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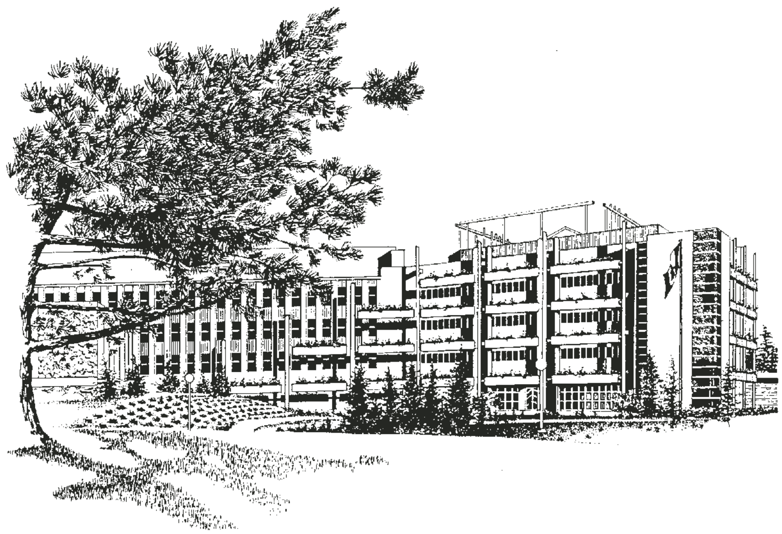

The Pacific Forestry Centre, Victoria, British Columbia

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Cover image: *Example of trees in the red attack stage of mountain pine beetle infestation.*

Abstract

Forest management decisions regarding the mountain pine beetle (*Dendroctonus ponderosae* Hopk.) are generally driven by the location, size, and impact of the beetle population. Information on infestations is collected using a variety of survey techniques, with the methodology and scale (level of detail) of the survey being defined by the management objectives. Questions regarding tree or stand level characterization of beetle impacts require different support data than are required at the landscape level. In this report, we present a summary of the different survey approaches for characterizing mountain pine beetle infestations (with emphasis on red attack stage), across a range of scales. The concept of an information hierarchy is also presented, whereby multiple sets of survey data may be nested for any given area of interest. For example, a lower cost overview survey may be used to guide the selection of locations requiring more intensive (and more expensive) surveys. The objective of this report is to review the tools and approaches available to forest managers for the detection, mapping, and monitoring of mountain pine beetle. The information content and limitations associated with each survey method are provided, in order to facilitate informed choices of survey methods and data sources. Survey recommendations, based upon the information hierarchy, are also included.

Résumé

Dans le domaine de la gestion forestière, les décisions concernant le Dendroctone du pin (*Dendroctonus ponderosae* Hopk.) sont généralement motivées par l'emplacement, la taille et l'impact de la population des scolytes. Les informations concernant l'infestation sont recueillies à l'aide de différentes techniques de relevé, la méthodologie et l'échelle (niveau de détail) des relevés étant décidés en fonction des objectifs de gestion. Les questions concernant la caractérisation des impacts des scolytes au niveau des arbres ou des boisés nécessitent des données de base différentes de celles concernant le paysage. Dans le présent rapport, nous présentons un résumé des différentes approches de relevé utilisées pour la caractérisation des infestations par les dendroctones du pin (en mettant l'accent sur la phase dite « rouge » de l'attaque) sur différentes échelles. Le concept de hiérarchie de l'information est également présenté, celui-ci consistant à insérer plusieurs groupes de données les uns dans les autres pour n'importe quel secteur intéressant. Par exemple, un relevé d'ensemble à coût modique peut être utilisé pour guider la sélection des emplacements nécessitant des relevés plus intensifs (et plus chers). L'objectif de ce rapport et d'examiner les outils et les approches dont disposent les gestionnaires forestiers pour la détection, la cartographie et la surveillance des dendroctones du pin. Les informations fournies par chaque méthode de relevé ainsi que les limitations qui leur sont associées sont exposées afin de faciliter le choix des méthodes de relevé et des sources de données. Des recommandations concernant les relevés, basées sur la hiérarchie d'information, sont également incluses.

Introduction

Forest management decisions regarding the mountain pine beetle (*Dendroctonus ponderosae* Hopk.) are generally driven by the location, size, and impact of the beetle population. For example, small groups of infested timber may be deemed to have sufficiently small impact that no action is taken. However, if monitoring indicates that the population is increasing, action may be taken to prevent or reduce future losses. Without control action, infestations within susceptible forests can expand until large numbers of trees are killed (Safranyik et al. 1974). Generally, the most severe infestations occur in mature stands of lodgepole pine (*Pinus contorta*), but other pines, such as ponderosa (*Pinus ponderosa*), and white (*Pinus monticola*) are also attacked.

In general, mountain pine beetles in British Columbia reproduce at a rate of one generation per year (Safranyik et al. 1974). Adults 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).

Information regarding the location, size, and impact of mountain pine beetle populations is collected using a variety of survey techniques. The survey approach is based upon the desired information required for a particular aspect of forest management. The survey may be done on a tree-by-tree basis on the ground, from an airborne platform, or using satellite sensors. As a result, the extent of the survey may range from a few hectares to millions of hectares. Each method has limitations, with the resulting data collected being applicable for differing management situations. The terms green, red, and grey attack stages indicate the visual appearance of the foliage on a tree infested by mountain pine beetle (Safranyik et al. 1974).

The methodology and scale of a survey is defined by the management question to be addressed. Questions regarding tree or stand level characterization of beetle impacts require different support data than required at the landscape level. Mountain pine beetle infestations are detected through systematic surveys conducted at regular time intervals. Detection is defined as identifying and documenting locations of previously affected trees and probable locations of currently attacked trees. Detection may be used to position field crews for infestation assessments or to facilitate a mitigation option (Safranyik et al. 1974). Mapping is defined as spatially explicit estimates of the number of trees affected, or of volume affected for a management unit (e.g., at the stand level; forest inventory polygon). Surveys must locate the infestations as quickly as possible in order to reduce the number of beetles (Safranyik et al. 1974). Under all population conditions, monitoring enables forest managers to anticipate the possible risks associated with the infestation. Monitoring is defined as repeatable, comparable estimation of beetle populations and impacts over time, in order to detect trends in population dynamics and spatial pattern.

Federal, provincial, and state governments are primarily interested in broad-scale detection of red attacked trees across their entire political jurisdiction. Aerial overview survey operations are used to satisfy this information need (Wiart 2003). This information is used to monitor and report on overall forest health (e.g., USDA Forest Service 2003). Government agencies concerned with forestry or environmental protection also use the red attack detection information for strategic planning (e.g., B.C. Ministry of Forests 2001). This planning includes identifying areas for more intensive information gathering, mitigation resources, timber sales, and targeted protection. The location of red attack trees provides clues to the location of green attack trees, facilitating mitigation activities.

Forestry companies and government agencies work together during timber supply reviews and in planning land and resource management. Sub-provincial or county level monitoring, typically from aerial sketch mapping, is used to alter volumes and areas that are in turn used to adjust the annual allowable cut and refine timber supply forecasts (B.C. Ministry of Forests 2003). The maps of forest damage may also be used to adjust land use plans and to provide information of ecological interest.

Forest licensees and private landholders require detection of red attacked trees at a larger scale, with more detailed information regarding attack locations and intensities across their land base (Wiart 2003). These general locations are then used to further target more detailed detection and mapping efforts. Results from local area mapping of red attack are used to guide surveys for associated green attack trees, and to aid in the design of logging and sanitation plans.

Each of these aforementioned information needs requires a different survey technique to provide the appropriate level of detail. Survey techniques also vary by the timing of the survey relative to the expression of the attack in the foliage of the tree crown. In general, green attack is not operationally detectable without having either actual physical contact with the trees in question or close range examination. Red attack is operationally detectable over the range of survey techniques (field, airborne, and satellite). While currently less reliable than red attack survey, grey attack may also be detected with a range of survey techniques. The red attack stage is the focus of the detection methods presented in this report.

Historically, mortality of lodgepole pine has been recorded anecdotally in the accounts of early explorers of British Columbia, through to the systematic surveys that occur today. The native range of mountain pine beetle includes southern and central British Columbia where pine species grow (Amman, 1978). Populations of mountain pine beetle are also historically present in southwestern Alberta. Insect-induced mortality of mature pine in British Columbia is largely a result of attack by mountain pine beetle. For example, surveys conducted by the Canadian Forest Service, Forest Insect and Disease Survey (FIDS), estimated annual losses averaging 7.8 million mature pine trees over 34 years (ending in 1995), peaking in 1983 at 80.4 million (Wood and Unger 1996). The extent of the current infestation in British Columbia is increasing annually, with areas reported at near 2 million ha in 2002 (Westfall 2003) and estimated at over 4 million ha in 2003 (B.C. Ministry of Forests 2003). In Figure 1 the annual impact of mountain pine beetle is contrasted with comparable areas disturbed by forest fire.

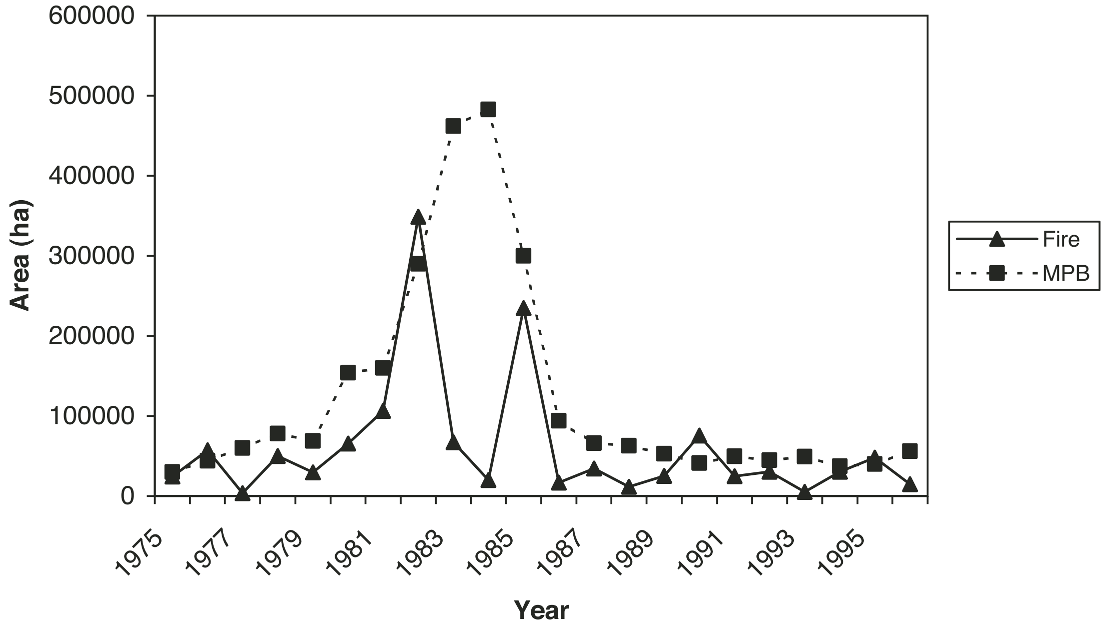


Figure 1. *British Columbia statistics on annual area burned by forest fires or killed by mountain pine beetle (Canadian Council of Forest Ministers 2003).*

The impact of mountain pine beetle is evident throughout its range, being the second highest contributor to tree mortality within the national forests of Colorado, South Dakota and Wyoming. Over 300 000 trees were killed during 1997, 1998, and 1999 within the Rocky Mountain region of the United States (Harris et al. 2001). The number of trees killed has increased every year from 1996 to 2001, with over 800 000 trees killed over a 142 410 ha (converted from a reported 300 000 acres) area (Johnson 2002).

Insect disturbances are systematically monitored on an annual basis to assess extent and impact upon forest resources. As a component of insect monitoring surveys, mountain pine beetle impacts are observed and recorded. Detection and mapping of mountain pine beetle, as a component of insect monitoring surveys, provide a record of tree mortality and therefore, the impact of the pest. These recordings are carried out using a range of techniques, each with its own advantages and disadvantages. Ground-based surveys are the most reliable source of information regarding the agent responsible for forest damage. Field surveys are undertaken judiciously due to high costs on a per hectare basis. Aerial surveys have the advantage of lower costs per hectare, and fairly reliable recognition of the damage agent. However, the points and polygons noted by the aerial surveyors tend to have issues related to positional accuracy and attack magnitude. Both the ground and aerial surveys produce data that must be digitized for further analysis or for integration with forest inventory data or decision support systems. Alternatively, digital remote sensing produces data that can be quickly integrated with forest inventory databases or models. Some digital remote sensing instruments can also offer high positional accuracy (Dial et al. 2003; Tao et al. 2004). However, depending on the sensor and type of processing used, the costs per hectare can be low or high. The choice of detection method must therefore be considered in the context of the value of the information to the forest manager.

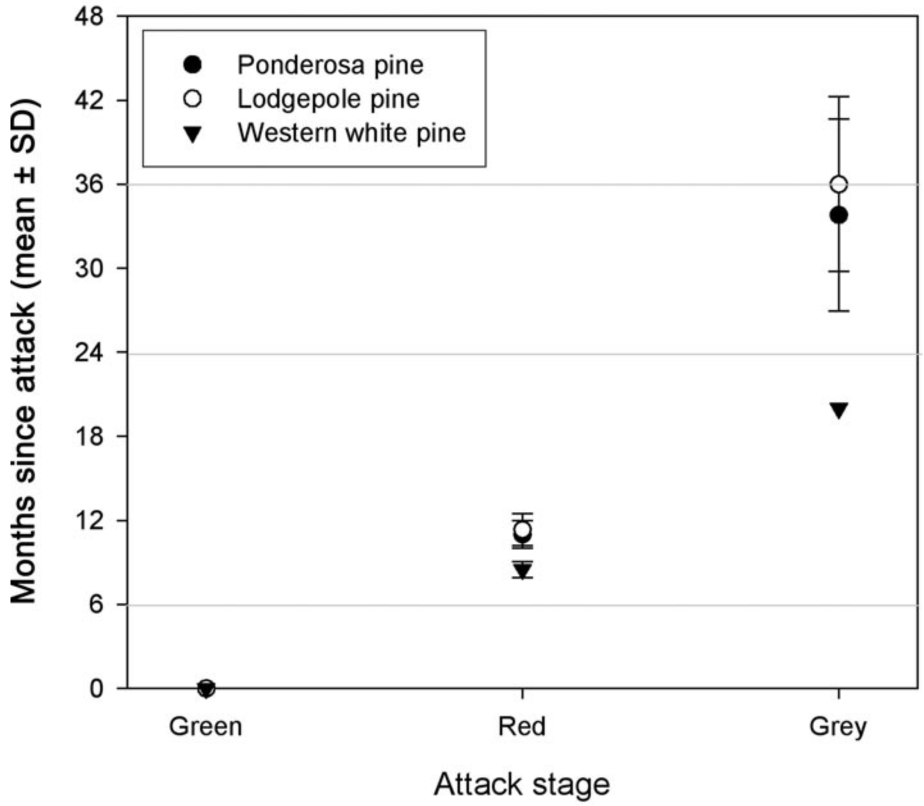


Figure 2. *Foliage changes following mass-attack at 12 sites in the Kamloops Forest District, between 1962 and 1967. The foliage conditions of 134 individuals from three species were monitored. Illustrated is the number of months for a sample of mass-attacked trees to reach 100% of a given attack stage; variability is demonstrated between stands (1 standard deviation error bars) and between species.*

When considering the differing approaches to detection, whether analogue or digital, it must be recalled that the fading of foliage in response to mountain pine beetle attack is not uniform among all individual attacked trees. In Figure 2 we present the rate at which sampled trees faded in response to attack by mountain pine beetle. During the base year, all trees were at green attack stage. Inspecting the same trees during the summer following the initial attack, some still appeared to be in the green attack stage, while other individuals had faded to red attack. Similarly, red attack and grey attack co-occurred during the second and third summers following attack. The general trend in fade rates is captured in Figure 3, where the fading of 15 lodgepole pine trees is indicated with the overlap between the expressions of attack stages in the crown foliage. Trends to note include no trees appearing as green stage after 12 months, all trees reaching red stage by 12 months, and grey stage initially evident after 13 months. The overlap of the red and grey stages subsequent to a 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 by attack stage). 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. The implication to any non-field based survey technique, even if it is highly accurate, is that it may not detect all attacked trees as the attack may not yet be evident in the foliage.

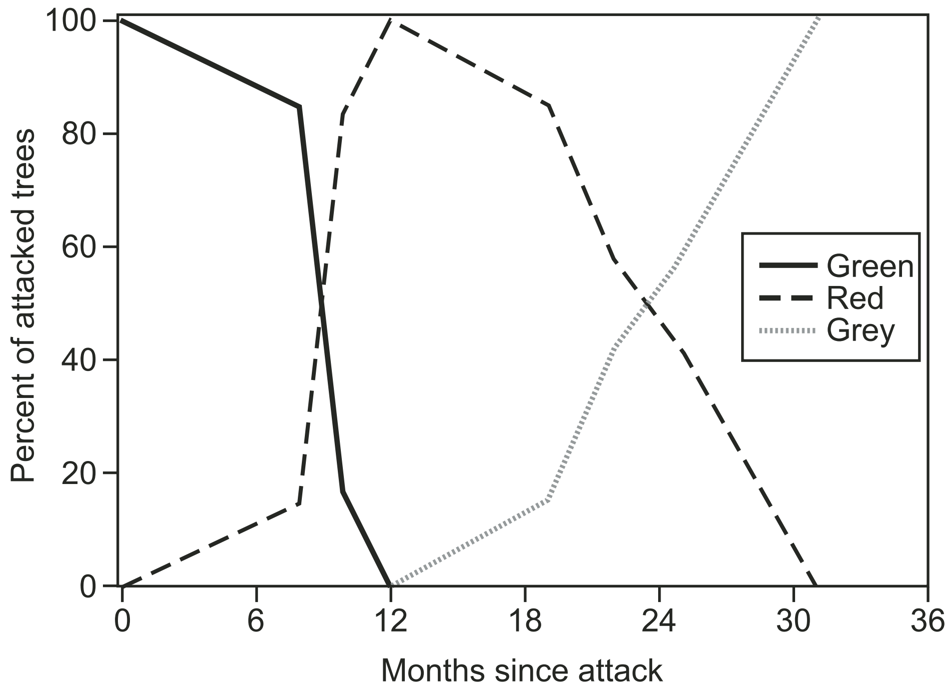


Figure 3. *Variability in foliage fade rate within a sample lodgepole pine stand (Fountain Valley Site 2, Kamloops Forest District, between 1962 and 1967) post mass-attack. This example stand was composed of 15 attacked trees.*

In this report, we present a summary of the different survey approaches for characterizing mountain pine beetle across a range of scales. The scale, or detail of the survey, is linked to the type of forest management that the data are intended to support. (after Shore 1985; B.C. Ministry of Forests 1995 and 2000):

1. Aerial survey – captures infestation extent and intensity;
2. Ground survey – on a sample basis to confirm insect species, evaluate timber killed or currently under attack (green attack), and to collect mensurational data;
3. Infestation trend assessment – to determine infestation trend and to support damaged forests (through brood assessment or counting the number of infested trees).

The objective of this report is to review the tools and approaches available to forest managers for the detection, mapping, and monitoring of mountain pine beetle. Survey recommendations, based upon the above survey hierarchy, are also included.

Aerial Survey

Aerial surveys allow for the detection of red trees by observers in fixed wing or rotary aircraft. Consideration of the viewing conditions and the pests must be included when planning an aerial survey. Of primary importance when undertaking an aerial survey are good visibility and a minimum cloud ceiling of about 1000 m. Clear and sunny days are preferred, but consistent high overcast sky, providing even illumination, is also acceptable. Broken cloud conditions or low sun angles are not recommended, as clusters of infested trees can be missed in the resulting shadows. The timing of the surveys generally coincide with the insects' specific survey bio-window. The bio-window is the optimum time for visual expression of major forest pests and related damage (B.C. Ministry of Forests 2000).

The topographic maps used during aerial surveys can be enhanced by aerial photographs, especially in areas of extensive pest damage on even terrain with few geographical features. Up-to-date aerial photos can be useful in showing logging, burns, and other details that observers can delineate from infested timber. If available, custom drawn GIS maps that highlight cut blocks, roads, water bodies and other landmarks, greatly improve the observer's ability to orient themselves quickly and thus enhance the accuracy of pest polygon placement.

The notes made by the observers during an aerial survey vary depending on the agency; however all surveys will note the location and identification of the pest and estimate the intensity of attack. The maps from multiple observers are combined and the infestations are digitized. Correct identification of tree species, insect pest and attack category are difficult from the air, and this survey method is only effective when combined with current information gathered in the area from ground surveys previous to and following the sketch mapping. Observer knowledge of the local forest and pests is also important for the mapping to be accurate.

The aerial survey maps must be supplemented with ground survey assessments to estimate the extent of the beetle population and the impact. The exact number of affected trees or area cannot be efficiently assessed using aerial surveys (Harris and Dawson 1979). This limitation results in survey maps where the estimate of intensity is noted as a class, rather than an exact value. Furthermore, location errors due to off-nadir viewing may make some surveys unreliable for dispatching ground crews (Aldrich et al. 1958). For a given area, assessment of aerial survey accuracy and presence of bias are best determined using a multistage sampling procedure, where aerial sketch mapping, global positioning system (GPS) point data, aerial photography, and ground plot data are all collected and compared, enabling cross-validation.

Sketch mapping

The most general approach to detection is to sketch map the red trees that are visible from a fixed wing aircraft. Notations are made on topographic maps at scales from 1:100 000 to 1:250 000 over millions of hectares, although provincial agencies in British Columbia occasionally use 1:50 000 scale base maps. (While potentially providing greater spatial precision, too large a map scale results in logistical problems in the aircraft, as too many maps are required to characterize the large areas typically mapped.) Sketch maps provide quick, quality information for strategic planning during epidemics (Heller et al. 1955; Aldrich et al. 1958; Waters et al. 1958). Consistency between observers can be verified with a small number of check flights that repeat the sampling of an area. If the mapping has been consistent, cumulative mortality in specific stands can be estimated by overlaying successive years of damage (with interpretation including consideration of the photo acquisition dates and variability in fade rates). Care must be taken to ensure that the above-mentioned scales are considered when undertaking additional analyses, especially if the analyses are spatial in nature. The sketch map data is collected to represent large areas, often at the regional or provincial level. As a result, the disturbance characteristics over the large area are well characterized, but issues related to the accuracy of the polygon boundaries may emerge when attempting to integrate with spatial datasets representing smaller areas.

Sketch mapping of disturbances has a long history in North America. Archival data exists over much of British Columbia and the Pacific Northwest[1] to aid in the understanding of disturbance activity over time. Much of the former Forest and Insect Disease Survey (FIDS) pest data collected for B.C. and the Yukon are available. For instance, there are over 2100 different maps depicting mountain pine beetle infestations from 1959-1995. There are other sketch maps of infestations, scanned in from archival reports dating back

1 For archival information on mountain pine beetle in British Columbia, see www.pfc.cfs.nrcan.gc.ca/entomology/mpb/historical/index_e.html

to 1928, that have been added to the historical collection on mountain pine beetle. Due to the nature of the data collection and digital conversion, the positional accuracy is variable and must be considered by users. An additional issue to consider regarding the archival data is the spatial extent of the survey. For instance, absence of infestation noted at a particular location or time may be due to the lack of a spatially exhaustive survey. Flight line information to accompany the sketch map survey results would ameliorate this issue.

A cost effective approach to improve the spatial accuracy and attack magnitude estimates of sketch mapped polygons is the use of Landsat imagery as an underlay for the sketch mapping. The sketch base map could contain the same information currently portrayed on the 1:100 000 scale map sheets (e.g., roads, urban areas, lakes, etc.), with the added benefit of a continuous view of the landscape from the image data, as a backdrop. Polygon placement will 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 (depending on the date of image acquisition).

Global positioning systems

Once sketch maps have been obtained, infested landscapes undergo more detailed aerial surveys conducted from a helicopter. Red trees are visually detected, their locations are recorded with a GPS, and noted on topographic maps of 1:20 000 to 1:50 000 scale. The helicopter pilot hovers above the centre of a group of attacked trees, and another person will capture the GPS waypoint for the site. An estimate of the number of infested trees at that location and the type of insect is also noted. The purpose of the GPS survey is to accurately locate the beetle impacts to aid in rendering local or regional strategic decisions.

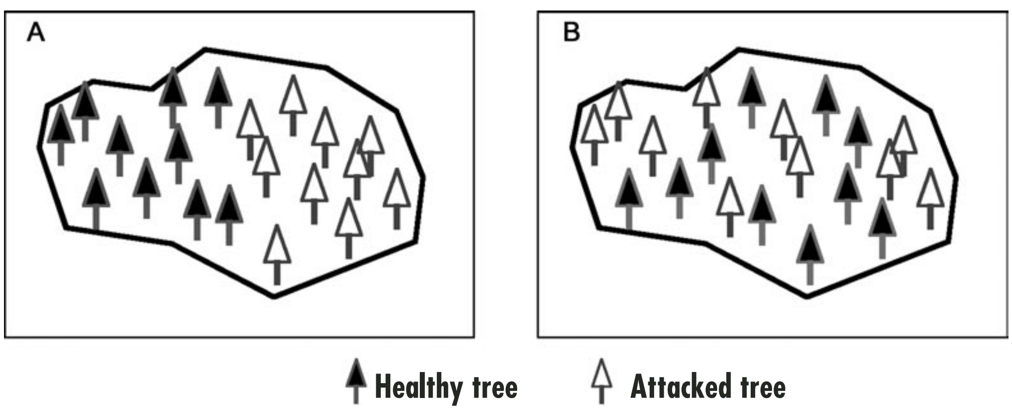
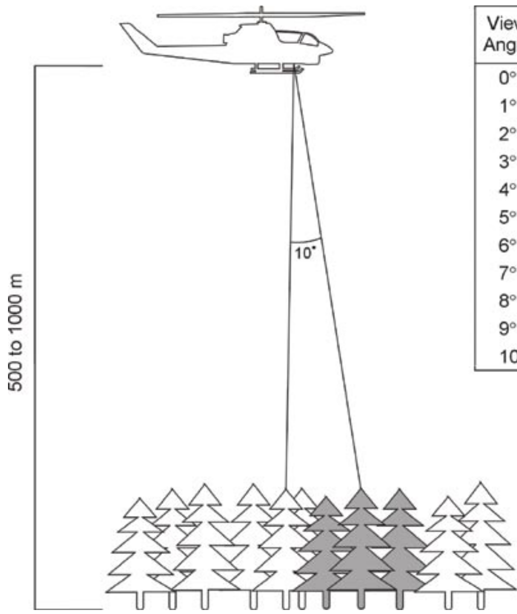


Figure 4. *Illustration of (a) concentrated attack, and (b) dispersed attack (after B.C. Ministry of Forests 2003).*

The likelihood of observers logging a non-existent red attack location (an error of commission) is extremely low. However, not detecting red attack areas on the landscape (errors of omission) depends on the survey effort covering an area. As mentioned above, knowledge of the population size is also required support information for helicopter GPS surveys. The density of the affected trees at a given point is also an issue. For a given survey point the trees identified may be dispersed or clustered, yet this is not captured in the survey (Figure 4; B.C. Ministry of Forests 2003). The use of GPS carries the errors associated with that technology (Kaplan 1996) and additional positional errors that are a function of the viewing platform. Slight angles between the viewing location and the perceived centre of the infestation can lead to errors in the position of the centroid of the infestation (Figure 5).



View Angle	Horizontal Distance From Nadir (m)	
	500 m flying height	1000 m flying height
0°	0.0	0.0
1°	8.7	17.5
2°	17.5	34.9
3°	26.2	52.4
4°	35.0	69.9
5°	43.7	87.5
6°	52.6	105.1
7°	61.4	122.8
8°	70.3	140.5
9°	79.2	158.4
10°	88.2	176.3

Figure 5. *Illustration of how flying height and view angle can affect positional accuracy of the aerial surveyed GPS points.*

Air photo interpretation

Aerial photography is the most common imagery used in a forest inventory to characterize forests and meet management objectives. Surveys that utilize aerial photography can be grouped into classes based upon the type of information collected (after Wear et al. 1966):

- Damage detection;
- Damage location;
- Damage Amount; and
- Estimation of the relative size of the insect population and the capacity for future damage.

Aerial photography is not as well suited to initial damage detection as visual aerial survey methods (such as sketch mapping); information regarding insect populations and potential for causing future damage is best collected through field survey. However, aerial photography can address the information need for generating mortality estimates and precise locating of infested areas. Either normal colour or colour-infrared photos can be visually interpreted for signs of mountain pine beetle red attack (Murtha 1972). The photos are collected at scales ranging from 1:1 000 to 1:65 000. At 1:8 000 individual trees can be identified; whereas, at 1:19 000 only the proportion of forest damage can be estimated (Gimbarzevsky et al. 1992). However, the extent of the area captured in the photograph is much smaller at a scale of 1:8 000. Furthermore, the results may be affected by the experience of the interpreters (Klein 1973). Additionally, ground surveys can define confidence limits around mortality estimates (Aldrich and Drooz 1967; Harris et al. 1982). For instance, Sharpnack and Wong (1982) present an approach where photos are used to calibrate damage estimates made from attack areas depicted on sketch maps. Photos may also be used in a more independent fashion to sample an area to estimate mortality rates (Hamilton 1981).

As mentioned, air photos may be used to generate estimates of damage (or mortality) and to locate the infested trees for salvage or to aid in mitigation activities. Air photos may be combined with samples of field data to reduce field costs while still generating robust estimates of infestation location and magnitude (Sharpnack and Wong 1982). A procedure for combining the two data-types is double sampling with regression (Wear et al. 1966). The method is based upon the premise that field measurements of damage or mortality are related to what can be interpreted from photos. Where field data is sampled and extrapolated with a regression-based approach using photo measurements, cost savings can be realized when appropriate conditions are met. If the photo plots are not substantially cheaper than the collection of field data, such an approach may not be warranted. The general approach, when using double sampling with regression for characterizing damage or mortality, is to sample field conditions within a predefined population area. Procedures for combining the field and photo-based estimates is provided in Wear et al. (1966). To compute the area damaged using this regression-based approach, measurements must be made both on the ground and from photographs. The nature of the field sample (i.e., number and distribution of plots) and the definition of the population area (i.e. size and shape) must also be correctly specified for robust estimates of damage to be generated. Meeting all statistical and operational requirements enables the final calculation of an estimate for the total amount of mountain pine beetle damage. The integration of field and photo data in a sampling and regression framework to make estimates of damage over large areas is analogous to the use of field data to calibrate damage estimates made from remotely sensed data.

Ground Survey

Ground surveys assess the population size, or the degree of forest infestation, within a local area. Sample plots are generally less than 1 ha. Population estimates indicate whether a local beetle population is increasing, static, or decreasing. Infestation estimates indicate the impact of a particular beetle population. Both types of techniques are used to drive the selection of the most appropriate management response.

Population assessments may be based upon field surveys or aerial surveys. Field surveys enable a brood assessment to be undertaken. Brood assessments are carried out in the late summer to fall and in the spring. Beginning in mid-July, population surveys with sketch mapping may be undertaken. These aerial surveys influence the placement of subsequent ground surveys. Aerial survey data collected over consecutive years may also be compared to indicate population trends.

Brood assessment ground surveys may be done in September to October based upon a timber cruising technique. The timber cruising operation records information including tree species, diameter at breast height, pest status (healthy, currently attacked, or partially attacked, pitch outs, and foliage colour) (Shore 1985; B.C. Ministry of Forests 1995). In the spring following attack, assessment surveys account for over- wintering brood mortality and losses to natural enemies [(i.e., parasites and predators, particularly woodpeckers (B.C. Ministry of Forests 1995)]. A fixed size bark area (typically 900 cm^2) is removed and examined to form a statistically valid sample of trees to determine the stand average trend ratio (Equation 1) and the percent over-wintering mortality (Equation 2) (Shore 1985).

The average trend ratio (r) for each stand is determined as follows:

$$r = \frac{\sum_{t} ((y+o)/g)}{t} \tag{1}$$

Where,

y = number eggs and larvae

o = number pupae and adults

g = number of galleries

t = number of sampled trees

Percent of over-wintering mortality may subsequently be computed for each stand as:

$$r = \frac{(r\_fall - r\_spring) \times 100}{r\_fall} \tag{2}$$

The results are used to indicate population trend. For instance, average population trend ratios can be interpreted as follows: if the result of r is less than 2.6, the population is decreasing. If r is from 2.6 to 4.0, the population is static. If r is greater than 4.0, the population is increasing. These values are heuristic in nature and should be used to support interpretation - not to act as sole source of information on the trends of a given population. Population trends may also be inferred from air photographs, with the area, or count, of red attacked trees compared in successive years. This relationship is useful as an indicator of the general population trend; however, this relationship should not supplant brood assessments.

Brood assessments are carried out in the months following the fading of foliage to red, indicative of trees attacked in the previous year (with survey beginning in approximately mid-July). The survey locates the green attacked trees containing the mountain pine beetle brood that will be the source of future infestations. Any survey system similar to prism or strip cruising will typically work. The surveys start near red trees and progress outward in a grid, or other systematic pattern, to locate the currently attacked trees. The crews must be well trained before they begin and their work must also be checked periodically; the extra time needed to properly train and check the crews is vital and cannot be neglected since the proper identification of attack category (Table 1) is critical to the success of the ground survey effort.

Table 1. Glossary of mountain pine beetle attack categories:

Attack category	Definition
Endemic	Mountain pine beetles attack and kill stressed trees, often in concert with secondary bark beetle species.
Incipient	Mountain pine beetle population within a stand is sufficiently large that healthy trees are killed. The killed trees usually occur in patches of various sizes and are generally confined within limited areas (e.g., stands).
Outbreak or Epidemic	Mountain pine beetle population and tree mortality occur at the landscape level.

Infestation assessment techniques range from simple identification of trees under attack to a complete mensuration of the infestation. Walkthroughs are used largely as an initial ground reconnaissance survey for determining the characteristics of attacked stands and to contribute toward determining information needs for more intensive surveys. Probes are systematic strip surveys that collect more detailed information than the walkthrough survey. Probe information is compiled on a polygon basis and includes attributes such as: location on map; size of beetles under bark; relative brood success; percentage of attack category; rate of spread; and stems per hectare (B.C. Ministry of Forests 1995). While useful, these survey techniques do not provide sufficient information for assessment of volume or area infested. Prism cruises, on the other hand, are used for detection and impact assessment, where the volume affected can be estimated on a stand basis. Line transects are also used for detection and impact assessment, and are more efficient than prism cruising (Safranyik and Linton 2002). With these data, affected volume and area can be estimated from the survey, and can potentially be statistically extrapolated to represent larger areas. An additional means to characterize the population trend of a mountain pine beetle infestation is by calculating a green-to-red ratio. A green-to-red ratio is the estimated number of currently attacked trees compared to the number of red attacked trees. This ratio gives a rough indication of the population growth.

Digital remote sensing

One advantage to using satellite images in mapping red attack stage trees is that they portray continuous data across the landscape. In this way, all areas in the image are examined for possible red attack, independent of accessibility or position in a watershed. Another advantage of mapping from satellite imagery is the reduction or elimination of interpreter bias afforded by automated classification algorithms. By avoiding visual interpretation, the products have greater consistency and reliability between different areas or dates. Increased reliability also results from the high positional accuracy of image data compared to aerial survey data. The standard pre-processing of satellite images results in data that can be confidently integrated with forest inventory polygons and other spatial data sets (e.g., elevation data, road access). The results of analysis of remotely sensed data are typically subjected to accuracy assessment protocols. This is a unique element of remote sensing analyses in contrast to the more heuristic assessments of the aerial survey products. The accuracy of an attribute, such as red attack, may be characterized in relation to an independent validation dataset. The use of an independent validation dataset allows for the characterization accuracy in terms of correct identification and the distribution of the error. Infested areas that are missed and, conversely, locations that are falsely indicated, may also be characterized (for theory see Congalton 1991; for an example see Franklin et al. 2003b).

Considerations for planning to map mountain pine beetle red attack using digital imagery include the spatial, temporal, spectral, and radiometric resolution of the imagery. Spatial resolution, or pixel size, ranges from less than a metre to greater than one kilometre for different sensors. Similar to airborne image collection, there is a trade-off between improving spatial resolution and both reducing image extent and increasing costs (Franklin et al. 2002). An understanding of the link between sensor acquisition characteristics and subsequent image information content is critical to the success in a mapping exercise (Lefsky and Cohen 2003). For instance, the ability to discern differing objects on the landscape is linked to the spatial resolution (Franklin et al. 2003a). If a single pixel is composed of more than one element (i.e., part tree crown, part shadow, part ground vegetation), the pixel represents the collective spectral characteristics the elements present. The spectral signatures that are developed in such an instance have a suppressed variance that diminishes the power of predictive algorithms. In the case when a single pixel represents only one element (i.e., a portion of a tree crown), the spectral signature is unique to that pixel (e.g., Wulder and Dymond 2004). The sensitivity to spectral differences between red attacked and healthy trees (spectral resolution) also varies between different sensors. However, sensitivity to the condition of vegetation is a high priority for developers of satellite sensors, resulting in many options. Temporal resolution, or image acquisition frequency, impacts the sensor's ability to collect information regarding a particular attack stage. Airborne digital sensors can be tasked to capture image data on cloud-free days that correspond to the bio-window for red attack detection, where feasible or possible. Typically, satellite sensors have fixed revisit rates, such as the 16 days between the acquisition of Landsat scenes over the same area. The revisit cycle is based upon factors such as sensor elevation, orbit characteristics, and scene footprint. New high spatial resolution space-borne satellites, such as IKONOS and QuickBird, have directable sensor heads. The directable sensor head enables the capture of images for areas other than those located directly below the sensor. Imagery collected off-nadir (not directly beneath the satellite) should be inspected and used with caution as the altered view angle impacts how the forest is characterized.

The key to employing digital data for mapping mountain pine beetle impacts is to match the information needs of managers with the image information content and resolution characteristics. For example, under endemic conditions, the information needs are for detection of single and small clusters of red attack trees. To produce this information, the imagery must have sufficiently high spatial and spectral resolution. In contrast, under epidemic conditions, the information needs are for quantifying the impact of large groups of red attack trees over large areas. Therefore, less expensive imagery with medium spatial resolution and moderate spectral resolution would be sufficient.

One advantage of digital imagery is that it may be geocorrected (two dimensions) or orthorectified (three dimensions); these corrections facilitate integration of the remotely sensed imagery with other spatial datasets, such as forest inventory polygons or GPS point data. These corrections also make it possible to compare images collected over multiple years, thereby providing an important monitoring tool. Additional strengths supporting the use of digital data are that objective, repeatable analysis of the data is carried out with equal effort across the landscape, and that digital techniques are applied in a systematic, consistent, and transparent manner. These features help reduce inconsistencies that can result from visual interpretation. The main impediments to the widespread use of digital data are often sophisticated processing needs, costs per hectare, and a mismatch between users needs and results generated. The use of aircraft results in similar considerations for airborne imagery collection as for aerial surveys. The optimum days for data collection have even light conditions, either clear of clouds or with high overcast clouds. The timing of the flights occurs when trees are in the red stage.

Airborne platforms

Digital images may be collected from airborne platforms over areas identified as infested during aerial surveys. The key differences between airborne images and aerial or ground surveys are that the spectral characteristics of the entire forest are captured and the data can be re-examined if uncertainties occur. Airborne imagery includes traditional air photos that are scanned into a digital format (Nelson et al. 2001), digital camera images, videography, multispectral scanners, and imaging spectrometers. Airborne images may be used to map the location of small clusters or scattered red trees. The results are used to direct ground surveys or to dispatch ground crews for sanitation treatment. The airborne digital imagery may be subjected to enhancements that highlight the locations of red attacked trees (Figure 6).

Digital camera technology is sophisticated enough for direct image capture. Most high-quality digital cameras are based on modified 35 mm or medium-format cameras. The spatial and spectral resolutions of these cameras match the quality of medium-speed film (Graham and Koh 2002). The digital format eliminates the developing and scanning necessary for film-based photographs to be analyzed in soft-copy format.

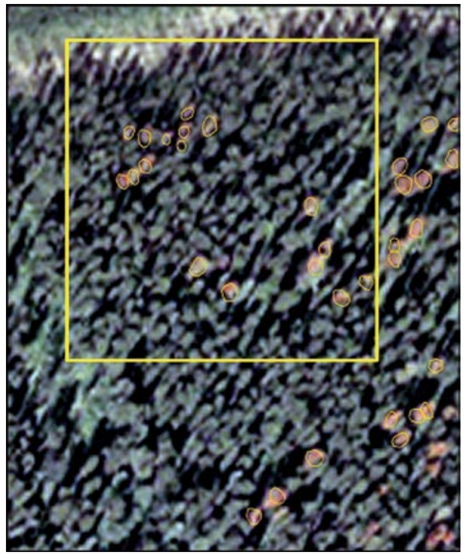


Figure 6. *Red attack trees delineated on a 1: 30 000 air photo. Image provided courtesy of Kim Forest Management Ltd., Prince George, British Columbia, Canada.*

Airborne scanners and imaging spectrometers collect digital images directly, similar to digital cameras. The spatial resolution (less than 1 m to greater than 10 m) and the sensitivity to different wavelengths of energy can be adjusted to address particular information needs. Red attack trees can be successfully detected, and the digital nature of the data provides for rapid integration with other digital datasets (Kneppeck and Ahern 1989; Ahern et al. 1986). Airborne scanners have not found wide operational implementation for mapping mountain pine beetle red attack largely due to high per-hectare costs.

Aerial videography provides some operational advantages over air photos including: lower cost, no delay for photographic development, option for including audio commentary, and high light sensitivity (Ciesla 2000). Additionally, camera settings can be adjusted during data collection in response to viewing the imagery as it is acquired. Similar to most airborne sensors, the disadvantages are primarily image extent and resolution characteristics. Otherwise, similar planning and processing options are available as they are with the digital camera systems described above.

Satellite platforms

Satellite images may be collected to map infested areas over a range of scales. Satellite imagery is similar to airborne imagery in that the data is continuous across the extent of the sampled area. In general, the comparatively high orbits of satellite systems result in more favourable viewing geometry when compared to those of airborne systems. Airborne systems often generate data that requires sophisticated processing to compensate for aircraft motion, view angles, and variable illumination conditions over the acquisition period. Satellite images are available over a range of spatial, spectral, and temporal scales. Therefore, they can be used to address a variety of strategic and tactical planning decisions. The large image extents of satellite imagery enable economies of scale (on a cost per hectare basis).

Mapping of red attack trees under epidemic conditions has been documented using satellite imagery. Due to the large cluster sizes and landscape-scale extent associated with epidemic conditions, low cost imagery from Landsat Thematic Mapper (single date) has been used to successfully map mountain pine beetle infestations (Franklin et al. 2003b). Higher accuracy of red attack mapping resulted from the use of multi-temporal Landsat Thematic Mapper and Enhanced Thematic Mapper datasets (Skakun et al. 2003). High spatial resolution sensors, such as QuickBird and IKONOS, are currently undergoing operational trials. While the Landsat mapping efforts have produced products representative of stand to landscape level characteristics, the higher spatial resolution satellites capture characteristics at the tree, or sub-stand level. The product generated from these high spatial resolution satellite systems may allow for the mapping of red attack in support of layout and planning activities.

Mapping methods

Green stage

Detecting green attack trees is a highly sought-after, yet elusive goal for remote sensing researchers. Water-stress of mass-attacked trees has been detected at the leaf-scale and at the branch scale (Murtha 1985; Ahern 1988; Rock et al. 1988). However, other studies have found low levels of detection where the data integrated foliage, branches, and other background objects (Puritch 1981).

The key issue in mapping green attack is the subtle change in the spectral signal. In order to detect this change, the number of objects within a pixel must be minimized and the relative differences maximized; this requires a sensor with high spatial and spectral resolution (such as the Compact Airborne Spectrographic Imager). To objectively classify such data, training data must be precisely located and representative of the attack stage of interest. The spatial resolution must be sufficiently high that individual pixels represent only the sunlit foliage of a tree crown. In turn, the spectral resolution of the sensor must also be fine enough, with sensitive enough optics, to enable a unique spectral signature to emerge that represents the green attack stage. A survey intended to capture the green attack stage of mountain pine beetle attack must be timed accordingly; the field calibration, data acquisition and processing, product development, and delivery must all occur within a time period which enables the forest manager to act upon the information generated. Environmental aspects such as cloud cover, drought stress, or snow accumulations, will also hamper the identification of trees under mountain pine beetle attack. The rate at which the foliage of a tree crown exhibits a mountain pine beetle attack is also variable (across all stages, not only green stage). The earlier the detection of attack is attempted, the higher the omission rate of actual attacked trees is likely to be. The fading of the foliage in the crown of a tree infested with mountain pine beetle is not a consistent, linear process (Figure 2). Additional insights on the variability in fade rates and associated detection possibilities can be found in Roberts et al. (2003). Problems with any of the above elements will impact the ability to detect or map green attack using remote sensing instruments. The accuracy for green attack detection must be high for it to be useful in a management context. The costs must also be lower than established field techniques that are based upon associating surveyed red attacked trees with the presence of green attack.

An alternative to high spectral resolution data for maximizing the difference in spectral signal is to compare the same trees before and after attack. This image need translates into multi-temporal sets of high-resolution data. Because high-resolution imagery tends to cover small areas, these data are often collected only in areas of known infestations. This approach may not be feasible in an operational setting unless high-resolution imagery was already being collected in endemic and insipient areas for other purposes.

Red stage

Detecting and mapping red attack trees has been successful at various scales and with a variety of digital sensors. However, the research has been largely targeted towards a specific set of conditions, and accuracy assessment protocols have been inconsistent. Therefore, the ability to map red attack with different tools under different conditions and attack intensity, requires additional research prior to being considered operational.

A key issue in mapping red attacked trees is the size of the clusters of red trees. The spectral difference between red attack and healthy trees is detectable under some conditions with some spectral mixing of pixels (Franklin et al. 2003b). If the cluster of red attacked trees is large with the attacked trees concentrated, the ability for the red attack to be mapped accurately is improved. The larger the cluster, the lower the spatial and spectral resolution required of the sensor. This relationship translates into low per-hectare costs for mapping epidemic conditions.

The highest accuracy in digitally mapping red attack has resulted from multi-temporal data. For the most accurate results, multi-temporal sets of images should be taken from the same sensor view angle and under similar illumination conditions. Otherwise, differences between two images may be an artefact of the data collection process, and can obscure more subtle changes in the landscape. For the same reason, similar radiometric and other corrections must be applied to each image (Peddle et al. 2003). Common practice is to geometrically correct a master image, then register all subsequent images to it, with an error of less than one pixel (also known as rubber-sheeting). This approach optimizes the likelihood that detected changes reliably indicate the situation on the ground.

Assigning agents to areas of detected change within a landscape can be the most difficult aspect of the remote sensing project. Foliage fading (to appear red or yellow) can occur for a range of reasons, including mountain pine beetle, other pests and diseases, drought, or senescence. Additional data can help at this point; a digital elevation model and an inventory of forest species can eliminate forests not susceptible to mountain pine beetle (Shore and Safranyik 1992). Furthermore, ground-validation or forest inventory data can help eliminate other agents.

Spatial processing of the image or ancillary data can aid in improving the accuracy of mapping of the red attack stage. One approach is to stratify the area into susceptible and non-susceptible stands or trees, based on entomological pest-host models (Shore and Safranyik 1992). This enhances the spectral differences between non-attacked and red attack areas. Damage caused by the mountain pine beetle was not confounded by uncontrolled natural stand variability and the relatively small spectral influence of a few damaged crowns within a small area (Franklin et al. 2003). The second key element of satellite image processing is to incorporate the temporal aspect of the change. This means using multi-date or multi-temporal imagery where the detection of change is based on the differences in the forest from year to year. An example of this analysis approach for mapping red attack incorporates multi-temporal data with a transformation of the spectral data in calculating the Enhanced Wetness Difference Index (EWDI) (Skakun et al. 2003).

Grey stage

Detection and mapping of grey attack trees has been as accurate as red attack mapping when it is included in the study design (Klein 1973; Harris et al. 1982; Gimbarzevsky et al. 1992). However, these studies tested only air photo interpretation. Extensive research indicates that techniques developed for assessing forest impacts similar to grey attack, which are caused by defoliators, may be used fir assessing the magnitude of the impact of mountain pine beetle infestation. The primary issue for mapping grey attack is the time between the attack and the data collection. If the killed trees are not harvested, they may not be mapped due to falling, the development of neighbouring crowns of healthy trees, the development of understorey species, or vigorous growth of ground cover. Intuitively, the use of data from a single date may be adequate for grey attack mapping because the difference between healthy and defoliated trees is relatively large. Yet, in practice, the range of spectral variability representing grey attack stage is large, often impeding robust algorithm development. Employing multi-temporal imagery may be required to consistently map grey attack stage. Care must be taken to differentiate changes due to mountain pine beetle from other changes occurring on the landscape in the intervening time. The mapping of red attack and the later inference of grey attack may be a more robust approach as the spectral signature of red attack is more unique (single date) and the multi-date spectral differences are also greater. When concerned with mapping, or accounting for areas that have been impacted by mountain pine beetle, access to salvage harvest records are required.

Data Integration

Forest inventory datasets are developed over a period of time, allowing for photo commissioning, collection, interpretation, digitization, etc. (Gillis and Leckie 1996). The capture of data for a forest inventory often happens on a 10-year cycle. Forest disturbance, such as that due to mountain pine beetle, can occur within an inventory cycle. A forest inventory database requires maintenance over time or the data can quickly become outdated. Polygon decomposition was developed as a tool to integrate different data layers, such as aerial survey data or satellite image classifications, with existing GIS data, in order to provide timely and accurate estimates of forest change (Wulder and Franklin 2001). Remotely sensed estimates of red attack are easily integrated with the forest inventory data (Figure 7). This integration with forest inventory data facilitates the polygon-specific accounting of areas impacted. However, the link between remotely sensed areas impacted to volume impacted requires additional investigation.

Detection and mapping of mountain pine beetle impacts can also be integrated into decision support systems. Various models exist to aid managers in the planning and treatment of forests with mountain pine beetle populations. One type of model assesses the infestation risk of different forest stands (Shore and Safranyik 1992; Chojnacky et al. 2000). Spatially explicit models, such as developed by Fall et al. (2002) may also be able to capitalize upon the input of remotely sensed estimates of infestation locations, to aid in providing baseline data for projections of the course of future outbreaks. These models require information on the current location of attacked trees to predict possible future risk. The attack maps generated through remote sensing can be used as input to these models. For example, the forest inventory and digital elevation data provide a rating of susceptibility for each stand (Shore and Safranyik 1992). Overlaying the point data from a detailed aerial survey provides intuitive information, but additional utility is found by integrating that data in the model to generate a relative risk index (Figure 8).

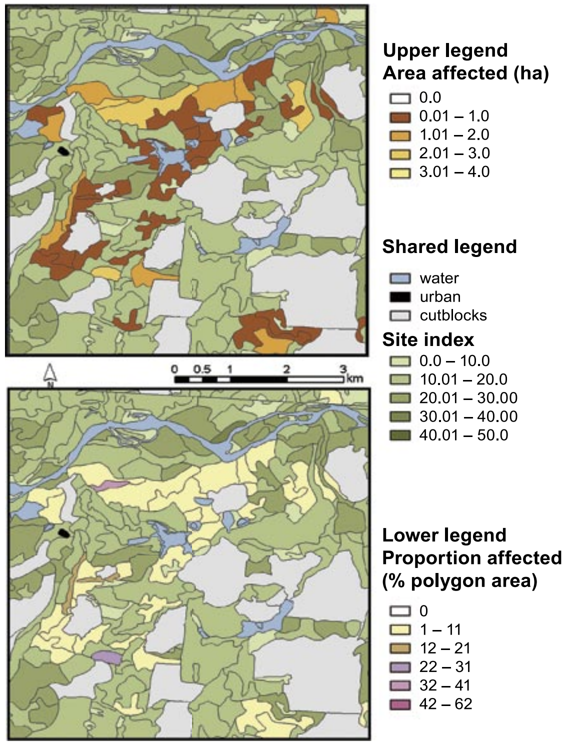


Figure 7. *Illustration of integrating mountain pine beetle maps into forest management information systems. Undisturbed forest management stands shaded by site index. Stands disturbed by mountain pine beetle shaded by area (number of hectares), in upper tile; or proportion (percent polygon area), depicted in lower tile. As indicated in the legend shared by both tiles, harvested stands are shaded grey.*

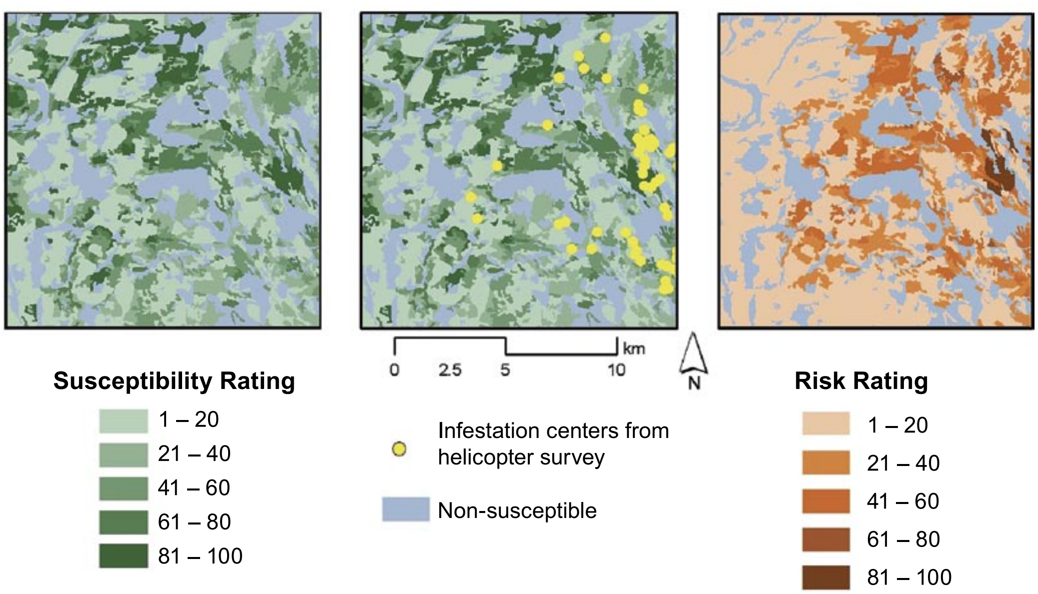


Figure 8. *Illustration of integration of global positioning data with the Shore and Safranyik Mountain Pine Beetle Risk Rating System.*

Management options and recommendations

Field based methods for the detection of mountain pine beetle are well established and routinely undertaken by forest managers. Mitigation and harvest planning decisions are made based upon these field surveys. These intensive field surveys benefit from the use of more spatially extensive survey techniques, operating in an information hierarchy, that enable stratification of the landscape. The landscape stratification can be used to focus field surveys in the areas most likely to be impacted by the mountain pine beetle.

Provincial and state governments are primarily interested in detection of red attack trees within their political boundaries (Wiart 2003). This information is used for reporting and strategic planning. At this scale, aerial sketch mapping is the recommended approach. To provide additional information regarding attack intensity and location of red attack, mapping approaches based upon medium resolution satellite imagery may be utilized. Additionally, to determine attack date, in order to aid shelf life studies, a change detection framework may be used that incorporates the time series analysis of multiple images. Also of interest at the provincial or state level is using samples of high-spatial resolution satellite data or aerial photography to provide an accurate and independent estimation of red attack over a larger population area. These samples of red attack locations may be used to validate disturbance magnitude and area estimates on a management unit level (following an approach akin to the double sampling procedure previously described for air photos).

Forestry licensees and government agencies require detection and mapping of infestations (red attack and grey attack trees) across their land base. At this scale, aerial sketch maps may no longer be appropriate. Medium to high-resolution satellite and airborne imagery are recommended for red attack mapping. Medium resolution is recommended under epidemic conditions. High-resolution is more appropriate for non-epidemic conditions. Aerial photographs, often collected to meet other management needs, are also an appropriate source of information for red attack mapping. Interpretation, either manual or digital, of attacked areas is required, but the low cost of the data may compensate for interpretation needs. The integration of red attack locations into the forest inventory is useful, as new attributes such as area or proportion of a polygon expected to be at red attack stage, enables synergistic applications with the forest inventory data and models. 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 forest managers. The result of the data integration of red attack mapping with forest inventory is a low cost approach to update and or audit forest inventory data within forest inventory measurement cycles.

Forestry licensees also require local area maps of red attack to determine locations of associated green attack trees through ground survey. At this scale, high spatial resolution imagery, either satellite or airborne, is recommended to map the red attacked trees accurately. The maps of red attacked trees are in turn used to guide the field surveys, and the field locating of green attack stage trees. Established field techniques are appropriate for *in situ* determination of mountain pine beetle attack.

Conclusions

In any survey methodology intended to meet forest management needs induced by mountain pine beetle activity, it is critically important to link the information need to the type of surveys undertaken. Survey data is inherently tied to a scale of information, with a related expectation of attribute and spatial accuracy. Higher order information needs may require acknowledgment of an information hierarchy where multiple sets of survey data are nested. For example, using lower cost general overview survey information as a guide to selecting locations for more intensive surveys enables cost efficiencies. An understanding of the information content of a range of data sources, as presented in this report, results in an ability to judiciously select the most appropriate data source to populate the information hierarchy to meet ultimate aims of mountain pine beetle mitigation and management. Many new survey options are available, from both airborne and satellite platforms, including a wide array of sensor types. While many new survey options are available, their applicability must ultimately be considered in relation to the information needs and business drivers. The new technologies are populating the information hierarchy between provincial overview and field surveys with an exciting multitude of options. Research and application based upon these new information sources, and subsequent integration with support datasets such as forest inventory data, heralds a new era in the survey of mountain pine beetle impacts.

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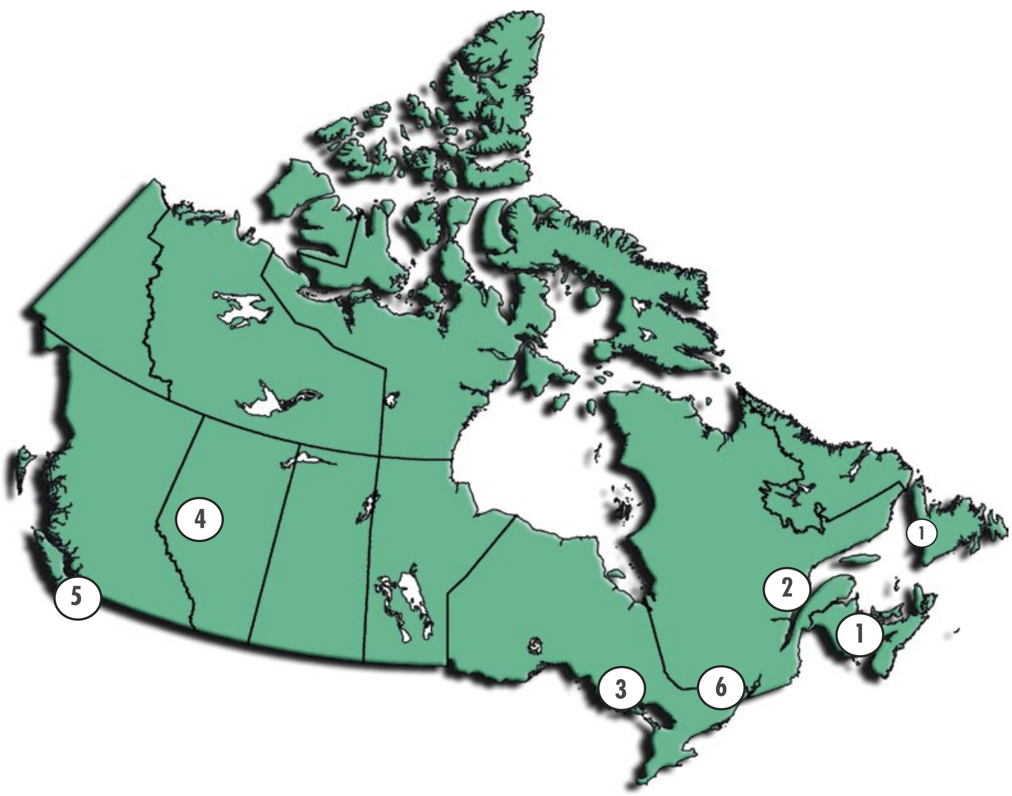

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