Rock-outcrop ecosystems as influenced by point-source pollution from a base-metal smelter, Flin Flon, Manitoba

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Abstract: Some impacts of atmospheric pollutants emanating from the Hudson Bay Mining and Smelting Company base metal (copper and zinc) smelter in Flin Flon were examined. Ten ridge-crest study sites were selected on PreCambrian rock outcrops along a 37.5 km southeast transect downwind to Cranberry Portage to reflect decreasing alteration of the jack pine/cryptogam cover. In addition, two control sites were selected at 33.2 and 47.3 km east-northeast of Flin Flon at locations where no detectable modifications to ridge-crest ecosystems were observed. At each study site tree and cryptogam covers were evaluated, and the thin organic layers (Folisols) and mineral soils were sampled to determine pollution impacts and Cu and Zn contents. Mean values for mineral-soil Cu were 32.8 ppm at 37.5 km from the smelter and increased exponentially to 3,683 ppm at 4.7 km. Equivalent mineral-soil Zn values were 273 ppm at 37.5 km and 6,088 ppm at 1.65 km. For organic soils Cu increased from 43 ppm at 37.5 km to 4,833 ppm at 4.7 km, while Zn values were 352 ppm at 37.5 km increasing to 11,464 ppm at 4.7 km. Paralleling this base-metal gradient are measurable impacts to the jack pine/cryptogam/Folisol ridge-crest ecosystems which range from little impact near Cranberry Portage to the almost complete loss of both the organic soil and vascular plants, and the total demise of cryptogams, close to the smelter.

Key words: pollution, cryptogams, ridge-crests, Folisols, base metals

Introduction

The impacts of point-source atmospheric pollutants from smelters operating in the boreal forest on the Canadian Shield have been the focus of numerous studies. These include, for the Sudbury, Ontario region, Gignac and Beckett (1986), Amiro and Courtin (1981), and Whitby *et al*. (1976). For Thompson, Manitoba; Hocking and Blauel (1977), and for Flin Flon; Henderson *et al*. (1998), McMartin *et al*. (1999), Henderson and McMartin (1995), Zoltai (1988), Hogan and Wotton (1984), Orlandini (1998), Scott (2000), and Wright *et al*. (1996). While these studies report evidence of damage and soil pollutant level increases, their conclusions vary as to direct impacts on soil-vegetation systems. There is, however, general agreement that cryptogams (lichens and mosses) as well as conifers are highly impacted, and that SO_2 fumigation and base metals often reach phytotoxic levels in soils close to smelters and contribute significantly to cover demise. The great majority of these studies concentrate on forested cover changes on lower elevation minerals soils and wetlands/peatlands, while few deal specifically with impacts to the upper portions of shield outcrops with their cryptogams, Folisols (thin organic soils overlying bedrock) and open pine/spruce cover (Whitby *et al*. 1976; Scott 2000). The present study addresses impacts to ridge-crest ecosystems in the vicinity of the Hudson Bay Mining and Smelting Company (HBMS) Cu-Zn smelter in Flin Flon. The three objectives are: 1) to estimate the degree to which Folisols have been altered; 2) to estimate changes in cryptogam and tree cover with distance from the smelter; and, 3) to see if ridge-crest soils show phytotoxic levels of Cu and Zn as the smelter is approached.

The Study Region

Flin Flon is located on the Saskatchewan/Manitoba boundary at 54° 45' N (Figure 1) on PreCambrian granitic and metavolcanic rocks containing sulphide ore bodies rich in non-ferrous metals. HBMS began smelting in 1930, with atmospheric emissions of gaseous and particulate pollutants being released from a single 30 m tall stack. This was replaced in 1974 by a 251 m stack. In addition to SO_2, Zn, Cu and Cd, emissions include As, Ni, Fe, Pb, Al-oxide and Hg, with dry and wet base metal fallout taking the form of metal particulate, metal oxide and metal sulfates (Franzin *et al.* 1979). Emissions levels for SO_2 have always been high, but the addition of electrostatic precipitators in 1982 has reduced particulate emissions considerably. Between 1981 and 1985 particulate pollution ranged between 11.5 and 43.4 tonnes per day, while in the 1996, 202,032 tonnes of SO_2 were released (Krawchuk 1998). The overall history of pollution has lead to tree and groundcover mortality on ridges, and to some extent on lowlands around the smelter. In addition, studies by Zoltai (1988) show an oval pattern of decreasing base metal contaminated lowland organic soils centred on Flin Flon, with a general northwest to southeast axis.

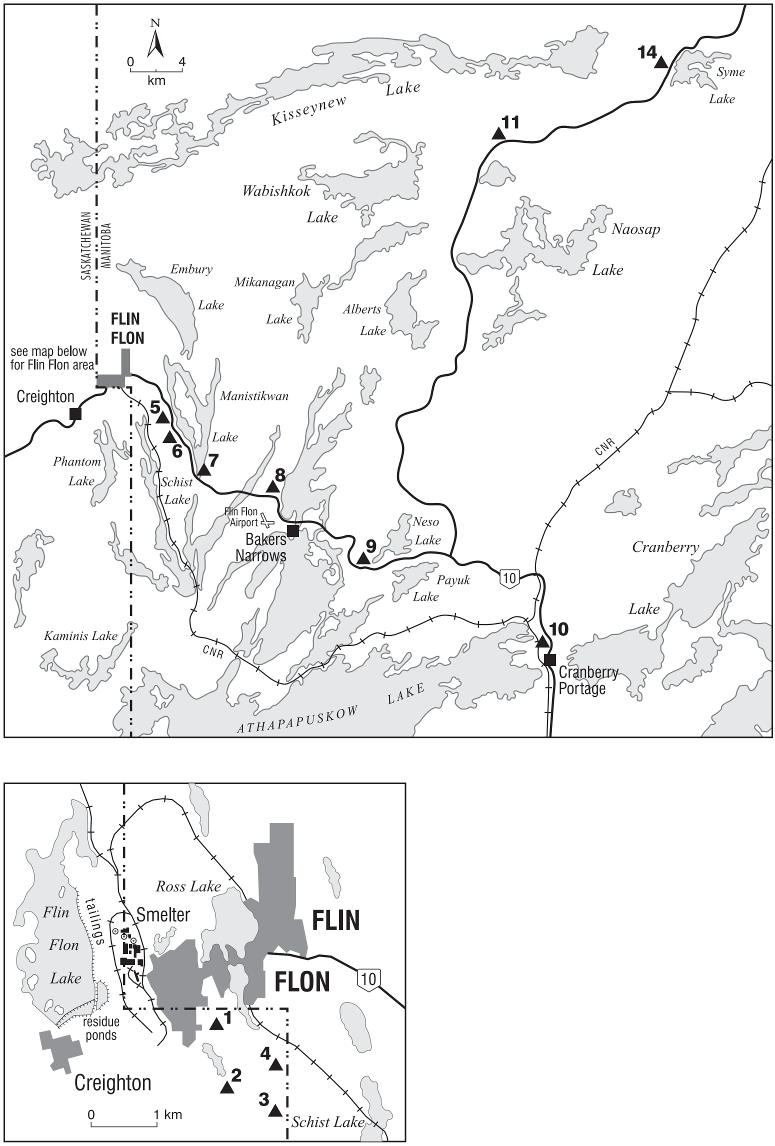

Figure 1: *Location of study sites near Flin Flon, Manitoba.*

Shield-bedrock outcrops form low rolling hills with glacially scoured crests that have been scratched relatively clean of any regolith. Intervening depressions are filled with discontinuous Quaternary tills, glaciolacustrine sediments, peats, alluvial deposits and numerous lakes. South of Cranberry Portage bedrock consists of Ordovician carbonate rocks completely buried by till and outwash. Undisturbed ridge crests include soil-free areas (with terricolous cryptogam cover) and thin Folisol-like organic profiles developed from accumulations of dead cryptogams together with some conifer and herbaceous residues. These Folisols are protected from erosion by the living cryptogam cover and provide an acidic substrate sufficient to support scattered jack pine *(Pinus banksiana*), and occasionally black spruce (*Picea mariana*). While soil acidity might be expected to increase as the smelter is approached, Hogan and Wotton (1984) found this not to be the case for lowland mineral soils and Scott (2000) found the same for ridge-crests.

Non-impacted lower slope and lowland forests are typical of the mixed-woods section of the Sub-humid Mid-Boreal Ecoclimatic Region (Scott 1995). Lowland peat cover consists of *Sphagnum* moss, tamarack (*Larix laricina*) and black spruce on Mesisols and Fibrisols. Where the landscape is gently rolling mineral soils such as Dystric Brunisols and Gleysols are found with covers of white spruce (*P. glauca*), birch (*Betula paparifera*), aspen (*Populus tremuloides*) and black poplar (*P. balsamifera*), and with a terricolous cover of lichens, especially *Cladina stellaris, C. mitis* and *C. rangiferina,* in open areas and feather mosses (*Pleurozium* spp.) under shade. In both these forest types epiphytic lichens on trunks and branches (*Usnea hirta, Evernia mesomorpha* and *Bryoria* sp.) and basal skirts of moss (*Pylaisiella polyaritha*) are the norm, while close to Flin Flon, all of these epiphytic species are missing, even in otherwise apparently healthy tree cover. Longton (1985) reports that the feathermoss *Pleurozium schreberi* is missing on shaded forest floors up to 15 km southeast of the smelter. On ridge crests not disturbed by pollution, cover consists of cryptogams overlying bedrock, and scattered jack pine, shrubs, herbaceous plants and cryptogams on thin acidic Folisols overlying bedrock. Such sites are particularly susceptible to soil moisture stress so aridity and windthrow take their toll on maturing pine. Occasionally these ridge-crest communities are burned off by lightning or human-induced fire, but immediately initiate the regeneration of a Folisol through a general crustose, foliose and fruticose lichen succession. Closer to the smelter all of these components are missing or severely damaged as the death of the cryptogams leads to the drying-out and erosion of the thin

Folisols, and regeneration of a lichen succession/Folisol is problematic. It is important to note that McMartin *et al*. (1999) have determined background soil base metal contents at >50 km from the smelter to be 21 ppm for Cu and 106 ppm for zinc. Phytotoxic levels for soil Cu and Zn were determined elsewhere by Linzon (1978) to be 100 ppm for Cu and 400 ppm for Zn.

Methods and Materials

Study site selection:

Following a preliminary reconnaissance between Flin Flon and Cranberry Portage, ten ridge-crest study sites were selected where conditions were considered similar in all respects except for pollution impacts (Figure 1). Crest-site selection was limited to five criteria: 1) conformity to the downwind pollution fallout pattern; 2) acidic bedrock; 3) past or present domination by cryptogams and open jack pine; 4) accessibility; and, 5) lack of disturbance by fire or other non-pollution anthropogenic impacts. No sites were selected southeast of Cranberry Portage due to carbonate bedrock and absence of outcrops. As the control site (# 10) at Cranberry Portage was later considered to exhibit minor pollution impacts, two additional control sites, #11 and #14, were selected 33.2 and 47.3 km respectively northeast of Flin Flon along the Sherridon Road. Here no pollution impacts were noted, and soil base metal contents approach background levels (Zoltai 1988). In addition, it was later determined that Site #4 was unsuitable due to human impacts so was not considered further. Study sites were surveyed in the summers of 1989, 1995 and 1996, with one additional visit in February, 1996.

Soil sampling:

At each ridge-crest study site the area covered by soil and non-soil was determined. While the Canadian System of Soil Classification (Soil Classification Working Group 1998) requires an organic layer (LF) overlying bedrock to be at least 10 cm thick to qualify as a Folisol, this study used a value of only one centimetre because here such a layer was not only capable of supporting fruticose lichen but often contained many living jack pine roots as well. Areas with either crustose or foliose lichen rarely were underlain by soil so were generally classified as non-soil together with truly bare rock. Often Folisols were much deeper than 1 cm and if jack pine is present these Folisols were completely permeated by a thick root mass. Some Folisols in depressions had shallow mineral regolith below them, and closer to the smelter most Folisols were missing so the only 'soils' available were mineral deposits in small depressions or rock fissures. At each site eight samples were collected randomly in a 10x10 m quadrat (excluding non-soil areas), however, at the almost-bare sites nearer the smelter sampling was subjective. Because of these conditions most ridge-crest soil samples close to the smelter were mineral, while at distances of over 6 km, most were organic.

Soil chemical and statistical analyses:

Soil samples were immediately air dried, and on return to the laboratory the organic samples had particles such as needles, wood and living lichen pieces removed before being ground, and then all samples were sieved through a 2 mm mesh sieve. Sub-samples were tested for organic matter content using the 'loss on ignition' technique (Carter 1993) and were classified as organic if they contained more than 30% organic matter. Sub-samples were leached of their base metals using EDTA-Extraction (Carter 1993) and Cu and Zn contents in ppm determined using Atomic Absorption Spectrophotometry (Model 1L151, Instrumentation Laboratory Inc., Wilmington, Mass.). Base metal data were analyzed by the Pearson Product Correlation Coefficient Analysis to determine the presence of positive or negative relationships. In addition, linear regression was used to determine the relation between Cu and Zn with distance, and an exponential regression analysis was performed using $\log_{10}$ metal concentration versus distance.

Vegetation sampling:

Each site was surveyed using three nested quadrats. Cover tree canopy, tree deadfall, shrubs and herbaceous species, were determined using the Braun-Blanquet Cover Scale in 20x20 m quadrats (Mueller-Dombois and Ellenberg 1974). For total cryptogam cover (both lichen and moss), the same 10x10 m quadrats used for soil studies were surveyed and cryptogams mapped using a grid layout, and percent cover determined from these maps. To differentiate between moss and crustose, foliose and fruticose lichen cover, five 2x2 m quadrats were selected randomly within the 10x10 m quadrat and mapped for each of these cryptogam groups.

Results

Soil and vegetation cover:

It is evident that close to the smelter there is an almost total absence of soil cover, and that the only remaining soil is regolith in rock fissures and the occasional small depression filled with eroded organic matter (Figure 2 and Table 1). At Site # 5, 6.3 km from the smelter, destruction of Folisols is less complete but >80% of outcrops are still without any soil cover. What pockets of Folisols remain support the occasional jack pine, and soil and non-soil areas have some lichen cover. By 10.4 km (Site # 7) pockets of eroded organic matter and intact Folisols cover some 30% of ridge crests, with only the occasional surface mineral layer. Here soil and non-soil areas are better covered by crustose lichens, and they share ridge-crests with some foliose and fruticose forms. By Site # 9 (23.9 km) a more typical boreal outcrop community is in place with 45% soil cover (primarily Folisols), 90% plant cover (mostly cryptogams), and a 30% tree canopy cover. The significant increase in plant cover is not due to tree canopy but to the presence of cryptogams on Folisols, and on bedrock. Differences between cover at Site # 10, and the two controls (# 11 and #

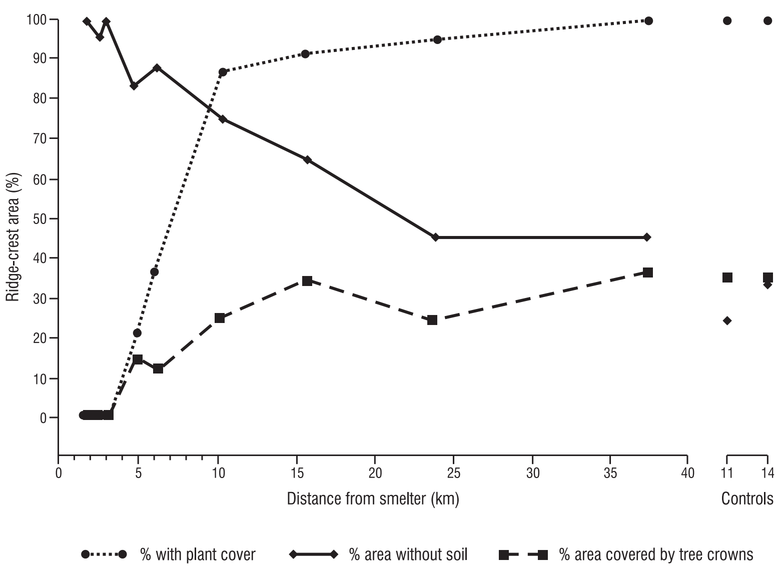

__Figure 2:__ Changes in soil and plant cover with distance southeast of the Flin Flon smelter.

Table 1: *Mean values for Cu and Zn for organic and mineral ridge-crest soils.*

		Copper ppm (means)			Zinc ppm (means)		
Site #	km to smelter	all samples	organic samples	mineral samples	all samples	organic samples	mineral samples
1	1.65	1126 (8) [1]	- (0)	1126 (8)	6089	-	6089
2	2.45	627 (8)	724 (1)	614 (7)	770	720	777
3	3.00	833 (7)	1156 (4)	644 (4)	992	1072	637
5	4.70	1689 (8)	4833 (2)	3683 (6)	3833	11465	1290
6	6.35	1963 (8)	2145 (7)	687 (1)	6670	7157	3264
7	10.40	1172 (8)	1247 (7)	686 (1)	5808	6292	2414
8	15.70	356 (8)	462 (6)	39 (2)	1502	1939	190
9	23.90	163 (8)	162 (7)	170 (1)	1135	1139	1104
10	37.50	40 (8)	43 (6)	33 (2)	332	352	273
11	33.20	21 (8)	12 (4)	29 (4)	139	121	157
14	47.30	19 (7)	19 (8)	- (0)	130	130	-

[1] Number of soil samples used is given in parentheses

14), are modest except that Folisols cover a larger percentage of the outcrops.

Figure 3 summarizes variations in cover within the cryptogam communities on those portions of ridge-crests that have no soil cover. Mosses only become a significant component of the cover by 23 km, and even at the controls they constitute less than 10% cover and are found under partial shade. Within the lichen community a distinct trend is seen where all types are absent close to the smelter but with crustose forms taking on a significant component beyond 5 km. Of interest is that up to 10 km, only crustose lichens such as *Candelariella vitellina, Rhizocarpon geographicum* and *Aspicilia cinerea* are detected in any numbers, and they are found more frequently overlying bedrock than on Folisols. Between 10.4 and 15.7 km (Sites # 7 and # 8) the trend is for crustose lichen cover to show a modest decline as foliose, and fruticose types take on significance. On little or non-impacted ridge-crests (Sites # 9 and # 10) typical foliose species include *Peltigera aphthosa, Umbilicaria torrefacta* and *Arctoparmelia centrifuga*, while fruticose species include *Sterocaulon alpinum, Cladonia bacillaris, C. carneola, C. squamosa, Cetraria nivalis*, and the three caribou lichen, *Cladina stellaris, C. mitis* and *C. rangiferina*. The only major difference between Site #10 and the two controls, Sites # 11 and # 14, is that fruticose lichens, especially the *Cladina* spp., increase significantly in cover, primarily at the expense of crustose types.

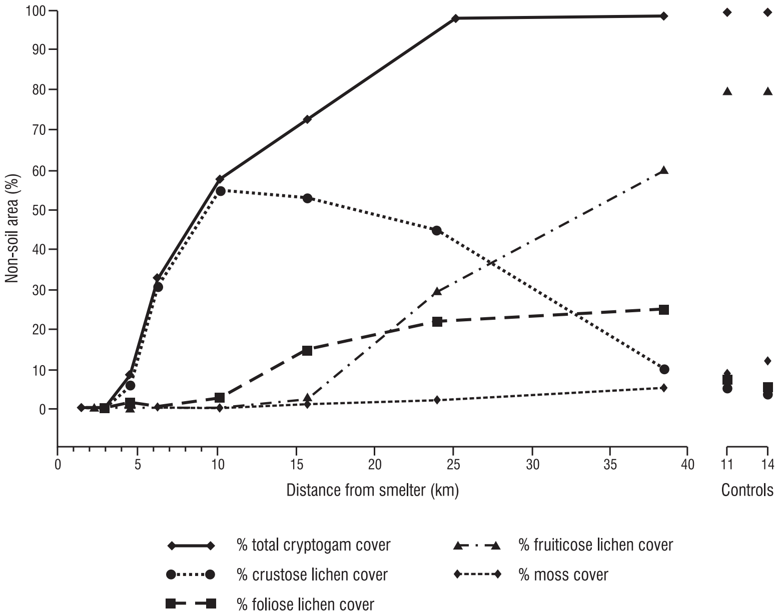

Figure 3: *Changes in cryptogam cover with distance southeast of the Flin Flon smelter.*

Soil copper and zinc levels:

Table 1 reports values for all soil-sample base metal contents from Site #10 to the smelter with maximum values being generally found at 4.7 to 6.35 km (Sites #5 and #6). The Pearson Product Correlation Coefficient Analysis for all soils between Sites #1 and #10 shows a significant correlation between Cu and distance, Zn and distance and between Cu and Zn with distance. For both Cu with distance and for Zn with distance, the relationship is shown to be negative log-linear (exponential) and significant at the 0.005 level. Analysis also showed a positive correlation between organic content and distance. Regressions were performed to determine the effects of differences in cation exchange capacity (CEC) that result from soils being either organic (higher CEC) or mineral (lower CEC). Figure 4 shows a log linear analysis for Cu from all soil samples with line of best fit for $\log_{10}$ copper (ppm) against distance (Table 2). Looking only at the organic-soil copper values against distance the Pearson Correlation Coefficient was significant at the 0.01 level, while linear analysis of Cu against distance shows a strong negative trend (at the 0.005

Table 2: *Linear regression analyses for log_{10} Cu and log_{10} Zn concentrations (ppm) against distance (km) from smelter to show exponential relationships between Sites # 1 and # 10.*

variable	base metal	r-value	r-square	t-test sample	t-value	confidence level	significant
All soil samples,	Cu	0.7375	0.5439	-9.072	-2.576	0.005	yes
sites #1 - #10	Zn	0.3976	0.1581	-3.599	-2.576	0.005	yes
Organic soils only,	Cu	0.9554	0.9128	-21.216	-2.576	0.005	yes
sites #1 - #10	Zn	0.8572	0.7348	-10.916	-2.576	0.005	yes
Mineral soils only,	Cu	0.6968	0.4855	-5.231	-2.576	0.005	yes
sites #1 - #10	Zn	0.4015	0.1612	-2.360	-2.576	0.005	no

significance level). Likewise for organic soils, Zn with distance and the association between Cu and Zu with distance were also significant. For mineral soils the Pearson Product Correlation with distance showed that the only significant relationship was between Cu and Zn.

Discussion and Conclusions

It is clear that together with the known influences of SO_2 fumigation (Longton 1985), phytotoxic levels from Cu and Zn may also play a significant role in ecosystem changes on ridge-crest sites downwind of the HBMS smelter in Flin Flon. Mean data from all soil samples at Site #10 are close to the upper background levels specified by McMartin *et al*. (1999). While Zn and Cu values are not above the phytotoxic threshold levels specified by Linzon (1978), it is possible that at Site #10 local variations in Cu and Zn, the possibility of toxicity by other pollutants, and other unknown variables, may account for the slightly lower fruticose lichen and Folisol cover here than at controls #11 and #14. At Site #9 the toxic threshold for Cu is barely exceeded while for Zn it is greatly exceeded, and for both Cu and Zn toxic levels are exceeded at all sites closer to the smelter.

Major differences are seen between the trends for Cu and Zn when organic and mineral soils are compared. For organic soils the strong correlation between distance and concentration is somewhat less dramatic than with previous lowland studies, but this is attributed to the fact that in the present study many sites were selected very close to the smelter while peak concentrations are found at approximately 5 km. Most mineral soils

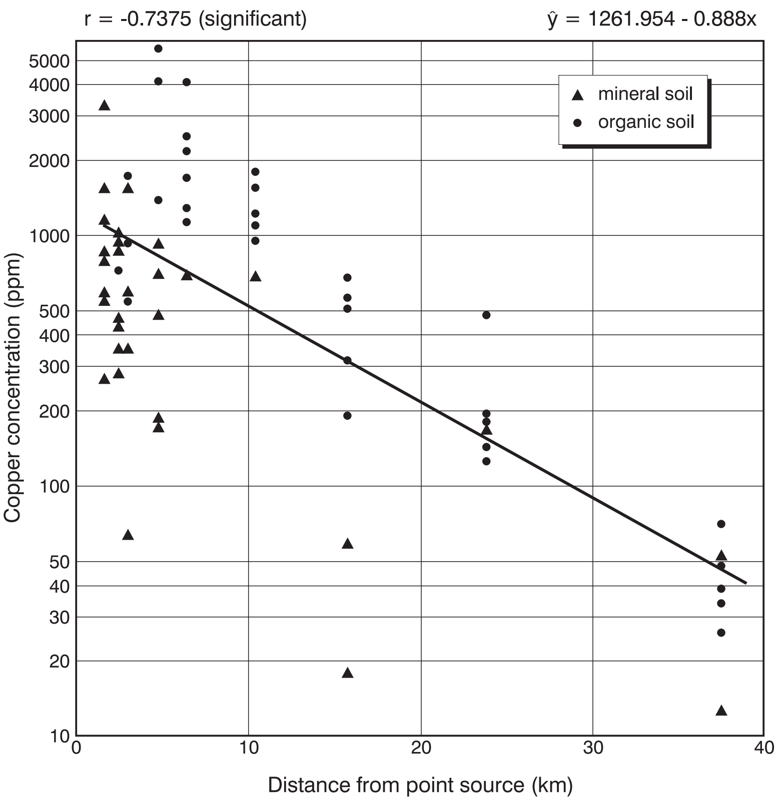

Figure 4: *Linear regressions for* log_{10} *Cu (ppm) versus distance for mineral and organic soil samples, Sites #1 to #10.*

are quite close to the smelter with only a few at greater distances, and they too show peak concentrations at about 5 km. They do not, however, show the exponential characteristics shown by Folisols.

Impacts to ridge-crest ecosystems support the conclusion that pollution has given rise to Folisol destruction as their protecting cover of living cryptogams is killed off, and that this is followed by their desiccation and removal by erosion. It is probable that much of the jack pine death between the smelter and Site #1 results from SO_2 fumigation, and direct heavy metal toxicity to trees and their symbiotic root mycorrhizae. However, occasional pine are still found in remnant pockets of organic material as close as Site # 5, and even closer to the smelter near Sites #3 and #2. Therefore, pine death beyond Site #1 is more likely the result of desiccation as they lose their water and nutrient-supplying Folisol. The fact that surviving pines have established extremely dense rooting systems to maximize use of the shrinking Folisol patches lends support to this conclusion. One intriguing observation is that following the loss of ridge Folisols some of the denuded rock at distances greater than 6 km regains some crustose lichen cover. While being speculative, it is possible that pollutant levels in the high CEC Folisols under well-developed fruticose lichens become very phytotoxic and can no longer support cryptogams, while levels from rainfall on bare rock are insufficient to prevent colonization by crustose lichens. Alterations to fallout patterns following stack elevation in 1974 would complicate this interpretation.

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References

AMIRO, B. and COURTIN, G. 1981 'Patterns of vegetation in the vicinity of an industrially disturbed ecosystem, Sudbury, Ontario' *Canadian Journal of Botany* 59, 1623-1639

CARTER, M. 1993 *Soil Sampling and Methods of Analysis* (Boca Raton, Fl.: Lewis Publishers)

FRANZIN, W., MCFARLANE, G. and LUTZ, A. 1979 'Atmospheric fallout in the vicinity of a base metal smelter at Flin Flon, Manitoba, Canada' *Environmental Science and Technology* 13, 1513-1522

GIGNAC, L.D. and BECKETT, P. 1986 'The effect of smelting operations on peatlands near Sudbury, Ontario, Canada' *Canadian Journal of Botany* 64, 1138-1147

HENDERSON, P., MCMARTIN, I., HALL, G., PERCIVAL, J. and WALKER, D. 1998 'The chemical and physical characteristics of heavy metal in humus and till in the vicinity of the base metal smelter at Flin Flon, Manitoba, Canada' *Environmental Geology* 34, 39-58

HENDERSON, P. and MCMARTIN, I. 1995 'Mercury distribution in humus and surficial sediments, Flin Flon, Manitoba, Canada' *Water, Air and Soil Pollution* 80, 1043-1046

HOCKING, D. and BLAUEL, R. 1977 *Progressive Heavy Metal Accumulation Associated with Forest Decline Near the Nickel Smelter at Thompson, Manitoba* Information Report NOR-X-169 (Edmonton: Northern Forest Research Centre)

HOGAN, G. and WOTTON, D. 1984 'Pollution distribution and effects in forests adjacent to smelters' *Journal of Environmental Quality* 13:3, 377-382

KRAWCHUK, B. 1998 *Manitoba Ambient Air Quality Annual Report for 1995 and 1996* Report No. 98-03 (Winnipeg: Manitoba Environment)

LINZON, S. 1978 *Phytotoxicology: Excessive Levels for Contaminants in Soil and Vegetation* (Toronto: Ministry of the Environment)

LONGTON, R. 1985 'Reproductive biology and susceptibility to air pollution in *Pleurozium schreberi* (Brid.) Mitt. (Musci) with particular reference to Manitoba, Canada' Monographs *of Systematic Botany of the Missouri Botanical Gardens* 11, 51-69

MCMARTIN, I., HENDERSON, P. and NIELSON 1999 'Impact of base metal smelter on the geochemistry of soils in the Flin Flon region, Manitoba and Saskatchewan' *Canadian Journal of Earth Science* 36, 141-160

MUELLER-DOMBOIS, D. and ELLENBERG, H. 1974 *Aims and Methods of Vegetation Ecology* (New York: Wiley)

ORLANDINI, R. 1998 *An Analysis of the Deposition of Zinc and Copper in Organic and Mineral Soils Found on Rock Outcrop Ridges Downwind of a Base Metal Smelter Located in Flin Flon, Manitoba* BSc Thesis, University of Winnipeg

SCOTT, G. 2000 'Soil acidity (pH) as influenced by point-source pollution from a base-metal smelter, Flin Flon, Manitoba' *Prairie Perspectives* 3, 97-110.

SCOTT, G. 1995 *Canada's Vegetation: A World Perspective* (Montréal: McGill-Queen's University Press)

SOIL CLASSIFICATION WORKING GROUP 1998 *The Canadian System of Soil Classification* (Ottawa: NTC Research Press)

WHITBY, L., STOKES, P., HUTCHINSON, T. and MYSLIK, G. 1976 'Ecological consequences of acidic and heavy-metal discharges from the Sudbury smelters' *Canadian Mineralogist* 14, 47-57

WRIGHT, R., ADKINS, A. and SCOTT, G. 1996 'Microbial diversity and activity in a Northern Stressed Ecosystem' *Manitoba Society of Soil Science Proceedings* (Winnipeg: Freshwater Institute) 159-170

ZOLTAI, S. 1988 'Distribution of base metals in peat near a smelter at Flin Flon, Manitoba' *Water, Air and Soil Pollution* 37: 217-228