DETECTION OF MOUNTAIN PINE BEETLE INFESTATIONS USING LANDSAT TM TASSELED CAP TRANSFORMATIONS

by

RAJEEV SHARMA

M.Sc., Meerut University, 1975

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE STUDIES
THE FACULTY OF FORESTRY
Department of Forest Resources Management

We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

November 2000

In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the head of my department or by his or her representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of Forest Resources Management

The University of British Columbia
Vancouver, Canada

Date Nov. 30, 2000

DE-6 (2/88)

Abstract

This study investigated the identification of probable mountain pine beetle (*Dendroctonus ponderosae* Hopk.) attacked sites using Tasseled Cap transformations namely, brightness, greenness and wetness, derived from Landsat-7 digital data in parts of Vanderhoof Forest District, in Prince George Forest Region, British Columbia. Lodgepole pine (*Pinus contorta* Dougl.) constitutes about 80 percent of the total forest vegetation in the study area. About 85 percent of lodgepole pine stands are greater than 60 years of age, and hence susceptible to mountain pine beetle attack. Landsat-7 ETM digital data (Bands1, 2,3,4,5&7), acquired on August 2, 1999 and September 12, 1999, were the primary remote sensing data source for the study. In addition, TRIM map sheets (1:20,000) derived road and river vectors, and 1:20,000 forest cover maps and a beetle infestation coverage maps of the area (prepared based on aerial sketch mapping and ground probes) were collateral data sources. Methodology consisted of: i) pre-processing of satellite data (atmospheric and geometric corrections), ii) computation of Tasseled Cap coefficients for the Landsat-7 data, since these were not available, iii) identification of mountain pine beetle attacked stands, and iv) accuracy assessment of attacked stands.

Some of the major observations based on results obtained were: i) Tasseled Cap indices for infestations of more than 30 attacked trees / site (< 0.09 ha in size) were found to vary in a relatively narrow range; however for infestation sites with less than 30 tree / site the Tasseled Cap indices had random and large dispersions; ii) values of Tasseled Cap indices for September were found to be lower than those for August for all the cover types; iii) differences between mean brightness, greenness, and wetness of healthy and attacked stands were statistically significant for August; iv) the identification accuracy for attacked lodgepole pine stands were 38.82 and 26.17 percent for August and September, respectively; v) a linear relationship was observed between the number of attacked trees at a site and identification accuracy for the August data but not for September data; vi) the poor identification accuracy was mainly due to the sub-pixel size of infestations.

Table of Contents

List of Tables

List of Figures

Acknowledgements

I am grateful to my supervisor, Dr. Peter A. Murtha, Faculty of Forestry, University of British Columbia, for his guidance and encouragement throughout my entire graduate program.

Sincere thanks for their interest, guidance, and time are extended to the thesis committee members, Dr. John A. McLean, Faculty of Forestry, University of British Columbia; and Dr. Peter L. Marshall, Faculty of Forestry, University of British Columbia.

In addition, several people helped in various ways during the course of this study. Janice Thurston, RPF, Plateau Forest Products Ltd., Vanderhoof, provided the Landsat data and beetle infestation coverage maps of the study area. Val Fletcher, RPF, Forest Health Sampling/Survey Specialist, Ministry of Forests, British Columbia, provided digital forest cover maps of the study area and relevant publications. Jerry Maedel, GIS and Remote Sensing Co-coordinator, FIRMS Lab, Faculty of Forestry, University of British Columbia, was always there to provide required support related to various remote sensing and GIS software. Jamie Heath, my fellow graduate student, gave me a field tour of mountain pine beetle infested lodgepole pine stands. I sincerely thank all of them.

The financial support received from Donald McPhee Scholarship is gratefully acknowledged.

Final thanks to my wife, Tara, for her continuous support and encouragement throughout my graduate school.

1. Introduction

1.1 Background

Mountain pine beetle (*Dendroctonus ponderosae* Hopk.), hereafter referred to as MPB, is one of the most serious pests of lodgepole pine (*Pinus contorta* Dougl.) forests in British Columbia. British Columbia has 48.79 million ha of productive forestland. This represents 51.48% of total province area. The current timber harvesting land base is 23.14 million ha., 47.42% of the productive forestland. Lodgepole pine forests make up 35% (17 million ha) of British Columbia's forested landscape and account for 25% (17.89 million m^3/year) of the total timber volumes harvested (B.C. Ministry of Forests 1998 and 2000).

The MPB is a natural part of lodgepole pine ecosystems and prefers lodgepole pine trees that are 80 years of age or older and have large diameter. However, lodgepole pine stands 60-80 years of age are also susceptible but to a lesser extent (Shore and Safranyik 1992). When climatic conditions (mild winters and warm summers) and food supplies (>25cm dbh lodgepole pine trees) are favorable over a long period of time, the large endemic population of beetles reaches epidemic proportions and attacks even young healthy trees, thus greatly influencing forest landuse planning and harvesting strategies. MPB outbreaks are not new to British Columbia. Since the first recorded infestations in 1913 in the Okanagan and Merrit areas, major infestations have occurred in Kootenay National Park and the Chilcotin Plateau in the 1930s, on Vancouver Island during the 1940-50s, near Takla and Babine lakes in the 1950s, and throughout much of the southern interior, Chilcotin Plateau and the Skeena and Nass river areas in the late 1970s and 1980s. The last major MPB outbreak was in 1982 in the Chilcotin plateau. Between 1972 and 1998, the beetle killed over 200 million mature pine trees in British Columbia (Unger 1993).

According to forest industry estimates, released on March 6, 2000 (The Dispatch 2000), current MPB outbreaks are in epidemic proportions in British Columbia. It is believed that current infestations are spread over an area of approximately 300,000 ha, in the west central part of British Columbia consisting of Lakes, Quesnel, Morice and Vanderhoof Forest Districts. Approximately 6 million m^3 of timber (equivalent to the total annual allowable cut of this area, valued at $1 billion) was already infested by MPB in the west central part of province. The epidemic nature of the infestations can be gauged from the fact that the number of approved

logging sites rose to 48,000 from a typical annual average of 6,000 sites. Due to the absence of a cold-snap in the winter of year 1999, that might have been effective in controlling the beetle population, the MPB epidemic is expected to increase again in the year 2000 (The Dispatch 2000). Beetle infestations have also been reported in other parts of British Columbia as well, such as in Arrowstone Provincial Park (MOEP 2000), and Lillooet District (BC, Ministry of Forests 2000). As much as $312.8 million already have been lost due to the 1998 west central epidemic. An additional $3.9 billion of government revenue could be lost over the next 10 years, if timber currently at risk to MPB attack were to be infested in the Cariboo, Prince George and Prince Rupert forest regions (The Dispatch 2000). Therefore, MPB management is one of the high priority areas for the British Columbia government.

The beetle management system essentially has three components: i) prevention, ii) detection and mapping and iii) control measures. However, salvaging beetle-killed trees and direct control methods aimed at reducing beetle population in currently infested trees have been the traditional management strategies. Preventive measures include prioritizing stands based on the potential for damage, facilitating planning of access roads for these stands, and initiating preventive management treatments. Current beetle control strategies include fell and burn, pesticide applications, single tree sanitation harvesting, partial cutting in small patches, and large clearcuts. Large clearcuts are used to reduce large beetle populations in severely infested areas, and involve conventional logging practices (Macmillan *et al.,* 1986).

1.2 Conventional MPB Detection Methods

Successful beetle infestations result in bright red trees in the summer following attack (Table 1). These can be identified either through aerial survey-based sketch-mapping, which aim at visual identification of red attack trees, or ground based methods (Forest Health Surveys Guidebook 1995). Aerial surveillance, especially of moderate to high-risk stands, helps in detecting the initial phases of beetle invasion and allows for the early implementation of effective control measures. However, aerial survey methods are seriously hampered by the fact that the current year attacks cannot be identified from the air. What can be detected is last year's attack, after the infested lodgepole pine foliage has turned red in color. However, by this time the beetles have already left the infected trees and colonized other trees. Therefore, there is almost a one year time gap between successful beetle attack and its detection from aerial survey based methods.

Table 1. MPB life stages, symptoms, foliar color change, and control options (Source: Unger 1993)

	Year-1			Year-2	
	Summer	Fall	Winter	Spring	Summer
	June-August	Sept. – Nov.	Dec. – Feb.	March - May	June - August
Insect stage	Flying adults, eggs	Parent adults, egg, larvae	Larvae, parent adults	Pupae, adults	Flying adults, eggs
Detection / symptoms	Boring dust, pitch tubes*, galleries	Boring dust, pitch tubes, galleries	Pitch tubes, galleries, woodpecker feeding,	Fading foliage, woodpecker feeding	Boring dust, pitch tubes*, galleries
Foliage color	Bright green	Dull green	Dull green	Yellowish green	Red -> Rusty red
Control	Pheromones, pesticides	Brood tree removal	Brood tree removal	Immediate utilization	

* Whitish pitch tubes indicate that tree has repelled or killed beetle by pitch exudation. Reddish brown tubes are indication of successful attack

Ground surveys are conducted when pockets of discolored trees first appear in a stand to verify the causal agent and the status of the brood (Unger 1993). When the beetle population is at epidemic proportions, ground based surveys, though most effective in detecting current attack, cannot meet the demand. There is not enough trained manpower available for such surveys and time and cost requirements are very high (The Dispatch 2000).

Shore and Safranyik (1992) developed a susceptibility and risk rating system for MPB in lodgepole pine stands. This system consists of computation of a Susceptibility Index and a Beetle Pressure Index. The Susceptibility Index is a measure of the potential loss of stand basal area in the event of MPB infestation, and is a long-term rating. It is designed to rate the susceptibility of the stand as a whole, not just the pine component of the stand. The Beetle Pressure Index is a measure of the magnitude of a MPB population affecting a stand and is dynamic in nature. Whereas the Susceptibility Index for a stand changes slowly over a large period of time, the Beetle Pressure Index may change over a short period of time. This method is highly input intensive. The inputs required are:

a) Susceptibility Index:

i) Average basal area / ha pine ≥ 15cm dbh;

ii) Average basal area/ha of all species ≥ 7.5 cm dbh;

iii) Average age of dominant and co-dominant species;

iv) Stand density of all species ≥ 7.5cm dbh;

v) Latitude, longitude; and elevation;

b) Beetle Pressure Index:

i) Number of infested trees inside the stand;

ii) Number of infested trees outside the stand within 3 km; and

iii) Distance from the stand being rated to the nearest edge of the MPB infestation.

All the inputs required are not part of conventional forest inventory database, particularly, the average basal area / ha of pine ≥15cm dbh, which is the most important variable. Besides, all the inputs required for the Beetle Pressure Index are in-season inputs and would have to be collected using expensive ground surveys. Shore *et al.,* (2000) carried out an accuracy assessment of the prediction capabilities of this system using 38 stands in the Cariboo Forest Region of British Columbia. A linear relationship ($R^2 = 0.67$) was found between the percentage of the total stand

basal area killed by the MPB and the Susceptibility Index. They suggested that the unexplained 33 percent variability could have been caused by variations in MPB population levels between stands, differences in host resistance, and differential effects of many variables such as age, stand density, and location.

Lodgepole pine forests are characterized by homogeneous even-aged stands. These stands can be equated to large mono-cropped agricultural areas in terms of uniformity of spectral response behavior; hence, they are particularly suitable for detection / mapping from satellite based remote sensing. This would be helpful in classifying lodgepole pine stands based on age and thus identifying the extent of susceptible lodgepole pine stands. Lodgepole pine older than 80 years of age are highly susceptible to MPB attack and are considered mature. Because of the successful prevention of forest fires during past 40 years, the proportion of mature trees to immature trees has increased to 3:1 in the Prince Rupert Forest Region and 3:2 in the Prince George and Cariboo Regions (The Dispatch 2000). Mature lodgepole pine stands provide ideal breeding grounds for MPB.

Considering the large extent of mature lodgepole pine in British Columbia and the limitations of the conventional survey methods in timely detection of MPB infestations in such a vast area, there is a need to explore and evaluate alternate methods to detect and map MPB infestations.

1.3 Possible Alternatives

Satellite-based remote sensing technology is one option. Vegetation health monitoring, which has direct relevance to forest disease and damage detection, has been one of the most researched and extensively applied applications of satellite data. Application of satellite data in detection, mapping, and monitoring of MPB infestations is attractive because of the stand characteristics, satellite data capabilities, sensor characteristics, availability of desktop PC image analysis software, and cost/benefit aspects. Because of their synoptic and repetitive data acquisition capabilities, and the digital nature of the multi-spectral data acquired, satellite based sensors hold promise to provide information on: i) the distribution of susceptible lodgepole pine, ii) the distribution pattern of existing infestations, iii) identification of possible direction of beetle spread, and iv) identification of existing red attack areas.

The underlying principle for use of remote sensing is that every surface feature has a unique spectral reflectance signature, which may change in the spatial and temporal domains. Spatial and temporal variability in vegetation reflectance arise from several vegetation related properties including leaf area index, canopy structure, land cover type, leaf optical properties, canopy crown cover, understory vegetation, and stress caused by a number of factors including disease and pests. These variations in leaf spectral response are captured through vegetation indices (VI's), which are dimensionless, radiometric measures usually involving linear combinations and/or ratios of spectral bands (Lillesand and Kieffer 2000). VI's may be computed from digital counts or surface reflectance, and require no additional ancillary information. Vegetation indices also minimize the effects of factors like the soil background, illumination and view geometry on the canopy radiometric response. Vegetated areas generally yield high values for VI's because of their relatively high infrared reflectance and low visible reflectance. The highest index value is assumed to represent maximum vegetation greenness. VI's have been related to several vegetation phenomena such as seasonal vegetation dynamics, forest clearance, leaf area index measurements, biomass estimation, percent ground cover estimation, photosynthetically active radiation estimation, and seasonal and inter-annual variations in the vegetation. In turn, these vegetation attributes are used in various models to study photosynthesis, carbon budgets, water balance, vegetation health monitoring, ecosystem productivity, land cover classification and carbon and biogeochemical cycles (Asrar *et al.*, 1984; Goward and Huemmrich 1992; Huete 1988; Justice *et al.*, 1985; Lillesand and Kieffer 2000; Sellers *et al.*, 1994). VI's are currently used by various agencies for monitoring vegetation to address food security, crop production, and fire probability.

VI's can be categorized into two groups (Baret and Guyot 1991; Major *et al.,* 1990; Qi *et al.*, 1994):

- **Ratio-based vegetation indices:** These are simple ratios of bands or band combinations. Examples: Ratio Vegetation Index (RVI) or Simple Ratio (SR), Normalized Difference Vegetation Index (NDVI),
- **Orthogonal vegetation indices:** based on perpendicular distance of vegetation or other features from the soil line in spectral space. Examples: Perpendicular Vegetation Index -PVI (Richardson and Weigand 1977), Greenness Vegetation Index-GVI derived from Tasseled Cap Transformations (Kauth and Thomas 1976).

The Tasseled Cap Transformation is one of the most widely used vegetation indices. Initially, this was proposed for agriculture dominated scenes, but it has been found subsequently useful for modeling fire hazards (Patterson and Yool 1998), mapping natural grasslands (Lauver and Whistler 1993), monitoring vegetated areas (Braga *et al.*, 1991), discriminating coniferous stands from deciduous stands (Crist *et al.*, 1986), estimating stand density (Crist *et al.*, 1986; Horler and Ahern 1986), estimating canopy water content (Cohen 1991), estimating forest succession (Hall *et al.*, 1991b), estimating the age and structure of forests (Cohen *et al.,* 1995); monitoring forest regeneration (Price and Jakubauskas 1998), identifying forest types and change detection in British Columbia (Sachs *et al.,* 1998), and change detection in forest vegetation condition (Coppin *et al.*, 2000). However, these transformations have not been used to identify MPB infestations.

Successful MPB infestations kill lodgepole pine trees, which cause distinct foliar color changes in the pine stands. Gradual death of lodgepole pine causes foliar color to change from green to yellow and then red. This is accompanied by the gradual drying of the foliage. Both these manifestations are associated with differences in spectral response from the tree canopy. Therefore, red attacked lodgepole pine stands should have different reflectance values compared to non-attacked stands. These spectral changes can be identified through the vegetation indices.

1.4 Objectives

The overall objective of this study was to identify probable MPB attacked lodgepole pine stands based on Tasseled Cap transformations of Landsat-7 ETM+ data. The detailed objectives were to:

- Compute Tasseled Cap coefficients for Landsat-7 Enhanced Thematic Mapper;
- Study changes in Tasseled Cap transforms: brightness, greenness and wetness, caused by variations in topography, MPB infestation size, and satellite data acquisition dates;
- Identify MPB attacked lodgepole pine stands from healthy lodgepole pine stands using single date and two date Tasseled Cap Transforms; and
- Assess the identification accuracy of MPB infested lodgepole pine stands.

This thesis is organized into the following sections: the concept of Tasseled Cap Transformations; a literature review on application of remote sensing in MPB attack detection in British Columbia; material and methods; results and discussions; and conclusions including possible further research areas.

2.0 Tasseled Cap Transformations

2.1 The Concept

VI's are differences and ratios of spectral bands that are used for vegetation monitoring. There are other forms of linear data transformations, which have also been used for vegetation monitoring. The Tasseled Cap transformation, developed by Kauth and Thomas (1976) for Landsat MSS data, is an example of such a transformation. They observed that data in a multi-dimensional spectral space is not distributed uniformly throughout. Instead, the data tend to be concentrated in certain regions of this space, giving rise to a structure. These structures present in data from a particular sensor are directly related to the actual physical characteristics of the scene classes. Hence, extraction of the information of these classes will be best, if the data structure can be viewed in its entirety and separated from other data structures. In an agricultural area, this structure is of the form of a 'Tasseled Cap'.

The Tasseled Cap transformations consist of: i) identifying data structures for a particular sensor and application; ii) changing the viewing perspective (i.e. rotating the axes) such that those structures can be viewed most directly; and iii) defining feature directions which correspond to spectral variations in a particular class (Crist and Kauth, 1986). Kauth and Thomas (1976) used four Landsat MSS bands in linear combinations to produce four indices called Brightness (BR), Greenness (GN), Yellowness (YN), and Nonsuch (NS). The MSS data are rotated such that the majority of information is contained in first two components (i.e. brightness and greenness) that are directly related to physical scene characteristics. Brightness is a weighted sum of all bands and is defined in the direction of the principal variation in soil reflectance. The second component Greenness is orthogonal to brightness and is a contrast between the near-infrared and visible bands. It is strongly related to the amount of green vegetation present in the scene. These two components have proved useful for evaluating soil and vegetation features in Landsat data (Kauth *et al.,* 1979; Thompson and Wehmanen 1980).

Crist and Cicone (1984) extended the Tasseled Cap concept to Landsat TM data and found that the six bands of data effectively occupy three dimensions- brightness, greenness and wetness, defining planes of soils, vegetation, and a transition zone between them. The third feature Wetness, is a contrast between short-wave infrared (SWIR) and visible/near-infrared (VNIR) data and is related to canopy and soil moisture.

Tasseled Cap transformations use the Gram-Schmidt orthogonalization procedure to generate components that are orthogonal to each other, meaning that the information in these components is uncorrelated, unlike the information in original bands. It also serves to reduce the dimensionality of the data. Another technique, Principal Component Analysis (PCA), has often been used to understand data dimensionality and to generate orthogonal components. With PCA the interpreter imposes no prior order or physical interpretation on the principal directions. These are determined by successive directions of maximum variation. In Tasseled Cap Transformations, the axis are aligned in directions that have physical significance. PCA is, thus, a statistical procedure requiring no *a priori* knowledge of features such as soils and vegetation (Jackson, 1983). The principal components generated for different scenes could be different depending on the variability in the data for that scene. In Tasseled Cap Transformations, because the components are defined based on physical characteristics of relevant scene classes (soil and vegetation), they are applicable for different scenes covering those same classes. Crist and Kauth (1986) pointed out that only the viewing perspective changes in these transformations; the data are fundamentally the same before and after its application.

2.2 Tasseled Cap Coefficients

The brightness, greenness and wetness images are generated by multiplying each TM band, pixel by pixel, by a corresponding coefficient. The coefficients are unit vectors that indicate direction. The general form of equation is:

$$TC_i = A_i*DN_1+Bi*DN_2+Ci* DN_3+Di* DN_4+Ei* DN_5+Fi* DN_7$$

where: Ai - Fi are band specific coefficients for Tasseled Cap component i, (i = 1 represents brightness, i = 2 represents greenness and i = 3 represents wetness); and DN_1 - DN_7 are Digital Numbers in spectral bands 1 to 5 and 7

Tasseled Cap coefficients for Landsat-4 and 5 are given in Table 2. Crist and Kauth (1986) suggested that a change to the sensor requires reworking of coefficients. This is necessary because of changes in the sensor characteristics. In case of ETM+, the spectral bandwidth was slightly different from Landsat-5 (Table 3) and the radiometry was different (Science Writers Guide to Landsat-7, 1999). A survey of the literature revealed that these coefficients for Landsat-7 ETM+ were not available or computed. Therefore, for this study new coefficients were required.

Table 2. Tasseled Cap Coefficients for Various Landsat Satellites

Landsat MSS: (Source: Kauth and Thomas 1976)

Feature	Band4	Band5	Band6	Band7
Brightness	0.433	0.632	0.586	0.264
Greenness	-0.290	-0.562	0.600	0.491
Yellowness	-0.829	0.522	-0.039	0.194
Nonsuch	0.223	0.012	-0.543	0.810

Landsat-4 Thematic Mapper (Source: Crist, and Cicone 1984)

Features	Band1	Band2	Band3	Band4	Band5	Band7
Brightness	0.33183	0.33121	0.55177	0.42514	0.48087	0.25252
Greenness	-0.24717	-0.16263	-0.40639	0.85468	0.05493	-0.11749
Wetness	0.13929	0.22490	0.40359	0.25178	-0.70133	-0.45732

Landsat-4 Thematic Mapper (Source: Crist *et al.*, 1986)

Features	Band1	Band2	Band3	Band4	Band5	Band7
Brightness	0.3037	0.2793	0.4743	0.5585	0.5082	0.1863
Greenness	-0.2848	-0.2435	-0.5436	0.7243	0.0840	-0.1800
Wetness	0.1509	0.1973	0.3279	0.3406	-0.7112	-0.4572
Haze	0.8832	-0.0819	-0.4580	-0.0032	-0.0563	0.0130
Fifth	0.0573	-0.0260	0.0335	-0.1943	0.4766	-0.8545
Sixth	0.1238	-0.9038	0.4041	0.0573	-0.0261	0.0240

Landsat-5 Thematic Mapper (Source: Crist *et al.*, 1986)

Features	Band1	Band2	Band3	Band4	Band5	Band7
Brightness	0.2909	0.2493	0.4806	0.5568	0.4438	0.1706
Greenness	-0.2728	-0.2174	-0.5508	0.7221	0.0733	-0.1648
Wetness	0.1446	0.1761	0.3322	0.3396	-0.6210	-0.4186
Haze	0.8461	-0.0731	-0.4640	-0.0032	-0.0492	0.0119
Fifth	0.0549	-0.0232	0.0339	-0.1937	0.4162	-0.7823
Sixth	0.1186	-0.8069	0.4094	0.0571	-0.0228	0.0220

Table 3. Spectral Bandwidth (micrometers) of Landsat-5 TM and Landsat-7 ETM+ (Source: Lillesand and Kieffer 2000)

Spectral Band-Width	Landsat-5 TM	Landsat-7 ETM+
Band1	0.45-0.52μ	0.45-0.52μ
Band2	0.52-0.60μ	0.53-0.61μ
Band3	0.63-0.69μ	0.63-0.69μ
Band4	0.76-0.90μ	0.78-0.90μ
Band5	1.55-1.75μ	1.55-1.75μ
Band6 (Thermal)	10.4-12.5μ	10.4-12.5μ
Band7	2.08-2.35μ	2.09-2.35μ
Band8 (Panchromatic)	N/A	0.52-0.90μ

2.3 Characteristics of different cover types

Figure 1 illustrates general locations of some important scene classes in the TM Tasseled Cap feature space. A typical crop over the growing cycle represents spectral development through emergence, greening, canopy closure and senescence. Depending on the crop and its development, this trajectory can be different, but it will lie within the 'Crops and soils' region in the feature space. The wetness dimension improves delineation between developing vegetation and senescing vegetation.

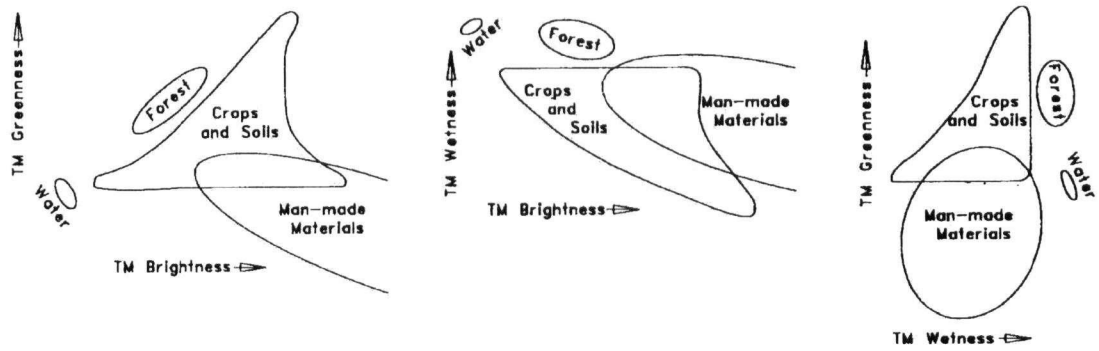


Figure 1. Approximate locations of various surface cover types in TM Tasseled Cap feature space (Crist *et al.*, 1986).

In Tasseled Cap feature space, forest vegetation occupies the front of the cap and is referred to as "badge of trees" (Crist *et al.*, 1986). It is mainly because of the increase in shadows in a forest stand as compared to crop or grass canopies. A forest stand contains a higher percentage of opaque stems, as compared to crop or grass canopy, thus increasing the incidence of deep shadows both on the lower level of the canopy and on leaves/needles in the tree crowns. Water shows minimum brightness and greenness values, but maximum wetness values and is separable from other classes in all dimensions.

3.0 Literature Review

Several studies have been carried out in the past to detect bark beetle infestations in British Columbia using both aerial and satellite based remote sensing data. Aerial data, mainly aerial color infra-red (CIR) photographs, have been used to identify spruce beetle (*Dendroctonus rufipennis kby.*) attack (Banner 1986; Churcher and McLean 1984; Murtha and Cozen 1985; Murtha 1985; Murtha and Fournier 1992), Douglas fir beetle infestations (Hall *et al.,* 1981; Hall *et al.,* 1983), MPB infestations (Hobbs 1983; Hobbs and Murtha 1984; Murtha and Wiart 1987; Murtha and Wiart 1989a andb).

Kneppeck and Ahern (1988) analyzed Airborne MEIS (Multi-detector Electro-optical Imaging Scanner) data, acquired at three different spatial resolutions (1.4m, 3.4m and 6m), to assess the detectability of red attack trees. They concluded that: i) with 6m resolution, individual red attack trees could not be identified on normal color composite, ii) with 3.4m resolution less red attack trees were identified compared to 23cm aerial photographs at a 1:100,000 scale, and iii) a 1.4m resolution image was found best for detection of red attack trees.

A number of studies (e.g., Ahern 1988; Ahern and Archibald 1986; Harris *et al.,* 1978; Murtha *et al.,* 2000; Rencz and Nemeth 1985; Sirois and Ahern 1988; Taylor 1998) have been carried out using satellite-based remote sensing to detect MPB infestations. Based on the analysis methods employed, the studies can be categorized into two classes: i) those based on visual interpretation, and ii) those based on digital image analysis techniques.

3.1 Visual Image Interpretation Based Studies

Attempts to use satellite remote sensing data for MPB detection in British Columbia date from 1978, when Harris *et al.,* used Landsat MSS data to detect MPB infestations. The results were not encouraging, largely because of the scattered nature of infestations and the coarse spatial resolution (80m) of Landsat MSS. Using single date MSS data, an identification accuracy of only 25% was achieved. Ahern and Archibald (1986), based on visual analysis of false color composites (red, near infrared, and short wave infrared spectral bands) showed that gray attacked areas were identifiable because of a distinct cyan color on false color images.

Sirois and Ahern (1988) carried out a study to identify red attack lodgepole pine stands near Babine Lake, Morice Forest District, British Columbia. Digital data from SPOT MLA (Multi-spectral Linear Array, resolution 20 m) and PLA (Panchromatic Linear Array, resolution 10 m) acquired on August 11, 1986, were used in the study. MPB infestations of five or more red trees, demarcated on forest stand maps at a 1:20,000 scale, were used as ground truth. Normal color aerial photographs, at a 1:10,000 scale, acquired in August 1986 were used to verify the results. Different band combinations of digitally enhanced SPOT data for three test areas were visually interpreted to estimate the lower limit of damage detectable from SPOT data. In all three areas, affected stands consisted of lodgepole pine stands between 141-250 years of age, crown closures of 36-45 percent, and heights of 28.5 to 37.4 m. However, the proportion of red attacked trees in each test area was different (Table 4).

Table 4. Proportion of red attacked trees in different study areas (Sirois and Ahern 1988)

Parameters	Area 1	Area 2	Area 3
Size	2-3 ha	2 ha	0.8ha
Proportion of red crowns	80-90%* red colored crown	20 % (35 red trees)	40% (>50 trees)

*red coloration of crown was caused due to heat and smoke from slash burning; such crowns were assumed to have similar spectral properties as that caused by MPB

The authors concluded that it was not possible to identify areas of scattered attack and that the minimum red attack damage detectable with the SPOT satellite was approximately 1 to 2 ha in size with 80 to 100 percent of red crowns. This degree of mortality was found to be very high for control programs where the requirement was to detect infestations of five or more trees. However it was concluded that SPOT data would be useful for inventory update following an outbreak that caused extensive mortality.

Taylor (1998) compared the identification accuracy of MPB and Douglas-fir beetle infestation detection obtained using aerial sketch mapping and visual interpretation of Landsat normal color composite images. Overview aerial sketch mapping, conducted from either helicopters or aircraft, is the primary technique used to detect beetle attacks in British Columbia and relies upon visual identification of yellow brown and/or red tree crowns. This study was conducted in the Fort St. James Forest District of the Prince George Forest Region. Lodgepole pine was the primary forest type and belonged to the mature or overmature age groups (>80 years of age). Landsat data acquired on July 22, 1998 were used in the study. Beetle infestation on three sample forest

cover maps were delineated using aerial sketch mapping, conducted on Aug. 6 and 28, 1998. Both supervised classification of digital data, as well as visual interpretation of satellite data by two independent skilled photointerpreters, were attempted to delineate bark beetle infested areas. The results presented in this paper are summarized in Table 5.

Table 5. Confusion matrix showing beetle infested area (ha) identified by visual interpretation (Taylor 1998)

Interpreter #1

		Aerial Sketch Mapping		
Landsat		Infested	Healthy	Total
	Infested	167	5191	5358
	Healthy	1111	25216	26327
	Total	1278	30407	31685

Interpreter #2

		Aerial Sketch Mapping		
Landsat		Infested	Healthy	Total
	Infested	271	6259	6530
	Healthy	1007	24148	25155
	Total	1278	30407	31685

What can be inferred from this is that the identification accuracy of beetle infested areas based on visual interpretation of Landsat satellite data was less than five percent in both cases, which is too low to be acceptable. Besides, both errors of omission and commission were very high. Because of this, the authors concluded that Landsat imagery was not a suitable replacement for aerial sketch mapping.

3.2 Digital Image Analysis Based Studies

During a joint study between the Canada Center for Remote Sensing (CCRS) and the British Columbia Ministry of Forests, Rencz and Nemeth (1985) evaluated the capabilities of Landsat MSS and Thematic Mapper Data (simulated from airborne multi-spectral scanner digital data) to detect MPB infestations in four test areas (each 5 x 8 km in size), near Tatla Lake, Whitton Lake, Clearwater Lake and Carpenter Lake in the Cariboo region of British Columbia. Landsat MSS data were acquired on two dates (September 18, 1975 and August 17, 1981).

Airborne scanner data were acquired on August 21, 1982. Normal color and color infrared photographs (1:30,000 scale), also acquired on August 21, 1982, were used to identify red attacked trees. Stereo airphotos (1:800 scale) acquired over each test area were interpreted for crown closure and for tree counts of healthy, red attack and gray attack trees to calculate levels of infestations. Infestation sites identified from the large-scale photography were categorized as gray attack (>30 % gray), red attack high (>67 % red) and red attack medium (>10 % red). Digital analysis was carried out for the following four data sets / combinations using a supervised classification:

- Simulated Landsat TM (Bands 2345)
- Combination 1: Single date Landsat MSS (Bands 4567)
- Combination 2: Two date Landsat MSS derived Normalized Difference Vegetation Index (NDVI)
- Combination 3: 4 band composite of Landsat MSS (Bands 5 and 7 from two dates)

Training sites were selected from infestation sites identified on the 1:30,000 scale aerial photographs. Identification accuracy was calculated for the three categories (red high, red medium and gray) for the Simulated Thematic Mapper. In the case of the MSS, only two classes (red attacked and gray attacked) were assessed. The results obtained are summarized in Table 6.

Table 6. Accuracy (%) achieved for identification of MPB infestations (Rencz and Nemeth 1985)

Study area	Simulated TM			Landsat MSS					
				Combination 1		Combination 2		Combination 3	
	1	2	3	1and2	3	1and2	3	1and2	3
Tatla Lake	66	94	66	60	55	10	16	65	60
Clearwater Lake	25	48	60	50	50	0	32	0	60
Whitton Lake	80	80	30	45	32				
Carpentor Lake	68	84	39						

1=Red High, 2= Red Medium, 3 Gray

Except at the Clearwater Lake site where the infestation was very small in size (few trees) and scattered, infestation sizes in the remaining sites were greater than 1.5 ha. Perhaps the scattered infestation was the reason for the poor identification accuracy observed at the in Clearwater Lake

site. A second observation was that the 30m Simulated TM data provided better identification accuracy than the 80m MSS data, obviously because of better discrimination capability. Rencz and Nemeth (1985) concluded that " ....spatial and spectral resolution of Thematic Mapper data will permit insect damage, specifically red attack in lodgepole pine, to be monitored where areas of outbreak exceed 1.5 ha". They further concluded that the size of the outbreak is the major influencing factor in successful insect damage detection. It was stated that infestations must be larger than 3.0 ha for detection to be reliable.

Murtha *et al.,* (2000) used spectral unmixing techniques to derive MPB attack probability using Landsat-5 TM digital data acquired on August 23, 1998. This study was carried out in a part of the Vanderhoof Forest District in the Prince George Forest Region. This area is characterized by small and scattered MPB infestations that are sub-pixel in size (i.e. smaller than the spatial resolution of Landsat TM). In a broad sense, spectral unmixing techniques tend to identify the relative proportion of cover types contributing to the composite reflectance from a pixel. The methodology consisted of: i) selecting forest polygons which (a) contained more than 50 percent under lodgepole pine and (b) where lodgepole pine stands were more than 60 years of age; ii) eliminating polygons where satellite data was under cloud / shadows; iii) stratifying the remaining polygons into three categories based on lodgepole pine stand age: 60-145, 146-170 and >170 years; iv) running a spectral unmixing algorithm on the six bands (B, 1,2,3,4,5 and 7) of Landsat data and generating images showing the percentage of each pixel consisting of an endmember; v) generating polygon level averages for each endmember from pixels under that polygon; vi) assigning a composite attack value to each polygon based on red and green attack fractions; and vii) classifying forest polygons into 10 probability classes of attack based on attack fraction. For this purpose, attack fraction was converted to a percentage and divided into 10 classes. The higher the value of attack fraction, the higher the probability of that stand have been attacked by MPB and vice-versa. Field verification of results through plant stress detection glasses assisted visual identification of red attacked trees through an aerial survey in part of the study area. This was followed by final accuracy assessment. The authors presented a comparison of percent attack probability of polygons in all 10 probability classes with presence or absence of red attacked trees as identified from the aerial survey. The overall identification accuracy at the polygon level was 79.30 percent (Table 7).

Table 7. The accuracy assessment results obtained using spectral unmixing procedures (Murtha *et al.*, 2000)

		Reference data (aerial survey)								Total
		Non-damaged	Damaged							
	Fraction %*	0-31	32-41	42-49	50-57	58-65	66-76	77-88	89-100	
LANDSAT	0-31	59	20	12	6		3	1	3	104
	32-41		2							2
	42-49			13						13
	50-57				14					14
	58-65					20				20
	66-76						14			14
	77-88							24		24
	89-100								26	26
	TOTAL	59	22	25	20	20	17	25	29	217

* Attack fraction probability percent

Overall accuracy = (59+2+13+14+20+14+24+26) =172 / 217 = 79.26%

Although this approach does not indicate the number of red attack trees, the relative size of infestation within a polygon and the relative location of red attacked trees within a polygon, it does indicate areas where efforts should be directed for costly and time consuming ground surveys to plan for control measures. As compared to conventional hazard rating systems (e.g. Shore and Safranyik 1992; Shore *at el.*, 2000), this approach is faster and more cost effective. A total area of 346,300 ha, covered by 19 British Columbia MoF map sheets, could be analyzed using only a part of Landsat scene within one month. Another advantage of this method is that an entire stand can be characterized as damaged or damaged. This is much closer to the forest inventory approach than is classification of individual pixels, which characterize the class of a particular pixel but not that of a forest stand. Besides, forest polygons could be further classified according to the damage severity.

3.3 Recent Initiatives

SELES: Spatially Explicit Landscape Event Simulator project

A joint team of experts from the Prince Rupert Forest Region, Morice and Lakes Forest Districts, British Columbia Parks, academic institutions and the private sector, led by MoF planning

systems biologist Don Morgan, is developing methods for modeling the general behavior of the bark beetles at a landscape level. This model is expected to help forest managers to look at beetle movement across a landscape over time, and predict bark beetle patterns. One of the important components of this project is the use of satellite imagery, acquired over a time period of 1993-1999, to track infestations over time and study beetle infestation spread pattern in the Lakes Forest District. Future expectations for use of satellite imagery are "to pick out detailed infestation information so that costly overview flights and ground probing will not be necessary". Results from this study are yet not available (BC MoF 1999).

Observations from the satellite data based studies on MPB detection described earlier, can be summarized as follows:

- Infestations larger than 1-2 ha can be delineated with reasonable accuracy using visual analysis techniques. However infestations of this size are very large from the point of view of control measures.
- Studies carried out so far have largely relied upon visual interpretation techniques. Theoretically, infestations of as small as 0.09 ha size should be possible to detect even with data of 30-m spatial resolution satellite data.
- The majority of the studies have attempted direct detection by employing classification algorithms operable at the pixel level, whereas in many cases infestation size is subpixel in nature.
- Spectral unmixing procedures, which operate at subpixel level, have shown by far the most promising result in identifying MPB infestations at the stand level.

Although MPB detection using satellite data are gaining momentum, it has to be supported by more studies involving analysis of different spatial resolution data, application of various digital analysis techniques, and using alternate concepts.

4.0 Material and Methods

The choice of the study area was largely determined by the availability of satellite data, aerial data and relevant ground truth information, acquired during a separate study on detection of MPB infestations using spectral unmixing techniques (Murtha *et al.*, 2000).

4.1 Study area

The study area covers parts of the Lakes Forest District (Prince Rupert Forest Region), bordering Tweedsmuir Provincial Park in west and Vanderhoof Forest District (Prince George Forest Region) in the east in British Columbia (Figure 2).

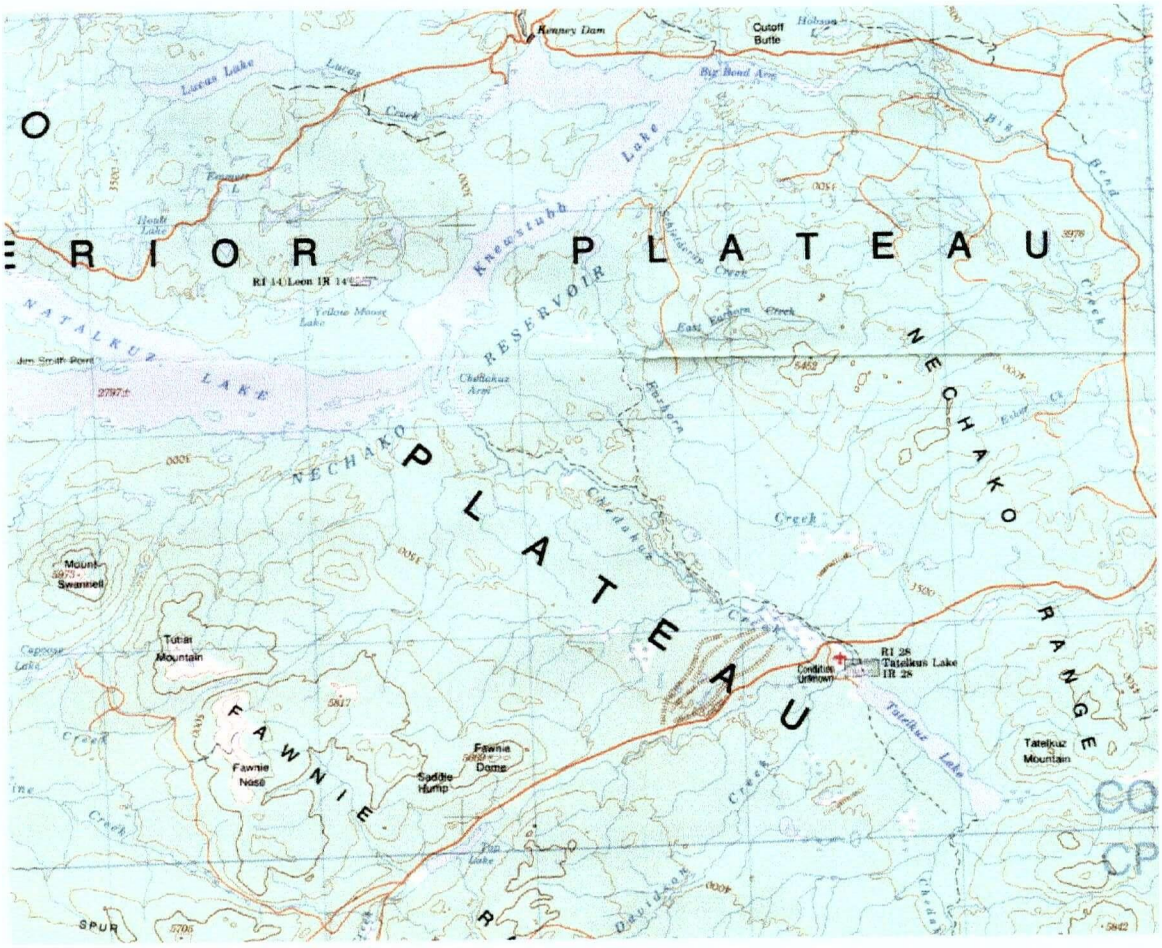


Figure 2. Location map of study area

It lies between longitudes 124^0 30' and 125^0 30' W and latitudes 53^0 00' and 53^0 40' N, and is covered by NTS Map sheet Number 93F at a 1:250,000 scale. Knewstubb Lake, Natalkuz Lake, Tatelkuz Lake, Tsacha Lake, Johnny Lake, Moose Lake and Capose Lake are some of the major water bodies in this area. Most of the area is inaccessible. Logging roads access only the eastern part, while the western part towards Tweedsmuir Park has no roads.

The major tree species in this area is lodgepole pine which constitutes about 80 percent of the total forest cover in the area (Table 8). The remaining 20 percent consist of balsam poplar (*Populus balsamifera*), aspen (*Populus tremuloides*), alpine fir (*Abies lasiocarpa*), black spruce (*Picea mariana*), and interior spruce (*Picea engelmannii*). The age of lodgepole pine stands varies from less than 20 years to a high of over 300 years (Table 9). About 66 percent of the lodgepole pine stands are more than 81 years of age and are susceptible to MPB attack (Shore and Safranyik 1992).

Table 8. Relative proportion (%) of different forest tree species in study area

Trees	No. of polygons	%	Area of polygons	%
Balsam poplar	2	0.01	18	0.01
Aspen	313	2.64	3742	1.58
Alpine fir	579	4.88	15677	6.59
Lodgepole pine	8489	71.53	186551	78.35
Spruce	1196	10.08	17236	7.24
Black spruce	264	2.22	2030	0.85
Engelmann spruce	9	0.09	199	0.08
White Spruce	1015	8.55	12617	5.30
Total	11867		238070	

Data source: MOF forest cover maps 093F13, 14, 15, 16, 23, 24, 25, 26, 33, 34, 35, 36, 43, 44, 45, 46, 53,5 4, 55, 56 (1:20,000 scale)

Table 9. Age-class distribution of lodgepole pine stands in study area

Age group	Area (ha)	Percent
<20	5085	2.75
21-40	2406	1.29
41-60	19288	10.34
61-80	39346	21.09
81-100	8662	4.64
101-120	13613	7.29
121-140	34675	18.59
141-160	35849	19.22
161-180	16095	8.62
181-200	8567	4.59
201-220	2075	1.11
221-240	663	0.36
241-260	37	0.02
261-280	136	0.07
281-300	25	0.01
301-320	29	0.01
	186551	100.00

Data Source: MOF forest cover maps 093F13, 14, 15, 16, 23, 24, 25, 26, 33, 34, 35, 36, 43, 44, 45, 46, 53,5 4, 55, 56 (1:20,000 scale)

4.2 Data Used

Landsat-7 ETM digital data (Bands1, 2, 3, 4, 5 and 7), acquired on August 2, 1999 and September 12, 1999, were used in this study. Details of other data used are given in Table 10. TRIM map sheets (1:20,000 scale) were used to derive road and river vectors used for geometric rectification of satellite data. Digital forest cover maps were used to identify lodgepole pine stands.

Table 10. Details of data used

Data	Source
Remote Sensing Data: Landsat-7 Enhanced Thematic Mapper digital data acquired on August,2, 1999 (path 50, row 23) and September 12, 1999 (path 49, row 23)	Plateau Forest Products Ltd., Vanderhoof, BC
MPB Infestation map	
TRIM data	FIRMS Lab / MoF
Forest Cover Map	BC MoF

4.3 Mountain Pine Beetle Infestations in the Study Area

The number of infested trees at a site has a great bearing on its identification using satellite data, generation of training sites, and accuracy assessment. Therefore, this information was collected from a beetle infestation map of the study area, prepared by Plateau Forest Products Ltd., Vanderhoof, BC. The map indicates sites of both red attacked trees (beetle attack of 1998) and the current attack of 1999. Information on red attacked trees was collected from interpretation of normal color aerial photographs, by a GPS survey carried out in the second quarter of August 1999, and by field verification from mid-September to the end of October, 1999. Information on green attack trees was collected based on a walkthrough (mid-September to end of October) and a beetle probe (using a 100m grid) in selected areas along the Vantine and Malaput roads (mid-September to end of November 1999).

The beetle infestation map was in Microstation file format with no database attached to it. Therefore, a 10 percent sample (530 ground observation points) was randomly selected from the map and a database showing number of red, and red plus green attack trees for each site was generated (Table 11). The size of the beetle infestation was very small and was scattered in nature. Approximately 87 percent of the infested sites had less than 10 red attacked trees. Since green attacked (GA) trees are also present along with red attacked (RA) trees at most of the infestation sites, at a 30-meter spatial resolution both RA and GA trees would be recorded by the satellite based sensor. Therefore, both red attacked and green attacked trees together were called "attacked trees". Since the size of area covered by attacked trees is still subpixel in size, pixels representing these sites were called probable sites of MPB attack.

Table 11: Size characteristics of beetle infestations in the total study area.
(Based on a 10 percent random sample from beetle infestation map, prepared by Plateau Forest Products, Ltd.)

Number of MPB infested trees per site	Red attack*		Attacked trees (Red + Current attack)**	
	No. of sites	%	No. of sites	%
<10	461	86.98	393	75.15
11-20	57	10.75	77	14.53
21-30	8	1.51	27	5.10
31-50	3	0.57	17	3.22
>50	1	-	16	3.02
Total	530	100.00	530	100.00

It was proposed that three test sites would be identified within the study area. MPB infestation sites in one test area would be used to calibrate the Tasseled Cap vegetation indices and the other two areas would be used for accuracy assessment (Figure 3). Test areas, A and B were completely covered by the beetle infestation map provided by Plateau Forest Products Ltd., but Test Area C was only partly covered. A database on MPB sites was prepared for all the three test areas based on complete enumeration.

Figure 3. A Landsat-7 ETM (September 12, 1999) pseudocolor composite of study area. Location of Test Areas is marked in red boxes.

4.4 Methodology

The analysis was carried out using a combination of PCI EASIPACE image processing software and ESRI ARC/VIEW geographic information system software. The major steps in the analysis included:

- Pre-processing of satellite data
- Computation of Tasseled Cap coefficients for Landsat-7
- Identification of MPB attacked stands
- Accuracy assessment of attacked tree identification

4.4.1 Pre-Processing of Satellite Data

Geo-Registration of Data Set

Sub-scenes of the study area, extracted from Landsat data of both acquisition dates, the forest cover map, beetle infestation coverage, and TRIM maps of the study area were co-registered, and transformed to NAD83 datum and Universal Transverse Mercator (UTM) projection, using a nearest neighbor resampling algorithm (root mean square error <0.5 pixel). TRIM maps were used as references for registration of other data sets. The GCPWORKS module of EASI/PACE was used to perform the geo-registration.

Atmospheric Correction

In order to get truly or nearly representative reflectance from satellite-based multi-spectral data for various cover feature types, an atmospheric correction is necessary. The reflectance of a ground feature recorded by ETM onboard the Landsat-7 satellite is controlled by a combination of: i) solar irradiance; ii) sensor parameters (gain and offset); iii) reflectance from surface features imaged; iv) illumination and viewing geometry of the scene; v) absorption and scattering by the atmosphere plus external atmospheric contributions to the incoming spectral reflectance from an object (Jensen 1996). Though many more complicated and advanced models are available for atmospheric correction (Hall *et al.,* 1991a; Moran *et al.,* 1992; Richter 1997), this study was carried out using the dark object subtraction technique developed by Chavez (1988). This technique is based on the premises that: i) atmospheric effects add a uniform offset to an image; and ii) all or nearly all near infra-red energy incident on clear deep water is absorbed. Though

this technique is one of the older ones, it is still widely used for atmospheric correction because of its simplicity and its requirement for little information beyond the image itself (Price *et al.,* 1997). The study area has a large number of both small and large water bodies. Ten training sites for clear water, in the deep portions of the large water bodies, were selected using band 4 (near infrared spectral region, where ideally reflectance should be zero or near zero) for each of the two Landsat images. The range of digital numbers (DN) in each band, for each of these 10 sites, were recorded and used for atmospheric correction.

4.4.2 Computation of Tasseled Cap Coefficients

The number of dimensions (n) available in spectral space is the number of spectral bands available from a sensor. In this case, there are six possible dimensions from six spectral bands (bands 1-5 and 7) from Landsat-7 ETM. The number of spectral indices (m) that may be calculated is also equal to the number of bands (n). In this case there are six possible indices namely: brightness, greenness, wetness, haze, fifth, and sixth. Often, only the first three indices are of interest. In this study, coefficients were computed for these three indices only.

The procedure consisted of identifying training sites for various cover types, computation of Tasseled Cap coefficients, and finally evaluation of brightness, greenness and wetness derived from the computed coefficients. For development of the three indices, four data points were required for dry soil, wet soil, healthy vegetation, and senescent vegetation. Dry soil and wet soil are required for development of the brightness index. Dry soil, wet soil, and healthy vegetation are required for the greenness index. All the points are required for the wetness index. Identifying training sites for healthy and senescent vegetation and dry and moist soil was done using the Imageworks module of the EASI/PACE image processing software. Normal color aerial photographs of the study area were used to select training sites. However, using single date data it was not possible to get the same vegetation at the senescent stage. Besides, it is also difficult to get senescent vegetation in a predominantly forested landscape. Therefore, sparse scrub vegetation was taken as senescent vegetation. Clusters of pixels belonging to dry soil, wet soil, vegetation and senescent vegetation were selected from the August 2, 1999 Landsat ETM+ data. Averaged digital numbers (DN) obtained for these sites were used to compute the coefficients of the different indices using the procedure given by Jackson (1983).

Brightness, greenness and wetness images generated using these coefficients were evaluated by comparing the relative distribution of various cover types in the brightness – greenness, greenness – wetness and wetness – brightness feature space against the distribution pattern observed for Landsat– 5 TM (Figure 1).

4.4.3 Effect of topography, infestation size and acquisition dates

In order to evaluate the effect of topography, an aspect map was prepared using TRIM 20-meter contour maps in ARC/VIEW. Tasseled Cap indices for a total of 90 observation points (Op), were randomly selected from mature lodgepole pine stands on flat terrain (Op=38), northwest aspects (Op=22), and southeast aspects (Op=30). The indices for both dates were extracted from the respective transformed images. The effect of infestation size on brightness, greenness and wetness indices was evaluated by extracting these indices for randomly selected infestation sites (Table 11), varying in number of attacked trees at each site. To study the effect of acquisition dates on brightness, greenness and wetness, indices values for both dates (August 2, 1999 and September 12, 1999) were extracted for randomly selected observation points for young lodgepole pine (<20 years in age, Op=37); mature lodgepole pine stands (>60 years of age); shrubs (Op=27); gravel roads (Op=46); and landing sites within cutblocks (Op=27).

4.4.4 Identification of Attacked Stands

Sites identified from the beetle infestation coverage were used to assign brightness, greenness and wetness indexes to attacked stands for both the dates of images. Because of the sub-pixel size of infestations and their scattered distribution, it was not possible to use supervised classification. K-Mean clustering techniques were used in this study instead. This iterative process, sometimes called "cluster busting" (Jensen 1996; Price *et al.*, 1997) was repeated to separate probable MPB infestations from other forest and nonforest classes.

4.4.5 Accuracy Assessment

Confusion matrices, also referred to as contingency tables or classification error matrices provide a means of evaluating the thematic accuracy of a classified image by comparing the class

assigned to a group of test pixels to the actual ground information at those sites (Congalton 1991; Lillesand and Kieffer 2000), and were used in this study for accuracy assessment. These matrices also help by identifying which categories are being confused, either by erroneously being excluded from one class (error of omission) or included in another (error of commission). In a confusion matrix, diagonal elements represent the identification accuracy, column totals represent errors of omission and row totals indicate error of commissions. Initially, it was proposed to assess identification accuracy in two test areas. However, complete enumeration of the beetle infestation map covering Test Areas A and B, revealed that there were only 15 and 32 sites, respectively, which had more than 30 attacked trees. This number was thought to be inadequate for accuracy assessment. Instead accuracy assessment was performed on the total study area. A total of 568 observation points (340 for attacked sites, 228 for healthy forest) were used for accuracy assessment. A confusion matrix was generated using the beetle infestation maps as reference data and probable MPB infested areas as identified from satellite data as image data. Among the variables produced from the confusion matrix were identification accuracy of MPB detection, producer's accuracy or error of omission, user accuracy or error of commission, and overall accuracy. Estimates of identification accuracy were also made for sites classified based on the number of infested trees.

5.0 Results and Discussion

5.1 Tasseled Cap Transformations

Derivation of Coefficients

Originally Tasseled Cap coefficients were developed using spectral signatures from agricultural crops. In the present case, forest cover was chosen as sites for healthy vegetation, first, because the present study primarily was based on spectral characteristics of forest cover, and second, because there were no agricultural crops in this area. In agricultural areas, senescent vegetation is represented by crops at maturity, when the crops are dry and characterized by a yellow/golden yellow color. Finding similar cover types in forested areas is not possible. Therefore, scrub vegetation was selected as sites for senescent vegetation. Training sites for wet soil were selected from bogs. Signatures from landings within cutblocks were used for dry soil. All the selected sites were checked for purity of spectral signatures and then the mean signature values for each site was derived. These mean signature values were used in computation of coefficients following the procedure described by Jackson (1983). The coefficients derived were:

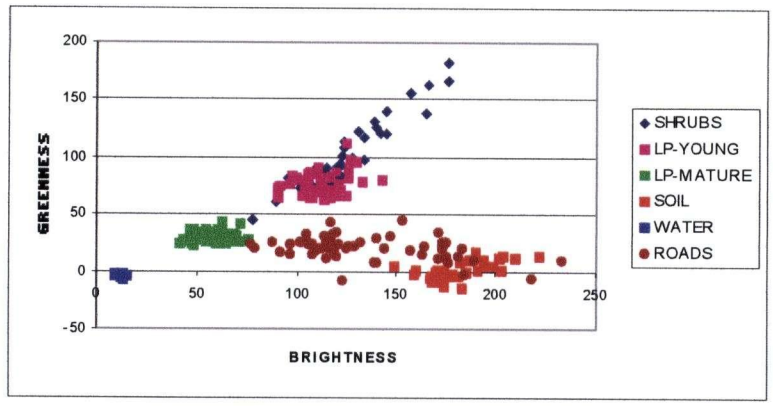
Brightness: (0.1099*B1) + (0.1557*B2) + (0.3023*B3) + (0.2931*B4) + (0.7420*B5) +(0.4855*B7)

Greenness: (-0.0865*B1) + (-0.0585*B2) + (-0.2291*B3) + (0.9375*B4) + (-0.1135*B5) + (-0.2115*B7)

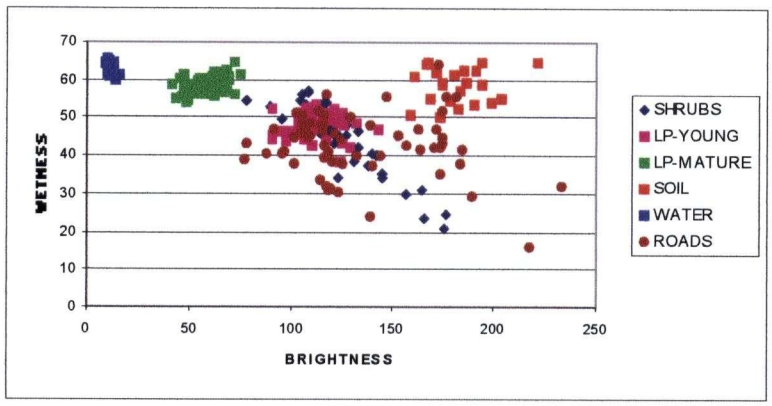
Wetness : (-0.2070*B1) + (-0.5812*B2) + (-0.6092*B3) + (-0.1515*B4) + (0.4741*B5) + (-0.0205*B7)

Evaluation of Coefficients

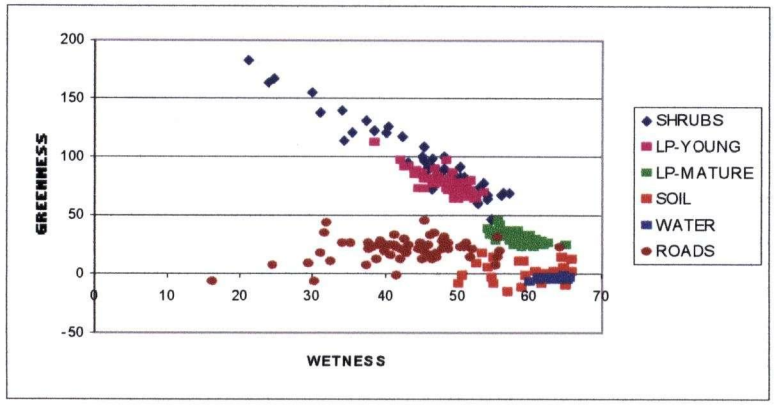
The reliability of these coefficients was tested by plotting the values for different cover types in greenness-brightness (Figure 4a), wetness-brightness (Figure 4b) and greenness-wetness (Figure 4c) two dimensional feature space. From these figures, the following observations can be made. Bare soil has the highest brightness value, greenness values for water and soils are lowest, and shrubs have high greenness values. Man-made features (gravel roads) showed the lowest wetness value. These observations compare favorably with those of Crist and Cicone (1986) for various cover types using Landsat-5 data (Figure 1).



(a)



(b)



(c)

Figure 4. Location of different cover types in brightness - greenness (a), brightness - wetness (b) and wetness-greenness (c) feature space derived from computed Tasseled Cap coefficients for Landsat-7 Thematic Mapper Data. (LP-YOUNG: young lodgepole pine stands; LP-MATURE: mature lodgepole pine stands)

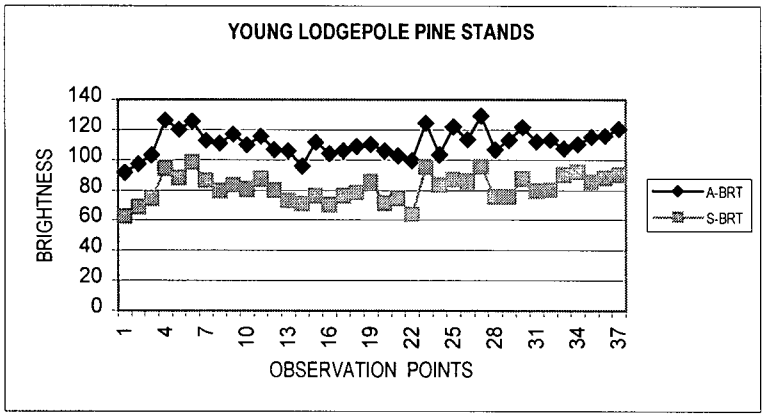
Brightness and greenness for a mature lodgepole pine stand are lower than for young lodgepole pine. This is due to the increased shadow effect and structure of leaves. Compared to young plantations, older forest stands contain a higher percentage of stems, which results in increased incidence of deep shadows both on the lower layers of the canopy and on the leaves in the tree crowns (Crist *et al.*, 1986).

5.2 Effect of Topography, Acquisition Dates and Infestation Size

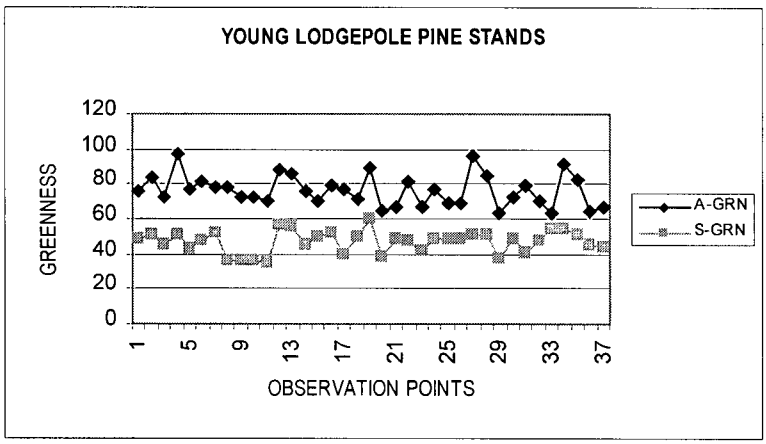
Comparison of Two Date Tasseled Cap Indices

Brightness, greenness and wetness indices values for both dates were extracted for randomly selected observation points (Op) for young lodgepole pine (<20 years in age, Op=37, Figure 5), mature lodgepole pine stands (>60 years of age, Op=70, Figure 6), shrubs (Op=27, Figure 7), gravel roads (Op=46, Figure 8), and landing sites within cutblocks (Op=27, Figure 9). There was a difference of 42 days between the two imaging dates. During this period it was expected that no significant change would have taken place in many cover classes. However, what was surprising was that even landing sites had consistently lower brightness values in September compared to August for all the 27 sites and the magnitude of this difference was almost constant. This happened most probably because of lower incident energy in September than August. In the case of young lodgepole pine plantations, both brightness as well as greenness were much lower in September. This might have been due to the effect of increased shadows in addition to lower incident energy.

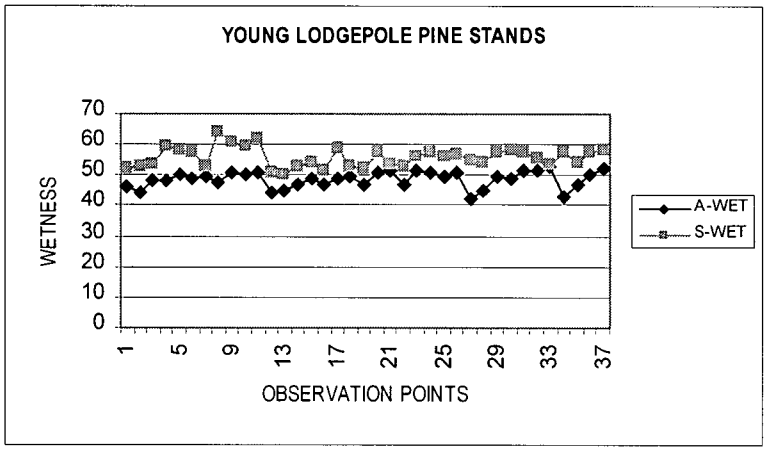
Another interesting observation is that wetness remained relatively unaffected, whereas brightness and greenness showed relatively large variability. This conforms to observations reported by Cohen and Spies (1992). They reported that brightness and greenness images captured the majority of the spectral variations associated with forest conditions, but were strongly influenced by topographic variations resulting in a large dynamic range. Wetness, on the other hand, was nearly insensitive to topographic variations and hence had a small dynamic range. The consistently low mean values for all the three indices for various cover types for the September data may be because of the combined influence of low incident energy, lower sun elevation angle, and the resultant longer shadows in September as compared to August. These observations indicate that the August data was better for discriminating various cover types than the September data.



(a)

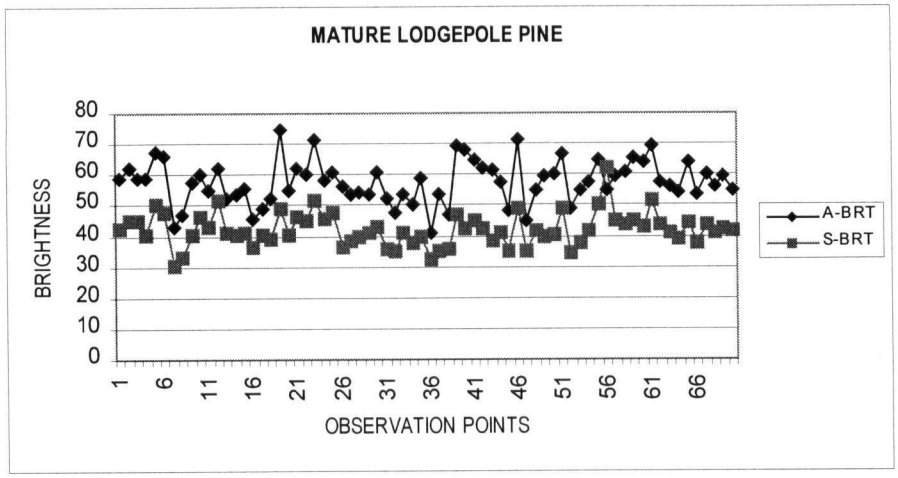


(b)

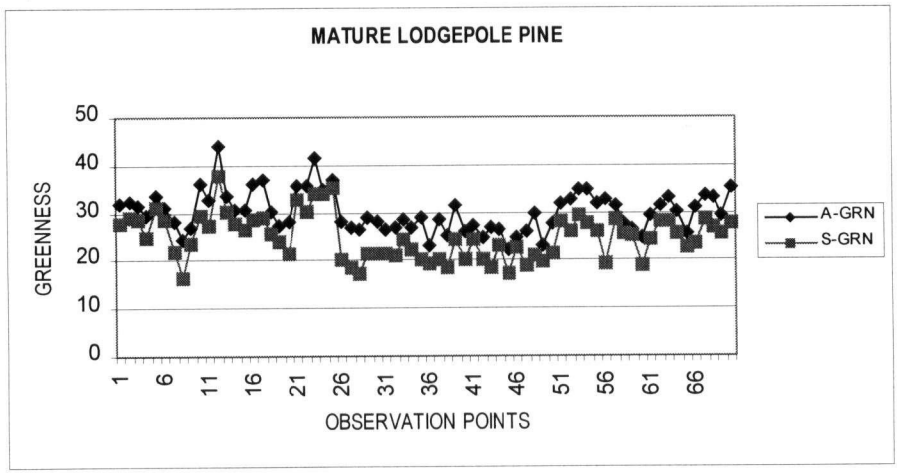


(c)

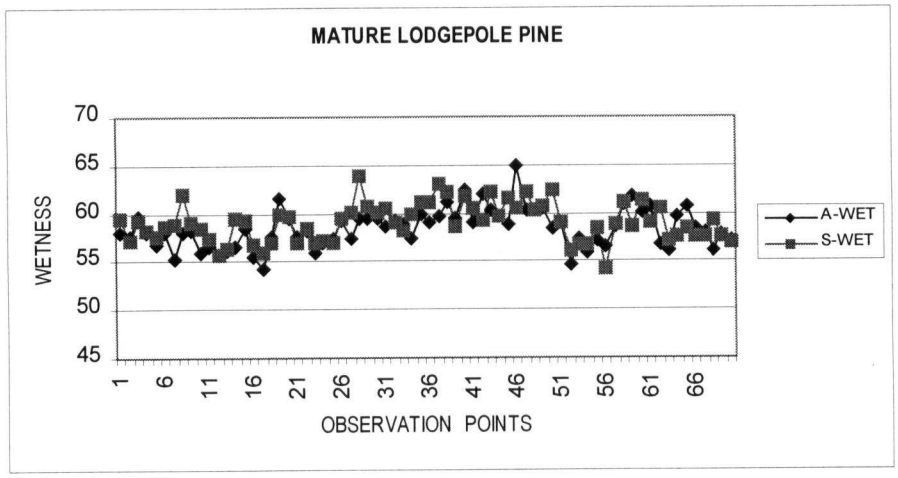
Figure 5. Comparison of two date Brightness (a), greenness (b) and wetness (c) indices for young lodgepole pine stands (A: August 2 1999, S: September 12, 1999, BRT: Brightness, GRN: Greenness, WET: Wetness).



(a)

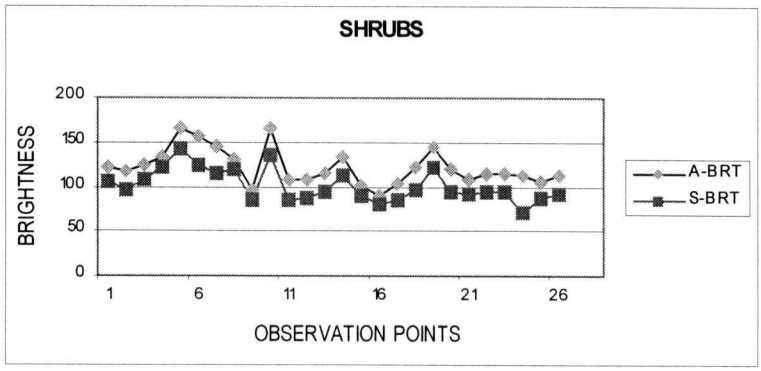


(b)

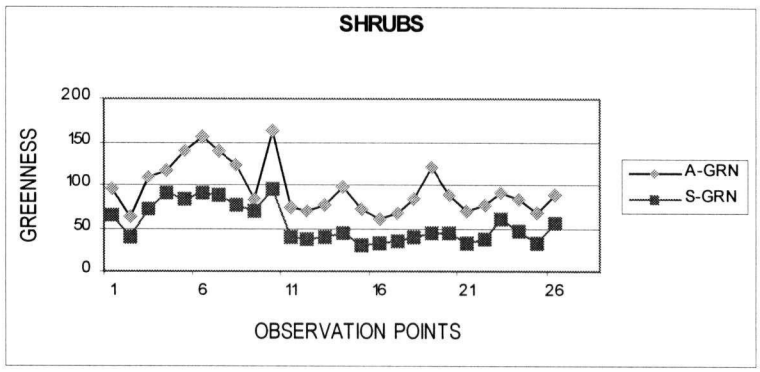


(c)

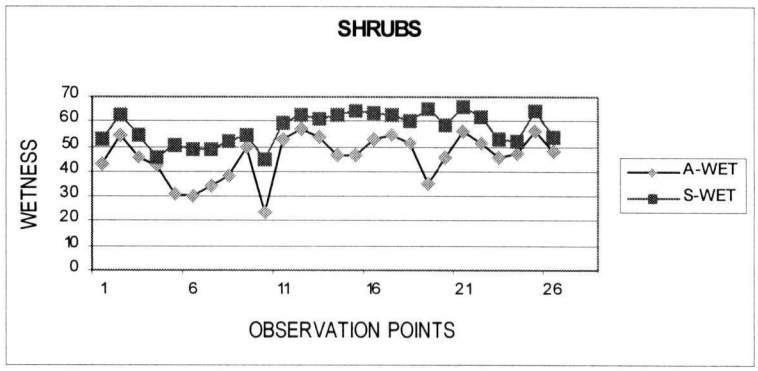
Figure 6. Comparison of two-date brightness (a), greenness (b) and wetness (c) indices for mature lodgepole pine stands (A: August 2 1999, S: September 12, 1999, BRT: Brightness, GRN: Greenness, WET: Wetness).



(a)

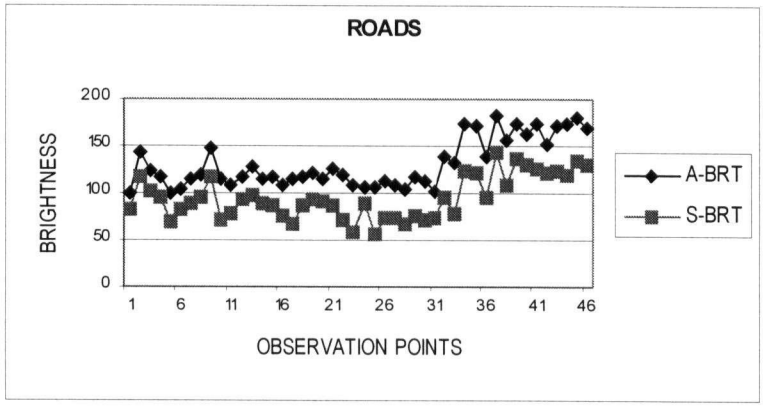


(b)

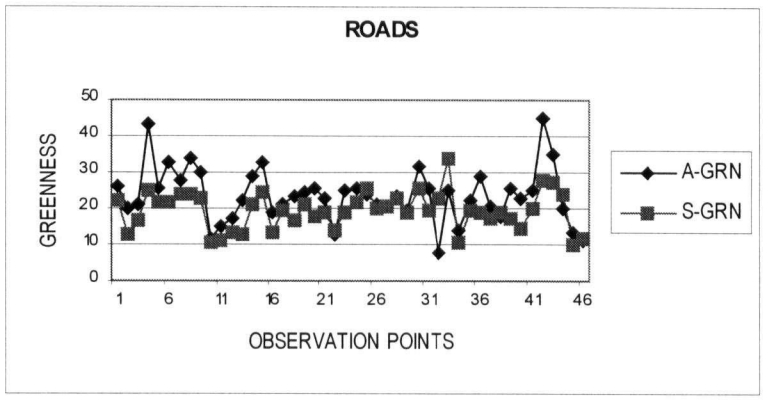


(c)

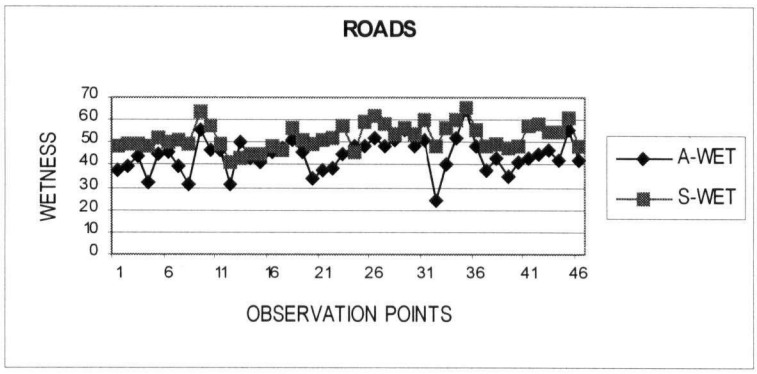
Figure 7. Comparison of two date brightness (a), greenness (b) and wetness (c) indices for shrubs (A: August 2 1999, S: September 12, 1999, BRT: Brightness, GRN: Greenness, WET: Wetness).



(a)

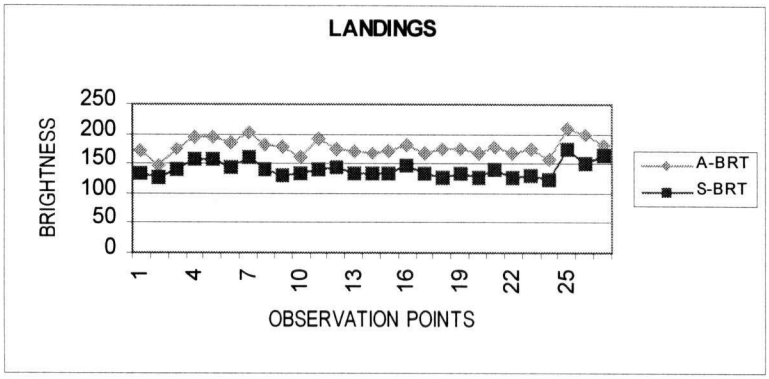


(b)

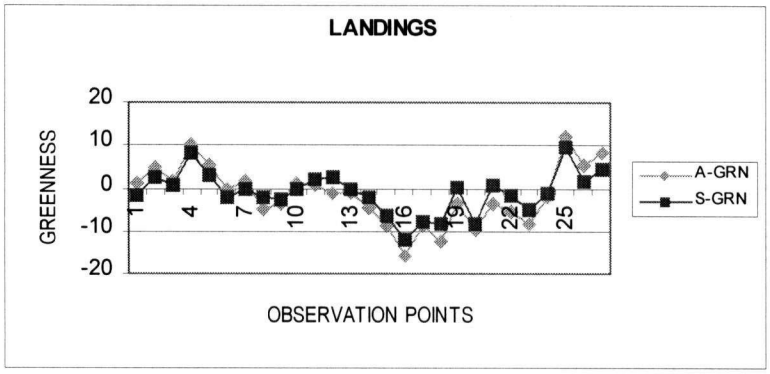


(c)

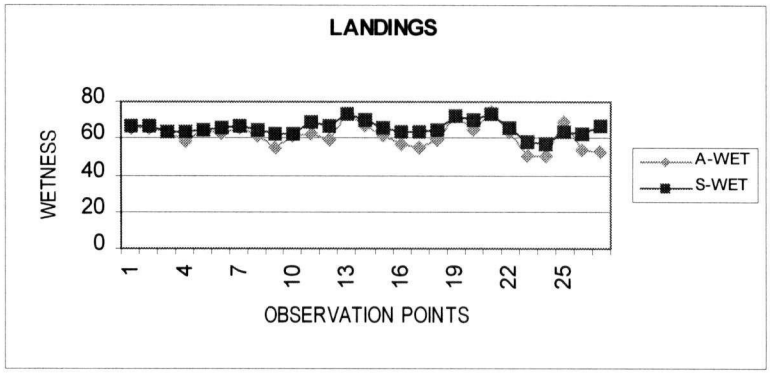
Figure 8. Comparison of two date brightness (a), greenness (b) and wetness (c) indices for roads (A: August 2 1999, S: September 12, 1999, BRT: Brightness, GRN: Greenness, WET: Wetness).



(a)



(b)



(c)

Figure 9. Comparison of two date brightness (a), greenness (b) and wetness (c) indices for landings (A: August 2 1999, S: September 12, 1999, BRT: Brightness, GRN: Greenness, WET: Wetness).

Effect Of Topography on Tasseled Cap Indices

Topography also plays an important role in influencing spectral signatures from land surfaces. In order to evaluate the effect of topography, an aspect map was prepared using TRIM 20-meter contour maps in ARC/VIEW. Tasseled Cap indices for 90 observation points were selected from lodgepole pine stands on flat terrain (Op=38), northwest aspects (Op=22), and southeast aspects (Op=30). The values for Tasseled Cap indices for both dates were extracted from the respective index images. The range of Tasseled Cap indices obtained indicated that brightness and greenness of lodgepole pine stands on southeast slopes was nearly twice those on northwest aspects, while those from stands on flat terrain fell in between (Figure 10). As reported earlier, wetness was not found to be sensitive to variations in topography. It was nearly the same for all lodgepole pine stands irrespective of aspect class.

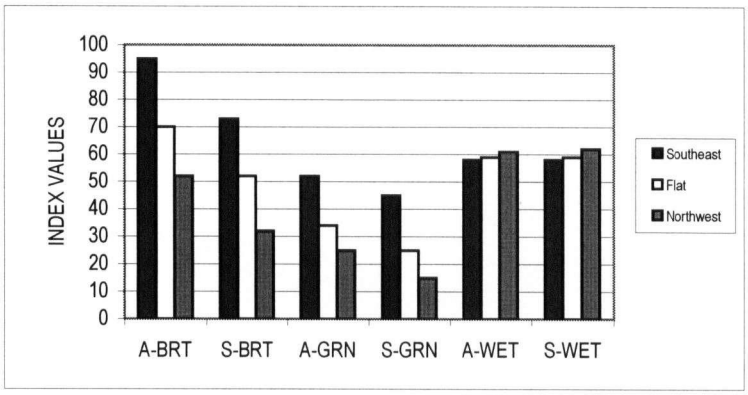


Figure 10. Brightness, greenness and wetness indices for mature lodgepole pine stands on different aspect classes (SE: Southeast, F: Flat, NW: Northwest aspect; A: August, S: September, BRT: Brightness, GRN: Greenness, WET: Wetness).

Effect of Infestation Size on Tasseled Cap Indices

Figure 11 shows the relationship between brightness, greenness and wetness and number of attacked trees per site for the August and September images. For sites containing less than 30 attacked trees, there was a large dispersion in values. After this threshold, all three indices varied within a relatively narrow range.

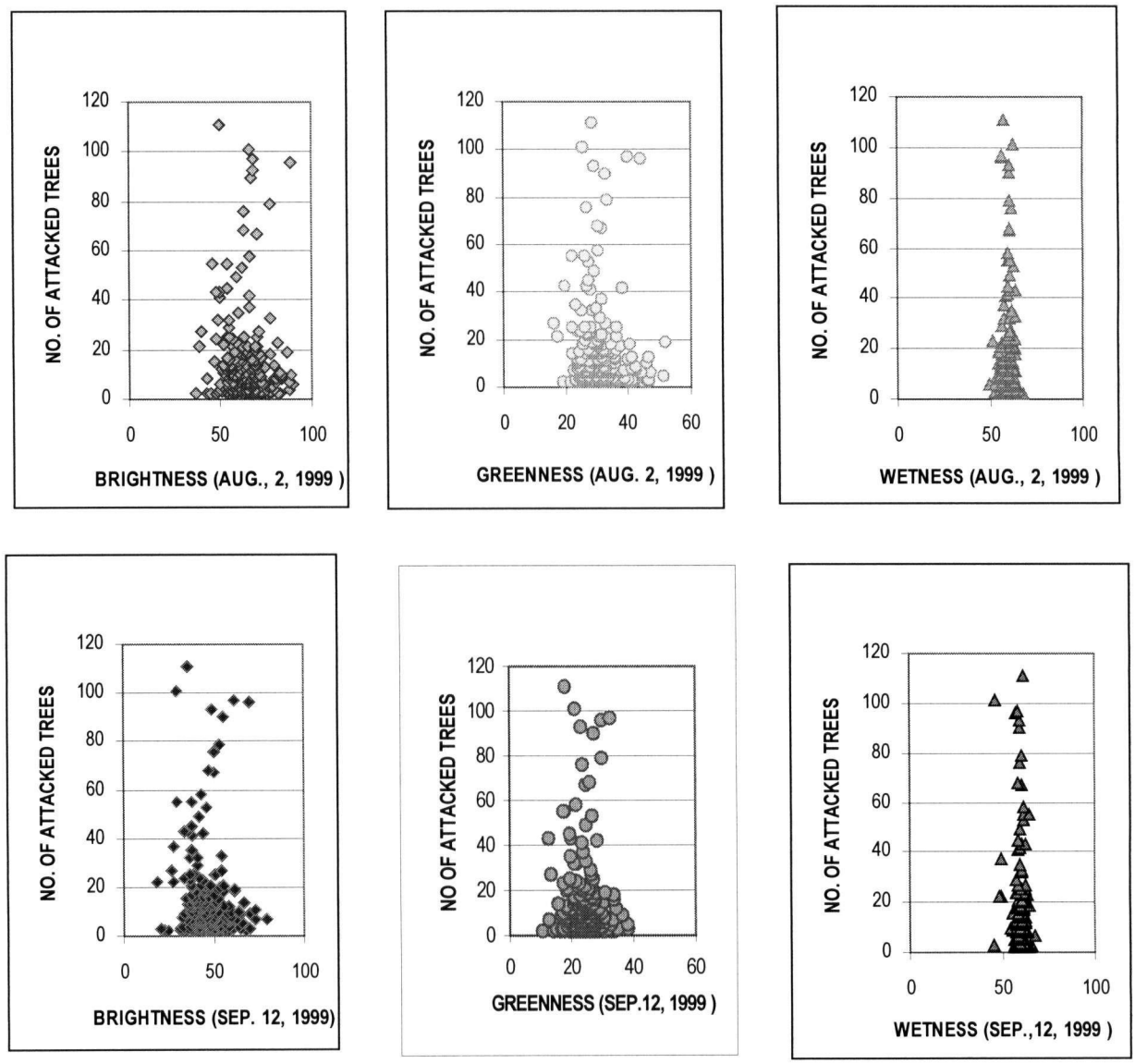


Figure 11. Relationship between number of MPB infested trees and Tasseled Cap indices

There are many reasons that may account for such a pattern. In vegetated areas, pixel level reflectance is influenced by the relative proportions of vegetation types, exposed soil if any, the reflectance interaction between soil and vegetation, and shadows, all modified by atmosphere (Richardson and Weigand 1990). One of the major problems in extracting vegetation information from satellite based sensors is that the spatial resolution of sensors is generally larger than the

vegetation objects, as is the case in this study area. Apparently, less than 30 infested lodgepole pine trees per pixel are not large enough to influence reflectance. This observation was significant from the point of view of the detection of MPB infestations in the study area by using a pixel level algorithm. As shown in Table 11, 95 percent of all the infestation sites had less than 30 attacked trees/site and hence, had a very low chances of getting detected based on pixel level algorithms. This indicated that use of subpixel level algorithms, such as spectral unmixing techniques, would be more appropriate than pixel level algorithms (Murtha *et al.,* 2000).

5.3 Identifying Attacked Stands

In order to test the separability of attacked stands from healthy lodgepole pine stands based on the Tasseled Cap indices, a t-test was performed on a set of randomly picked 22 observation sites which had >30 attacked trees /site and 22 observation points for non-attacked mature lodgepole pine stands. The results were evaluated at 40 degrees of freedom. The differences in the brightness, greenness and wetness values of healthy and attacked stands were significant at the .05 significance level (Table 12). However, these observations are based on a very small sample size.

Table12: Average Difference between Healthy and Attacked MPB Stands (August 2, 1999)

	Brightness		Greenness		Wetness	
	Healthy	Attacked	Healthy	Attacked	Healthy	Attacked
Mean	57.41	62.71	32.53	29.91	57.34	59.71
SD	6.83	8.42	3.91	3.70	1.51	1.57
t-value	2.2929		2.2829		5.1032	

$t_{0.025,\ 40} = 2.021$

Classification Based on Tasseled Cap Indices

Change detection techniques were intended to be used for identifying attacked stands from healthy ones. This was due to the expected change in Tasseled Cap indices from August to September because of further disintegration of chlorophyll, needle structure, and moisture stress caused by disruption of water and nutrient uptake due to growth of blue stain fungus (*Ceratocystis montia*, or *Ophiostoma setosum* *) in the xylem and phloem tissue.

---

*Which of these two fungi mainly grow in the lodgepole pine after the successful MPB attack, is still an area of active research (Breuil 2000, personal communication).

However, differences were observed not only in attacked stands, but in all other cover classes as well. Such uniform changes across all the cover types perhaps can be explained by the lower sun angle and the lower incident radiation in September compared to August. There would also be more shadows within forest stands due to the lower sun elevation angle, which might mask the spectral changes caused due to deterioration in lodgepole pine stand health. Even in the event of no change, the healthy stands would have lower reflectance in September than August and be confused with attacked stands. This problem is further complicated because of the extremely small size of the infestations.

Prior to any change detection, it is imperative that images be registered with each other. While multi-date image registration was within acceptable accuracy of 0.5 pixels (15 meters) such a shift across two date images with small infestation sizes could itself create a large degree of per-pixel spectral ambiguity. Moreover, it is suggested that the multi-temporal data for change detection should have been acquired during nearly same period of time so as to avoid the influence of extraneous factors on the reflectance of features / cover types of interest (Coppin and Bauer 1996). Therefore, change detection analysis was not pursued further.

Since differences between the brightness, greenness, and wetness of healthy and attacked lodgepole pine stands were statistically significant, an unsupervised classification was performed on all the three tasseled cap indices, for both dates separately. Multiple iterations were run: a) to separate vegetation from non-vegetation features; b) separate lodgepole pine stands from other vegetation; and c) classify lodgepole pine stands into different spectral subclasses. Clusters belonging to attacked stands were identified based on information on the location of attacked stands identified from the beetle infestations coverage map.

5.4 Accuracy Assessment

Assessment of identification accuracy for attacked stands were made for both the dates, using the procedure given by Lillesand and Kieffer (2000). Producers accuracy includes the effects of error of omission, whereas, users accuracy takes into account the error of commission. Overall identification accuracy of attacked stands was found to be only 38.82% and 26.17% (Tables 13 and Table 15) for the August and September images, respectively. A linear relationship was observed between the number of attacked trees and identification accuracy for August (Table 14). However, the same relationship was not observed for the September image (Table 16). The low identification accuracy observed for the majority of the reference ground points largely was due to

Table 13. Accuracy estimates based on a 10% random sample (August 2, 1999)

Satellite	Reference data*			
		Attacked	Healthy	Total
	Attacked	132	60	192
	Healthy	208	168	376
	Total	340	228	568

* Ground data provided by Plateau Forest Ltd., Vanderhoof

Producer's Accuracy:
Attacked = 132/340 = 38.82%
Healthy = 168/228 = 73.68%
Overall accuracy = (132+168)/568 = 52.82%

User's Accuracy
Attacked = 132/192 = 68.75%
Healthy = 168/376 = 44.68%

Table 14. Accuracy (%) based on the number of attacked trees/site (August 2, 1999)

Satellite	Reference data*					
	Number of attacked trees per site					
	<10	11-20	21-30	31-80	>80	TOTAL
	31.34	34.55	53.85	53.85	72	38.82
	(63/201)	(22/64)	(7/13)	(14/26)	(26/36)	(132/340)

* Ground data provided by Plateau Forest Ltd., Vanderhoof

Table 15. Accuracy estimates based on a 10% random sample (September 12, 1999)

Satellite	Reference data*			
		Attacked	Healthy	Total
	Attacked	89	103	192
	Healthy	251	125	376
	Total	340	228	568

* Ground data provided by Plateau Forest Ltd., Vanderhoof

Producer's Accuracy:
Attacked = 89/340 = 26.17%
Healthy = 125/228 = 54.82%
Overall accuracy = (89+125)/568 = 37.67%

User's Accuracy
Attacked = 89/192 = 46.35%
Healthy = 125/376 = 33.24%

Table 16. Accuracy (%) based on the number of attacked trees/site (September 12, 1999)

Satellite	Reference data*					
	Number of attacked trees per site					
	<10	11-20	21-30	31-80	>80	TOTAL
	21.89	31.25	38.46	30.76	33.33	26.17
	(44/201)	(20/64)	5/13	(8/26)	(12/36)	89/340

* Ground data provided by Plateau Forest Ltd., Vanderhoof

the extremely small and scattered nature of the MPB infestations in the study area. Because of this, pixel based accuracy assessment procedures were not adequate. Instead, a larger unit, such as stand, should be taken as a base for accuracy assessment. This is supported by the observed correspondence of the distribution of attacked sites (identified from beetle infestation coverage) and probable attacked areas identified from the three Tasseled Cap indices (Figure12 - 14).

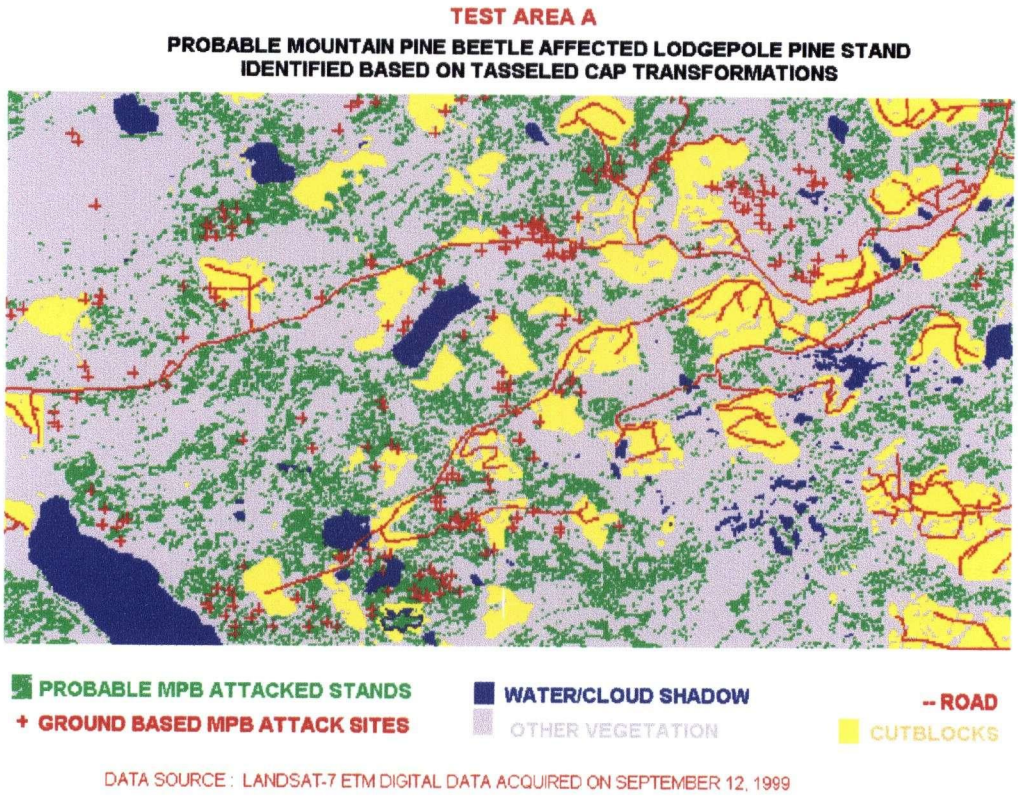


Figure 12. Probable MPB infestation map derived from Tasseled Cap indices - Test area A.

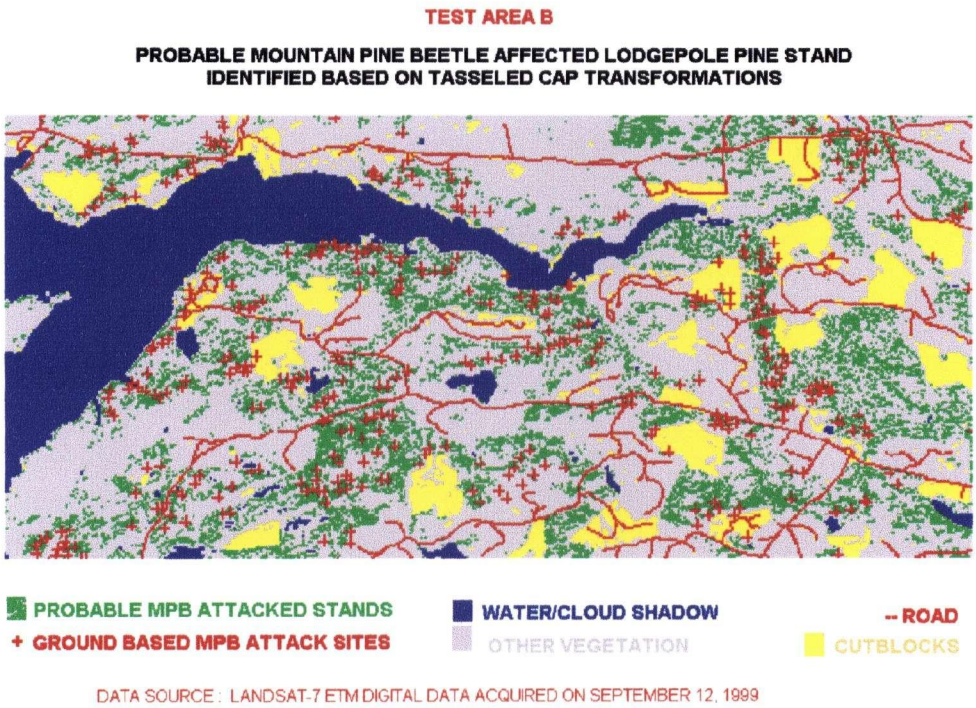


Figure 13. Probable MPB infestation map derived from Tasseled Cap indices - Test area B.

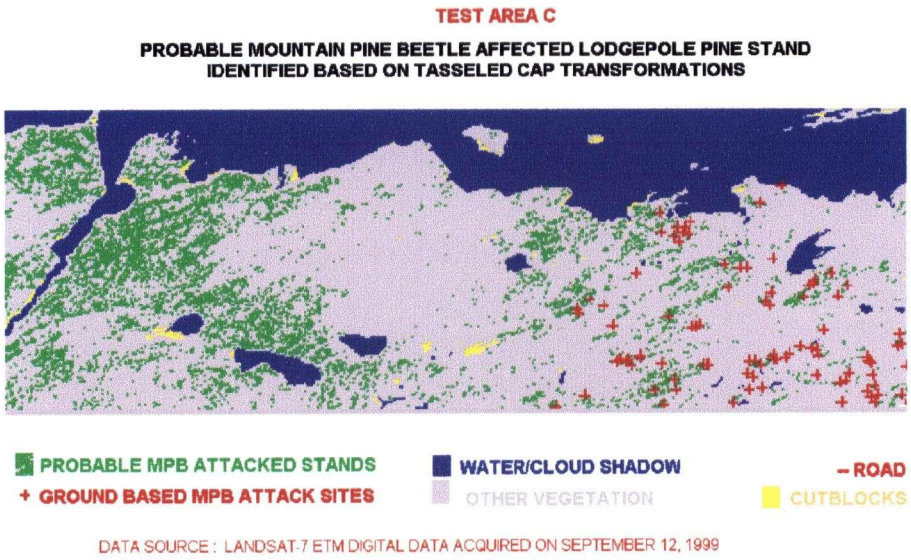


Figure 14. Probable MPB infestation map derived from Tasseled Cap indices - Test area C.

6.0 Conclusions

The following conclusions can be drawn from this study:

- The location of different cover types in brightness-greenness, greenness-wetness, and wetness-brightness feature space based on Landsat-7 Tasseled Cap coefficients compared well with the respective pattern observed for such cover types for Landat-5. This suggests that computed Tasseled Cap coefficients could be used for generation of brightness, greenness and wetness indices for the intended applications.
- The values of Tasseled Cap indices for September were found to be lower than those for August for all the cover types. The main reason for this was thought to be the lower incident solar energy in September.
- Tasseled Cap indices for infestations of more than about 30 attacked trees per site were found to vary in a relatively narrow range. However, for infestation sites with less than 30 affected trees per site the Tasseled Cap indices had random and large dispersions.
- Tasseled Cap indices for mature lodgepole pine stands were strongly influenced by topographic variations.
- Differences between mean brightness, greenness, and wetness of MPB attacked stands and healthy lodgepole pine stands were statistically significant for August.
- It was possible to separate probable susceptible lodgepole pine stands using clustering techniques operated on a combination of all three Tasseled Cap indices.
- Accuracy assessments made at the pixel level gave unsatisfactory results. The identification accuracy for attacked lodgepole pine stands was 38.82 and 26.17 percent for August and September, respectively.
- A linear relationship was observed between the number of attacked trees at a site and identification accuracy for the August data but not for the September data.
- The poor identification accuracy was mainly due to the sub-pixel size of infestations. Therefore, pixel based comparison for accuracy assessment does not seem to be an adequate procedure for accuracy assessment.
- The distribution pattern of attacked stands, as identified from ground based beetle probes, compares well with the spatial pattern of susceptible lodgepole pine stands identified based on Tasseled Cap indices. Therefore, accuracy assessment at the stand level instead at pixel level, appears to be the appropriate level in the case of small infestation sizes.

7.0 Further Research Areas

In order to evaluate the efficiency of tasseled cap transformations in identification of MPB infestations, similar studies may be conducted in test areas where the MPB infestations are at least of a Landsat TM pixel size (i.e. 30 x 30 meters) in spatial extent. One such area could be near Tweedsmuir National Park where large-scale incidence of MPB infestations has been reported.

Topographic variations strongly influence the spectral reflectance from the same object. Therefore, an evaluation of the available procedures for normalizing the effect of these variations on spectral reflectance, should also be done.

Another study could be the application of multi-spectral (4-meter spatial resolution) data from the IKONOS satellite to identify MPB infestations. Digital data from such high spatial resolutions could be effective in detection of small-scattered infestations, as was the case in the present study area.

It would be desirable to use a sub-pixel algorithm, such as spectral unmixing procedures, to detect and identify MPB infestations which are sub-pixel in spatial extent. However, it would be worthwhile to evaluate the efficiency of spectral unmixing procedures in detecting the MPB infestations of varying sizes, contained within a pixel.

Another important aspect, which needs to be systematically explored, is the identification of the stage when the changes in the spectral reflectance behavior of a successfully attacked tree begin to take place. Analysis of multi-temporal satellite data of optimum spatial resolution may provide some answers on this.

References

Ahern, F.J, 1988. The effects of bark beetle stress on the foliar spectral reflectance of lodgepole pine. International Journal of Remote Sensing, 9 (9): 1451-1468.

Ahern, F.J., and Archibald, P.D., 1986. Thematic Mapper information about Canadian Forests: early results from across the country, Proc. of the 10th Canadian Symposium on Remote Sensing, pp: 683-697.

Asrar, G., Fuchs, M., Kanemasu, E.T., and Hatfield, J.L., 1984. Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat. Agronomy J., 76: 300-306.

Banner, A, V., 1986. Detection of bark beetle - attacked spruce using computer based image analysis. M.Sc. Thesis. Faculty of Forestry, University of British Columbia, Vancouver, British Columbia, 145pp.

Baret, R., and Guyot, G., 1991. Potentials and limits of vegetation indices for LAI and APAR assessment. Remote Sensing of Environment, 35:161-173.

Forest Health Surveys Guidebook, 1995. BC Ministry of Forests and BC Environment.

B.C. Ministry of Forests, A socio-economic analysis of mountain pine beetle management in British Columbia, Forest Practices Branch, http://www.for.gov.bc.ca/hfp/pubs/interest/mpbecon/index.htm, November 28, 2000.

BC Ministry of Forests, http://www.for.gov.bc.ca/PAB/News/Features/beetles/lakes.htm, November 28, 2000.

BC Ministry of Forests, http://www.for.gov.bc.ca/kamloops/district/lillooet/fh2.htm, November 28, 2000

BC Ministry of Forests, 2000. Just the facts: A review of silviculture and other forestry statistics.

Braga, R E. G., Da Silva., and Mara, R. L. F., 1991. Monitoring the green areas around Tucurui (Brazil) using 'Tasseled Cap' transformation. Proc. 24th International Symposium on Remote Sensing of Environment, Rio de Janeiro, Brazil, Vol. 1: 255-263.

Breuil, C., 2000. Associate Dean, Graduate Studies and Research, Faculty of Forestry, The University of British Columbia, Vancouver, (Personal Communication).

Chavez, P.S., 1988. An improved dark-object subtraction technique for atmospheric scattering correction of multi-spectral data. Remote Sensing of Environment, 24:459-479.

Churcher, J.J., and McLean, J. A., 1984. Visual detection of beetle -attacked white spruce trees using aerial photography. Proc. RNRF symposium on the applications of remote sensing to resources management. Amer. Soc. of Photogrammetry, Falls Church, Virginia, pp. 137-143.

Cohen, W.B., 1991. Response of vegetation indices to changes in three measures of leaf water stress. Photogrammetric Engineering and Remote Sensing, 57:195-202.

Cohen, W.B., and Spies, T. A., 1992. Estimating structural attributes of Douglas-fir/ western hemlock forest stands from Landsat and SPOT imagery. Remote Sensing of Environment, 41:1-17.

Cohen, W.B., Spies, T. A., and Fiorella, M., 1995. Estimating the age and structure of forests in a multi-ownership landscape of western Oregon, U.S.A. International Journal of Remote Sensing, 16(4): 721-746.

Congalton, R.G., 1991. A review of assessing the accuracy of classifications of remotely sensed data. Remote Sensing of Environment, (37) 35-46.

Coppin, P., K. Nackaerts, K., Queen, L., and Brewer, K., 2000. Operational monitoring of green biomass change for forest management. In press "Photogrammetric Engineering and Remote Sensing". (Personal Communication)

Coppin, P. R., and Bauer, M.E., 1996. Digital change detection in forest ecosystems with remote sensing imagery. Remote Sensing Reviews, Vol.13, pp. 207-234.

Crist, E.P., and Kauth, R. J., 1986.The Tasseled Cap De-Mystified. Photogrammetric Engineering and Remote Sensing, 52(1): 81-86.

Crist, E. P., Laurin, R., and Cicone, R.C., 1986. Vegetation and soils information contained in transformed thematic mapper data. Proceedings of IGARSS'86 symposium, 1465-70.

Crist, E.P., and Cicone, R.C., 1984. Application of the Tasseled Cap concept to simulated Thematic Mapper data. Photogrammetric Engineering and Remote Sensing, 50 (3): 343-352.

Goward, S.N., and Huemmrich, K.F., 1992. Vegetation canopy PAR absorptance and normalized difference vegetation index: an assessment using SAIL model. Remote Sensing of Environment, 39:119-140.

Hall, F.G., Strebal, D. E., Nickeson, J. E., and Goetz, S.J., 1991a. Radiometric rectification: Toward a common radiometric response among multi-date, multi-sensor images. Remote Sensing of Environment, (35): 11-27.

Hall, F.G., Botkins, D.B., Strebel, D. E., Woods, K.D., and Goetz, S.J., 1991b. Large scale patterns of forest successions determined by remote sensing. Ecology, 72:628-640.

Hall, P. M., McLean, J. A., and Murtha, P.A., 1983. Dye-layer density analysis identifies new Douglas fir beetle attacks. Canadian Journal of Forest Research, 13(2): 279-282.

Hall, P.M., McLean, J. A., and Murtha, P.A., 1981. Remote sensing of douglas fir trees newly infested by bark beetles. Proc. Eighth Biennial Workshop on Color Aerial Photography, American Society of Photogrammetry, Falls Church, Virginia, pp. 91-98.

Harris, J.W.E., Dawson, A. F., and Goodenough, D., 1978. Evaluation of Landsat data for forest pest detection and damage appraisal surveys in British Columbia. Canadian Forest Service, Pacific Forest Research Centre, Pub. Rep. BC -X -182, 12 pp.

Hobbs, A.J., 1983. Effects of air photo scale on early detection of mountain pine beetle. M.Sc. Thesis, Dept. Forestry / Remote sensing, Univ. of British Columbia, Vancouver, British Columbia, 137 pp.

Hobbs, A. J., and Murtha, P.A., 1984. Visual interpretation of four scales of aerial photography for early detection of mountain pine beetle infestations. Proc. RNRF symposium on the applications of remote sensing to resources management. American Society of Photogrammetry, Falls Church, Virginia, pp. 433-444.

Horler, D. N. H. and Ahern, F. J., 1986. Forestry information content of Thematic Mapper Data. International Journal of Remote Sensing, Vol. 7 (3): 405-428.

Huete, A. R., 1988. A Soil Adjusted Vegetation Index (SAVI). Remote Sensing of Environment, 25:295-309.

Jackson, R. D., 1983. Spectral indices in n-space. Remote Sensing of Environment, 13:409-421.

Jensen, J., 1996. Introductory digital image processing: a remote sensing perspective. Second edition. Prentice Hall, 316p.

Justice, C.O., Townshend, J.R.G, Holben, B.N., and Tucker, C. J., 1985. Analysis of the phenology of global vegetation using meteorological satellite data. International Journal of Remote Sensing, 6:1271-1318.

Kauth, R. J., and Thomas, G.S., 1976. The Tasseled Cap - a graphic description of the spectral - temporal development of agricultural crops as seen by Landsat. Proc. of symp. on Machine Processing of Remotely Sensed data, Purdue University, West Lafayette, Indiana, 21 June - 1 July, 4B41-4B51.

Kauth, R.J., Lambeck, P.F., Richardson, W.R., Thomas, A., and Pentland, A.P., 1979. Feature extraction applied to agricultural crops as seen by Landsat. Proc. of the Technical sessions, The LACIE Symp., NASA Johnson Space Center, Houston, Texas, (II):705-721.

Kneppeck, I. D., and Ahern, F.J., 1988. A comparison of images from a pushbroom scanner with normal color aerial photography for detecting scattered recent conifer mortality. Photogrammetric Engineering and Remote Sensing,

Lauver, C. L., and Whistler, J. L., 1993. A hierarchical classification of Landsat TM imagery to identify natural grassland areas and rare species habitat. Photogrammetric Engineering and Remote Sensing, vol.59 (5): 627-634

Lillesand, T. M., and Kieffer, R.W., 2000. Remote Sensing and Image Interpretation, Fourth Edition, John Wiley & Sons, New York.

Major, D. J., Baret, F., and Guyot., G., 1990. A ratio vegetation Index adjusted for soil brightness. International Journal of Remote Sensing, 11(5): 727-740.

McMullen, L. H., Safranyik, L., and Linton, D. A., 1986. Suppression of mountain pine beetle infestations in lodgepole pine forests. Canadian Forest Service Pacific Forestry Centre, Inf. Rep. No. British Columbia-X-276.

Moran, S.M., Jackson, R. D., Slater, P.N., and Teillet, P.M., 1992. Evaluation of simplified procedures for retrieval of land surface reflectance factors from satellite sensor output. Remote Sensing of Environment, (41): 169-184.

MOEP, http://www.env.gov.bc.ca/main/newsrel/fisc9900/february/ib418.htm, November 28, 2000

Murtha, P.A., and Cozens, R., 1985. Color infrared photo interpretation and ground surveys to evaluate spruce beetle attack. Canadian Journal of Remote Sensing, 11(2): 177-187.

Murtha., P.A., 1985. Photo interpretation of spruce beetle attacked spruce. Canadian Journal of Remote Sensing, 11(1): 93-102.

Murtha, P.A., and Fournier, R.A., 1992. Varying reflectance patterns influence photo interpretation of dead tree crowns. Canadian Journal of Remote Sensing, 18(3): 167-173.

Murtha., P.A., and Wiart, R. J., 1989a. PC-Based digital analysis of mountain pine beetle current-attacked and non-attacked lodgepole pine. Canadian Journal of Remote Sensing, Vol15 (1): 70-76.

Murtha., P.A., and Wiart, R. J., 1989b. Cluster analysis of pine crown foliage patterns aid identification of mountain pine beetle current-attack. Photogrammetric Engineering and Remote Sensing, Vol.55 (1): 83-96.

Murtha., P.A., and Wiart, R. J., 1987. PC-Based digital image analysis for mountain pine beetle green attack: preliminary results. Canadian Journal of Remote Sensing, Vol. 13(2): 92-95.

Murtha., P.A., Bortolot, Z., and Thurston, J., 2000. A Landsat TM spectral unmixing mountain pine beetle attack-fraction probability map in the Vanderhoof Forest District, British Columbia, Proc. of Remote Sensing Symposium (on CD).

Patterson, M. W. and Yool, S. R., 1998. Mapping fire-induced vegetation mortality using Landsat 5 Thematic Mapper data: A comparison of linear transformation techniques. Remote Sensing of Environment 65:122-132.

Price, K.P., and Jakubauskas, M.E., 1998. Spectral retrogression and insect damage in lodgepole pine successional forests. International Journal of Remote Sensing, Vol. 19(8):1603-1611.

Price, K.P., Stephen, L.E., Nellis, M.D., Lee, R.Y., and Boyce, R., 1997. Mapping land cover in a High Plains agro-ecosystem using a multi-date Landsat Thematic Mapper modeling approach. Transactions of Kansas Academy of Sciences, 100(1/2): 21-33.

Qi. J., Chebouni, A., Huete, A. R., Kerr, Y.H., and Sorooshian., 1994. A modified soil adjusted vegetation index. Remote Sensing of Environment, 48:119-126.

Rencj, A.N., and Nemeth, S., 1985. Detection of mountain pine beetle infestation using Landsat and simulated thematic mapper data. Canadian Journal of Remote Sensing, 11(1): 50-58.

Richardson, A.J., and Weigand, C.L., 1990. Comparison of two models for simulating the soil-vegetation composite reflectance of a developing cotton canopy. International Journal of Remote Sensing, 11(3):447-459.

Richardson, A.J., and Wiegand, C.L., 1977. Distinguishing vegetation from soil background information. Photogrammetric Engineering and Remote Sensing, 43:1541-1552.

Richter, R., 1997. Correction of atmospheric and topographic effects for high spatial resolution satellite imagery. International Journal of Remote Sensing, 18(5):997-1110.

Sachs. D.L., Sollins, P., and Cohen, W.B., 1998. Detecting landscape changes in the interior of British Columbia from 1975 to 1992 using satellite imagery. Canadian Journal of Remote Sensing, Vol. 28:23-36.

Science writers guide to Landsat-7, http://landsat.gsfc.nasa.gov/announcements/L7_Writers_Guide.html, November 28, 2000.

Seller, P.J., Tucker, C. J., Collatz, G. J., Los, S., Justice, C.O., Dazlich, D. A., and Randall, D. A. 1994. A global 10*10 NDVI data set for climate studies. Part 2- the adjustment of the NDVI and generation of global fields of terrestrial biophysical parameters. International Journal of Remote Sensing, Vol. 15:3519-3545.

Shore, T. L., Safranyik, L., and Lemieux, J.P., 2000. Susceptibility of lodgepole pine stands to the mountain pine beetle: testing of a rating system. Canadian Journal of Forest Research, Vol.30: 44-49.

Shore, T. L., and Safranyik, L., 1992. A system for rating the susceptibility and risk of lodgepole pine stands to mountain pine beetle. For. Can. PFC-File Rep. 5203.17pp.

Sirois, J and Ahern, F.J., 1988. An investigation of SPOT HRV Data for detecting recent mountain pine beetle mortality. Canadian Journal of Remote Sensing, 14(2): 104-108.

Taylor, S. P., 1998. A comparison between aerial sketch mapping and Landsat survey techniques for detecting attacked trees by mountain pine beetle and Douglas-fir beetles (BC MOF internal report).

The Dispatch, Vol.1-4, CLMA and NFPA Emergency Task Force, www.mountainpinebeetle.com, November 28, 2000.

Thompson, D. R., and Wehmanen, O. A., 1980. Using Landsat digital data to detect moisture stress in corn-soybean growing regions. Photogrammetric Engineering and Remote Sensing, 46:1087-1093.

Unger, L., 1993. Mountain Pine Beetle. Forestry Canada, Forest Insect and Disease Survey, Forest Pest Leaflet No. 76, 7p.