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Surveying mountain pine beetle damage of forests: A review of remote sensing opportunities

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Abstract

The severity and large spatial extent of the current mountain pine beetle outbreak in western North America has prompted research into methods for surveying the location and extent of beetle impacts using remotely sensed data. New forms of remotely sensed data and methods of image analysis have emerged in recent years, which have the potential to provide information on mountain pine beetle red-attack damage that complements information gathered from existing survey methods. The main objective of this review is to summarize previous and current contributions of remote sensing to the survey of mountain pine beetle impacts. The potential and limits of remotely sensed data for the detection and mapping of mountain pine beetle impacts, over a range of attack stages, are identified and synthesized. The secondary objective of this review is to highlight those methods or data sources that currently have operational potential and that the authors believe warrant further research in support of ongoing planning and management activities. Emphasis is placed on the different information needs associated with the various spatial scales of forest management: regional, landscape, and local. The findings of this review indicate that remotely sensed data is useful for mapping red-attack damage across a range of image data types and scales of inquiry. The review concludes with recommendations for future research, and suggestions for operational standards to guide the use of remotely sensed data for the survey of mountain pine beetle impacts.

Keywords: Mountain pine beetle; Remote sensing; Forest health; Survey; Detection; Planning; Management

1. Introduction

At epidemic population levels, mountain pine beetles (*Dendroctonus ponderosae*) generally spread through mature stands and cause extensive mortality of large-diameter trees. Even though virtually all species of pine within the mountain pine beetle's range are suitable hosts (Furniss and Schenk, 1969; Smith et al., 1981), lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) is considered the beetle's primary host, due to the size, intensity, and the commercial impact of mountain pine beetle epidemics.

The impact of mountain pine beetle is evident throughout its biological range, being the second highest contributor to tree mortality (as ranked by total area of mortality, after sub alpine fir decline) within the national forests of the Rocky Mountain Forest Region of the United States (Colorado, Kansas, Nebraska, South Dakota, and Wyoming). Approximately 315,800 trees were killed by mountain pine beetle in the Rocky Mountain Forest Region from 1997 to 1999 (Harris et al., 2001). In 2003, approximately 1,015,700 trees were killed in this same region (Harris, 2004). A summary of the area in the United States affected by the outbreak of mountain pine beetle from 1999 to 2003 is provided in Table 1.

In Canada, the mountain pine beetle population has reached epidemic levels, primarily in British Columbia, with the area of infested forest increasing from approximately 164,000 ha in 1999 to 7,089,902 ha in 2004 (Westfall, 2005). The biological range of the primary host, lodgepole pine, exceeds the current range of the mountain pine beetle. Recent research has indicated that the beetle is expanding into new geographic areas (Carroll et al., 2004). The two main factors that have contributed to the successful expansion of the beetle population in British Columbia include the large amount of mature lodgepole pine on the land base, which has tripled in the last

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Table 1
Mountain pine beetle outbreak in the United States (ha) 1999–2003

State	1999	2000	2001	2002	2003
California	9700	30400	29600	186800	614800
Colorado	71800	139500	151200	209600	227100
Idaho	84300	122300	170000	339300	341900
Montana	77400	40600	111700	249500	291200
Nevada	1400	800	1200	2600	2400
New Mexico	0	0	0	3800	0
Oregon	46200	43600	76300	182300	186000
South Dakota	19000	13900	102200	102900	189600
Utah	3700	2200	17300	26700	53400
Washington	65000	63100	134800	173100	223800
Wyoming	6200	9500	55000	88000	88900
Total	384700	465900	849300	1564600	2219100

Source: United States Department of Agriculture, 2004.

century as a result of intensive fire suppression activities (Taylor and Carroll, 2004) and several successive years of favorable climatic conditions, resulting in an increase in climatically suitable areas for brood development (Carroll et al., 2004).

Information on the extent and severity of the beetle infestation is required for a wide variety of forest planning, management, and modeling activities. Different information needs require suitable survey methods that provide the appropriate level of detail. Furthermore, the timing of the surveys must be coordinated relative to the expression of attack in the tree-crown foliage, which can vary substantially. Information requirements are discussed in the following section and in detail in Wulder et al. (2004a).

Research concerning the application of remotely sensed data for the detection and mapping of mountain pine beetle infestations has been ongoing since the early 1960s. In recent years, the number and types of remote sensing instruments have increased and image-processing capabilities have improved (Wulder and Franklin, 2003). Given the devastating impacts of the current mountain pine beetle outbreak in western North America (Westfall, 2005; Harris, 2004) it is prudent to assess what new remotely sensed methods or data sources may have potential for detecting and mapping the areas affected by the beetle. Since outbreaks of mountain pine beetle have occurred in the past and will likely occur again in the future (Taylor and Carroll, 2004), lessons learned from research conducted during this current outbreak may be applied in future outbreaks. For example, documenting the potential and limits of various data sources, under various infestation conditions, is useful information for ongoing monitoring of the current infestation; however, it will also be helpful for addressing the information needs of future infestations.

Previous reviews have explored the application of remote sensing to forest health issues and have summarized the state of remote sensing technology up to the early 1980s (Puritch, 1981; Gimbarzevsky, 1984). In general, these reviews covered a broad range of detection and mapping applications for a variety of forest pests. Aerial photography was identified in these reviews as the most frequently acquired remotely sensed data type; both true color and color infrared (CIR) photos were used to map various damage agents, at various scales. The damage agent, scale of photos, and methods and timing of data collection, influenced the degree to which the forest health studies included in these reviews were successful at fulfilling their objectives (Puritch, 1981; Gimbarzevsky, 1984). Recent reviews have continued to emphasize the utility of aerial photography (Ciesla, 2000; Roberts et al., 2003) for surveying damage caused by mountain pine beetle.

The objective of this review is to present the potential and limits of remotely sensed data in the detection and mapping of mountain pine beetle impacts, over a range of infestation stages. What differentiates this review from its predecessors is the focus on mountain pine beetle, exclusive of other pests and damage agents, as well as an emphasis on relevant technological developments in the field of remote sensing. To meet this stated objective, materials pertinent to the detection and mapping of mountain pine beetle impacts have been gathered and synthesized. This review is structured around the information needs of the end user, represented at three distinct scales: regional, landscape, and local. Due to differing organizational mandates and stewardship responsibilities at each of these scales, the information needs of forest managers vary in terms of the level of detail and precision required. The appropriate use of remote sensing technology must be considered within the context of these information needs.

The review begins with background information regarding the biology of the mountain pine beetle and a brief synopsis of the relevant technical aspects of remotely sensed imagery. The concepts and implications associated with the spatial, spectral, and temporal resolutions of remotely sensed data are presented. Due to its significance for survey planning and execution, information on the temporal sequence of mountain pine beetle attack and the progression of foliage discoloration are also presented. The review continues with highlights from significant research completed to date, and recommendations and potential directions for future research priorities are provided. Finally, the review concludes with guidelines for the appropriate use of remotely sensed data when surveying the impacts of mountain pine beetle infestations. The context of this paper is shaped by the current mountain pine beetle outbreak in British Columbia, Canada and many of the methods and examples presented are specific to this area. However, the information needs associated with the three spatial scales (regional, landscape, and local) are common to all jurisdictions, as is the potential of remote sensing technologies to provide information on mountain pine beetle impacts that contributes to forest management activities.

2. Background

2.1. Information requirements for forest management

The information needs of forest managers, in the context of addressing an infestation of mountain pine beetle, range from strategic planning over large areas, to detailed and precise location information for sanitation logging and treatment (Wulder et al., 2004a). Consequently, the scale and methods of current information collection ranges from broad (aerial overview sketch mapping), to more detailed (helicopter Global Positioning System (GPS) surveys and maps of infested stands derived from aerial photography), to even more detailed ground surveys. Information regarding mountain pine beetle location and extent is required for planning, modeling, forest inventory updates, sanitation logging, and block layout; therefore, information requirements vary in terms of the level of detail and precision required. In North America, government agencies exercise their mandates at both the regional scale (e.g. province, state, USDA Forest Service regions) and the landscape scale (e.g. forest districts, national forests) (British Columbia Ministry of Forests, 2003b). In British Columbia, forestry companies work cooperatively at the landscape scale with both government and other companies, and more independently at local scales (British Columbia Ministry of Forests, 2003c).

Within the context of information needs, it is important to distinguish between a general survey and a detailed survey. A general survey is usually conducted for non-operational purposes, using a fixed-wing aircraft. An observer manually captures (e.g. by drawing directly onto a hardcopy map or using a stylus on a tablet PC) information on the location, extent, and severity of beetle impacts at scales of 1:100,000 or 1:250,000. These general surveys are not considered sufficiently accurate for operational applications, and are often used as a stratification tool to determine locations for subsequent, more detailed surveys (British Columbia Ministry of Forests, 1995). General surveys are often completed in the context of broader forest health surveys, which include a wide variety of forest damage agents. The aerial overview survey program in British Columbia is an example of a general type of survey that captures information on a number of forest damage agents, as well as capturing the location and extent of mountain pine beetle red-attack damage (British Columbia Ministry of Forests, 2003b). In contrast, detailed surveys are typically conducted in a rotary or fixed-wing aircraft, with an observer capturing (typically with a GPS device) information at scales of 1:40,000 or 1:50,000 (British Columbia Ministry of Forests, 1995). Detailed surveys are designed to accurately map the location, extent, and severity of mountain pine beetle infestations for operational purposes, with the data being used to direct the location of follow-up ground surveys and mitigation activities. General surveys may be undertaken at the regional or landscape scale, while detailed surveys are more likely to be undertaken at landscape and local scales.

2.2. The biological cycle of mountain pine beetle

The phenology of the mountain pine beetle and the associated host response has implications for the timing at which surveys of beetle damage are undertaken (Fig. 1). In general, mountain pine beetles in British Columbia produce a single generation per year (Safranyik et al., 1974; Carroll and Safranyik, 2004). Adult beetles typically attack trees in August, and lay eggs, which complete their development cycle into mature adults approximately 1 year later (Amman and Cole, 1983). The mountain pine beetle uses two tactics to overcome the defenses of a healthy tree. First, the beetles may attack in large numbers through a cooperative behavior termed as a mass attack. By rapidly concentrating their attack on selected trees, the beetles are capable of exhausting the host's defensive response (Safranyik et al., 1974; Berryman, 1976; Raffa and Berryman, 1983; Berryman et al., 1989). Secondly, the beetles have a close association with several microorganisms, which the beetles carry into the tree with them when they attack. In particular, the spores of two blue-stain fungi (*Ophiostoma clavigerum* and *Ophiostoma montium*) are inoculated into the tree as the beetles bore through the tree's bark (Fig. 1). These fungal spores penetrate living cells in the phloem and xylem (Safranyik et al., 1975; Ballard et al., 1982, 1984; Solheim, 1995), resulting in desiccation and disruption of transpiration (Mathre, 1964), effectively stopping resin production by the tree (Carroll and Safranyik, 2004).

Immediately following a mass attack, the foliage of trees remains visibly unchanged; however, a drop in sapwood moisture has been measured as a consequence of the attack (Reid, 1961; Yamaoka et al., 1990). Once the tree is killed, but still with green foliage, the host tree is in the green-attack stage. The first visible sign of impact is a change in foliage color from

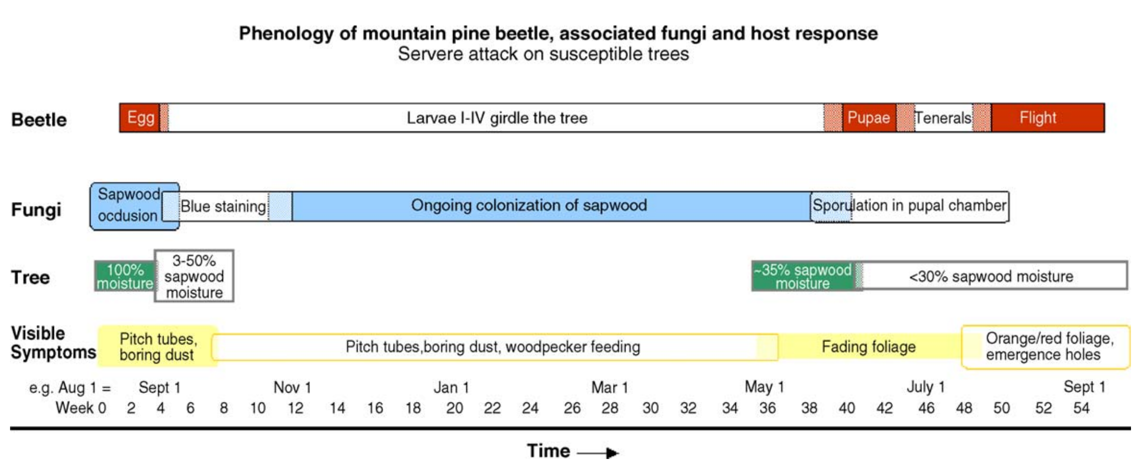


Fig. 1. Example of the phenology of the mountain pine beetle, associated fungi and host response assuming a 1-year life cycle and successful colonization of a suitable host.

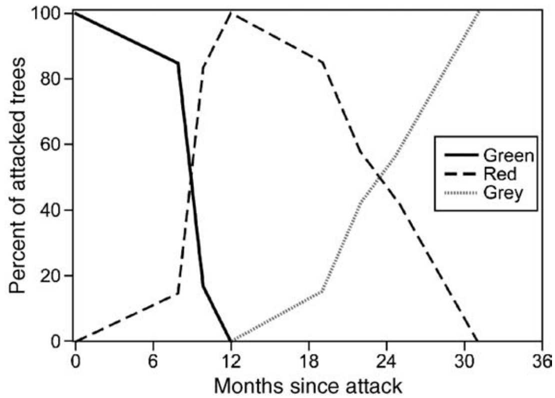


Fig. 2. Variability in fading rate of foliage within an example lodgepole pine stand (Fountain Valley Site 2, Kamloops Forest District, between 1962 and 1967) post-mass-attack. This example stand was composed of 15 attacked trees.

green to greenish-yellow that usually begins in the top of the crown. These trees are referred to as faders. Generally, the foliage fades from green to yellow to red over the spring and summer following attack (Amman, 1982; Henigman et al., 1999). The leaves gradually desiccate and the pigment molecules break down; initially the green chlorophyll pigment molecules are lost, then the yellow carotenes and red anthocyanins (Hill et al., 1967). Slowly, the needles drop until the tree is completely defoliated. Twelve-months after being attacked, over 90% of the killed trees will have red needles (red-attack). Three years after being attacked, most trees will have lost all needles (gray-attack) (Fig. 2) (British Columbia Ministry of Forests, 1995). There is variability associated with the progression of attack stages; the rate at which the foliage will discolor varies by species and by site (Fig. 3) (Safranyik, 2004).

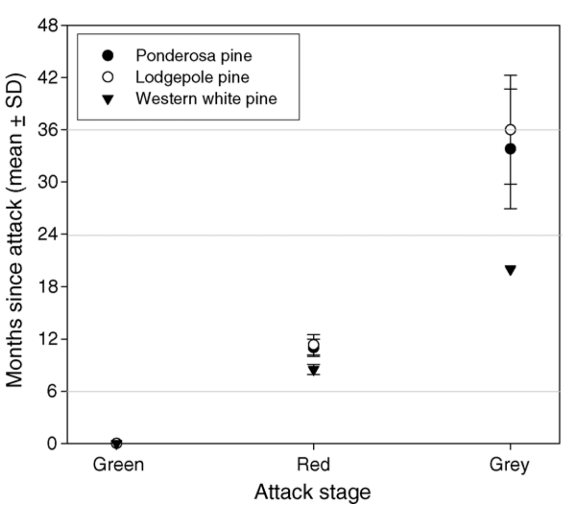


Fig. 3. Illustrated is the number of months for a sample of mass-attacked trees to reach 100% of a given attack stage; variability is demonstrated between stands (1 standard deviation error bars) and between species. Foliage changes following mass-attack at 13 sites in the Kamloops and Nelson Forest Districts, between 1962 and 1967. The foliage conditions of 246 individuals from three species were monitored.

2.3. Remotely sensed image characteristics and information content

The key to the successful application of remotely sensed data for the detection and mapping of mountain pine beetle impacts is to match the appropriate sensor and image analysis methods to the information requirements. Fig. 4 illustrates the relationship between spatial resolution, spectral resolution, and image information content. Three different image pixel sizes are depicted on Fig. 4, as represented by three boxes of different sizes placed upon the digital photo of an area that was infested with mountain pine beetle. The larger frame represents a $30\ m \times 30\ m$ area (e.g. equivalent to a Landsat Thematic Mapper pixel (TM)); the mid-size frame represents a $4\ m \times 4\ m$ area (e.g. equivalent to am IKONOS multispectral pixel); and the smallest frame represents a $1\ m \times 1\ m$ area (e.g. equivalent to an IKONOS panchromatic pixel). Moderate spatial resolution remotely sensed data typically includes data that has a spatial resolution greater than $5\ m \times 5\ m$, to a maximum size of $30\ m \times 30\ m$ (Franklin and Wulder, 2002). Within the largest frame in Fig. 4 ($30\ m \times 30\ m$), red-attack trees, faders, and healthy trees are present. In addition, there are shadows, understorey, and other elements of a typical pine stand. The spectral response for that particular pixel is an amalgam of all the elements present (Lefsky and Cohen, 2003). This amalgamation of stand elements may dilute the spectral response of the red-attack trees present in the pixel, and therefore make mapping red-attack from this single date of imagery difficult. However, a multi-date approach, which focuses on the relative difference in spectral response between two image dates, could be used to detect the damaged trees (e.g. if the first image date was selected for a time prior to the infestation, or conversely a later date was selected when the infestation has increased and the number of trees with red-attack damage had increased).

High spatial resolution remotely sensed data typically has a spatial resolution less than or equal to $5\ m \times 5\ m$ (Franklin and Wulder, 2002). High spatial resolution multispectral data (in this example, illustrated by the mid-sized frame of $4\ m \times 4\ m$) contains fewer elements and, therefore, would be capable of higher accuracy in red-attack mapping. The trade-off for the higher resolution image is a smaller overall image extent. For example, a Landsat TM image covers an area approximately 34,225 km^2 with a 185 km swath width (at a cost of approximately US\$ 0.02/km^2), whereas an IKONOS image (minimum order size) covers an area approximately 100 km^2 and a swath width of 11 km (at a cost of approximately US\$ 7.00/km^2). The high spatial resolution panchromatic example, represented by the smallest frame in Fig. 4 ($1\ m \times 1\ m$), begins to capture conditions of the forest stand that are single stand elements, such as a portion of a sunlit tree crown. However, the panchromatic data has a lower spectral resolution (i.e. a single spectral channel covering a broad range of wavelengths), providing detection capabilities inferior to the multiple, narrow spectral bands associated with multispectral sensors (Guyot et al., 1989; Lefsky and Cohen, 2003).

Fig. 4. Illustration of information content of three common image spatial resolutions of 30 m × 30 m, 4 m × 4 m, and 1 m × 1 m. Larger pixels tend to amalgamate a greater variety of stand elements. Underlying image is a true-color digital photograph. (Image provided courtesy of J. Heath, Terrasaurus Ltd., Vancouver, BC.)

The temporal resolution of a sensor may also influence possible applications. Sensors that overpass an area daily (airborne or satellite) are more likely to capture data under optimum weather conditions. Based upon the satellite's orbit, sensors have a predetermined acquisition schedule. For example, the Landsat sensors will revisit the same location once every 16 days. For these sensors, the acquisition of a high quality image (e.g. no clouds or haze) relies on the co-occurrence of optimum weather conditions with satellite overpass. This type of sensor may not be logistically feasible for forest health applications if there is only a short period of time when the particular forest health issue manifests in the foliage and is detectable. The advantage of a sensor with a fixed schedule is the ability to resample the same location on previous or subsequent dates; standardized image characteristics facilitate the comparison of repeated samples. Providing the images are archived and captured with a similar view angle, the images may be used for comparing current and former conditions during analysis and interpretation.

2.4. Spatial characteristics of attack

Mountain pine beetle populations exist in one of four distinct states, representing the nature of the beetle population and damage to the host species: endemic, incipient epidemic, epidemic (e.g. outbreak), and post-epidemic (Safranyik, 2004). The characteristics of each level of infestation are included in Table 2. Endemic populations exist between outbreak collapse and incipient populations and typically focus on weakened trees. For beetle populations to remain at this level, extreme mortality must occur within each generation of beetles. Incipient epidemic populations are those that can successfully mass attack a large diameter host tree. Under favorable conditions, infested spots will increase in size and coalesce to form larger patches of infestation, particularly in areas with extensive, contiguous regions of mature lodgepole pine. If these favorable conditions are sustained over long periods of time, epidemic population levels will result. Finally, when epidemic outbreaks collapse due to host depletion or sudden, severe low temperatures, beetle populations will continue in a post-epidemic state, with continuing population decline as a result of increased competition for suitable hosts or increased host resistance (Safranyik, 2004). At endemic population levels, high spatial resolution remotely sensed data would be required for damage surveys, although even with this detailed data, detection can be difficult if the beetles have primarily infested trees that are not in the upper layer of the canopy (e.g. red crowns of infested trees are obscured by the crowns of taller uninfested trees) (Safranyik, 2004). As the mountain pine beetle population increases to the incipient epidemic level, high to moderate spatial resolution remotely sensed data is best suited for detection, but the suitable data choice may depend on the area of coverage desired. Under epidemic conditions, moderate spatial resolution remotely sensed data would be sufficient for detection (Table 3).

2.5. Temporal characteristics of attack

Of critical importance to the detection of mountain pine beetle damage via remotely sensed data is the variability in fade rates (i.e. the rate at which the foliage changes color) caused by climate and phenology. The timing of the changes in foliage depends on tree genetics, tree condition, and the local environment (Safranyik et al., 1974). The general trend in fade rates is captured in Fig. 2, where the fading of 15 lodgepole pine trees is followed over 3 years, with the overlap between the tree crown expressions of attack stages illustrated. Noteworthy trends include no trees remaining at green-attack stage after 12

Table 2
Characteristics associated with different population states of mountain pine beetle (after Safranyik, 2004)

Population state	Population characteristics
Endemic	• Widespread in mature pine forests; however, they are restricted to weakened and decadent trees • Frequently found in trees attacked by secondary bark beetle species. Trees containing mountain pine beetles can be very difficult to locate on the ground and even from the air since many of these trees will be in the intermediate to suppressed crown classes, the faded crowns of which are partially hidden below the crowns of taller, uninfested trees • Currently attacked trees are often not located near brood trees • There is no obvious relationship between the probability of attack and tree dbh • Yearly tree mortality is normally less than volume growth
Incipient epidemic	• Most infested trees are in the larger diameter classes • Clumps of infested trees are scattered and confined to some stands • The infested clumps vary considerably in size and number from year to year but tend to grow over time • Frequently, the groups of infested trees first appear in the following situations: draws and gullies, edges of swamps or other places with wide fluctuations in the water table; places where lodgepole pine is growing among patches of aspen, perhaps indicating the presence of root disease; dry, south and west-facing slopes
Epidemic	• Resilient to large proportional losses through natural mortality • Generation mortality is usually in the range of 80–95%, corresponding to potential rates of population increase of two–eight-fold. The usual annual rate of increase, however, is two–four-fold when measured over the entire epidemic area • Infestations are widespread and exist at the landscape level • There are usually large annual increases in both infested areas and numbers of infested trees
Post-epidemic	• Populations collapse due to either the depletion of most of the large-diameter susceptible host trees in an area or an adverse weather event causing widespread beetle mortality • As a consequence of population collapse, the potential for beetles to successfully colonize any remaining healthy, large-diameter trees through mass attacks diminishes. Therefore, most successfully attacked trees are once again from the intermediate or suppressed crown classes • Populations continue to decline until they return to the endemic state

months, all trees reaching red-attack stage by 12 months, and the gray-attack stage initially evident after 13 months. The overlap of the red and gray stages is also evident. Fig. 3 presents data from trees that were inspected annually to determine the link between mountain pine beetle attack and the corresponding fading of the tree crown. The trees that were attacked (green-attack stage) in year 1 were all at the red-attack stage after 10–12 months. A remote sensing survey for red-attack trees before that 10-month period may have missed those trees that were late to change color. Similarly, surveys between 18 and 36 months would need to include both red-attack and gray-attack trees to generate an accurate estimate of beetle impact (e.g. tree mortality). The variability in the rate of change is greater over larger areas, where there is more variability in tree characteristics and environmental conditions.

2.6. Spectral characteristics of attack

Each different attack stage has different spectral characteristics. Green-attack is one form of non-visual stress, whereas for red-attack, detection may be made visually (Safranyik et al., 1974). Gray-attack can also be detected visually, and since most of the tree's needles have been shed, gray-attack trees have a pattern of reflectance closer to completely defoliated trees, than to trees with red foliage (Safranyik et al., 1974). This therefore increases the chance that trees defoliated by other damage agents could be mistaken as mountain pine beetle gray-attack. Non-visual symptoms of stress are difficult to detect using remote sensing. Based on the sequence of biophysical events documented in the biological literature, non-visual symptoms of stress due to bark beetle mass-attack are most likely the result of moisture stress (Nebeker et al., 1993). A review of studies detecting non-visual symptoms of stress (caused by mountain pine beetle infestation) summarized the research done in the 1960s and 1970s (Puritch, 1981) and identified some studies that had success in detecting water stress at the leaf-level: slight effects could be detected within 45–90 days of attack by mountain pine beetle. Similar small spectral changes were found in green foliage of stressed red pine (Rock et al., 1988) and broad-leaved species (Rohde and Olson, 1970). In general, detection of non-visual symptoms of

Table 3
Image data requirements for red-attack detection at three levels of mountain pine beetle populations

Mountain pine beetle population level	Forest damage characteristics	Spatial resolution requirements
Endemic	Single or small groups of trees	High
Incipient	Small to large groups of trees	High or moderate
Epidemic	Large groups of trees over large areas	Moderate

stress was poor when the data integrated foliage, branches, and other background elements common to forests (Puritch, 1981).

A study of lodgepole pine foliage, using the Compact Airborne Spectrographic Imager (CASI), detected differences in the spectral reflectance of attacked versus non-attacked trees (Ahern, 1988). Fig. 5 illustrates how some of the effects were greater on the current foliage compared to previous-year foliage. Ahern (1988) cautioned that the changes detected at the leaf-scale might not be generalized to entire trees, where branches, understorey vegetation, and other background objects dilute the signal. An independent study using an airborne sensor investigated the spectral reflectance for entire trees and found that the reflectance distributions of green-attack trees and healthy trees overlapped considerably (Fig. 6) (Heath, 2001).

Conifer foliage may be damaged and become red due to a variety of agents, such as insects, root rot, fungi, and drought (Henigman et al., 1999; Vollenweider and Günthardt-Goerg, 2005). Independent of the damage agent, foliar moisture declines, chlorophyll and other pigment molecules break down, followed by a break down of intra-cellular and cellular structures (Hill et al., 1967; Sims and Gamon, 2002; Vollenweider and Günthardt-Goerg, 2005). This change manifests as an increase in the spectral reflectance of red wavelengths and a drop in green reflectance (Ahern, 1988; Herrmann et al., 1988; Rock et al., 1988; Leckie et al., 1988; Curran et al., 1990). In addition to the changes in the visible spectrum, red-attack foliage has a higher reflectance of wavelengths near 850–1100 nm (Fig. 5) (Ahern, 1988).

In summary, the background information provided highlights the complexities associated with detecting and mapping mountain pine beetle damage. The temporal, spatial, and spectral characteristics of infestations directly determine the detectability of the damage, while the characteristics of the remotely sensed data determine under what conditions it will be most successful. For example, red-attack damage caused by epidemic population levels of mountain pine beetle, are relatively straightforward to detect and map accurately, due to the distinct spectral properties of the red-attack and the large spatial extent of a typical outbreak. Conversely, red-attack damage caused by endemic or incipient epidemic populations require data with a higher spatial resolution, due to the small and spatially dispersed patches of red-attack associated with these levels of infestation. Table 4 outlines the spatial and spectral properties of several remote sensing instruments that are currently operational and that have potential for surveying mountain pine beetle damage.

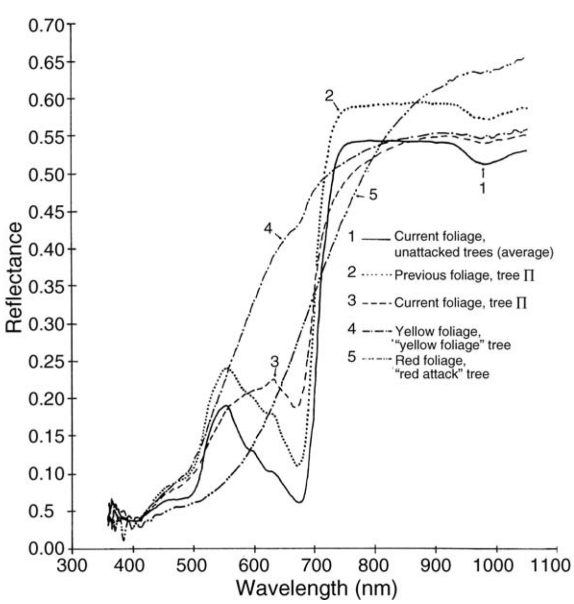


Fig. 5. Spectral reflectance curves for foliage from different individual trees illustrating healthy (unattacked) compared to green-attack (on foliage from current and previous year), fading (yellow attack), and red-attack. (With permission, Ahern, 1988.)

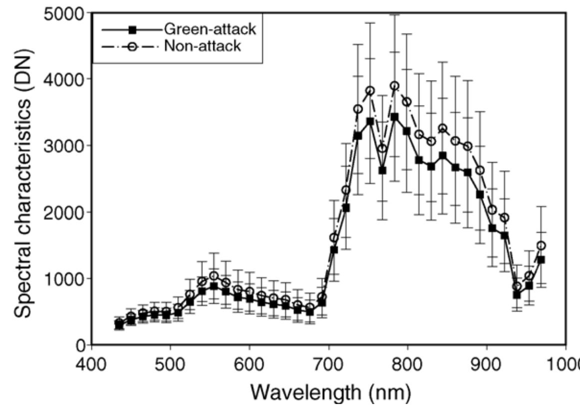


Fig. 6. Spectral characteristics (digital number, DN, mean and ±1 standard deviation) of 24 green-attack trees and 25 non-attack trees (modified after Heath, 2001).

3. Regional scale

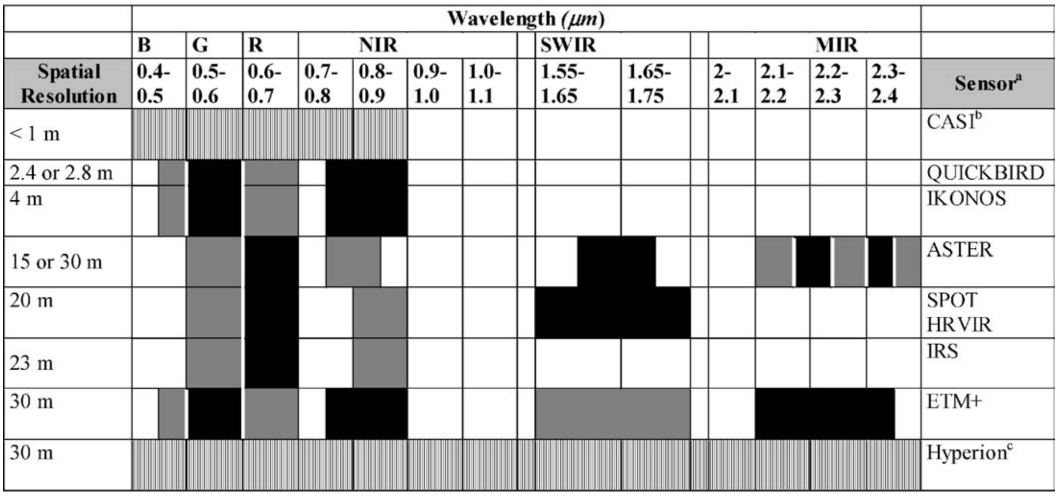
3.1. Information requirements

Within the context of the current extensive outbreak of mountain pine beetle in British Columbia, the provincial government is primarily interested in the detection of trees at the red-attack stage (Wiart, 2003). The government funds annual aerial overview surveys, which are designed to detect and document a broad range of forest health issues, including the locations of mountain pine beetle red-attack (British Columbia Ministry of Forests, 2000). The government uses the red-attack information from these general surveys to inform strategic planning, with the objective of minimizing both the spread of beetles, and the loss of timber values and associated Crown revenue (British Columbia Ministry of Forests, 2003a). The relatively coarse level information contained in the overview surveys is used to define management zones, allocate resources for mitigation and control, and identify areas requiring more detailed surveys (British Columbia Ministry of Forests, 2003b).

3.2. Research highlights

Over large jurisdictions, aerial overview surveys (also known as sketch maps) have been implemented as an effective,

Table 4
Spatial resolution and approximate spectral resolution of multi-spectral sensors commonly used for vegetation mapping



Shaded blocks represent different spectral bands. Blocks of narrower width tend to indicate a sensor with greater spectral sensitivity. [a] Sensor information: ASTER, Advanced Spaceborne Thermal Emission and Reflection Radiometer (http://asterweb.jpl.nasa.gov); CASI, Compact Airborne Spectrographic Imager (http://www.itres.com); Hyperion (http://eo1.gsfc.nasa.gov); IKONOS (http://www.spaceimaging.com); IRS, Indian Remote Sensing (http://www.isro.org); ETM+, Landsat Enhanced Thematic Mapper (http://landsat7.usgs.gov); QUICKBIRD (http://www.digitalglobe.com); SPOT HRVIR, SPOT High Resolution Visible Infrared (http://www.spotimage.fr). [b] CASI channels programmable in size; >2 nm width depending on application (Anger, C.; Mah, S.; Babey, S. 1994. Technological enhancements to the compact airborne spectrographic imager (CASI). In: First International Airborne Remote Sensing Conference and Exhibition. Strasbourg, France. CASI spatial resolution is a function of flying condition (Wulder, M.A., Mah, S., Trudeau, D., 1996. Mission planning for operational data acquisition campaigns with the *casi*. In: Proceedings of the Second International Airborne Remote Sensing Conference and Exhibition, vol. 3. San Francisco, 24–27 June, pp. 53–62). [c] Hyperion collects 220 bands of spectral data over the 400–2500 nm spectral range.

low-cost detection and mapping method for mountain pine beetle red-attack (British Columbia Ministry of Forests, 2000; Alberta Sustainable Resource Development, 2004; Schraeder-Patton, 2003). Aerial overview surveys were found to provide information for planning during epidemics (Heller et al., 1955; Aldrich et al., 1958). However, research into the accuracy of the estimates generated from aerial overview sketch mapping of red-attack have identified some positional and attribution limitations (Aldrich et al., 1958; Nelson et al., 2004). Harris and Dawson (1979) conducted a test of aerial overview mapping, with the objective of characterizing the variability between interpreters. Their results indicated that the interpreter's estimates of the number of red trees varied from the actual number of red trees present in the simulation area by a range of −42 to 73%. This same study also compared the estimates of red-attack mapping generated from the aerial overview survey to estimates generated from the interpretation of aerial photography. The area identified as red-attack from the sketch mapping was, on average, 34% larger than the area identified from the photos. Conversely, the number of red-attack trees estimated from the sketch mapping was, on average, 39% less than the number of red-attack trees estimated from the photos, and this underestimation tended to increase with increasing density of red-attack trees.

Location inaccuracy is the largest source of error associated with overview surveys, resulting from off-nadir viewing, variations in lighting conditions, and interpreter experience and fatigue, among others (Aldrich et al., 1958; Leckie et al., 2005). These errors manifest when damage supposedly caused by the mountain pine beetle is identified in forest stands with attributes that are inconsistent with biological knowledge of the beetle (e.g. mountain pine beetle red-attack damage is identified in stands that contain no pine species). These errors are particularly evident when the results of the overview surveys are compared to estimates generated from higher spatial resolution surveys, such as helicopter GPS surveys or satellite imagery (Wulder et al., 2005). In recognition of the issues associated with aerial overview sketch mapping, the training of observers has become more extensive, and rigorous standards for data collection have been developed (British Columbia Ministry of Forests, 2000).

3.3. Future directions

At the regional scale, information needs necessitate a broad, synoptic assessment of red-attack. Data collection at this scale must be cost effective given the large area involved. In addition, the information must be generated quickly to capture changes in foliage color. Issues associated with the location and attribute errors of the overview sketch mapping, are insignificant when the considered within the context for which program was created. In British Columbia, the overview survey has effectively met provincial level information needs for several decades. The advantages of the aerial overview survey are numerous. Firstly, the program is cost effective—no other remotely sensed data source available today can provide information on the comprehensive range of forest health issues, within the required timeframe, for a similar cost. Secondly, the interpreters' expertise can utilize cues to map the extent and severity of each pest and disease, such as the identification of tree species, and knowledge of pest habitats, past areas of infestation, and the spatial characteristics associated with each pest. Finally, the overview surveys provide sufficient information to direct the allocation of resources for more detailed surveys over limited areas, as required. Therefore, when considered within the context for which they were intended, the advantages of the aerial overview survey program far outweigh the disadvantages.

The positional accuracy of the overview survey may be enhanced by the use of digital imagery (e.g. Landsat TM or Enhanced Thematic Mapper (ETM+)) as part of the base map used for data collection; this ancillary data is commonly used in hardcopy form by the sketch mapping program in British Columbia. Currently, base maps used for sketch mapping often integrate features similar to those included on a planimetric base map (e.g. drainage networks, roads, contours), with the addition of up-to-date harvest blocks and forest road networks (British Columbia Ministry of Forests, 2000). Imagery such as Landsat TM would offer a continuous view of the landscape, and the additional contextual information contained in the image would facilitate greater accuracy in the placement of red-attack polygons.

Another method that may improve the precision and positional accuracy of the sketch-mapping program is to implement a digital sketch mapping system. The United States Department of Agriculture (USDA) Forest Service and the provinces of Alberta, Manitoba, and Quebec have adopted the use of a tablet computer with Geographic Information System (GIS) software, which facilitates direct digitization of the sketch mapping information (Schraeder-Patton, 2003). This method incorporates a global positioning system (GPS) into the mapping process, enabling accurate navigation and precise location on the digital map at all times. With this method, digital imagery, such as orthophotos, satellite imagery, or other ancillary data may be used as a backdrop for digitizing areas of infestation. However, there are additional costs associated with implementing a digital sketch mapping system, which may negate the cost effectiveness of the current sketch-mapping program (over the short term).

The inconsistency of mapping amongst interpreters or across jurisdictions may be accounted for by the use of confidence intervals or estimates of error. Such estimates could be derived by randomly sampling the sketch-mapped area with higher spatial resolution data (e.g. aerial photography) (e.g. Harris et al., 1982; Gimbarzevsky et al., 1992). These error estimates help end users understand the limitations and appropriate application of these data sources.

4. Landscape scale

4.1. Information requirements

There is overlap in the information requirements at the provincial and landscape levels. Generally, activities such as timber supply reviews and resource management planning occur at the landscape level—not at the provincial level; however, these activities make use of the aerial overview survey information (British Columbia Ministry of Forests, 2003a). More detailed survey information, where available, is also used for these activities. Tactical planning at the landscape level provides the structure for implementing the broad objectives outlined in a strategic plan, and includes activities such as the scheduling of harvesting and road construction. This type of planning relies on detailed surveys at the landscape level, which provide spatially explicit estimates of the number of trees or total wood volume affected. Information on red-attack mapping at this scale is also used to identify specific areas requiring more detailed ground survey.

4.2. Research highlights

At the landscape scale, research has been dominated by the use of aerial photography to map mountain pine beetle red-attack. In the late 1970s, research focused on multi-stage surveys using aerial sketch mapping, large-scale color aerial photography, and ground sampling. From these surveys, estimates were generated of total area infested, numbers of trees killed, and timber volume lost. Studies were conducted in both ponderosa and lodgepole pine forests (Ciesla and Klein, 1978; Klein et al., 1979). In the early 1980s high altitude panoramic photography became the focus of research; panoramic photography had both a high spatial resolution and a large area coverage, facilitating stratification, multi-stage sampling, and tree counts. Today, standard 1:30,000 aerial photography can produce similar results to those of panoramic photography, without the large area coverage.

Klein et al. (1980) and Klein (1982) conducted a study using a multi-stage sampling design, incorporating high-resolution CIR panoramic air photos (1:30,000 at nadir; decreasing outward from nadir to a minimum of 1:60,000) and ground plots. The accuracy of the visual interpretation was greater when the photo was taken within 19° of nadir, compared to when the photo was taken between 20° and 40° from nadir; the difference between the estimates of mortality generated from these two different camera angles was found to be statistically significant. The advantage of this multi-stage sampling design is that it provides a quantitative impact estimate and an associated error estimate; with this type of error estimation, forest managers are better able to interpret the mapping results and adjust their decision making accordingly.

Using multi-stage sampling methods similar to those of Klein et al. (1980), Klein (1982), and Dillman and White (1982) evaluated the utility of panoramic photography for estimating mortality in ponderosa pine forests caused by mountain pine beetle. With a two-stage stratified sampling design, they used both ground and photo plots to derive tree counts of mortality and compared those to mortality estimates derived from conventional methods (aerial overview sketch mapping). Overall, they concluded that panoramic photography was a potentially cost effective alternative to conventional survey for estimating tree counts.

Technological advancements have facilitated the use of digital imagery for surveys of red-attack damage. Early attempts to detect red crowns from multi-spectral scanners had limited success. This was often attributed to the mixed pixels (many objects or features per pixel) in the 80 m resolution of the Landsat MSS sensor (Harris et al., 1978). Single- and multi-date Landsat TM and ETM+ imagery has been used to successfully map mountain pine beetle red-attack damage at the landscape level. The accuracies attainable with these data have consistently been around 70%, with higher accuracies being found for more extensive areas of red-attack damage. Rencz and Nemeth (1985) used a 30 m resolution Landsat TM image to visually detect the presence of mountain pine beetle red-attack, achieving >90% accuracy in identifying red-attack trees in clusters larger than 1.5 ha in size. The results indicated that 30 m resolution imagery had potential for mapping infestations that were at the epidemic level. Franklin et al. (2003) used an automated detection algorithm (as opposed to a visual interpretation) on a 30 m Landsat TM image. This study detected clusters of red trees smaller than 0.2 ha; however, with lower accuracy than was reported by Rencz and Nemeth (1985). The resulting classification mapped red-attack with 73.3% based on 360 independent mountain pine beetle field and aerial survey validation points.

Research into the use of multi-date imagery for detecting insect infestations has also been undertaken. In general, the results of these studies indicate that the use of multiple images acquired before, or within 1 or 2 years of the insect attack, were more effective than single-date imagery (Harris et al., 1978; Byrne et al., 1980). The use of multi-date imagery, in conjunction with the Tasselled Cap Transformation, led to the development of the Enhanced Wetness Difference Index (EWDI) for general surveys of red-attack damage (Skakun et al., 2003). This study reported 67% accuracy for detecting groups of 10–29 red-attack trees and 75% for detecting groups of 30–50 red-attack trees. These results reinforce the idea that the spatial resolution of the imagery must be selected according to the nature of the infestation under investigation. In this case, moderate resolution data, such as Landsat TM, may be more appropriate for larger infestations at epidemic population levels, than for smaller or more spatially disperse infestations at the endemic or incipient population levels.

4.3. Future directions

A range of photographic scales and image spatial resolutions have been investigated for the assessment of red-attack damage at landscape scales. At a moderate spatial resolution, new generation satellites such as ASTER or Hyperion offer improved spectral sensitivity in excess of existing Landsat instruments (Table 3). However, whether digital or analogue, the image characteristics must match the information needs (e.g. Ciesla, 1974; Sirois and Ahern, 1988). For large areas, this may mean a hierarchy with a number of stratified or random sub-areas mapped with high spatial resolution data, as part of a double sampling strategy. This type of information hierarchy may result in more efficient and more effective mapping of mountain pine beetle locations and impact. These types of data sources may be most useful to forest managers where aerial photography or helicopter GPS survey data was not, or cannot, be collected, and where the level of detail provided by a field survey is not warranted for the management objectives under consideration.

Gray-attack mapping has not been a focus area for mountain pine beetle mapping in the past and gray-attack locations are not normally collected during aerial overview surveys in British Columbia (Westfall, 2005). However, information on gray-attack locations can be important for assessing cumulative mortality, success of mitigation efforts, calculating beetle spread, and for planning salvage operations. These applications would be most successfully conducted at the landscape level. Techniques applicable to these operations could be developed by further research, especially using digital remotely sensed data. The mapping of defoliation can be confounded by issues around the mixture of healthy and defoliated vegetation occurring together in a stand (Leckie, 1987; Hall et al., 1995). Defoliation is more consistently distinguishable from healthy trees when there is larger percentage of mortality within a stand (Vogelmann and Rock, 1986; Leckie, 1987; Wastenson et al., 1987). Multi-stage sampling approaches may also aid in detection of gray-attack.

5. Local scale

5.1. Information requirements

The current outbreak of mountain pine beetle in British Columbia has resulted in a shift in management efforts at the local level; rather than attempting to address all levels of infestation severity across the total extent of the current outbreak, management efforts are focusing on the detection and mitigation of sites with minimal levels of new infestation (British Columbia Ministry of Forests, 2003d). The objective of this shift in management efforts is to reduce or contain the outbreak to a size and distribution that can be handled within the capacity of the existing forest industry infrastructure (British Columbia Ministry of Forests, 2003b). At this scale, the required information includes: the number of individual red-attack tree crowns, the location of individual red-attack tree crowns, and the species of red-attack tree (British Columbia Ministry of Forests, 2004). Information is provided in support of field visits and harvest planning; therefore, errors of commission (where non red-attack trees are erroneously identified as red-attack) must be minimized. Operationally, the deployment of field crews to locations falsely identified as red-attack is more problematic than identifying a location with actual red-attack damage, but miscounting the number of red trees present; location accuracy is therefore more important than count accuracy.

Detailed surveys of red-attack trees at the stand level are completed using helicopter GPS surveys or high-resolution photography. The location of red-attack at this scale is used to determine the probable locations of green-attack trees (based upon understanding of beetle biology). Ground crews are dispatched to search for green-attack trees and the data collected is used for operational planning (e.g. block layout for sanitation logging).

5.2. Research highlights

Helicopter surveys conducted with a GPS are considered the benchmark for operational accuracy in the detection and mapping of mountain pine beetle impacts at the local scale (British Columbia Ministry of Forests, 2004). These heli-GPS surveys have a horizontal accuracy of approximately 20 m, and low errors of commission (<5%) (British Columbia Ministry of Forests, 2004). With this method, clusters of red-attack trees are identified, and either tree counts (if clusters are small and data are collected as points) or severity (if clusters are large and data collected as a polygon) is recorded. The helicopter is positioned over the cluster and a GPS position is collected. Research has examined the uncertainty and error associated with the point estimates derived from the heli-GPS surveys. For example, the errors associated with a set of 6151 heli-GPS survey points collected in the Morice Timber Supply Area, British Columbia, between the years 1999 and 2002 have been investigated (Nelson et al., 2004). Corresponding ground data were also collected at these locations. The results of this study indicated that errors associated with the heli-GPS points (as determined by direct comparison to the ground surveys) were small; when estimating numbers of attacked trees, 87.2% of heli-GPS points have errors less than ±10 trees (Nelson et al., 2004).

Aerial photography is also being used operationally for red-attack surveys in those areas identified for suppression in British Columbia's strategic beetle management plan (British Columbia Ministry of Forests, 2003b). The management objective in suppression areas is to reduce populations and maintain them at a relatively low level. Photographs are collected between July and mid-September, at scales ranging from 1:10,000 to 1:30,000 for larger management areas (Westfall, 2005). The photographs are digitized (scanned) and visually interpreted using digital photogrammetric software. Individual red-attack trees are identified, tagged, and tallied. The output maps showing the location of red-attack trees are compiled. The accuracy of this approach is reported to be high (>90%) with errors originating more from two red crowns being counted as one crown, rather than red-attack trees being omitted (Westfall, 2005).

Large-scale aerial photography, used in the context of a multi-stage sampling design, has also been the subject of extensive research. Harris et al. (1982) used aerial overview sketch mapping to stratify the landscape and select areas where 1:5000 scale aerial photography and ground plots were subsequently collected. The ratio of ground counts to photo counts was 1.1 for red-attack trees and 1.5 for gray-attack trees (photo counts always underestimated the number of red and gray trees). The ground measurements were subsequently used to adjust the estimates of the number of trees and total volume killed, as generated from the photos. Klein (1973) generated similar results with a study that employed double sampling to compare estimates of the number of red-attack trees interpreted from 1:5000 air photos with ground estimates of red-attack tree counts. Trees killed by mountain pine beetle were identified on the photo as being either faders (i.e. trees whose crown discolors the season following attack) or old faders (i.e. trees attacked and killed the previous year and are now red-attack) and snags (i.e. gray-attack). Five different air photo interpreters were used in this study. More than 94% of the variance in the estimates was associated with the ground truth, indicating that the estimates were relatively consistent between plots, and between interpreters. Tree counts were underestimated by the photos; errors of omission resulted from the difficulty in distinguishing multiple adjacent red-attack tree crowns, or understorey red-attack crowns that were obscured in the photo.

Gimbarzevsky et al. (1992) used a similar double sampling approach to calibrate the counts of red trees taken from the interpretation of 1:6000 air photos to counts collected from ground plots. The ground count to photo count ratio was 1.19 for red trees, 3.23 for gray trees, and 1.60 for the total number of trees (red, gray, and non-attack). This same study found that the counts of red-attack trees taken from 1:6000 versus 1:8000 air photos varied by an average of 5%. Kneppeck and Ahern (1989) compared counts of red-attack trees from an airborne scanner image to counts taken from 1:10,000 air photos. Counts of red trees from 1.4 m resolution imagery were higher (136%), while counts from 3.4 m resolution imagery were lower (71%). The results from these studies indicate that detailed surveys can also benefit from a multi-stage sampling approach where a small sample of ground counts is used to adjust estimates generated from other data sources.

Researchers have also attempted to use aerial photography to detect green-attack trees (e.g. Murtha, 1972). A study using 1:1000 CIR air photos examined the spectral reflectance from two non-attack trees, six green-attack trees, and four red-attack trees suggesting that the differences in the spectral reflectance of these trees were a result of their attack state (Murtha and Wiart, 1987). Subsequent studies have had difficulty distinguishing green-attack tree crowns from non-attack tree crowns using high resolution air photos, as a result of the variability and overlap in the spectral signals from green-attack and non-attack crowns (Murtha and Wiart, 1989a; Murtha and Wiart, 1989b). While aerial photography has been successful for mapping individual trees with red-attack damage, research aimed at green-attack detection has been inconclusive.

The increasing availability of high spatial resolution satellite imagery, with image pixels representing areas on the ground that are less than 5 m × 5 m in size, has prompted investigation into the utility of these data for red-attack detection and mapping. White et al. (2004) investigated the merits of using IKONOS 4 m multi-spectral data for mapping red-attack at a study site near Prince George, British Columbia. IKONOS provides global coverage, a consistent acquisition schedule, and near nadir-viewing angles. The resolution of the sensor is suitable for high accuracy photogrammetric processing and mapping applications (Tao et al., 2004). In addition, the IKONOS 4 m multi-spectral channels have similar spectral properties in the visible and near infrared wavelengths as Landsat ETM+. White et al. (2004) examined the use of an unsupervised clustering of image spectral values to detect mountain pine beetle red-attack at susceptible sites (i.e. with known risk factors for infestation), which were considered to be lightly infested (1–5% of trees red-attacked) or moderately infested (>5% and <20% trees red-attacked). A 4 m buffer (analogous to a single IKONOS pixel) was applied to the red-attack pixel identified on the IKONOS imagery to account for positional error. When compared to the independent validation data collected from the aerial photography, it was found that 70.1% (lightly infested sites) and 92.5% (moderately infested sites) of the red-attack trees existing on the ground were correctly identified through the classification of the remotely sensed IKONOS imagery. Analysis of red-attack trees that were missed in the classification of the IKONOS imagery indicated that detection of red-attack was most effective for larger tree crowns (diameter >1.5 m) that were <11 m from other red-attack trees.

5.3. Future directions

Future research should continue to use high spatial resolution satellite imagery and airborne sensors for the detection and mapping of red- and gray-attack. With high spatial resolution data, the greatest challenge for model development lies in correlating the spatial location of measured ground data points to the corresponding pixel in the image. Recent research has indicated that IKONOS is well suited to the detection of small groups, or individual red-attack trees (White et al., 2004). Other high-resolution data sources are currently available (i.e. QuickBird), with additional high spatial resolution sensors scheduled for deployment (Wulder et al., 2004b). Both QuickBird and IKONOS have global coverage, a consistent acquisition schedule (although they do not constantly collect imagery for archival purposes), and the capability to acquire imagery with near nadir viewing angles. These factors make these data sources operationally feasible, although the cost of QuickBird and IKONOS imagery, may limit their use to site-specific applications where other forms of data are not available or are not practicable. However, regardless of cost, there may be an operational niche for QuickBird or IKONOS data where aerial photography or helicopter GPS survey data were not, or could not, be collected, and where the level of detail provided by a field survey is not required by the management objective under consideration. At the local scale, information generated from IKONOS or QuickBird imagery can be used to support field visits and operational level planning. In addition, archival IKONOS or QuickBird imagery, where available, may be useful in retrospective analyses for detection and mapping of mountain pine beetle red-attack in previous years where no other high spatial resolution data source was collected.

Research is also required to establish methods for conducting detailed gray-attack surveys to determine the level of cumulative mortality within a stand. These studies could be operationally viable for inventory updates, and would aid in the development of salvage harvest plans that must account for the shelf life (the rate of decay of trees killed by mountain pine beetle) of the dead trees. The difficulty in distinguishing mountain pine beetle gray-attack from the impacts of other damage agents complicates the process of detection and may require the use of an image time series, or a change detection approach; however, where there are large areas of mortality, distinguishing mountain pine beetle gray-attack is not problematic.

In general, green-attack is not operationally detectable without direct physical contact with the trees in question. This implies that it is not possible to detect green-attack with any of the remote sensing sensors that are currently in use. Furthermore, significant gaps remain in the body of green-attack research that pose barriers to the operational adaptation and implementation of green-attack detection methods. Regardless of the technical limitations to successfully detecting green-attack that presently exist, there are also substantial logistical limitations to the operational feasibility of undertaking a remotely sensed green-attack survey. Current methods of identifying green-attack depend upon ground crews using known locations of existing red-attack to look for probable locations of green-attack. Therefore, for a remotely sensed green-attack survey method to be significantly better than the current method, large areas of apparently healthy forest would have to be surveyed annually in order to identify green-attack trees. These surveys would require the use of data that have both high spatial and high spectral resolution. Furthermore, selecting an appropriate time to conduct a survey would be difficult, because the rate at which the foliage of a tree crown shows the symptoms of a mountain pine beetle attack is variable. Given the difficulty in mapping green-attack, all studies should include a rigorous design such as randomly sampling the trees within an image area, using all the sampled trees in the analysis, and using independent samples for calibration and validation (British Columbia Ministry of Forests, 2003d).

6. Conclusions

Extensive research has been conducted into the use of remotely sensed data for the detection and mapping of the impacts of mountain pine beetle. This research has explored a variety of analogue and digital data sources, collected across a range of spatial scales. Each data source provides information relevant to various spatial scales, which in this review have been categorized as regional, landscape, and local.

For regional scale information needs (e.g. province, state), aerial overview sketch mapping is sufficiently reliable for general surveys of mountain pine beetle red-attack. It is recommended that estimates of the area infested should be reported with confidence intervals or other estimates of error. The positional errors in the overview sketch-mapping make it unsuitable for operational applications; however, the cost effectiveness and rapid turnaround time of the overview surveys make it the best available source for regional-scale general forest health surveys.

Landscape scale activities such as timber supply reviews and land and resource management planning are based on both general and detailed surveys. Data selection and approach should be based upon conditions specific to the area and the issue (information need) under consideration. At the landscape level, moderate spatial resolution remotely sensed data (Landsat TM and ETM+) have been used to map red-attack with a consistent overall accuracy of approximately 70–75%. Research at the landscape scale should include new generation satellite sensors such as ASTER or Hyperion. These sensors present improved spectral sensitivity, and therefore new opportunities, for surveys of red-attack damage. Further research is required to establish methods for conducting detailed surveys of cumulative mortality (red- and gray-attack damage) following successive years of infestation. Building on lessons learned from past research using multi-stage sampling designs, the long-term goal of this research should also be to develop low-cost techniques for integrating local and landscape scale information to provide more accurate estimates of mortality.

At the local scale, forest managers rely on spatially accurate detailed surveys of red-attack damage to plan ground surveys of green-attack and to plan mitigation actions for infested stands. At this scale, reliable detailed surveys of red-attack trees can be completed using large-scale aerial photography or high spatial resolution satellite imagery. IKONOS data has been used to map red-attack damage with overall accuracies of 71% in sites with low levels of infestation (between 1 and 5% of the stand is infested), and 92% in sites with moderate levels of infestation (between 5 and 20% of the stand is infested). At the local scale, a multi-stage sampling design may facilitate improved accuracy estimates of mortality and associated error.

Validation of red-attack estimates is recommended; in particular, the true positive rate for red-attack should be reported with confidence intervals or similar statistical estimates of error. The true positive rate is the attribute specific accuracy for red-attack; this measure reports how many red-attack trees identified from the image source were actually identified in the validation data (British Columbia Ministry of Forests, 2003d). To facilitate this, a multi-stage sampling design or a double sampling design is recommended.

The timing of mountain pine beetle surveys is critical. In addition, the ability to quickly turn the data into valuable information is a necessity. Although timing is variable, it is possible to provide some general guidelines. It is recommended that field surveys for green-attack commence six weeks after beetle flight. For red-attack, data collection is recommended from mid-July to the end of September the year following attack. From that September until July of the third year after attack, surveys could be conducted for cumulative mortality (red- and gray-attack damage). Exclusive gray-attack mapping should be timed for after August of the third year following attack.

Finally, the nature of the infestation (i.e. endemic, incipient epidemic, epidemic, post-epidemic) and the scale associated with the information needs (i.e. regional, landscape, local) should guide the selection of an appropriate data source. Moderate spatial resolution data, such as Landsat TM and ETM+, are better suited to mapping epidemic levels of infestation. High spatial resolution data, such as IKONOS and QuickBird, are suitable for identifying small clusters of red-attack trees associated with endemic and incipient epidemic beetle populations. The relative costs, availability, and processing requirements of the various data sources are all important considerations for the end-user. Remote sensing can be a valuable tool in providing information for the management of mountain pine beetle; however, the image source must be selected in accordance with both the information requirement of the end user and the infestation level. Furthermore, the current technical limitations of remote sensing technology, which prevent the successful detection of green-attack, must be openly communicated in order to prevent the premature allocation of resources to the operational implementation of unproven and untested techniques.

The findings of this review indicate that a number of remotely sensed data sources are useful for mapping red-attack damage across a range of spatial scales. Remotely sensed data is advantageous for filling spatial or temporal gaps in other data collection methods, and as a result, is complementary to existing methods of red-attack detection. Furthermore, remotely sensed data expands the red-attack survey options available to forest managers, and should therefore be considered as a viable data source for detecting and monitoring mountain pine beetle damage.

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