Effects of Sulphur Dioxide on the Forest Ecosystem

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I. INTRODUCTION

In situ recovery of oil from sulphur-bearing deposits and subsequent processing to produce petroleum products necessitates the removal, handling, and disposal of sulphur by-products. Containment and recovery of sulphur are important goals from both the resource management and environmental protection viewpoints. Knowing the environmental effects of sulphur compounds allows industry to make informed and intelligent decisions on how much sulphur to contain and how much to release as an aerially dispersed waste.

Due to the nature of sulphur in oil deposits, and the process employed for oil extraction, a part of the sulphur is converted to SO_2 and is emitted into the atmosphere. To date the petroleum industry in Canada in general and the oil sands recovery industry in particular have acted in a responsible manner in containment of sulphur compounds and in the release of aerial sulphides. Historically, however, North America and Europe have suffered considerably from sulphurous gas releases that have destroyed vast areas of forest and contaminated lands and lakes. Current global concerns were summarized by Dochinger and Seligo (1976) in the proceedings of the first international symposium on acid precipitation and the forest ecosystem thus:

Major findings presented at the Symposium indicated that: (1) precipitation is becoming increasingly acidic in northwestern Europe, northeastern United States and eastern Canada; (2) this increase is related to greater emissions of sulphur and other acid-forming compounds into the atmosphere from various industrial and urban sources; (3) the acidity may be associated with both indigenous and remote sources; (4) the acidifying pollutants are deposited on the land in both wet and dry forms; (5) serious effects of acid precipitation have been observed in Scandinavia and North America. In addition to major impacts already identified, such as loss of fisheries and changes in some forest ecosystems, scientists at the Symposium expressed concern for other more subtle, long-term effects on the biosphere which might result from acid precipitation.

II. OVERVIEW OF THE IMPACT OF SULPHUR DIOXIDE ON THE ECOSYSTEM

Concerns about sulphur dioxide release into the environment are justified. Globally, sulphur dioxide acts as an acidifying agent that is contributing substantially to changes in chemical climate. Locally, where large quantities of sulphur dioxide are released, marked changes have been measured in precipitation chemistry as well as in aquatic, edaphic, and vegetational components of the ecosystem.

Aquatic changes that have been measured around industrial activities in Canada, the U.S.A., Sweden and Norway include an increase in the acidity of waters of lakes and rivers. Swedish hydrologists have reported significant increases in sulphate content of certain affected river systems. These changes have been shown to result in the impoverishment of aquatic communities. In lakes around Sudbury, Ontario and in southern Norway, fish fauna have been shown to suffer reductions in growth, diversity, and abundance. In Norway salmon have been eliminated from several rivers and hundreds of lakes have been lost for sport fishing due to changes in water pH.

Deposition of sulphur dioxide onto forest soils results in changes to many soil processes and properties. Forest soils with lower buffering capacity are more sensitive to SO_2 damage than those with higher buffering capacity. Soil acidity caused by sulphur depositions has been shown to create an imbalance between available nutrients for plant growth. SO_2 has been shown to bring about such changes either as a result of its direct effect on soil chemistry (solubilization of various ions) or through its effect on soil microflora responsible for nutrient cycling, or both.

Elements in soil that are normally unavailable to vegetation, such as aluminum, can be released under acidic conditions and become phytotoxic elements. Aluminum is a common element in soils throughout the world including both the North and South American continents.

Forest vegetation is also affected directly by sulphur dioxide aerial emissions. Various levels and durations of SO_2 exposure have been shown to cause injuries such as foliar chlorosis, necrosis, premature foliar loss, inhibition of growth, and eventually plant death. Plant injuries in turn result in stand injuries such as decreased organic matter and increment per area, and changes in numbers, abundance, and coverage of vegetation. Translated into economic terms, losses are due to reduced fiber yields, or reduced foliar quality and quantity, as in the case of ornamentals, shelterbelts, recreational and watershed values, and wildlife habitat.

III. EFFECT OF SO_2 ON THE GROWTH OF FOREST VEGETATION

The growth and yield of vegetation are the direct result of physiological and biochemical activities within the tissues. The environmental factors such as temperature, moisture, light, etc. play an important role in determining the rate of metabolic activity. It has been suggested that air pollutants in the atmosphere can affect tree metabolism either temporarily or permanently depending upon the concentration and length of exposure.

The air pollution effects of SO_2 on forest vegetation are twofold. First, there is a direct effect on vegetation, and secondly there is an indirect effect through contamination of soils. SO_2 can alter the soil nutrient balance and modify the growing medium for plants and soil microorganisms. This section is restricted to the effects of SO_2 on vegetation.

Sulphur dioxide is one of the major air pollutants released from industrial activity in the Alberta Oil Sands area and has the potential to cause severe damage to the forest vegetation. The general belief that vegetation must exhibit visual symptoms for damage to occur is misleading. In many greenhouse studies, SO_2 has been shown to reduce the growth and yield of vegetation in the absence of visual symptoms. This may be the result of disturbances at the ultrastructural or biochemical level or both. SO_2 injury to vegetation at the visual symptom level may be irreversible. Therefore, the development of techniques to detect injury at the previsual symptom level is highly desirable.

The objectives of our air pollution research program at the Northern Forest Research Centre are (1) to develop sensitive and reliable methods for detecting air pollutant injury to forest vegetation prior to visual symptom development, (2) to establish threshold levels of air pollutant injury to vegetation, and (3) to screen candidate revegetation species on the basis of their true tolerance to air pollutants.

There are a number of physiological or biochemical processes in plant metabolism that are interfered with before the development of visual symptoms of SO_2 phytotoxicity. Our work at the Northern Forest Research Centre has provided sufficient experimental evidence to support this point of view. We believe that SO_2 injury to vegetation is brought about in the following progression:

1. Injury at the subcellular level or ultrastructural level
2. Injury at the biochemical level
3. Injury at the cellular level
4. Injury at the visual symptom level

In order to identify air pollution injury at an early stage, detection will have to be carried out at the physiological or biochemical level. We will now report some of our own work on the effect of SO_2 on biochemical and ultrastructural functions in pine needle tissues before and after the development of visual symptoms.

EFFECT OF SO_2 ON CHLOROPHYLL CONTENT

Since most plants exposed to high concentration of SO_2 show discoloration, it was thought desirable to study the effect of SO_2 on chlorophyll metabolism. The needles from lodgepole pine seedlings (5-6 months old) were treated with aqueous SO_2 for about 22 h and changes in chlorophyll content were determined spectrophotometrically. The needles that were incubated in 10-100 ppm aqueous SO_2 solution looked quite normal and green whereas those exposed to higher concentrations (250-500 ppm) exhibited increasing degrees of discoloration or leaching. On the basis of biological activity of SO_2 (phytotoxicity), it has been suggested that there is 1 to 1000 relationship between gaseous and aqueous SO_2 concentrations respectively.

The low concentrations (10-100 ppm SO_2) did not result in any appreciable changes in total chlorophyll content. However, higher concentrations (250-500 ppm SO_2) produced a sharp drop in the pH of the incubation medium and total chlorophyll content *(Table 1)*. At 500 ppm, the pH dropped to 3.95 and chlorophyll content was reduced to about half that of the control values. These results suggest that loss of chlorophyll may be a result of high acidity in the incubation medium. However, the HCl control adjusted to the same pH as produced by 500 ppm SO_2 showed only about 4% decrease in chlorophyll content compared to the regular control. It is therefore evident that the pigment destruction resulted mainly from direct effects of SO_2 and was not acid-regulated.

Further experiments showed that SO_2 destroyed chlorophyll molecules by releasing magnesium from the pigments. Magnesium is an important component of the functional chlorophyll molecules.

EFFECT OF SO_2 ON ULTRASTRUCTURAL ORGANIZATION OF CELLS

Electron microscopy has been used to study the effect of air pollutants such as nitrogen oxides and ozone on the ultrastructural organization of plant tissues. However, very little is known about SO_2 in this respect.

According to cytological examinations, the tip of the pine needle is composed of old and fully differentiated cells and the base contains very young and actively growing cells. About 1-cm sections excised from the tips and bases of pine needles were incubated for 22 h in different concentrations of aqueous SO_2 solutions, and the ultrastructural changes in chloroplasts were examined by means of electron microscopy.

In older, mature tissues, aqueous concentrations of 100-500 ppm SO_2 caused swelling of thylakoid discs and disintegrated other intrachloroplast membranes, resulting in the formation of small vesicles. Chloroplast structural injury was more pronounced in older tissues than in younger tissues. In general, electron microscopy showed that older, fully matured tissue is more sensitive to SO_2 injury than the younger actively growing tissue.

EFFECT OF GASEOUS SO_2 ON BIOCHEMICAL FUNCTIONS

Recently we have been fumigating plants with gaseous SO_2 to determine if aqueous and gaseous SO_2 produce similar effects. The biochemical results obtained with gaseous SO_2 were very similar to those produced by aqueous SO_2 solutions.

The results from the preliminary experiments car-

TABLE 1

The Effect of Various Concentrations of SO_2 on Total Chlorophyll Content of Pine Needles

Treatment	pH of Incubation Medium	Chlorophyll Content (Mg/1)	% of Control
Control	7.20	65.27	100.00
10ppm SO_2	7.18	64.13	98.25
25 ppm SO_2	7.13	63.50	97.29
50 ppm SO_2	7.10	63.82	97.78
100 ppm SO_2	7.00	63.38	97.10
250 ppm SO_2	6.60	47.98	73.51
500 ppm SO_2	3.95	34.69	53.15
HCl control	3.95	62.71	96.08

ried out with plants exposed to .17 ppm SO_2 for different lengths of time (Alberta ambient air quality standards) showed a 20-30% decline in the various biochemical parameters measured. However, 24-28 h after fumigation, there was a considerable recovery of these biochemical functions. The limited amount of our experimental data suggests that the present federal and provincial ambient air quality standards are quite effective in preventing any permanent damage to lodgepole and jack pine trees. Work is currently underway to determine the effect of SO_2 on a wide range of forest vegetation. It will enable us to confirm the existing ambient air quality standards or help establish new standards in the light of experiments with native plant and tree species.

IV. IMPACT ASSESSMENT

The main purpose of impact assessment is to clarify the significance and risk of air pollution injury to various environmental parameters. The essence of a good assessment lies in presenting facts, not opinions, resulting from clear, direct, scientifically based methods and techniques.

The primary objectives in this process are identification, evaluation, and quantification of impact. Data gathered to these ends should also contribute towards understanding the interdependency of various impacts and allow comparison of alternatives where possible.

The major considerations for impact assessment of aerial emissions from the *in situ* petroleum industry on forest soil and vegetation are 1) the baseline character and conditions of the forest environment, 2) aerial emission factors, and 3) the interactions between the aerial emissions and the forest environment. From these interactions a concise overview of impacts should be able to be drawn. Further, predictions of future impacts of alternative proposed emissions could also be made.

An expanded list of considerations would be as follows:

1. Baseline Character and Conditions of the Forest Environment

The environmental parameters which may influence the dispersal or nature of the aerial emissions released need consideration. So do the forest climate, soil, and vegetative elements which may be affected.

1.1. *Physical environment considerations*

1.1.1 *Climate:* Consider, as they relate to dispersal of atmospheric pollutants, *temperature* (daily and seasonal variations, extremes); temperature inversions (type, frequency, and intensity); *winds* (velocity, frequency, direction, and duration of wind speeds); *precipitation* (kind, amount, duration, and frequency); incidence of fog (kind, duration, frequency); incidence of critical meteorological phenomena resulting from combined effects of its components (e.g., limited mixing conditions, drought, or wind scorch); *air quality;* and *air pollution potential.* Also, with relevance to the susceptibility of bioreceptors consider incident light energy, intensities, durations, and qualities; relative humidity, temperature means, extremes and fluctuations on the meso and micro-scales outside and within forest canopy; relationships of these parameters to regional climate measurements.

1.1.2 *Land:* Consider: topography, surficial geology and bedrock formations, mineral resources, and general land use capabilities; description of the soils throughout the area, including soil types, composition, structure, nutrient level and availability, moisture conditions, and erosional potential; and generalized terrain stability/susceptibility based on terrain performance after denuding or disturbance.

1.2 *Biological environment considerations*

1.2.1. *Flora:* Consider *vegetative communities,* their species composition, vigour and abundance in ways relatable to other components; *soil microorganisms* and their roles in nutrient cycling, food chains, and other soil properties; and relationships of vegetative elements to habitat and food sources of animals and birds.

2. Air Emission Factors

2.1 *Emissions*

Consider *gaseous* and *particulate emissions* fully: quantities, chemical composition, physical state, particle sizes and distributions, temperature, and exit velocity. Consider quantity data in terms of means and standard deviations on annual, seasonal, monthly, and daily bases for each component, and peak half-hourly averages in running time for SO_2.

Consider all potential operational and malfunctional fluctuations in emissions, operational alternatives for controlled fluctuation of emissions, and contingency plans for emergency disruptions or rare environmental events.

2.2 *Atmospheric chemistry and physics*

Consider all atmospheric chemical and physical transformations and reactions of emitted materials during their entire residence in the atmosphere.

2.3 *Dispersion, transport, and ultimate deposition*

By means of modeling and intensive actual measurements under a range of atmospheric conditions including extremes, consider the dispersion, transport, and eventual deposition of all emitted materials, including the percentage of each component deposited within a series of isopols. Estimate the quantity and form of each substance entering long-range transport (greater than 300 km).

Consider the form in which each component is deposited, whether as dust, dry fallout, or precipitation scavenging.

3. Interactions Between the Aerial Emissions and the Environment

Consider interactions at all stages from first impingement to ultimate fate of each component of emissions, including direct and indirect effects, short and long-term and cumulative, synergistic, antagonistic or potentiating effects of more than one pollutant acting in concert.

Optimally, data to consider this would be gathered by detailed, precise measurements and observations and would be presented in sufficient quantity and suitable form for clear and objective evaluation of quality and impact.

3.1 *Physical environment*

3.1.1 *Atmosphere:* Consider effects on radiation transmissability and consequently, on light quality, and meso- and micro-scale temperature and humidity.

Consider precipitation quantity and quality changes, including grossfall, throughfall, and stemflow.

3.1.2 *Land:* Consider short- and long-term and cumulative effects on soil properties, including direct toxicity; pH; titratable acidity; nutrients and their location and availability; quantity, rate, and quality of leachates; and erosional potential.

3.2 *Biological environment*

Consider biological transformation of each component of the emissions and determine its passage through biological systems and its ultimate stabilized form and fate.

3.2.1 *Flora:* Consider effects (as under main heading 3) on plants at all levels, including trees, shrubs, forbs, grasses, bryophytes, lichens, and litter and soil microorganisms; nutrient cycling organisms, especially nitrogen fixers; and effects on habitat and food species, including where indirect connections exist, as through invertebrate intermediaries, and including aquatic as well as terrestrial species and seasonal variations.

Consider synergistic or predispositional interactions with other natural stress factors such as diseases, insects, and climatic or nutritional stresses in both directions (i.e., pollutant-other stress, other stress-pollutant), and for all components of emissions.

4. *Impact Assessment and Predictions*

4.1 Describe concisely the overview of all forest soil and vegetative impacts discerned.

4.2 Predict future impacts of various alternative proposed emissions. Cross-referencing predictions to elements of data in the foregoing compilation.

In further comment: impact evaluation of soil and vegetation should be prefaced by definition of the total emissions and their dispersal patterns. Certainly emission qualities and quantities are familiar measurements to many chemical process engineers. In summary this information can be obtained by standardized stack sampling procedures, spectral plume analysis procedures or through estimates from process analysis. The precision and accuracy of these data are critical in allowing a straight-to-the-point assessment of impact possibilities and an overall reduction of field assessment work necessary to yield creditable impact evaluations. In the Alberta Oil Sands area for example, the clear definition of the total emissions is important in determining what elemental analysis should be conducted on soil and vegetational samples, what vegetation and soil responses should be carefully monitored, and which synergistic or predispositional responses to be alert for.

Similarly, the data on emission release rates, durations, and dispersion patterns that occur under various meteorological conditions are important in predicting dosages that forest areas will receive.

Predictions as to which directional sectors of a forest will receive the majority of the emissions over time can be made from meteorological wind data (speed and direction) and precipitation-wind roses.

As effective dispersion of emissions is highly dependent on the state of the atmosphere, meteorological modeling of dispersal under conditions of limited mixing is imperative to derive maximum surface concentration figures and persistance of these maximums within forest areas. The three plume dispersion models where higher emission concentrations are likely to occur are 1) the coning model, 2) the inversion break up model, and 3) the limited mixing model (Carpenter *et al.* 1971). When these conditions actually occur they can be integrated with the wind directional data, to further define those areas most likely to be affected.

Delineation of impingement areas is critical to efficient use of field evaluation time and expenses. It also makes possible, a more accurate extrapolation of the evaluations. Verification of the modeling systems' prediction values can be accomplished through establishment of a statistically sound grid network of ambient air quality stations or through mini sonde balloon lapse rate calculations coordinated with visible plume configuration trials. The former can be relatively expensive, depending on the number of stations needed to cover the area adequately.

V. ECOLOGICAL BENCH-MARKING AND BIOMONITORING OF SOIL AND VEGETATION

Definition of the real environmental impact of emissions on forests can best be accomplished by summating specific effects to various forest components. Paramount to evaluation of environmental impact on soil and vegetation is the formulation of discrete answerable questions on emission spread as indicated by deposition on the forest, accumulation and transfer of emitted elements by soil and vegetation, definition of vegetation responses, and changes induced in the soil.

Forest areas are not uniform in composition, but rather vary widely in vegetation and soils. Therefore, careful definition of soil and vegetation to obtain a data baseline needs to be accomplished before comparison and extrapolations can be effectively made. This process is termed ecological bench-marking.

1. Area Overview and Site Selection

General identification and descriptions of the various vegetational and soil parameters should be carried out for the dispersal and impingement patterns derived for the area. Inclusion of emission-free control areas is important for comparative purposes.

For many areas of North America there are forest cover maps and soil survey maps available, which provide good identification of dominant vegetation and soil types. Aerial reconnaissance and photographic documentation techniques also provide an overview of the forest. A well-planned multistage design is one approach to identification of the various vegetational and landform units. This method involves the use of overview imagery, such as would be obtained from the ERTS satellite imagery or high level small-scale aerial photography, as the summary base. Then, by means of sampling stages ranked according to detail produced (such as utilizing various larger scale imagery and finally ground truthing), the spectral signatures represented on the overview imagery are identified to a predetermined confidence level. Ideally, to facilitate differentiation of the major landform and vegetational cover types, both large- and small-scale normal and infra red color aerial photography would be taken. Following this, the vegetative and landform units can be separated into more fully defined units on the basis of selected relevant criteria such as species composition, density, ground cover, aspect, and elevation.

Aerial imagery taken at a previous date is sometimes available for overview purposes. Low-level aerial reconnaissance over the area can be important to delineate the current condition of the forest canopy and in observing and photographing plume dispersion patterns (if a visible plume is produced). Methods to delineate invisible plumes that utilize real time sulphur dioxide sensory and recording equipment mounted on helicopters have also been devised and are effective.

Infra red scanning techniques have been employed with some success in defining canopy condition. This method allows rapid delineation of forest areas under stress. Follow-up ground work is necessary to determine the cause of stress. Also, infra red scanners have shown poor desults in differentiating between degrees of progressive decline.

In summary, the overview process provides a data base on forest composition (e.g., forest cover types, their dominance and density) topography and landform features (e.g., elevations, slopes, aspects, water bodies, wet areas) forest canopy condition (e.g., areas of aerially detectable stress) and area logistics (e.g., road and river access, helicopter landing sites). This allows decisions on the number and location of on-the-ground soil and vegetation plot sites to be made logically rather than randomly. A totally random sample design has severe economic and logistic drawbacks in highly variable areas such as forest. Because of this variability, large numbers of ground evaluation sites would be required to provide valid comparisons with any degree of statistical confidence. As ground site work is very costly and time-consuming, it is considered expedient to prejudice the sample using well-defined characters, and effectively reduce the number of sites required. Other considerations in site selection relate to land and water use factors such as forest crop value, animal habitat, watershed value, and recreational use of the particular area.

2. Choosing Site-Specific Bench Marks and Biomonitors

Well-designed ground evaluation and sampling procedures should provide the type, accuracy, and quantity of data required with a reasonable expenditure of time and effort in the field. To accomplish this, statistical designs must be carefully blended with biological evaluation and chemical analysis methods. In brief this means that each combination of sampling or evaluation procedures conducted on forest vegetation and soils should be replicated adequately to meet a set of statistical design criteria. It is also important that control data be provided for comparison purposes.

Evaluation of soil and vegetation for impacts from sulphur dioxide and other accompanying aerial emissions are being conducted by the Northern Forest Research Centre of the Canadian Forestry Service at various locations throughout the northern boreal forest. Included are the forests in the Alberta Oil Sands area, where evaluations and biomonitoring are being conducted as part of the joint federal-provincial Alberta Oil Sands Environmental Research Program (AOSERP).

In general the dominant forest cover types throughout the northern boreal region — and consequently the ones most selected for study — are: 1) the pine stands that occupy the well-drained more open sites, 2) the poplar-white spruce-white birch mixedwood representing more intermediate sites, and 3) the black spruce stands occupying the wetter, poorly drained sites.

As part of the bench-marking process detailed descriptions and measurements are made of the vegetation and soils at each of the various selected sites. For reference purposes species lists are prepared of the trees, vascular plants, ground cover bryophytes and lichens, and corticolous lichens (those inhabiting tree bark). Cover and frequency of occurrence are measured for all groups, with records taken of tree stand density and age class. Soils are documented by description and photography of their horizons, and measures made of their general chemical nature such as acidity (pH), conductivity, and moisture content.

The bench-marking process is made more detailed by measuring and documenting the parameters which are to be used in specific biomonitoring or sequential measurement of soil changes. Vegetation and soils are used as indicators because they:

1) are important basic components of the ecosystem that clean air guidelines and regulations are aimed at protecting
2) are available and readily sampled at most sites
3) are stationary and ordinarily are stable in their compositions
4) show reasonably equal reactions if sufficient sample numbers are taken
5) provide real summations of influence on specific sites
6) can be subjected to controlled environments for testing purposes.

Approaches that the Northern Forest Research Centre is currently using in definition of aerial emission deposition and impact on soil and vegetation are discussed below. Where possible, soil and vegetation sites are equipped with continuous air quality stations to allow comparison of receptor data and provide an additional data base for evaluation of vegetative response.

2.1 *Deposition and accumulation of emitted elements on forest vegetation and soils*

2.1.1. Elemental analysis of vegetation inhabiting the site: Plant species chosen to represent the forest community are sampled. Groups sampled include trees, vascular plants, lichen and bryophyte ground cover, and corticolous lichens.

Selection of species for elemental analysis is based on criteria such as predominance in the area and forest community, ability of the plant to act as an accumulator, foliar retention span, and contribution of the plant species to ecosystem maintenance, including roles in animal food chains and soil nutrient cycling processes.

Corticolous lichens and ground cover lichens and mosses are generally good accumulators of aerially deposited elements. Tree foliage is an effective accumulator of many aerially deposited elements, and tree bark is also a useful indicator. Best results from tree foliage are usually obtained from upper exposed crowns on the side facing the emission source. The measure of sulphur content in plants can be used as an indicator of sulphur dioxide in an area but not for its effects. Plants used as sulphur indicators yield only relative deposition and accumulation results.

Accurate measure of total sulphur in vegetative materials has posed some problems due to the volatile nature of many sulphur compounds. Recent comparative trials by scientists at NFRC have demonstrated that the oxygen combustion method (Chan 1975) followed by the Johnson-Nishita (1952) analytical procedure provides an accurate and repeatable measure of total sulphur in plant materials.

Measurements of other aerially emitted, more stable elements provide more clear-cut information about deposition and accumulation. Examples are vanadium, chromium, nickel, and other heavy metal cations that occur as trace elements in oil sand deposits and which may be aerially emitted. Acid digestion, low temperature dry ashing, or oxygen combustion followed by atomic absorption unit analysis are used in determination of these elements.

2.1.2 Elemental analysis of soil components: Forest soils have a layer of surface organic materials covering them. This layer, termed the LFH (standing for litter, fermentation, and humus zones), is composed mainly of materials deposited into it from the vegetative cover. The LFH is the major zone of accumulation in the forest system. Its composition is extremely important because it is the area where much nutrient recycling takes place. This is mainly accomplished by the decomposition of the litter through microfloral activity.

Sampling and analyzing the LFH is one of the best overall measurements of deposition and accumulation of aerially emitted elements. Because it is an organic layer, it is analyzed just the way the vegetation is.

Beneath the LFH lies the soil mineral horizons, the upper portions of which are inhabited by the forest vegetation root systems. Here the soluble nutrients (as leached out of the LFH), water, and some trace mineral elements are picked up by the vegetation. Critical are changes in composition or chemistry of this system that aerially deposited elements may bring or catalyse. In the mineral soil it is useful to measure emitted elements and parameters that indicate soil chemistry shifts, such as pH and availability of exchangeable elements in soil as influenced by chemical changes. These latter two measurements are especially important where sulphur dioxide is being emitted because it has considerable potential to acidify soil.

2.1.3 Collection and analysis of precipitation: Precipitation washes sulphur dioxide and other emissions out from the atmosphere and deposits them onto forests in modified concentrations. As this modified deposition may have a direct influence on soils and vegetation, it has been found expedient to collect the precipitation at sites and analyze its composition.

Also, when precipitation falls on the forest canopy it functions as a mechanism to wash off emission elements previously deposited on vegetative surfaces and carry them to the soil. To determine this influence, comparisons of precipitation that runs off trees (termed stem flow) and precipitation that does not contact the vegetation (termed through flow) are made.

During winter when snowfall blankets the soil and vegetative ground cover, the snow acts as an emission accumulator. Measuring sulphur and other elements trapped in this snow layer yields good information as to what has been deposited over the winter period and what amounts will be transferred to the soil during spring melt.

2.2 *Forest vegetation responses to aerial emissions*

The assessment of forest vegetation for responses to aerial emisions usually includes the evaluation of current status and establishment of detailed baseline data for future comparisons.

Plots for specific documentation of the vegetation are established within the forest cover types represented at each site. Forest vegetation is divided for reference into four groups: trees, vascular plants, lichen and bryophyte ground cover, and corticolous lichens. Responses of vegetation to sulphur dioxide aerial emissions are known to range from no measurable response at all through changes in plant metabolism and condition to species depletion. Because the response range is so wide, measures must be equally wide-ranging. Each vegetative group on the plot is quantified and described as to composition, cover, and frequency of occurrence, and the condition of its species is documented in detail. Documentation processes include written descriptions and measurements, photography and various types of sample collections.

Condition description and quantification involve evaluation of the various plant parts such as the foliage, buds, and cambial tissues with anatomical, morphological, physiological, and biochemical parameters measured. Examples of visual examination methods used to rate vegetative responses to aerial sulphur dioxide emission are given below.

2.2.1 Tree species indices: Where high dosages of sulphur dioxide have impinged on forests, gross alterations in leaf color and form often occur. These alterations are termed visible foliar symptoms and are well known for tree species. As well, microscopic evaluation of injured tissues aids diagnosis of sulphur dioxide injury. Tree species differ both in their foliar sensitivity to sulphur dioxide and their ability to survive once injured. In areas where tree foliar symptoms are produced, the following indices can be constructed around these differences:

1) Tree species foliar sensitivity indices — measure of percentage of foliage injured on an individual species.

2) Tree species injury index — summation of foliar injury plus mortality of an individual species.

3) Tree species site injury index (Sidhu and Singh 1977.) — summation of all tree species showing foliar injury plus mortality.

2.2.2 Lichen species indices: Lichen species display a wide range of sensitivity to air pollutants. Some lichens are the most sensitive forest plants to sulphur dioxide and other emissions known. Lichen evaluations can thus provide a first indication as to whether aerial emissions are causing changes to the forest floral system. Lichen indices used are based on

1) Lichen species depletion — where zones of aerial emissions can be mapped according to these depletions. (Desloover and Leblanc 1968)

2) Lichen luxuriance and density reduction — where quantification of these factors is used to determine impact zones. (Skorepa and Vitt 1976)

3) Lichen Transplants — where healthy lichens are moved into suspect pollution zones as indicative monitors.

On the near horizon are various physiological and biochemical field evaluation techniques which will provide both earlier detection of response and finer distinction of injuries.

The very sensitive biochemical assay methods as described in this paper are good examples of such techniques.

REFERENCES

Carpenter, S. B. et al: 1971. Principal Plume dispersion models: TVA Power Plants. A.P.C.A. 21:491-495.

Chan, C.C.Y.: 1975. Determination of total sulfur in vegetation by a turbidimetric method following an oxygen-flask combustion. Anal. Lett. 8:655-663.

Desloover, J. and F. Le Blanc: 1968. Mapping atmospheric pollution on the basis of lichen sensitivity. pp. 42-56. *In* Proc. Symp. Recent Adv. Trop. Ecol.

Dochinger, L. S. and T. A. Seliga: 1976. Editors. Proceedings, First International Symposium on Acid Precipitation and the Forest Ecosystem. U.S. Dept. Agric. Tech. Rep. NE-23.

Johnson, C. M. and H. Nishita: 1952. Microestimation of sulfur in plant materials, soils and irrigation waters. Anal. Chem. 24:736-742.

Sidhu, S. S. and P. Singh: 1977. Foliar sulfur content and related damage to forest vegetation near a linerboard mill in Newfoundland. Plant Dis. Pap. 61 CD 1. pp. 7-11.

Skorepa, A. C. and D. H. Vitt: 1976. A quantitative study of epiphytic lichen vegetation in relation to SO_2 pollution in western Alberta. Environ. Can., For. Serv., North. For. Res. Cent. Inf. Rep. NOR-X-161.