AIR POLLUTION AND FOREST DECLINE NEAR A NICKEL SMELTER

THE THOMPSON, MANITOBA SMOKE EASEMENT SURVEY 1972-74

BY

R.A. BLAUEL AND D. HOCKING

INFORMATION REPORT NOR-X-115
OCTOBER, 1974

NORTHERN FOREST RESEARCH CENTRE
CANADIAN FORESTRY SERVICE
ENVIRONMENT CANADA
5320 - 122 STREET
EDMONTON, ALBERTA
T6H 3S5

Air Pollution and Forest Decline Near a Nickel Smelter

by

R. A. Blauel and D. Hocking

Northern Forest Research Centre, Canadian Forestry Service

Department of the Environment, Edmonton, Alberta

SUMMARY

Large quantities of sulphur dioxide and particulate matter are being released from a high stack near Thompson as a means of smelter waste disposal. Atmospheric dispersal of these pollutants has resulted in over 50 square miles of patchy forest decline. All components of the forest vegetation exhibit effects of direct pollutant deposition. Impacts range from patches of tree decline and mortality through to general depletion of sensitive cryptogams. This decline will intensify and the area of decline will expand under current pollutant emission rates.

Contamination of soil organic matter has been detected over a much greater area. Levels of sulphur and nickel are highly elevated near the smokestack and decrease with distance from it.

Nickel and possibly other heavy metals are building up to toxic levels which will be impossible to correct economically. This represents a high potential for severe site degradation as a further outcome to aerial dispersal and dilution of the smelter wastes.

RESUME

Près de Thompson, une haute cheminée laisse fumer de grandes quantités de bioxide de souffre et de particules, déchets d'une fonderie. Ces matières polluantes se dispersent dans l'atmosphère et plus de 50 milles carrés de forêts sont partiellement affectées. Toutes les parties de la végétation forestière souffrent directement de la déposition de ces matières. On voit çà et là des groupes d'arbres qui périclitent ou meurent, ou bien la déplétion générale des sensibles cryptogames. Le taux de pollution augmentera vu que l'émission de matière polluante a été augmentée.

La contamination de la matière organique du sol se trouve sur une superficie beaucoup plus vaste. Les quantités de souffre et de nickel sont très élevées près de la cheminée et elles diminuent à mesure que l'on s'en éloigne.

Le niveau de toxicité du nickel et possiblement d'autres métaux lourds augmente à un tel rythme que l'on ne pourra plus les enlever économiquement. La forêt est susceptible de se dégrader encore plus fortement.

CONTENTS

	PAGE
LIST OF FIGURES	ii
LIST OF TABLES	iv
1. INTRODUCTION	1
2. BACKGROUND	1
2.1 Air pollutants released	3
2.2 Plume characteristics	5
2.3 Wind speed and direction	5
3. METHODS	5
3.1 Aerial surveys and photography	5
3.2 Ground examinations and sampling	8
3.3 Microscopic examinations	10
3.4 Chemical analyses	10
3.4.1 Soils	10
3.4.2 Foliage and surface organic layer	11
4. RESULTS	11
4.1 Aerial surveys and aerial photo interpretation	11
4.2 Ground examinations	15
4.2.1 Trees	19
4.2.2 Higher plant ground cover	19
4.2.3 Ground and corticolous cryptogams	22
4.3 Microscopic examinations	22
4.4 Chemical analyses	22
5. DISCUSSION AND CONCLUSIONS	26
ACKNOWLEDGEMENTS	32
REFERENCES	33
TABLES	34
APPENDIX: Summary of forest injury in the Thompson Smoke Easement area from 1963 through 1971.	38

LIST OF FIGURES

		PAGE
Fig. 1.	The smelter stack smoke release at Thompson, Manitoba	2
Fig. 2.	A lofting plume	4
Fig. 3.	A low coning plume	4
Fig. 4.	A fanning plume	4
Fig. 5.	A looping plume	4
Fig. 6.	Smelter smoke direction	6
Fig. 7.	Wind speeds	6
Fig. 8.	Map of Thompson with aerial photo flight lines	7
Fig. 9.	Map of Thompson with locations of sites and decline zones	9
Fig. 10.	A partially defoliated declining forest	12
Fig. 11.	A forest with normal foliage	12
Fig. 12.	Part of the tailings pond	12
Fig. 13.	Discolored patches of forest	13
Fig. 14.	A severely declining patch of forest	13
Fig. 15.	Normal forest cover	13
Fig. 16.	A patch of severely declining forest	14
Fig. 17.	Normally foliated forest cover	14
Fig. 18.	Normal crown foliage of black spruce	16
Fig. 19.	Reduced, discolored crown foliage of black spruce	16
Fig. 20.	Black spruce top foliage, side away from the smelter stack	16
Fig. 21.	Black spruce top foliage, side towards the smelter stack	16
Fig. 22.	Reduced crown foliage of jack pine and aspen poplar	17
Fig. 23.	Foliage symptoms on jack pine	17
Fig. 24.	Foliage symptoms on jack pine	17

		PAGE
Fig. 25.	Normal jack pine foliage	17
Fig. 26.	Needles from jack pine showing the side facing towards the smoke stack	18
Fig. 27.	Typical ground cover near smelter stack	20
Fig. 28.	Typical ground cover distant from smelter stack	20
Fig. 29.	Dead remnants of corticolous lichens	21
Fig. 30.	Lush growth of corticolous lichens	21
Fig. 31.	Breakdown of mesophyll tissue beneath stoma in jack pine needle	23
Fig. 32.	Hypertrophy of resin canal epithelial cells in jack pine needle	23
Fig. 33.	Normal jack pine needle, showing healthy mesophyll tissue and resin canal epithelial cells	23
Fig. 34.	Jack pine needle vascular bundle showing hypertrophy of of vascular parenchyma cells	24
Fig. 35.	Jack pine needle vascular bundle showing normal vascular parenchyma cells	24
Fig. 36.	Complex tissue abnormalities and breakdown in severely lesioned jack pine needles	25
Fig. 37.	Normal tissues in jack pine needles	25

LIST OF TABLES

		PAGE
1.	Pollutant emissions from the smokestack at Thompson.	3
2.	Vegetation condition at ground examination sites: trees.	34
3.	Vegetation condition at ground examination sites: higher plant ground cover, corticolous and ground cryptogams.	35
4.	Sulphur and nickel content of foliage, surface litter, and soil.	36
5.	Types of forest injury caused by air pollution, with observations near Thompson.	37

1. *INTRODUCTION*

The condition of the forest near Thompson, Manitoba has been surveyed annually since 1960 by the Canadian Forestry Service, at the request of the Department of Mines, Resources and Environmental Management, Government of Manitoba. In 1965 an area of light forest injury was reported extending south of the smelter. In 1966, the aerial coverage was reduced to direct flight lines between the outlying SO_2 detection box locations. The coverage continued until 1970 with no damage of any significance being reported. International Nickel Co. of Canada Ltd. reported that no damage to vegetation in the easement area had been detected by 1970.

In 1971, aerial coverage was changed and survey of the forest around the smelter revealed patches of discoloration. A ground check in a discolored area one mile due south of the smelter showed that forest vegetation was under severe stress, with injury to most species represented and death of many individuals. These effects were attributed to smelter smokestack emissions in a report summarizing survey observations to that date (Blauel 1971, also see Appendix).

Further surveys were carried out to determine the types, intensities, and amounts of injury to the forest community, to diagnose the causes, and to provide a basis for prediction of the rate of progression of injury in the future. This report summarizes the highlights of results from these recent surveys.

2. *BACKGROUND*

In 1960 the International Nickel Co. of Canada Ltd. began to conduct a nickel mining and smelting operation at Thompson that can process

TYPES OF SMOKE PLUMES AS FORMED BY ATMOSPHERIC CONDITIONS

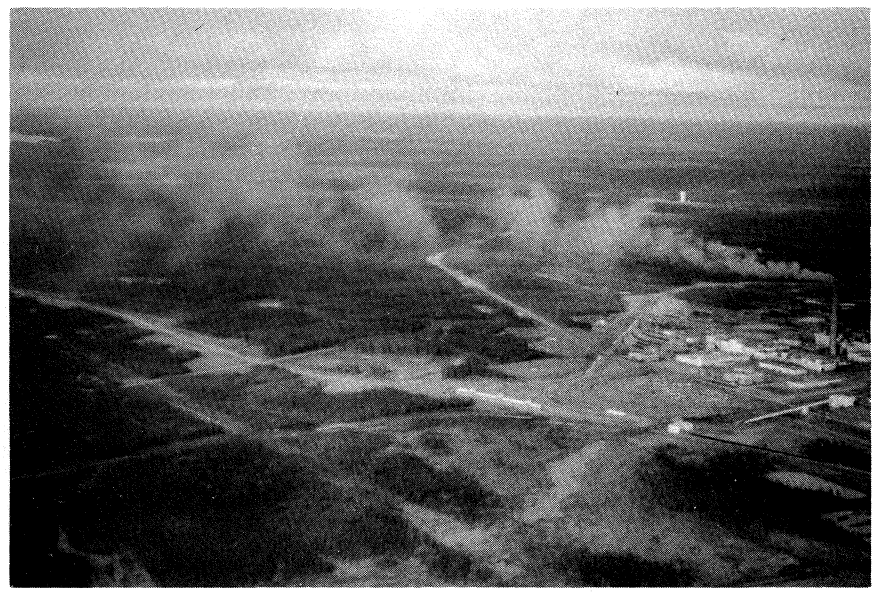


Fig. 1 The smelter stack smoke release at Thompson, Manitoba. The density and color of the plume indicate considerable particulate matter in the smoke.

20,000 tons of ore daily. Wastes from the processing operations are discharged into a large liquid tailings area (Fig. 9) and into the atmosphere from a 500-ft smokestack. Cyclone extractors and electrostatic precipitators reduce aerial emissions of particulate matter from the smokestack. Atmospheric dilution and dispersal are relied upon to dispose of the released air pollutants. The Manitoba Government approved a smoke easement area at the time of plant start-up.

2.1 Air Pollutants Released

Day-to-day chemical composition of the smoke plume varies in part according to the ore body currently being mined and processed. Effluent includes sulphur dioxide and particulates such as the heavy metals nickel, iron, lead, zinc, copper, and cadmium; and non-metals such as arsenic and cobalt.

Typical stack survey analyses are summarized in Table 1. Data are not available for elements not listed.

Table 1.* Pollutant emissions from the smokestack at Thompson, Manitoba.

Pollutant	1971	1973
Sulphur dioxide gas	1700 tons/day	1200 tons/day
Particulates		
nickel	90 lb/h	160 lb/h
lead	.8 lb/h	.1 lb/h
zinc	.9 lb/h	.7 lb/h
cadmium	.1 lb/h	.1 lb/h
Total particulates	30 tons/day	30 tons/day

* These data obtained from the International Nickel Co. of Canada Ltd., and reported here with permission.

TYPES OF SMOKE PLUMES AS FORMED BY ATMOSPHERIC CONDITIONS

Fig. 2 A lofting plume showing rising smoke being diluted and dispersed by the atmosphere.

Fig. 3 A low coning plume showing dispersal and impingement of smoke on the forest.

Fig. 4 A fanning plume showing long range transport of smoke by the atmosphere.

Fig. 5 A looping plume showing impingement of smoke on the forest.

2.2 Plume Characteristics

The main smokestack at Thompson is 500 ft high with top diameter of 30 ft. Smoke emerges at an average temperature of 357^{0}F and an average rate of 1.3 million cu ft/min in a continuously dense, luminescent, orange-brown colored plume (Fig. 1). Dispersal configurations of the plume were observed during the course of aerial surveys. *Lofting* (Fig. 2) and *coning* (Figs. 1 and 3) plumes occurred most frequently. *Fanning* (Fig. 4) plumes were also seen and a *looping* (Fig. 5) plume was observed twice during a 5-day survey period. Looping and low coning plumes result in the direct impingement of visibly concentrated smoke onto the forest near the smelter. Fanning plumes retain visible integrity and a potential for concentrated impingement for at least 20 miles, accounting for long distance spread (Fig. 4).

2.3 Windspeed and Direction

Records obtained from the Atmospheric Environment Service at Thompson airport provide two observations of importance to this survey. The wind is most frequently to the southern half of the quadrant (Fig. 6) and calm (less than 1 mph) for over 11% of the time (Fig. 7).

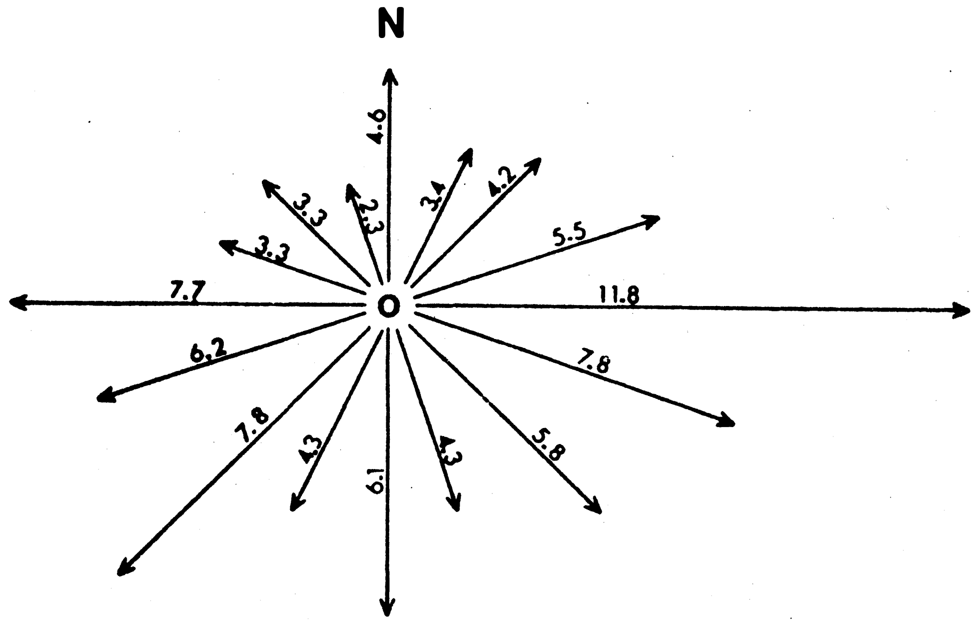
3. *METHODS*

Methods employed included aerial reconnaissance and photography, ground examinations and sampling, and laboratory examinations and analyses.

3.1 Aerial Surveys and Photography

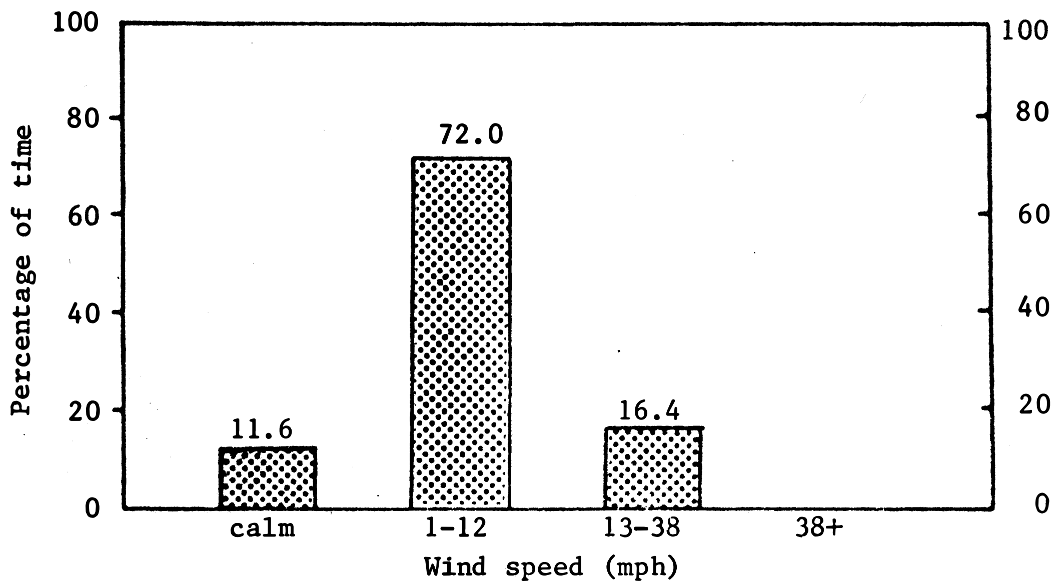
Aerial reconnaissance and ground surveys of vegetation and soil were conducted July 19-25, 1972, and June 18-19, 1974. Light fixed-wing aircraft and helicopters (provided by the Manitoba Government) were used.

Fig. 6 Smelter Smoke Direction expressed in percentage of time (based on frequency in hours) recorded over a 32 month period, May, 1970 - August, 1972, from the Thompson Airport.



Total is 88.4% of time; the balance of time was calm (11.6%).

Fig. 7 Wind Speed expressed in percentage of time (based on observations taken at 6 hour intervals)recorded over a 32 month period, May, 1970 - August, 1972, from the Thompson Airport



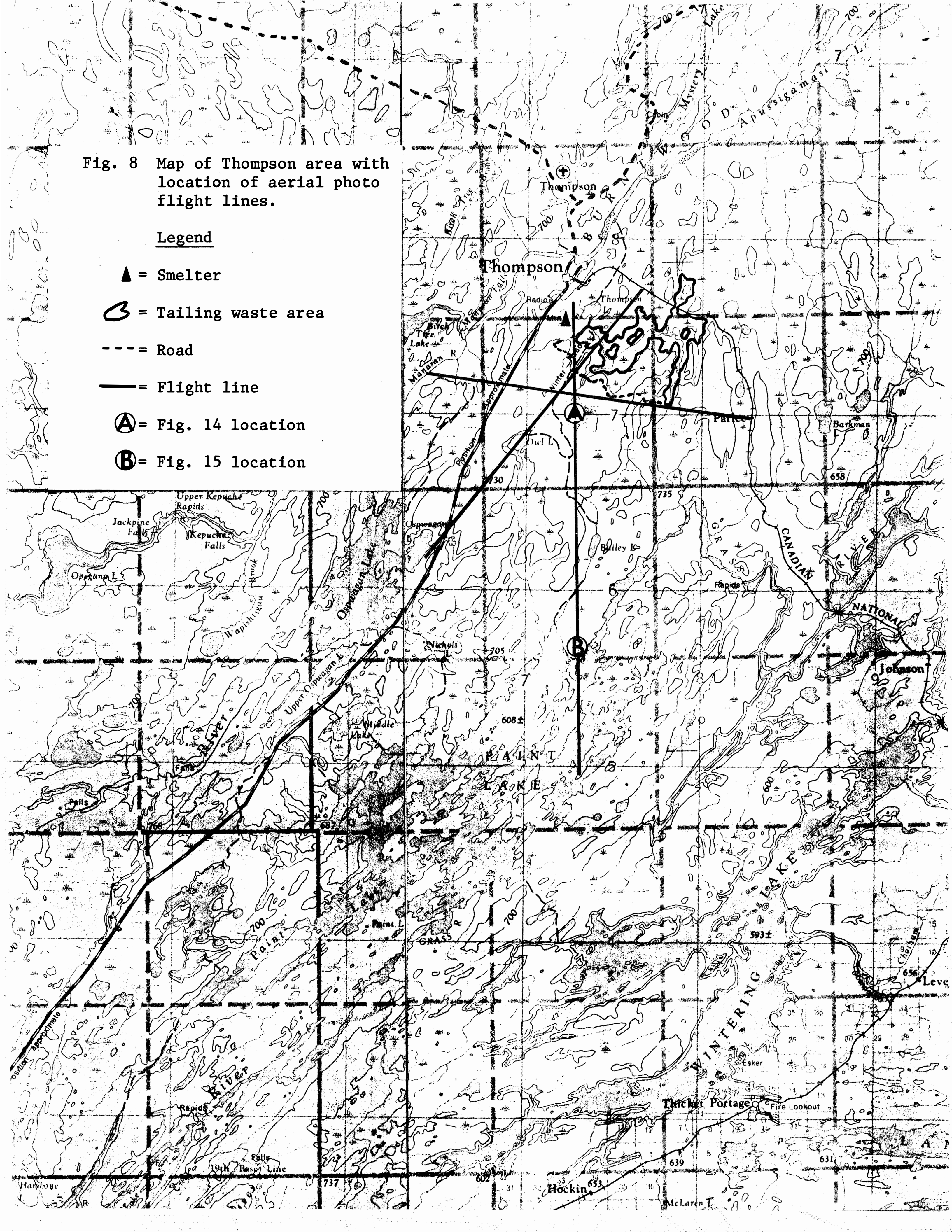


Fig. 8 Map of Thompson area with location of aerial photo flight lines.

Areas where vegetation was visibly discolored were mapped and photographed in color and false-color infrared.

Aerial photography was taken on August 14, 1972, and May 21, 1973, by the Canadian Centre for Remote Sensing. There were three low level flight lines (Fig. 8) yielding images at a scale of 1:20,000. Photography was in panchromatic black and white, color, and false-color infrared.

3.2 Ground Examinations and Sampling

On the basis of the aerial reconnaissance, sites showing clearly visible decline in areas not subject to water inundation were selected for intensive examination (Fig. 9). The forest vegetation was divided for reference into four groups: trees, higher plant ground cover (small shrubs and herbs), corticolous cryptogams (bryophytes and lichens), and ground cryptogams. For each group, detailed notes were made of coloration, size, shape, symptoms, and general condition of various plant parts. Foliage samples for chemical analysis were placed directly into plastic bags and sealed. Foliage samples for microscopic examination were placed directly into vials of formalin-acetic acid (F.A.A.-fixative). Reference specimens of plants, representative of the site as a whole, were photographed and collected for preservation in herbarium mounts, Riker mounts, or collector cards as appropriate.

Separate samples of the soil surface organic layer ("LFH" horizon) and of mineral soil ("A" horizon, 0-4 in. depth) were collected at least 100 yards from disturbed ground and were placed directly into plastic bags, sealed, and returned to the laboratory for chemical analysis.

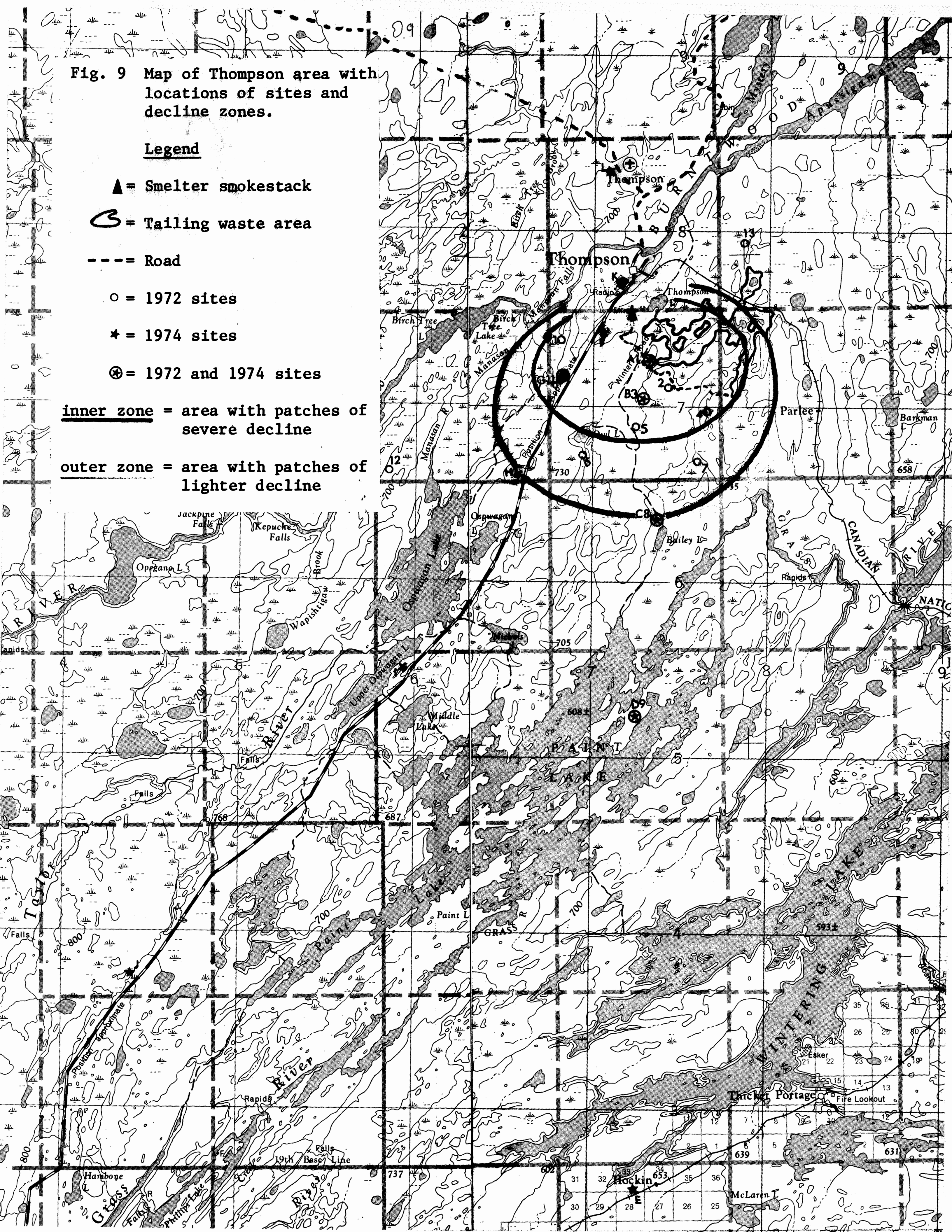


Fig. 9 Map of Thompson area with locations of sites and decline zones.

3.3 Microscopic Examination

The fixed plant specimens were dehydrated through a standard tertiary-butyl alcohol series, embedded in paraffin wax, serially sectioned at 10 μ thickness, and mounted on glass slides. Sections were stained with Feulgen-Fast Green and examined by phase-contrast light microscopy.

Tissue and cellular characters were compared with standard reference preparations made from normal needles and from tissues of known exposure to pollutant gases, and to published descriptions (Stewart *et al.* 1973, C.C. Gordon pers. comm.). Pollutant-caused abnormalities are quite distinct from the effects of such stresses as frost, drought, or flooding.

3.4 Chemical Analyses

The quantities of available sulphate (in soils) and total sulphate (in vegetation and in soil surface organic layer) and of total nickel were determined on samples from each 1974 ground site (see Fig. 9). Sulphur was chosen as indicative of sulphur dioxide depositions and nickel as a comparative marker indicative of heavy metal particulates released by the smelter.

3.4.1 Chemical analysis of soils. Soil samples were air-dried and ground to pass through a 2-mm mesh sieve. Readily soluble sulfates were extracted with 0.005 M $CaCl_2$ solution (Beaton *et al.* 1968). Sulfate was determined by turbidimetry using 20-60 mesh $BaCl_2.2H_2O$ crystals and preparing a relatively stable colorless $BaSO_4$ suspension (Bradsley and Lancaster 1965). The absorbance of the suspension was measured at 420 nm wavelength with a Perkin-Elmer double beam spectrophotometer (Model 124D).

Nickel content was determined by atomic absorption spectrophotometry using HF-HCl extracts prepared by the method employed at the Alberta Soil Survey Laboratory (Anon.). Samples were passed through a double-beam instrument (Perkin-Elmer Model 303 with DCR-1 attachment). Instrument settings were those recommended by the Perkin-Elmer Corp. (1973). The fuel-air mixture (acetylene-compressed air) was adjusted to give an oxidizing (lean, blue) flame. The radiation source was a Westinghouse Ni hollow cathode lamp filled with neon vapor. The monochromator was adjusted to 232 nm.

3.4.2 Chemical analysis of foliage and surface organic layer. Foliage samples were first washed twice in distilled water. All samples were oven-dried at 80^{0}C overnight, ground to 20-mesh size, ashed at 440^{0}C in a muffle furnace and extracted with HCl. Sulphate was determined by turbidimetry and Ni by atomic absorption spectroscopy as described above.

4. RESULTS

4.1 Aerial Surveys and Aerial Photo Interpretation

Forest cover in the Thompson area is mainly black spruce-jack pine with scattered poplars and birches. Aerial reconnaissance revealed patches of forest in a large area (Fig. 9) to the west, south, and east of the smelter that were visibly different in color and texture (Figs. 12 and 13) from normal forest (Fig. 14). These discolored patches of forest decreased in frequency and intensity with distance from the smokestack. This area had been reported earlier (Blauel 1971), and comprises subjective zones of generally moderate and light decline (Fig. 9), based on the frequency and intensity of patches of injured vegetation. The total area visibly affected is about 50 square miles, of which about a quarter contains

Fig. 10 A partially defoliated declining forest, indicated by the blue-green color and rough texture (photo taken 3 miles south of the smelter stack at Site A, Fig. 8).

Fig. 10 & 11 False color infrared vertical aerial photos Scale 1:20,000.

Fig. 11 A forest with normal foliage indicated by the pink-magenta color and smoother texture (photo taken 11 miles south of the smelter stack at Site B, Fig. 8).

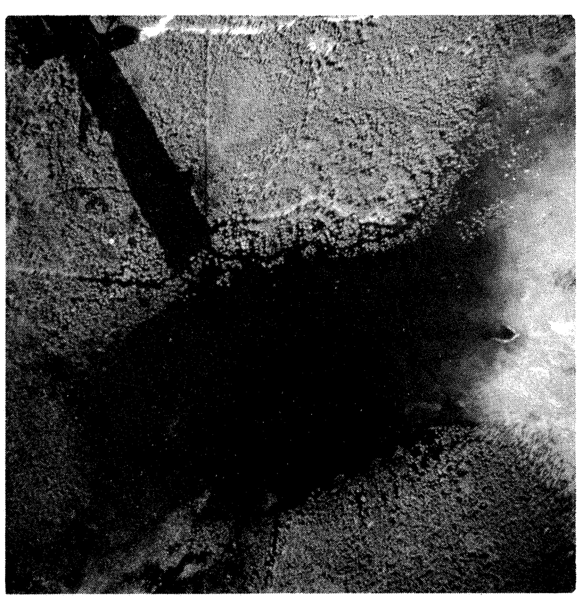


Fig. 12 Part of the tailings pond showing dead trees outlining the water inundation. (Color vertical aerial photo, Scale 1:20,000.)

Fig. 13 Discolored patches of forest a few miles south of the smelter stack. Such discoloration indicates severe forest decline. These discoloration patches were common where smoke plumes were seen impinging on the forest.

Fig. 14 A severely declining patch of forest 3 miles south of the smelter stack (a low level aerial color photo).

Fig. 15 Normal forest cover 12 miles south of the smelter stack (a low level aerial color photo).

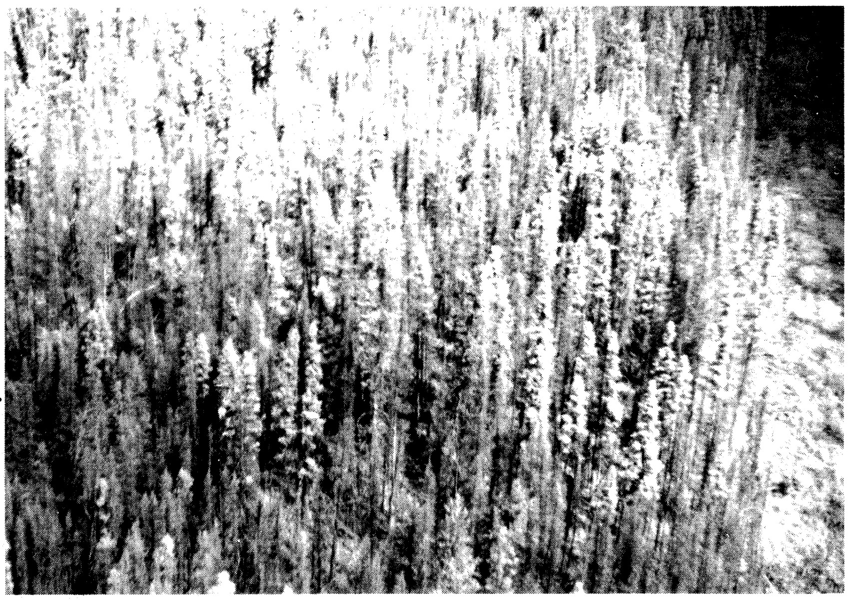


Fig. 16 A patch of severely declining forest a few miles south of the smelter stack (a low level infrared aerial photo). Tree defoliation shows up as a blue-green color.

Fig. 17 Normally foliated forest cover 12 miles south of the smelter stack (a low level infrared aerial photo). The normal foliation appears pink.

severely affected patches and another fifth is affected by water inundation from the tailings pond.

This large area of forest decline is distinguishable on the false color infrared aerial photography by patches of blue-green hue and rough texture (Fig. 10). This blue-green hue decreases in photographs further away from the source of air pollution. Normal forest distant from the smokestack appears magenta-pink and smoother in texture (Fig. 11).

Areas of forest decline along the margins of the liquid tailings pond are clearly delineated on the color aerial photographs (Fig. 12) and are indicated in Fig. 10. Low-level observations of standing snags further define marginal decline along water body contours and water courses.

Forest injury appeared on low-level color photographs as randomly distributed patches of greyish-brown to light green decreasing in frequency and intensity with distance from the smokestack (Figs. 13 and 14; compare with Fig. 15). The maximum radial distance for which discoloration was thus apparent was about 8 miles. On low-level falsecolor infrared photographs, injured trees appeared light blue-green (Fig. 16), compared to a magenta hue for healthy trees (Fig. 17). Declining trees in an injured area showed scattered tops of magenta hue (Fig. 16). Injury was often more prominent on the side of the tree which was nearest the smokestack.

4.2 Ground Examinations

The 13 sites shown on Figure 9 clearly showed the impact of the air pollutants on the four groups of forest vegetation (Tables 2 and 3). The effects on vegetation were less severe as distance from the smokestack increased.

A detailed description of conditions and symptomology follows for the four classes of forest vegetation (i.e. trees, higher plant

Fig. 18 Normal crown foliage of black spruce on Site D-9, 14 miles south of the smelter stack.

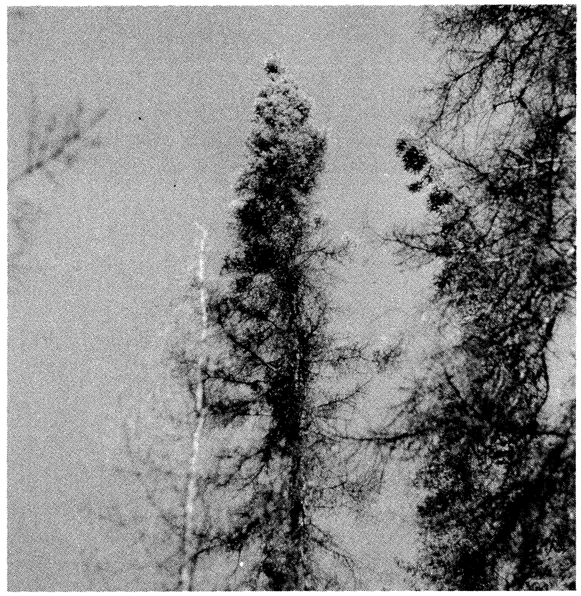


Fig. 19 Reduced, discolored crown foliage of black spruce on Site A-1, 1.5 miles south of the smelter stack.

Fig. 20 Black spruce top foliage, side away from the smelter stack.

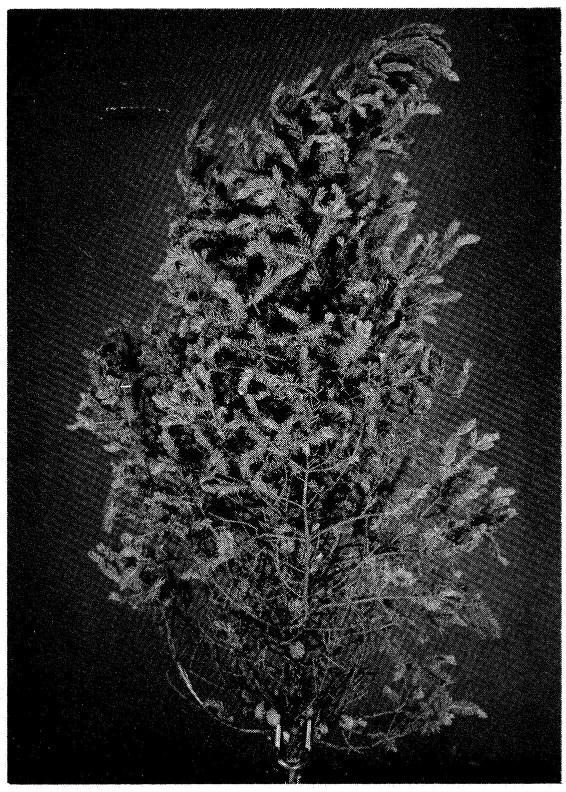


Fig. 21 Same top as Fig. 20 side towards the smelter stack. Note the increased foliar discoloration.

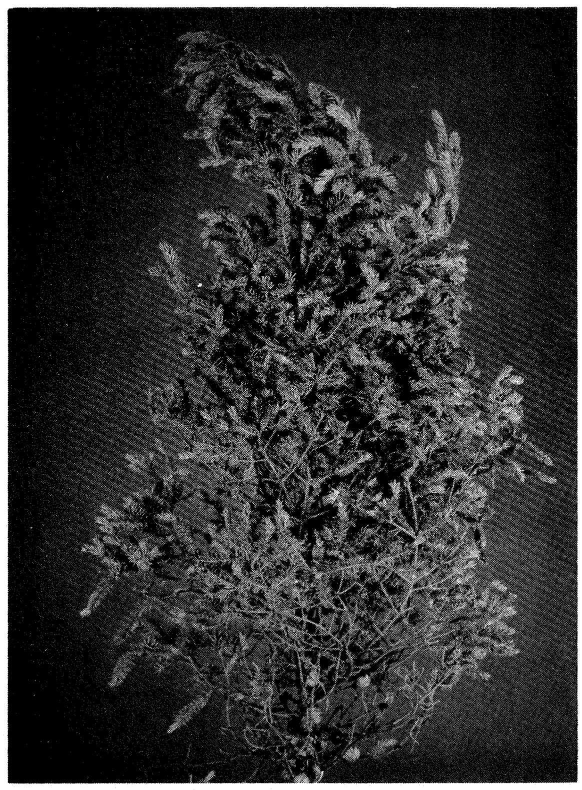


Fig. 22

Fig. 22

←Reduced crown foliage of jack pine and aspen poplar on Site A, 1.5 miles south of the smelter stack.

Fig. 23

↓ Foliage symptoms on jack pine at Site A-1, 1.5 miles south of the stack. Note the browned needle tips, the absence of current year needle growth and the loss of foliage.

Fig. 24

↓ Foliage symptoms on jack pine at Site 2, 2.5 miles miles south of the stack. Note the needle discolorations and stunting.

Fig. 23

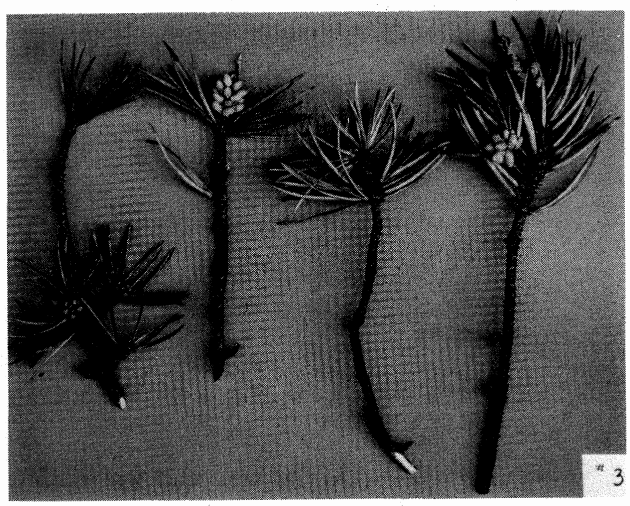


Fig. 24

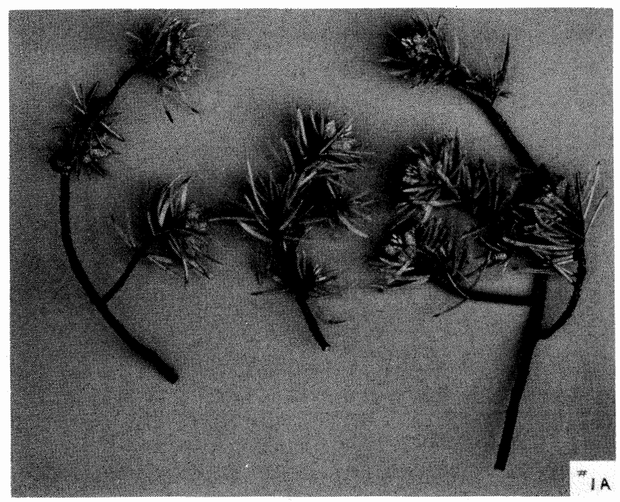


Fig. 25

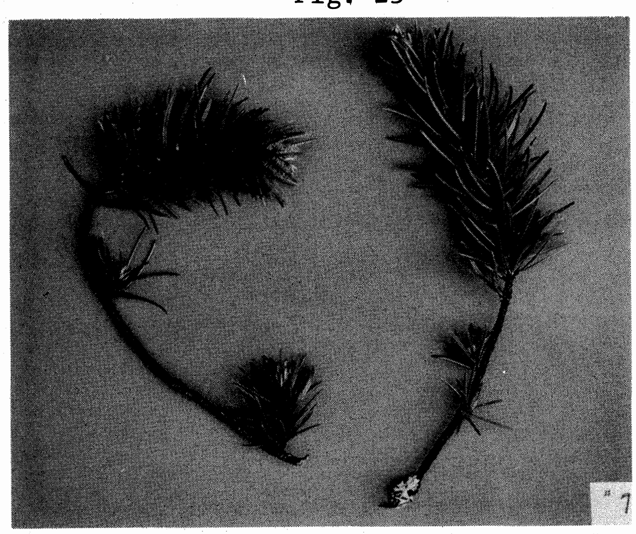


Fig. 25

←Normal jack pine foliage at Site D-9, 14 miles south of the stack. Note the color, new growth and needle retention.

A B

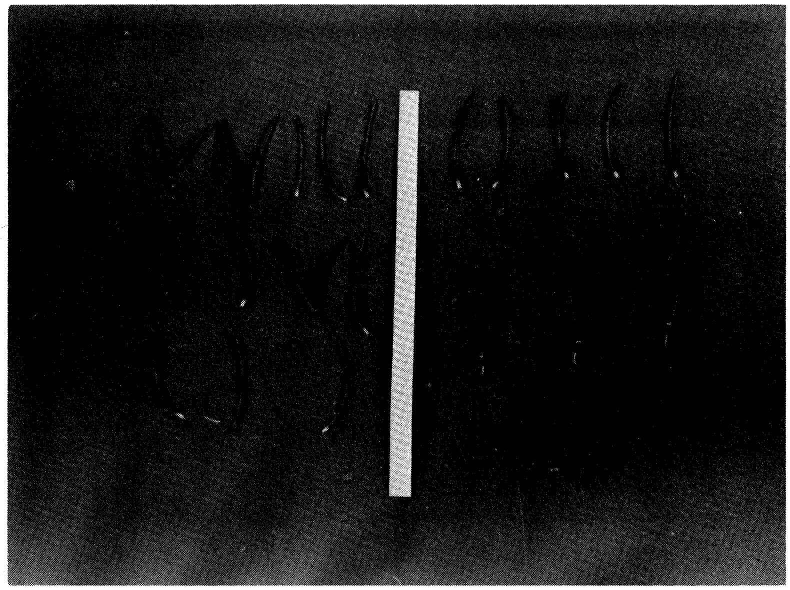


Fig. 26 Needles from jack pine showing the side facing towards the smokestack.

A. Collected 3.5 miles south of the smokestack from Site B-3 (Fig. 9). Large yellow-brown lesions were commonplace.

B. Collected 30 miles south of the smokestack from Site E (Fig. 9). The absence of large lesions was typical.

ground cover, ground and corticolous cryptogams) on a severely affected site (Site 1, Fig. 9). Site 1 is located 1.5 miles SSE of the smelter in a dense, black spruce-jack pine forest with a few poplars.

4.2.1 Trees. Thirty percent of all trees were dead, including 70% of the jack pine, most so recently as to retain dead foliage, a few others for so long as to be shedding bark. The remaining live trees exhibited symptoms of serious decline. Detailed condition varied with the species and individually. Foliage was much reduced in all species (Figs. 19 and 21; compare to normal foliage in Fig. 18 for black spruce). Jack pine and black spruce, which normally retain 4-5 years' foliage, carried only current and 1 or 2 years' foliage (Figs. 23 and 24; contrast with Fig. 25). On the severely declining trees, remaining foliage was stunted, chlorotic (yellowed), and often had necrotic (brown) lesions and tips, sometimes banded (Figs. 19, 21, 23, 24 and 26). For both jack pine and black spruce these symptoms were always more numerous on the side of individual needles (and on the side of the tree) facing towards the smokestack (Figs. 20 and 21). Internodal growth was much reduced.

Poplar foliage, although much reduced in quantity (Fig. 21), appeared generally normal in size and color.

Generally, understory trees and seedlings also suffered high mortality or expressed severe decline symptoms.

4.2.2 Higher plant ground cover. Higher plant ground cover was absent or much reduced (Fig. 27) compared to the cover prevailing at distant similar sites (Fig. 28). Dead remnants were present indicating former cover. In exposed locations, only chlorotic individual plants of a few resistant species remained. In sheltered microsites more species survived

Fig. 27 Typical depleted ground cover on Site A-1, 1.5 miles south of the smelter stack.

Fig. 28 Typical ground cover on Site D-9, 14 miles south of the smelter stack.

Fig. 29 Dead remnants of corticolous lichens on spruce at Site A-1 1.5 miles south of the smelter stack.

Fig. 30 Lush growth of corticolous lichens on spruce at Site D-9, 14 miles south of the smelter stack.

in better condition.

4.2.3 Ground and corticolous cryptogams. Ground and corticolous cryptogams were reduced to dead, desiccated remnants (Figs. 27 and 29). The types and quantities of remnants present indicated that the former lichen and bryophyte communities had been very rich and diverse, similar to those 14 miles south of Thompson (Figs. 28 and 30). Death of ground cryptogams in particular gave the area a denuded appearance because they had constituted most of the former ground cover (Fig. 27; contrast with Fig. 28).

4.3 Microscopic Examinations

Microscopic examinations of affected jack pine needles from Thompson revealed signs typical of sulphur dioxide injury. Specifically, in material from Thompson there was breakdown of mesophyll tissue below stomata (Fig. 31), hypertrophy of resin canal epithelial cells (Fig. 32; compare with normal tissues in Fig. 33), and hypertrophy of vascular parenchyma cells (Fig. 34; contrast with Fig. 35). Besides typical sulphur dioxide injury, there was abundant microscopic evidence of generalized tissue abnormalities and breakdown (Fig. 36; contrast with healthy tissue Fig. 37). These abnormalities were more frequent on samples from sites closer to the smokestack and were absent on samples from distant sites (Table 2).

4.4 Chemical Analyses

Chemical analyses of the sulphur and nickel content of foliage and of soil surface organic matter showed a marked gradient with extremely high concentrations near the smokestack, consistently decreasing with

Fig. 31 Breakdown of mesophyll tissue beneath stoma in jack pine needle. (Cross section X 4,000).

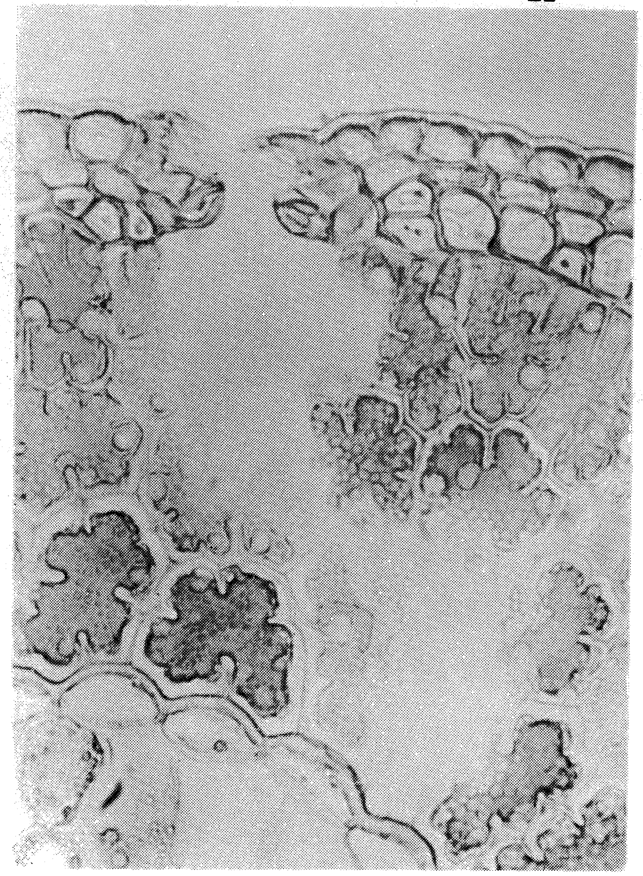
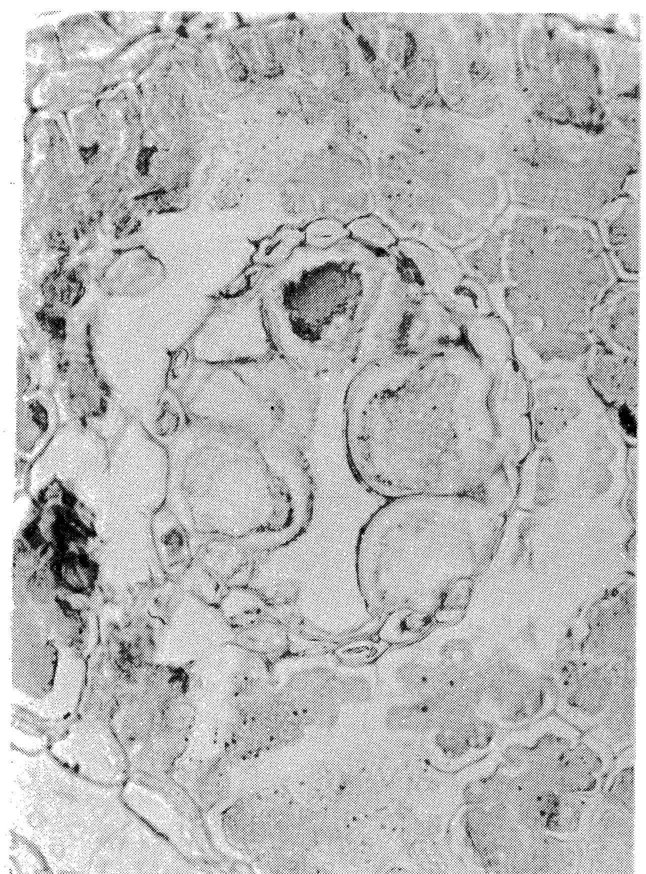


Fig. 33 Normal jack pine needle, showing healthy mesophyll tissue and resin canal epithelial cells (Cross section X 3,500).
↓

Fig. 32 Hypertrophy of resin canal epithelial cells in jack pine needle (Cross section X 4,000).



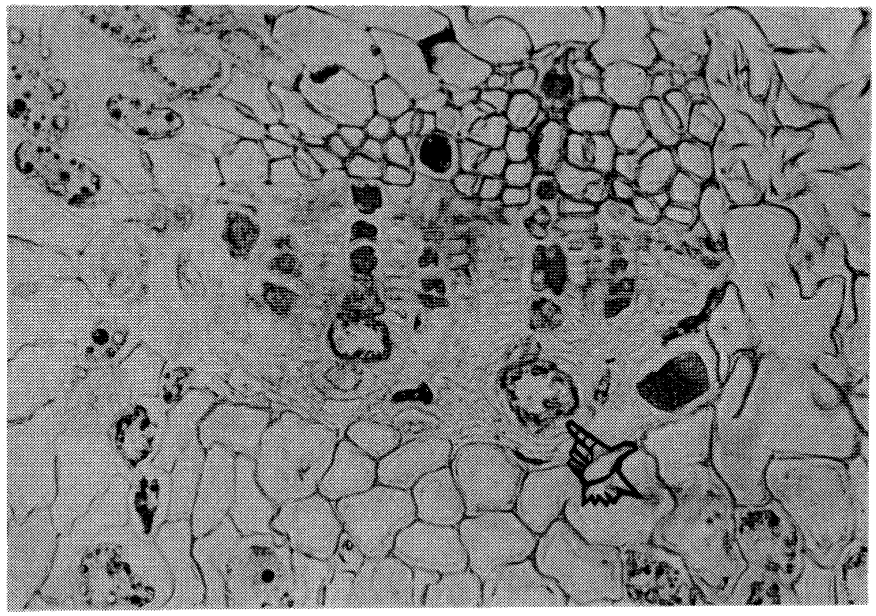


Fig. 34

Jack pine needle vascular bundle showing hypertrophy of vascular parenchyma cells. (Cross section X 4,000).

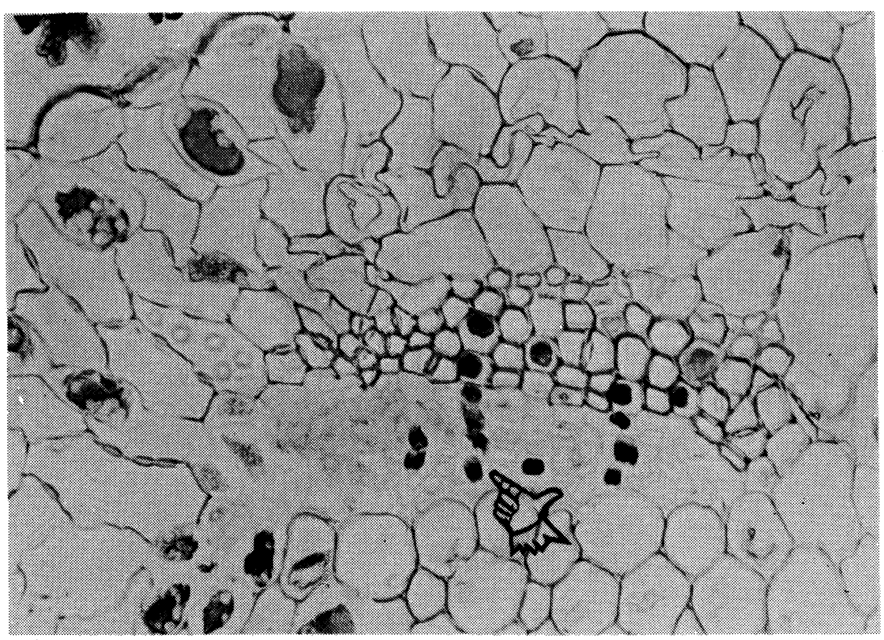


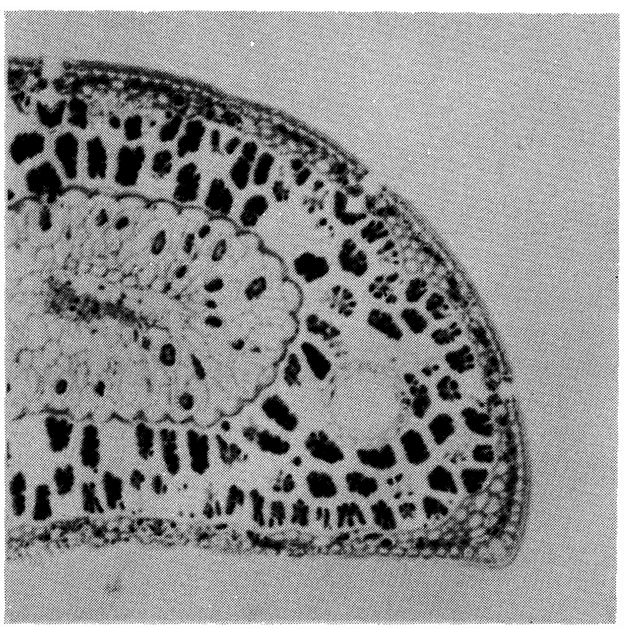
Fig. 35

Jack pine needle vascular bundle showing normal vascular parenchyma cells (Cross section X 4,000).

Fig. 36

Complex tissue abnormalities and breakdown in severely lesioned jack pine needles (Cross section X 800).

Fig. 37 Normal tissues in jack pine needles. (Cross section X 800).



distance (Table 4). The sulphur gradient declined more slowly than the nickel gradient, reflecting more efficient transport of the gaseous component. A gradient was not present in the mineral soil, but nickel content was high in all samples. Elevated nickel and sulphur levels in foliage and soil surface organic matter were detected at least 15 miles to the south and southwest of the stack and 5 miles to the north.

5. DISCUSSION AND CONCLUSIONS

Aerial and ground examinations have revealed varying degrees of patchy forest decline within an area of about 50 square miles near Thompson. In the more severely affected patches up to 80% of trees are dead, a similar proportion of higher plant ground cover is dead, and nearly all lichens and mosses are dead. At issue is the cause of this decline and mortality.

Once trees are dead, it may be impossible to determine the precise cause because of secondary tissue breakdown after death. The question is further complicated if there may have been several contributing causes. But the causes of decline in *dying* trees can be diagnosed with higher confidence. A logical sequence of examinations may be followed.

A variety of hypotheses might be advanced to explain the present forest decline. We have considered and rejected as primary causes the following potential ones. While some common forest diseases and insects were present in the area, there were none capable of causing the observed symptoms. Because soil or moisture factors might be contributing to the patchiness of the initial effects, they were considered as possible primary causes. However, no nutritional or moisture problems could cause the full set of symptoms observed. Also, the sidedness of symptom expression points to an atmospheric source.

Some nutritional deficiencies could induce some chlorosis in trees and might contribute to susceptibility to other disease agencies. But nutritional deficiency alone would not produce the microscopic symptoms observed and would certainly not account for the high mortality of lichens and mosses.

Although the distribution of injury at times coincided with low-lying areas subject to periodic water inundation, the correlation was far from complete. That is, areas showing the same set of stress symptoms were commonly located on higher ground not subject to water inundation. Areas undoubtedly killed by water inundation near the tailings area were easily distinguishable on aerial photography and on the ground. Finally, drought may be ruled out as a potential cause by the distribution patterns of symptoms and by records showing normal precipitation in the area.

The declining forest near Thompson is subjected to over half a million tons of sulphur dioxide and over 10,000 tons of heavy metals and other particulates per year, both known toxicants to plant life. The factors affecting sulphur dioxide impact on the forest and its symptomology are very complex (Loman *et al.* 1972). At Thompson there are also the toxic effects of heavy metals. For example, "chlorotic symptoms induced by heavy metals frequently resemble nutrient deficiency symptoms of essential elements" (Nash 1973). The effects may be synergistic. For example, as in Sudbury, the acidity contributed by the sulphur dioxide could make more available the heavy metals normally chelated in the soil surface organic matter (Whitby 1974).

Table 5 lists the types of forest injury that may be caused by air pollution in a matrix with the levels of the forest biosystem in which the effects may be observed. In every applicable cell of the matrix that we studied near Thompson we observed detrimental changes attributable to air pollutants. There were minimal signs of *acute* fumigation; rather, the signs suggested chronic, low-level, cumulative fumigation, except for small patches. Particularly useful in diagnosis are microscopic examinations of structural changes in conifer needles. Specimens from the area of forest decline showed changes diagnostic for sulphur dioxide injury. Other tissue abnormalities that were present were quite distinct from those caused by frost, drought, flood or winter injury and are probably attributable to heavy metal particulates and interactions with other pollutant components. No other cause could account for the observed needle lesions.

The observed gradient in frequency and severity of injury matches that of sulphur and nickel in foliage and surface organic matter. The distribution pattern around the smokestack reflects the dominant wind directions. Much of the area immediately to the north of the smokestack has been deforested by fire and urban development, so signs of advanced forest decline are not prominent. But because some wind does blow northwards, toxicants are accumulating there also and we can expect to see serious forest decline in future years.

Local variations in distribution of toxicants and other stresses account for the patchiness of the forest decline near Thompson. Distribution of the toxicants is dependent primarily on wind. Variations in atmospheric conditions affect dispersal, dilution, and impingement of air pollutants in the overall distribution pattern. Factors such as minor topographic variations can also account for variation in other types of contributing forest stresses. Detailed explanation of variation in symptom expression would require detailed examination of dispersal conditions, emission patterns, and site factors.

So there is abundant evidence that the primary cause of the forest decline near Thompson is air pollution from the smelter smokestack. What are the implications? At issue is the effectiveness of atmospheric dilution and dispersal as a technique for disposal of air pollutants. It must be recognized that in present circumstances, this forest decline is *progressive*.

The area of visible forest decline is at present confined to a distance of about 8 miles south from the stack. But we detected elevated levels of pollutants in foliage and in soil surface organic matter 15 miles or more from the source. This extrapolates to an area much greater than that of the visibly affected forest.

Levels of sulphur and nickel in foliage resemble those near Sudbury, Ontario (McGovern and Balsillie 1973), where devastation of much of the forest is widespread and complete. Current impacts on the forest near Thompson are mostly due to direct absorbtion of pollutants by the vegetation. This type of injury will intensify as emissions continue.

Although toxicant levels in the soil have not yet reached those near Sudbury, this is explainable by the strong chelating properties of the surface organic matter (Whitby 1974), in which toxicant levels are extremely high and increasing near Thompson. Continued emission of large volumes of acid-producing sulphur dioxide will likely lead to release of heavy metals from the surface organic matter through conversion to soluble forms available to uptake by vegetation. Available nickel, particularly, is toxic to vegetation at relatively low levels in the soil (Hunter and Vergano 1952, cited by Treshow 1970). As the nickel in the surface organic layer is leached into the levels of mineral soil, where most trees are rooted, we can expect far more serious and more widespread decline of the forest near Thompson, accompanied by a soil contamination problem similar to that at Sudbury.

The rate of spread of the decline is directly dependent on the rate of accumulation of toxicants. Deposition of the pollutants is in a roughly circular pattern. Area within a circle increases with the square of radial growth, so the target for pollutant deposition grows larger with distance from the source. Thus, if emissions continue at the present rate, the radial extent of the decline will increase more and more slowly. But the actual *area affected* will grow at a relatively constant rate: to date about 50 square miles in 12 years, or about 4 square miles a year.

An important distinction needs finally to be drawn between the sulphur dioxide and the heavy metal particulate fractions of the smelter emissions. Sulphur, as an element, is essential to life and certain amounts of it can be dealt with and recycled in biosystems provided it does not arrive at too high a rate or in a form that is phytotoxic. Heavy metals by contrast are cumulative and non-biodegradable, many being poisonous to biosystems. Although some are also essential in minute amounts, very small excesses are poisonous *and they are not readily recycled*. Soil that has become sterile through addition of excess sulphur dioxide can be rendered productive with reasonable economy by lime treatments. But soil poisoning with heavy metals has to date been permanent because no economic treatment is known.

In conclusion, current stress and injury to large areas of forest are caused by direct absorbtion of air pollutants. More serious is the accumulation of air pollutants to dangerously high levels in the soil. This damage to the environment has been caused through disposal of smelter wastes by dilution and dispersal in the air. Enormous quantities of gaseous and particulate wastes are still being disposed of in this way. Continuation of this practice can only result in intensification and spread of the injury and serious soil contamination of the type which occurs near Sudbury.

ACKNOWLEDGEMENTS

The authors express their appreciation to the Department of Mines, Resources and Environmental Management of the Province of Manitoba for transport and assistance, to the Canadian Centre for Remote Sensing for provision of the aerial imagery, to Dr. C.C. Gordon at the University of Montana for data on microscopic symptoms diagnosis, to Mr. Y. Kalra of the Northern Forest Research Centre for assistance with chemical analysis, and to Mr. John Muir, also of the Northern Forest Research Centre, for advice and support throughout the study.

REFERENCES

Anon. Soil Laboratory Analysis. Alberta Dep. Agr., Alberta Soil Survey, Edmonton. Mimeo.

Beaton, J.D., G.R. Burns, and J. Platou. 1968. Determination of sulphur in soils and plant material. Tech. Bull. No. 14, Sulphur Inst., Washington, D.C.

Blauel, R.A. 1971. The Thompson Smoke Easement Survey. Misc. Rep. NOR-Y-4. Environ. Can., Can. For. Serv., N. For. Res. Centre, Edmonton, Alta.

Bradsley, C.E. and J.D. Lancaster. 1965. Sulfur. pp. 1102-1116. *In* C.A. Black *et al.*, (ed.). Methods of Soil Analysis. Am. Soc. Agron. Monogr. No. 9, Madison, Wis.

Hunter, J.G. and O. Vergano. 1952. Nickel toxicity in plants. Ann. Appl. Biol. 39:279-284.

Loman, A.A., R.A. Blauel, and D. Hocking. 1972. Sulphur dioxide and forest vegetation. Inform. Rep. NOR-X-49. Environ. Can., Can. For. Serv., N. For. Res. Centre, Edmonton, Alta.

McGovern, P.C. and D. Balsillie. 1973. Sulphur dioxide (1972) and heavy metal (1971) levels and vegetation effects in the Sudbury area. Ont. Min. Environ., Air Manage. Br., Sudbury, Ont.

Nash, T.H. 1973. The effect of air pollution on other plants, particularly vascular plants. *In:* Ferry, B.W., M.S. Baddeley and D.L. Hawksworth (ed.) *Air Pollution and Lichens*. U. Toronto Press.

Perkin-Elmer Corp. 1973. Analytical Methods for Atomic Absorption Spectrophotometry. Perkin-Elmer Corp., Norwalk, Conn.

Stewart, D., M. Treshow, and F.M. Harmer. 1973. Pathological anatomy of conifer needle necrosis. Can. J. Bot. 51:983-988.

Treshow, M. 1970. *Environment and Plant Response*. McGraw-Hill, N.Y.

Whitby, L.M. 1974. Effect of smelter emissions on soil organic matter. Bull. Ecol. Soc. Amer. 55(2):36 (Abs.)

Table 2 - Tree condition at ground examination sites

Site	Tree Species	Dead trees (%)	Foliar symptoms					
			External				Microscopic	
			stunting	chlorosis	tip necrosis	lesions	SO_2-caused	other
1	Pj	70	+	+	+	+	+	+
	Sb	20	+	+	+	+	0	0
2	Pj	80*	+	+	+	+	+	+
	Sb	78*	+	+	+	+	0	0
3	Pj	65	+	+	-	+	+	+
	Sb	45	+	+	-	+	+	+
4	Pj	46*	+	+	-	+	+	+
	Sb	46*	+	+	-	+	+	+
5	Sb	40	+	+	-	+	+	+
6	Sb	20	+	+	-	-	+	-
7	Pj	42*	+	+	-	+	+	+
	Sb	20*	+	+	-	-	0	0
8	Pj	15	+	+	-	+	+	+
	S6	5	+	+	-	-	+	+
9	Pj	>5	-	-	-	-	-	-
	Sb	>5	-	-	-	-	-	-
10	Pj	85	+	+	-	-	+	-
	Sb	40	+	+	-	-	+	-
11	Pj	40	+	+	+	+	+	+
	Sb	10	+	+	-	+	0	0
12	Pj	>5	-	-	-	-	-	-
	Sb	>5	-	-	-	-	-	-
13	Pj	>5	-	-	-	-	-	-
	Sb	>5	-	-	-	-	-	-

Key to symbols

\+ = present

\- = absent

0 = not studied

Pj = jack pine

Sb = black spruce

* Actual counts made on site; others estimated on site or from aerial photographs.

Table 3 - Condition of higher plant ground cover, ground and corticolous cryptogams at ground examination sites

	Higher plant ground cover			Ground cryptogams			Corticolous cryptogams		
Site	cover depletion	species depletion	chlorosis	cover depletion	species depletion	discoloration	cover depletion	species depletion	discoloration
1	+++[1]	+++[1]	+[2]	+++[1]	+++[1]	+[2]	+++[1]	+++[1]	+[2]
2	+++	+++	+	+++	+++	+	+++	+++	+
3	+++	+++	+	+++	+++	+	+++	+++	+
4	++	++	+	+++	+++	+	+++	+++	+
5	++	++	+	+++	+++	+	+++	+++	+
6	+	-	-	++	+	+	++	++	+
7	+	-	+	++	+	+	++	++	+
8	+	-	-	++	+	+	++	+	+
9	-	-	-	-	-	-	-	-	-
10	++	+	+	+++	+++	+	+++	+++	+
11	++	+	+	+++	+++	+	+++	+++	+
12	-	-	-	-	-	-	-	-	-
13	-	-	-	-	-	-	-	-	-

[1]Key: The number of +++'s indicates the relative depletion of cover or species (marked by dead remnants); - indicates no apparent depletion.

[2]Key: + = present
- = absent

Table 4 - Sulphur and nickel content of foliage, surface litter and soil.

Site location	Foliage (Jack pine, 1-yr.-old needles)		Surface organic layer (LFH Horizon)		Mineral soil ("A" Horizon, 0-4")	
	Sulphur (ppm)	Nickel (ppm)	Sulphur (ppm)	Nickel (ppm)	Sulphur (ppm)	Nickel (ppm)
South of stack						
A. 1.5 miles	869	73	1199	2030	6	162
B. 3.5	605	57	1232	1730	5	108
C. 7	484	37	891	502	5	77
D. 15	209	13	649	79	3	105
E. 31	275	5	418	72	3	112
S.W. of stack						
F. 1 mile	not sampled	not sampled	2882	2215	22	111
G. 3	not sampled	not sampled	1562	1265	21	78
H. 7	not sampled	not sampled	693	365	3	87
I. 15	not sampled	not sampled	726	138	12	107
J. 28	not sampled	not sampled	583	55	6	93
North of stack						
K. 1.5 mile	not sampled	not sampled	1254	640	33	119
L. 5	not sampled	not sampled	957	257	16	125

Table 5 - Types of forest injury caused by air pollution, with observations near Thompson

Types of injury or observable effects	Level of biosystem in which incidence away be observed				
	part of a plant	individual plant	number of individuals	population (stand)	ecosystem
changes in cell components	0	Na	Na	Na	Na
changes in cell structure	x	Na	Na	Na	Na
changes in metabolism	0	0	Na	Na	Na
degree of foliar chlorosis or necrosis	x	x	x	Na	Na
premature foliar senescence	x	x	x	Na	Na
premature foliar abcission	x	x	x	Na	Na
inhibited foliar growth	x	x	x	Na	Na
inhibited terminal growth	x	x	x	Na	Na
inhibited increment growth	x	x	x	Na	Na
predisposition to other stresses	0	0	0	Na	Na
plant death(s)	Na	x	x	Na	Na
percentage of plants injured	Na	Na	x	x	x
percentage of dead plants	Na	Na	x	x	x
reduced number of species	Na	Na	Na	x	x
reduced abundance	Na	Na	Na	x	x
reduced coverage	Na	Na	Na	x	x
decreased net bioproductivity	Na	Na	Na	x	x

x = detrimental changes have occurred at Thompson.

\- = no changes have occurred.

Na = not applicable to the category.

0 = not studied at Thompson.

APPENDIX

SUMMARY OF FOREST INJURY IN THE THOMPSON SMOKE EASEMENT AREA FROM 1963 THROUGH 1971

Smelter operation began in 1961
First symptoms observed in 1963

Year	Species & Injury	Location & SO_2 Station No.
1963	Balsam poplar (light injury to the foliage)	Isbister Lake #9 Witchai Lake #12 Natawahunan Lake #8
1964	White birch, balsam poplar, dogwood, trembling aspen, high-bush cranberry, white spruce (light injury to the foliage)	Natawahunan Lake #8 Witchai Lake #12 Aspwagan Lake #17 Paint Lake #18 Wintering Lake #5 and #19 In a 35 mile area extending to the northeast and south-east of Thompson
1965	Black spruce (light injury to 10% of the trees)	Natawahunan Lake #8
	Alder (10% of the foliage injured on 50% of the trees)	Burntwood River #10 Natawahunan Lake #8
	White birch (light injury to a few trees)	Isbister Lake #9 Burntwood River #10
	Saskatoon (10% of the foliage injured on 30% of the trees)	Wintering Lake (S) #19
	Balsam poplar (10% of the foliage injured on 30% of the trees)	Harding Lake #15
	White spruce (10% of the foliage injured on 30% of the trees)	Harding Lake #15
	Jack pine, trembling aspen (light injury to the foliage)	In an area extending for 2½ to 3 miles immediately south of the smelter in a band about one mile in width