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Remote Sensing and Vegetation Damage: A Theory for Detection and Assessment*

What constitutes remote sensing evidence of vegetation damage? How is vegetation damage interpreted from remotely sensed data? How can the damage be assessed?

INTRODUCTION

WITH SPECIAL REFERENCE to forest trees, the purpose of this paper is to consider and attempt to answer three questions relative to vegetation damage and remote sensing: (1) What constitutes remote sensing evidence of vegetation damage? (2) How is vegetation damage interpreted from remotely sensed data? and (3) How can the damage be assessed?

ABSTRACT: *This paper discusses the philosophical and technical aspects of remote sensing for vegetation damage assessment. Answers are presented for these questions: (1) What constitutes remote sensing evidence of vegetation damage? (2) How is vegetation damage interpreted from remotely sensed data? and (3) How can the damage be assessed? The answers to these questions are discussed in detail relevant to normal color and color-infrared aerial photography. Consideration is given to details of film reaction to variations in spectral reflectance patterns. Damages showing morphological or physiological changes are discussed relative to spectral reflectance changes and presented as a means to code damage types. An hypothesis for quantitatively monitoring forest damage is presented.*

In 1972, Murtha defined forest damage as "... any type and intensity of an effect, on one or more trees, produced by an external agent, that temporarily or permanently reduces the financial value, or impairs or removes the biological ability of growth and reproduction, or both." The definition is still applicable because recent evidence which will be presented verifies the definition, and indicates that it is relevant to remote sensing.

However, since 1972 considerable academic discussion has surrounded various viewpoints and practical applications concerned with remote sensing and vegetation damage. In 1976, Murtha recommended to Commission VII, International Society for Photogrammetry (ISP) that " ... studies be done to determine 'damage' on a more refined basis ... " than aerial estimations or counts of plants killed. The outgoing President of Commission VII, ISP, Dr. Sayn-Wittgenstein, wrote in 1977, "In forest protection the need is to concentrate far more selectivity on major insect pests and on situations where something can be done about problems that are identified. There should be less attention paid to damage assessments in purely scientific or biological terms and more to economics." Because of the diver-

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gent opinions, there is a need to review some basic ideas now. Although this paper has a threefold purpose as stated at the onset, the overall objective is to provide an applicable hypothesis for vegetation damage assessment by remote sensing techniques.

What Constitutes Remote Sensing Evidence of Vegetation Damage?

To interpret vegetation damage from aerial photographs, an interpreter must be aware of four areas of generalization:

- the possible damaging agents;
- manifestations of damage;
- effects of damage on spectral reflectance; and
- the resulting image on the areial photographs.

Damaging Agents

In any forest situation the forest manager may be faced with a perplexing variety of agents that could at any one time cause damage to the trees. They could range from insects, disease, fire, water, air pollution, and storms to enthusiastic recreationists and beaver. Any one could become a problem at any particular instance.

The perplexing "thorn-in-the-side" of the photo interpreter is the realization that many damage syndromes may be caused by one agent, and many agents can cause a specific damage syndrome. Unless there are identifiable associated features such as floodwaters from a beaverpond, burn patterns from a ground fire, a "ringworm" pattern associated with *Poria weirii* root rot, or trails associated with recreational impact, the interpreter requires a ground analysis to make the association of tree damage with a particular cause. Educated inferences can be made but, until remote sensing data interpretation receives the recognition it deserves from honest apprisals of results, ground checking and association analysis are required.

Most certainly, some of the forestry problems could be avoided by silvicultural practices once the forester and the entomologist got together to define forest practices and situations in order to reduce or eliminate the threat of insect damages. A recent example was outlined in a paper by Heller and Miller (1977), where remote sensing data were used to define stands susceptible to attack by the Douglas-fir tussock moth (*Orgyia pseudotsugata* (McD.)).

However, to concentrate on major pests and forget other possibilities could have unfortunate sidelights. For example, the North Thompson River valley has seen severe mortality caused by the Douglas-fir tussock moth, but recent studies have shown a volume loss, not only from the obvious tussock moth kill but also caused by SO_2 (Murtha and Trerise, 1977). Since many effects operate in a forest complex, the photo interpreter can only interpret symptoms or manifestations of damage.

Manifestations of Damage

Perhaps more has been written in confused terms about the manifestations of damage than should be, but virtually every "remote sensing for 'χ' damage" paper has some sort of description of the damage syndrome, and even the briefest of compilations of descriptions would show the tremendous variability of descriptions. Basically, there are two major manifestations of damage. Either the tree has suffered from a change in morphology, or a change in physiology, or sometimes both concurrently. If neither has been affected, then the tree has not been damaged. Morphological damage involves a change in shape or outline of the tree. Defoliation, either from the entire tree or a small branch, loss of branches, or even cellular collapse, are examples of morphological change. The other major type of damage is physiological damage, and this can be defined as a change in function as expressed by a deviation from a normal pattern. The normal tree has a specific set of functions required for maintenance of its biology. Physiological damage may be described as a decrease in photosynthates, deterioration of chloroplasts, interruption of translocates, including water, etc. Often the effects are not immediately visually apparent, but a subsequent change occurs to emphasize the damage. For example, a tree with a "problem" that interferes with the translocation of water may not be noted until the cells lose turgidity and collapse, thus causing the "wilted look." In this instance a morphological change has been effected. But even with other physiological damage, a change in morphology also occurs, e.g., growth reduction, needle loss, top dieback. One of the effects of damage is a change in the spectral signature.

Effects of Damage on Spectral Reflectance

One of the first visual symptoms of physiological damage is yellowing of the foliage, but this may not be the first change in spectral reflectance. Consider a generalized spectral reflectance curve for a normal green leaf (Figure 1-1). It usually shows a peak (10 to 20 percent reflectance)

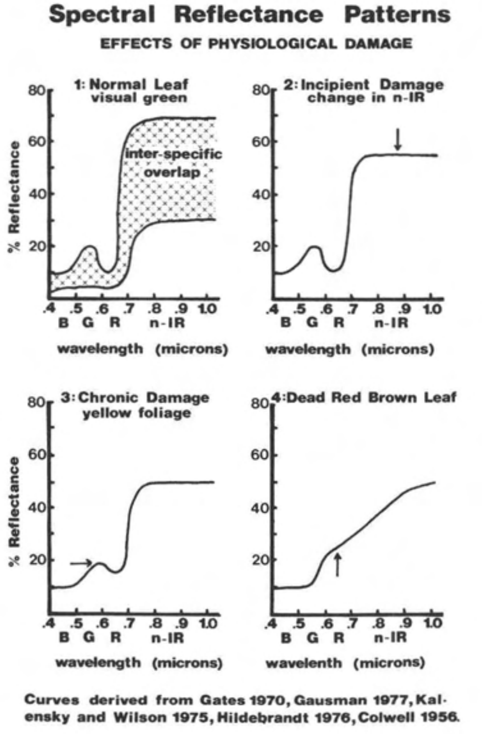

FIG. 1. Generalized spectral reflectance patterns for (1) a normal green leaf; (2) leaf with incipient damage indicated extravisually by a change in the level of near-infrared reflectance; (3) a yellowed leaf after a period of chronic damage; and, finally, (4) a dead red-brown leaf. Arrows derived from Colwell (1956), Gates (1970), Gausman (1977), Kalensky and Wilson, (1975), and Hildebrandt (1976).

in the green (500 to 600 nm) region and a lower level (8 to 10 percent) reflectance in both the blue (400 to 500 nm) and red (600 to 700 nm) regions, and a considerably higher level of reflectance (30 to 70 percent) in the near-infrared (700 to 900 nm) (Hildebrandt, 1976). The exact levels are determined by species, site, tree age, young *vs.* old foliage, nutrient status, etc. It is the *deviation* from this generalized curve from which changes in function may be defined. For example, chlorophylls 'a' and 'b' absorb light energy in the blue and red regions of the spectrum and reflect in the green. A change in the amount of chlorophyll causes a change in the absorption of blue and red light. For if the absorption of light is affected in any way, a change in the spectral reflectance pattern occurs, hence the functioning of the plant has changed. If the change is associated with an external factor, then damage could be occurring.

Extra visually, or in the near-infrared region (700 to 900 nm), a change is hypothesized to occur first. Perhaps the most recent evidence for this change was reported by Lillisand *et al.* (1975) who stated, "... the infrared photos show areas of damage at the end of 6½ hours that were not apparent on the visible band imagery at the end of an observation period of approximately 24 hours." (Bawden (1933) provided the first example.) Therefore, the first change in the spectral reflectance pattern is taken to be a change in the near-infrared region (Figure 1-2). Under certain circumstances the change could be an increase (Thomas *et al.*, 1966). Gausman (1977) stated that both crystals and cytoplasm as well as other structures contributed to the reflectance of near-infrared light. If physiological damage affects the functioning of the cell, then it is quite probable that it is also affecting the size and number of cellular crystals and the amount of cytoplasm.

Continuing chronic damage (e.g., a low-level effect over a long period) eventually causes a deterioration of chloroplasts. This change in physiology is generally visually noted as a yellowing of the foliage. Therefore, the second hypothesized change in spectral reflectance is the shifting of the green peak towards the red wave-length (Figure 1-3). This change may or may not be accompanied by a continued change in the near-infrared. Since such spectral changes require *in situ* measurements, there is virtually no evidence to indicate that the green to yellow peak-shift occurs before, somewhat after, shortly after, or almost concurrently with the near-infrared change. If the time period is short, i.e., measured in hours and not days, the period to obtain remote sensor data indicative of an extravisual change prior to a visual change is very critically short. If the second change, i.e., yellowing, did *not* occur, then it is incorrect to refer to the near-infrared change as a pre-visual change. Therefore, the near-infrared change is referred to in this paper as an *extra-visual change*.

The final generalized change is the reddening of the dead foliage (Figure 1-4). This change is accompanied by a continuing shift of the visual peak towards red, and thus an increase in red reflectance is noted. At this point, the near-infrared reflectance may be affected by environmental factors. If the foliage is air-dry, the dried cells are highly reflective of near-infrared and, if the dead foliage is wet, the reflection is decreased, since water is a well known poor reflector of near-infrared.

Morphological damage affects spectral re-

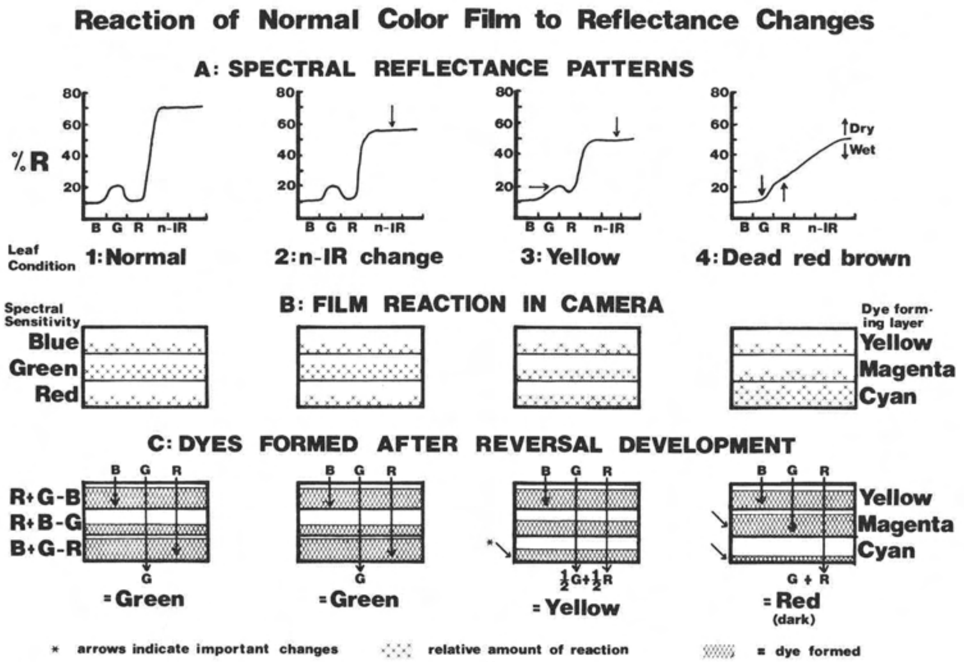

FIG. 2. Schematic reaction of normal-color film to differences in spectral reflectance, relative amounts of dyes formed, and visual color of image.

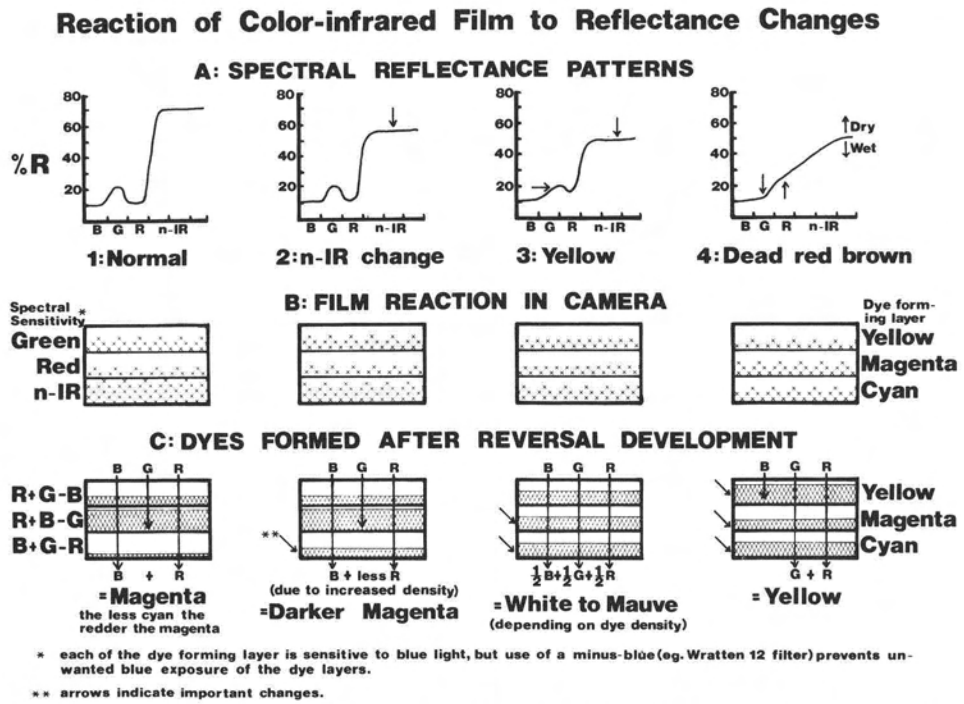

FIG. 3. Schematic reaction of color-infrared film to differences in spectral reflectance, relative amounts of dyes formed, and visual color of image.

TABLE 1. TRADITIONAL DYE-LAYERS OF POSITIVE COLOR FILMS.

Dye	Primary Color Components	Color Absorbed
Yellow	Red plus Green	Blue
Magenta	Red plus Blue	Green
Cyan	Blue plus Green	Red

flectance only when new surfaces are exposed, e.g., the number of contained shadows in the crown is changed. Morphological changes are best described on the basis of form, texture, and boundary patterns. Damages which affect spectral reflectance are best associated with physiological changes, and spectral reflectance differences affect differences in the film image.

IMAGE ON THE AERIAL PHOTOGRAPH

Finally, the photo interpreter must be aware of the effect of spectral reflectance changes on the image in the aerial photograph. In a diagramatic fashion, the results of the four general reflectance patterns are shown as they would affect normal-color (Figure 2) or color-infrared (Figure 3) aerial photographic transparencies. Here it is important to remember that the dyes in color transparencies are subtractive such that, when light is passed through, components of white light are subtracted (Table 1).

For example, when green foliage is photographed (Figure 2-1), the blue light affects a small part of the blue sensitive or yellow dye-forming layer, the green light affects more of the green-sensitive or magenta-forming layer, and the red light affects a small portion of the red-sensitive or cyan dye-forming layer. Since the amount of dye formed is inversely proportional to the exposure, after reversal development, relatively thick layers of yellow and cyan dyes are formed, and a proportionally thinner layer of the magenta dye is formed. Since yellow absorbs or "subtracts" blue light, and cyan subtracts red (Table 1), and the thin magenta layer passes more green light than it can absorb, the visual effect is to see the green foliage as a green hue. The hues seen for each spectral reflectance curve are shown in Figure 2. Note also that changes in the near-infrared reflectance are not recorded in the normal color film since it has only blue, green, and red spectral sensitivities. The situations for the color-infrared are depicted in Figure 3.

A normal leaf (Figure 3-1) is generally seen on color-infrared photos as a magenta (blue plus red) hue. Because of the high level of near-infrared reflectance, very little of the cyan dye was formed. Since cyan subtracts red light, and since there is very little or no cyan, most of the red light is transmitted. Because of the make-up of the film sensitivities, the formerly green sensitive, yellow dye-layer is also thin and consequently blue light is also passed through the yellow dye layer. A combination of blue and red gives the magenta hue (Figure 3-C1).

If a decrease in near-infrared reflectance occurs, the ultimate result is an increase in the density of the cyan dye-layer (Figure 3-C2). Very small (e.g., 0.02) density differences are difficult to see visually. Murtha and Hamilton (1969) measured density differences as small as 0.01 brought about by simulated animal damage on conifers. The differences were due to differences in the near-infrared pattern, since it was noted that only when a *concurrent* visual reflectance pattern change occurred was there a visual hue or *color* change in the image as seen on color-infrared films. Thus, a yellow, unhealthy leaf has a mauve tone on color-infrared films, when at the same time it may be seen as a "yellow" hue on normal color film. A dead tree with dry-green foliage, e.g., a cut Christmas tree, will be seen as a light magenta hue, since the dry foliage is highly reflective of near-infrared. It is for this reason that bark beetle infested trees are so difficult to interpret on aerial photographs before the foliage turns red brown.

The above models of film reaction assume perfect reacting conditions. Of course, it is known that exposure is affected by atmospheric attenuation at various altitudes. The image is also affected by scale, and image-merging occurs with decreasing scales. Image merging reduces the effect or overrides the effect of small or subtle spectral reflectance differences. Much of the photo interpretation literature has centered on these very special problems. Articles by Ashley *et al.* (1976), Ciesla (1977), Myers (1974), and Rohde (1977) have focused attention on such problems.

After consideration of the above four major points, the question is posed again: "What constitutes remote sensing evidence of vegetation damage?" The answer is now simple: a detrimental change in form or a change in function of the vegetation as it is seen on the remote sensing data.

HOW IS VEGETATION DAMAGE INTERPRETED FROM REMOTE SENSING DATA?

Many problems are associated with this

second question. The principal problems may be listed:

- one damaging agent can produce several damage syndromes;
- one damage syndrome can be produced by widely different and totally unrelated causes; and
- specifically, the effects of given damaging agents on spectral reflectance patterns are unknown, as are even the spectral signatures for a normal plant.

Thus, the approaches to interpretation have been based entirely on

- *a priori* knowledge,
- keys, and
- image enhancement techniques.

Related to the problems, some interpretation techniques have yielded empirical results that can, for the most part, be relied upon. *A priori* professional knowledge has been the most prevalent approach in interpretation of vegetation damage. Even the 1975 *Manual of Remote Sensing*, published by the American Society of Photogrammetry (Thorley *et al.*, 1975), followed the traditional approach to damage detection and assessment in that individual agents were discussed separately; e.g., foliage diseases, diebacks and wilts, root rots, stem diseases, and leaf-eating insects. This single purpose approach has limitations whether for initial inventories or for sequential monitoring. The basic problem is caused by the myriad of syndromes effected by one damage agent, and this poses a secondary problem: Which syndrome does the interpreter search for during interpretation? Ciesla (1977) suggested that the experienced interpreters "... were able to separate mortality by host tree in using the subtle differences in tones of red (on normal-color film) in the same manner as they were able to do during aerial sketch-map surveys." In this instance, *a priori* knowledge was well adapted to a specific problem in which one damage syndrome was interpreted and separated from other trees with a similar damage syndrome. Were there other possible syndromes?

Keys are probably the best approach to tackle the problem of too many damage syndromes. Murtha (1972, 1976) outlined a detailed classification for damage types, e.g., Type I damage = total defoliation, Type II = partial defoliation, Type III = visual color change, concurrent with near-IR, and Type IV = extravisual spectral change that may be recorded by remote sensors. (Lillesand *et al.* (1975) has provided the most recent photographic example of Damage Type IV: extravisual changes in near-infrared.) Proponents of normal-color film-use only, have to ignore the near-infrared changes and must concentrate on visual spectral changes (refer to Figures 1, 2, and 3). (Refer to Appendix I for the Key to Damage Types (Murtha 1976).)

Which damage syndrome is interpreted by means of the key? Consider, for example, the flow or sequence of damage syndromes that may occur when a tree suffers from the chronic effects of air pollution, e.g., fluoride (Figure 4).

First, the physiology of the tree is affected and results in changes within the plant cells, and a concurrent decrease or increase in near-infrared reflectance occurs. When interpreted, this is damage type IV A (increased cyan density) or IV B (decreased density). (It is suspected that Type IV A will be

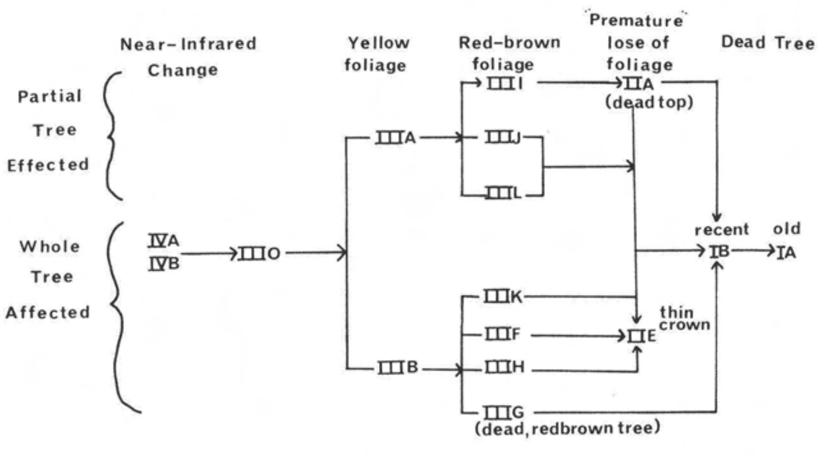

FIG. 4. Flow diagram of damage types for different stages of tree decline for trees suffering from fume damage. (Damage Types from key to Murtha (1972, 1976).)

the most common.) When the near-infrared reflectance change has been great enough to effect a visual density change in the cyan dye-layer, it is interpreted as Type IIIO, and is especially evident when comparisons are made with the same host species displaying different magenta hues. In some circumstances, a tree may be killed very rapidly during hot dry weather. Desiccation of the foliage is so rapid that the normal process of chloroplast breakdown does not occur. Consequently, long after the tree is dead the foliage is still green. On color-infrared photographs, the dead green tree appears a very light magenta, almost pink. The hues can be explained, and the tree is also classified as Type IIIO, and is noted especially well when compared to others of the same species.

However, if the chronic effects of fume damage persist, chloroplast breakdown occurs and Damage Type III B—the yellowed tree, is seen. Yellow foliage generally persists for less than one growing season; thus, when the foliage dies, it turns red brown. If only *older* foliage is affected, Damage Types III K (whole tree) or III L (few branches affected) are seen. In most cases *current-year* foliage is seen displaying the red-brown syndrome, in which case it could be the tree top (III 1), lateral branches (III J), the entire crown with all foliage red brown (III G), the older foliage absent (III H), or with the older foliage dark green (III F). The next obvious damage syndromes are IIA (a dead top) and premature loss of older foliage (II E). These are very common syndromes, well documented in literature of chronic damage effects (Carlson and Dewey, 1971; Carlson, 1974). The final stages are total defoliation. Type I B is used to designate a recently defoliated tree. Limbs, branches, and bark are present and the tree has a dark tone; gray on normal color photographs, dark blue-green on color-infrared photos. Finally, after the bark has exfoliated, some limbs and branches may be gone. The tree has a whitish appearance on both types of photos.

Figure 4, the flow of damage types, illustrates the problem facing the interpreter caused by a myriad of damage syndromes resulting from a single cause. In order properly to assess the impact of the damage, *all syndromes must be interpreted*.

Additional image enhancement aids have been used in the interpretation of damages. Murtha and Hamilton (1969) used an optical densitometer to assess cyan dye-layer density variations. Talerico, Walker, and Skratt (1977) used density measurements and ratioing techniques to estimate gypsy moth defoliation, while Lillesand *et al.* (1975) used a scanning densitometer to aid in root-rot discrimination. The correct use of image enhancement techniques follows or depends directly on the adequate knowledge of the manifestation of forest damage, the effects of damage on spectral reflectance, and the effect on the resulting image produced by remote sensor data. Image enhancement techniques are reviewed elsewhere (Lintz and Simonett, 1976).

How is vegetation damage interpreted from remote sensing data? The judicious use of professional *a priori* knowledge, tempered and categorized by keys and aided by image enhancement techniques, gives the most efficient approach for interpretation of vegetation damage.

How Can Vegetation Damage be Assessed from Remote Sensing Data?

Assessment of vegetation damage involves numerical evaluation. The simplest and easiest are—

- counting of individuals affected;
- delineation of the areal extent of the damage;
- multiplying area by ground surveys of crop production estimates to obtain damage volume estimates;
- stratification of area into damage intensity levels; or
- multiplying area of various damage intensities by predetermined volumes.

The above are some of the methods used in inventories (how much is where) and monitoring (obtaining indications of change). The third and fifth situations are used when some form of economic evaluation is desired. However, most of the studies have been based on dead, defoliated trees. Other damage types should also be included in assessments.

Murtha and Trerise (1977) reported the diameter increment decrease in the heavy SO_2 damage zone in pine stands that could be categorized as Damage Type II E (premature loss of old foliage) (Figure 5) and related this damage type to previously mapped levels of SO_2 damage. Stands less affected did not show similar diameter increment decreases. Reference to Figure 4 shows that II E is part way along the damage route but, instead of concentrating on II E trees for volume loss determinations, a worthwhile starting point could be III O, the probable initial point of crop loss. Because of these uncertainties, many studies are needed to relate crop volume losses to details of photo interpretation.

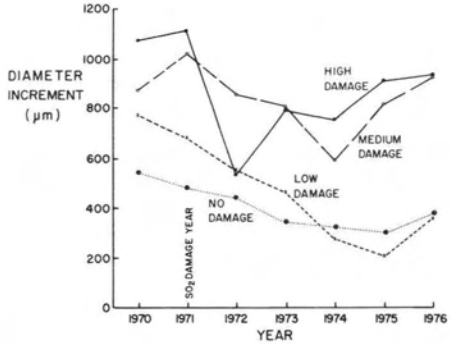

FIG. 5. Diameter increments for three SO_2 damage intensity zones and a control zone. Note the diameter increment decrease for the "High Damage" zone. These trees now display the IIE "premature loss of older foliage," or IIB "top dieback in hardwoods," damage syndromes (from Murtha and Trerise, 1977).

In complex situations, such as the long-term chronic effects of fume damage, the need is for monitoring and impact assessment on an annual basis to show increase, decrease, or an entropy state in the damage. Recent studies have shown that the damage types may be ordinally ranked in order to place more emphasis on current impacts, or be left unranked to place emphasis on the total impact. The damage types of Figure 4 are ordinally ranked and weighted in Table 2 to place greater emphasis on current impact in chronic situations. In each damage order, the percentage of the number of trees affected according to the total number of live trees counted on large-scale photo plots is calculated. In situations where the damage zone is known, it is necessary to establish photo plots in similar stands outside of the effects of damage. Average percentage values of "damaged trees" in the control plots may be determined. These values represent a value for damage to be expected in "normal stands" and as such should be deducted for each order. Finally, the weight value should be assigned to the calculation. Therefore, the general formula to express current impact of forest damage is—

$$\left[\frac{n}{\sum N} \times 100 - C\right] W = \text{plot damage value}$$

where N is the number of affected trees,
$\sum N$ is the total number of live trees,
C is the percentage of damage per order (Table 2) in control plots, and
W is the arbitrarily assigned weight (Table 2).

TABLE 2. ORDINAL STAGES AND RANK VALUE WEIGHTS IN ORDER TO EMPHASIZE CURRENT IMPACTS OF CONTINUING CHRONIC DAMAGE.

Damage Types	Order	Rank Weight
IVA, IVB	1	7
IIIO	2	6
IIIA, IIIB	3	5
IIIF, -G, -H, -I, -J, -K	4	4
IIA, IIE	5	3
IB	6	2
IA	7	1

In Table 3, some of the calculated plot damage values are presented, and differences between the control plots and the damage plots are clearly indicated. "Damage values" are shown in Table 4 for some photo plots in another forest region close to Kamloops, B.C. Plot No. 26 in Table 3 had trees showing severe premature loss of older foliage, indicative of the effects of chronic damage.

In a recent study in British Columbia, it was found that the plot damage values in a control zone generally are less than 60. In the damage zones the values range as:

very light—from 60 to 130;
light—from 131 to 195;
medium—from 196 to 260; and
heavy—is 260 or larger.

In clearly defined instances where damage is known to occur with an obvious boundary to the areal distribution of the damage, the photo plot damage values can be used to delineate intensities of damage. For example, in the North Thompson River Valley, calculation of the photo plot damage values in 1977 enabled the reconstruction of the zones of damage as they happened in 1971 (Murtha and Trerise, 1977). Premature loss of older foliage (Damage Type II E) and top dieback (II A and II B) were most prevalent in the heavy damage zones. In the photo plots, 25 percent of the trees in the heavy damage zone suffered top dieback, 14 percent in the medium damage zone, and 3 percent in the low damage zone, and an average of 1 percent of the trees had top dieback in the control or no damage zone. Photo plot sampling on a repeated basis gives the opportunity to assess whether damage levels are increasing, decreasing, or remaining static.

However, in other circumstances, where it is a question of determining if damage has started to occur and not how much has occurred, a reliable means of "internal" photo plot "*control*" must be found. Damage in any photo plot is relative to other trees in the

TABLE 3. SOME CONTROL PLOT AND SOME DAMAGE PLOT VALUES FROM A FOREST ZONE SUFFERING FROM FUME DAMAGE IN BRITISH COLUMBIA.

Control Plots	IB	IIA	IIE	IIIB	IIIO	Total Live Trees/ Photo Plot	Damage Value
1	—	4	4	—	—	54	25
2	—	7	—	—	—	93	15
3	—	5	—	—	—	54	13
4	1	2	6	—	2	62	41
5	—	3	4	—	—	130	0

Damage Zone Plots	IB	IIA	IIE	IIIG	IIIB	IIIO	Total Live Trees/ Photo Plot	Damage Value
1	—	8	—	8	5	—	67	92
2	13	3	—	—	1	—	7	716
3	1	11	—	—	5	1	27	73
4	7	5	4	1	—	5	56	143
5	2	8	3	7	—	—	45	196

plot, or to previous samples of the same plot. The control should form a base-line from which deviations may be noted. Because of film density variations caused by film-batch, developing, and reproduction, a gray-scale on the side of the film is a very tenuous reference point for biological details. The control could be a "normal" tree within the photo plot. The internal plot control was illustrated in a report by Murtha and Hamilton (1969) where red-filter optical density values of damaged trees had been plotted as a deviation from control trees. Clearly indicated was the fact that the greater the level of damage (including girdling in the main stem), the greater the deviation from the control baseline. The hypothesis fits with the key to damages types, including the incipient phases of Type IV or the IIIO phase with an obvious magenta tone difference among the host trees on the color-infrared original transparencies. Therefore, during interpretation of damage, any tree of the host species that does not exhibit any of the damage syndromes as described by Murtha (1972, 1976) can be considered a normal tree.

The above hypothesis on assessing forest damage is being tested in the Tranquille Forest in central British Columbia. Question: "How do you field check an extravisual damage syndrome in a tree crown?" Answer: "Trust the remote sensing data and skilled interpretation. If you're lucky (or is it unlucky (the tree may exhibit a visual damage syndrome or even die in the following few years. Then again, it could recover .... "

SUMMARY

The remote sensing evidence of vegetation damage is data indicative of a detrimental change in form or data indicative of a change in the normal functioning of the plant. Such data are concerned with changes in morphology as indicated by variations in texture and outline and changes in spectral reflectance patterns. In order to interpret the

TABLE 4. PHOTO PLOT DAMAGE VALUES OBTAINED FROM SCALE COLOR-INFRARED PHOTOS, TRANQUILLE FOREST, B.C.

Plot No.	IB	IIA	IIE	IIIG etc.**	IIIB	IIIO	Live Trees	Damage Value
22*	42	13	10	5	—	—	142	135
23	1	3	4	1	4	2	153	12
24	7	3	5	3	—	3	142	23
25	11	4	5	4	3	2	98	39
26	1	5	10	4	—	4	94	75
27*	12	4	7	—	23	—	72	193

* Plot numbers 22 and 27 were located in a zone of poor moisture drainage.

** Includes all damage types in the 4th order of damage, Table 2.

damage, the judicious use of professional *a priori* knowledge, tempered and categorized by keys and aided by image enhancement techniques, if necessary, gives the most efficient approach for interpretation of vegetation damage. To communicate damage syndromes, a categorical approach should be adopted in which damage types are clearly recognized. Such recognition provides an approach for damage assessment, permits a quantification of the damage data, and eliminates qualitative judgments.

In remote sensing for vegetation damage, the need is to concentrate on monitoring activities in areas where forest values are highest. The economics of the situation vary with the value of the product (e.g., pulpwood *vs.* recreation). Therefore, monitoring activities that include assessment of damage in scientific and biological terms necessarily precedes any economic evaluation. An hypothesis to assess vegetation damage by remote sensing techniques has been presented.

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Appendix I
Dichotomous Key to Air Photo Interpretation of Forest Damage Types[1]

1a[2] *Morphological:* on black and white or color aerial photographs a change in form is the prominent characteristic of the damage 2
2a *Type I Damage:* the trees are completely defoliated, or almost completely defoliated 3
3a Limbs and smaller branches are gone, only the main trunk is residual .... Damage Type IA
3b Limbs and branches are present 4
4a Conifer 5
5a Scattered individuals .... Damage Type IB
5b Large, extensive group .... Damage Type IC
4b Hardwood 6
6a Scattered individuals .... Damage Type ID
6b Large, extensive group .... Damage Type IE
2b *Type II Damage:* trees that show some defoliation through the presence of bare branches, or some form of malformation 7
7a Defoliated branches are concentrated at top or towards top of tree 8
8a Conifer .... Damage Type IIA
8b Hardwood .... Damage Type IIB
7b The defoliated branches are scattered throughout the crown, with, or without loss of limbs or branches, malformation may be present 9
9a Conifer 10
10a Malformation or obvious loss of some branches .... Damage Type IIC
10b Most branches are present, no prominent malformation 11
11a Current year's foliage missing .... Damage Type IID
11b 2nd year foliage missing, current year's foliage is present .... Damage Type IIE
9b Hardwood 12
12a Loss of some branches, or malformed .... Damage Type IIF
12b No loss of branches .... Damage Type IIG
1b *Physiological:* on color photographs, a change in the spectral reflectance pattern which is usually noted by a change in color of the foliage, or a measurable density variation in false-color photographs 13
13a *Type III Damage:* the foliage is another color when it is compared to normal foliage, on normal-color or false-color aerial photographs taken during summer . 14
14a Normal-color aerial photograph 15
15a Current foliage yellowing or yellowish 16
16a Conifer 17
17a Few branches affected .... Damage Type IIIA
17b All or nearly all branches affected .... Damage Type IIIB
16b Hardwood 18
18a Few branches affected .... Damage Type IIIC
18b All or nearly all branches affected .... Damage Type IIID
15b Some or all foliage red-brown, brown or turning brown 19
19a Conifer with red-brown foliage 20
20a Current foliage red-brown 21

[1] Source of key: Murtha (1972) used by permission of the author who developed the key while employed in a research capacity with the Canadian Forestry Service, Ottawa. Copies of the publication are available from Canadian Forestry Service, Environment Canada, Ottawa, Canada.

[2] There are two choices for each division in the key, the numbers represent the level or stage, while "a" and "b" represent the two choices involved.

21a All or nearly all of crown affected 22
22a Red-brown foliage associated with topographical pattern
....Damage Type IIIE
22b Older foliage dark-green, red-brown or absent 23
23a Older foliage dark-green or red-brown 24
24a Dark-green old foliage
....Damage Type IIIF
24b Red-brown old foliage
....Damage Type IIIG
23b Older foliage absent
....Damage Type IIH
21b Only a few or scattered branches with current foliage red-brown, or damage concentrated toward crown top 25
25a Terminal leader or upper crown red-brown
....Damage Type IIII
25b Lateral branches affected
....Damage Type IIIJ
20b Older foliage red-brown (current foliage not red-brown) 26
26a All or nearly all branches affected
....Damage Type IIIK
26b Few branches affected ....Damage Type IIIL
19b Hardwood with red-brown foliage 27
27a Few branches with red-brown foliage
....Damage Type IIIM
27b All or nearly all the crown red-brown
....Damage Type IIIN
14b False-color aerial photograph 28
28a Foliage of suspect tree a darker or lighter magenta tone than comparable unaffected tree
....Damage Type IIIO
28b Suspect trees not a magenta tone 29
29a Foliage appears mauve or yellow, if mauve see key item 15a, if yellow see key item 15b.
29b Trees appear blue, blue-green, silvery, which indicates defoliations. See key item 2a.
13b *Type IV Damage:* trees show no visible sign of damage, but a measurable density variation may be made 30
30a Red-filter optical density measurements on original false-color transparency indicate higher than average optical density for the affected tree when it is compared with an unaffected tree when it is compared with an unaffected tree of the same species in the same photo frame ....Damage Type IVA
30b Red-filter optical density measurements on original false-color transparencies indicate a lighter than average density ....Damage Type IVB

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