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Invited Paper
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MODELLING TREE DAMAGE-TYPE PATTERNS FOR PHOTO INTERPRETATION OF SO_2 INJURY

ZUSAMMENFASSUNG: ABSTRACT: SOMMAIRE

The known effects of sulfur dioxide (SO_2) on forest trees are reviewed and discussed in photo interpretation terms. Acute and chronic injuries cause many different damage syndromes over short and long terms, and can cause considerable confusion during photo interpretation. However, modelling the "flow pattern" of the damage syndromes as they progress from initial effects to the final (dead-tree) syndrome facilitates interpretation. The generalized flow patterns of SO_2 caused damage syndromes for coniferous and deciduous boreal trees are presented. The patterns are illustrated with specific examples.

INTRODUCTION

The separation of SO_2 (sulfur dioxide) caused damages to trees from other sources of damage is a perplexing problem faced by the photo interpreter. A damaged tree can be interpreted from the remote sensing data. However, without ground data and correlation analysis performed to show relationships between the photo interpreted data and the ground data it has been virtually impossible for the interpreter to state the cause of the damage.

In many remote sensing studies, the cause of damage has been defined because of a priori knowledge. Such knowledge has included the collection of insects, laboratory culture of pathogens, or foliar analysis for chemical elements such as sulfur. Yet in other studies, the evidence has been mostly circumstantial, and it has been assumed that a damaged tree close to a known source of stress (i.e. air pollution such as SO_2) has been affected by the particular stress. Without the costly ground analysis technique, what remote sensing evidence is available to link cause and effect? It is the purpose of this paper to show that modelling of tree damage-type patterns reveals a "signature" for SO_2-caused damage to trees.

Injury, Stress, Strain, Damage

The participants at the Symposium on Remote Sensing for Vegetation Damage unanimously passed a resolution that "authors should take greater care in use of words such as damage, etc., and carefully define them

The speed of the injury and the intensity of the damage are related to the condition of the stomata (open or closed), the degree of development or growth state of the foliage (newly formed or late in the growing season), and the relative humidity and air temperature of the time of exposure (Webster, 1967). During periods when the stomata are open, the SO_2 enters the leaf, reacts with water vapour (H_2O) in the spongy mesophyll and other tissues of the leaf to produce sulfurous acid (H_2SO_3) and sulfites. Plants have the capacity to oxidise sulfites to sulfates at a given rate. It was stated by Webster (1967) that:

> "If the rate of absorption of the gas and production of sulphites does not exceed the capacity of the plant to convert the latter to sulphates, then the plant may be able to tolerate the level of pollution indefinitely although the accumulation of sulphates and reduction in the buffer capacity of the leaf may proceed to a point where the leaf is subjected to a process resembling normal senescence."

There is some evidence that chronic fumigations by SO_2 affect the growth of woody plant species. Dochinger and Jensen (1975) and Jensen and Dochinger (1979) reported reduction of height growth of seedlings fumigated with 0.25 ppm SO_2, which in turn was related to a reduced growth rate. Acute SO_2 fumigation has also been noted to affect radial growth of pines. Murtha and Trerise (1977) reported a case whereby diameter increment increase was reduced about 50% the year following an acute SO_2 fumigation.

Several authors have studied the response of various tree species to SO_2. Generally, hardwoods are more susceptible to chronic damage than are conifers and some species of hardwoods are more susceptible than are other species of hardwoods. Intraspecific reaction has been documented, and Houston (1974) reported clones of *Pinus strobus* L. varied in response to SO_2, whereas Dochinger and Jensen (1975) reported variable responses in hybrid poplar (*Populus deltoides* Bartr. X *P. trichocarpa* Torr. & Gray) clones. Enderlein and Vogl (1966) discussed the sensitivity differences for several species of conifer. A generalized ranking of boreal tree species susceptibilites to SO_2 fumigations is presented in Table 1.

In addition to differential responses to SO_2 among clones of a given species, the short and long term effects cause considerable variation in strain syndromes which range from the initial responses of the plant, including the inhibition of photosynthesis (Bennett & Hill, 1973), chlorophyll breakdown (Carlson, 1974), premature loss of foliage (Jensen & Dochinger, 1979), and ultimately to the death of the plant (Webster, 1967). In some instances the affected plant may linger as a chlorotic dwarf, with obviously suppressed growth for several years (Dochinger *et al.*, 1970).

Carlson (1974) described the injury to Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) needles induced by airborne sulfur compounds including SO_2. His description for the effects on Douglas-fir needles could be considered classic:

> "All of the Douglas-fir needles on which histology was done showed a distinct pathological syndrome unlike any caused by infectious disease. The mesophyll was always damaged before elements in the vascular cylinder were affected. Mesophyll parenchyma first granulated as the chloroplasts broke down, then plasmolyzed and collapsed. Then, within the

vascular cylinder, the albuminous cells of the phloem, phloem elements, and transfusion parenchyma hypertrophied and eventually collapsed. In the final stage of necrosis the endodermis also collapsed."

The descriptions by Carlson (1974), Dochinger et al. (1970), Webster (1967), and many others can be used to model a flow pattern of damage types for SO_2 strain to trees that can be used by photo interpretaters for the assessment of SO_2 damage.

Patterns of SO_2 Caused Damage:

SO_2 is an airborne gas that is influenced by wind patterns and topography. At Wawa, in northern Ontario, Canada, prevailing wind patterns have created an ellyptical-shaped damage zone, with the long asis in the direction of the prevailing wind-flow off Lake Superior (Murtha, 1972b, 1973). Vegetation on topographic positions exposed to the source of chronic levels of SO_2 pollution were recorded as displaying greater levels of damage than did vegetation in topographically sheltered areas.

In cases of acute SO_2 pollution and relatively little influence from winds, SO_2 acts like water: it flows along the path of least resistance and seeks the lower topographic elevations. The SO_2 ponds in depressions and is dammed by obstructions. It flows past trees, causing damage to the exposed side, and leaving the unexposed side undamaged. The patterns of acute damage caused by high concentrations of SO_2 after an industrial accident near Vinsulla, B.C. were described by Murtha (1972). It was noted on aerial photographs that the SO_2:

" ... was essentially dammed by rows of trees (along the fence-rows). The concentration of dammed SO_2 fumes increased and damage occurred. After building up concentrations in the dammed pools, the gas flowed, like water, around the natural dam and along the path of least resistance. Because of topographic variations and natural buffers, damage within a zone could be variable in intensity. When the gas moved over a stand of trees, the tops were frequently damaged, while the lower branches remained untouched."

Because of the variable reaction of trees, and the influence of wind and topography, special attention should be paid to photo-visible tree crowns. Experience has shown that the upper portion of the tree crown may be affected, whereas the lower portions, or protected portions of the crown may remain untouched.

SO_2 Related Damage Types:

A study of the literature has indicated that there are numerous SO_2 caused strain syndromes which may be called damage types. Murtha (1972a) presented a key to the photo interpretation of damage types for trees, and in essence presented a method for the photo interpreter to describe the syndromes as they are perceived during photo interpretation. Assignment of a damage type to a tree strain condition did not include citation of a specific stress. It is therefore useful to describe the SO_2 related strain syndromes in terms of damage types as defined by Murtha (1972a). The damage types associated with varing degrees of SO_2 damage are presented in Table 2.

The damage types given in Table 2 are photo interpretation damage types, and are based on the strain symptoms interpretable on the photo-visible portions of the tree crown. The symptoms seen are directly related to the photo scale (Carlson, 1978; Murtha, 1978; Zealear *et al.*, 1971). At very large scales (e.g., 1:1200) virtually all the symptoms are interpretable, but as the scale becomes smaller, certain symptoms are no longer resolved on the photographs. The first symptoms lost to the interpreter are the finer details in the crown, small bare branch tips, damaged individual leaves, etc. In the following discussion of the relation between SO_2 caused strain syndromes, and the damage types interpreted on the aerial photographs, it is assumed that large scale (±1:1200) photographs are being examined. Additionally, since color-infrared photographs record changes in near-infrared spectral reflectance, as well as at green and red wavelengths, the discussion is also related to color-infrared photos. The flow patterns of damage types for conifers and hardwoods are discussed in the next section.

SO_2 Damage Type Flow Patterns

The sequence of damage types for conifers affected by SO_2 has been modelled in Figure 1, whereas the patterns for hardwoods has been modelled in Figure 2. (The damage type descriptors were presented in Table 2.) The patterns for Figures 1 and 2 were derived after observation of, and subsequent photo interpretation of fume-damaged trees in interior British Columbia (Murtha, 1971; Murtha & Trerise, 1977), coastal British Columbia (Murtha, 1978), northern Ontario (Murtha, 1972b). Additional material examined to model the patterns included reports by Carlson (1974, 1978), Carlson and Dewey (1971), Jacobson (1970), and Zealer *et al.* (1971).

When a tree has been injured by SO_2, it has been reported that shortly before the chloroplast breakdown occurs (Carlson, 1974), cellular inclusions are affected and photosynthesis is inhibited (Bennett & Hill, 1973). Gausman (1977) has described the near-infrared reflectance resulting from cellular inclusions, and Webster (1967) has compared the process to senescence. Since it is known that near-infrared reflectance changes (usually a decrease) when foliage senesces, it is suggested that an initial decrease in near-infrared reflectance could occur before any visible change. Although this fact has yet to be confirmed by controlled studies, the damage type as recorded on the film and measured by densitometry would be IVA (increased cyan dye layer density) or IVB (decreased cyan dye layer density). When the response has been great enough to be seen (visually on the photos), the damage types are IIIOa (darker-), or IIIOb (lighter-magenta hue) (Murtha, 1978). The IIIOa and IIIOb syndromes are especially evident when comparisons are made with the same host tree species in the same photo frame, since trees of the same species can be differentially responsive to SO_2 injury. Evidence from numerous plots in SO_2 damage zones suggest that damage type IIIOb is more frequently seen than IIIOa (Table 3). Damage type IIIOb is considered a more advanced strain syndrome and thus would be evident for longer time periods. Damage type IIIOb is particularly evident in hardwoods in perimeter zones of SO_2 pollution. When interveinal necrosis has occurred and a large number of leaves have been affected, and have subsequently bleached to the "ivory color" as described by Webster (1967), the affected crowns will appear as a lighter magenta hue on color-infrared photos. Such trees are also classified as damage type IIIOb.

Because of image merging damage type (IIIOb) is also more frequently seen on smaller-scale (-1:3000) than on the very large scale (1:1000) photos (Case I, Table 3).

When the chronic effects of fume damage persist, chloroplast breakdown occurs and yellowed foliage is perceived and noted as damage type IIIB on conifers. Conifers, especially white pine in perimiter SO_2 damage zones, frequently display such chlorotic foliage (Dochinger et al., 1970). When yellowed foliage is seen on hardwoods it is classified as damage type IIID. After the yellow-foliage stage, the foliage frequently dies, and when the entire crown is seen with dead red-brown foliage, the damage type is IIIG (IIIN in hardwoods). Acute fumigations by SO_2 have killed the foliage in many trees virtually overnight (Murtha, 1971), and damage type IIIG will be very widespread, but the trees can recover (Murtha & Trerise, 1977).

In some cases the entire crown is not affected and it is only the upper portion, or one side of the crown, that yellows or blanches, producing damage type IIIA in conifers (IIIC in hardwoods) and when the foliage dies, damage type III I (or IIIM) is produced. Trees affected by acute levels of SO_2 frequently show directional damage, with the damaged side facing the source of SO_2. In zones of chronic SO_2 stress, directional damage is likely to be noted relative to trees in exposed topographic positions.

When current year foliage in the upper crown is displaying the red-brown (straw yellow) syndrome it is damage type III I (or IIIM in hardwoods). Dead foliage is usually abscissed) relatively quickly, and a tree with dead foliage at or near the top may be seen next as a dead defoliated top IIA (IIB in hardwoods). If needles have been prematurely abscissed and new growth has occurred, the tree is seen with an obviously thin crown, damage type IIE (IIG in hardwoods) is interpreted. Zones of chronic SO_2 fumigation frequently have many thin-crowned conifers, or hardwood with many inner branches showing (Case II, Table 3).

Trees which have died during the previous one or two years (Ib or ID) may be interpreted because of the dark appearance of the exposed branches. Trees that have been dead for several years usually have lost some branches, bark has been exfoliated and the exposed wood has been bleached white. Old dead trees are designated as damage type IA.

The damage types described above are typical of SO_2 strain syndromes. However, because of differential inter- and intraspecific variation, all damage types may be seen on the same aerial photograph. The frequency of occurence of any given damage type varies with the intensity of the SO_2 fumigation. Damage zones can be delineated based on the frequency of occurrence of damage types. Perimeter zones usually have a higher occurrence of damage type IIIOb whereas zones of greater damage show more thin crowned, dead-topped or dead trees. Table 3 illustrates three case studies, where Cases I and II concentrated on damage to hardwoods and Case III was a study on conifers.

Cases I, II and III represent, in relative terms, light, medium and heavy damage situations. As the damage increases the percentages of a given damage type shift from the IIIOb stage (Case I), to the partial defoliation stage (i.e. IIA and IIE) (Case II) to a high percentage of dead trees (IA, (Murtha, 1978). For purposes of clarity in discussion, the following definitions are presented:

a) injury: any stress on a tree which impairs health and results in strain which may be noted because of either temporary or permanent syndromes;
b) stress: any environmental factor capable of inducing a potentially injurious strain on the tree (Levitt, 1972);
c) strain: any physical or chemical change produced by stress (Levitt, 1972);
d) damage: any loss, either biological or economic, due to injury;
e) damage type: any syndrome, expressed by the tree of either temporary or permanent strain.

Levitt (1972) notes that stress induces strain in the plant, and describes strains as either "elastic" (reversible) or "plastic" (irreversible). It has been generally noted that sulfur dioxide (SO_2) causes irreversible strain on the foliage, if the tree has been exposed to sufficient quantities of SO_2. Some plants are more resistant to SO_2 than are other plants, and some clones are more resistant than other clones. In fact, plants respond differently to SO_2 stress, but when they do respond, the strain reactions are similar and are revealed by patterns of damage types that can be interpreted from air photographs. The effects of SO_2 in forest trees are discussed in the next section.

Effects of SO_2 on Forest Trees

SO_2 causes either acute or chronic injury to plant cells, the degree of resultant damage depends on the length of exposure, concentration of SO_2, and leaf condition at the time of exposure.

Acute injury is caused by high concentrations of SO_2 acting over relatively short time periods. The strain syndromes are recognized, on the ground with foliage sample in hand, by clearly defined areas of dead tissue (called necrotic tissue) between leaf veins or on the leaf margin, which initially are dull, but later, dry-up and give a reddish brown color, or bleach to an ivory color (Webster, 1967). In cases of extremely high concentrations of SO_2, the entire leaf may be killed, along with the growing shoot or leader. Common sources of unusually high concentrations of SO_2 are industrial accidents. Severely strained foliage is generally abscissed and depending on the growing season it may be replaced in the same year, if the fumigations are not repeated. In rare cases, the branches may be killed, or more generally some of the smaller branch shoots or newly formed leaders may be killed.

Chronic SO_2 injury is caused by long exposure of foliage to relatively low concentrations of the gas. The chronic strain symptoms appear as " ... yellow to brown inter-veined chlorosis (called chloratic tissue) due to plasmolysis and injury of some of the mesophyll and palisade cells" (Webster, 1967). Affected foliage usually has an increased sulfate content. Some of the leaves may be prematurely shed, and trees in polluted areas are often deficient of foliage. The sulfur content of foliage increases relative to the length of exposure, and reflects the degree of pollution in an area. SO_2 damage is generally confirmed by foliar analysis for unusually high sulfur content.

1B) (Case III). When the percentage of IIIOb trees is high, the percentage of dead trees is low (Case I). When the percentage of partially defoliated trees is high, the percentage of IIIOb trees has dropped substantially, and the percentage of dead trees remains low. When the percentage of dead trees is high, the percentage of trees in the other categories is substantially reduced.

Summary

It is suggested here that the model for the sequential flow of damage types represents a unique signature for the photo interpretation of SO_2 injury. The percentage or number of trees displaying a particular damage type will vary with the intensity of the SO_2 fumigation, the distance from the source of SO_2, and the tree species present in the affected area. The compounding factors are the direction of the prevailing winds, climatic patterns such as temperature inversions, air temperature and relative humidity, the influence of topography, and the growing stage of the plant during the fumigation. Although other forms of air pollution such as fluoride, ozone, etc. may cause somewhat similar patterns, other stress vectors such as insects, disease or even poor site conditions do not give the same or even similar patterns of damage types. Most, if not virtually all insect and disease vectors are host specific, whereas site effects can be evaluated on the basis of terrain analysis. SO_2 injury is airborne, affects more than one or two species of tree, is influenced by winds and topography, and diminishes with distance from the source. When trees are affected by SO_2, there is a defined sequence of damage types which were modelled and can be used by the interpreter to assess SO_2 caused damage.

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Table 1. Ranking of susceptabilities of boreal forest tree species to the effects of SO_2. (Rankings are derived from a review of tree reactions described in papers cited in the "Literature Cited" section of the end of this paper.

Rank	Tree Species	
Most susceptible	white birch	- *Betula papyrifera* Marsh
	trembling aspen	- *Populus tremuloides* Michx.
	cottonwood	- *Populus trichocarpa* T. & G.
	white pine	- *Pinus strobus* L.
	jack pine	- *Pinus banksiana* Lamb
	balsam fir	- *Abies balsamea* (L.) Mill
	red maple	- *Acer rubrum* L.
	white spruce	- *Picea glauca* (Moench) Voss
Least susceptible	black spruce	- *Picea mariana* (Mill) BSP

Table 2. Description of coniferous damage types (strain symptoms) used to describe the effects of SO_2, as seen in large-scale normal-color, or color-infrared aerial photographs. Hardwood damage type equivalents are given in brackets (after Murtha 1972a).

Damage Type	Description
IA	Tree dead, bark exfoliated, exposed wood bleached whitish through weathering (long dead tree).
IB (ID)	Tree totally defoliated, limbs and branches maintain bark, and are dark toned on the photographs.
IIA (IIB)	Terminal leader or upper branches dead and defoliated, lower crown still retains green foliage.
IIE (IIG)	A thin-crowned tree, premature loss of inner-branch foliage, inner crown branches visible on aerial photographs, current foliage is present.
IIIA (IIIC)	Some foliage yellowed, most of the tree crown is not yellowed, and residual foliage is the normal green hue.
IIIB (IIID)	Entire crown is yellowed; (this strain syndrome shows as a mauve hue on color-infrared photos).
IIIG (IIIN)	Entire crown shows dead, red-brown foliage.
III I (IIIM)	Terminal portion of a conifer crown, or varying amounts of foliage in the upper portion of a hardwood crown, display dead, red-brown hues.
IIIOa	Foliage is seen as a darker magenta hue on color infrared photos, the darker-than-normal magenta hue is noted by comparison with other trees of the same species.
IIIOb	Foliage of these trees is seen as a lighter magenta hue on color infrared photos and is noted by comparison with other trees of the same species in the same photo frame.
IVA	Red-filtered optical density measurements on color-infrared photos show a greater cyan dye-layer density than that shown for a normal tree.
IVB	Red-filtered optical density measurements on color-infrared air photos show a lesser cyan dye-layer density than that shown for a normal tree.

Table 3. Percent of trees by damage type with comparison of control zone and test zone (i.e., SO_2 affected) trees in natural unmanaged forest situations.

		No. of Photo Plots	Total Trees	Damage Types IA	IB	IIA-B	IIE-G	IIIB-D	IIIG-N	IIII-M	IIIOa	IIIOb
Case 1	Control	28	259	7.3	0	19.3	1.5	1.9	0	27.0	3.0	6.2
	Test	24	434	2.5	3.7	32.5	0.5	2.5	8.3	14.0	3.0	38.7
Case II	Control	30	1546	0.4	0.2	0.1	5.1	0.2	0	0	0	0
	Test	54	1465	1.2	2.6	3.1	53.0	1.4	1.2	13.0	0.6	7.8
Case III	Control	13	634	7.2	0.3	6.6	4.6	9.8	0.3	0.3	0.6	0.1
	Test	42	2313	20.4	5.7	13.4	6.0	11.9	0.2	0.6	1.6	2.8

1. Case I - Interpretation on original color-infrared transparencies, 1:3500, 23 cm^2 format.
2. Cases II & III - Interpretation on original color-infrared transparencies, 1:1200, 70 mm format.
3. Photo plots were approximately 1/10 hectare (1/4 acre) in each case.

FIGURE 1.

Flow diagram of damage types for different stages of tree decline for conifers suffering from SO_2 fume damage.

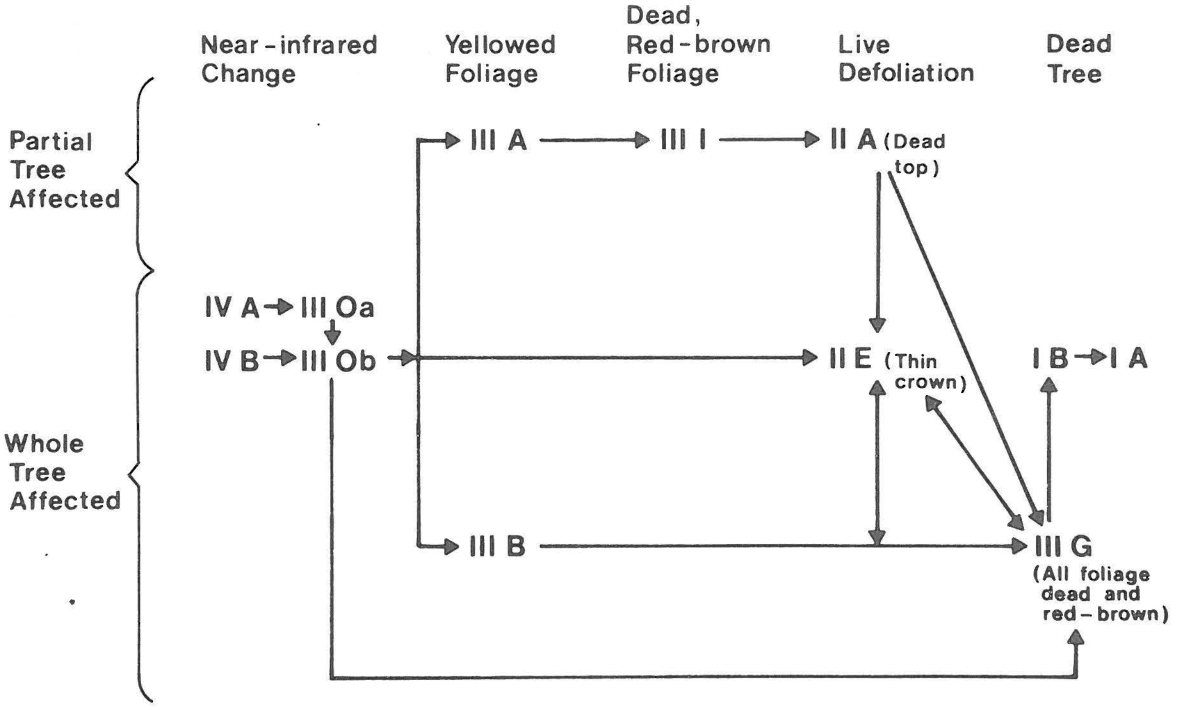

FIGURE 2.

Flow diagram of damage types for different stages of tree decline for hardwoods suffering from SO_2 fume damage.