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Extravisual Damage Detection? Defining the Standard Normal Tree

By using color infrared photography, it was possible to designate the faster (normal) growing trees in a Douglas-fir stand.

Abstract: *Large-scale (1:1200) color-infrared aerial photographs of an interior British Columbia Douglas-fir (*Pseudotsuga menziesii *(Mirb.) Franco) stand were obtained on 9 June 1976. The trees were examined by optical visual analysis techniques for evidence of tree damages, and all damages were classified according to damage type. Red-, green-, and blue-filter analytical optical densitometric measurements were taken from the developed cyan, magenta, and yellow film dye-layers of the classified tree images. Red:green-, red:blue-, and green:blue-filter density ratios were calculated. The data were stratified according to the damage classification. The trees were subsequently field checked for accuracy of species designation, damage type classification, height, age, and any noticeable pathological condition. Radial increment cores were taken for diameter increment analysis.*

Results of the analysis indicated that the diameter increments were related to the damage classification. Damage Types III Oa and III Ob were noted because of a darker or lighter magenta hue than the neighboring "normal" trees. The diameter increment analysis indicated reduced radial increment for the trees classified as Damage Type III Ob. Although the trees were classified as Damage Type III O on the 1976 color-infrared air photos because of their darker or lighter magenta hue, they could not be separated visually on the ground even in 1978 by crown characteristics. These same III Ob trees showed significantly ($p < 0.05$) reduced radial increments when compared to normal trees. Thus, by using color infrared photography, a way has been found for the forester to designate the faster growing trees in a Douglas-fir stand.

Introduction

The purpose of this paper is to present some of the results of a three-year study dealing with interpretations of large-scale color-infrared aerial photographs for evidences of forest damage. Traditionally, forest damage has been defined on the basis of dead trees. However, there is a need to define forest damage in terms of healthy or normal trees. Such terms should be meaningful to the management forester as well as to the photo interpreter.

Dead trees, either defoliated or with dead discolored foliage, are easily recognized on large-scale color or color-infrared air photos. The problem is that the relationships between the symptoms of incipient damage as interpreted from the large-scale air photos and evidence of damage as collected on the ground are poorly understood. It is generally known that, when a tree is injured, it passes through a sequence of damage syndromes before it dies (Murtha, 1978). Severe injury kills the tree rapidly—consequently, the progression of syndromes is very rapid, even to the point that abscissic acid has not formed, and the dead foliage clings onto the tree for several months. Such may be the case with bark beetles or large quantities of SO_2. In cases of chronic injury (i.e., low levels of injury acting over a long period of time, usually several years), the decline and death of the tree is very slow, and the tree may linger in a sub-healthy state for several years. To the management forester these are the slow-growing trees, the ones that

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should be thinned out early in the rotation, that are more susceptible to further damage, and in essence, are the trees that cause problems for the forester. To the photo interpreter, these trees should be defined as abnormal, and thus the remaining healthy trees should be defined as the "normal" trees. The normal trees are the trees that the forester may want to carry through to crop maturity. Can the standard normal trees be defined (interpreted) on large-scale color-infrared photographs? The objective of the present study was to define by photo interpretation techniques, and to verify by ground measurements, the "normal standard" tree which could then be used as an "in-photo-standard-tree" against which other damages could be compared.

Literature Review

Detection of damage to vegetation on infrared photos before it can be (is) recorded on films sensitive only to the visual spectrum has been termed "previsual" detection. The assumption was that the damage would eventually become visually perceptive. Bawden (1933) provided one of the first photographic examples of detection of damage on infrared films before it was visually evident. Lillesand *et al.* (1975) reported a more recent example. (Interestingly, both examples were obtained under laboratory conditions.) There has been virtually no repeatable aerial photographic evidence of "previsual" damage detection, although some authors have attempted to provide explanations of the phenomenon (e.g., Fox, 1978).

Murtha (1978) discussed a theory of vegetation damage interpretation and the possible relation between vegetation damage and the effect on color infrared film. One of the first effects of damage was hypothesized to be a change in the level of near-infrared reflectance. The effect was termed *extra-visual* since it was implied that the near-infrared change may not necessarily be followed by a visual change. If it is followed by a visual change, it could then be correctly referred to as a "previsual" change.

The change in near-infrared reflectance relative to vegetation damage and its subsequent effect on the developed dye-layer densities has been studied. Analysis of variance (ANOVA) of densitometric data derived from densitometric readings on the cyan dye-layer of *original* photographs has indicated a relationship between levels of simulated damage on conifers and the density of the developed cyan dye-layer. A greater density of developed cyan dye-layer was correlated with increasing levels of damage (Murtha and Hamilton, 1969). Lillesand et al. (1978) have related stress in hardwoods to the developed densities of the dye-layers in color-infrared photographs. Since promising results have been obtained previously from the densitometric analysis of *original* color-infrared photos, it was decided to use densitometric analysis in order to *quantitatively* define forest damage. This decision was based on two assumptions:

- That there is a near-infrared reflectance change associated with the "first" symptoms of vegetation damage, and
- that there is sufficient change in the near-infrared reflectance to cause variations in the developed cyan dye-layer densities.

To analyze densitometric measures of tree crowns for evidence of forest damage, the trees must be stratified into different populations. Accordingly, the images of the tree crowns could be *qualitatively* interpreted according to damage types defined by Murtha (1972, 1978). These damage types are defined in Table 1.

It should be noted that, whereas Murtha (1972) defined Damage Type III O as "... a darker or lighter magenta tone than a comparable unaffected tree ...", in Table 1, Damage Type III Oa indicates a *darker* magenta, and III Ob indicates on color-infrared photos a *lighter* magenta-hued tree than the comparable normal magenta tree. Murtha (1978) explained that the darker magenta was due to "... increased density of the cyan dye layer ...", and conversely, the lighter magenta was due to "... decreased density of the cyan dye layer." The normal magenta without any other damage classification applied to it would become the "healthy" tree. Thus, a procedural method could be to qualitatively classify the trees according to damage types (Table 1) and then to take densitometer measurements which would then be stratified according to damage types. The trees should then be field checked for accuracy of damage type classification, and additional evidence of damage. The detailed methods actually used in this study are presented in the next section.

Methods

Air Photography

Large-scale (1:1200), color-infrared (Kodak Aerochrome film, 2443) photographs were taken 9 June 1976 with two 70-mm Vinten cameras equipped with 6-inch lenses and Wratten #12 plus CC20M filters. The reconnaissance cameras were mounted on the wingtips of a Cessna 180 (Williams, 1978). Both cameras were controlled by the same intervoltometer and, consequently, both films were exposed virtually simultaneously. The alignment of the cameras perpendicular to the line of flight permitted photo sidelap of about 85 percent. An on-board, closed circuit return beam vidicon (RBV) system permitted the photography of predefined photo plots. The subject of the photography was a Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stand located north of the Lac-du-Bois rangelands, in the Tranquille Provincial Forest near Kamloops, British Columbia.

TABLE 1. DESCRIPTION OF CONIFEROUS FOREST DAMAGE TYPES (AFTER MURTHA 1972, 1978) USED TO DESCRIBE THE TREE DAMAGES AS SEEN ON LARGE-SCALE, COLOR-INFRARED AERIAL PHOTOGRAPHS. [HARDWOOD DAMAGE TYPE EQUIVALENT GIVEN IN BACKETS.]

Damage Type	Description
IA	Tree dead, bark exfoliated, exposed wood bleached whitish through weathering.
IB [ID]	Tree totally defoliated, limbs and branches maintain bark and are dark toned; recently dead tree.
IIA [IIB]	Dead top, may be 10 cm to more than one metre long.
IIC	Top broken off
IIE [IIG]	A thin-crowned tree, premature loss of older foliage in conifers, branches clearly visible, current foliage present.
IIIA [IIIC]	Some foliage yellowed, most of tree crown appears healthy.
IIIB [IIID]	Entire crown yellowed (this damage type appears as a mauve hue for the tree crown on color infrared photos).
IIIG [IIIN]	Entire crown shows dead, red-brown foliage.
IIIH, −I, −J, −K, −L [IIIM]	Describes location or quantity of dead red-brown foliage, i.e., III I is a conifer with a dead red-brown terminal leader, or the upper one meter (±) of the crown dead, and turned red-brown.
III Oa	These trees have a darker magenta hue than the "normal" trees, noted by comparisons.
III Ob	These trees have a lighter magenta hue than the normal trees.

PHOTO INTERPRETATION

On each stereo pair, the procedure described below was followed:

- number all trees;
- identify species of tree;
- identify damaged trees and indicate damage type according to Table 1;
- using a MacBeth TR524 densitometer, take blue-, green-, and red-filtered transmission-density readings of the image of each tree crown to obtain optical densities of the yellow, magenta, and cyan dye-layers, respectively;
- stratify the density readings according to the damage type classification;
- calculate the red to green-, red to blue-, and green to blue-filter density ratios; and
- test densitometer calculations for significance.

FIELD WORK

After the photo interpretation was completed and the densitometer readings were taken and analyzed, the color-infrared photographs were field checked. The check included the following items for each tree classified as damaged and a maximum of five randomly selected normal trees on each stereo pair:

- species identification check;
- damage type classification check;
- diameter at breast height (DBH) measurement in centimetres (cm);
- total tree height measurement in metres (m);
- increment cores at breast height taken from a random sample of damage-classified and normal trees (the increment cores were retained for laboratory analysis);
- visual inspection for additional evidence of damage, e.g., fire scars, bark beetle borings, pathogens, etc.; and
- acquisition of a ground photo of subject tree.

LABORATORY ANALYSIS

The Swedish built "Addo-X" tree-ring analyzer was used to measure radial increment growth during the last 25 years on a randomly selected sample of increment cores. The measurements were taken to the closest 0.01 mm. Total age was counted to determine stand age. The radial increment data were stratified according to damage type classification, and these data—along with diameter, height, densitometric dye-layer densities, and density ratios—were statistically tested. One way analyses of variance were carried out using the computer package MIDAS.* Finally, further analyses were carried out on the diameter and radial increment data converted to basal area.

RESULTS

The increment core age data indicated that the stand of Douglas-fir was a predominantly even-

* MIDAS, Michigan Interactive Data Analysis System (Fox and Guire, 1976).

aged 70-year-old stand with scattered old growth (120-year-old) trees. The 70-mm aerial photographs displayed over 4,000 trees which were interpreted for damage syndromes and which were subjected to optical densitometry. The stand was considered "healthy" because only 5 percent of the trees displayed any evidence of damage, and on these trees no outstanding or uniquely identifiable agent was designated as the causal damage agent. In essence, the damage seems to have resulted from a unique combination of abiotic and biotic factors which, over the years, had caused damage syndromes to appear in the crowns of some trees.

Because it is the purpose of this study to define damage relative to "normal" trees, only those trees displaying symptoms of damage and which were classified as healthy (HH), III Oa, III Ob, II E (Table 1), and a compound damage type III Ob/II E were selected for correlation tests between photointerpretation and field data. Trees with obvious damage symptoms, i.e., defoliated, deadtops, dead crowns, *etc.*, were not included in the analysis.

The results of the ANOVA analyses are presented in Table 2, and indicate that the trees classified as damaged and the randomly selected normal (HH in Table 2) trees come from overlapping populations of height and diameter classes that would be difficult to substratify solely on field data. In this study, the substratifications were based entirely on photointerpretation of the photo-visible tree crowns *prior* to any sort of field check.

ANOVA of the densitometer ratios indicated significantly different damage class groupings. The red/green-filtered ratios, which reflect the relative ratios of near-infrared to red spectral reflectance, indicated that most damage classes were significantly different from each other (and thus mutually exclusive), except that the II E and III Ob classes were not significantly different. The compound damage class III Ob/II E was significantly different from both the III Ob and II E individual classes. ANOVA of the red/blue-filtered densitometer ratios, which reflect the ratio of the near-infrared to green spectral reflectance, also showed significantly different classes, except that the HH and II E classes were not significantly different. The ratio data tend to confirm that analysis of relative spectral reflectance data, which include the near-infrared and a visible band, either green or red, provides information relative to tree damage classes. Or, as it can be expressed in other terms, these data are relative to the healthy trees. The red/green-filtered densitometric ratio indicated that the normal trees

TABLE 2. RESULTS OF ANOVA ON THE VARIOUS TREE POPULATIONS CLASSIFIED ACCORDING TO DAMAGE TYPE CLASSES FOR FIELD DATA, PHOTO DYE-LAYER DENSITIES, AND DENSITOMETRIC RATIOS

Damage Class	n	Field Data ($\bar{x} \pm$ S.D.)*	
		Height (m)	DBH (cm)
HH	69	26.01 ± 5.09 c**	36.15 ± 8.23 c
III Oa	22	24.86 ± 6.60 c	35.07 ± 10.51 c
III Ob	46	29.50 ± 6.83 b	40.16 ± 10.70 b
II E	22	31.53 ± 4.84 ab	47.05 ± 20.83 ab
III Ob/II E	49	32.88 ± 7.83 a	52.26 ± 19.61 a

Damage Class	Dye-layer densities ($\bar{x} \pm$ S.D.)		
	Red filter	Green Filter	Blue Filter
HH	0.504 ± 0.051 b	1.028 ± 0.163 b	1.175 ± 0.211 b
III Oa	0.544 ± 0.061 a	1.281 ± 0.172 a	1.491 ± 0.231 a
III Ob	0.501 ± 0.059 b	0.911 ± 0.171 c	1.063 ± 0.192 c
II E	0.553 ± 0.554 a	1.044 ± 0.134 b	1.249 ± 0.193 b
III Ob/II E	0.550 ± 0.063 a	0.907 ± 0.155 c	1.107 ± 0.193 b

Damage Class	Densitometer Ratios ($\bar{x} \pm$ S.D.)		
	Red/Green	Red/Blue	Green/Blue
HH	0.495 ± 0.040 c	0.436 ± 0.050 c	0.881 ± 0.058 a
III Oa	0.427 ± 0.037 d	0.368 ± 0.034 d	0.864 ± 0.058 ab
III Ob	0.560 ± 0.075 b	0.479 ± 0.055 b	0.858 ± 0.046 b
II E	0.533 ± 0.035 b	0.447 ± 0.038 c	0.839 ± 0.039 bc
III Ob/II E	0.615 ± 0.072 a	0.504 ± 0.057 a	0.820 ± 0.352 c

* Mean ± standard deviation

** Mean between categories followed by a different letter are significantly different according to ANOVA, $p < 0.05$.

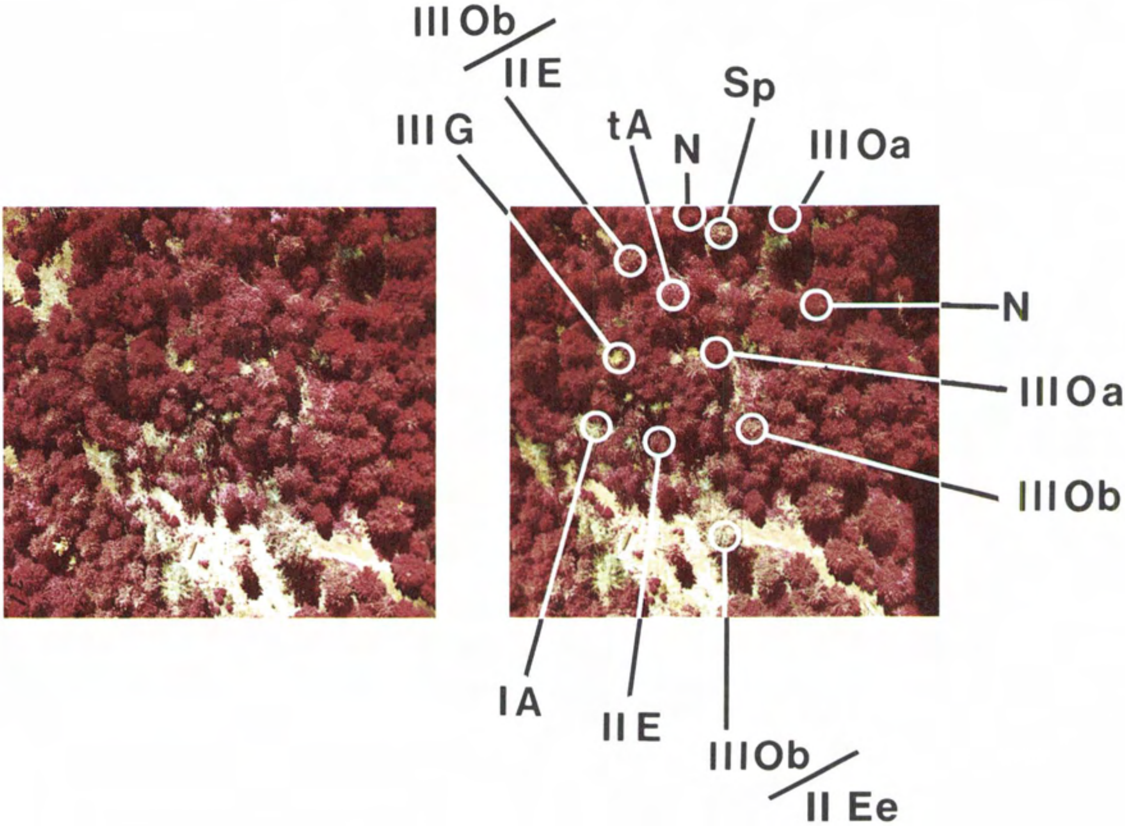

PLATE 1. Photo-plot 31 illustrates several Douglas-fir with various tree conditions.

III Oa	tree with *darker* magenta hue.
III Ob	tree with *lighter* magenta hue.
II E	premature loss of older foliage, exposed branches.
III Ob/II E	compound damage type.
III Ob/II Ee	extreme case of a compound damage type on an old growth tree.
I A	dead defoliated tree.
III G	dead tree, red brown foliage.
N	normal tree without evidence of damage syndromes.
Sp	Engelmann spruce (*Picea engelmannii* Parry).
ta	Trembling aspen (*Populus tremuloides* Michx.).

Damage type III Oa is considered the first air photo evidence of tree damage. Even though the photographs were taken 9 June 1976, there were still no visual symptoms of damage found on the III Oa trees during the field check in June 1978, except for the reduced radial increment.

were significantly different from all other classes. The fact that photointerpretation and optical densitometry produced significantly different damage classes does not automatically prove the trees are in fact damaged. *Damage* is defined as any loss, either biological or economic, due to injury. And *injury* is defined as any stress on a tree which impairs health and results in strain which is noted because of either temporary or permanent syndromes. In this study the photointerpretation so far has classified and evaluated the damage syndromes. Was there any evidence of real damage? A loss of growth would be one real economic indicator of damage. This aspect is discussed below.

ANOVA of the densitometer ratios, as reported in Table 2, basically confirmed the subjective interpretations, that damage type III Oa had a darker tone than the normal trees, and that both the III Ob and the III Ob/II E have a lighter tone than the normal trees. Plate 1 demonstrates the variability of the magenta tones among the Douglas-fir crowns. Normal trees have a middle or average magenta tone, whereas the incipient damage types show variations from the normal. It is hypothesized that the sequence of damage types runs from the normal tree to III Oa, then III Ob, then III Ob/II E. Trees which display premature loss of older foliage are considered to show either

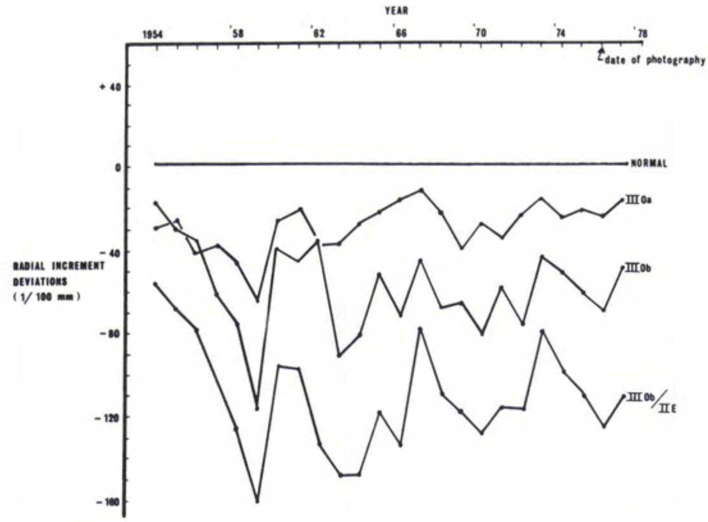

FIG. 1. Radial increment deviations from normal trees for damage types III Oa, III Ob, and III Ob/II E. The negative deviations indicate that the trees stratified as normal are also "plus-growth" trees and show a better growth increment than the "damage-type" trees. The trees were stratified according to photo interpretations of damage classes (Table 1) prior to field checking.

results of previous damage stress, or a more advanced damage effect than that displayed by either of the incipient damage classes, III Oa or III Ob. Visually, on the ground, the III Oa and III Ob trees could not be separated from the normal trees. Only when the trees showed the advanced damage class II E, i.e., premature loss of older foliage, could they be separated on the ground from normal trees.

Figure 1 indicates the growth differences between the various incipient tree conditions and the normal (HH) trees, with the normal trees having the best radial increment. To eliminate variations in growth patterns caused especially by climatic patterns, and to show more specifically the growth relations among the various damage classes, the radial increments for the normal trees were designated as zero for each year for the past 25 years. Then, the differences in mean annual radial increment between each of the incipient damage type (III Oa, III Ob, or III Ob/II E) and the normal trees were plotted as a deviation (positive or negative) from the normal trees. According to Figure 1 all trees classified as damaged had noticeably slower growth than the normal trees. The decreasing growth ranking is the same as the hypothesized sequences of damage types ranging from normal to III Oa to III Ob to III Ob/II E.

The mean diameter increments for each damage class for the last decade of tree growth are given in Table 3. ANOVA indicated significant differences among all classes except between the individual classes of III Ob and II E. The groupings are similar to the results obtained by ANOVA analysis of the red/green-filtered densitometric ratios, except that the rankings are different. This was to be expected, since the HH trees should be the fastest growing, and thus be ranked first. Similarly, the ratios are related to spectral reflectance, and damage type III Oa is defined as the "darker-than" case, and III Ob is defined as the "lighter-than-normal" case; thus, the red/green value of HH was expected to lie between III Oa and III Ob.

The growth data were converted to basal area, a forestry expression for stand growth which is often used by foresters to define growing stock in a stand. Basal area increment is a better expression for stand growth than is simple radial increment because basal area increment corrects for variation in diameter among trees and, thus, gives a far more accurate reflection of which trees are adding the most volume of wood. The basal area increment

TABLE 3. MEAN DIAMETER INCREMENT FOR DAMAGE CLASSES FOR LAST DECADE OF TREE GROWTH

Damage class	Diameter Increment (mm) $\bar{x} \pm$ S.D.	
HH	2.04 ± 1.11	a*
III Oa	1.85 ± 0.88	b
III Ob	1.31 ± 0.80	c
II E	1.42 ± 0.70	c
III Ob/II E	1.04 ± 0.70	d

* Means followed by the same letter not significantly different, ANOVA, $P < 0.05$.

TABLE 4. COMPARISON OF BASAL AREA INCREMENTS FOR YEARS 1967 TO 1977 DERIVED FROM TREE GROWTH DATA

Damage Class	n	Basal Area (cm²)										
		1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
HH (1)	69	17.9	19.2	23.7	24.1	22.6	21.7	16.7	16.5	22.1	25.6	27.4
III Oa (2)	22	16.3	17.4	20.2	22.5	20.3	20.6	15.1	14.3	19.1	25.6	25.2
III Ob (3)	45	14.6	13.2	18.5	17.9	18.3	16.9	13.0	11.0	14.2	17.9	19.8
III Ob/II E (4)	49	17.4	15.0	20.0	18.9	15.9	16.7	13.3	9.9	14.2	17.4	19.0
II E (5)	22	22.2	16.9	22.5	23.5	23.3	21.4	17.5	13.8	18.2	22.9	22.8
		n.s.*	3,4 < 1**	n.s.	3,4 < 1	4 < 1,5	n.s.	n.s.	3,4 < 2	3,4 < 1	3,4, < 1,2	3,4 < 1

* n.s. = not significantly different.
** 3,4 < 1 = Damage Class 3 and 4 (III Ob and III Ob/II E) is significantly less than damage class 1 (HH).

data are given in Table 4. The years 1967, 1969, 1972, and 1973 did not show significant differences in basal area increment. All other years showed significant differences. Damage classes III Ob and III Ob/II E are significantly ($p < 0.05$) slower growing classes than the normal trees. It is also important to note that the II E trees are putting on almost as much basal area increment as are the healthy trees.

It was suggested previously that the II E trees represented either a previous damage stress or a more advanced damage effect. The basal area increment data confirm the "previous stress" possibility from which the trees have evidently recovered.

DISCUSSION AND CONCLUSION

Injury is defined as an act which impairs health whereas damage is defined as loss due to injury. A growth pattern which is "less-than normal" should be defined as an indication of damage. In the color-infrared photos examined, incipient damage types were identified on the basis of a "darker" or "lighter" magenta hue than that displayed by the normal trees. The normal trees are identified on the basis of an overview of the same photo frame; normal trees have the even-medium magenta hue on the color-infrared photos. They are not *too dark* or *too light* a magenta hue. The *magenta* hue is emphasized here; different hues (i.e., mauve) are associated with other tree conditions (i.e., yellowing foliage). Thus, a normal standard tree may be defined on the basis of a comparatively even tone and lack of noticeable damage symptoms.

From the forestry viewpoint, it is interesting to note that the normal trees identified in this study were also the best growing trees in the stand. Thus, it appears that the multitude of magenta hue variations as seen on color-infrared large-scale (1:1200) aerial photographs are related to the condition of the tree, and the relatively even-hued magenta tree crowns represent not only the "normal" tree population, but also the best growing trees in the stand.

In the interior of British Columbia, Douglas-fir responds to selective logging. It is desirable to remove the slow growing trees from a stand; thus, the trees classified as damage type III Ob and III Ob/II E could be selected for thinning from the stand in a selective logging program.

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