PROGRESSIVE HEAVY METAL ACCUMULATION ASSOCIATED WITH FOREST DECLINE NEAR THE NICKEL SMELTER AT THOMPSON, MANITOBA

BY

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INFORMATION REPORT NOR-X-169
FEBRUARY 1977

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Hocking, D. and R.A. Blauel. 1977. Progressive heavy metal accumulation associated with forest decline near the nickel smelter at Thompson, Manitoba. Environ. Can., Can. For. Serv., North. For. Res. Cent. Inf. Rep. NOR-X-169.

ABSTRACT

Heavy metals, indicated by nickel and copper, were determined in soils and forest vegetation around the nickel smelter at Thompson, Manitoba. A steep gradient of decreasing concentrations with increasing distance from the smokestack was evident on three transects. Sharp increases were noted in concentrations measured in two successive years. Concentrations within 2-5 km of the smokestack are approaching levels likely to lead to persistent soil toxicity and accompanying regeneration problems. Associated decline of the vegetation, described in earlier studies, was confirmed as continuing.

RESUME

Les sols à végétation forestière autour de la fonderie de nickel de Thompson, au Manitoba, renferment des particules de métaux lourds, notamment du nickel et du cuivre. On a observé par trois transects des concentrations très décroissantes de couches de fumée polluante à mesure que la distance de la source de pollution augmentait. Des concentrations mesurées deux années de suite ont indiqué des augmentations prononcées. Les concentrations mesurées à 2 à 5 km de la cheminée se rapprochent des niveaux qui pourront probablement conduire à la toxicité persistante du sol conduisant à des problèmes de régénération. On confirme que le déclin de la végétation, associé à ce phénomène et qui fut décrit dans certaines études antérieures, se poursuit.

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INTRODUCTION

Nickel smelting has been conducted near Thompson, Manitoba, since 1960. A 152-m high smokestack discharges gaseous and particulate matter into the atmosphere. Principal pollutants are sulphur dioxide and a variety of particulates including the elements iron, nickel, copper, manganese, cobalt, arsenic, zinc, lead, cadmium, silicon, magnesium, and aluminum.

Forest condition in the area has been surveyed annually by the Canadian Forestry Service at the request of the Manitoba Government. A general area description and survey results to 1974 were summarized in a report (Blauel and Hocking 1974) that described patchy forest decline occurring within an area of 128 km^2 (50 $miles^2$) and severe decline, including the general depletion of cryptogams and varying amounts of plant and tree mortality, over 31 km^2 (12 $miles^2$). That report attributed forest decline to direct absorption of the air pollutants and warned of toxic pollutant accumulation in the soil.

The present report adds more recent information on pollutant accumulation, showing that pollutant accumulation is steadily increasing, and confirms the continuing forest decline.

POLLUTANTS RELEASED

Composition of the stack plume varies with the ore being smelted and with the operating efficiency of dust collection equipment. International Nickel Company of Canada Ltd. has supplied emission data from stack sampling programs (Table 1) and has stated that dust emissions have reached 101 tonnes (100 tons) per day during periods of equipment malfunction (INCO 1974). Initial stack sampling by the Manitoba Government indicates that methods then in use could be in error by as much as ± 50% (Capowski 1974).

Table 1. Pollutant emissions from the smokestack at Thompson, Manitoba. (Data supplied by International Nickel Company of Canada Ltd.; methods used may have a variance of ± 50%.)

Pollutant	1972	1973	1974	1975[1]
Sulphur dioxide gas In tonne/day (tons/day)	1717 (1700)	1212 (1200)	1277 (1265)	1272 (1260)
Particulates:				
Total In tonne/day (tons/day)	30.3 (30)	30.3 (30)	18.8 (18.7)	18.4 (18.3)
Elemental composition In kg/h (lb/h)				
Nickel	40.8 (90)	72.6 (160)	43.5 (96)	29.9 (66.0)
Copper	*	*	3.04 (6.7)	5.71 (12.6)
Lead	.36 (.8)	.04 (.1)	*	1.36 (3.0)
Zinc	.41 (.9)	.32 (.7)	.23 (.5)	*
Cadmium	.04 (.1)	.04 (.1)	*	.09 (0.2)
Cobalt	*	*	.95 (2.1)	*
Arsenic	*	*	.77 (1.7)	1.54 (3.4)

* data not available

[1] 1975 data obtained from the Manitoba Environmental Control Branch; adjusted to same base (concentrate roasting rate).

METHODS

Aerial surveys and ground examinations and sampling were conducted June 4–10, 1975. Ground sampling sites were as described earlier (Blauel and Hocking 1974), except on the southwest transect where human activities had

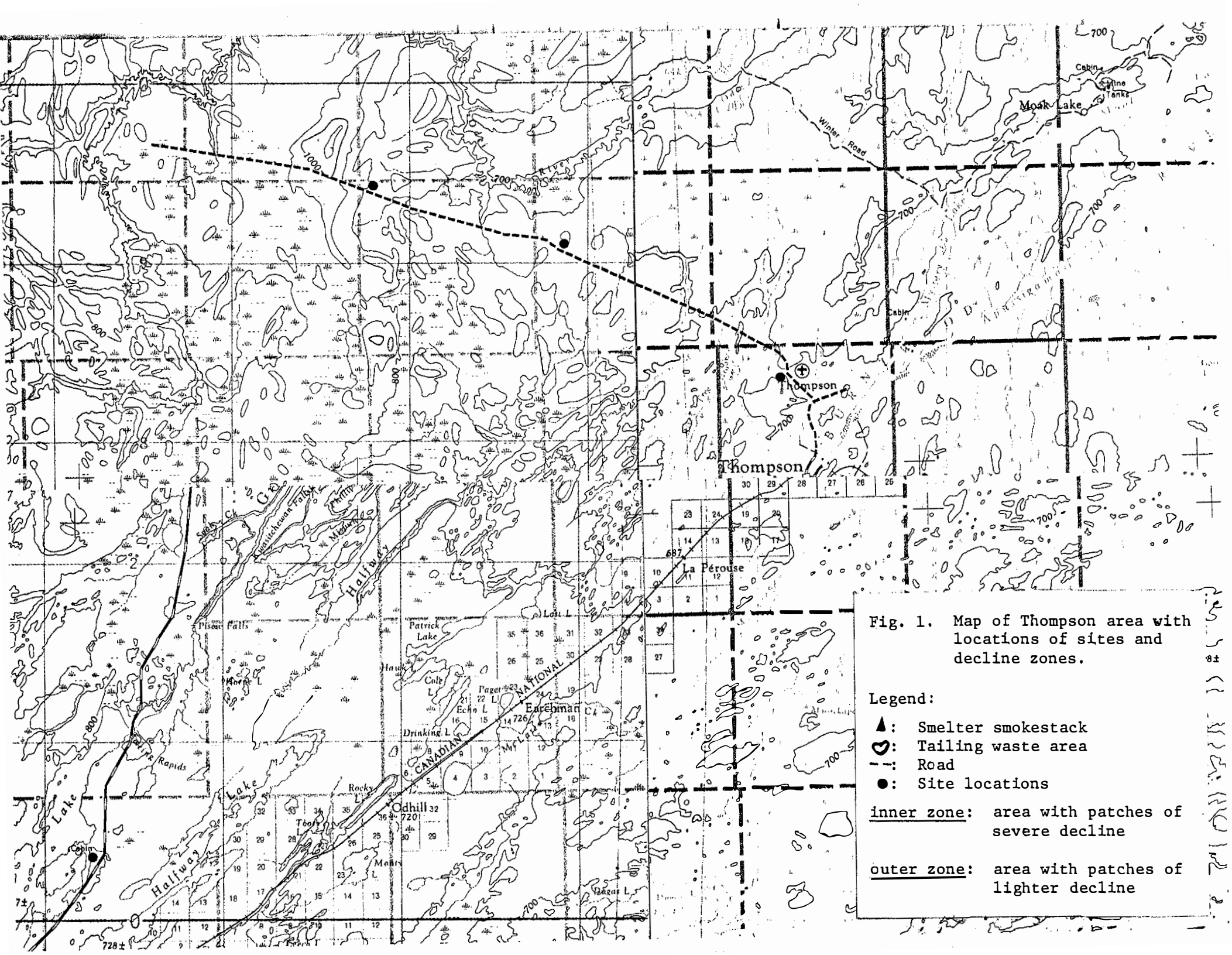


Fig. 1. Map of Thompson area with locations of sites and decline zones.

Legend:

▲: Smelter smokestack
: Tailing waste area
– –: Road
●: Site locations

inner zone: area with patches of severe decline

outer zone: area with patches of lighter decline

disturbed earlier sites. Actual sites sampled on the three transects are shown in Fig. 1.

On each site, observations, photographs, and notes on vegetation condition were compared with conditions noted for the corresponding site in 1974. The notes and photographs detailed the presence and/or absence, coloration, size, shape, symptoms, and general condition of trees, small shrubs and herbs, corticolous cryptogams, and ground cryptogams.

Samples of jack pine (Pinus banksiana Lamb.) foliage, corticolous lichens, mosses, soil surface organic layer (LFH horizon), and mineral soil at two depths: 1-6 cm (A horizon) and 20-30 cm (B horizon) were collected for chemical analysis. One set of snow samples (bulk collection to just above ground vegetation) was collected on the south transect on December 18, 1974.

Sample handling, preparation, and analysis were as previously described (Blauel and Hocking 1974). Sulphur was determined by turbidimetry and other elements by atomic absorption spectrophotometry using appropriate lamps and monochrometer settings. Arsenic and selenium were determined on some samples by the Calgary Analytical Laboratory of Environment Canada's Inland Waters Directorate using atomic absorption spectrophotometry of acid extracts. Ten percent of samples were analyzed in duplicate. Determinations in duplicate samples showed a variance that averaged ± 8% and ranged from 0 to ± 12%.

RESULTS

Assessments of vegetation condition confirmed and extended the results given in our earlier report (Blauel and Hocking 1974). In brief, tree and plant mortality, species depletion, cover depletion, and discolorations were high to extreme on sites within the "severe" injury zone on Fig. 1, and declined in intensity with increasing distance from the smokestack. In trees and woody shrubs the current, newly emerged foliage (where present) was generally free from visible injury. However, older coniferous foliage and the ground vegetation exhibited continuing stress and progressive decline. Notable were further discoloration and reduced

density and luxuriance of epiphytic lichens, a proven quantitative indication of air pollution effects (Skorepa and Vitt 1976). The pollutant-sensitive corticolous lichens, including Alectoria glabra, Cetraria halei, Evernia mesomorpha, Hypogymnia physodes, Parmelia sulcata, Usnea subfloridana, and other Usnea species, were dead or conspicuously absent on sites near the smelter. These species were markedly reduced in both luxuriance and density at sites up to 11 km distant from the smelter. At sites near the smelter, the only live epiphytes were those known to be very resistant to air pollutant stress, namely a few Parmeliopsis spp. and crustose lichens.

The ground cover bryophytes, which make up the major portion of the ground cover in the area, also displayed severe symptoms. At sites near the smelter most of the ground lichens common to the area, such as species of Peltigera, Cladina, and Cladonia, were either dead and in various stages of decomposition or were missing. Similarly, mosses and liverworts were either dead or displayed severe stress symptoms. The intensity of stress symptoms varied with the microsite, and was least where there was most protection from direct exposure to the air pollutants.

The commonly occurring mosses included species of Pleurozium, Aulacomium, Sphagnum, Tomenthypnum, Hylocomium, Polytrichum, and Dicranum.

Accumulation of sulphur and nickel in the soil surface organic material (LFH horizon) increased sharply between June 1974 and June 1975 (Figs. 2-4) at all sites, while maintaining the strong gradient of decreasing concentration with increasing distance from the stack. Copper accumulation in the soil surface organic layer showed a gradient with distance that paralleled that of nickel (Figs. 2 - 4). Full numerical data are in Table 2.

In the mineral soil there was some indication of increased pollutant load in the 1-6 cm level (A horizon). There was no evidence in the 1975 data that contaminants had been significantly leached to the deeper, 20-30 cm level (B horizon) (Table 2).

Fig. 2. Comparative nickel, sulphur, and copper concentrations found in soil LFH samples from sites south of the smelter stack, 1974 and 1975

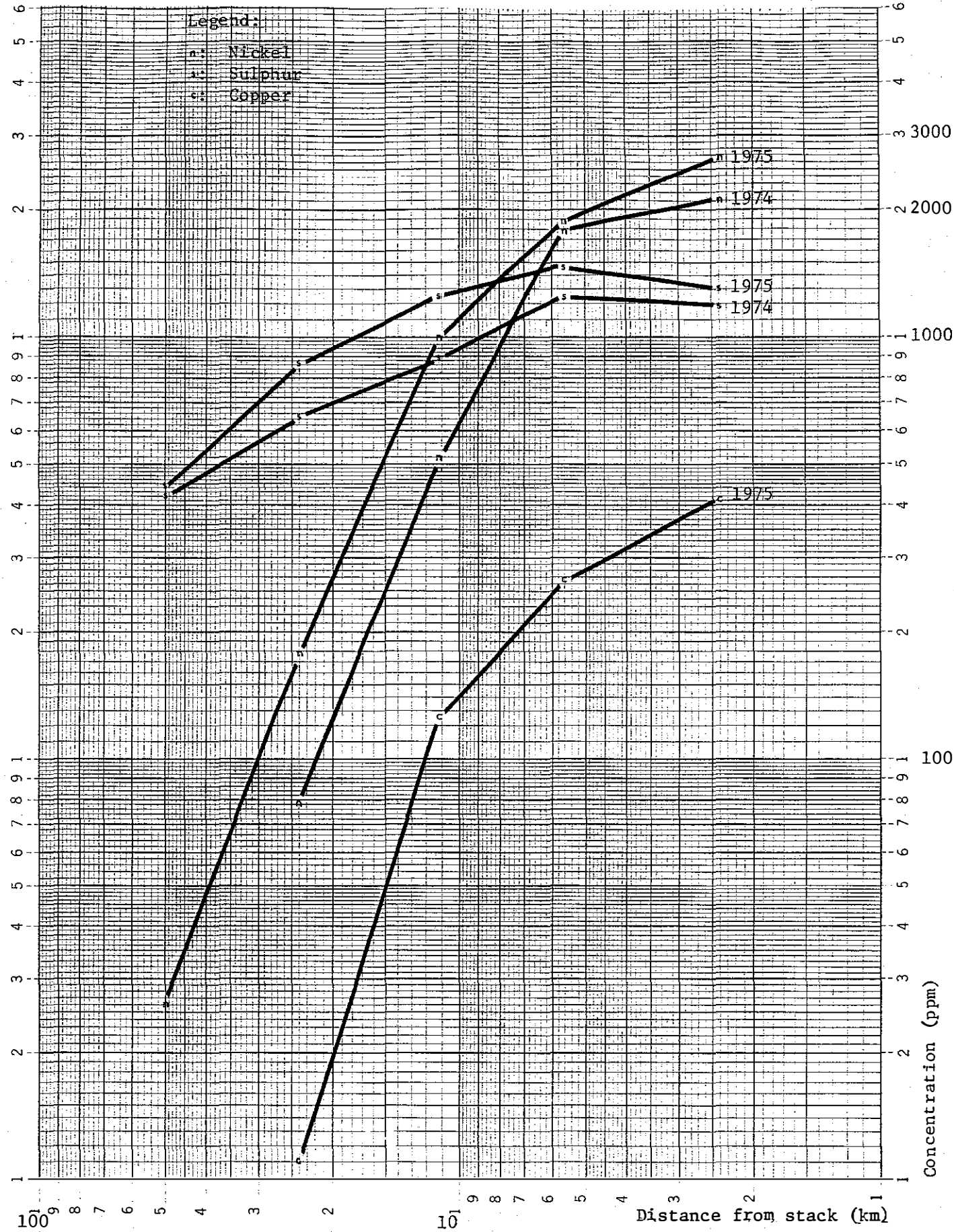


Fig. 3. Comparative nickel, sulphur, and copper concentrations found in soil LFH samples from sites north and northwest of the smelter stack, 1974 and 1975

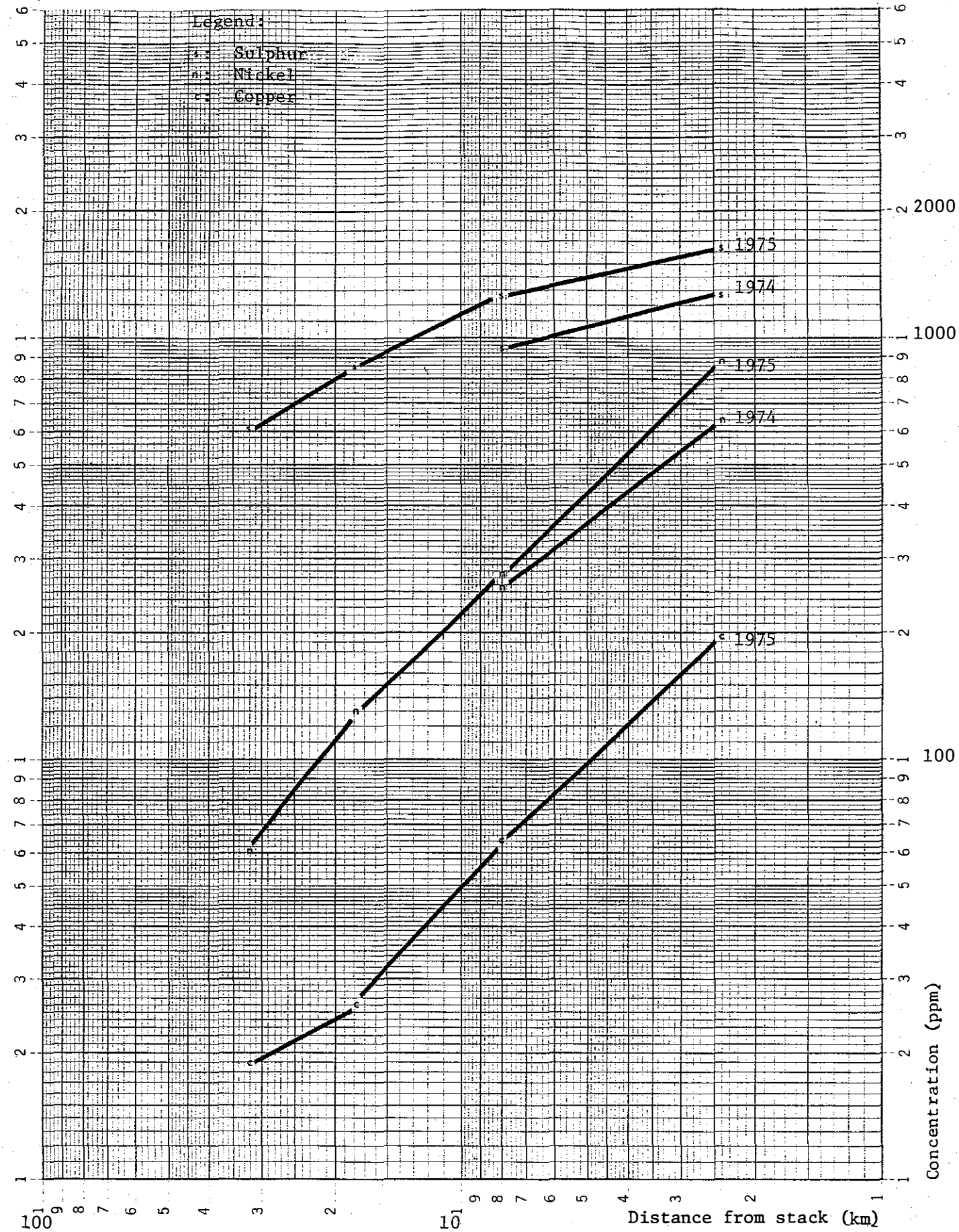


Fig. 4. Comparative nickel, sulphur, and copper concentrations found in soil LFH samples from sites southwest of the smelter stack, 1974 and 1975

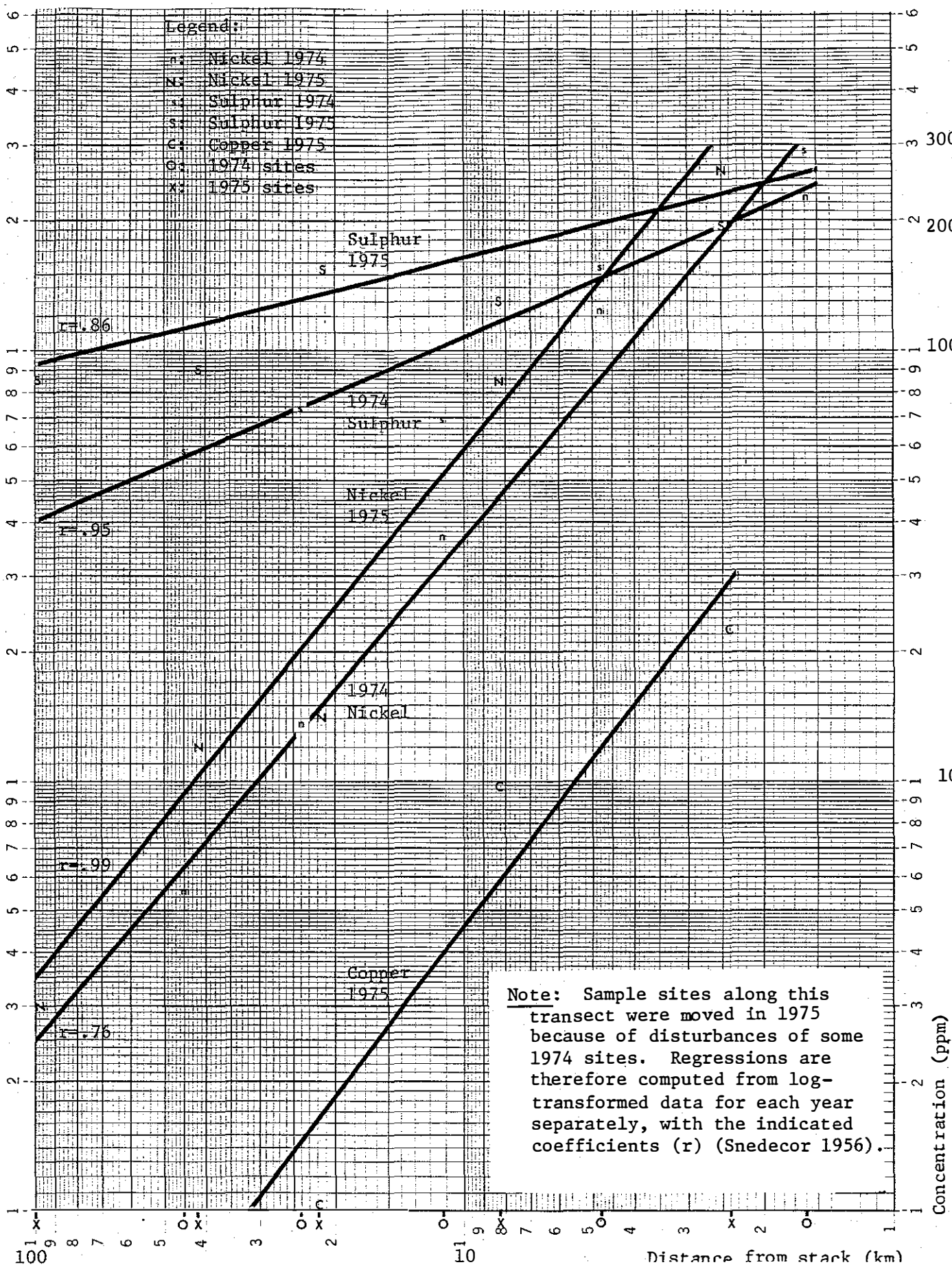


Table 2: Sulphur, nickel, and copper content (ppm) of surface litter and soil[1]

Direction & Distance (km) from stack	Surface Organic Layer (LFH Horizon)					Mineral Soil							
						A Horizon (1974: 0-4", 1975: 1-6 cm)					B Horizon (20-30 cm)		
	S[2]		Ni		Cu	S[3]		Ni		Cu	S[3]	Ni	Cu
	1974	1975	1974	1975	1975	1974	1975	1974	1975	1975	1975	1975	1975
South													
2.4	1199	1210	2030	2628	403	6	9	162	64	6	3	89	26
5.6	1232	1440	1730	1808	266	5	11	108	203	13	3	83	27
11.2	891	1210	502	976	127	5	4	77	107	14	4	91	35
24	649	870	79	177	10	3	12	105	56	14	3	68	23
49.6	418	430	72	26	0[4]	3	23	112	26	0[4]	8	73	26
Southwest													
1.6	2882		2215			22		111					
2.4		1880		2610	225		88		570	57	7	200	17
4.8	1562		1265			21		78					
8.3		1270		830	99		110		230	32	11	150	33
11.2	693		365			3		87					
21.9		1510		140	8		31		150	13	2	340	42
24	726		138			12		107					
41.8		900		120	2		204		60	13	14	180	57
44.8	583		55			6		93					
105.8		890		30	5		68		20	5	**	**	**
North and Northwest													
2.4	1254	1610	640	880	197	33	153	119	770	101	*	*	*
8	957	1260	257	270	64	16	61	125	90	27	*	*	*
17.3	*	840	*	130	26	*	24	*	50	13	*	*	*
32	*	600	*	60	19	*	47	*	70	14	*	*	*

[1] Data for 1974 previously appeared in Blauel & Hocking (1974) and are reproduced here for comparison

[2] Total sulphur

[3] Readily soluble sulphur

[4] Less than detection limit of instrument

** Rock; not sampled

* Data not available

Table 3. Sulphur, nickel, and copper content (ppm) in jack pine foliage

Direction & Distance (km) From Stack	Sulphur			Nickel			Copper		
	1 yr[1]	2 yr	3 yr	1 yr	2 yr	3 yr	1 yr	2 yr	3 yr
South									
2.4	610	670	-	36	43	-	48	71	-
5.6	580	570	580	15	16	9	28	26	24
11.2	540	540	580	21	20	5	5	4	3
24	450	350	340	10	10	10	3	2	2
49.6	400	280	290	0[2]	7	10	2	3	3
Southwest									
2.4	670	560	560	1	1	0[2]	11	10	8
8.3	470	420	480	0[2]	0[2]	0[2]	7	7	5
21.9	420	430	200	0[2]	0[2]	1	6	5	4
41.8	480	400	400	0[2]	0[2]	0[2]	3	3	2
105.8	290	260	300	0[2]	0[2]	0[2]	3	1	2
North & Northwest									
2.4	610	540	440	5	5	2	44	39	39
8	390	430	350	17	21	15	6	5	6
17.3	400	420	410	8	11	10	3	2	2
32	360	350	350	0[2]	2	1	0[2]	0[2]	0[2]

[1] Age of needles

[2] Less than detection limit of instrument

- Sample material not present on site

Table 4. Pollutant contents (ppm) of corticolous lichens and ground bryophytes near Thompson

Direction & Distance (km) from stack	Corticolous lichens		Ground bryophytes		
	Nickel	Copper	Sulphur	Nickel	Copper
South					
2.4	560	236	1080	2038	289
5.6	310	118	1010	1348	215
11.2	230	61	1230	727	97
24	160	26	1170	154	27
49.6	80	13	230[1]	33[1]	5[1]
Southwest					
2.4	160	50	1270	1139	132
8.3	110	34	1220	284	36
21.9	90	25	1450	71	20
41.8	40	12	1070	50	10
105.8	20	7	900	12	5
North and Northwest					
2.4	350	123	1740	318	106
8	190	42	1350	357	64
17.3	90	16	1070	130	21
32	60	10	750	49	9

[1] Sample included ground lichens

Table 5. Pollutant contents (ppm) of snow collected near Thompson, December 18, 1974[1]

km (miles) S.E. of smelter stack	Nickel	Copper	Zinc	Arsenic	Selenium	Sulphur	Nitrate
1.6 (1.0)	9.27	6.08	.04	.02	.002	8.13	.25
2.4 (1.5)	2.49	2.09	.02	<.01[2]	.002	2.81	.23
5.6 (3.5)	.26	.18	.04	<.01	.001	.95	.25
8.5 (5.0)	.38	.09	.01	<.01	<.001[2]	.78	.30

[1] Data previously reported in Supplement to NOR-X-115 which was not included in the first two printings.

[2] Less than the detection limit of instrument.

Note: Cadmium and lead were sought but not detected in snow. If present they would be less than .01 and .3 ppm respectively, the detection limits of the instrument.

Table 6. Arsenic (ppm) in foliage, litter, and soil sampled around Thompson in August 1974[1]

Location km (miles)	Jack pine foliage (1-yr-old needles)	Soil surface litter (LFH horizon)	Mineral soil (A horizon)
S. of smelter			
2.4 (1.5)	8.0	29.0	.60
5.6 (3.5)	2.0	13.0	.31
11 (7)	.9	6.0	.39
24 (15)	.4	1.6	.34
50 (31)	.2	1.4	.27
SW. of smelter			
1.6 (1)	not sampled	51.0	.50
4.8 (3)		17.0	.34
11 (7)		6.0	.32
24 (15)		2.3	.18
45 (28)		1.6	.22
N. of smelter			
2.4 (1.5)		9.6	.29
8.0 (5)		3.0	.32

[1] Data previously reported in Supplement to NOR-X-115 which was not included in the first two printings.

The content of sulphur, nickel, and copper in jack pine foliage exhibited a similar but less pronounced trend of decreasing concentration with distance away from the stack (Table 3). This trend appeared to be independent of the age of foliage, when analyzed separately (Table 3). The same concentration gradient was more pronounced in the pollutant content of ground bryophytes and corticolous lichens (Table 4), and was also evident in snow (Table 5).

Significant arsenic was present in jack pine foliage and in the soil organic matter. Concentrations were higher on sites closer to the stack than on distant sites (Table 6), and were closely correlated between vegetation and soil.

DISCUSSION AND CONCLUSIONS

The forest decline around Thompson was related in our earlier report (Blauel and Hocking 1974) to cumulative effects of the smelter emissions. Examination of annual survey data indicated that the level of injury had developed progressively during the entire period of smelter operations, starting with initial signs recorded only 2 years after operations started (op. cit.).

Data in the present report show that pollutant accumulation is steadily increasing and that the associated forest injuries are also continuing.

Pollutant-sensitive epiphytic lichens have disappeared from sites near the smelter and are in depauperate condition at sites up to 11 km distant. That they were formerly abundant is evident from comparisons with ecologically similar sites* distant from the smelter, and from the dead remnants at nearer sites. Likewise, the ground lichens and bryophytes show evidence of severe stress. These degradations to the lichen and bryophyte communities have been correlated elsewhere with severe long term sulphur dioxide contaminations (Gilbert 1970; Vick and Bevan 1976).

* Similarity factors are aspect, soil moisture, tree and plant species composition, and stand density.

Pollutant accumulation in the area is steadily increasing. Levels of nickel in the soil surface organic matter are similar to those found near Sudbury by Hutchinson and Whitby (1974) (Fig. 5), where vegetative decline and erosion are well advanced. There are indications that the surface contamination at Thompson is being moved into the upper A mineral soil (Table 2), although not yet being leached into the deeper zones.

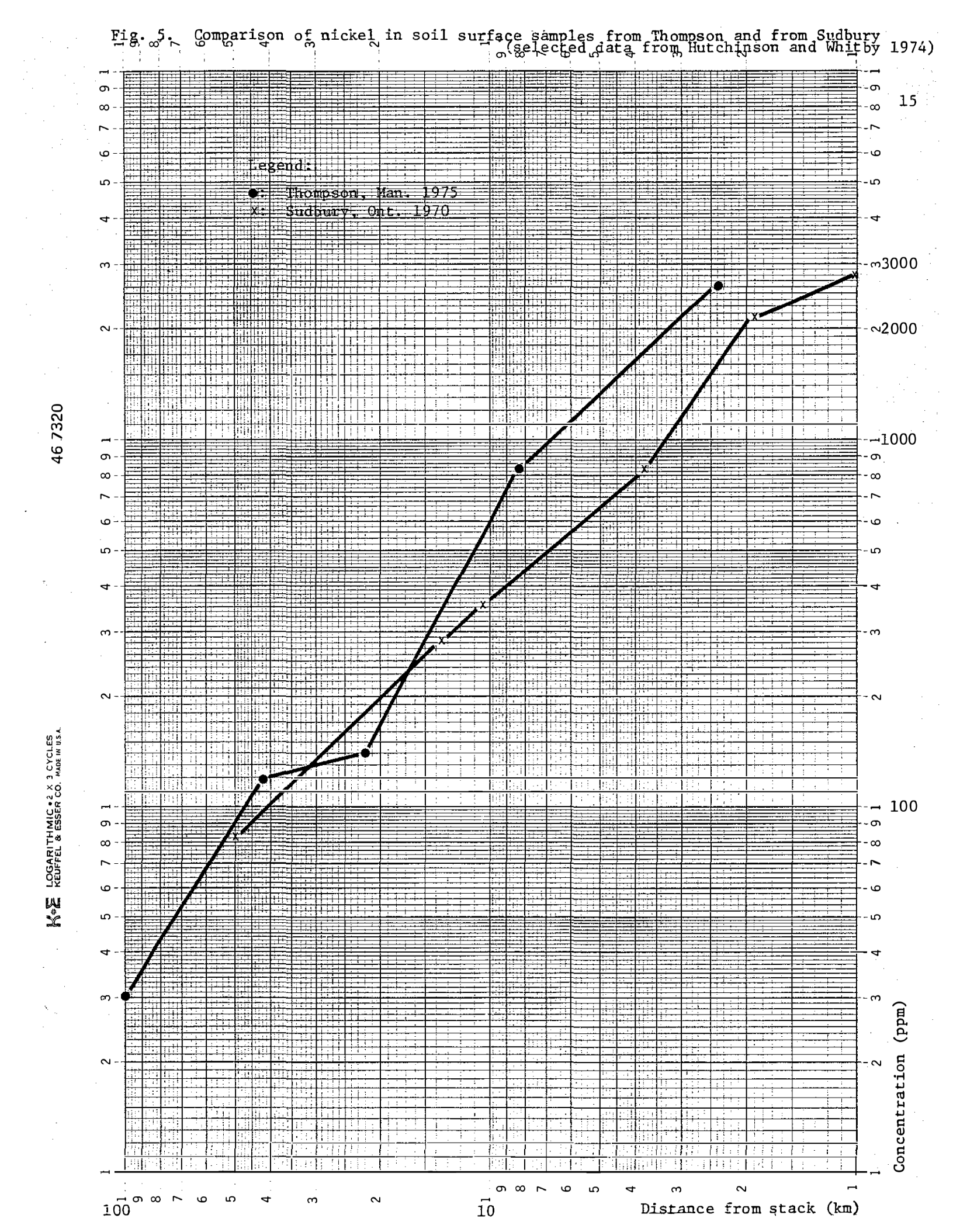
Also, a strong gradient of accumulated copper was found in the soil surface organic matter. Nickel and copper acting together have synergistic effects; that is, their joint toxicity is greater than the sum of their separate toxicities (Hutchinson 1973). The widespread distribution of these two elements is indicative of similar widespread distribution of the other particulate emissions, probably in the proportions indicated by INCO's release figure (Table 1). We have confirmed the presence of one of these: arsenic, an element known for serious effects on animals feeding near a smelter (Harkins and Swain 1908). Entry of many of these elements into the soil chemical and biological cycles initiates major site degradation, because they cannot be neutralized or removed easily (Bowen 1975).

The contamination already present near the smelter is sufficient to seriously inhibit plant growth if the contaminants become available to the plants (Whitby and Hutchinson 1974). In these areas, widespread mortality is evident among the ground cryptogams, which constitute about half of the normal ground cover. These species are important to the stability of the ecosystem because they contribute to soil formation and because their removal renders the soil more susceptible to erosion.

High contamination of soil with heavy metals is also likely to affect the activities of microorganisms (Somers 1961; Hartman 1974; Jordan and Lechevalier 1975; Gingell *et al*. 1976) known to be crucial to the recycling and replenishment of soil nutrients vital to forest ecosystem health and productivity.

There is considerable evidence of the longevity of contamination by heavy metals. Bowen (1975) indicates that heavy metals in most

Fig. 5. Comparison of nickel in soil surface samples from Thompson and from Sudbury (selected data from Hutchinson and Whitby 1974)



soils will be present as humates or fulvates. In most forest soils, fulvic acids predominate; heavy metal fulvates have an estimated half life of 50-500 years, less than that of humates (1400 years). Soil acidity has an important bearing on mobility of heavy metals, and acidity is strongly affected by sulphur dioxide, a usual component of smelter emissions. However, in a rare instance of metal pollution in the absence of sulphur dioxide, Tyler (1975) describes forest decline attributed to particulate contamination arising from a brass mill in operation for 300 years.

Similarly research on sewage sludge contaminated with zinc, nickel, copper, and other heavy metals has resulted in strong recommendations to avoid application or disposal of the sludge on agricultural land because of serious adverse effects on crop plants due to the heavy metals. Continued application of these sludges in some areas has resulted in long-term metal contamination of the soil (Le Riche 1968, Chumbley 1971, Swanwick and O'Gorman 1973, Bolton 1975, Mackenzie and Purves 1975).

Persistent problems in attempts to revegetate soils contaminated by smelter-released air pollutants have been attributed to the presence of heavy metals (Gemmell 1975, Whitby 1975), which requires novel and heroic measures (Weston et al. 1965) such as burying the contaminated layer under several feet of clean soil. At Ducktown, Tennessee, vegetation recovery was minimal 70 years after contamination (Hutchinson and Whitby 1974). Buchauer (1973) has reported extensive vegetation injury owing more to metal contamination than to sulphur dioxide near zinc smelters at Palmerton, Pennsylvania. In other parts of the world, soil contamination by metals and resulting persistent vegetation injury have been reported in Yugoslavia (Djuric et al. 1973), Poland (Gresta and Godzik 1969), Japan (Usui and Suzuki (1973), Sweden (Rühling and Tyler 1969), and Britain (Roberts 1972; Roberts and Goodman 1974). Many other cases could be cited. The trend is clear: wherever uncontained smelter emissions have occurred, they have been associated with extensive and persistent vegetation injury and soil degradation.

At Thompson, degradation has not yet progressed very far". Soil surface contamination to levels resembling those that have led to persistent problems elsewhere extends at Thompson to a distance of only 2-5 km from the smokestack. The installation of containment measures now could prevent or at least greatly retard further degradation. But to ensure this, both particulates and sulphur dioxide will need to be contained. Continued large-scale sulphur dioxide emissions will expand the area of depletion of ground cryptogams, leading to soil instability. The present high levels of sulphur dioxide emissions could, through acidification, mobilize metals already present in the soil surface organic matter, rapidly carrying them into plant rooting zones (Whitby 1974). In fact, the rate of acidification by sulphur dioxide could be enhanced by reducing only the particulate load, because many metal oxides are either amphoteric or basic and help to neutralize the sulphur dioxide (Buchauer 1973). Also, death of ground lichens and bryophytes, generally sensitive to sulphur dioxide, leads to disintegration through oxidation of the organic layer presently chelating the heavy metals at the soil surface.

In conclusion, the Thompson area displays all indications of progressive forest decline and soil degradation through cumulative contamination with heavy metals. Elsewhere, this has always led to extensive and persistent devastation. If emissions continue unabated, such effects can be anticipated for the Thompson area.

ACKNOWLEDGMENTS

The authors wish to thank the Manitoba Department of Mines, Resources and Environmental Management for logistical support, and the technical staff of the Northern Forest Research Centre for their many valuable contributions.

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