
	sludge		2.20	1.72	1.96
jack pine twigs	control	spring	--	1.29	1.41
	sludge		--	1.94	1.84
	control	summer	1.48	1.34	1.65
	sludge		1.66	1.16	2.05
	control	winter	2.64	2.78	2.04
	sludge		1.79	2.00	3.34*

Table 34. cont.

jack pine	control	spring	--	1.93	4.79
	sludge		--	2.84	2.82
	control	summer	1.63	1.84	2.29
	sludge		2.01	1.51	1.67
	control	winter	2.64	2.53	1.86
	sludge		1.79	2.03	2.11
orange hawk-	control	spring	--	3.93	2.42
	sludge		--	6.77*	4.34
	control	summer	3.82	--	3.90
	sludge		9.62*	--	5.86
panic grass	control	spring	--	0.74	0.85
	sludge		--	0.30	0.54
	control	summer	0.97	--	1.08
	sludge		2.27	--	0.83
sedge	control	spring	--	1.31	1.73
	sludge		--	1.72	2.23
	control	summer	3.98	--	4.75
	sludge		2.51	--	2.99

samples collected in 1980 included all cherries; 1981 and 1982 samples included only pin cherry (P.pensylvanica)
samples collected in 1980 included all brambles; 1981 and 1982 samples included only red raspberry (R.idaeus)

*value is significantly different (.10 level) from controls

Table 35. Mean Ni concentrations in forages collected off the jack pine clearcut from 1980-1982.

Species	Treatment	Season	Year 1980	1981	1982
brambles	control	spring	--	0.62	0.39
	sludge		--	0.41	0.60
	control	summer	1.94	1.61	1.34
	sludge		1.94	1.87	1.84
	control	winter	0.98	1.17	1.49
	sludge		2.43*	1.64	1.03
cherry twigs	control	spring	--	0.90	1.27
	sludge		--	1.15	1.07
	control	summer	1.15	0.93	1.31
	sludge		1.53*	1.07	1.15
	control	winter	2.39	1.63	1.64
	sludge		1.28	1.93	1.34
cherry leaves	control	spring	--	1.37	1.19
	sludge		--	0.69	0.77
	control	summer	2.06	1.66	1.87
	sludge		1.77	1.91	2.00
jack pine twigs	control	spring	--	1.49	1.51
	sludge		--	1.63	1.84
	control	summer	1.76	1.18	1.88
	sludge		1.81	1.90*	1.20
	control	winter	1.72	1.68	1.41
	sludge		2.31*	2.22	1.86

Table 35. cont.

jack pine needles	control	spring	--	0.88	0.45
	sludge		--	0.66	1.46*
	control	summer	1.63	1.84	2.08
	sludge		1.76	1.69	1.86
	control	winter	1.26	1.46	1.11
	sludge		1.55	1.78	1.53
orange hawk-weed	control	spring	--	2.83	2.75
	sludge		--	3.54	3.83
	control	summer	3.74	4.38	2.54
	sludge		5.44*	4.66	4.87*
panic grass	control	spring	--	0.44	0.41
	sludge		--	0.77*	0.34
	control	summer	0.69	0.95	0.85
	sludge		1.26*	0.66	0.75
sedge	control	spring	--	0.68	0.27
	sludge		--	0.41	0.63
	control	summer	1.24	1.43	1.86
	sludge		1.50	1.56	1.28

samples collected in 1980 included all cherries; 1981 and 1982 samples included only pin cherry (P. pensylvanica)

samples collected in 1980 included all brambles; 1981 and 1982 samples included only red raspberry (R. idaeus)

*value is significantly different (.10 level) from controls

Table 36. Mean Zn concentrations in forages collected off the jack pine clearcut from 1980-1982.

Species	Treatment	Season	Year 1980	1981	1982
brambles	control	spring	--	34.5	41.1
	sludge		--	24.8	28.7
	control	summer	53.2	63.8	69.4
	sludge		65.6	68.7	53.9
	control	winter	56.6	73.0	93.7
	sludge		78.3*	70.7	80.9
cherry twigs	control	spring	--	74.8	60.6
	sludge		--	85.7	70.9
	control	summer	48.2	56.4	47.3
	sludge		94.0	42.8	47.6
	control	winter	51.9	65.0	64.2
	sludge		55.9	53.9	60.4
cherry leaves	control	spring	--	8.11	7.66
	sludge		--	13.1	12.8
	control	summer	18.6	17.1	16.0
	sludge		25.2	18.6	18.8
jack pine twigs	control	spring	--	166	210
	sludge		--	185	187
	control	summer	50.3	63.4	53.9
	sludge		56.2	74.6	67.3
	control	winter	151	108	114
	sludge		67.8	135	85.5

Table 36. cont.

jack pine needles	control	spring	--	95.0	66.0
	sludge		--	77.4	80.9
	control	summer	43.2	46.1	49.3
	sludge		45.6	66.4	53.1
	control	winter	151	109	136
	sludge		67.8	103	96.4
orange hawk-weed	control	spring	--	93.9	86.3
	sludge		--	73.0	86.4
	control	summer	115	--	132
	sludge		154	--	114
panic grass	control	spring	--	8.83	11.2
	sludge		--	5.57	9.22
	control	summer	14.8	--	19.6
	sludge		30.1*	--	18.8
sedge	control	spring	--	21.7	26.1
	sludge		--	25.4	15.2
	control	summer	53.0	--	38.1
	sludge		65.6	--	51.0

samples collected in 1980 included all cherries; 1981 and 1982 samples included only pin cherry (*P. pensylvanica*)
samples collected in 1980 included all brambles; 1981 and 1982 samples included only red raspberry (*R. idaeus*)

*value is significantly different (.10 level) from controls

Table 37. Mean Cd concentrations in forages collected off the aspen study area from 1982-1984.

Species	Treatment	Season	Year 1982	1983	1984
wild straw-berry	control	spring	1.19a	1.64	--
	trails only		2.32b	1.83	1.46
	sludge		1.76b	1.55	1.03
	control	summer	0.73	0.65	--
	trails only		0.82	0.48	0.43
	sludge		0.95	0.53	0.45
orange hawk-weed	control	spring	0.95	1.13	--
	trails only		0.96	0.73	0.65
	sludge		0.73	1.00	1.12
	control	summer	0.92	0.72	--
	trails only		0.69	0.69	0.58
	sludge		0.74	0.82	0.49
panic grass	control	spring	0.25a	0.18a	--
	trails only		0.12b	0.36b	0.20
	sludge		0.26a	0.21ab	0.14
	control	summer	0.28a	0.15	--
	trails only		0.26ab	0.26	0.16
	sludge		0.12b	0.22	0.12
bigtooth aspen	control	spring	0.49	0.45	--
	trails only		0.22	0.31	0.47
	sludge		0.41	0.41	0.28
	control	summer	0.34	0.15	--
	trails only		0.28	0.30	0.23
	sludge		0.39	0.15	0.19
	control	winter	--	--	--
	trails only		0.28	0.25	0.32
	sludge		0.39	0.36	0.41

Table 37. cont.

tremb-ling aspen	control	spring	0.48	0.34	--
	trails only		0.48	0.39	0.51
	sludge		0.44	0.28	0.33
	control	summer	0.34	0.18	--
	trails only		0.38	0.28	0.39
	sludge		0.39	0.29	0.43
	control	winter	--	--	--
	trails only		0.26	0.43	0.41
	sludge		0.28	0.15	0.30
pin cherry	control	spring	0.55	0.21	--
	trails only		0.36	0.36	0.73
	sludge		0.53	0.47	0.40
	control	summer	0.26	0.30	--
	trails only		0.29	0.20	0.41
	sludge		0.32	0.22	0.26
	control	winter	--	--	--
	trails only		0.36	0.55	0.33
	sludge		0.39	0.23	0.54
bracken fern	control	spring	0.25a	0.18a	--
	trails only		0.12b	0.36b	0.20
	sludge		0.26a	0.21ab	0.14
	control	summer	0.28a	0.15	--
	trails only		0.26ab	0.26	0.16
	sludge		0.12b	0.22	0.12

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 38. Mean Cr concentrations in forages collected off the aspen study area from 1982-1984.

Species	Treatment	Season	Year 1982	Year 1983	Year 1984
wild straw-berry	control	spring	1.54	1.27	--
	trails only		1.33	1.45	1.67
	sludge		1.50	1.98	2.16
	control	summer	1.51	1.72	--
	trails only		2.06	2.27	1.74
	sludge		1.78	2.13	1.93
orange hawk-weed	control	spring	2.77	1.66	--
	trails only		1.54	1.62	1.61
	sludge		2.50	3.20	2.32
	control	summer	2.09	2.11	--
	trails only		2.25	1.72	2.84
	sludge		2.15	1.65	1.79
panic grass	control	spring	1.45	0.70	--
	trails only		1.27	1.36	0.88
	sludge		0.55	1.05	1.41
	control	summer	0.71	0.65	--
	trails only		0.84	0.80	1.13
	sludge		0.72	0.69	0.68
bigtooth aspen	control	spring	0.27	0.20	--
	trails only		0.61	0.34	0.39
	sludge		0.31	0.44	0.45
	control	summer	0.40	0.68	--
	trails only		0.56	0.67	0.18
	sludge		0.36	0.45	0.52
	control	winter	--	--	--
	trails only		2.52	1.90	2.86
	sludge		1.53	1.79	1.57

Table 38. cont.

tremb-ling aspen	control	spring	0.48	0.49	--
	trails only		0.59	0.72	0.69
	sludge		0.30	0.53	0.54
	control	summer	0.64	0.34	--
	trails only		0.42	0.63	0.51
	sludge		0.48	0.47	0.66
	control	winter	--	--	--
	trails only		1.12	1.31	1.06
	sludge		1.05	1.16	1.32
pin cherry	control	spring	1.54	1.36	--
	trails only		1.33	1.42	1.90
	sludge		1.50	1.35	3.18
	control	summer	1.28	1.80	--
	trails only		1.14	1.10	1.11
	sludge		1.40	1.25	1.78
	control	winter	--	--	--
	trails only		1.54	1.79	2.34
	sludge		2.80	1.77	2.84
bracken fern	control	spring	0.90	0.65	--
	trails only		0.86	0.42	0.99
	sludge		0.60	0.83	0.82
	control	summer	0.23	0.17	--
	trails only		0.41	0.37	0.60
	sludge		0.44	0.32	0.52

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 39. Mean Cu concentrations in forages collected off the aspen study area from 1982-1984.

Species	Treatment	Season	Year 1982	1983	1984
wild strawberry	control	spring	4.67	3.41	--
	trails only		2.32	3.29	2.79
	sludge		3.66	3.34	3.11
	control	summer	3.52	2.43	--
	trails only		3.43	3.64	2.53
	sludge		2.72	3.17	2.76
orange hawkweed	control	spring	1.97	1.75	--
	trails only		2.71	1.18	2.12
	sludge		1.95	3.64	2.04
	control	summer	3.07	3.48	--
	trails only		3.36	2.59	2.66
	sludge		2.65	3.95	2.59
panic grass	control	spring	0.30	0.73ab	--
	trails only		0.39	1.31b	0.54
	sludge		0.58	0.95a	0.41
	control	summer	0.99	1.15	--
	trails only		1.03	1.33	1.25
	sludge		1.12	0.74	1.31
bigtooth aspen	control	spring	2.02	1.75	--
	trails only		1.69	1.51	1.68
	sludge		1.84	1.87	1.22
	control	summer	1.53	1.86	--
	trails only		1.44	1.41	1.43
	sludge		1.45	1.18	1.73
	control	winter	--	--	--
	trails only		6.27	4.82	2.66
	sludge		4.99	4.33	3.10

Table 39. cont.

tremb-ling aspen	control	spring	1.87	1.44	--
	trails only		1.13	1.74	1.37
	sludge		1.95	1.48	1.72
	control	summer	1.60	1.45	--
	trails only		1.70	2.59	2.27
	sludge		1.21	1.62	1.63
	control	winter	--	--	--
	trails only		7.38	6.97	5.42
	sludge		8.72	6.74	7.40
pin cherry	control	spring	1.38	1.74	--
	trails only		1.49	1.35	1.46
	sludge		1.15	1.66	1.53
	control	summer	2.22	1.35	--
	trails only		1.51	1.35	1.98
	sludge		1.54	1.12	1.72
	control	winter	--	--	--
	trails only		6.17	5.15	6.09
	sludge		8.35	6.42	6.94
bracken fern	control	spring	2.42a	3.17ab	--
	trails only		2.23a	2.93a	2.27
	sludge		3.71b	2.36b	3.18
	control	summer	2.35	2.69	--
	trails only		1.97	2.13	2.28
	sludge		1.89	1.51	2.70

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 40. Mean Ni concentrations in forages collected off the aspen study area from 1982-1984.

Species	Treatment	Season	Year 1982	1983	1984
wild straw-berry	control	spring	1.31	1.25	--
	trails only		1.87	1.68	1.58
	sludge		1.90	1.74	1.16
	control	summer	1.42	1.45	--
	trails only		1.69	1.30	0.95
	sludge		0.85	1.76	0.88
orange hawk-weed	control	spring	1.43	1.68a	--
	trails only		1.49	1.80ab	1.33
	sludge		1.53	2.86b	1.92
	control	summer	3.31	2.24	--
	trails only		3.29	2.77	1.39
	sludge		2.18	2.45	2.78
panic grass	control	spring	0.94	0.59	--
	trails only		0.50	0.68	0.86
	sludge		1.02	0.75	0.72
	control	summer	0.93	1.06	--
	trails only		1.33	0.79	0.91
	sludge		0.80	0.60	0.80
bigtooth aspen	control	spring	1.80	1.42	--
	trails only		1.79	1.55	1.82
	sludge		1.79	1.75	1.49
	control	summer	1.98	1.23a	--
	trails only		1.81	2.42b	1.76
	sludge		1.56	1.89ab	1.92
	control	winter	--	--	--
	trails only		2.71	2.40	3.11
	sludge		1.41	2.34	3.03

Table 40. cont.

tremb-ling aspen	control	spring	1.72	1.65	--
	trails only		1.04	1.27	1.56
	sludge		1.49	1.73	1.24
	control	summer	2.00	1.67	--
	trails only		1.16	2.20	1.86
	sludge		1.78	1.65	1.90
	control	winter	--	--	--
	trails only		2.89	3.17	2.55
	sludge		2.53	2.62	2.95
pin cherry	control	spring	1.10	1.39	--
	trails only		1.62	1.44	2.32
	sludge		1.47	1.23	1.52
	control	summer	1.15	0.86	--
	trails only		1.90	1.69	1.45
	sludge		1.15	1.19	1.21
	control	winter	--	--	--
	trails only		1.41	1.37	1.96
	sludge		1.73	1.43	1.78
bracken fern	control	spring	1.09	0.98	--
	trails only		0.85	0.71	0.79
	sludge		0.74	1.10	0.66
	control	summer	0.87	0.68	--
	trails only		1.03	0.80	1.12
	sludge		0.77	0.39	0.74

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 41. Mean Zn concentrations in forages collected off the aspen study area from 1982-1984.

Species	Treatment	Season	Year 1982	1983	1984
wild straw-berry	control	spring	66.4	92.4	--
	trails only		88.1	45.2	90.9
	sludge		81.5	54.1	77.6
	control	summer	79.0	87.1	--
	trails only		66.9	67.0	68.8
	sludge		72.8	88.0	44.7
orange hawk-weed	control	spring	151	112	--
	trails only		172	155	131
	sludge		192	158	170
	control	summer	99.7	163	--
	trails only		121	115	84.5
	sludge		129	132	102
panic grass	control	spring	22.6	46.3	--
	trails only		31.6	35.2	23.3
	sludge		29.8	39.5	28.0
	control	summer	104a	142	--
	trails only		124a	141	118
	sludge		156b	130	135
bigtooth aspen	control	spring	84.6	75.0	--
	trails only		74.6	72.0	65.2
	sludge		74.6	54.8	57.1
	control	summer	40.2	35.2	--
	trails only		44.3	43.8	33.2
	sludge		48.8	60.9	64.8
	control	winter	--	--	--
	trails only		118	73.1	84.1
	sludge		68.2	78.3	97.9

Table 41. cont.

tremb-ling aspen	control	spring	79.3a	51.2	--
	trails only		38.8b	75.5	91.1
	sludge		97.5a	72.4	61.3
	control	summer	49.4	59.6	--
	trails only		42.1	35.7	46.7
	sludge		41.0	37.4	56.5
	control	winter	--	--	--
	trails only		81.6	75.2	61.7
	sludge		78.1	67.5	79.5
pin chery	control	spring	63.8	89.2	--
	trails only		73.8	82.3	62.9
	sludge		74.2	59.9	74.8
	control	summer	44.7	40.1	--
	trails only		42.6	37.8	55.6
	sludge		30.8	57.2	34.6
	control	winter	--	--	--
	trails only		73.8	80.8	147a
	sludge		54.7	77.5	69.7b
bracken fern	control	spring	77.1	83.6	--
	trails only		62.8	58.4	72.2
	sludge		68.0	67.6	57.2
	control	summer	105	75.5	--
	trails only		85.2	88.4	103
	sludge		112	96.3	91.1

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 42. Mean Cd concentrations in forages collected off the oak study area from 1982-1984.

Species	Treatment	Season	Year 1982	1983	1984
bracken fern	control	spring	0.29	0.51	--
	trails only		0.35	0.25	0.22
	sludge		0.23	0.26	0.34
	control	summer	0.26	0.35	--
	trails only		0.24	0.32	0.43
	sludge		0.48	0.33	0.21
red oak	control	spring	0.70	1.06	--
	trails only		0.72	0.60	0.69
	sludge		0.60	0.83	0.96
	control	summer	0.38	0.59	--
	trails only		0.44	0.36	0.60
	sludge		0.51	0.58	0.37
white oak	control	spring	0.51	1.66a	--
	trails only		0.78	0.83b	1.02
	sludge		0.61	0.77b	0.88
	control	summer	0.41	0.40	--
	trails only		0.23	0.34	0.21
	sludge		0.24	0.64	0.24
red maple	control	spring	0.34	0.32	--
	trails only		0.54	0.39	0.65
	sludge		0.69	0.33	0.39
	control	summer	0.41	0.32	--
	trails only		0.43	0.36	0.55
	sludge		0.64	0.83	0.67
	control	winter	--	--	--
	trails only		0.20	0.38	0.16
	sludge		0.14	0.24	0.19

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 43. Mean Cr concentrations in forages collected off the oak study area from 1982-1984.

Species	Treatment	Season	Year 1982	1983	1984
bracken fern	control	spring	0.35	0.25	--
	trails only		0.24	0.42	0.30
	sludge		0.78	0.25	0.32
	control	summer	0.14	0.12	--
	trails only		0.25	0.26	0.10
	sludge		0.22	0.18	0.05
red oak	control	spring	0.64a	0.80	--
	trails only		0.70a	0.87	0.78
	sludge		1.29b	0.72	1.16
	control	summer	0.72a	0.68	--
	trails only		0.98a	0.60	0.86
	sludge		0.28b	0.54	0.56
white oak	control	spring	0.34	0.42	--
	trails only		0.51	0.37	0.75
	sludge		0.47	0.49	0.52
	control	summer	0.68	0.62	--
	trails only		0.84	0.78	0.74
	sludge		0.88	0.71	1.10
red maple	control	spring	0.47	0.40	--
	trails only		0.53	0.28	0.41
	sludge		0.66	0.57	0.39
	control	summer	1.18	1.66a	--
	trails only		1.37	1.13b	1.23
	sludge		1.14	1.14b	1.33
	control	winter	--	--	--
	trails only		0.94	1.16	1.30
	sludge		1.21	1.37	1.08

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 44. Mean Cu concentrations in forages collected off the oak study area from 1982-1984.

Species	Treatment	Season	Year 1982	1983	1984
bracken fern	control	spring	1.79	1.32	--
	trails only		1.88	1.88	1.67
	sludge		1.56	1.32	1.62
	control	summer	2.75	2.30	--
	trails only		1.86	2.01	1.80
	sludge		2.20	1.75	1.46
red oak	control	spring	1.61a	1.96ab	--
	trails only		1.89a	1.49a	1.93
	sludge		2.70b	2.35b	2.23
	control	summer	1.82	1.47a	--
	trails only		1.64	1.81ab	1.97
	sludge		1.47	2.07b	1.87
white oak	control	spring	2.93	3.22	--
	trails only		2.60	2.37	2.96
	sludge		2.04	2.86	2.14
	control	summer	1.43	1.50	--
	trails only		1.63	1.70	1.32
	sludge		1.69	1.28	1.29
red maple	control	spring	2.38	2.06	--
	trails only		2.00	2.66	2.18
	sludge		2.27	2.38	1.80
	control	summer	1.63	1.0[illegible]	--
	trails only		1.72	1.97	1.95
	sludge		1.85	1.77	1.22
	control	winter	--	--	--
	trails only		4.45	6.58	6.11a
	sludge		3.47	6.33	4.28b

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 45. Mean Ni concentrations in forages collected off the oak study area from 1982-1984.

Species	Treatment	Season	Year 1982	Year 1983	Year 1984
bracken fern	control	spring	0.47	0.37	--
	trails only		0.42	0.57	0.67
	sludge		0.74	0.72	0.31
	control	summer	1.12	1.09	--
	trails only		1.39	1.00	1.11
	sludge		1.54	1.65	1.38
red oak	control	spring	1.26	1.56	--
	trails only		1.43	1.27	1.69
	sludge		1.35	1.91	1.39
	control	summer	1.53	1.25	--
	trails only		1.30	2.28	1.57
	sludge		1.72	1.60	1.84
white oak	control	spring	1.70	1.23	--
	trails only		1.54	1.42	1.31
	sludge		1.29	1.72	1.77
	control	summer	1.42	1.28	--
	trails only		1.01	1.26	1.17
	sludge		0.94	1.59	1.17
red maple	control	spring	1.11	1.74	--
	trails only		1.31	1.01	0.96
	sludge		1.21	1.35	1.62
	control	summer	1.35	1.44	--
	trails only		0.70	1.13	1.29
	sludge		1.32	0.95	0.92
	control	winter	--	--	--
	trails only		0.93	1.20	1.04
	sludge		1.54	2.50	1.14

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 46. Mean Zn concentrations in forages collected off the oak study area from 1982-1984.

Species	Treatment	Season	Year 1982	1983	1984
bracken fern	control	spring	38.2	50.2	--
	trails only		59.6	24.5	33.0
	sludge		20.1	38.5	29.8
	control	summer	67.5	58.8	--
	trails only		87.2	43.2	75.2
	sludge		43.4	77.2	84.1
red oak	control	spring	61.9	50.7a	--
	trails only		65.8	51.6ab	62.8
	sludge		71.8	74.1b	84.9
	control	summer	58.6a	84.4	--
	trails only		60.2ab	85.4	93.2
			36.0b	61.7	102
white oak	control	spring	69.5	32.9	--
	trails only		45.9	64.6	37.8
	sludge		97.4	68.8	70.5
	control	summer	47.1	82.5	--
	trails only		54.2	102	79.4
	sludge		47.2	81.2	89.6
red maple	control	spring	110	93.8	--
	trails only		80.4	78.7	51.1
	sludge		83.6	70.9	91.2
	control	summer	54.1	69.5	--
	trails only		42.3	64.1	68.8
	sludge		50.7	89.4	73.0
	control	winter	--	--	--
	trails only		145	189	157
	sludge		119	62.2	151

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 47. Mean Cd concentrations in forages collected off the jack pine/ red pine study area from 1982-1984.

Species	Treatment	Season	Year 1982	1983	1984
sedge	control	spring	--	0.35	--
	trails only		--	0.51	0.82
	sludge		--	0.57	0.69
	control	summer	0.51	0.60a	--
	trails only		0.57	0.89a	0.69
	sludge		0.55	1.64b	0.71
bracken fern	control	spring	--	1.27a	--
	trails only		--	1.35a	1.43
	sludge		--	1.61b	1.23
	control	summer	0.48	0.73	--
	trails only		0.79	0.30	0.59
	sludge		0.55	0.68	0.66
red oak	control	spring	--	0.12	--
	trails only		--	0.17	0.52
	sludge		--	0.24	0.36
	control	summer	0.44	0.66	--
	trails only		0.71	0.60	0.49
	sludge		0.36	0.46	0.84
	control	winter	--	--	--
	trails only		0.34	0.09	0.27
	sludge		0.16	0.29	0.26

Table 47 cont.

red maple	control	spring	--	0.16	--
	trails only		--	0.34	0.44
	sludge		--	0.18	0.35
	control	summer	0.38	0.61	--
	trails only		0.40	0.74	0.38
	sludge		0.56	0.81	0.69
	control	winter	--	--	--
	trails only		0.12	0.31	0.26
	sludge		0.18	0.31	0.14

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 48. Mean Cr concentrations in forages collected off the jack pine/ red pine study area from 1982-1984.

Species	Treatment	Season	Year 1982	1983	1984
sedge	control	spring	--	0.79	--
	trails only		--	0.90	0.67
	sludge		--	0.75	0.68
	control	summer	0.44	0.57	--
	trails only		0.57	0.55	0.45
	sludge		0.36	0.37	0.50
bracken fern	control	spring	--	0.97	--
	trails only		--	0.93	0.81
	sludge		--	1.01	0.84
	control	summer	0.55	0.44	--
	trails only		0.42	0.69	0.39
	sludge		0.51	0.41	0.49
red oak	control	spring	--	1.20	--
	trails only		--	0.71	0.88
	sludge		--	0.92	1.03
	control	summer	0.75	0.67	--
	trails only		0.76	0.68	0.42
	sludge		0.91	0.37	0.82
	control	winter	--	--	--
	trails only		0.88	1.08	1.02
	sludge		1.12	1.13	1.10

Table 48 cont.

red maple	control	spring	--	1.03	--
	trails only		--	1.32	1.07
	sludge		--	0.82	1.20
	control	summer	0.68	0.39	--
	trails only		0.79	0.24	0.35
	sludge		0.59	0.40	0.12
	control	winter	--	--	--
	trails only		0.80	1.26	1.14
	sludge		0.94	1.02	0.83

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 49. Mean Cu concentrations in forages collected off the jack pine/ red pine study area from 1982-1984.

Species	Treatment	Season	Year 1982	1983	1984
sedge	control	spring	--	2.96ab	--
	trails only		--	3.41a	2.69
	sludge		--	2.76b	1.80
	control	summer	3.62	3.34	--
	trails only		3.80	1.97	2.70
	sludge		2.93	3.28	3.23
bracken fern	control	spring	--	2.51	--
	trails only		--	2.73	2.94
	sludge		--	2.06	1.47
	control	summer	3.31	2.55a	--
	trails only		3.29	3.80b	3.11
	sludge		3.92	3.51b	4.06
red oak	control	spring	--	1.27	--
	trails only		--	1.51	1.26
	sludge		--	1.40	1.10
	control	summer	1.40	1.80	--
	trails only		1.79	1.97	2.72
	sludge		1.94	1.91	1.65
	control	winter	--	3.50	--
	trails only		3.04	2.78	3.72
	sludge		4.27	2.51	2.96

Table 49 cont.

red maple	control	spring	--	1.31	--
	trails only		--	0.85	1.47
	sludge		--	1.17	0.94
	control	summer	1.63	1.88	--
	trails only		1.69	1.83	2.03
	sludge		1.45	1.65	1.82
	control	winter	--	--	--
	trails only		7.62	6.76	7.65
	sludge		6.25	6.98	5.75

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 50. Mean Ni concentrations in forages collected off the jack pine/ red pine study area from 1982-1984.

Species	Treatment	Season	Year 1982	1983	1984
sedge	control	spring	--	1.37	--
	trails only		--	1.15	1.25
	sludge		--	1.11	1.34
	control	summer	1.12	1.34a	--
	trails only		1.05	1.06ab	1.25
	sludge		1.12	1.00b	0.89
bracken fern	control	spring	--	0.80	--
	trails only		--	1.17	1.32
	sludge		--	1.22	1.29
	control	summer	1.45	1.33	--
	trails only		1.63	1.67	1.40
	sludge		1.12	1.31	1.26
red oak	control	spring	--	1.28	--
	trails only		--	1.16	1.32
	sludge		--	1.03	1.42
	control	summer	1.62a	1.26	--
	trails only		1.71ab	1.47	1.31
	sludge		1.18b	1.40	1.65
	control	winter	--	0.76a	--
	trails only		1.31	1.84ab	1.54
	sludge		1.69	1.29b	1.37

Table 50 cont.

red maple	control	spring	--	0.97	--
	trails only		--	1.24	1.17
	sludge		--	1.05	1.16
	control	summer	1.24	1.36	--
	trails only		1.28	1.69	1.93
	sludge		1.26	1.29	1.39
	control	winter	--	1.37	--
	trails only		1.02	1.24	1.95
	sludge		1.33	1.63	1.38

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 51. Mean Zn concentrations in forages collected off the jack pine/ red pine study area from 1982-1984.

Species	Treatment	Season	Year 1982	1983	1984
sedge	control	summer	--	37.5	--
	trails only		--	26.9	36.2
	sludge		--	32.7	46.2
	control	summer	63.1	59.0	--
	trails only		73.9	77.5	56.5
	sludge		57.8	51.1	66.0
bracken fern	control	spring	--	43.3	--
	trails only		--	45.8	55.3
	sludge		--	56.4	51.7
	control	summer	74.0	88.0	--
	trails only		67.4	65.7	61.2
	sludge		99.2	52.1	85.6
red oak	control	spring	--	28.5a	--
	trails only		--	40.6ab	57.3
	sludge		--	65.1b	43.8
	control	summer	67.3	62.1	--
	trails only		64.2	89.1	81.2
	sludge		69.8	84.4	69.9
	control	winter	--	193	--
	trails only		297	270	265
	sludge		250	302	316

Table 51 cont.

red maple	control	spring	--	18.1a	--
	trails only		--	37.6b	15.5
	sludge		--	40.7b	25.0
	control	summer	55.9	58.5	--
	trails only		40.3	75.2	67.7
	sludge		43.3	50.8	46.9
	control	winter	--	207	--
	trails only		221	162	214
	sludge		168	174	152

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 52. Mean Cd concentrations in forages collected off the mixed hardwoods study area from 1982-1984.

Species	Treatment	Season	Year		
			1982	1983	1984
white ash	control	spring	--	0.23	--
	trails only		--	0.17	0.30
	sludge		--	0.39	0.47
	control	summer	0.68	0.58	--
	trails only		0.87	0.57	0.66
	sludge		0.57	0.72	0.49
hophorn-beam	control	spring	--	0.29	--
	trails only		--	0.48	0.58
	sludge		--	0.48	0.51
	control	summer	0.32a	0.35	--
	trails only		0.47a	0.59	0.20
	sludge		0.16b	0.37	0.35
sugar maple	control	spring	--	0.32	--
	trails only		--	0.45	0.31
	sludge		--	0.20	0.29
	control	summer	0.51	0.75a	--
	trails only		0.68	0.59b	0.69
	sludge		0.50	0.56b	0.49
	control	winter	--	--	--
	trails only		0.49	0.53	0.62
	sludge		0.44	0.64	0.59

Table 52 cont.

American beech	control	spring	--	0.45	--
	trails only		--	0.26	0.53
	sludge		--	0.22	0.36
	control	summer	0.65	0.31	--
	trails only		0.78	0.65	0.34
	sludge		0.41	0.39	0.68
	control	winter	--	0.96a	--
	trails only		0.29	0.22b	0.19
	sludge		0.35	0.32b	0.36

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 53. Mean Cr concentrations in forages collected off the mixed hardwoods study area from 1982-1984.

Species	Treatment	Season	Year 1982	Year 1983	Year 1984
white ash	control	spring	--	1.53	--
	trails only		--	1.30	1.60
	sludge		--	1.32	1.88
	control	summer	0.79	0.71	--
	trails only		0.58	0.52	0.81
	sludge		0.50	0.31	0.90
hophorn-beam	control	spring	--	0.46a	--
	trails only		--	0.66ab	0.86
	sludge		--	0.88b	0.49
	control	summer	0.36	0.35	--
	trails only		0.71	0.31	0.48
	sludge		0.32	0.22	0.47
sugar maple	control	spring	--	1.05	--
	trails only		--	1.16	0.98
	sludge		--	0.80	1.09
	control	summer	0.42	0.70	--
	trails only		0.62	0.57	0.55
	sludge		0.47	0.38	0.51
	control	winter	--	--	--
	trails only		2.47	1.46	2.00
	sludge		1.31	1.37	1.72

Table 53 cont.

American beech	control	spring	--	0.96a	--
	trails only		--	0.60b	0.68
	sludge		--	0.59b	0.66
	control	summer	0.28	0.55	--
	trails only		0.26	0.41	0.32
	sludge		0.31	0.42	0.45
	control	winter	--	1.17	--
	trails only		2.70	1.80	2.65
	sludge		1.43	1.93	2.01

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 54. Mean Cu concentrations in forages collected off the mixed hardwoods study area from 1982-1984.

Species	Treatment	Season	Year 1982	1983	1984
white ash	control	spring	--	6.54a	--
	trails only		--	8.96a	4.99
	sludge		--	12.3b	5.89
	control	summer	6.04	7.55ab	--
	trails only		5.55	6.62a	8.04
	sludge		6.67	10.8b	5.77
hophorn-beam	control	spring	--	3.58	--
	trails only		--	3.62	4.18
	sludge		--	3.75	3.66
	control	summer	4.91	4.74	--
	trails only		4.12	4.72	5.33
	sludge		5.15	4.50	5.09
sugar maple	control	spring	--	2.12	--
	trails only		--	3.95	3.72
	sludge		--	2.03	2.67
	control	summer	4.11	5.39	--
	trails only		4.94	8.14	4.28
	sludge		4.45	5.15	5.27
	control	winter	--	--	--
	trails only		10.6	10.8	7.58
	sludge		7.40	6.57	8.09

Table 54 cont.

American beech	control	spring	--	5.16	--
	trails only		--	5.12	3.76a
	sludge		--	3.46	6.47b
	control	summer	5.76	6.00	--
	trails only		6.39	6.32	7.06
	sludge		4.71	8.02	5.94
	control	winter	--	10.6	--
	trails only		19.8	12.8	15.6
	sludge		12.5	9.63	13.6

* values within a year and season with the same letter are not significantly different (at the .10 level)

'able 55. Mean Ni concentrations in forages collected off :he mixed hardwoods study area from 1982-1984.

¦pecies	Treatment	Season	Year		
			1982	1983	1984
'hite ash	control	spring	--	0.50	--
	trails only		--	0.52	0.62
	sludge		--	0.29	0.53
	control	summer	0.64	0.69	--
	trails only		0.97	0.77	0.81
	sludge		0.88	0.93	0.74
ophorn-beam	control	spring	--	0.47	--
	trails only		--	0.45	0.32
	sludge		--	0.15	0.38
	control	summer	0.72	0.48	--
	trails only		0.67	0.98	1.36
	sludge		1.04	0.74	0.94
ugar maple	control	spring	--	0.78	--
	trails only		--	0.63	0.46
	sludge		--	0.75	0.23
	control	summer	1.16	1.25a	--
	trails only		1.59	1.03ab	0.95
	sludge		0.94	0.81b	1.31
	control	winter	--	0.83	--
	trails only		1.13	2.12	1.81
	sludge		1.47	1.75	1.24

Table 56. Mean Zn concentrations in forages collected off the mixed hardwoods study area from 1982-1984.

Species	Treatment	Season	Year		
			1982	1983	1984
white ash	control	spring	--	30.4a	--
	trails only		--	42.4b	27.6
	sludge		--	38.3b	17.2
	control	summer	74.3	61.8	--
	trails only		50.0	98.6	53.7
	sludge		49.3	81.6	84.0
hophorn-beam	control	spring	--	52.0	--
	trails only		--	71.7	69.8
	sludge		--	33.2	59.8
	control	summer	46.2	34.7 a	--
	trails only		64.7	77.3 b	50.5
	sludge		65.0	44.0 ab	67.7
sugar maple	control	spring	--	20.7	--
	trails only		--	17.2	41.1
	sludge		--	22.5	37.6
	control	summer	49.0	79.3	--
	trails only		41.4	63.2	88.4
	sludge		69.5	68.7	59.8
	control	winter	--	--	--
	trails only		148	211	206
	sludge		159	196	156

Table 56 cont.

American beech	control	spring	--	69.7	--
	trails only		--	57.2	41.6
	sludge		--	72.0	38.7
	control	summer	63.4	81.8	--
	trails only		73.5	53.4	70.9a
	sludge		69.5	59.9	116b
	control	winter	--	158	--
	trails only		164	128	195
	sludge		133	116	171

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 57. Mean Cd concentrations in small mammals tissues collected off the jack pine clearcut from 1980-1982.

Species	Treatment	Tissue	Year 1980	1981	1982
white-footed mouse	control	liver	0.17	0.16	0.26
	sludge		0.21	0.25	0.21
	control	kidney	0.28	0.40	0.24
	sludge		0.49	0.39	0.35
	control	muscle	0.03	0.00	0.00
	sludge		0.00	0.00	0.00
	control	bone	0.00	0.00	0.00
	sludge		0.00	0.01	0.00
13-lined ground squirrel	control	liver	0.38	0.35	0.45
	sludge		0.39	0.42	0.53
	control	kidney	0.84	0.41	0.66
	sludge		0.51*	0.66	0.45
	control	muscle	0.00	0.00	0.00
	sludge		0.00	0.00	0.00
	control	bone	0.02	0.01	0.00
	sludge		0.00	0.01	0.00
meadow jumping mouse	control	liver	--	0.08	--
	sludge		--	0.04	--
	control	kidney	--	0.12	--
	sludge		--	0.10	--
	control	muscle	--	0.00	--
	sludge		--	0.00	--
	control	bone	--	0.00	--
	sludge		--	0.00	--

* value is significantly different (.10 level) from control

Table 58. Mean Cr concentrations in small mammals tissues collected off the jack pine clearcut from 1980-1982.

Species	Treatment	Tissue	Year 1980	1981	1982
white-footed mouse	control	liver	0.50	0.73	0.44
	sludge		0.35	0.46	0.40
	control	kidney	0.73	0.96	0.79
	sludge		0.87	1.29	0.71
	control	muscle	0.00	0.00	0.00
	sludge		0.00	0.00	0.00
	control	bone	0.00	0.00	0.00
	sludge		0.01	0.00	0.01
13-lined ground squirrel	control	liver	0.77	0.70	1.26
	sludge		0.88	0.86	0.60*
	control	kidney	0.48	0.40	0.60
	sludge		0.35	0.55	0.51
	control	muscle	0.00	0.00	0.00
	sludge		0.00	0.00	0.00
	control	bone	0.02	0.00	0.00
	sludge		0.00	0.00	0.00
meadow jumping mouse	control	liver	--	0.10	--
	sludge		--	0.17*	--
	control	kidney	--	0.23	--
	sludge		--	0.27	--
	control	muscle	--	0.00	--
	sludge		--	0.00	--
	control	bone	--	0.00	--
	sludge		--	0.00	--

* value is significantly different (.10 level) from control

Table 59. Mean Cu concentrations in small mammals tissues collected off the jack pine clearcut from 1980-1982.

Species	Treatment	Tissue	Year 1980	1981	1982
white-footed mouse	control	liver	17.0	10.5	8.34
	sludge		8.81	7.70	16.4
	control	kidney	2.51	3.91	3.98
	sludge		2.74	1.58	2.92
	control	muscle	0.95	1.83	1.72
	sludge		1.65	0.79	1.37
	control	bone	1.63	2.35	1.54
	sludge		1.64	1.90	1.68
13-lined ground squirrel	control	liver	3.56	7.79	8.17
	sludge		4.38	6.90	3.45
	control	kidney	7.53	3.96	9.48
	sludge		4.27*	6.07	3.42
	control	muscle	1.36	0.60	1.12
	sludge		0.96	1.37*	1.69
	control	bone	1.48	0.98	1.02
	sludge		1.32	1.81	0.92
meadow jumping mouse	control	liver	--	3.47	--
	sludge		--	7.04*	--
	control	kidney	--	2.38	--
	sludge		--	4.27	--
	control	muscle	--	0.79	--
	sludge		--	1.33	--
	control	bone	--	1.73	--
	sludge		--	1.02	--

* value is significantly different (.10 level) from control

Table 60. Mean Ni concentrations in small mammals tissues collected off the jack pine clearcut from 1980-1982.

Species	Treatment	Tissue	Year 1980	1981	1982
white-footed mouse	control	liver	0.93	0.56	0.83
	sludge		0.35	0.72	0.34*
	control	kidney	0.30	0.67	0.37
	sludge		0.47	0.31	0.22
	control	muscle	0.00	0.00	0.00
	sludge		0.00	0.00	0.00
	control	bone	0.00	0.00	0.00
	sludge		0.00	0.00	0.00
13-lined ground squirrel	control	liver	0.32	0.24	0.29
	sludge		0.41	0.64	0.26
	control	kidney	0.11	0.15	0.09
	sludge		0.08	0.11	0.19
	control	muscle	0.00	0.00	0.00
	sludge		0.00	0.00	0.00
	control	bone	0.01	0.00	0.00
	sludge		0.00	0.00	0.00
meadow jumping mouse	control	liver	--	0.62	--
	sludge		--	0.13*	--
	control	kidney	--	0.05	--
	sludge		--	0.11	--
	control	muscle	--	0.00	--
	sludge		--	0.00	--
	control	bone	--	0.00	--
	sludge		--	0.00	--

* value is significantly different (.10 level) from control

Table 61. Mean Zn concentrations in small mammals tissues collected off the jack pine clearcut from 1980-1982.

Species	Treatment	Tissue	Year 1980	981	1982
white-footed mouse	control	liver	57.6	57.8	44.6
	sludge		60.7	47.0	78.9*
	control	kidney	69.3	71.4	68.8
	sludge		80.5	67.3	92.2
	control	muscle	13.0	9.32	10.7
	sludge		4.52	19.7*	9.74
	control	bone	50.0	72.9	66.0
	sludge		49.3	75.1	65.0
13-lined ground squirrel	control	liver	62.9	93.9	83.3
	sludge		71.1	104	59.3
	control	kidney	98.4	79.9	189
	sludge		93.4	118	78.9
	control	muscle	4.60	8.33	18.1
	sludge		9.58	8.61	6.04
	control	bone	42.5	29.9	89.8
	sludge		69.5	46.8	59.4
meadow jumping mouse	control	liver	--	48.5	--
	sludge		--	52.0	--
	control	kidney	--	62.4	--
	sludge		--	91.7*	--
	control	muscle	--	13.3	--
	sludge		--	7.85	--
	control	bone	--	52.4	--
	sludge		--	99.1	--

* value is significantly different (.10 level) from control

Table 62. Mean Cd concentrations in small mammals tissues collected off the aspen study area from 1982-1984.

Species	Treatment	Tissue	Year 1982	1983	1984
eastern meadow vole	control	liver	0.08	0.05	0.12a
	trails only		0.07	0.01	0.05b
	sludge		0.04	0.04	0.03b
	control	kidney	0.47	0.22	0.62
	trails only		0.31	0.41	0.30
	sludge		0.31	0.42	0.26
	control	muscle	0.00	0.00	0.00
	trails only		0.00	0.00	0.00
	sludge		0.00	0.00	0.00
	control	bone	0.00	0.00	0.00
	trails only		0.00	0.00	0.00
	sludge		0.00	0.00	0.00
13-lined ground squirrel	control	liver	1.77	--	--
	trails only		0.49	--	--
	sludge		0.64	--	--
	control	kidney	0.73	--	--
	trails only		0.56	--	--
	sludge		0.99	--	--
	control	muscle	0.00	--	--
	trails only		0.00	--	--
	sludge		0.00	--	--
	control	bone	0.08	--	--
	trails only		0.18	--	--
	sludge		0.21	--	--

Table 62. cont.

woodland jumping mouse	control	liver	0.18a	0.22a	0.10
	trails only		0.07a	0.64b	0.16
	sludge		0.64b	0.47c	0.20
	control	kidney	0.27a	0.57	0.54
	trails only		0.22a	0.49	0.37
	sludge		0.83b	0.30	0.39
	control	muscle	0.00	0.00	0.00
	trails only		0.00	0.00	0.00
	sludge		0.00	0.00	0.00
	control	bone	0.00	0.02	0.01
	trails only		0.00	0.00	0.00
	sludge		0.00	0.00	0.01
eastern chipmunk	control	liver	0.48	--	--
	trails only		0.48	--	--
	sludge		0.61	--	--
	control	kidney	0.80	--	--
	trails only		0.46	--	--
	sludge		0.59	--	--
	control	muscle	0.00	--	--
	trails only		0.00	--	--
	sludge		0.00	--	--
	control	bone	0.04	--	--
	trails only		0.02	--	--
	sludge		0.04	--	--

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 63. Mean Cr concentrations in small mammals tissues collected off the aspen study area from 1982-1984.

Species	Treatment	Tissue	Year 1982	1983	1984
eastern meadow vole	control	liver	2.34	1.75	1.24
	trails only		1.42	3.74	1.81
	sludge		1.51	1.13	1.32
	control	kidney	10.6	16.9	21.9
	trails only		23.3	29.8	9.83
	sludge		13.5	9.93	27.6
	control	muscle	2.51a	1.76	1.18
	trails only		1.15b	3.15	1.70
	sludge		1.63ab	1.56	2.17
	control	bone	0.54	0.36	0.60
	trails only		0.88	0.27	0.83
	sludge		0.85	1.07	0.64
13-lined ground squirrel	control	liver	0.22	--	--
	trails only		0.78	--	--
	sludge		0.24	--	--
	control	kidney	0.27	--	--
	trails only		0.48	--	--
	sludge		0.06	--	--
	control	muscle	0.04	--	--
	trails only		0.00	--	--
	sludge		0.00	--	--
	control	bone	0.22	0.00	0.00
	trails only		0.05	0.00	0.00
	sludge		0.21	0.00	0.00

Table 63. cont.

woodland jumping mouse	control	liver	0.82	0.69	0.27
	trails only		0.44	0.73	0.20
	sludge		0.34	0.45	0.52
	control	kidney	0.51	0.34	0.75
	trails only		0.72	0.67	0.33
	sludge		0.15	0.71	0.56
	control	muscle	0.00	0.00	0.00
	trails only		0.00	0.00	0.00
	sludge		0.00	0.00	0.00
	control	bone	0.40	0.19	0.57
	trails only		0.41	0.48	0.72
	sludge		0.90	0.65	0.27
eastern chipmunk	control	liver	0.16	--	--
	trails only		0.83	--	--
	sludge		0.27	--	--
	control	kidney	0.21	--	--
	trails only		0.90	--	--
	sludge		0.62	--	--
	control	muscle	0.01	--	--
	trails only		0.01	--	--
	sludge		0.00	--	--
	control	bone	0.04	--	--
	trails only		0.02	--	--
	sludge		0.01	--	--

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 64. Mean Cu concentrations in small mammals tissues collected off the aspen study area from 1982-1984.

Species	Treatment	Tissue	Year		
			1982	1983	1984
eastern meadow vole	control	liver	17.4	23.9	7.13
	trails only		9.55	11.3	25.1
	sludge		22.2	29.6	16.4
	control	kidney	28.8	22.5	26.2
	trails only		12.5	33.2	30.2
	sludge		25.5	17.2	19.7
	control	muscle	0.96	1.17	1.27a
	trails only		0.61	0.72	2.31b
	sludge		1.67	0.80	1.70b
	control	bone	2.33	3.12	2.43
	trails only		3.46	2.70	3.87
	sludge		4.69	3.99	3.02
13-lined ground squirrel	control	liver	3.45	--	--
	trails only		7.53	--	--
	sludge		4.27	--	--
	control	kidney	3.96	--	--
	trails only		6.07	--	--
	sludge		9.22	--	--
	control	muscle	1.30	--	--
	trails only		1.07	--	--
	sludge		1.75	--	--
	control	bone	1.88	--	--
	trails only		2.05	--	--
	sludge		1.15	--	--

Table 64. cont.

woodland jumping mouse	control	liver	13.1	11.7	7.42
	trails only		6.33	12.3	11.6
	sludge		19.6	15.4	21.8
	control	kidney	10.8	15.3	29.0
	trails only		13.4	21.5	36.2
	sludge		25.9	9.28	28.5
	control	muscle	2.36	5.42	5.05
	trails only		3.60	4.97	3.71
	sludge		3.42	2.57	5.40
	control	bone	1.16	2.06a	2.76
	trails only		3.57	5.34b	1.85
	sludge		4.60	3.95ab	2.92
eastern chipmunk	control	liver	6.74	--	--
	trails only		7.39	--	--
	sludge		3.08	--	--
	control	kidney	7.50	--	--
	trails only		8.19	--	--
	sludge		3.96	--	--
	control	muscle	0.44	--	--
	trails only		0.73	--	--
	sludge		0.86	--	--
	control	bone	2.78	--	--
	trails only		3.07	--	--
	sludge		2.76	--	--

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 65. Mean Ni concentrations in small mammals tissues collected off the aspen study area from 1982-1984.

Species	Treatment	Tissue	Year 1982	1983	1984
eastern meadow vole	control	liver	0.44	0.33	0.41
	trails only		0.22	0.29	0.31
	sludge		0.42	0.29	0.34
	control	kidney	0.95	0.67	0.93
	trails only		0.51	0.89	1.15
	sludge		0.72	0.56	0.97
	control	muscle	0.00	0.00	0.00
	trails only		0.00	0.01	0.00
	sludge		0.00	0.00	0.00
	control	bone	0.00	0.00	0.00
	trails only		0.00	0.00	0.00
	sludge		0.00	0.00	0.00
13-lined ground squirrel	control	liver	0.40	--	--
	trails only		0.28	--	--
	sludge		0.30	--	--
	control	kidney	0.20	--	--
	trails only		0.11	--	--
	sludge		0.06	--	--
	control	muscle	0.00	--	--
	trails only		0.00	--	--
	sludge		0.00	--	--
	control	bone	0.31	--	--
	trails only		0.12	--	--
	sludge		0.22	--	--

Table 65. cont.

woodland jumping mouse	control	liver	0.08	0.11	0.34a
	trails only		0.13	0.21	0.12b
	sludge		0.07	0.19	0.06b
	control	kidney	0.13	0.18	0.30
	trails only		0.18	0.25	0.26
	sludge		0.22	0.37	0.17
	control	muscle	0.00	0.02	0.00
	trails only		0.00	0.00	0.00
	sludge		0.00	0.01	0.00
	control	bone	0.00	0.00	0.00
	trails only		0.00	0.00	0.00
	sludge		0.00	0.00	0.01
eastern chipmunk	control	liver	0.04	--	--
	trails only		0.08	--	--
	sludge		0.15	--	--
	control	kidney	0.03	--	--
	trails only		0.13	--	--
	sludge		0.09	--	--
	control	muscle	0.00	--	--
	trails only		0.00	--	--
	sludge		0.00	--	--
	control	bone	0.00	--	--
	trails only		0.04	--	--
	sludge		0.00	--	--

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 66. Mean Zn concentrations in small mammals tissues collected off the aspen study area from 19 2-19 4.

Species	Treatment	Tissue	Year		
			1982	1983	1984
eastern meadow vole	control	liver	41.5	25.6	43.4
	trails only		38.9	39.4	64.0
	sludge		46.9	21.6	41.4
	control	kidney	36.5	60.1	20.0a
	trails only		57.7	47.5	39.ab
	sludge		39.4	57.0	67.4b
	control	muscle	13.6	5.90	7.78
	trails only		6.97	13.0	4.48
	sludge		9.94	4.57	5.12
	control	bone	57.7	40.7	55.3
	trails only		54.2	72.0	33.6
	sludge		64.9	63.6	65.8
13-lined ground squirrel	control	liver	78.5	--	--
	trails only		86.3	--	--
	sludge		87.4	--	--
	control	kidney	59.6a	--	--
	trails only		95.9b	--	--
	sludge		147c	--	--
	control	muscle	5.23	--	--
	trails only		17.2	--	--
	sludge		14.5	--	--
	control	bone	21.3	--	--
	trails only		14.1	--	--
	sludge		26.0	--	--

Table 66. cont.

woodland jumping mouse	control	liver	55.1	74.0a	56.2
	trails only		57.0	35.1b	44.4
	sludge		53.9	20.0b	24.8
	control	kidney	40.6	43.5	30.4
	trails only		34.9	32.4	53.2
	sludge		23.4	24.8	47.7
	control	muscle	7.35	10.2	7.08
	trails only		14.1	13.5	6.81
	sludge		9.84	6.49	6.97
	control	bone	28.7	38.3a	37.7
	trails only		28.7	18.7b	29.5
	sludge		23.9	39.6ab	24.8
eastern chipmunk	control	liver	65.5	--	--
	trails only		27.0	--	--
	sludge		56.0	--	--
	control	kidney	40.5	--	--
	trails only		18.9	--	--
	sludge		90.8	--	--
	control	muscle	4.53	--	--
	trails only		9.55	--	--
	sludge		19.3	--	--
	control	bone	22.7	--	--
	trails only		19.8	--	--
	sludge		35.1	--	--

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 67. Mean Cd concentrations in small mammals tissues collected off the oak study area from 1982-1984.

Species	Treatment	Tissue	Year		
			1982	1983	1984
white-footed mouse	control	liver	0.13	0.16a	0.12
	trails only		0.09	0.07b	0.09
	sludge		0.18	0.14ab	0.13
	control	kidney	0.16	0.21ab	0.16
	trails only		0.21	0.38b	0.14
	sludge		0.25	0.20a	0.25
	control	muscle	0.02	0.00	0.00
	trails only		0.00	0.00	0.01
	sludge		0.00	0.00	0.00
	control	bone	0.08	0.01	0.02
	trails only		0.03	0.00	0.01
	sludge		0.03	0.01	0.01

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 68. Mean Cr concentrations in small mammals tissues collected off the oak study area from 1982-1984.

Species	Treatment	Tissue	Year 1982	Year 1983	Year 1984
white-footed mouse	control	liver	0.75	0.72	0.61
	trails only		0.52	1.10	1.35
	sludge		1.37	0.68	0.54
	control	kidney	1.32	1.54a	1.21
	trails only		1.05	2.86b	1.42
	sludge		6.26	1.88ab	3.07
	control	muscle	0.00	0.00	0.01
	trails only		0.00	0.00	0.00
	sludge		0.00	0.00	0.00
	control	bone	0.20	0.31	0.14
	trails only		0.06	0.15	0.10
	sludge		0.38	0.09	0.07

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 69. Mean Cu concentrations in small mammals tissues collected off the oak study area from 1982-1984.

Species	Treatment	Tissue	Year 1982	1983	1984
white-footed mouse	control	liver	15.4	20.0	17.0
	trails only		18.0	10.8	20.9
	sludge		12.1	17.5	11.4
	control	kidney	10.5	11.5a	22.3
	trails only		26.0	22.8b	20.6
	sludge		17.4	8.62a	10.5
	control	muscle	0.99	1.20	1.56
	trails only		1.38	0.95	0.79
	sludge		1.54	0.83	0.93
	control	bone	1.07	2.23	1.15
	trails only		0.72	1.07	1.28
	sludge		2.21	2.80	1.62

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 70. Mean Ni concentrations in small mammals tissues collected off the oak study area from 1982-1984.

Species	Treatment	Tissue	Year 1982	1983	1984
white-footed mouse	control	liver	0.32	0.27	0.24
	trails only		0.07	0.11	0.15
	sludge		0.47	0.17	0.21
	control	kidney	0.09	0.15	0.07
	trails only		0.12	0.11	0.16
	sludge		0.08	0.10	0.08
	control	muscle	0.00	0.00	0.00
	trails only		0.00	0.00	0.00
	sludge		0.00	0.00	0.00
	control	bone	0.00	0.00	0.00
	trails only		0.00	0.00	0.00
	sludge		0.00	0.00	0.00

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 71. Mean Zn concentrations in small mammals tissues collected off the oak study area from 1982-1984.

Species	Treatment	Tissue	Year		
			1982	1983	1984
white-footed mouse	control	liver	38.4	52.5	64.8
	trails only		79.6	77.9	57.2
	sludge		44.2	64.4	57.8
	control	kidney	35.5	24.8a	39.5
	trails only		53.0	30.4ab	34.9
	sludge		29.8	47.7b	26.6
	control	muscle	17.4	30.9	17.7
	trails only		21.9	15.6	21.2
	sludge		13.7	19.7	18.8
	control	bone	78.5	77.9	68.8
	trails only		74.3	98.4	114
	sludge		90.8	80.2	85.5

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 72. Mean Cd concentrations in small mammals tissues collected off the jack pine/ red pine study area from 1982-1984.

Species	Treatment	Tissue	Year 1982	Year 1983	Year 1984
white-footed mouse	control	liver	--	--	0.11
	trails only		--	--	0.18
	sludge		--	--	0.15
	control	kidney	--	--	0.33
	trails only		--	--	0.56
	sludge		--	--	0.20
	control	muscle	--	--	0.00
	trails only		--	--	0.00
	sludge		--	--	0.00
	control	bone	--	--	0.00
	trails only		--	--	0.00
	sludge		--	--	0.00
eastern chipmunk	control	liver	--	0.06	--
	trails only		--	0.05	--
	sludge		--	0.12	--
	control	kidney	--	0.30	--
	trails only		--	0.26	--
	sludge		--	0.41	--
	control	muscle	--	0.01	--
	trails only		--	0.00	--
	sludge		--	0.00	--
	control	bone	--	0.00	--
	trails only		--	0.00	--
	sludge		--	0.00	--

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 73. Mean Cr concentrations in small mammals tissues collected off the jack pine/ red pine study area from 1982-1984.

Species	Treatment	Tissue	Year 1982	1983	1984
white-footed mouse	control	liver	--	--	0.74
	trails only		--	--	0.50
	sludge		--	--	1.21
	control	kidney	--	--	1.54
	trails only		--	--	1.41
	sludge		--	--	2.17
	control	muscle	--	--	0.00
	trails only		--	--	0.00
	sludge		--	--	0.00
	control	bone	--	--	0.12a
	trails only		--	--	0.08b
	sludge		--	--	0.06b
eastern chipmunk	control	liver	--	1.27	--
	trails only		--	1.16	--
	sludge		--	1.41	--
	control	kidney	--	3.11	--
	trails only		--	1.68	--
	sludge		--	1.90	--
	control	muscle	--	0.00	--
	trails only		--	0.00	--
	sludge		--	0.00	--
	control	bone	--	0.12	--
	trails only		--	0.11	--
	sludge		--	0.08	--

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 74. Mean Cu concentrations in small mammals tissues collected off the jack pine/ red pine study area from 1982-1984.

Species	Treatment	Tissue	Year 1982	Year 1983	Year 1984
white-footed mouse	control	liver	--	--	10.8
	trails only		--	--	19.3
	sludge		--	--	17.2
	control	kidney	--	--	16.2a
	trails only		--	--	13.8b
	sludge		--	--	10.9c
	control	muscle	--	--	0.54
	trails only		--	--	1.18
	sludge		--	--	0.35
	control	bone	--	--	1.04
	trails only		--	--	1.51
	sludge		--	--	1.05
eastern chipmunk	control	liver	--	21.2	--
	trails only		--	14.5	--
	sludge		--	30.5	--
	control	kidney	--	18.0	--
	trails only		--	27.0	--
	sludge		--	12.9	--
	control	muscle	--	0.30	--
	trails only		--	0.76	--
	sludge		--	0.80	--
	control	bone	--	1.41a	--
	trails only		--	1.80b	--
	sludge		--	1.62ab	--

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 75. Mean Ni concentrations in small mammals tissues collected off the jack pine/ red pine study area from 1982-1984.

Species	Treatment	Tissue	Year 1982	Year 1983	Year 1984
white-footed mouse	control	liver	--	--	0.15
	trails only		--	--	0.11
	sludge		--	--	0.10
	control	kidney	--	--	0.08
	trails only		--	--	0.05
	sludge		--	--	0.05
	control	muscle	--	--	0.00
	trails only		--	--	0.00
	sludge		--	--	0.00
	control	bone	--	--	0.00
	trails only		--	--	0.00
	sludge		--	--	0.00
eastern chipmunk	control	liver	--	0.14a	--
	trails only		--	0.25b	--
	sludge		--	0.19ab	--
	control	kidney	--	0.09	--
	trails only		--	0.15	--
	sludge		--	0.07	--
	control	muscle	--	0.00	--
	trails only		--	0.00	--
	sludge		--	0.00	--
	control	bone	--	0.00	--
	trails only		--	0.00	--
	sludge		--	0.01	--

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 76. Mean Zn concentrations in small mammals tissues collected off the jack pine/ red pine study area from 1982-1984.

Species	Treatment	Tissue	Year 1982	Year 1983	Year 1984
white-footed mouse	control	liver	--	--	40.2
	trails only		--	--	30.5
	sludge		--	--	30.8
	control	kidney	--	--	39.5a
	trails only		--	--	22.6b
	sludge		--	--	25.2b
	control	muscle	--	--	22.2
	trails only		--	--	17.7
	sludge		--	--	15.4
	control	bone	--	--	56.3
	trails only		--	--	30.7
	sludge		--	--	53.4
eastern chipmunk	control	liver	--	60.0	--
	trails only		--	53.4	--
	sludge		--	36.9	--
	control	kidney	--	49.3	--
	trails only		--	30.9	--
	sludge		--	46.2	--
	control	muscle	--	12.9a	--
	trails only		--	21.0b	--
	sludge		--	28.9b	--
	control	bone	--	68.5	--
	trails only		--	53.9	--
	sludge		--	62.8	--

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 77. Mean Cd concentrations in small mammals tissues collected off the hardwoods study area from 1982-1984.

Species	Treatment	Tissue	Year 1982	Year 1983	Year 1984
white-footed mouse	control	liver	0.27	0.30	0.29
	trails only		0.70	0.23	0.34
	sludge		0.48	0.35	0.23
	control	kidney	0.13	0.22a	0.45
	trails only		0.29	0.42b	0.33
	sludge		0.28	0.54b	0.57
	control	muscle	0.00	0.00	0.00
	trails only		0.00	0.00	0.00
	sludge		0.00	0.00	0.00
	control	bone	0.01	0.00	0.01
	trails only		0.11	0.00	0.01
	sludge		0.00	0.00	0.01
eastern chipmunk	control	liver	0.78	1.20a	1.18
	trails only		1.31	0.70b	0.80
	sludge		0.73	0.88b	0.96
	control	kidney	0.79a	1.31	1.34
	trails only		1.60b	1.42	0.75
	sludge		1.73b	1.10	1.39
	control	muscle	0.00	0.00	0.00
	trails only		0.00	0.00	0.00
	sludge		0.00	0.00	0.00
	control	bone	0.06	0.00	0.00
	trails only		0.00	0.00	0.00
	sludge		0.00	0.00	0.00

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 78. Mean Cr concentrations in small mammals tissues collected off the hardwoods study area from 1982-1984.

Species	Treatment	Tissue	Year		
			1982	1983	1984
white-footed mouse	control	liver	0.25	0.49	0.46
	trails only		0.93	0.53	0.79
	sludge		0.69	0.59	0.30
	control	kidney	1.13a	1.49	0.98
	trails only		0.69a	0.86	0.73
	sludge		8.64b	0.80	2.33
	control	muscle	0.00	0.05	0.01
	trails only		0.00	0.00	0.01
	sludge		0.00	0.00	0.00
	control	bone	0.16	0.34	0.36
	trails only		0.79	0.49	0.44
	sludge		0.35	0.80	0.65
eastern chipmunk	control	liver	0.49	0.60	0.71
	trails only		0.74	1.26	0.54
	sludge		0.82	0.47	0.65
	control	kidney	1.89	1.53	1.15
	trails only		0.58	1.49	1.52
	sludge		0.60	0.85	0.77
	control	muscle	0.00	0.00	0.00
	trails only		0.00	0.00	0.00
	sludge		0.00	0.00	0.00
	control	bone	0.00	0.00	0.00
	trails only		0.00	0.01	0.00
	sludge		0.00	0.00	0.00

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 79. Mean Cu concentrations in small mammals tissues collected off the hardwoods study area from 1982-1984.

Species	Treatment	Tissue	Year 1982	Year 1983	Year 1984
white-footed mouse	control	liver	19.4	17.0	6.53
	trails only		13.4	16.0	9.41
	sludge		7.39	9.25	15.9
	control	kidney	15.1	12.5	7.50
	trails only		15.0	19.2	18.4
	sludge		20.6	18.4	15.0
	control	muscle	0.98	0.74	1.22
	trails only		1.04	0.93	0.51
	sludge		0.42	0.86	0.81
	control	bone	3.71	2.05	3.28
	trails only		1.35	3.73	3.34
	sludge		2.01	2.41	2.59
eastern chipmunk	control	liver	6.22a	6.95	9.72
	trails only		18.4b	7.93	8.61
	sludge		7.39a	12.4	10.2
	control	kidney	4.94	8.11a	6.37
	trails only		11.2	13.9b	7.91
	sludge		7.50	6.71a	9.17
	control	muscle	0.73	0.68	0.93
	trails only		0.62	1.26	0.36
	sludge		0.80	0.51	0.45
	control	bone	2.64	2.22	2.67
	trails only		1.07	2.02	1.06
	sludge		0.96	1.41	1.90

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 80. Mean Ni concentrations in small mammals tissues collected off the hardwoods study area from 1982-1984.

Species	Treatment	Tissue	Year 1982	1983	1984
white-footed mouse	control	liver	0.17	0.28	0.33
	trails only		0.92	0.21	0.18
	sludge		0.12	0.11	0.19
	control	kidney	0.33	0.49	0.50
	trails only		0.44	0.71	0.33
	sludge		0.86	0.64	0.46
	control	muscle	0.00	0.00	0.00
	trails only		0.00	0.00	0.00
	sludge		0.00	0.00	0.00
	control	bone	0.00	0.01	0.00
	trails only		0.93	0.00	0.00
	sludge		0.00	0.00	0.00
eastern chipmunk	control	liver	0.05	0.63a	0.53
	trails only		0.15	0.27b	0.46
	sludge		0.22	0.13b	0.31
	control	kidney	0.03	0.09	0.16
	trails only		0.11	0.34	0.26
	sludge		0.10	0.14	0.19
	control	muscle	0.00	0.00	0.00
	trails only		0.00	0.00	0.00
	sludge		0.00	0.00	0.00
	control	bone	0.00	0.00	0.00
	trails only		0.00	0.00	0.00
	sludge		0.00	0.00	0.00

* values within a year and season with the same letter are not significantly different (at the .10 level)

Table 81. Mean Zn concentrations in small mammals tissues collected off the hardwoods study area from 1982-1984.

Species	Treatment	Tissue	Year 1982	Year 1983	Year 1984
white-footed mouse	control	liver	36.5	48.2	31.3
	trails only		75.3	40.3	39.3
	sludge		38.8	45.5	35.6
	control	kidney	57.5	61.5	60.7
	trails only		33.6	73.3	58.0
	sludge		42.8	62.4	41.4
	control	muscle	8.76	8.02	13.5
	trails only		14.1	16.4	31.9
	sludge		11.8	34.6	20.0
	control	bone	71.3	50.7	33.6a
	trails only		45.2	92.9	54.7b
	sludge		49.6	30.7	84.4b
eastern chipmunk	control	liver	144	74.4	56.5
	trails only		86.9	57.8	93.5
	sludge		90.8	85.1	77.9
	control	kidney	69.6	68.8	89.0
	trails only		81.8	82.2	83.4
	sludge		52.2	112	49.7
	control	muscle	10.7	4.82	7.93
	trails only		7.84	9.81	6.76
	sludge		6.21	5.08	4.69
	control	bone	36.7	41.1	27.0
	trails only		27.6	19.9	45.6
	sludge		64.2	37.7	43.8

* values within a year and season with the same letter are not significantly different (at the .10 level)