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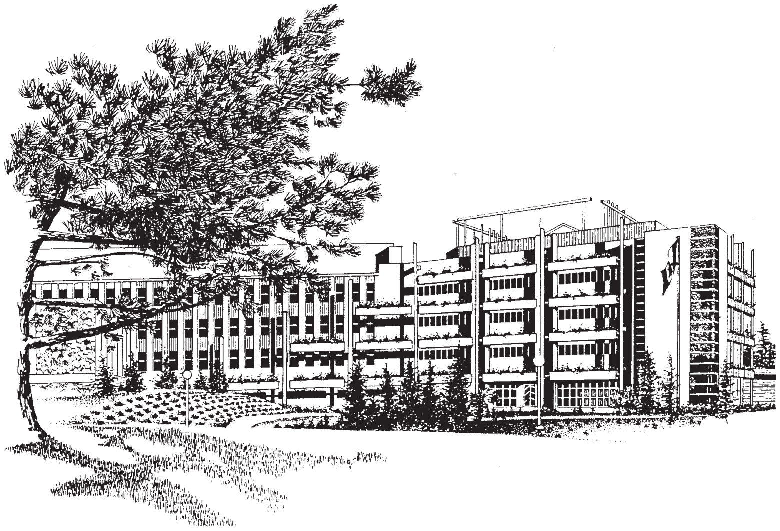

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Abstract

In this report, we review the literature relevant to the previous and current contributions of remote sensing to the survey of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) impacts. The potential and limits of remotely sensed data for the detection and mapping of mountain pine beetle impacts are identified and synthesized. Following this synthesis, recommendations are made regarding those methods or data sources that currently have operational potential, and those methods or data sources that warrant further research in support of ongoing planning and management activities. This report emphasizes that the key to the successful application of remotely sensed data for mountain pine beetle survey and detection is to match the sensor to the information requirements for managing mountain pine beetle. The data available from field collection, airborne surveys, and remote sensing can form a multi-stage design, where small-scale characterizations (large area, lower cost) may be used to determine where large-scale data (smaller area, higher cost) are collected. In this way, information obtained from remotely sensed data can complement and enhance existing information on mountain pine beetle impacts.

Résumé

Le présent rapport résume l’information publiée sur les applications antérieures et actuelles de la télédétection au relevé des ravages causés par le dendroctone du pin ponderosa (*Dendroctonus ponderosae* Hopkins). Il présente un sommaire des applications possibles et des limites des données de télédétection pour repérer et cartographier ces ravages. Cette synthèse est suivie de recommandations quant aux procédés et sources de données qui sont directement exploitables ou qui pourraient être adaptés pour appuyer les activités de planification et de gestion. Le facteur qui détermine l’utilité des données de télédétection pour le repérage du dendroctone et le relevé des dommages laissés par son passage est le choix de capteurs en fonction de la nature des informations requises pour la lutte. Les données issues des collectes sur le terrain, des relevés aériens et de la télédétection peuvent toutes être intégrées dans un plan multi échelles, où une appréciation plus générale (grande superficie, coût moins élevé) permettrait de repérer les secteurs qu’il serait utile de caractériser de façon plus détaillée (plus petite superficie, coût plus élevé). La télédétection peut ainsi suppléer l’information existante dans les relevés des ravages causés par le dendroctone du pin ponderosa.

1 Executive Summary

Changes in leaf pigments, tissue structure, and moisture content resulting from an infestation of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) are detectable with remote sensing instruments. In this report, we review the literature relevant to the survey of mountain pine beetle attack over a range of attack stages. The focus of the review is on the potential utility and limits of remotely sensed data in capturing and characterizing the impacts of mountain pine beetle attack.

This report is organized into several distinct sections that provide the reader with sufficient background material to enable an objective interpretation and evaluation of the various studies that are presented. We begin by identifying the information of needs of resource managers who are faced with the task of implementing mountain pine beetle management scenarios (both proactive and reactive). These identified business drivers (provincial and management information needs requiring infestation information) form the context of the review. Definitions of relevant terms used throughout this report are also provided for clarity. A description of the link between the response of trees to attack by mountain pine beetle, and the detectability of this response with remote sensing instruments, follows. The studies related to the survey of mountain pine beetle impacts were organized by the attack stages of green, red, and grey. We have also included relevant studies of other disturbances that confer insights in support of the objectives of this review (for instance, an infestation of defoliating insects impacts trees in a manner that resembles the grey stage of a mountain pine beetle attack from a remote sensing perspective).

Several conclusions may be drawn from examining the studies presented in this review. First, the remote sensing state-of-the-art mapping of the green-attack stage of mountain pine beetle is currently inconclusive and insufficient to warrant the development of operational programs. Second, the research related to the mapping of red-attack stage is maturing, with some applications appearing suitable for operational implementation, with appropriate reference to the intended use of the information. Finally, the mapping of grey-attack stage has typically been the by-product of red-attack research, rather than receiving the research focus required to demonstrate clear trends applicable for operational implementation.

The recommendations regarding the operational application of remotely sensed data are made in the context of business drivers and the related potential utility and limits of a given image data source, and mountain pine beetle attack stage. Remotely sensed data sources cannot supplant existing survey methods; rather, remotely sensed data should be viewed as a data source for augmenting or complementing existing methods of detection and mapping. Studies focusing on detection of green-attack have not yet met the suite of requirements (timing, accuracy, repeatability) necessary to facilitate operational applications. Current methods, which use the locations of red-attack damage to guide the subsequent dispatch of field crews to conduct surveys for green-attack detection, continue to be the most effective method for detecting green-attack. It is recommended that red-attack research involving imagery with high spatial and/or spectral resolution be pursued to potentially enable greater detail or accuracy in the mapping of mountain pine beetle impact. The mapping of grey-attack is also recommended as a focus for further research. The mapping of grey-attack may be as simple as mapping red-attack in imagery indicating previous years attack.

At the provincial scale, it is recommended that the aerial overview sketch mapping programs be maintained; however, improvements to this approach should be considered. For instance, the use of a satellite image underlay may allow for improved spatial placement of sketched attacked polygons by providing a geographic context. At the local scale, the continued use of large-scale air photos for tactical planning is recommended. However, alterations could be made to the sampling design in order that the information derived from the photos may be rolled up for strategic planning at the landscape level. High spatial resolution satellite data may also be used for some applications at this level of detail. The data collected by satellite sensors can provide information for both tactical and strategic planning; it is our recommendation that managers take advantage of all available information that is suitable to their scale of inquiry. Satellite data and analyses enable the construction of landscape level datasets that have high positional and attribute accuracy. This synoptic data can provide context for the targeted acquisition of more detailed information.

The key to the successful application of remotely sensed data for mountain pine beetle survey and detection is to match the sensor to the information requirements for managing mountain pine beetle. The data sources available from field collection, airborne surveys, and remote sensing can form a multistage design, where small scale characterizations (large area, lower cost) may be used to determine where large scale data (smaller area, higher cost) are collected. Furthermore, statistically sound sampling programs of small areas can be scaled-up for mapping of larger areas. This spatial data can then provide input to models of mountain pine beetle biology to improve our ability to plan for and mitigate mountain pine beetle impacts.

2 Introduction

Remote sensing research into the operational mapping of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) impacts has been under investigation since the early 1960s. When the mountain pine beetle population becomes epidemic, the beetles are capable of attacking and killing live trees. Generally the beetles spread through mature stands of lodgepole pine (*Pinus contorta*), often resulting in extensive mortality. Mountain pine beetle also impact other pine species including ponderosa pine (*Pinus ponderosa*) and white bark pine (*Pinus albicalus*). Given the current outbreak and devastating impacts (Westfall 2003), it is prudent to reassess what new techniques or data sources have potential for mapping mountain pine beetle impacts. Remote sensing as a science has changed dramatically over the past 20 years, with an increasing number and variety of sensors and improved image processing capabilities. The identification of the approaches with operational potential may suggest appropriate areas for further research designed to support planning and mitigation activities. Detection and mapping of attacked trees enables planning and mitigation activities through delineation and documentation of the current impact, and serves as a driver in parameterizing models of beetle spread designed to reduce future risks and impacts.

Previous reviews addressing remote sensing of forest health have summarized the state of the art up to the 1980s (Puritch 1981; Gimbarzevsky 1984). In general, these reviews found that aerial photography was the most frequently acquired data-type. Both normal colour and colour-infrared (CIR) photos were applied to various targets, scales, and damage agents. These factors, along with the techniques employed and the timing of the data collection, all influenced the success of the studies. The research summarized in these reviews captured a range of applications using remote sensing for detection and mapping of forest pests.

More recently, the application of remote sensing in forest health operations was reviewed in a report prepared for the United States Department of Agriculture, Forest Health Technology Enterprise Team (Ciesla 2000). This report provides a comprehensive and reliable reference for forest health managers. It also emphasizes results-oriented mission planning, including suggestions regarding data collection method, accuracy assessment, and sensor selection (Table 1). With respect to bark beetle damage, the report emphasizes the operational reliability of aerial photography and provides additional examples from aerial sketch mapping, airborne video, and satellite imagery. Similarly, a review of local (British Columbia) studies using remote sensing for mountain pine beetle emphasized aerial photography for operational applications (Roberts et al. 2003).

Table 1. Comparison of alternative remote sensing systems for acquiring data of importance in forest health protection (Modified after Ciesla 2000).

Criteria	Aerial sketch mapping	Aerial Photographs (all formats)	Digital Camera (e.g., Kodak DCS 420)	Earth-Orbiting Satellites	
				e.g., Landsat	e.g., IKONOS, Quickbird
Acquisition cost	Low	Low to high	Low	Low	Medium
Spatial resolution	Medium to high	High	High	Medium	High
Spectral range	Visible	Visible; Near-IR	Visible; Near-IR	Visible; Near-, mid-, thermal-IR; microwave	Visible; Near-, mid-IR
Temporal resolution	User- and weather -defined	User- and weather -defined	User- and weather -defined	1 – 16 days, depending on satellite used.	1-4 days depending on satellite used.
Processing time	Short	Medium	Short	Medium	Medium
Reliability of data	Difficult to measure	High	Undetermined	Medium	High
Probability of acquisition during specified bio-window	High	Variable; depending on location	Medium to high	Low	High
Data in digital format	Digital data capability is under development	Analog data can be converted to digital	Yes	Yes	Yes
Currently operational	Yes – widely used	Yes – on a project basis	Under development	Under development	Under development

These earlier reviews have summarized research completed prior to the 1980s, or current operational applications; a gap therefore remains in reviewing the new methods and techniques developed for surveying mountain pine beetle impacts that have emerged from the research literature. The last twenty years have seen remarkable development and diversification of digital remote sensing technology applicable to forest characterization applications (Wulder and Franklin 2003). Many of the technological developments enable development of operational applications, or provide for further research opportunities. Technology transfer from research to operational organizations may also be actively pursued, as the acquiring of data is less complex and the required hardware and software are increasingly affordable and user friendly.

The objective of this review is to indicate the potential utility and limits of remotely sensed data in the detection and mapping of mountain pine beetle impact over a range of attack stages. To meet this objective, materials relevant to the detection and mapping of mountain pine beetle impacts have been gathered, synthesized, and reviewed. The focus of the review is on materials subject to peer-review, with lesser emphasis on reports and theses. The review encompasses remote sensing methods for detection and mapping of trees killed by mountain pine beetles through green, red and grey stages of attack.

3 Context of review

This review emphasizes consideration of the information requirements for the various levels of forest management existing in British Columbia (B.C.), Canada. However, the information needs of forest managers vary from different areas of concern to differing levels of required detail, and these varying information needs relate directly to the differing organizational mandates and stewardship responsibilities of the agencies involved. To enable clarity in this review, the definitions of key terms were summarized from Wulder et al. (2004). Following the statement of pertinent definitions is a summary of the various information needs or business drivers for mountain pine beetle impact information.

In order to enhance the utility of this document and make the review accessible to a wider audience, background material on both the mountain pine beetle and the science of remote sensing is included. For readers not familiar with mountain pine beetle, we have included a primer on the phenology of the symptoms of mass-attack by mountain pine beetle (Section 4). How the mass attack by mountain pine beetle is expressed in foliage of the tree crowns, viewable from above, is of especial interest from the remote sensing perspective. The timing of physical changes in the trees determines the appropriate time for surveys and, to a lesser extent, the methods of survey employed; thus an understanding of the chronology and response of a mountain pine beetle infestation is imperative. Next, we present a primer on important considerations for users of remote sensing technology (Section 5). This background section includes information to support the evaluation of the design of remote sensing studies. Following this background material, we present numerous studies involving mountain pine beetle detection and mapping.

The review addresses the three stages of the symptoms of mass-attack by mountain pine beetle: green-attack (Section 6.1), red-attack (Section 6.2), and grey-attack (Section 6.3). Each section includes a discussion of the remote sensing literature, both directly and indirectly related to the attack stage, followed by a study-by-study summary of the purpose, methods, results, and building blocks applicable to the objective of this review. These building blocks are essentially research precedents that may be used to identify the trends and gaps in the remote sensing literature. The Conclusion (Section 7) synthesizes the potential utility and limits of remote sensing attacks by mountain pine beetle at different scales and at different stages. From this we make Recommendations (Section 8) for operational application and for future research.

3.1 Definitions

The following terms are used throughout the text of this document and are defined here for consistency and clarity:

Location survey: Detects and documents locations of affected trees for probable locations of currently attacked trees.

Assessment survey: Documents the impact of the attack as spatially explicit estimates of the number of trees affected or of volume affected.

Strategic Planning: Defines broad goals and objectives.

Tactical planning: Defines how to achieve the strategic goals and objectives.

3.2 Business drivers

Different business drivers are applicable at different scales. The Ministry of Forests in the provincial government of British Columbia conducts business at the provincial scale as well as at the landscape scale, as exemplified by beetle management units, timber supply areas, and forest districts (B.C. Ministry of Forests 2003b). Licensees work co-operatively at the landscape scale and more independently at local scales (B.C. Ministry of Forests 2003c). Over the entire province, the Ministry of Forests is primarily interested in the detection of red-attack stage trees (Wiart 2003). In order to gather information on provincial forest health, an aerial sketch mapping program is conducted on an annual basis to provide a synoptic view of forest health. To this end, several pests and forest health issues, including mountain pine beetle red-attack, are targeted through the survey (e.g., Westfall 2003). The Ministry of Forests also uses the red-attack detection information from the aerial sketch mapping program for strategic planning, which includes the identification of areas requiring more intensive information gathering and for the allocation of mitigation resources (B.C. Ministry of Forests 2003b). At landscape scales, estimates of mountain pine beetle impact are used to adjust the annual allowable cut and timber supply forecasts (B.C. Ministry of Forests 2003a). At these scales, the provincial government works together with licensees who are becoming increasingly responsible for completing timber supply reviews and for planning and resource management (e.g., B.C. Ministry of Forests 2003c). These processes rely on assessment surveys for landscape-scale maps of red- and grey-attacked tree volumes and areas.

At local scales, licensees within British Columbia use the location surveys of red-attack trees to determine the probable locations of green-attack trees for their strategic planning (B.C. Ministry of Forests 1995). Furthermore, this information contributes to reporting on the British Columbia Ministry of Forestry Performance Measure 1, which indicates the area and percent of susceptible forested land base where existing infested areas have been identified, evaluated, and assigned a management strategy (B.C. Ministry of Forests 2003b). Licensees also require impact assessments at local scales. Assessment survey results are used in conjunction with forest inventory and other information to design logging and sanitation plans. This information contributes to reporting on the British Columbia Ministry of Forestry Performance Measure 2 that indicates the proportion of infested timber that has been treated (B.C. Ministry of Forests 2003b).

4 Phenology of the symptoms of mountain pine beetle attack

In general, mountain pine beetles in British Columbia reproduce at a rate of one generation per year (Safranyik et al. 1974). Adult beetles attack trees in August, and lay eggs that develop into mature adults approximately one year later. The beetles must attack in large numbers to overcome the defences of a healthy tree and this is referred to as mass-attack. Once killed, but still with green foliage, the host tree is in the green-attack stage. The foliage of the host tree changes gradually. 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 (grey-attack) (B.C. Ministry of Forests 1995).

Mountain pine beetle flight generally occurs at the same time each year, however the exact date of onset and the duration of flight are variable. This occurs as the development rate of beetles is dramatically affected by ambient temperature (Amman and Cole 1983; Bentz et al. 1991). The result is inter-site and inter-year variation in the date of flights (Amman 1973; Langor 1989; Safranyik et al. 2000). Genetic differences may also contribute to this variation (Bentz et al. 2001). Under warmer conditions, adults may start flying around 46 weeks after eggs were laid. Whereas under cooler conditions, the flights may not start until 52 weeks after the eggs were laid (Reid 1962; Logan and Bentz 1999).

The first symptom manifested by a mass-attacked tree is a drop in sapwood moisture (Reid 1961; Yamaoka et al. 1990) (Figure 1). This occurs as a consequence of fungi colonizing the water-transport system of the tree. The beetles carry various microbes, the most aggressive of which is *Ophiostoma clavigerum*, one of the blue-stain fungi (Yamaoka et al. 1990; Solheim 1995). The initial colonization of the sapwood can take 3 – 7 weeks after mass-attack and continues throughout the winter (Reid et al. 1967; Solheim 1995). The amount of time it takes for the change in sapwood moisture to occur varies depending on the tree characteristics and site locations such as climate (Carroll and Safranyik 2004; Carroll et al. 2004).

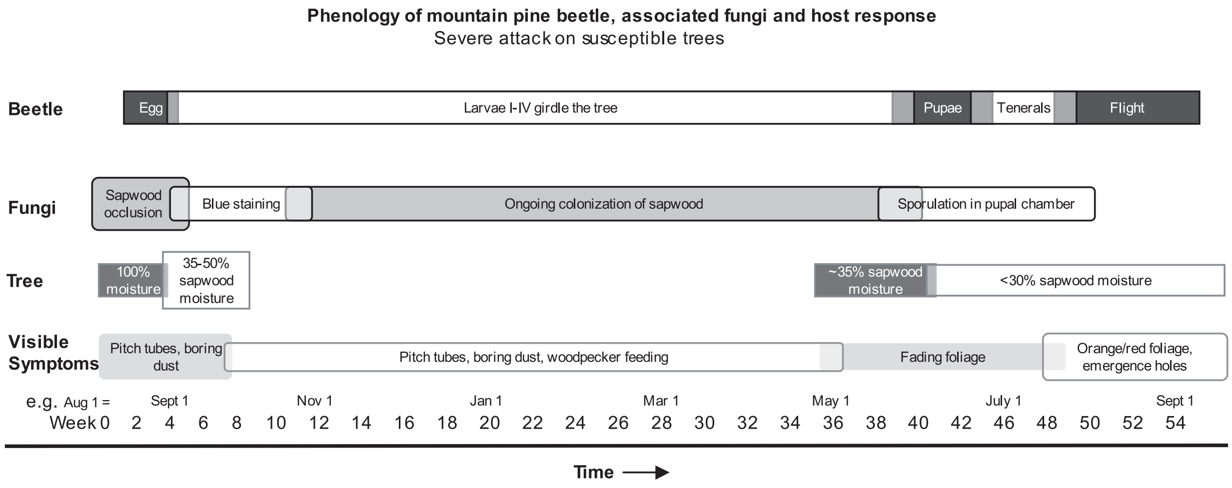


Figure 1. Example of the phenology of the mountain pine beetle, associated fungi and host response assuming a 1-year life cycle and successful colonization of a suitable host.

The timing of later symptoms is also highly variable. The foliage fades from green to yellow to red over the spring and summer following attack (Amman 1982; Henigman et al. 1999) (Figure 1). The leaves gradually desiccate and the pigments breakdown, initially the green chlorophyll pigments are lost, then the yellow carotenes and red anthocyanins (Hill et al. 1967). Gradually, the needles drop until the tree is completely defoliated.

Of critical importance to the remote sensing detection of mountain pine beetle attacks is variability in fade rates based upon climate and phenology. The timing of the changes in foliage depends on tree genetics, condition and the local environment. Figure 2 presents data from trees that were inspected annually to determine the link between mountain pine beetle attack and resultant fading of the tree crown. A sample of trees within a forest district that were attacked (green-attack stage) in year one, all were at the red-attack stage after 10 to 12 months. A remote sensing survey for red-attack trees prior to 10 months may have missed those individuals who changed slowly. Similarly, surveys between 18 months and 36 months would have to include both red-attack and grey-attack trees for an accurate estimate of beetle impact. The variability in the rate of change makes it essential for different methods of data collection (e.g., aerial photography and field work) for a single location to occur within the same time period. The general trend in fade rates is captured in Figure 3, where the fading of 15 lodgepole pine trees is tracked, with the overlap between the crown expression of attack stages illustrated. The noteworthy trends in this figure are that no trees appeared as green stage after 12 months, all trees reached red stage by 12 months, and grey stage was initially evident after 13 months. The overlap of the red and grey stages post successful mountain pine beetle attack, is also evident. While this is a limited sample, additional samples support the same trends (refer to Figure 2 error bars for an indication of the range of variability). The variability in the rate of change is greater over larger areas as more variability in tree characteristics and environments occurs. In general, red-attack surveys should occur from mid-July to mid-September for most of British Columbia. Exact dates depend on local conditions.

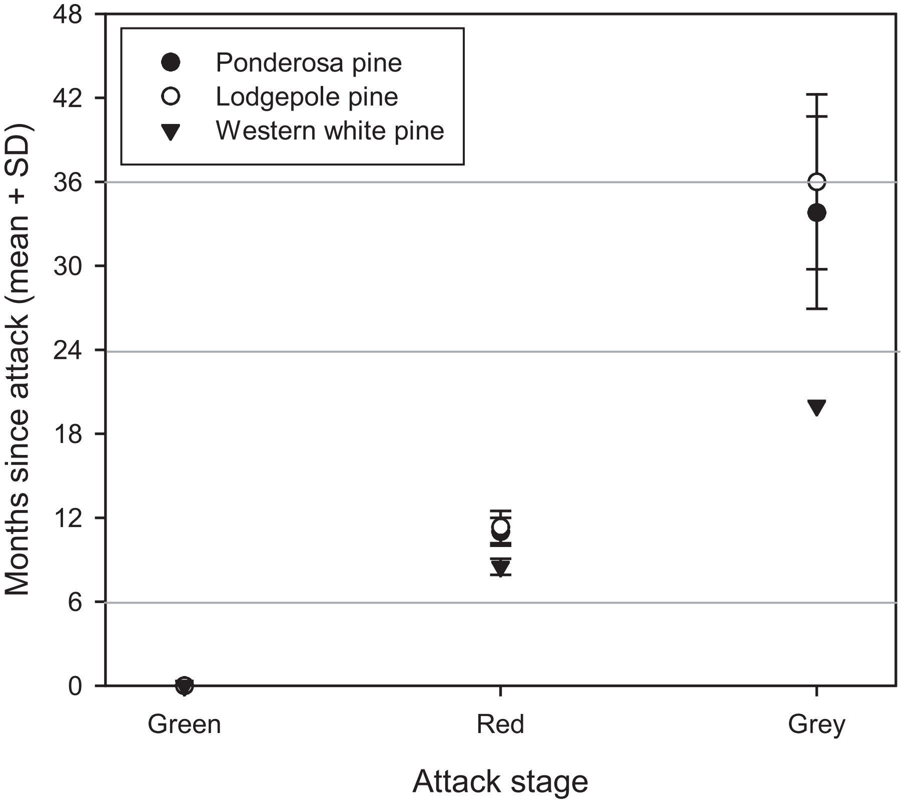


Figure 2. The number of months for 100% of a sample of mass-attacked trees to reach a given attack stage; variability is demonstrated between stands (one standard deviation error bars) and between species. These foliage changes followed mass-attack at 12 sites in the Kamloops Forest District, between 1962 and 1967. The foliage conditions of 134 individuals from three species were monitored.

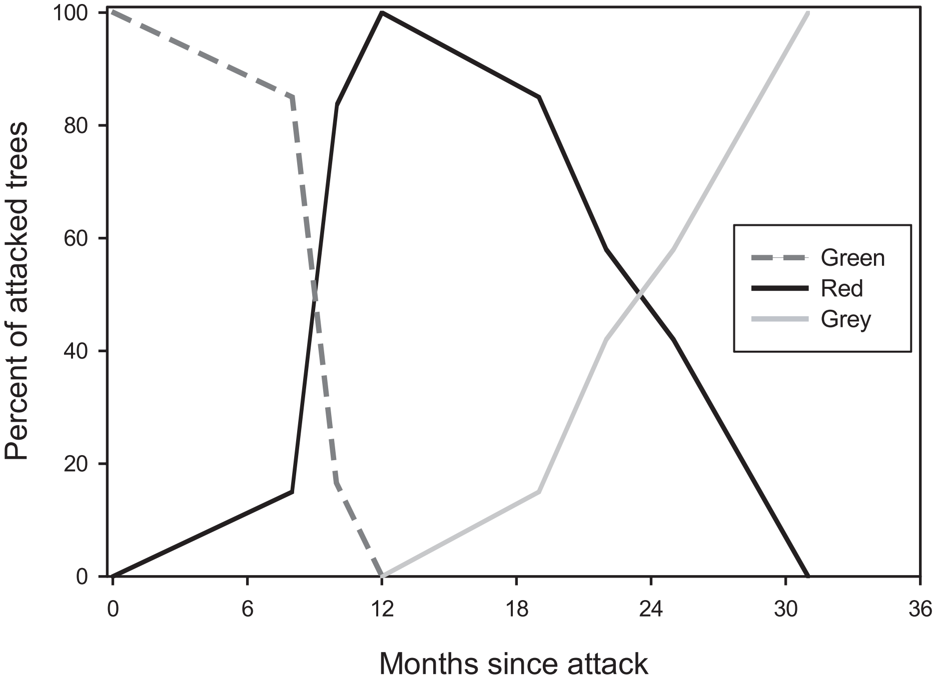


Figure 3. Variability in fading rate of foliage within an example lodgepole pine stand (Fountain Valley Site 2, Kamloops Forest District, between 1962 and 1967) post mass-attack. This example stand was composed of 15 attacked trees.

5 Technological considerations of remote sensing

Changes in foliage characteristics are potentially detectable with remote sensing instruments because the physical components that comprise a leaf interact with the electromagnetic spectrum. Pigments (primarily chlorophylls) absorb within the 0.50-0.75 μm wavelengths of electromagnetic energy (visible light) (Wiegand et al. 1972). The structure of leaf mesophyll (inner tissues) causes high reflectance of 0.75-1.35 μm wavelengths (near infrared). Further, leaf moisture content results in strong absorption in the wavelengths between 1.35-2.5 μm (infrared). The presence or absence of leaves may be detectable because the leaf as a whole has higher spectral reflectance from 0.55 – 0.70 μm compared to the tree branches (Williams 1991). Knowledge of these patterns allows for research into detecting changes in foliage characteristics using remotely sensed data. In this section, we summarize the common operational approaches for using air photos and some possible sampling approaches (Section 5.1), summarize the key factors influencing digital data collection (Section 5.2), review the essentials of assessing the accuracy of any remote sensing study (Section 5.3), and describe some of the factors affecting costs.

5.1 Aerial photography and sampling strategies

This remote sensing review would be incomplete without a summary of established practices for operational remote sensing utilizing aerial photographs and sample based surveys. Aerial photography is a key component of forest insect assessment and management surveys. Frayer and Furnival (1999) indicate that aerial photo plots and corresponding field plots for general forest inventory began in 1946, with the increased use of aerial photography for forest damage appraisal beginning in the 1950s (Waters et al. 1958). The scattered nature of forest damage, coupled with the large expanses of forests in North America, frustrated ground surveyors. In contrast, air photos could be collected at relatively low costs per hectare, relatively quickly, with good positional accuracy and constituted a permanent record. Aerial photography is the operational standard in British Columbia for surveys of the red-attack stage of mountain pine beetle infestation. Photographs are collected between July and mid-September, at scales from 1:10,000 to 1:30,000 for larger land holdings (P. Hall, British Columbia Ministry of Forests, Victoria, B.C., pers. comm.) (Table 2). Photographs may be visually interpreted or analyzed using image processing software. Individual red-attack trees are counted and mapped for reporting and for planning mitigation efforts. The accuracy of this approach is reported to be very high (>90%) with errors originating more from two red crowns being counted as one than from trees being omitted (R. Reich, British Columbia Ministry of Forests, Victoria, B.C., pers. comm.).

Table 2. Photo coverages depicted by typical combinations of photo scale and flying height for a 152 mm focal length camera (from Wolf and Dewitt, 2000).

Scale	Flying elevation (m)	Hectares per photo
1:2000	304	21
1:6000	912	190
1:12,000	1,820	760
1:30,000	4,560	4,800

Aerial photography is used in conjunction with ground samples for assessment surveys. Double sampling is one technique for the integration of aerial photography with other data sources. Double sampling occurs when selected units are measured twice and a large sample size is relied on to estimate the population characteristics (Titus 1979). “Double sampling for stratification” occurs when the entire sample is used to weight classes in a proportional sampling design. From this design, selected units are re-sampled in more detail and provide information about each class. That approach is commonly used in the U.S. Forest Service inventory – where air photos provide timber volume classes and ground plots are sampled for precise volume estimates within each class (USDA Forest Service 1992; Frayer and Furnival 1999). “Double sampling with regression” combines the information from photo plots and ground plots to estimate the characteristics of the larger area (Wear et al. 1966) (Figure 4). The advantage of double sampling is that high-cost, high-quality ground plots are minimized and the low-cost data from photo plots has a higher quality. Photo-plots may be laid out in a random, stratified random, or grid sampling design. In the classic design, a sub-set of the areas covered by photo-plots is ground-surveyed. A regression between the attribute values from each survey provides the information necessary to adjust the estimate over the entire study area (Bickford 1952). A similar approach is used in the B.C. Vegetation Resource Inventory where stand age, height, and volume estimates are adjusted from the initial photo interpretation using the ground inventory (B.C. Ministry of Forests 2001). In this case however, inventory polygons that are subjected to ground surveys are selected based on the probability proportional to size with replacement (B.C. Ministry of Sustainable Resource Management 2002).

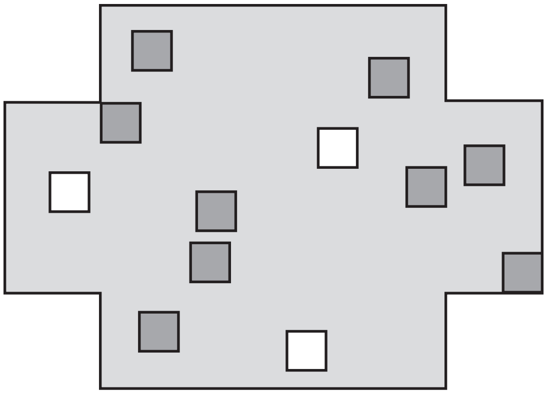


Figure 4. Illustration of classic double sampling design. The large polygon represents the study area and the squares represent photo plots. White squares are photo plots that also contain field survey points.

In addition to double sampling, multistage sampling is another useful approach for remote sensing assessment surveys using aerial photography. A multistage design is a technique of sub-sampling, or sampling within sample units (Titus 1979). The sub-sample is used to estimate the characteristics of the sample unit. The advantage of sub-sampling is the increase in sampling efficiency, which results in lower costs. For example, an aerial overview survey may identify a number of large areas with mountain pine beetle infestation. These can define the primary sampling units (Figure 5a). To estimate the impact on timber volume, large-scale air photos could be collected as secondary sampling units and 10% of the area interpreted using standard inventory techniques (Figure 5b). A further sub-sample of 1% of the area is subjected to field verification. These field plots are located based on a stratified random design, so that they fall within areas interpreted on the air photos as infested. The example was intended to illustrate some of the principles of multistage sampling: that information at smaller scales is used to design the sampling at larger scales, and that sub-samples are a fraction of the sample unit. For implementation, most good textbooks on experimental design cover multistage sampling (e.g., Krebs 1989) and refer to Cochran (1977).

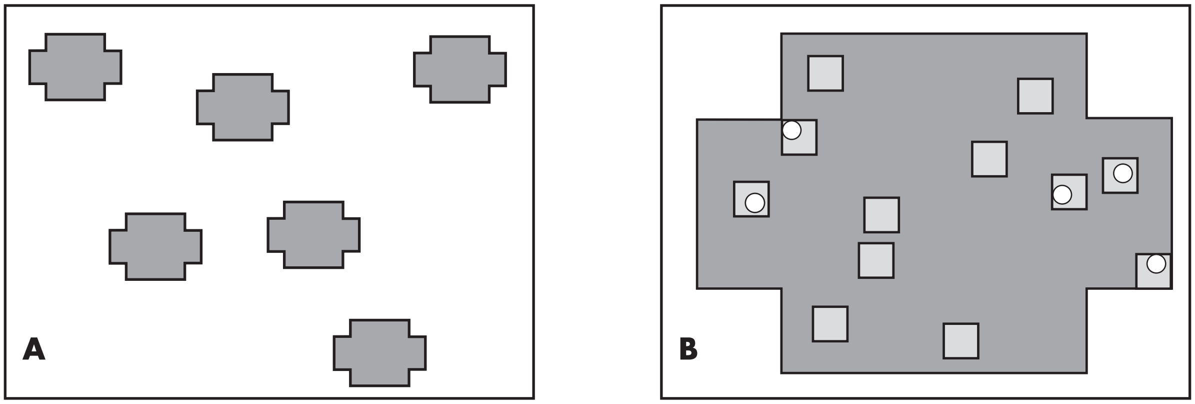


Figure 5. Illustration of multi-stage sampling design. a) Primary sampling units distributed over study area. b) Sub-sampling design within a primary sampling unit. Squares represent secondary sampling unit (e.g., photo-plots), and circles represent tertiary sampling units (e.g., ground plots).

5.2 Planning digital data collection

A key advantage offered by remote sensing is that the data are continuous across the extent of the sampled area; whereas, polygon delineation from aerial viewing or air photos is discrete units. Furthermore, digital image processing techniques exert the same sampling effort on every unit. In contrast, sampling effort in aerial surveys may be affected by viewing angle, flying conditions, and human nature (McConnell 1995). An additional advantage offered by digital image processing is the standardized algorithms that reduce the influence of the operator and inconsistencies sometimes found in visual interpretation (Wulder 1998).

The spatial, spectral, and radiometric characteristics of a sensor dictate the type and quality of information within each pixel. Spatial resolution refers to the pixel size collected by a given sensor and has implications to the size of the features that can be detected. The spatial resolution of the imagery will dictate the information content of a given pixel (Table 3). As noted in Lefsky and Cohen (2003), sensor characteristics combine to result in unique information content. In a mountain pine beetle context, the digital number of a given 30 m Landsat pixel will be based upon factors such as the number of trees, the stand structure (age, strata, closure), species mixture, attack state, and understorey composition. As a result, the range of spectral characteristics that define a disturbed pixel may overlap with those of a healthy stand. One solution to the problem of mixed pixels is to use data with high spatial resolution. The trade-offs, however, are cost and extent (Figure 6) (Franklin et al. 2002). In general, the extent of the data collection area decreases as spatial resolution increases. Therefore, a given management unit may require more processing time and increased costs when utilizing data collected at higher spatial resolutions.

Table 3. Example instrument-related spatial resolution ranges and levels of plant recognition in forestry to be expected at selected image scales (from Wulder 1998).

Type or photo scale	Approximate range of spatial resolution (m)	General level of plant discrimination
Common satellite images	30 (ETM+ multispectral) 15 (ETM+ panchromatic) 20 (SPOT multispectral) 10 (SPOT panchromatic)	Separation of forest types (stand-level characteristics)
Small satellites	>1 (panchromatic) >3 (multispectral)	Recognition of large individual trees and of forest types (genus and species)
Airborne multispectral scanners	>0.3	Initial identification of large individual trees and large shrubs
Airborne video	>0.04	Identification of individual trees and large shrubs
Digital frame camera	>0.04	Identification of individual trees and large shrubs
1:25 000 to 1:50 000	0.31 to 0.62*	Recognition of large individual trees and forest types
1:10 000 to 1:25 000	0.12 to 0.31*	Direct identification of major cover types and species occurring in pure stands
1:2 500 to 1:10 000	0.026 to 0.12*	Identification of individual trees and large shrubs

* Based upon a typical aerial film and camera configuration utilizing a 150 mm lens.

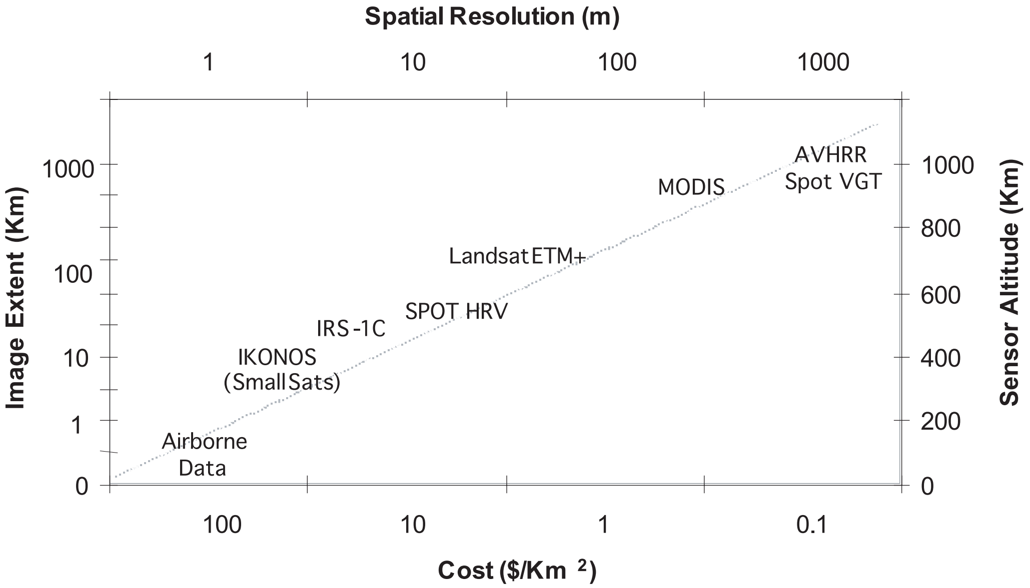
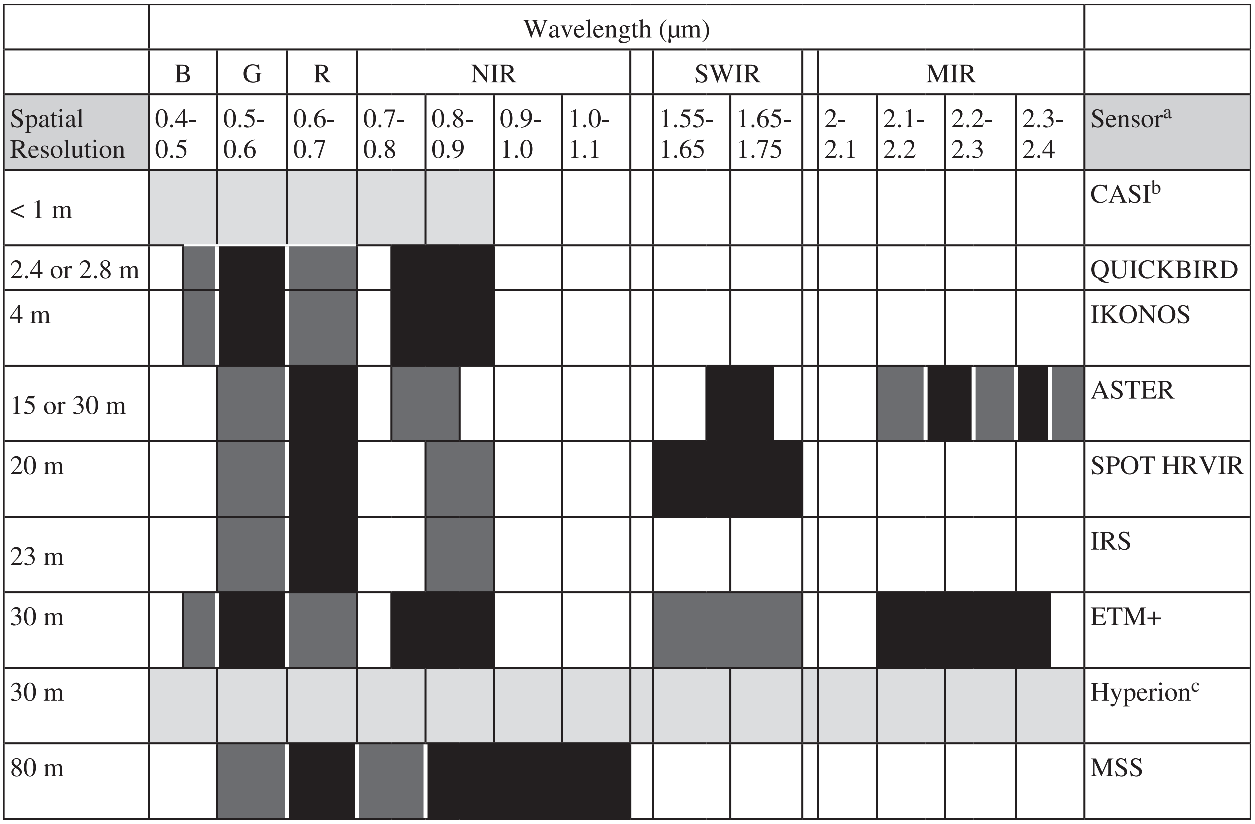


Figure 6. Generalized relationship between image extent, spatial resolution, sensor altitude, and costs of several typical sources of remotely sensed data (reproduced with permission from Franklin et al. 2002).

The spectral resolution refers to the number, spacing and width (along the electromagnetic spectrum) of separate wavelength band slices that a sensor records. The greater the number of discrete wavelength band slices, the greater the potential to discriminate features of interest. The spectral bandwidth (range of wavelengths) and band locations must be appropriately positioned and be sufficiently sensitive to the differences between healthy and attacked foliage (Riley 1989). When determining an appropriate spectral resolution for a given application, it is important to note that smaller differences in the pattern of spectral reflectance can often be detected under laboratory conditions compared to what can be distinguished in the field (Koch et al. 1990). Conditions that are constant in the lab, but variable in the field include: atmospheric conditions, influence of surrounding objects, angle between the light source and the surface, and the angle between the surface and the point of observation. Furthermore, aerial or satellite data contains a mixture of plant and background spectral information, including shadows (Koch et al. 1990). In the case of mountain pine beetle attacked trees, a pixel may contain only healthy trees, only attacked trees, or a mixture of both. The “mixed pixels” can make classification difficult because they have spectral properties somewhere in-between “pure pixels” representing differing features.

In selecting a suitable sensor, there may be trade-offs between the spectral and radiometric quality and the spatial resolution (Table 4). Panchromatic data are collected as a single sensor band that is at a higher spatial resolution than the multispectral data that are collected by the same sensor (Table 5). This panchromatic data can be “fused” with lower resolution multispectral data to improve the accuracy of visual interpretation and the detection of linear (e.g., road) and edge (e.g., lake shore) features in the image.

Table 4. Spatial resolution and approximate spectral resolution of multispectral sensors commonly used for vegetation mapping (sources include Jensen 2000). Shaded blocks represent different spectral bands. Blocks of narrower width tend to indicate a sensor with greater spectral sensitivity.



	Wavelength (μm)															
	B	G	R	NIR					SWIR			MIR				
Spatial Resolution	0.4-0.5	0.5-0.6	0.6-0.7	0.7-0.8	0.8-0.9	0.9-1.0	1.0-1.1		1.55-1.65	1.65-1.75		2-2.1	2.1-2.2	2.2-2.3	2.3-2.4	Sensor[a]
< 1 m	░	░	░	░	░											CASI[b]
2.4 or 2.8 m	▨	■	▨	■	■											QUICKBIRD
4 m	▨	■	▨	■	■											IKONOS
15 or 30 m		▨	■	▨	▨				■	■			▨■	▨■	■▨	ASTER
20 m		▨	■		▨				■	■						SPOT HRVIR
23 m		▨	■		▨											IRS
30 m	▨	■	▨	■	■				▨	▨			■	■	■	ETM+
30 m	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	Hyperion[c]
80 m		▨	■	▨	■	■	■									MSS

[a] Sensor information:

ASTER – Advanced Spaceborne Thermal Emission and Reflection Radiometer (asterweb.jpl.nasa.gov)

CASI – Compact Airborne Spectrographic Imager (www.itres.com)

Hyperion (eo1.gsfc.nasa.gov)

IKONOS (www.spaceimaging.com)

IRS – Indian Remote Sensing (www.isro.org)

ETM+ – Landsat Enhanced Thematic Mapper (landsat7.usgs.gov)

QUICKBIRD (www.digitalglobe.com)

SPOT HRVIR – SPOT High Resolution Visible Infrared (www.spotimage.fr)

MSS – Landsat Multispectral Scanner (edc.usgs.gov/products/satellite/mss.html)

[b] CASI channels programmable in size; >2nm width depending on application (Anger et al. 1994); CASI spatial resolution is a function of flying conditions (Wulder et al. 1996).

[c] Hyperion collects 220 bands of spectral data over the 400 to 2500 nm spectral range.

Table 5. Spectral and spatial characteristics of panchromatic band of sensors commonly used in vegetation mapping.

Spatial resolution	Panchromatic wavelength(μm)	Sensor
61cm (at nadir)	0.45 - 0.90	Quickbird
1 m	0.45 - 0.90	IKONOS
5.8 m	0.5 - 0.59	IRS
10 m	0.61 - 0.68	SPOT HRVIR
15 m	0.52 - 0.90	Landsat ETM

In addition to spectral and radiometric considerations, users of remotely sensed data also need to find a match between the spatial resolution and the information content of available imagery (Lefsky and Cohen 2003).

Three different pixel sizes illustrate the relationship between spatial and spectral resolution and information content (Figure 7). The larger frame represents a 30 x 30 m pixel (e.g., Landsat multispectral), the mid-size frame represents a 4 x 4 m pixel (e.g., IKONOS multispectral) and the smallest frame represents a 1 x 1 m pixel (e.g., IKONOS panchromatic). All were placed upon the digital photo of an area undergoing mountain pine beetle attack. Within the large frame, for instance, red-attack trees and green trees can be visually interpreted. Also present 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 and would not result in an effective signal for the mapping of red-attack in this particular pixel. Higher spatial resolution multispectral data, in this example illustrated by the mid-sized frame, contains fewer elements, therefore, would be capable of higher accuracy in red-attack mapping. The trade-off for the higher resolution is smaller image extent (Figure 6) (Franklin et al. 2002). For example, a Landsat TM image has a swath width of 185 km whereas a Quickbird image has a swath width of 16.5 km at nadir (20.8 km off nadir). The high spatial resolution panchromatic example, represented by the smallest frame, begins to capture stand conditions that are not entirely based upon mixtures. The small pixel may capture a single stand element, such as a portion of a sunlit tree crown. For algorithm development, it is preferable that groups of pixels capture the distinct signal rather than single pixels. The compromise with the panchromatic data is the lower spectral resolution. The single broad spectral range is inferior to detection capabilities of narrower spectral bands captured with multispectral sensors. Research has demonstrated that across this range of spatial resolutions, above limitations considered, success has been found using satellite and airborne systems to map red-attack (see Section 6.2). While the pixels are mixtures of various stand elements and characteristics, image processing techniques can be applied to capitalize upon the image information content present.

The temporal resolution of a sensor may also influence possible applications. The temporal resolution is defined as the frequency with which any given ground location will be sampled by a sensor. One factor that combines with temporal resolution is the role of weather conditions in the quality of remotely sensed data. Certain sensors, such as airborne or daily-overpass satellites can be used to capture data under optimum weather conditions. However, other sensors have pre-determined schedules, such as the Landsat satellites with 16-day overpass cycles. Therefore, successful data collection relies on the co-occurrence of optimum weather collection and sensor availability. This type of sensor may be impractical if there is only a small timeframe in which the manifestation of a particular forest health issue is exhibited by the foliage and thereby detectable through remote sensing. The advantage of a sensor with a pre-determined schedule, such as the Landsat satellites, is the capability to resample the same location on previous (through an image archive) or subsequent dates. In addition, the standardized image characteristics of these sensors facilitate the consistency of repeated samples.

Figure 7. Illustration of information content of three common image spatial resolutions of 30x30 m, 4 x 4 m, and 1 x 1 m. Larger pixels tend to amalgamate a greater variety of stand elements. Underlying image is a true-colour digital photograph (from Wulder and Dymond 2004).

5.3 Assessing accuracy of results

The map products created as a result of surveying mountain pine beetle impacts with remote sensing technologies can be subjected to an accuracy assessment. A transparent and robustly applied accuracy assessment provides a level of confidence to users of the map products. Specifically, an accuracy assessment provides information on the success of the detection methods used and identifies possible sources of error. This information is especially important for comparing and evaluating different mapping techniques and in the development of new methods. Accuracy assessment information is of key importance in an operational setting. An error matrix is a useful mechanism for summarizing results and facilitating the calculation of accuracy measures; an example generated for a hypothetical mountain pine beetle is presented in Table 6. An error matrix enables a quantitative comparison of classes, or attributes, between independent validation data with the mapped results (Congalton and Greene 1999). The comparison may be between the results of an analysis based upon remotely sensed data and field data, or between outcomes using different methodologies. This type of accuracy assessment protocol can also be applied to the results of non-digital methodologies including aerial surveys and photo-interpretation.

In Table 6, the overall accuracy is the percent of correctly classified sample points (e.g., 576/583 = 98.7%). The overall accuracy provides a general indication of the accuracy of the map if all classes were of equal importance. If all classes were not of equal importance, the overall accuracy may misrepresent the accuracy of the map. In our example, most of the ground-validation sites were of healthy trees. Therefore, the overall accuracy was dominated by the accuracy of the healthy class. It was not a valid indication of accuracy for the map as a whole. Each individual class had two measures of accuracy: producer's and user's. The producer's accuracy is the percent of reference sites for a particular class that were correctly classified during the remote sensing process. For example, in Table 6, only 80% of the attacked trees in the study area (as identified by the reference source) were identified by the remote sensing method (e.g., 16/20=80%). The corollary of the producer's accuracy was the omission error: the number of reference sites, for a particular class, which were omitted from the remotely sensed class (e.g., 4/20=20%). Continuing our example, 20% of the attacked trees were missed by the remote sensing method. The user's accuracy is the percent of remotely sensed sites that were correctly classified and from our example, 84% of attacked trees were correctly mapped (e.g., 16/19=84%). The corollary of the user's accuracy was the commission error: the number of reference sites for a particular class that were erroneously included in the remotely sensed class. For our example, 16% of attacked trees were mistakenly identified as healthy trees (e.g., 3/19=16%). The most useful single indicator of accuracy for an attack map is the user's accuracy for the attack class; also known as the true-positive rate (Kohavi and Provost 1998).

Table 6. Example of error (confusion) matrix for a hypothetical mountain pine beetle detection study with two classes.

	Ground-validated healthy trees	Ground-validated attacked trees	Sum	User's accuracy
Remotely sensed healthy trees	560	4	564	99.2%
Remotely sensed attacked trees	3	16	19	84.2%
Sum	563	20	583	**Overall accuracy**
Producer's accuracy	99%	80%		99%

A second example of an error matrix was provided to illustrate how confusion can arise when more than two classes occur (Table 7). In this example, the attacked class was split into green-attack and red-attack trees. A total of 100 stems were examined in the hypothetical ground survey. Fifty were found to be healthy, 20 green-attacked and 30 red-attacked. The overall accuracy of 84% underestimated the reliability of the results for users interested in red-attack detection, as the user's accuracy for red-attacked trees is 92%. Furthermore, the overall accuracy overestimated the reliability of the green-attack results, in which case the user's accuracy is only 61%.

Table 7. Example of error (confusion) matrix for a hypothetical mountain pine beetle detection study with three classes.

	Ground-validated healthy trees	Ground-validated green-attacked trees	Ground-validated red-attacked trees	Sum	User's accuracy
Remotely sensed healthy trees	45	4	1	50	90%
Remotely sensed green-attacked trees	5	14	4	23	61%
Remotely sensed red-attacked trees	0	2	25	27	92%
Sum	50	20	30	100	**Overall accuracy**
Producer's accuracy	90%	70%	83%		84%

Measures of accuracy clearly depend on the quality and quantity of the validation data available. For example, the sites used to test the accuracy should not have been previously used in the classification process for calibration, or the accuracy assessment may be erroneously high (Congalton and Greene 1999). The size of the sampling unit should reflect the resolution of the final product (Stehman and Czaplewski 1998). If the sampling unit is much smaller than, for example, the pixel size, it is unclear if matching classes is due to the site being within the pixel or other pixel content. Furthermore, the sampling design should reflect the importance of different classes. If all classes are equally important then a stratified sample design could be applied, with the number of samples proportional to the area of each class. If one class is more important, then at least an equal number of samples should be taken in that class, even if it is rare on the landscape.

The basic error matrix presented in Table 6 is the minimum standard for evaluating mapping results. Additional information may be conferred by incorporating the area of each class and by defining confidence intervals for the accuracy estimates (Czaplewski 2003). Table 8 provides an example of sample allocation proportional to area. These additional sources of information were illustrated on a per-pixel basis, where each unit classified occupies one ha. The user's and producer's accuracy estimates had 90% confidence limits added. For example, there was a 90% probability that the true positive rate (user's accuracy) for healthy trees likely fell between 83% and 94%. The estimate for the overall accuracy was reported at 84 %, but, given the sample size of 100, likely fell between 77% and 89%. A greater sample size would result in a narrower confidence interval. If an overall accuracy of 84% had resulted from 250 samples, the 90% confidence limits would have been 74% – 84%. The class area estimates are most useful if the ground-truth points were a random sample of the study area. If so, then the class area estimated from the ground-truth points accurately reflects the true area. Assuming this was the case for our hypothetical example, the mapped areas were slightly underestimated for the healthy trees and slightly overestimated for the green-attacked and red-attacked classes.

Table 8. Example of a hypothetical error (confusion) matrix plus incorporation of sample size and area for evaluating the map. Each ground-validated plot represented 1/10000th of the total study area.

	Ground-validated healthy pixels	Ground-validated green-attacked pixels	Ground-validated red-attacked pixels	Sum	User's accuracy with 90% confidence interval	Class area estimated from ground-validated plots (n*10000)	Class area estimated from entire map (ha)
Remotely sensed healthy pixels	45	4	1	50	90% (83 - 94%)	500 000	459 623
Remotely sensed green-attacked pixels	5	14	4	23	61% (51 – 68%)	230 000	243 003
Remotely sensed red-attacked pixels	0	2	25	27	92% (85 – 97%)	270 000	297 374
Sum	50	20	30	100	Overall accuracy		
Producer's accuracy with 90% confidence intervals	90% (83 - 94)	70% (61 - 77)	83% (74 - 88)		84% (77 - 89)		
Class area estimated from ground-truth plots (n*10000)	500 000	200 000	300 000			Total	1 000 000

There are a range of factors that must be considered to develop a statistically robust accuracy assessment (Cochran 1977). The interpretation of the subsequent accuracy of an attack map is linked to the study design. For instance, the classification scheme used in the mapping must be the same as the one used for the testing or validation data (Congalton and Greene 1999). The sample unit and the number of samples collected are a function of the classification scheme, the minimum mapping area, the extent of the mapping area, and the desired width of the confidence intervals (Congalton and Greene 1999; Czaplewski 2003). The sample design should, first and foremost, select samples without bias so the accuracy assessment is valid over the entire map area. Spatial autocorrelation can create a bias in the estimate of accuracy if it is not taken into account as part of the sampling design (Congalton and Greene 1999). Simple random sampling and stratified random sampling are the most robust sampling designs from a statistical perspective (Congalton and Green 1999; Czaplewski 2003). A valid accuracy assessment is most likely to occur if the design is based on an understanding of the characteristics of the remotely sensed data, the classification scheme, the processing methodology, and the biology related to the apparent forest condition.

5.4 Factors affecting costs

Previous studies can provide insight into the relative costs of data acquisition and processing, and factors that impact costs (recall Figure 6). The general components of a remote sensing study budget are: data acquisition (sketches, photos or images); pre-processing (digitizing sketches, scanning photos or georeferencing images); processing (interpretation or classification) and validation (ground-checking and accuracy assessment). Data acquisition costs varied depending on the sensor. Airborne surveyors or sensors provide relatively low cost data if the weather and location to be surveyed are such that travel and waiting time for the aircraft and crew are minimized. Some earth-orbiting satellites can be tasked to image a specific area during a requested period of time, if suitable weather conditions occur. Unfortunately, these custom-order datasets tend to be more expensive than those from satellites that revisit a given area on a set return-interval and capture the images, despite clear or cloudy weather. Another cost trade-off is the extent of the area surveyed and the desired spatial resolution or scale (Figure 6).

The processing time required for remote sensing analysis and interpretation varies depending on the sensor and the study design. For example, a comparison found aerial sketch-mapping to be about 10 % of the costs per acre of air photo interpretation (Waters et al. 1958). This was largely due to the hours required: 4.7 for aerial sketch-mapping and 19 for air photo interpretation. The percentage breakdown of annual costs for a complete multistage sampling program of mountain pine beetle infestation in the state of Montana was, 20% for aerial sketch mapping, 23% for aerial photography, and 55% for ground survey (Bennett et al. 1980). The remaining costs were for data analysis and report writing. A cross-Canada survey of methods for measuring forest damage found operational costs to be lowest per hectare for sketch mapping. Comparing on a per hectare basis, panoramic photography acquisition was about 2.25 times the cost for sketch mapping, and 1:25,000 scale air photo acquisition costs were 11.25 times the cost for sketch mapping (Leckie et al. 1983).

6 Remote sensing detection and mapping of forest damage – review of published results

This section of the review examines studies on detecting green-attack (Section 6.1) separately from those detecting red-attack (Section 6.2) and grey-attack (Section 6.3). Each different attack stage has unique spectral characteristics associated with it. Green-attack is a form of non-visual stress, whereas for red-attack detection, visual, photographic and digital sensors are used. Grey-attack can also be detected visually; however, grey-attack has a pattern of reflectance closer to completely defoliated trees than those with red foliage. Each section includes a discussion of the remote sensing literature directly and indirectly related to the attack stage, followed by a study-by-study summary of the purpose, methods, results and building blocks applicable to the objective of this review. Each building block summarized the concepts learned from each study, which indicated the potential and limits of remotely sensed data in the detection and mapping of mountain pine beetle impact. For each attack stage these building blocks were used to identify trends and gaps in the remote sensing literature.

6.1 Green-attack

6.1.1 General results of detecting non-visual symptoms of stress

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 results of moisture stress (see Section 4 for details). A review of studies detecting non-visual symptoms of stress summarized the research done in the 1960s and 1970s (Puritch 1981). This review found successes in detecting water stress at the leaf-level: slight affects could be detected within 45 to 90 days of attack. 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). However, detection results were poor where the data integrated foliage, branches, and other background elements common to forests (Puritch 1981).

One theory of detecting the non-visual symptoms of stress due to bark beetles focuses on the decrease in near-infrared (NIR) reflectance (Figure 8); this change in NIR reflectance is subtle and within the variability caused by species, site, and age (Murtha 1978). The change in near-infrared reflectance may be masked in air photos by atmospheric conditions, scale, or image processing (Murtha 1978; 1983). The visual interpretation of healthy trees compared to attacked trees hinges on the distinction between a variegated magenta colour pattern and a non-variegated pattern in colour-infrared (CIR) photography (Murtha 1985a, 1972). This difference is attributed by Murtha (1985b) to the new foliage on stressed trees darkening to resemble the old foliage.

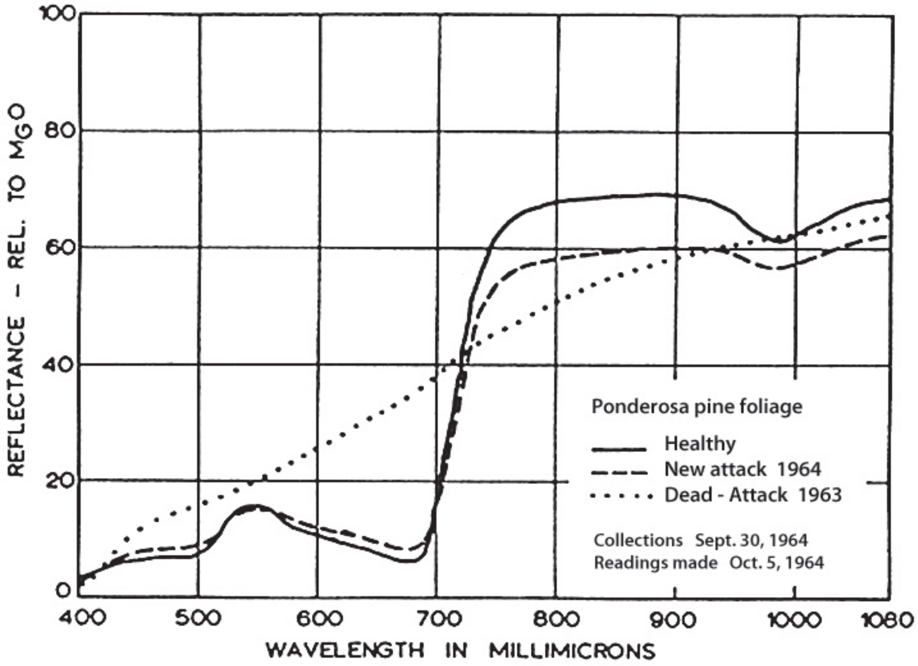


Figure 8. Spectral response curve showing drop in near-IR reflectance for green-attack foliage and increase in red reflectance for red-attack foliage (From Heller 1968, source cited as National Bureau of Standards).

A study of pine foliage detected bark-beetle induced differences in the spectral reflectance of attacked compared to healthy trees (Ahern 1988). Some of the effects were greater on the current foliage compared to previous-year foliage. The authors cautioned that the changes detected at the leaf-scale may not be detectable for entire trees where the signal is diluted by branches, understorey vegetation, and other background objects. The follow-up publication using an airborne sensor did not report results for detecting green-attack (Kneppeck and Ahern 1989). Heath (2001) investigated the spectral reflectance related to individual trees. That study showed the reflectance distribution from green-attack trees overlapped the distribution from healthy trees using an airborne sensor (Figure 9) (Heath 2001). The detection of damage associated with the southern pine beetle was investigated with an airborne mounted digital camera with a 1 m spatial resolution (Carter et al. 1998). In this study, select lens filters were utilized to capture characteristics in 6 to 10 nm bandwidths centred at 675, 698, and 840 nm. This research illustrated that trees with yellow to brown foliage were identifiable as attacked. Trees with pre-visual symptoms were not readily identifiable. Similar to Heath (2001) above, the authors identify a lack of contrast between trees at an early stage of attack with healthy trees.

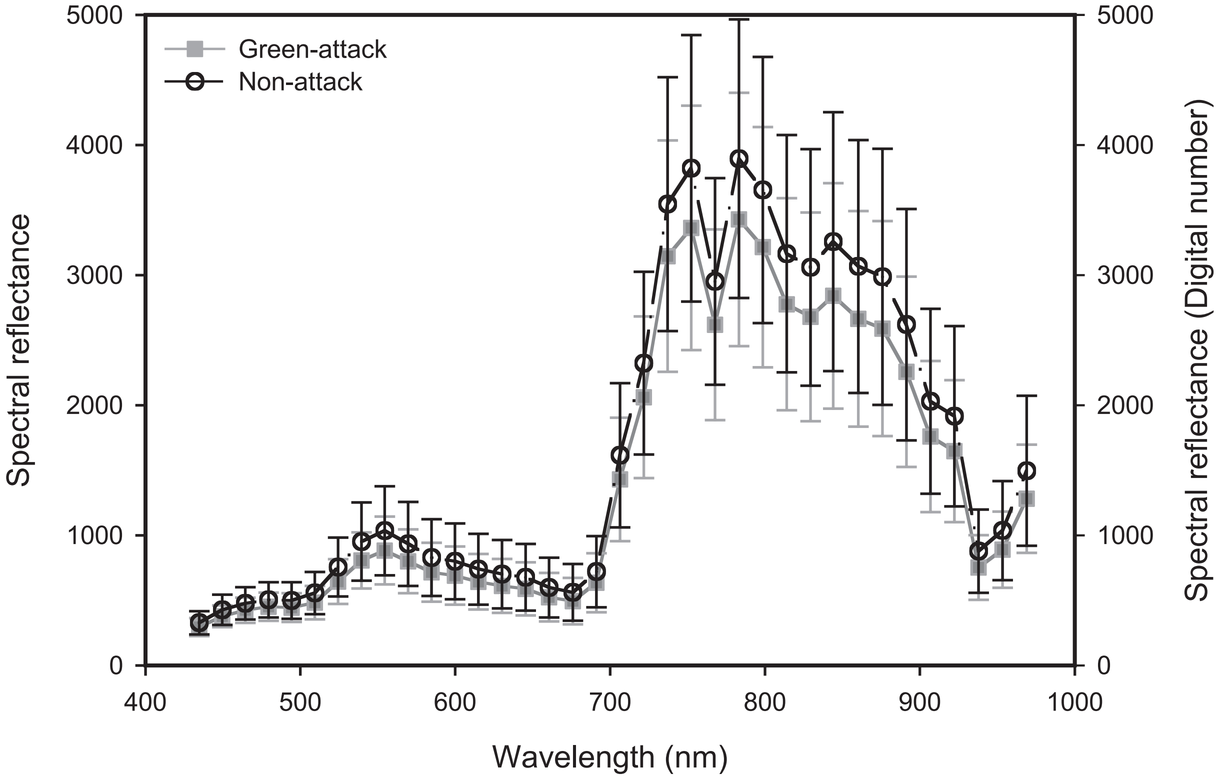


Figure 9. Average spectral reflectance (± standard deviation) of 24 green-attack trees and 25 non-attacked trees. (Modified after Heath 2001).

6.1.2 Specific studies detecting green-attack

Study: Murtha and Wiart 1987

- **Purpose:** "…to report on some preliminary results concerning PC-based digital interpretation of mountain pine beetle green-attack and its subsequent analysis in LOTUS."
- **Resolution of Sensor:** 1:1,000 scale 70 mm CIR photographs scanned with a 100 micrometre scanner; 10 cm pixel.
- **Extent:** 32 ha
- **Methods**:
    - Classification: 45 tree crowns delineated by visual interpretation.
        - trees in same class were combined, not used as replicates
- **Results:** Graphs for each class depicting different spectral reflectance
    - 2 non-attack trees, 6 green-attack trees, 4 red-attack trees
    - Presented statistics: None
- **Building blocks:** Study indicated that the spectral reflectance of some individual trees may be the result of their attack-state. Results were preliminary and include a caveat that the results are based upon 12 of a possible 45 measured trees.

Study: Murtha and Wiart 1989 a and b

- **Purpose:**
    - 1989a: "1. that detectable digital differences do exist between non-attacked and current-attacked pine-crown digital images; and 2. that the natural foliage age-class spectral variations in the crown of a conifer need to be accounted for during digital analysis."
    - 1989b: "… to describe the foliage digital patterns associated with mountain pine beetle current-attack and non-attack pine."
- **Resolution of Sensor:** 1:2,000 CIR aerial photographs digitized, 20 cm pixel
- **Methods:**
    - Classification: 34 non-attack and 34 current attack crowns outlined by visual interpretation of ground data.
- **Results:**
    - Table of cluster means and standard deviations
    - Graphs of tree ID number vs. DN for each spectral band
    - Presented statistics: Used ANOVA F values to determine significant differences in spectral characteristics of non-attack and current-attack clusters
- **Building Blocks:** The results indicated that separation of green-attack tree crowns from non-attack crowns using spectral data is difficult given the amount of variability and overlap between attacked and non-attacked samples.

Beyond the peer-reviewed literature there are reports, conference proceedings, and theses that document green-attack studies (Table 9). High spatial resolution air photos indicate that some green-attack trees are detectable (Murtha 1972; Hobbs 1983). However, they can be confused with healthy trees and trees stressed for reasons other than attack by mountain pine beetle. Hyperspectral studies have shown promise for bands centred around 539.5 and 706.4 (Heath 2001). However, the spectral signatures of healthy and green trees largely overlapped (Heath 2001; ITRES 2001). This overlap contributes to difficulties when attempting to map the two classes.

The difficult nature of mapping green-attack manifests in the assessments of accuracy in these studies (Table 9). For example, in some studies, the same set of ground-survey stems were used to both parameterize and validate green-attack algorithms, due to the difficulty in obtaining separate calibration and validation data. However, the practice of using the same data for both calibration and validation inflates the resulting estimates of accuracy (Congalton and Greene 1999) (also see Section 5.3). Notwithstanding, the estimates of error were still high. Similarly, the estimates of accuracy are also inflated by eliminating reference data that are known to have produced false-positive results. For example, eliminating stressed trees that are not undergoing attack by mountain pine beetles (Hobbs 1983; ITRES 2001; EIT 2002). The ground validation of only 2 or 3 select locations, representing limited areas, is insufficient to indicate operational potential of a given approach.

Table 9. Classification accuracy of four additional green-attack studies.

		Green-attack				
Sensor	Classification method	Producer's accuracy	True positive	Sample size (trees)	Extent of area mapped	Reference
Aerial photography	Visual interpretation	92-96%	80-90%	32-66	approx. 25 ha[a]	Hobbs 1983
CASI hyperspectral scanner	Discriminant analysis	67-83%	64-71%	16-20	Not applicable for method	Heath 2001
CASI hyperspectral scanner	Proprietary algorithm	81%	84%	26	approx. 5.8 ha[a]	ITRES 2001
GER 3715 hyperspectral scanner	Proprietary algorithm	33-63%	63%	10-31	Two x 0.5 ha	EIT 2002

[a] Estimated from report

6.1.3 Research trends, gaps, and recommendations

The trend in research for green-attack detection is directly linked to the subtle signal of green-attack stress: research on green-attack detection initially involved the use of CIR aerial photography, and more recently has involved the use of hyperspectral airborne sensors. In order to successfully detect green-attack, the mixing of signals within a pixel must be minimized, necessitating a data source with a high spatial resolution. Furthermore, the spectral sensitivity of the sensor must be maximized (i.e., the data source must have a high spectral resolution). Airborne sensors will continue to provide the optimal combination of spatial and spectral resolutions for the foreseeable future.

Significant gaps remain in the body of green-attack research, which pose barriers to the operational adaptation and implementation of green-attack detection methods (e.g.,, consistent and transparent accuracy assessment protocols). The results presented in the non-peer reviewed studies examined here are undermined by the lack of rigorous study designs and robust accuracy assessment protocols. For example, a rigorous study design would randomly sample the trees within an image area and retain a portion of the sampled trees for calibration and a separate, independent set of samples for validation. Positional accuracy must also be considered in order to ensure that field-measured trees align with those on the imagery.

Methodological gaps also remain a barrier to the widespread implementation of green-attack detection. The prevalence of visual interpretation methods and/or proprietary algorithms developed for specific conditions, in specific locations, prevent the replication of the results reported in these studies. Detailed communication of methods and algorithms are required to support independent testing and the eventual operational adaptation of these methods.

All of the reviewed studies, which reported the successful detection of green-attack, applied their methodology within forest stands already containing red-attack damage. A high level of infestation by mountain pine beetle (as evidenced by the red-attack damage) increases the likelihood that a tree identified as having pre-visual stress would be under attack by mountain pine beetle. Operationally, field surveys currently use the location of red-attack damage to find green-attack and determine stands requiring sanitation treatment. Therefore, the use of remote sensing technologies to detect green-attack in stands already containing red-attack damage would not be operationally useful.

Methods of detecting green-attack will only be operationally viable when green-attack trees can be consistently and accurately identified in areas where there are disproportionately more green-attack trees than red-attack trees. In regions with a full suppression management strategy (where no red-attack trees are currently present), this information would be highly valued and could be acted upon quickly. The implication of this survey niche is a need to fly over large areas of forest that have potential for infestation (e.g., lodgepole pine dominated stands) that are not currently known to be under attack by mountain pine beetle. Flying over large areas with a sensor that has both high spatial and high spectral resolution (e.g., airborne hyperspectral) would be very costly (i.e., flying costs, processing and interpretation costs). Further, to make such an approach operationally viable, the accuracy of the green-attack detection method would either have to be higher than the current method of mapping green-attack (using ground crews deployed on the basis of the known spatial association with existing red-attack damage) or much cheaper. The flying costs would therefore have to be low, and much of the processing would need to be automated to reduce costs.

The current body of research on green-attack detection with remotely sensed data is inconclusive. Many research issues, including those outlined above, need to be resolved before operational green-attack survey can be considered. Research trials must be designed in the context of information requirements and operational limitations. Methodologies must be clearly documented and results must be subjected to a well-designed accuracy assessment protocol.

6.2 Red-attack

6.2.1 General results of mapping foliar damage

Conifer foliage may be damaged and become red by a variety of agents such as insects, root rot, fungi, and drought (Henigman et al. 1999). Independent of the agent, foliar moisture drops, chlorophyll and other pigments breakdown, followed by a breakdown of intra-cellular and cellular structures (Hill et al. 1967). Spectrally, the change is an increase in the spectral reflectance of red wavelengths of light and a drop in green reflectance (Ahern 1988; Herrmann et al. 1988; Rock et al. 1988; Curran et al. 1990) (e.g., Figure 8). In addition to the changes in the visible spectrum, red-attack foliage has a higher reflectance of wavelengths near 850 nm – 1100 nm (Ahern 1988).

Given the changes in spectral reflectance, a range of methods has successfully detected red tree crowns with remote sensing technology. Aerial surveys were found to provide high quality information for tactical planning during epidemics (Heller et al. 1955; Aldrich et al. 1958; Waters et al. 1958). The limitation of not detecting individual red trees from the airplane was deemed to not be a problem under epidemic conditions. However, location errors due to off-nadir viewing made some surveys unreliable for dispatching ground crews (Aldrich et al. 1958).

Aerial surveys were found to provide complementary information compared to high spatial resolution air photos (Waters et al. 1958). One example of successfully mapping red foliage from colour aerial photography was the Fraser fir (*Abies fraseri*) mortality caused by balsam woolly aphids (*Chermes piceae*) (Aldrich and Drooz 1967). Both the estimates of current and cumulative mortality had confidence limits defined from ground surveys. A key step in this process was incorporating the forest type in the mapping of mortality and in the design of the ground surveys.

Early attempts to detect red crowns from multispectral scanners had limited success. This was often attributed to the mixed pixels in the 80 m resolution of the Landsat MSS sensor (Harris et al. 1978). However, at 7 m and 25 m resolution, appropriate spectral band location and size can result in good detection of red trees (Ahern et al. 1986). Other researchers quickly identified that multi-date imagery, within one or two years of the insect attack, was more effective than single-date imagery (Harris et al. 1978; Byrne et al. 1980). As multi-spectral sensor technology and processing have improved, so too has their ability to detect red crowns (Leckie and Ostaff 1988; Leckie et al. 1988; Franklin 1989). White et al. 2005, in a recent study, demonstrated the use of high spatial resolution (4 m) imagery from the IKONOS satellite, to map red-attacked trees and groups of trees.

6.2.2 Specific studies mapping red-attack

Study: Klein 1973 (grey-attack results presented in section 6.3.2)

- **Purpose:** "…to determine the feasibility of detecting mountain pine beetle-killed lodgepole pine with 35-mm colour aerial photographs at a 1:5,000 scale."
- **Resolution of Sensor:** photo 35 mm, 1:5,000 air photo
- **Extent:** Not reported
- **Methods:**
  - Classification: Visual interpretation of red-attack trees and grey-attack trees
  - Verification method: Ground-counts with trees of a minimum size of 7.0 inches diameter
- **Results:**
  - Presented statistics: Linear regression between density of killed trees by ground count or by photo count. R-squared values ranged from 0.63 to 0.96
- **Building Blocks:** Red-attack was detectable from 1:5,000 air photos; however, inconsistent relationship with ground counts reinforces the necessity for confidence intervals on assessment surveys.

Study: Ciesla 1974

- **Purpose:** "… evaluate ultra-small scale photos from mapping forest insect damage."
- **Resolution of Sensor:** High altitude aerial photography, CIR, 1:126,720
- **Extent:** Not reported
- **Methods:**
  - Classification: Visual interpretation
  - Multi-stage design

  - Verification method: High spatial resolution air photos and ground surveys
- **Results:** Solid areas of red trees more readily detected than more scattered attacks
  - Presented statistics: None
- **Building blocks:** The resolution of appropriate photos or images must be driven by the characteristics of the infestation the user wants to detect.

Study: Harris and Dawson 1979

- **Purpose:** "This study evaluates sketch-mapping and aerial photography."
- **Resolution of Sensor:** Aerial sketch mapping on 1:125,00 and 1:250,000 topographic maps
- **Extent:** Not reported
- **Methods:**
  - Classification: Visual interpretation of red-attack trees (cause may have been mountain pine beetle or Douglas-fir beetle)
  - Verification method: Air photos, 70 mm and 35 mm cameras, hand-held oblique and vertical; 1:70,000 to 1:120,000
- **Results:**
  - Presented statistics: Counts of red-attack trees from sketch-mapping were, on average, 39% below the estimates from air photos
    - ⊙ Counts of red-attack trees from sketch-mapping ranged from –73% to +376% compared to the estimates from air photos
    - ⊙ Area affected from sketch-mapping was, on average, larger than estimates from air photos
    - ⊙ A simulation exercise of sketch-mapping found considerable variation between observers (deviation ranged from –41% to 73%)
    - ⊙ Spatial overlay of sketches and air photo interpretation indicate large spatial differences
- **Building blocks:** Inconsistency within aerial sketch-mapping indicated that confidence intervals or other estimates of error should be reported for informed use of area-infested information. That inconsistency increased further when compared with air photo interpretation results, which indicated that it is necessary for a sub-sample of locations to be cross-verified using an additional location survey method. Aerial sketch-mapping appears to be reliable only for location surveys.

Study: Klein et al. 1980; Klein 1982

- **Purpose:** "Panoramic colour IR aerial photography taken from a U-2C was evaluated to determine its effectiveness in quantifying annual mortality of lodgepole pine caused by mountain pine beetle."

- **Resolution of Sensor:** Panoramic aerial photography (CIR) Approximately 1:63,360
- **Extent:** Reported as approximately 300 square miles
- **Methods:**
    - Pre-processing: Contrast improved with yellow or red filters
        - Stratified land cover type to eliminate areas without host species
        - Quick survey of air photos identified areas for more detailed mapping
        - Air photo extents identified sub-plots for ground surveys
    - Classification: Visual interpretation for faders
        - Grid cells with less than 0.06 faders/acre were recorded as zero
        - Sub-set of grid cells with >0.06 faders/acre were examined in detail
    - Multi-stage design
    - Verification method: Sub-plots of 20 grid cells were ground surveyed, all red trees greater than a reported 5 inches DBH were counted
- **Results:**
    - Presented statistics: Accuracy higher within 10 degrees of nadir compared to 20 – 40 degrees from nadir
        - 10.3 % standard error for number of faders
        - 13.6 % standard error for volume of faders
        - The quick surveys underestimated the number of attacked trees in a 160 acre plot. The ratios comparing detailed to quick counts ranged from 1.32 to 24.24.
    - New statistics: For the 10 acre sub-plots, the range of air photo to ground counts was from 0.6 to 4.73.
- **Building blocks:** Sampling design provided quantitative impact estimates that provide solid information to base decisions on. Inconsistent relationship between air photo interpretation and ground counts reinforces the limits of visual interpretation and the importance of ground counts for assessment surveys.

Study: Dillman and White 1982

- **Purpose:** " … (1) evaluate a multistage sampling using panoramic photography to measure current tree mortality in the Front Range of Colorado and (2) compare mortality estimates and costs from this system with those from a conventional survey".
- **Resolution of Sensor:** High altitude panoramic photography 1:26,000 CIR
- **Extent:** 5.5 million acres
- **Methods:**
    - Pre-processing: Primary sampling units about 15,000 acres, divided into 112 acres secondary sampling units, divided into 4.5 acre tertiary sampling units

        - Counts of red-attack trees done quickly for all tertiary units (4.5 acres) and used to select among the 80 primary units for further analysis
        - Careful red-attack counts were then done for each secondary unit (112 acres) within selected primary units
    - Classification: Visual interpretation of orange to red trees
    - Verification method: Ground-surveys on 75 of the tertiary sampling units
    - Multi-stage design
- **Results:**
    - Presented statistics: Total number of trees killed in 1978 was 167,687 (±SE 23,206), or a standard error of 13.8%
        - Conventional survey had a standard error of 15%
- **Building Blocks:** Supports value of multi-scale sampling design for assessment surveys.

Study: Harris et al. 1982 (grey-attack results presented in section 6.3.2)

- **Purpose:** "… to develop a low-cost method for estimating numbers and volumes of killed trees where (1) aerial sketch-mapping supplemented by oblique photography with hand-held cameras cannot supply the required information; (2) damage is too heavy for easy mapping; or (3) estimates of sampling error are desired. A multistage sampling system using aerial sketch-mapping, vertical colour aerial photography, and ground sampling was tested."
- **Resolution of Sensor:** Aerial sketch maps and aerial photography, 70 mm, 1:5,000
- **Extent:** 14,750 ha
- **Methods:**
    - Pre-processing: Aerial sketch maps identified areas for air photo mapping
        - Air photo extents identified sub-plots for ground surveys
    - Classification: Visual interpretation of red trees and grey trees
    - Multi-stage design
    - Verification method: Count and DBH class of all lodgepole pine in sub-plots in classes: healthy, green-attack, red-attack, grey-attack
        - Counts used to correct the number estimated from air photos
- **Results:**
    - Presented statistics: Red ground: 1,125; air photo: 1,042
        - The average subplot ground count to air photo count ratio was 1.09 for red and grey.
        - Volume killed based on ground corrected counts and diameter and breast height statistics
- **Building blocks:** Supports value of multi-scale sampling design for assessment surveys.

Study: Rencz and Nemeth 1985

- **Purpose:** "… to develop cost-effective procedures for the detection and mapping of mountain pine beetle (MPB) infestations using LANDSAT MSS and simulated LANDSAT TM digital data."
- **Resolution of Sensor:** MSS satellite (80 m) and airborne (19.5 m) Sept. 18, 1975 and Aug. 17, 1981
- **Extent:** Four areas, 5 km x 8 km each
- **Methods:**
  - Pre-processing: 19.5 m resolution re-sampled to 30 m
    - Used only the four bands (from 11) that were closest to TM bands
    - Multi-date images registered to each other to within one pixel
  - Classification: At least 15 training sites were identified in 1:30,000 photographs: grey-attack, high red-attack, moderate red-attack
    - Single-date imagery was classified using parallelepiped
    - Multidate imagery was visually interpreted
  - Verification method: Air photos colour and CIR, 1:30,000 and 1:800
- **Results:**
  - Presented statistics
    - Using single-date, simulated TM data, high accuracies obtained where clusters of red trees greater than 1.5 ha.
      - 80% – 94% for moderate attack
      - 66% – 80% for high attack (most often misclassified as moderate)
      - +90% if two red-attack classes combined into one
    - Using single-date Landsat MSS produced lower accuracy than using simulated TM
      - 45% – 60% accuracy for red-attack
      - errors caused by pixels including a mix of attack and non-attack, variable crown closure and topographic effects on reflectance
    - Using multi-temporal MSS data was not successful due to pixels including a mix of attack and non-attack and difficulty in registering the images
- **Building Blocks:** First study in this review that used digital image to successfully detect red-attack. Indicated 30 m resolution data has good potential for mapping bark beetle infestations. Also indicated that 80 m spatial resolution probably too low for red-attack mapping in the study areas. However, poor results from multidate imagery, were possibly due to separation in time. Considerable changes between images could be due to a number of factors, therefore obscuring change due to beetles

Study: Sirois and Ahern 1988

- **Purpose:** "SPOT multispectral and panchromatic data were investigated to determine their ability to detect recent mountain pine beetle mortality ('red-attack').
- **Resolution of Sensor**: SPOT HRV, 10 m panchromatic, 20 m multispectral
- **Extent:** 24 x 40 km
- **Methods:**
  - Pre-processing: Geometric correction and resampling of 20 m to 10 m so the multispectral and panchromatic could be overlain
    - Linear colour enhancement or PCA
  - Classification: Visual interpretation
  - Verification method: 1:10,000 colour air photos, visually inspected for areas of healthy, red-attack or grey-attack trees, in turn verified by ground surveys
- **Results:**
  - Successful classification of clusters that are 1-2 ha in size with 80%-100% red trees.
  - Presented statistics: None
- **Building Blocks:** Reinforces that digital imagery may be useful for location surveys. Reinforces that the information content of the appropriate photos or images must be driven by the characteristics of the infestation the user wants to detect.

Study: Kneppeck and Ahern 1989

- **Purpose:** "… evaluate the potential of the MEIS-II linear pushbroom array imager for detecting red crowns of trees probably killed by the mountain pine beetle in comparison to conventional methods involving the use of 230-mm (1:10,000-scale) normal colour photographs."
- **Resolution of Sensor:** MEIS-II (Multi-detector Electro-optical Imaging Scanner) airborne sensor with pixel sizes of 1.4 m, 3.4 m, and 6.0 m
- **Extent:** Not reported
- **Methods:**
  - Pre-processing: Enhanced: 480 nm, 548 nm, 675 nm; use of NIR (698 – 776 nm) made detection of red-attack more uncertain
  - Classification: Visual interpretation for red trees
  - Verification method: Compared with interpretation of 230 mm, 1:10,000 air photos
- **Results:**
  - Presented statistics:
    - 136% of red-attack trees counted in 1.4 m MEIS compared to air photos
    - 71% of red-attack trees counted in 3.4 m MEIS compared to air photos

        - ⊙ Red trees seldom detected in 6.0 m MEIS data
- **Building Blocks:** Indicates that airborne digital imagers or scanners could provide an alternative to aerial photography from an accuracy perspective.

Study: Gimbarzevsky et al. 1992 (grey-attack results presented in section 6.3.2)

- **Purpose:** "… to investigate the operational use of available remote sensing techniques for identification of beetle-killed forest stands … direct comparisons of visual observations (from ground-checks and sketch-mapping from low-flying aircraft), a variety of film types and scales of aerial photography, and MSS imagery, all from the same study area."
- **Resolution of Sensor:** Aerial photography, normal colour, CIR and MSS airborne imagery
    - o Aerial photography produced at 1:56,000, 1:19,000, and 1:8,000 scales
    - o Aerial photography, 70 mm, 1:6,000, and 1:1,000 from twin-camera system
- **Extent:** 370 km^2
- **Methods:**
    - o Pre-processing: MSS images identified areas for 1:1,000 air photo mapping
        - ⊙ All data used to identify damage detection criteria
    - o Classification: Visual interpretation of species and green, red or grey crown colour
        - ⊙ Counts of trees at 1:6,000 adjusted based on ground surveys
        - ⊙ Moderate stands had dead lodgepole pine averaging less than 40% of the total conifer stems and severe stands with more that 40%
        - ⊙ Note that a light intensity class was initially included but "from analysis of large-scale photo-plots and ground data of 13 sub-plots…there was very little damage rated light"
    - o Verification method: 13 x 0.25 ha sub-plots were ground-surveyed
- **Results:**
    - o 1:19,000: percent damage in a stand can be estimated
    - o 1:8,000: individual trees can be detected and counted
    - o 1:1,000: individual branches can be detected, background objects can be distinguished
    - o Presented statistics: 1:1000 scale stereo-pairs resulted in detection and counting of almost all trees
    - o Counts from 1:6000 scale stereo-pairs were multiplied by 1.19 for red trees, and 1.60 for the total number of trees based on ground counts
    - o New statistics: For the red-attack trees, the range of 1:8000 air photo to 1:6000 count ratios was from 0.47 to 2.4

        - ⊙ For the healthy trees, the range of 1:8000 air photo to 1:6000 count ratios was from 0.72 to 1.5
- **Building Blocks:** Reinforces inconsistency with air photo interpretation and need for reporting of confidence intervals or similar estimates of error when used for an assessment survey.

Study: B.C. Ministry of Forests 2000

- **Purpose:** "This report provides provincial standards for aerial overview mapping…"
- **Resolution of Sensor:** Aerial sketch mapping, 1:100,000 – 1:250,000
- **Extent:** Province of B.C.
- **Methods:**
    - o Classification: Visual interpretation
        - ⊙ small infestations of 2-30 trees, estimated at 0.25 ha
        - ⊙ small infestations of 31-50 trees, estimated at 0.50 ha
        - ⊙ larger areas and classified as light (1%-10%), moderate (11%-29%), or severe (>29%)
    - o Verification method: Check flights of a sample of detected red trees
- **Results:**
    - o Presented statistics: Maximum acceptable error is 30%
- **Building Blocks:** Scale and acceptable error indicated that aerial overview sketch maps are location surveys only, and not assessment surveys.

Study: Franklin et al. 2003

- **Purpose:** "… red-attack damage caused by mountain pine beetle infestation was classified using Landsat TM imagery, acquired on 12 September, 1999, within strata developed from GIS forest inventory data and with reference to field data and aerial survey information."
- **Resolution of Sensor:** 30 m Landsat TM
- **Extent:** 5070 km^2
- **Methods:**
    - o Pre-processing: Geocorrection and atmospheric correction
        - ⊙ Used forest inventory polygons to mask out areas with low susceptibility to mountain pine beetle
    - o Classification: Training areas developed from 50 m diameter field plots and aerial photos
        - ⊙ Maximum-likelihood classification of red-attack or healthy
    - o Verification method: Same method as training areas but sites not used in classification

- **Results:**
  - Detecting clusters of red trees smaller than 0.20 ha
  - Presented statistics: Overall accuracy: 72.3%
    - Red-attack accuracy 73.3%
    - Healthy accuracy 71.1%
- **Building Blocks:** Demonstrated that digital sensors with moderate resolution could provide reliable red-attack mapping at the landscape scale. Of the studies reviewed, this was the first successful use of an objective detection algorithm rather than visual interpretation.

Study: Skakun et al. 2003

- **Purpose: "…** to identify mountain pine beetle attacked lodgepole pine stands in the Prince George Forest Region, British Columbia, based on the analysis of full-leaf on (summer) Landsat-7 ETM+ TCT-derived EWDI data."
- **Resolution of Sensor:** Multi-temporal, Landsat TM, 30 m
  - Sept 12, 1999, June 26, 2000, August 16, 2001
- **Extent:** Not reported
- **Methods:**
  - Pre-processing: Geometric and atmospheric corrections
    - Tasselled Cap wetness transformation
    - Image differencing between dates
    - Used forest inventory polygons to mask out areas with low susceptibility
  - Classification: Training sites from heli-GPS survey with two levels: 10-29 red-attack trees within 0.25 ha or 30-50 red-attack trees within 0.5 ha
    - 100 sites used for training chosen randomly from overall data set
    - Training sites and interpretation used to define thresholds
    - Discriminant analysis
  - Verification method: Test sites detected using same procedure as training sites.
    - 120 sites used for testing chosen randomly from overall data set
- **Results:**
  - Presented statistics: Healthy, 10-29 red-attack and 30-50 red-attack each had statistically different spectral signatures for wetness average and variance.
    - 67% accuracy for 10-29 red trees and 75% for 30-50 red trees from 1-year enhanced wetness difference index (EWDI)
- **Building blocks:** Tested before-and-after images can be useful for detecting red-attack. Reinforced that digital sensors with moderate resolution could provide reliable red-attack mapping at the landscape scale. Reinforced that the information content of the appropri-

ate photos or images must be driven by the characteristics of the infestation the user wants to detect.

Study: Wulder et al. 2005

- **Purpose:** "…to demonstrate the use of the polygon decomposition tool in mapping certain aspects of a MPB infestation, such as the area and proportion of red-attack within GIS polygons, and forest stand susceptibility to red-attack."
- **Resolution of Sensor:** Aerial sketch maps
    - Helicopter survey points
    - Multi-temporal, Landsat TM, 30 m
    - June 26, 2000 and August 16, 2001
- **Extent:** 5000 km^2
- **Methods:**
    - Pre-processing of Landsat: Used forest inventory polygons to mask out areas with low susceptibility
        - Geometric correction and atmospheric correction
        - Tasselled Cap wetness transformation
        - Image differencing between dates
        - Thresholding to detect red-attack
    - Classification: Intersect aerial sketch map points and polygons with forest inventory polygons
        - Intersect helicopter survey points with forest inventory polygons
        - Intersect classified TM pixels with forest inventory polygons
- **Results:**
    - Presented statistics: Helicopter survey points and classified TM pixels more likely than sketch mapping to detect red-attack in stands where the attributes are consistent with beetle biology (e.g., pine dominated, older, larger diameter, intermediate crown closure.)
    - Percent of polygons with red-attack that were dominated by pine
        - Sketch mapping: 39%
        - Helicopter survey: 71%
        - Classified TM: 73%
    - Percent of polygons with detected red-attack but not dominated by pine
        - Sketch mapping: 61%
        - Helicopter survey: 29%
        - Classified TM: 27%

- **Building Blocks:** Demonstrated new technique for an assessment survey based on red-attack maps from remote sensing. Reinforced usefulness of moderate resolution sensor data and helicopter-GPS surveys. Reinforced that aerial overview sketch-mapping should be limited to use as a location survey at the provincial scale.

Study: White et al. 2005

- **Purpose:** To identify small, scattered pockets of red-attack suitable for suppression activities.
- **Resolution of Sensor:** IKONOS 4-m multispectral
- **Extent:** Phase 1 area = 143 square km; Phase 2 area = 429 square km
- **Methods:**
  - o Classification: Unsupervised clustering, visual identification of red-attack trees using independent calibration data for sites with low and moderate levels of MPB infestation.
  - o Verification method: Used 1:20,000 colour aerial photography as a proxy for field data. A sub-sample of the red-attack trees identified on the air photos were rigorously field checked to ensure photos could serve as a reliable proxy for a full ground-truth data set. Buffers were used around the IKONOS red-attack pixels in order to compensate for positional error in the co-registration of IKONOS imagery and air photos.
- **Results:**
  - o Presented statistics: True positive accuracy ranged from 71% (low attack) to 92% (medium attack). Omission error ranged from 29% (low attack) to 8% (medium attack). Commission error ranged from 10% (low attack) to 2% (medium attack).
- **Building Blocks:** Red-attack was detectable from 4-m multispectral IKONOS imagery; however, sites with low levels of infestation (<5%) remain more difficult to characterize than sites with moderate levels of infestation (5%-20%) which is likely a function of the 4-m spatial resolution. The reporting of accuracy by buffer size can be used to reflect different management or treatment objectives. Stem maps generated from 1:20,000 scale aerial photography can be used reliably as a proxy for ground-truth data.

Additional methods for detecting red-attack trees have been presented at conferences, and in reports, and theses. For example, a direct comparison of normal and CIR photography at 1:20,000 concluded that normal colour photos were preferred for operational use (Winquist and Vandenbrink 1982). Promising methods were developed for Landsat TM data, including stratification of stressed lodgepole pine stands combined with multi-date imagery and spectral unmixing (Murtha et al. 2003). The result was a true-positive rate of 67% with the minimum detectable unit being a single red-attack tree. Some studies have been undertaken where the green- and red-attack stages are combined for mapping and validation. For instance, a Tasselled Cap transformation of Landsat TM data, had moderate results (Producer's Accuracy: 38.8%, User's Accuracy: 68.7%) (Sharma and Murtha 2001; Murtha et al. 2003). Spectral unmixing of Landsat TM data for detecting combined green- and red-attacked trees had a high producer's accuracy: 100%, but a low user's accuracy: 60% (Murtha et al. 2001).

6.2.3 Research trends, gaps, and recommendations

Research on aerial overview sketch-mapping of red-attack found some positional and attribution limitations (Aldrich et al. 1958; B.C. Ministry of Forests 2000). Direct comparisons found aerial overview sketch-mapping to be less reliable on the landscape scale compared to small scale aerial photography (Harris and Dawson 1979) or moderate resolution digital imagery (Wulder et al. 2005). Estimates of area infested should be reported with confidence intervals or other estimates of error. Aerial sketch-mapping appears to be reliable for location surveys at the provincial scale.

At the landscape scale, both analogue and digital technology had good results for location surveys and assessment surveys (e.g., Dillman and White 1982; Rencz and Nemeth 1985). This reliability resulted primarily from the strong signal of red-attack crowns and from the high positional accuracy of the technology. While both types of technology had this reliability, they had different limitations. Panoramic aerial photography was limited by the inconsistency between photo-interpreters, and inconsistency between the mapped results and the ground-counts (e.g., Klein et al. 1980; Klein 1982). Moderate resolution digital imagery was limited by the cluster-size of red-attack trees (e.g., Skakun et al. 2003). Single-tree attacks or small red clusters result in pixels with mixed healthy and attacked trees, which may not be distinguishable from healthy forest (Section 5.2) on moderate spatial resolution images. Acknowledgement of these limitations should come in the form of reporting accuracy assessments and estimating mountain pine beetle impact with confidence intervals or similar statistical estimates of error. White et al. 2005 demonstrate an approach using 4-m high spatial resolution IKONOS imagery for the mapping of red-attack. In this study, individual trees and small groups of red-attack trees are mapped with a focus on areas that were not highly infested. Mapping accuracy was best for locations where the attacked trees were found in groups rather than standing alone. Red-attack was detectable from 4-m multispectral IKONOS imagery. Sites with low levels of infestation (<5%) remain difficult to capture with a consistently high level of accuracy despite the relatively high spatial resolution of the sensor, yet the 71% accuracy may be suitable for some applications. Sites with moderate levels of infestation (5%-20%) can be consistently identified with high levels of accuracy (92%). Omission and commission rates must be monitored to ensure the integrity of the mapping algorithms applied. Low levels of attack were found to have higher rates for both commission and omission than the medium attack level. Omission error ranged from 29% (low attack) to 8% (medium attack) and commission error ranged from 10% (low attack) to 2% (medium attack).

Research into local mapping of red-attack trees showed good map accuracy of even small cluster of red trees based on high spatial resolution air photos (e.g., Klein 1973) or digital images (e.g., Kneppeck and Ahern 1989). The limitations identified at this scale were similar to those found at the landscape scale: the inconsistency of air photo interpretation (e.g., Gimbarzevsky et al. 1992) and the mixed pixels of digital imagery (Kneppeck and Ahern 1989). These limitations need to be respected in both research and operational applications through accuracy assessments and error estimates.

For estimating confidence limits (e.g., Dillman and White 1982) or adjusting impact assessments (e.g., Harris et al. 1982), a multi-stage sampling design was demonstrated to be an efficient and cost effective method at the landscape scale. Part of the power of multi-stage sampling came from the use of different survey methods at different scales. This minimized the impact of the limitations of any single methodology. Similar methods could be applied at the provincial scale in British Columbia to provide confidence limits on the aerial overview mapping. Similar methods could also be used with digital imagery or to integrate analogue and digital datasets.

While red-attack mapping has experienced more research effort than green-attack mapping, gaps were identified in the body of reviewed literature. For example, accuracy assessments were inconsistent. Only with reliable standards for measuring accuracy will research methods become attractive to the operational community.

One recommendation for improving the accuracy of sketch-mapping is to provide a Landsat image as part of the base for sketch-mapping. The current preferred base map integrates a 1:100,000 National

Topographic System map with cut blocks and forestry roads (B.C. Ministry of Forests 2000). The Landsat image would provide the benefit of a continuous view of the landscape from the image data as a backdrop. Polygon placement would be aided from the additional context information conferred by the imagery. Magnitude labelling can also be reassessed post aerial survey, as the actual disturbance outlined may be evident in the imagery.

A large range of photographic scales has been investigated for red-attack mapping. However, digital remote sensing has only researched a small range of the spectral and spatial resolutions available, with Landsat based approaches showing some operational utility. Also at a moderate spatial resolution, the new generation of satellites such as ASTER or Hyperion present improved spectral sensitivity (Table 4). High spatial resolution of sensors such as CASI, digital cameras, and Quickbird also remain relatively unexplored. Further research and development of these digital technologies is recommended due to the array of published techniques that are available for widespread testing and possible operational adoption.

Whether digital or analogue, the image characteristics must match the information needs (e.g., Ciesla 1974, Sirios 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. The higher resolution imagery can itself be used to develop the algorithms for mapping at lower resolutions over a larger area (DeFries et al. 1998). For example, digital orthophotos can be interpreted to delineate training areas for classification of Landsat TM imagery (Scrivani et al. 2001). This type of information hierarchy may result in more efficient mapping of mountain pine beetle locations and impact.

6.3 Grey-attack

6.3.1 General results of mapping complete defoliation

Leaf drop, or complete defoliation, has been more extensively studied in remote sensing compared to detecting red trees. This may be due to the large number of agents causing defoliation (Heller and Bega 1973) and because the presence or absence of leaves can be part of the forest seasonality (Reed et al. 1994; Dymond et al. 2002). Defoliation can cause spectral changes in the tree crowns of conifers. Increasing levels of defoliation are associated with an increase in reflectance in the visible wavelengths, a decrease in near-infrared reflectance, and an increase in mid-infrared reflectance (Leckie et al. 1988; Ekstrand 1994) (Figure 10). This reflectance pattern is closer to one from a bare branch than to a fully foliated branch.

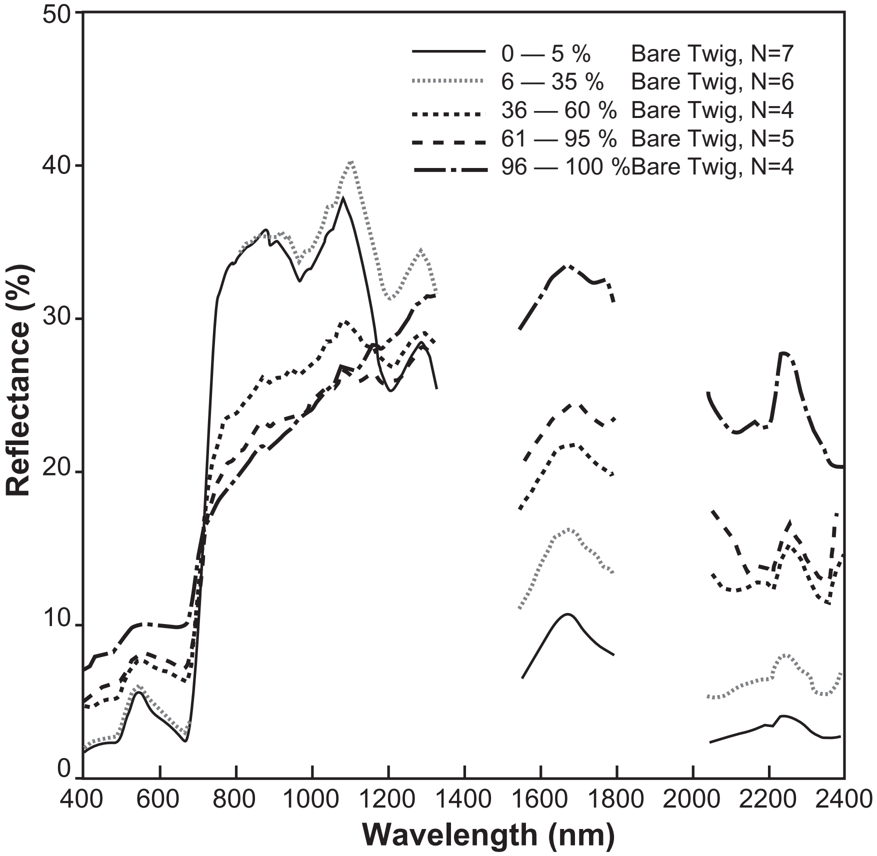


Figure 10. Average spectral reflectance for branches with a range of defoliation (reproduced with permission, Leckie et al. 1988).

Studies of defoliation that specified trees with > 80% defoliation have been successful across a range of scales and sensors. They include very high spatial resolution (< 1 m) detection using aerial photography (Ashley et al. 1976; Hamilton 1981), and airborne multispectral scanners (Leckie et al. 1992). They also include high spatial resolution (1 m – 2 m) detection using aerial photography (Hall et al. 1995). Larger area surveys have been successful at mapping defoliations at moderate spatial resolutions (10 m – 50 m) from: aerial sketch-mapping (MacLean and MacKinnon 1996), high altitude or panoramic aerial photography (Caylor and Pierce 1982; Ciesla 1974) and from satellite multispectral scanners (Vogelmann and Rock 1986, 1988). Low resolution (50 m – 250 m) data contributes to long-term monitoring of forest defoliation as classes of forest damage (Vogelmann 1988).

Successful methods often take into account environmental factors, which influence the species, health, and spectral response (Brockhaus et al. 1993; Ekstrand 1994; Radeloff et al. 1999). Another method employs spectral mixture analysis to improve the effective resolution of the sensor (Radeloff et al. 1999). Pre-classification change detection based on multi-temporal images offers a suite of techniques to detect differences in forest canopy condition (Lambin and Strahler 1994; Collins and Woodcock 1996). For example, classification of a merged dataset was compared with principal components analysis and image differencing as techniques for mapping gypsy moth defoliation (Muchoney and Haack 1994). Tasselled Cap indices computed from a multi-temporal dataset produced good results for evaluating conifer mortality (Macomber and Woodcock 1994) and spruce budworm defoliation (Franklin et al. 1995). Vegetation indices have also improved defoliation mapping from single-date imagery. The vegetation index may be developed using a standard approach such as NDVI or Tasselled Cap (Franklin and Raske 1994) or developed specifically for the study (Brockhaus et al. 1992).

6.3.2 Specific studies mapping grey-attack

Study: Klein 1973 (red-attack results presented in section 6.2.2)

- **Purpose:** “to determine the feasibility of detecting mountain pine beetle-killed lodgepole pine with 35-mm colour aerial photographs at a 1:5,000 scale.”
- **Resolution of Sensor:** 1:5,000 air photo
- **Extent:** Not reported
- **Methods:**
  - Classification: Visual interpretation of red-attack trees and grey-attack trees
  - Verification method: Ground-counts of trees > 7.0 inches diameter
- **Results:**
  - Presented statistics: Linear regression between density of killed trees by ground count or by photo count. R-squared values ranged from 0.61 to 0.90
- **Building Blocks:** Results were very similar to red-attack results. Therefore, variability in relationship likely due more to the detection process than ability to detect a given stage.

Study: Harris et al. 1982 (red-attack results presented in section 6.2.2)

- **Purpose:** “… to develop a low-cost method for estimating numbers and volumes of killed trees where (1) aerial sketch-mapping supplemented by oblique photography with hand-held cameras cannot supply the required information; (2) damage is too heavy for easy mapping; or (3) estimates of sampling error are desired. A multistage sampling system using aerial sketch-mapping, vertical colour aerial photography, and ground sampling was tested.”
- **Resolution of Sensor:** Aerial sketch maps and aerial photography, 1:5,000
- **Extent:** 14,750 ha
- **Methods:**
  - Pre-processing: Aerial sketch maps identified areas for air photo mapping
    - Air photo extents identified sub-plots for ground surveys
  - Classification: Visual interpretation of red trees and grey trees
  - Verification method: Count and diameter class of all lodgepole pine in sub-plots in classes: healthy, green-attack, red-attack, grey-attack
    - Counts used to correct the number estimated from air photos
  - Multi-stage design
- **Results:**
  - Presented statistics
    - Grey ground: 168; air photo: 115

    - ⦿ The average subplot ground count to air photo count ratio was 1.09 for red and grey.
    - ⦿ Volume killed based on ground corrected counts and diameter statistics
- **Building Blocks:** It may be possible to map cumulative mortality at a higher accuracy than a single attack-stage, however, fewer classes tend to lead to higher accuracies (see Section 5.3 for details).

Study: Gimbarzevsky et al. 1992 (red-attack results presented in section 6.2.2)

- **Purpose:** "… to investigate the operational use of available remote sensing techniques for identification of beetle-killed forest stands … direct comparisons of visual observations (from ground-checks and sketch-mapping from low-flying aircraft), a variety of film types and scales of aerial photography, and MSS imagery, all from the same study area."
- **Resolution of Sensor:** Aerial photography, normal colour, CIR and MSS airborne
  - o Aerial photography produced at 1:56,000, 1:19,000 and 1:8,000 scales
  - o Supplementary aerial photography, 1:6,000 and 1:1,000
- **Extent:** 370 km^2
- **Methods:**
  - o Pre-processing: MSS images identified areas for 1:1,000 air photo mapping
    - ⦿ All data used to identify damage detection criteria
  - o Classification: Visual interpretation of species and green, red or grey crown colour
    - ⦿ Moderate stands with dead lodgepole pine averaging less than 40% of the total conifer stems and Severe stands with more that 40%
  - o Verification method: 13 x 0.25 ha sub-plots were ground-surveyed
- **Results:** 1:19,000: percent damage in a stand can be estimated
  - o 1:8,000: individual trees can be detected and counted
  - o 1:1,000: individual branches can be detected, background objects can be distinguished
  - o Presented statistics: 1:1,000 scale stereo-pairs resulted in detection and counting of almost all trees
    - ⦿ Counts from 1:6,000 scale stereo-pairs were multiplied by 3.23 for grey trees based on ground counts
  - o New statistics: For the grey-attack trees, the range of 1:8,000 air photo to 1:6,000 count ratios was from 0.18 to 2.06
- **Building Blocks:** Higher multiplier for grey-attack than for red-attack indicates different ability to detect different attack stages. Much larger range in number of grey-attack trees at different scales than for red-attack indicated that grey-attack trees may be more difficult to detect.

6.3.3 Research trends, gaps, and recommendations

Grey-attack mapping has not been a focus area for mountain pine beetle mapping in the past. However, it can be important for assessing cumulative mortality, success of mitigation efforts, calculating beetle spread, and for planning salvage operations. Techniques applicable to these operations could be developed by further research, especially in digital remote sensing. 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). Fortunately, defoliation is easier to separate from healthy trees at higher degree of defoliation, or percent mortality within a stand (Vogelmann and Rock 1986; Leckie 1987; Wastenson et al. 1987). Therefore, assessment surveys of cumulative defoliation could be operationally viable. Furthermore, the advantages of a multistage approach, as found in air photo applications, would also apply to grey-attack mapping.

From a practical standpoint, the relative accuracy and demonstrated techniques for red-attack mapping, may point to a lagged mapping of grey-attack. Following upon assumptions of fade rates, red-attack mapping from the previous year can be assumed to be grey-attack in the subsequent year(s) (recall Figure 3). Depending on the operational need for the grey-attack data such a lagged mapping approach may be viable.

7 Conclusion

Infestation of lodgepole pine, ponderosa pine and white bark pine by mountain pine beetles results in foliar changes that are both non-visual and visual. The detection of those changes depends on the degree of change, on the timing of a survey, and on the potential utility and limits of the sensors and techniques used. Appropriate data selection to meet the defined information needs, and subsequent assessment of the accuracy of mapping results, will aid in ensuring successful use of remotely sensed data. Operational applications also depend, in part, on the costs of implementing a new survey system.

The subtlety of the spectral change in the green-attack stage renders detection problematic. Based upon an understanding of the nature of remotely sensed data, the complexity of forest structure, and results from existing studies, the operational application of remote sensing to detect green-attack is not currently possible. Basic field and lab studies to characterize the range of spectral response of healthy trees and green-attacked trees may be useful research activities in the short term. These calibration studies should be undertaken after consultation with precedents in the available literature, as basic response is related to leaf stress and diminished vigour. Further image classification research should focus on sensors with high spatial and spectral resolution, which have the greatest sensitivity to, and therefore likelihood of, detecting green-attack. Any application of spectral-response findings to bark beetle management should be constrained by operational realities, such as the presence of a mixed pixel as opposed to a distinct and unique spectral response. Feasibility of any green-attack detection technique should be gauged in consideration of operational requirements. Finding green-attacked trees in areas where there are no red-attack stage trees would be useful. Finding green-attack trees in areas where there are already red-attack stage trees present is of limited operational use, as the understood spread characteristics of the mountain pine beetle would have provided similar information from the red-attacked trees. Having to map large areas with an airborne system would act to negate any costs savings that may have been envisioned through supplanting field visits with over-flights using a digital remote sensing system. Field based techniques exist to locate green-attacked trees using red-attack trees as a starting point; supplanting of this operational activity is not currently possible with remotely sensed data.

Red-attack mapping has been demonstrated with a range of sensors and techniques. There is a long history of air photo interpretation for both location surveys and assessment surveys at local and landscape scales. There is a shorter history for digital technologies. Fortunately, the state-of-the-art provides operationally applicable techniques for landscape scales. Successful applications of satellite imagery for location surveys include single date (Franklin et al. 2003), and multi-date (Skakun et al. 2003) techniques. Techniques are also available for assessment surveys through data integration (Wulder et al. 2005). Additional research is still required to establish techniques using high spatial and spectral resolution imagery for local red-attack surveys. Results to date indicate these datasets may enable detail or accuracy in the mapping of mountain pine beetle locations and impact. In addition, integrating those results into models of mountain pine beetle biology could improve our ability to plan for and mitigate future impacts.

Aerial overview surveys are still the most cost-effective way to collect infestation information over large areas. However, this approach also has limitations. For example, in British Columbia there is a minimum 70% accuracy standard (B.C. Ministry of Forests 2000). The positional and attribute accuracy of overview sketch mapping limit it to location surveys. Simple use of moderate resolution image data for context when undertaking an aerial overview survey may provide a cost effective approach to improve the spatial accuracy and attack magnitude estimates. It may also provide an introduction to remotely sensed data for those new to the technology.

Integration of data at various scales can offer significant cost savings through double-sampling, multistage sampling, polygon decomposition, or use of an information hierarchy. Double sampling offers adjustment of remotely sensed estimates from fieldwork. Multistage sampling offers efficient collection of higher-cost data in a way that allows results to be scaled up to the landscape. Polygon decomposition allows location surveys with constant pixel sizes to be integrated with a forest inventory and used for assessment surveys (Wulder et al. 2005). An information hierarchy reduces the amount of costly ground data by using high spatial resolution imagery in training the classification algorithms of moderate resolution imagery.

The mapping of the grey-attack stage of mountain pine beetle attack is not common in the literature. The mapping of grey-attack with remotely sensed data could benefit from the substantial research on the impact of other defoliating insects. Additional research to determine the potential and limits to grey-attack stage mapping with medium- and high-spatial resolution data may be useful. Prior to expending resources on grey-attack stage mapping, the information need must be clarified. For example, shelf-life studies or updating inventories may benefit from assessment surveys of grey-attack trees. The mapping of red-attack in a previous year would provide insights to levels of grey-attack that could be expected.

Future research and development is recommended in terms of standardizing accuracy assessments, testing the new capabilities of digital sensors, and revisiting the structure of the data hierarchy. For example, small scale (e.g., ASTER) characterizations may be used to determine where large scale data is collected (e.g., Quickbird). Long term goals of a remote sensing program in support of red-attack assessment surveys would be to develop low-cost techniques for integrating stand and landscape scale information. For example, multistage sampling methods are currently being developed and tested as part of the national forest inventory system in the United States (Czaplewski 1999; Hansen 2001; Hoppus et al. 2001).

At landscape scales, there is an opportunity to use satellite-based remote sensing to provide information with characteristics complementary to current operational activities of overview sketch mapping and local scale ground surveys. This could provide assessment surveys of mountain pine beetle impact for timber supply reviews and land-use planning. Medium to high-resolution satellite and airborne imagery are recommended for red-attack and, if deemed useful, grey-attack mapping at landscape scales. Medium resolution is recommended under epidemic conditions (Table 10). High spatial resolution imagery is more appropriate for non-epidemic conditions.

At the local scale, aerial photographs remain a valuable source of information for red-attack mapping for licensees. High spatial resolution imagery, either satellite or airborne, is required to map the red-attacked trees accurately (Table 10). Interpretation, either manual or digital, of attacked areas is required, but the low cost of aerial photography may compensate for processing costs. The maps of red-attacked trees are in-turn, used to guide the field surveys for currently-infested trees. Established field techniques are appropriate for *in situ* determination of mountain pine beetle attack.

Between forest inventory updates, the results of red-attack mapping programs can be integrated into forest inventory databases. This integration as new attributes such as area or proportion of a polygon expected to be at red-attack stage, enables synergistic applications with existing forest inventory data and models (Wulder et al. 2005). For instance, other attributes in the forest inventory database may be used to vet the results of the red-attack mapping. Layout, access, and operability are examples of elements that may be combined with the red-attack information to aid managers. The result of the data integration of red-attack mapping with forest inventory is a low cost approach to update or audit forest inventory data between forest inventory measurement cycles.

Table 10. Image data requirements for red-attack detection at three levels of mountain pine beetle populations.

MPB population	Forest damage characteristics	Spatial resolution requirements	Spectral resolution requirements
Endemic Level	Single or small groups of trees	High	High
Incipient Level	Small groups of trees	High or medium	High or moderate
Epidemic Level	Large groups of trees over large areas	Medium	Moderate

It is important for forest managers to link their choice of survey method or data source to their specific information need(s) and their scale of inquiry. Remotely sensed data is inherently tied to a scale of information, with a related expectation of attribute and spatial accuracy (Table 10). Higher order information needs may require acknowledgment of an information hierarchy where multiple sets of survey data are nested. Lower cost, more general, overview survey information is a practical guide to the placement of higher cost, more specific, surveys. Using lower cost information as a guide to selection of locations for more intensive surveys enables cost efficiencies. If data is collected using established multi-stage design, the information can be rolled up to populate larger area information needs. An understanding of the information content of a range of data sources, as presented in this report, results in an ability to carefully select the most appropriate data source to populate the information hierarchy and meet the aims of mountain pine beetle mitigation and management.

Many new survey options are available on both airborne and satellite platforms, including a wide array of sensor types. The applicability of these options must be considered in relation to information needs and business drivers. The new technologies are populating the hierarchy between provincial overview and large-scale photography with a multitude of options. Regardless of what approach is taken, users need to recall the variability in the rates at which the mountain pine attack stages manifest in the crown foliage. Matching remotely sensed and field measured data must be done with due consideration of timing. Continued research, focused on meeting operational needs and utilizing existing and emerging data sources, will allow for an increase in monitoring and mitigation opportunities and effectiveness.

8 Recommendations

Scheduling of data collection:

The use of remotely sensed data to detect and map green-attack in order to meet operational objectives is not recommended. The timing of detection surveys for red- or grey-attack should coincide with the mountain pine beetle's survey bio-window. A bio-window is the optimum time for visual expression of major forest pests and related damage (B.C. Ministry of Forests 2000). For red-attack, data collection is recommended from mid-July to the end of September of the year following attack. From that September until July of the third year after attack, surveys could be conducted for cumulative mortality. Grey-attack mapping should be scheduled after August of the third year following attack (Wulder et al. 2004).

Provincial scale operations:

For provincial reporting and strategic planning, aerial overview sketch mapping is reliable for location surveys of red-attack (at the provincial scale). Estimates of area infested should be reported with confidence intervals or other estimates of error. A double sampling approach based upon air photo based estimates of red-attack would allow for an increase in precision of area estimates, and would also provide an indication of the uncertainty associated with the estimates of red-attack damage. The positional errors in the overview mapping make it unsuitable for assessment surveys. Potentially, positional accuracy could be improved by providing a Landsat image, or another image source of a comparable resolution, as part of the base map used to manually sketch the red-attack damage. Similarly, a digital sketch mapping system may also help facilitate greater accuracy in the sketch mapping product.

Landscape scale operations:

Both location surveys and assessment surveys may be completed at the landscape scale. Landscape scale operations such as timber supply reviews and land use planning are based, in part, on assessment surveys. Reliable methods for assessment surveys include both air photo and satellite image mapping of red-attack damage. We recommend reporting the true-positive rate, the full error matrix used in the accuracy assessment, and the use of confidence intervals or similar statistical estimates of error when reporting estimates of red-attack damage. To determine estimates of error, we recommend a multi-stage sampling design or a double sampling design as efficient and cost effective methods at landscape scales. Data selection and approach can be based upon conditions specific to the area and the information need under consideration.

Local scale operations:

Licensees rely on local scale reconnaissance surveys (e.g. typically, helicopter-GPS) for planning ground surveys of currently infested (green-attack) trees. At this scale, reliable location surveys of red-attack trees can be done using aerial photography, or high spatial resolution satellite imagery (White et al. 2005). Licensees also require assessment surveys for tactical planning and reporting on the proportion of infested timber that was treated, and we recommend the use of aerial photography (at 1:20,000 or 1:30,000 scale), or high spatial resolution satellite imagery, for this application. A double-sampling design in conjunction with the ground survey would allow for adjustment of the mountain pine beetle impact and reporting with confidence intervals, or similar statistical estimates of error.

Green-attack research:

Given the technical and logistical limitations to successfully detecting green-attack, the use of remotely sensed data to meet operational needs for green-attack detection and mapping is not recommended. Existing field survey techniques, which rely on known red-attack locations to identify sites with potential green-attack damage, continue to be the most effective method for detecting green-attack. Logistically, a remotely-sensed solution for green-attack detection would involve flying over large areas of forest that have potential for infestation (e.g., lodgepole pine dominated stands), but which are not currently known to be under attack by mountain pine beetle. Flying over large areas with a sensor that has both high spatial and high spectral resolutions (e.g., airborne hyperspectral) would be very costly (i.e., flying costs, processing and interpretation costs). Further, to make such an approach operationally viable, the accuracy of the green-attack detection method would either have to be higher than the current field survey method of mapping green-attack, or significantly more cost effective. For such a method to be cost effective, data acquisition (flying time) would have to be low, and much of the image processing would have to be automated. The detection of the green-attack stage of mountain pine beetle attack is not a trivial remote sensing issue. This difficulty should be considered prior to embarking on any green-attack detection research with operational mapping aims. In terms of pure research opportunities, any future studies should strive for detection of green-attack trees in areas where there are disproportionately more green-attack than red-attack (ideally, where there are no red-attacked trees). Otherwise, the known association between green- and red-attack trees would bias the outcome and not result in an operationally viable example. In regions with a full suppression management strategy (where no red-attack trees are currently present), information on green-attack locations would be highly valued. For any research that is attempted, we recommend a rigorous study design and the reporting of the true-positive rate, the full error matrix used in the accuracy assessment, and the estimation of mountain pine beetle locations or impact with confidence intervals or similar statistical estimates of error.

Red-attack research:

Future studies should build upon recent trials using high spatial resolution imagery from earth orbiting satellites and airborne sensors. At a moderate spatial resolution, the new generation of satellites such as ASTER or Hyperion present improved spectral sensitivity and therefore offer new opportunities for detecting and mapping red-attack damage. Long term goals should be to develop low-cost techniques for integrating stand and landscape scale information, building on lessons learned from past research using multi-stage sampling designs. We recommend all studies report the true-positive rate, the full error matrix used in the accuracy assessment, and the estimation of mountain pine beetle locations or impact with confidence intervals or similar statistical estimates of error. Remotely sensed data cannot supplant existing survey methods for red-attack detection. Rather, the efficient and accurate mapping of red-attack damage with remotely sensed data, at a range of scales and for a variety of information requirements, should be seen as a way to augment or complement the existing hierarchy of survey methods.

Grey-attack research:

Research is required to establish methods for conducting assessment surveys to determine the level of cumulative mortality within a stand or landscape. Depending on issues such as extent over which the information is desired and level of accuracy required, photos, satellite imagery, or a multistage design may be appropriate. We recommend all studies report the true-positive rate, the full error matrix used in the accuracy assessment, and the estimation of mountain pine beetle locations or impact with confidence intervals or similar statistical estimates of error. These studies could be operationally viable for inventory updates and to aid in developing harvest plans with reference to the shelf life of attacked trees. Mapping grey-attack from previous years red-attack could be investigated for operational utility, such as for area attacked and area expected to be standing dead, or for the cumulative effects of a longer-term series of attack at a given location.

Matching data sources to information needs:

The key to the successful application of remotely sensed data for mountain pine beetle survey and detection is to match the sensor to the information requirements for managing mountain pine beetle. The data sources available from field collection, airborne surveys, and remote sensing can form a multistage design, where small scale characterizations (large area, lower cost) may be used to determine where large scale data (smaller area, higher cost) are collected. Furthermore, statistically sound sampling programs of small areas can be scaled-up for mapping of larger areas.

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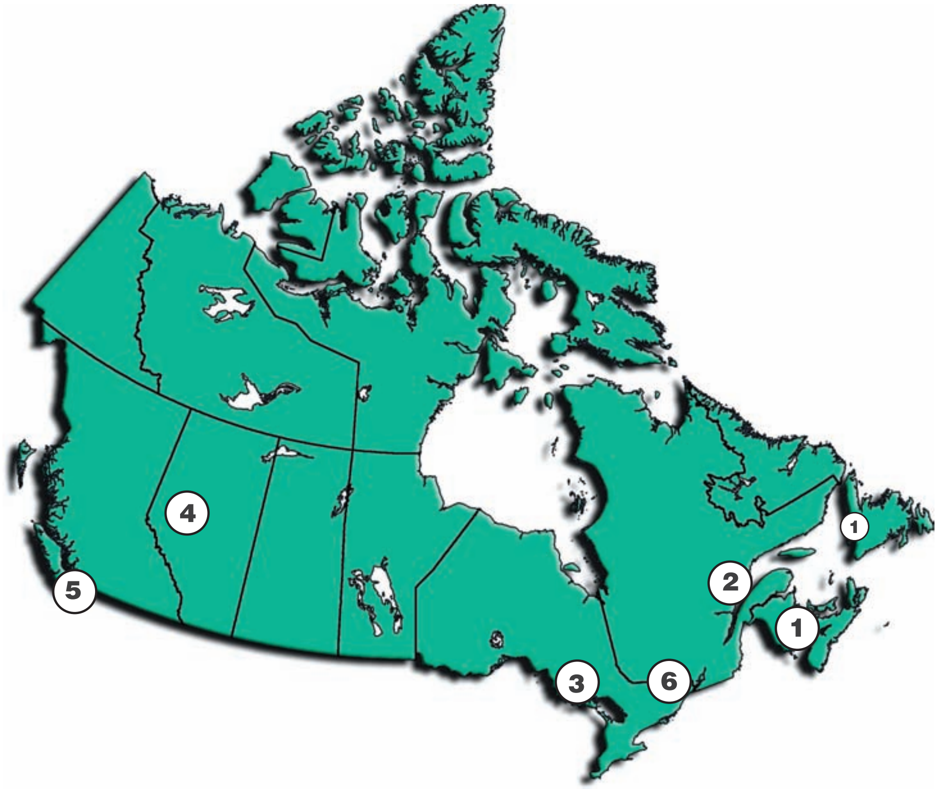

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