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The Impact of Gold Smelter Emissions on Vegetation and Soils of a Sub-Arctic Forest-Tundra Transition Ecosystem

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Gold smelters near Yellowknife in Canada's Northwest Territories have emitted large quantities of sulfur dioxide and arsenic since inception of roasting in 1941. Although particulate wastes are well contained by baghouse filters in the one remaining operating smelter, significant gaseous emissions continue. Soil and vegetation were sampled at 52 sites over an area of about 40 km radius from the source. Plant ecology was studied at 43 of those sites. After preliminary multi-element screening that indicated only arsenic was a serious persistent contaminant, x-ray fluorescence was used to measure arsenic content in sampled materials. The plant ecology data were synthesized into an Index of Vitality with numerical ratings of pertinent factors. In the marginal forests and rocky outcrops of the area, indicator species of vegetation permitted a division into zones of severe, moderate, mild, or no impact in order of increasing distance from the current center of emissions. Severe impact, including killing of trees, is local only. Analyses of foliage indicate little uptake of arsenic which, together with the presence of SO_2 symptoms, point to SO_2 as the main factor causing decline of vegetation. A separate study, abstracted here, supports this view by providing data that show a frequency of at least 2 significant fumigation episodes per growing season. Soil analyses indicate extremely high arsenic contamination near the stack. A monotonic pattern of dispersion yielded a function explainable in terms of rapid condensation of gaseous emissions. The relationship of arsenic in surface soil and vegetation to distance is approximately an inverse square.

Gold was discovered near Yellowknife in the 1930's. The deposits currently mined contain gold finely divided in ore bodies high in arsenopyrite (FeAsS). This interferes with cyanide extraction of gold and is removed by roasting in air, which converts the arsenic and sulfur to arsenic trioxide (As_4O_6) and sulfur dioxide (SO_2). Roasting was introduced for a few months in 1941 and resumed continuously in 1948. The gaseous and particulate waste products were vented into the atmosphere through stacks on the properties of the Consolidated Mining and Smelting Company of Canada Ltd. (Con. Mine) and the Giant Yellowknife Gold Mines Ltd. (Giant Mine).

Con. Mine installed a wet scrubber system in 1949 with the aim of curbing the large scale dispersion of arsenic into the environment. The resulting arsenic-containing slurry is held in ponds whose arsenic content is about 20,000 long tons. Con. Mine ceased roasting in 1971, when a different separating system was adopted. Giant Mine installed a Cottrell precipitator in 1951 and a second precipitator in 1955. Increased milling and roasting took place in 1957 and a new roaster was installed in 1958. In the fall of the same year, particulate emissions were greatly reduced through installation of a bag house dust collector; the As_4O_6 dust removed by it is stored in sealed stopes, containing arsenic that we estimate as not less than 40,000 long tons. A further increase in roasting by Giant Mine took place in 1971.

Known and estimated total arsenic emissions for the period 1947–1974 are summarized in Table I, showing changes as-

Table I. Ground level[a] sulfur dioxide atmospheric concentration.

Year	Hours monitored	Hourly averages[b,c] >0.17 ppm	Maximum instantaneous level (ppm)
1973	4080	5	0.25
1974	6095	11	0.42
1975	7960	34	0.37

[a] Sampling intakes were at 3 meter level.
[b] During growing season (May – October).
[c] 0.17 ppm is the desirable maximum hourly average SO_2 concentration, Canadian Air Quality Objectives, and is a threshold level for injury to many plants.

sociated with expansion of roasting and installation of containment equipment. No containment measures have been attempted for the other major pollutant, SO_2, whose mass emissions have increased with each expansion of roasting and now average 37.7 long tons/day[1] at Giant Mine.

These considerable emissions have been implicated in several studies of environmental effects. A study of human health in the Yellowknife area found above average incidence of respiratory, psychoneurotic, and other disorders.[3] Another study[4] found that Giant Mine was discharging high levels of arsenic, copper, and zinc into Yellowknife Bay and that Con. Mine's effluent was affecting five inland lakes. Further studies confirmed contamination of Yellowknife Bay by seepage from Giant Mine property,[5] and of Kam Lake by overflows from the Con. Mine tailings pond.[6] Arsenic contamination of benthic organisms and fish in Kam Lake was reported.[7] A brief survey detected high contamination of soil, water, snow, and vegetation near Yellowknife with arsenic, antimony, mercury, and cobalt.[8] Human hair samples showed higher than normal mean values of arsenic and mercury.[8]

Table II. Arsenic (long tons) released into the air near Yellowknife.

Year	Giant Mine	Con. Mine[a]
1947	0	0
1948	0	388
1949	2600	678
1950	2600	75
1951	2600	80
1952	644[a]	50
1953	1156[a]	51
1954	1952	67
1955	1041	70
1956	977	68
1957	1066	65
1958	542	62
1959	19	70
1960	27	98
1961	54	116
1962	54	97
1963	54	79
1964	81	36
1965	61	60
1966	40	51
1967	20	51
1968	42	52
1969	76	54
1970	79	64
1971	315	0
1972	143	0
1973	145	0
1974	79	0
Total	16,467	2484[a]

[a] Data supplied by the company. Other data from Reference 2 (before 1970) or supplied as personal communication by Northwest Region, Environment Protection Service.

Public concern generated by the foregoing resulted in a further Yellowknife Environmental Survey by the Canadian Government, of which the present report is a part. Data for air monitoring are being reported elsewhere but indicate frequent episodes of SO_2 concentrations exceeding plant injury thresholds. A summary of the relevant concentration frequency data[2] are presented in Table II. Aquatic ecosystems were excluded from the present survey owing to lack of funds and an existing adequate data base consisting of the reports cited earlier and several additional studies.[9,11]

The effects of air pollution on vascular plants have been documented extensively.[12] In recent years there have also been many studies on the effects of air pollution on cryptogams,

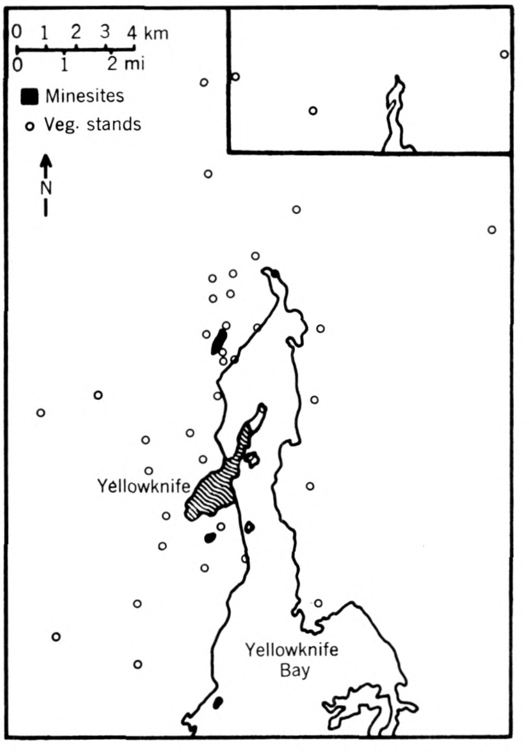

Figure 1. Locations of sampling sites in relation to minesites and Yellowknife town.

particularly corticolous lichens.[13–17] Conversely, degree of pollution may be inferred from study of lichens, using the principle that different lichens have different tolerance limits.[13–21] Characteristically, few lichens occur in polluted areas and the number of species increases with increasing distance from the pollution source. Toxitolerant species may increase in importance in polluted areas.[18,19]

Objectives of the present study were to survey the nature and extent of terrestrial contamination and effects on plant ecology resulting from the air pollution. The study area belongs to the Northwestern Transition section of the Boreal Forest Region, a huge zone of open sub-arctic woodland extending from Hudson's Bay almost to the Mackenzie Delta.[22] The Yellowknife area is a mosaic of forest, scrub, rocky outcrops, lakes, and clearings, with a complex history of fire and human activities that complicates analysis of air pollution effects. The upland vegetation is dominated by mostly young black and white spruce, paper birch, poplars, willows, and other shrubs; with a rich and complex understory of cryptogams, widely recognized as sensitive indicators of SO_2 pollution. Soils, where present, are generally shallow; about a third of the land area is bare rock.

Methods

The survey consisted of widespread sampling (52 sites, Figure 1) of vegetation and soils for determination of levels and patterns of contamination, and a study of plant ecology and condition in a forest stand and on a nearby rocky outcrop at 43 of the sites, selected to represent major effect parameters such as soil type, direction and distance from sources. These sites covered an area of about 40 km radius from Yellowknife. The most distant point, near Rae, was at the edge of the geological Precambrian Shield and hence the western limit imposed by geography. The southern limit was Great Slave Lake; the northern and eastern limits were the available access roads.

At each site, 4 one-quart samples of soil were taken from a photographed profile, (A0, A1, A2, and B horizons). Samples were also taken of willow browse (new growth only, selected because it is a favored browse for ungulates), black spruce (needles of previous year and, separately, twigs of previous year), rock lichens (green crustose species, growing on bare rock), and soil surface lichens (varying species depending on availability). Neither sampling pattern nor data were stratified for soil types, which were found to be similar across all sample sites.

On forested sites, percent cover of each individual plant species was estimated in three 1 m^2 quadrats and also in a 15 × 20 m plot. Density, height, and other basic ecological parameters were also included; plant condition was noted and photographed and trees were sampled for growth-ring counts and evidence of anomalies or discontinuities. On treeless rocky outcrops (generally about 15 × 15 m units with at least 50% surface rock), total percent cover was estimated for each plant species on bare rock (lithic) or organic (non-lithic) sections. Detailed notes were made of conditions, especially of the dominant lichens.

For analysis, soils were dried at low temperature, ground and screened to 2 mm. Vegetation was first washed, then either wet-ground and dried or dried and ground to 2 mm. Sub-samples of these were further ground for analysis. Check samples were prepared by spiking with known amounts of standard solutions, drying at low temperature and regrinding.

Preliminary multi-element screening of selected samples suggested that only arsenic was of paramount importance as a contaminant. Low level contamination by antimony and mercury was noted. Cobalt levels in samples were not correlated to distance from mine stacks.

Analyses for total arsenic were by x-ray fluorescence[24] on a 40 kV Philips unit. Molybdenum or tungsten tubes were used, and the fluorescent radiation detected with a scintillation counter with a (200) LiF monochromator system. Samples were pressed at 17.5 mg/cm^2 in cellulose to produce a sample disc of diameter 2.54 cm. Since under the measurement conditions the critical minimum depth for arsenic Kα radiation was exceeded by 0.5 g samples, a sample weight of about 1.0 g was always employed.

Since the matrices and hence absorption effects were different in each sample, each was spiked at an appropriate level with standard sodium arsenite solution as described above, dried at 80°C, and reground; the spiked and unspiked samples were analyzed together. Several standards were spiked at several levels, and plots of these results showed that the overall procedure was highly reliable when appropriate spiking levels were used. The observed detection limit was 20 ppm arsenic (dry weight basis); the 95% confidence limits are the greater of ± 10% or ± 5 ppm. The only interference noted was lead, whose Lα radiation is close to Kα for arsenic. Since in all samples of significant arsenic content the amount of lead is comparatively negligible, this intereference is not significant.

Results: Arsenic Contamination

Selected data for arsenic content are summarized in Table III. The combined soil surface (A0) and soil lichen data are 90% described by the empirical equation:

$$A = 1650/x^2 + 550/y^2 + 25$$

where A is arsenic contamination level (ppm), x is the distance (km) from the stack of Giant Mine and y is the distance (km) from the stack at Con. Mine, for a value of $0.25 < x$ and/or $y < 80+$. The distribution of arsenic contamination expressed in the best fit function is shown in plan and profile in Figures 2 and 3.

Table III. Arsenic contamination of lichens and soils near Yellowknife.

Sites				Arsenic content (ppm dry weight)				
				In Lichens		In Soils		
Distance (km) Giant	Bearing (°) Giant	Distance (km) Con.	Bearing (°) Con.	On Rock	On Soil	A0 Horizon	A1 Horizon	A2 Horizon
0.28	45	7.32	5	11438	N.D.[b]	21213	3383	N.D.
0.54	248	6.90	359	N.E.[a]	4556	2590	583	303
0.70	180	6.41	4	N.E.	5041	4311	1661	48
1.00	180	6.11	4	N.E.	682	735	250	422
1.04	343	8.10	1	1300	3583	3898	5579	1016
1.12	154	6.16	8	N.E.	1387	7001	1219	538
1.20	90	7.28	13	663	371	328	948	257
1.33	13	8.43	5	420	589	608	78	21
2.20	183	4.91	3	438	538	597	527	102
2.87	151	4.94	21	505	657	1314	N.D.	N.D.
4.30	168	3.18	24	306	701	1300	N.D.	N.D.
4.44	188	2.71	356	N.D.	N.D.	396	N.D.	N.D.
4.75	240	5.98	322	293	797	385	N.D.	N.D.
6.60	180	0.64	39	524	1360	1076	232	26
7.75	173	1.43	115	389	456	881	119	316
8.02	184	0.92	193	1008	1526	1800	430	6
8.42	356	15.50	359	128	330	636	N.D.	N.D.
45.23	284	47.08	292	30	38	21	N.D.	N.D.
75.77	289	78.02	294	20	12	10	N.D.	N.D.

[a]N.E. = non-existent at that site.
[b]N.D. = not determined.

The levels of arsenic in lichens on bare rock are generally similar to those in soil lichens as shown in Table II, but the distribution equation is somewhat different, probably owing to local terrain effects and absorption differences. Arsenic in spruce and willow foliage was below detection limits at all sites except immediately adjacent to the sources, where it was 30 ppm (dry weight basis).

Arsenic levels in soil near Con. Mine and Giant Mine decrease rapidly with depth (Table III, Figure 4). Depths of soil horizons varied greatly but were generally not more than a few cm.

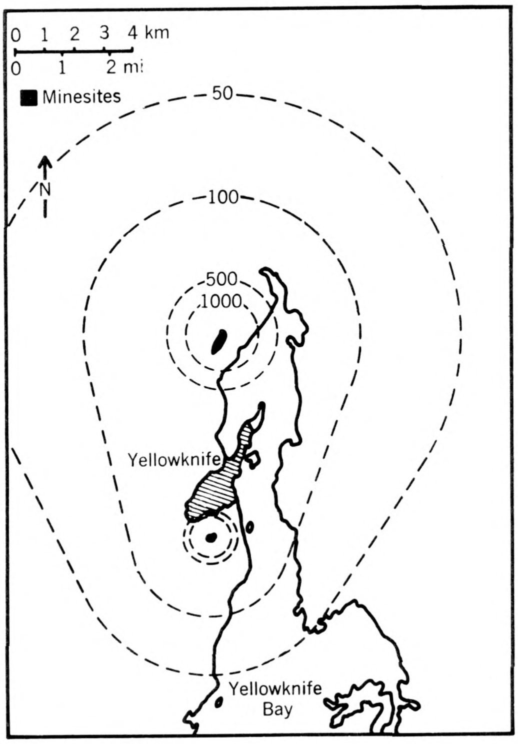

Figure 2. Arsenic contamination (ppm) in surface soils and lichens around Yellowknife.

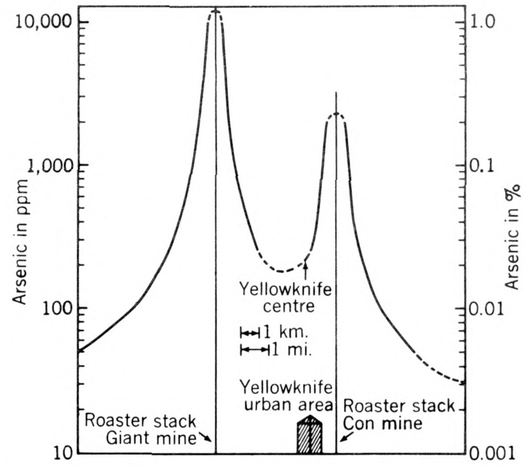

Figure 3. Profile of arsenic in surface soils and lichens around sources. Note logarithmic scale.

The condition of vegetation in the area may be viewed in four zones:

1. Beyond about 13 km E, 10+ km N, 20 km W and 12 km S of the Giant Mine, vegetation appears normal as evidenced by high % ground cover of the sensitive *Cladina* spp and *Cladonia amaourcraea*, and abundant epiphytic growth.
2. From zone (1) to 4 km N and E, 2 km S and SE, 1 km NE of the Giant smokestack and directly S and E of Yellowknife town, there is mild deterioration of vegetation.
3. From zone (2) to 1 km from the Giant stack, especially on higher outcrops, there is clear evidence suggestive of air pollution effects: epiphytic lichens totally absent, fruticose lichens stunted, epipetric lichen cover diminished and foliose thalli disintegrating.
4. Within 1 km of the stack, especially to the W and NW, there is drastic deterioration of both forest and outcrop vegetation. Trees and shrubs, the only remaining components, exhibit symptoms of SO_2 injury.

Plant Ecology Effects

The forest stands at the various sites were composed of at least 5 distinct community types defined by a standard diversity index. This heterogeneity made the data of little comparative value among sites for detecting air pollution effects, although distinct signs were noted on sites near the sources. Plant communities on the rocky outcrops were much more homogeneous across sites and hence more useful for comparing effects.

Familiarity with the mass of data gathered led to development of an "Index of Vitality," by the following steps:

1. Those community parameters having a wide range of values and a general disparity between distant and near stack stands were selected through two stages.
2. The factors were given 1–10 ratings based on abundance/presence/absence of species and their relative health.
3. The ratings were summed for each site to give the "Index of Vitality," where 0 = total death and 100 = absolute lack of stress symptoms.

Full numerical data for forest stands and rocky outcrops are deposited, along with photographs and specimens, at the Northern Forest Research Centre, Edmonton. The synthesized indices of vitality for all sites are shown in Table IV, in order of decreasing values of Index of Vitality and showing correlation with distance from Giant Mine stack.

Discussion and Conclusions

The magnitude and distribution of arsenic in the soil and vegetation of the Yellowknife area are quite unaccountable by natural processes and are fully consistent with attribution

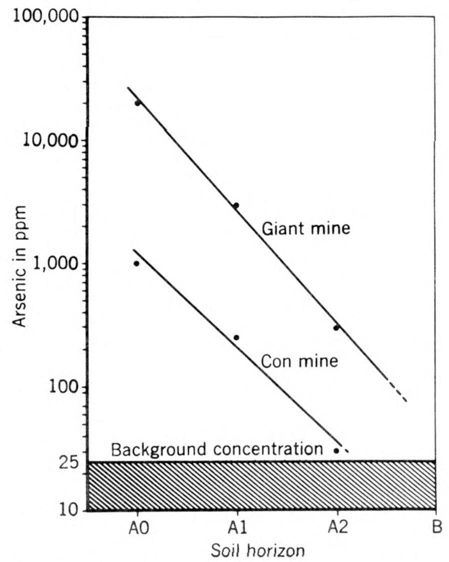

Figure 4. Typical profiles of arsenic concentration near mine sites.

Table IV. Indices of vitality for plant communities around Yellowknife.

Site No.[a]	Index of Vitality[b]	Site No.	Index of Vitality
50	3.2	39	43.6
40	9.5	3	45.3
10	11.3	25	49.6
51	12.1	42	52.7
2	13.0	1	53.1
52	14.8	29	54.9
27	18.2	28	55.5
31	22.6	22	56.1
8	23.9	20	57.8
46	25.5	30	58.1
33	29.7	9	58.5
23	29.9	24	64.2
45	30.7	15	65.2
48	33.8	41	66.2
37	35.8	21	66.3
26	37.3	19	70.7
49	38.6	38	75.5
7	40.7	14	87.1
32	41.1	17	96.5

[a] Sites listed in order of increasing distance from Giant Mine stack.
[b] See text for derivation of Index of Vitality; in essence, 100 = no signs of injury, 0 = all plants dead.

to the two gold smelters, Giant and Con. Mines. The distribution function computed from our data yields several important implications.

The arsenic contamination level in surface soils and vegetation due to smelters falls off roughly as the inverse square of the distance from the smelter in a monotonic pattern. The steepness of the profile indicates particulate fallout rather than gaseous dispersion, perhaps due to rapid condensation of As_4O_6 vapor. The contribution due to Con. Mine is about ⅓ of that due to Giant Mine. This differs from the ⅐ expected from the history of airborne emissions, which may indicate remobilization of arsenic from the slurry ponds at Con. Mine. The final term indicates a background level not higher and probably significantly lower than 25 ppm arsenic at 80+ km.

In the Yellowknife area, with its predominantly very young forest, the traditional study of epiphyte-pollution correlation was not readily feasible. Outcrop vegetation furnished most of the significant data. Outcrops are relatively undisturbed and stable, have an excellent cover and variety of pollution-sensitive plants (lichens), and are dry and elevated therefore relatively more susceptible to air pollution.

Severe deterioration of plant cover and community structure are local phenomena in the Yellowknife area. Only within 1 km of the Giant stack is there severe vegetational degradation, although mild signs and symptoms of pollution stress may be traced at least 25 km westward, in the form of gradually simplified community structure. However some of the most abundant lichens in the Yellowknife area, especially *Actinogyra muehlenbergii, Cladonia chlorophaea, Hypogymnia physodes,* and *Parmelia sulcata,* are reported as being relatively toxitolerant.[25]

It seems probable that the SO_2 emissions documented during the growing seasons have been primarily responsible for the depletion of lichens, since analysis of some living specimens indicated very high tolerance for arsenic, the only other major contaminant. But it is not possible to state definitely the relative contributions of the arsenic or other trace pollutants, nor of other forms of disturbance in the area's complex history of fires and clearing.

In summary, our study has found a deteriorating vegetative ecology around the pollutant sources and a massive local contamination with arsenic.

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