Augmenting the existing survey hierarchy for mountain pine beetle red-attack damage with satellite remotely sensed data[1]

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ABSTRACT

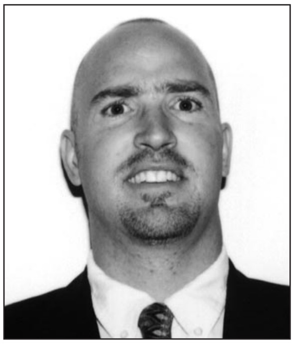
Estimates of the location and extent of the red-attack stage of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) infestations are critical for forest management. The degree of spatial and temporal precision required for these estimates varies according to the management objectives and the nature of the infestation. This paper outlines the range of information requirements associated with mountain pine beetle infestations, from the perspectives of forest inventory, planning, and modeling. Current methods used to detect and map red-attack damage form a hierarchy of increasingly detailed data sources. The capability of satellite-based remotely sensed data to integrate into this hierarchy and provide data that is complementary to existing survey methods is presented, with specific examples using medium (Landsat) and high (IKONOS) spatial resolution imagery. The importance of matching the information requirement to the appropriate data source is emphasized as a means to reduce the overhead associated with data collection and processing.

Key words: mountain pine beetle, red-attack, remote sensing, detection, Landsat, IKONOS

RÉSUMÉ

Les estimés sur la localisation et l'étendue des ravages sévères des infestations du dendroctone du pin (*Dendroctonus ponderosae* Hopkins) sont essentiels en aménagement forestier. Le niveau de précision spatiale et temporelle requis pour ces estimés varie en fonction des objectifs d'aménagement et la nature de l'infestation. Cet article souligne l'étendue des besoins d'information associés aux infestations du dendroctone du pin selon une perspective d'inventaire forestier, de planification et de modélisation. Les méthodes actuelles utilisées pour détecter et cartographier les dégâts sévères forment une hiérarchie croissante de sources de sources de données détaillées. La capacité des données en provenance de la télédétection de faire partie de cette hiérarchie et de fournir des données qui sont complémentaires aux méthodes de sondage actuelles est illustrée au moyen d'exemples spécifiques utilisant l'imagerie à résolution spatiale moyenne (Landsat) et à haute résolution (IKONOS). L'importance de faire concorder les besoins d'information avec la source appropriée de données est mise en évidence afin de réduire les coûts associés à la collecte et au traitement des données.

Mots clés : dendroctone du pin, attaque sévère, télédétection, Landsat, IKONOS



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Introduction

The mountain pine beetle (*Dendroctonus ponderosae* Hopkins) has a range covering much of the western United States and Canada. A major host, lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.), experiences extensive mortality when susceptibility to attack is high, particularly during sustained periods of warm, dry weather over several years, and when abundant reserves of host trees are accessible to the beetles. These susceptibility and host conditions have converged in recent years, leading to outbreak levels of insect populations in the United States and British Columbia. In British Columbia, the outbreak has reached historic proportions. From 2002 to 2003, the area infested with mountain pine beetle doubled, increasing from approximately 2.0 million hectares to 4.2 million hectares (British Columbia Ministry of Forests 2003a).

In general, the mountain pine beetle reproduces at a rate of one generation per year under typical climate conditions in British Columbia (Safranyik *et al.* 1974). While exceptions can occur, 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) (British Columbia Ministry of Forests 1995). The change in foliage colour, particularly to red, may be detected with remote sensing instruments (Bentz and Endreson 2004).

The infestation cycle of the mountain pine beetle is well understood (Cole *et al.* 1976). The mountain pine beetle is endemic to North American lodgepole pine forests, and at low population levels, the infestation is limited to single infested trees. These trees often have some weakness that predisposes them to infestation. At the incipient level, favourable conditions (e.g., weather) facilitate an increase in the beetle population, allowing the beetles to overcome the defences of healthy trees in a phenomenon known as mass-attack. Populations persist at this level due to continued favourable conditions, ultimately resulting in an increase in the mountain pine beetle population to the epidemic or outbreak level. Outbreaks are characterized by large populations of beetles, dispersed across the landscape. These outbreak populations are very resilient to natural mortality, and these populations can rebound following widespread mortality (Carroll and Safranyik 2004).

From a forest management perspective, estimates of the location and extent of mountain pine beetle red-attack is critical; however, the degree of precision required for these estimates varies according to the management objective under consideration (i.e., strategic, tactical, operational) and the nature of the infestation (i.e., endemic, incipient, outbreak). The range of information requirements is matched by a hierarchy of different data sources that are currently used to map red-attack damage (e.g., aerial overview surveys, helicopter surveys, aerial photography, field surveys), with each data source offering a different level of detail on location and extent. In this communication, the use of remotely sensed data to map mountain pine beetle red-attack is presented as a source of information that can assist in satisfying those information requirements. In the context of this paper, the term remote sensing refers to satellite-based remotely sensed data that are collected in digital form (e.g., Landsat ETM+, SPOT, IKONOS, QuickBird). These forms of remote sensing provide new opportunities for detection and mapping of mountain pine beetle red-attack, which can augment or complement existing data sources.

Maps of infestation location and extent drive mitigation and prediction activities related to attacks of mountain pine beetle. For example, the placement of field crews relies on accurate detection of insect activities over large areas. Output from decision support models are improved through the inclusion of accurate maps of attack conditions. The integration of remotely sensed data with existing forest inventories in a Geographic Information System (GIS) environment generates value-added information for forest managers. In turn, the forest inventory provide a context for, and source of, validation data for the red-attack information extracted from the remotely sensed data.

The objective of this paper is to provide practical guidelines to potential users regarding those satellite-based remotely sensed data sources that are most appropriate for specific information needs associated with the detection and mapping of mountain pine beetle red-attack. These remotely sensed data sources cannot supplant existing methods of data collection; however, this paper explores the manner in which these new data sources may fit into the existing data hierarchy, providing complementary information or filling data gaps. Issues addressed include the potential and limitations of particular data sources, the processing requirements or level of effort associated with using these data, and the range of results that are attainable, in terms of accuracy results reported in the literature. Examples of each pairing of data source and information requirement will be illustrated by an example.

Information Requirements for Forest Management

Business drivers or information needs, constrain the collection of data. The information needs of forest managers, in the context of addressing an infestation of mountain pine beetle, range from strategic planning over large areas, to detailed and precise locations for sanitation logging and individual tree treatment. Consequently, the scale of current information collection ranges from very broad (aerial overview sketch mapping), to more detailed (helicopter Global Positioning System (GPS) surveys and maps of infested stands derived from aerial photography), to even more detailed ground surveys for layout of blocks for sanitation logging and for fall and burn treatment. Information regarding mountain pine beetle location and extent is required for forest inventory, planning and modeling.

The Canadian Forest Service held a workshop in June 2003 to provide focus for remote sensing research priorities for the Federal Mountain Pine Beetle Initiative (Wiart 2003). The key business drivers, as described by provincial government and industrial forest managers in attendance at the workshop, included provincial level red-attack mapping, and operational mapping of red-attack for layout and sanitation. The latter was identified as having the highest priority. As a result, this paper focuses exclusively on the information requirements associated with the detection and mapping of mountain pine beetle red-attack. The following sections address the specific business drivers associated with forest inventory, forest planning, and forest modeling.

Forest inventory

Forest inventories capture forest composition and distribution at a specific point in time. Growth and yield projections, updates, and reinventories are all methods used to keep forest inventories current. The length of the forest inventory update cycle varies by jurisdiction, ranging anywhere from one to 10 years. When infestations of mountain pine beetle reach the outbreak level, the damage caused by the beetles can dramatically and rapidly alter the composition of forests, thereby accelerating the need to update the forest inventory. The maintenance of the forest inventory is critical, since the inventory often forms the cornerstone for forest planning and modeling activities. In order to maintain the inventory for mountain pine beetle related disturbance, a timely and cost effective data source is required that can easily be integrated into the existing inventory. Apart from updating the inventory with the impact of the beetle (e.g., mortality and area or percent of the stand affected), updates to stand volume are also necessary since forest planning activities are often dependent on accurate volume information. Methods for integrating information on beetle impacts into the forest inventory are possible using a range of conventional and remotely sensed data sources (Wulder *et al.* 2005).

Forest planning

Forest planning typically occurs at three levels: strategic, tactical, and operational. At the strategic level, forest managers are primarily interested in planning over long periods of time (several hundred years) and large spatial extents (province or state level); strategic plans address broad objectives, and as a result, are normally satisfied with coarse-level information. Strategic-level information on the intensity and spatial extent of the mountain pine beetle infestation is required for activities such as timber supply review, biodiversity conservation, and land use planning (Wiart 2003). Knowledge of the current level of infestation and predictions of the future spread of the infestation help to ensure that future management options are not compromised by current operational activities in addressing the infestation. A key component of strategic-level planning is the modeling of various management scenarios and treatment activities over a protracted timeframe, in order to determine the impact of management actions on the beetle population, spread of the beetle, and total wood volume (Eng *et al.* 2004).

Tactical-level planning commonly addresses a five- to twenty-year period and a spatial extent analogous to a landscape or larger management unit. In a forestry context, this level of planning provides the structure for implementing the broad objectives outlined in the strategic plans and includes activities such as the scheduling of harvesting and road construction. Operational plans are considered low-level plans, providing the specific details necessary to execute each activity scheduled in the tactical plan. Block layout and road engineering are examples of the site-specific detail included in an operational plan. Overall, forest planning requires information on the red-attack stage of mountain pine beetle infestations, at various spatial and temporal resolutions — and with varying levels of accuracy and precision.

The time frames associated with the typical planning scenarios described above are completely upset when an outbreak of mountain pine beetle occurs, resulting in an atypical planning cycle. For example, in British Columbia, higher-level strategic plans with very short time frames are being completed to drive and expedite Annual Allowable Cut reviews, which have resulted in harvesting uplifts (British Columbia Ministry of Forests 2004). The data driving these short-term strategic plans include the aerial overview sketch mapping and projections of beetle-spread, as derived from stand- and landscape-level models of beetle impact and spread dynamics. Under an epidemic scenario, tactical-level planning often occurs on an annual basis. Overview sketch mapping is used to identify areas suitable for suppression that will, with the input from more detailed aerial survey data, generate operational (harvesting and treatment) plans.

Forest modeling

Several different mountain pine beetle-focused models have been developed at both the stand level and the landscape level (e.g., Shore and Safranyik 1992). These models attempt to address a range of questions:

- Where and when will the beetles attack?
- How severe will the damage be?
- What management response will be most effective?

In the specific case of a model designed to describe the evolution of spatial and temporal patterns of mountain pine beetle attack within a lodgepole pine forest, data describing both the currently infested and uninfested stems within the forest are required (Heavilin *et al.* In press). In this model, each cell represents either the density of red-attack trees, a measure of the current beetle population that will emerge to infest new trees the following year, or the number of live trees available for attack in future years. The model couples mountain pine beetle density-dependent attack dynamics and dispersal expectations with a Leslie matrix that describes the changing demographics of the forest, for predicting the yearly spread of infested trees across the landscape. Models of this type require landscape-scale information regarding the number of red-attack trees and live trees, summed to a given resolution.

As previously indicated, the ability to model the impact of various beetle management scenarios is an important component of strategic-level forest planning. Inclusion of beetle impacts in management scenarios requires an accurate depiction of beetle population dynamics. Several models have been developed to describe the temperature-dependent growth of mountain pine beetle populations (Safranyik *et al.* 1975, Bentz *et al.*1991, Logan and Bentz 1999, Carroll *et al.* 2004, Logan and Powell 2004). A population dynamics model is currently being developed for mountain pine beetle, allowing the dynamics of beetle and host to be explored in the context of various management control options (Riel *et al.* 2004). Other models predict the duration and impact of an infestation by diameter at breast height class, or alternatively, predict the stand mortality (percentage of basal area killed) based on the stand susceptibility rating (Bentz *et al.* 1993, Shore *et al.* 2000).

Forest models that attempt to predict the spread and potential magnitude of an infestation require information on the location and extent of mountain pine beetle-infested trees (Powell *et al.* 2000, Heavilin *et al.* In press). Such predictive models may be calibrated by baseline information characterizing the stands currently infested, or stands that have been infested in the past. Information on beetle impacts may be used to parameterize models and validate assumptions, or alternatively, support the backcasting of models by providing tangible data to reconstruct the history of beetle infestation spread (within the limits of sensor lifespan). As is the case with forest planning, the information requirements of forest modeling that are inclusive of bark beetle populations are quite variable and depend on the scale of the model and its temporal parameters (Biesinger *et al.* 2000). For example, some models require area-based estimates of beetle severity or mortality; other models require information on individual tree impacts.

Existing Methods for Detection and Mapping of Mountain Pine Beetle Red-Attack

Existing methods of red-attack detection and mapping occur in a hierarchy of data types from coarse-scale aerial overview surveys, to very detailed ground surveys. Each level of this existing data hierarchy satisfies the specific information requirements of forest inventory, modeling, and planning. A summary of existing methods of survey and their associated costs are provided in Table 1; a more detailed review is available in Wulder *et al.* (2004).

Aerial overview surveys are often the most appropriate techniques for large-area surveying of mountain pine beetle impacts due to the inherent speed and efficiency with which they can be completed. The Canadian Forest Service was responsible for conducting the overview surveys between 1914 and 1995; the provincial British Columbia Ministry of Forests assumed responsibility for the surveys in 1995 (British Columbia Ministry of Forests 1995). The aerial overview surveys, conducted on an annual basis, are designed to cover the maximum possible area, and provide general reconnaissance on trends in forest health at the provincial level. Most importantly, the information gathered in the aerial overview survey is made available for strategic planning within three months of survey completion. The objective of the overview survey is to detect and delineate a wide variety of forest health concerns at map scales ranging from 1:100 000 to 1:250 000. To meet this objective, surveys are conducted using fixed-wing aircraft that fly at speeds of 150 to 170 km/hour, at altitudes ranging from 500 to 1000 metres (British Columbia Ministry of Forests 2000). On a strategic level, this information is used to direct resources to address forest health concerns, particularly where there are increasing populations of specific forest pests. In the United States, similar aerial surveys are conducted by the Forest Health Protection branch of the USDA Forest Service (Schraeder-Patton 2003, Harris 2004).

Aerial overview surveys provide sufficient information to characterize the general location of the damage, to approximate the gross area of damage, and to indicate the general trend in damage from one year to the next. However, the shortcomings of these overview surveys, which include large errors of omission when damage is very light, a lack of rigorous positional accuracy, and the variability in estimates of attack magnitude, limit the utility of overview surveys directing operational activities. What these surveys do provide, however, especially in a province the size of British Columbia with vast tracts of managed forest, is an initial stratification of the landscape that can direct the collection of more detailed infestation information with greater spatial accuracy. The red-attack detection information from the aerial sketch mapping program is primarily used for strategic planning, the identification of areas requiring more intensive survey, and for the allocation of mitigation resources (British Columbia Ministry of Forests 2003a). In addition, this information is used to adjust the annual allowable cut and timber supply forecasts (British Columbia Ministry of Forests 2003b).

The issues associated with the location error and attribute accuracy issues of the overview sketch mapping are not significant when the aerial overview survey program is considered within the context for which it was created. In British Columbia, the survey program has been effectively meeting provincial- level information needs for several decades. The aerial overview survey has many advantages. Firstly, the program is cost-effective — no other remotely sensed data source available today can provide information on the comprehensive range of forest health issues, within the required timeframe, for a similar cost. Secondly, the interpreters' expertise can utilize cues to map the extent and severity of each pest and disease, such as the identification of tree species, and knowledge of pest habitats, past areas of infestation, and the spatial characteristics associated with each pest. Thirdly, the overview provides sufficient information to direct the allocation of resources for more detailed surveys over limited areas, as required. Finally, the aerial overview survey is the only complete set of relatively consistently collected forest health data that exists for the majority of the provincial landbase, providing valuable historical context to infestations over time and space. Therefore, when considered within the context for which the overview surveys were intended, the advantages of the aerial overview survey program far outweigh the disadvantages.

In British Columbia, more detailed aerial surveys, conducted mainly for the detection and mapping of bark beetles over smaller areas, are the responsibility of forest districts or licensees. These surveys are normally completed at a scale of 1:20 000 using a helicopter with a Global Positioning System (GPS) and a GPS position is taken at the centroid of individual infestation clusters. For each cluster, the number of infested trees is estimated and the damaging agent is recorded. The size of the clusters may vary; cluster area, shape, and compactness are not recorded (Nelson *et al.* 2004). The information collected from helicopter GPS surveys is used primarily for expediting the deployment of field crews to find green-attack in areas where suppression activities are recommended. An advantage over other survey methods is the low error of commission; the surveyor gets a good look at each crown and can differentiate between porcupine girdling, flooding, mechanical damage, and bark beetle. The disadvantage is that there may be errors of omission if the coverage of the helicopter-GPS survey is not systematic across areas of lodgepole pine forests.

In 2004, British Columbia experimented with the use of 1:30 000 conventional colour aerial photography for more detailed detection and mapping of red-attack. Photos were

Table 1. Methods currently used to detect and map mountain pine beetle infestations in British Columbia

Method	Scale	Cost/ ha	Description	Corresponding information need
Aerial overview survey	1:100 000 to 1:250 000	\$0.01[a]	General location of damage, approximate gross area of damage, general trend in damage from one year to another at the provincial level. Note: The mountain pine beetle is only one of many forest health issues addressed in the sketch mapping survey.	Used for strategic planning, the identification of areas requiring more intensive survey, and for the allocation of mitigation resources (Ministry of Forests 2003b).
Helicopter GPS survey	Variable (Output to 1:20 000)	\$0.15[b]	A GPS position is taken at the centroid of individual infestation clusters. For each cluster, the number of infested trees is estimated and the infesting insect species recorded. The size of the clusters may vary; cluster area, shape and compactness are not recorded, rendering the helicopter GPS data difficult for subsequent use by field crews. British Columbia spends approximately \$2 million on helicopter GPS surveys annually.	The information collected from helicopter GPS surveys is used primarily for expediting the deployment of field crews to areas which are eligible for suppression activities, or which require sanitation harvesting.
Photo surveys (measle maps)	1:30 000 aerial photography	\$0.21[c]	In spring 2004, British Columbia decided to replace helicopter GPS surveys with measle maps generated from 1:30 000 air photos. Photos must be collected according to rigorous photogrammetric standards established by the province. These standards facilitate the use of the photos for other applications (i.e., base mapping) and thereby aid in recovery of the acquisition costs.	Similar to helicopter GPS surveys
Field surveys	1:1	\$11[d]	Ground surveys of mountain pine beetle are intended to verify information gathered from aerial surveys and take two forms: walk-throughs and probes. Walkthroughs are designed to delineate most recent attack and are undertaken if the aerial survey indicates an area is determined to be less than 5% red-attack or more than 25% red-attack. If the aerial survey determines that the area is between 5% and 25% red-attack, a full probe is conducted, provided the area is harvestable. Walkthroughs are unsystematic, reconnaissance type surveys, used to assess the stand and identify spatially discrete pockets of infestation. Probes are systematic strip surveys that collect very detailed information on stand conditions.	The information gathered from the probes is used for the purposes of designing logging and sanitation plans.

[a]Tim Ebata, personal communication, October 8, 2004
[b]http://www.for.gov.bc.ca/hcp/fia/landbase/dfam/AerialDetectionStandardforBarkBeetleManagement.doc
[c]Tim Ebata, Personal communication, October 7, 2004. Although the per-hectare cost of the photography is the same as the helicopter GPS surveys, the total costs for the measle maps are estimated to be significantly higher. Helicopter GPS surveys focus on smaller areas and can be cancelled for logistical reasons (i.e. inclement weather). Approximately twice as much area was covered with photography that would have been done with helicopter GPS, however the air photos are useful for a wide range of different applications.
[d]Wiart, R. 2003.

acquired in those areas that had been identified for suppression in the province's strategic beetle management plan (British Columbia Ministry of Forests 2003a). The air photos were collected between July and mid-September, and were then digitized (scanned) at a high resolution (maximum of 14 microns). Red-attack damage was visually interpreted from the photos using digital photogrammetric software (softcopy) and an output "measle map" of red-attack areas was generated. The photos provide a permanent record of the survey and may be used for other purposes, such as the update of topographic base maps. The measle maps are a hybrid product composed both of polygons (depicting broad areas of red-attack), and points (providing a specific location and number of red-attack trees).

Despite the many advantages of this form of survey, the B.C. Ministry of Forests may not continue with the use of air-photos for red-attack detection, due to several logistical issues. Firstly, the photos were collected to rigorous photogrammetric standards, in order that the photos could be used for other applications, such as planimetric base mapping (Geographic Data BC 2005). Unfortunately, these standards prevented the collection of photos in conditions that were suitable for areas where red-attack mapping was a priority, but unacceptable according to the standards required to meet other base mapping uses (e.g., part of the flight line may have had too much cloud cover). Secondly, logistical considerations such as weather and contractual arrangements further confounded the success of the photography program. Air photo acquisition requires significant planning upfront, and in the context of the mountain pine beetle, this planning has to take place before there is a good sense of how the beetle population has faired over the winter. Finally, to achieve economies of scale, flight lines had to be designed to cross over many non-forested areas, as well as areas considered to be unsuitable for beetle suppression. In contrast, the helicopter GPS surveys have the advantage of collecting data in less than ideal conditions and in very specific locations. Furthermore, the helicopter surveys can be cancelled and redeployed in other areas with very short notice when evidence of significant changes in bark beetle management strategy becomes obvious (e.g., rapid population expansion of beetles in a specific area may negate suppression efforts and resources can therefore be reallocated to other areas).

Ground surveys of mountain pine beetle are intended to confirm information gathered from aerial surveys and provide more detailed mortality estimates. Ground surveys vary in terms of the intensity, quality, and quantity of data collected, depending on the survey objective. These surveys generally take two forms — walkthroughs or probes. In British Columbia, guidelines for using the appropriate ground survey method are provided by the provincial government (British Columbia Ministry of Forests 1995). When the aerial overview survey indicates that an area is < 5% red-attack, walkthroughs are designed to delineate spatially discrete pockets of current (green) attack. Walkthroughs are unsystematic, reconnaissance-level surveys. They are often used to determine if surveys that are more detailed are required. If the aerial survey determines that an area is between 5% and 25% red-attack, a full probe is conducted, provided the area is harvestable. Full probes are systematic strip surveys that collect very detailed information on stand conditions. The information gathered from the probes is used for the purposes of designing logging and sanitation plans. Finally, if an area is determined to be more than 25% red-attack, walkthroughs may be conducted to verify the status of the insect population.

In reality, the forest licensees and forest district administrative staff already know where certain types of surveys need to be done based on their experience and the operability if the area. In areas where a suppression strategy is being implemented, detailed aerial surveys will often automatically be scheduled, and where the detailed aerial survey identifies small patches of red-attack damage in marginally operable terrain, ground surveys will be scheduled to facilitate the layout of fall and burn treatments. This same information can be used to plan harvesting of the damaged trees, if the terrain is suitable and there is a viable economic situation for those doing the harvesting. For infestations that are located in operable areas, walkthroughs or modified full probes are conducted to delineate block boundaries that will incorporate the greatest amount of green-attack and collect other information related to harvesting. If the infestations are small and require small patch harvesting because they are near an existing road or cutblock, a full probe will often be used to attempt to minimize the harvest of uninfested volume.

Satellite Remote Sensing for Detection and Mapping of Mountain Pine Beetle Red-Attack

A variety of satellite remotely sensed image data have been used in a research context to successfully detect and map mountain pine beetle red-attack, providing varying levels of precision, and in turn, providing information that can be integrated into the existing hierarchy of survey data. Table 2 provides a summary of some of the remotely sensed data sources currently available. All of the data sources included in Table 2 either have been used, or have strong potential for use (based on their spatial and spectral properties), in mapping mountain pine beetle red-attack. Fig. 1 provides an illustration of the trade-offs associated with spatial resolution and data costs. Other factors, such as the radiometric and spectral properties of the image, and the image extent, will affect the utility of a remotely sensed data source for any given application, and must therefore be considered before data is selected (Franklin *et al.* 2002). Fig. 2 illustrates the different information content of a medium spatial resolution data source (Landsat) and a high spatial resolution data source (IKONOS). In the Landsat image, the patterns of cutblocks and roads are discernable across the landscape; however, details regarding individual cutblocks or roads are more clearly visible in the IKONOS image. The following section outlines some recent examples where remotely sensed data, of varying spatial and spectral resolutions, have been used to map mountain pine beetle red-attack. First, the attributes of each data source, including cost and availability are described. Second, the methods used to pre-process the imagery, classify red-attack, and assess the accuracy of the final outputs are presented. Finally, the potential and limits of each data source are discussed and recommendations for the most appropriate use of the data source are provided.

Medium spatial resolution data: Landsat TM and ETM+

Sensor specifications, data cost and availability

Medium spatial resolution remotely sensed imagery provides an information source that bridges the requirements of strategic and tactical levels of planning. The spatial resolution for multispectral sensors that are currently operational varies from 10 metre (SPOT 5) to 30 metre (Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+)) (Table 2). The cost per square kilometre also varies, ranging from \$0.02 for Landsat to \$1.22 for SPOT 5. The Landsat satellite will revisit the same location once every 16 days, while the SPOT 5 satellite will do so every 26 days (for nadir viewing). Due to its low cost, availability, large area coverage, and program longevity, Landsat TM and ETM+ data are the most widely used remotely sensed imagery for terrestrial

Table 2. Remotely sensed data sources that have potential for mountain pine beetle red-attack mapping

Sensor	Swath width (km)	Archive[a] Cost/km^2 (Cad$)	Acquisition[a] Cost/km^2 (Cad$)	Revisit cycle	Spatial resolution (m)	Spectral range (nm)
Landsat 5 TM	185	$0.02	N/A	16 days	30 MS	450–2350
Landsat 7 ETM+	185	$0.03	N/A	16 days	15 PAN 30 MS	450–2350
SPOT 1–4	60	$0.43/$km^2$ for 1986–2001 $0.69/$km^2$ for 2002+ 60 km^2 minimum	$1000/scene plus archive cost/km^2 (see left)	26 days (nadir) 1–4 days (oblique)	10 PAN 20 MS	500–1730
SPOT 5	60	$2.45/$km^2$ for 2.5 m $1.22/$km^2$ for 5 m and 10 m 20 km^2 minimum	$1000/scene plus archive cost/km^2 (see left)	26 days (nadir) 1–4 days (oblique)	2.5, 5 PAN 10 MS	500–1730
IKONOS 2	11	$9.10/$km^2$ for PAN or MS $12.74/$km^2$ for bundle 49 km^2 minimum	$23.40/$km^2$ for PAN or MS $32.76/$km^2$ for bundle 100 km^2 minimum	3 days	1 PAN 4 MS	450–850
Quickbird-2	16.5	$23.40/ km^2 for PAN or MS $31.20/$km^2$ for bundle 25 km^2 minimum	$28.60/ km^2 for PAN or MS $36.40/$km^2$ for bundle 64 km^2 minimum	1–3 days	0.61 PAN 2.44 MS	450–900

[a]Prices quoted are valid as of November, 2004.

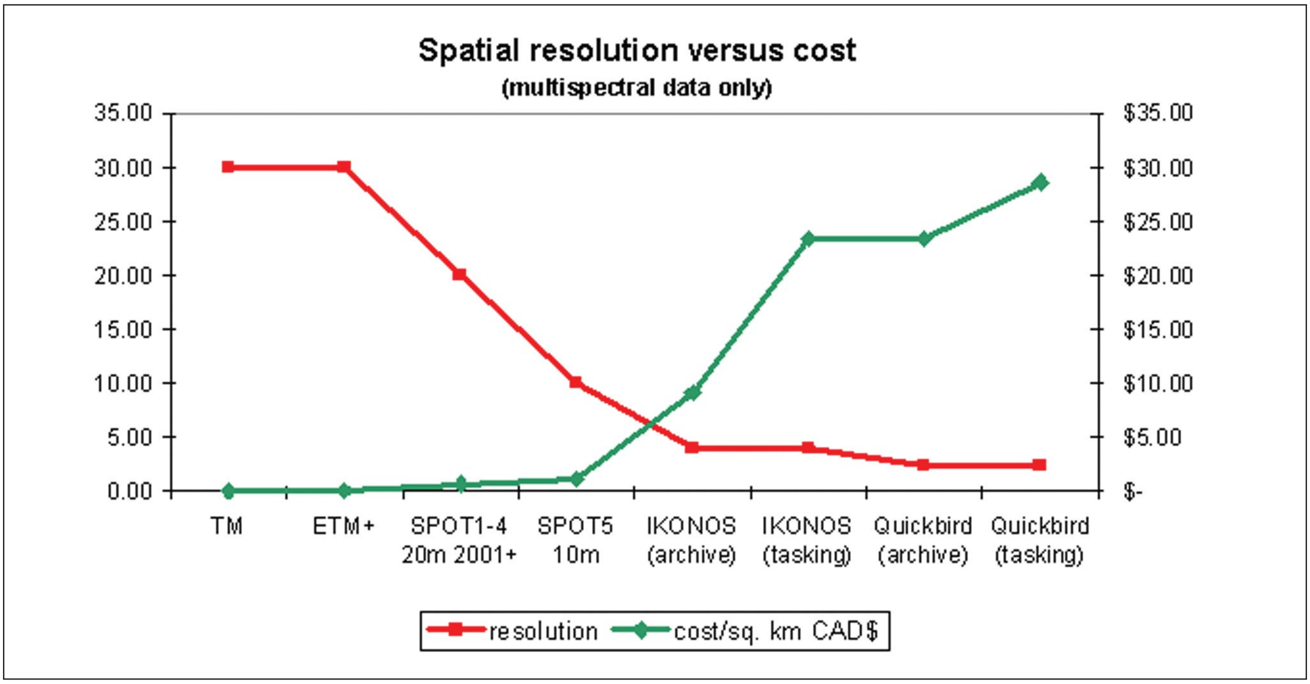

Fig. 1. Trade-offs between spatial resolution and data costs per square kilometre.

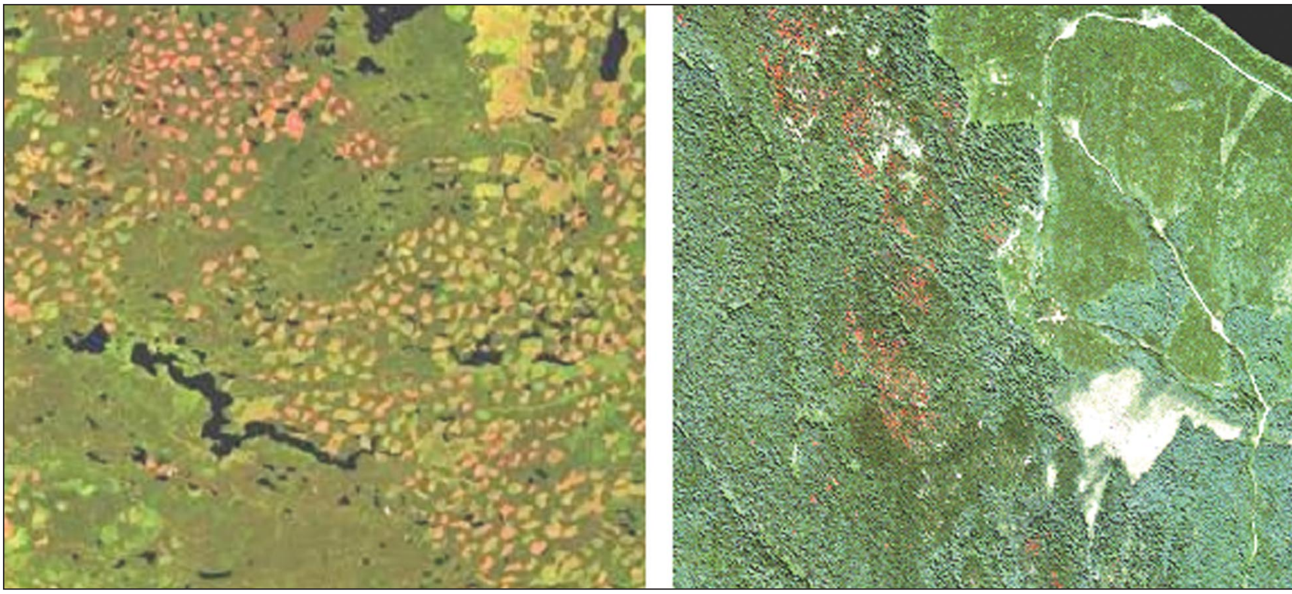

Fig. 2. The information content of a medium spatial resolution sensor, Landsat ETM+, (left) compared to the information content of a high spatial resolution sensor, IKONOS, (right). The IKONOS image is provided courtesy of Space Imaging Inc.

applications. Unfortunately, recent technical problems with the ETM+ sensor have affected the quality of the data collected (Cohen and Goward 2004, Maxwell 2004). Mountain pine beetle red-attack has been mapped using both single date and multi-date Landsat imagery.

Application examples

Single date Landsat imagery

Franklin *et al.* (2003) used a 1999 Landsat TM image for the detection and mapping of mountain pine beetle red-attack in the Fort St. James Forest District, British Columbia, Canada (Fig. 3). A supervised classification methodology was chosen for this site due to the large amount of field data and aerial survey point data (collected by helicopter GPS survey) available for calibration and validation. The field and aerial survey data, collected in August and September of 1999, identified known locations of red-attack. Before classification, the field and aerial survey data were stratified using an existing GIS forest inventory polygon dataset. Strata of forest composition and structure were defined using a number of forest inventory attributes. The strata were designed to fulfill two objectives: first, to improve the confidence associated with the field and aerial survey data; and second, to reduce the spectral variability inherent in the natural forest conditions (Franklin *et al.* 2001). For example, susceptibility to mountain pine beetle is known to increase in stands which are over 60 years of age and which have a high pine component (Safranyik *et al.* 1974). Consequently, red-attack calibration sites located in inventory polygons with less than 40% lodgepole pine, or less than 60 years of age were not used. Areas of infestations by other pests, which were identified in either the field or aerial survey information, were not used as red-attack training sites. Points identifying grey-attack were likewise excluded from the calibration and validation sample. To minimize spectral variance associated with edge effects, training sites located on the edge of cut-blocks, roads, rivers, and lakes were removed using an edge filter. In total, 360 of the field and aerial survey points identifying sites of known red-attack locations were selected. Through a similar process of stratification, a non-attacked forest stratum was generated and a set of points, comparable in size to that of the red-attack calibration set, was selected. A total of 100 points from each of the attack and non-attack data sets were reserved for use as an independent validation data set. The remaining points (260 for each of attack and non-attack) formed the calibration data set. These calibration data were used to generate unique spectral signatures for red-attack and non-attack, which in turn were used in the classification process.

Pre-processing of the Landsat TM image included the co-registration of the imagery to the GIS forest inventory data set using 40 ground control points distributed throughout the Landsat scene and a cubic convolution resampling algorithm. A standard model was used for the atmospheric correction to obtain reflectance values (Richter 1990). The signatures generated from the calibration points of red-attack and non-attack forest were used as input training data for a supervised maximum likelihood classification algorithm. The classification was performed using all six of the Landsat TM optical bands and each pixel in the image was assigned to the class to which it had the highest probability of being a class member (red-attack or non-attack).

The accuracy of the output classification was assessed using the reserved, independent validation points. Accuracy is determined by comparing the validation points, which indicate known locations of mountain pine beetle red-attack damage and non-infested areas, to the red-attack map generated from the Landsat data. Assuming these two data sources are appropriately co-located, a tally of correspondence and non-correspondence is made. The proportion of validation points which correspond to the Landsat map (both attacked and non-attacked) is the overall accuracy. Separate accuracies for each class (red-attack and non-attack) are also reported. A review of accuracy assessment procedures used with remotely sensed data in a forestry context is provided by Czaplewski (2003).

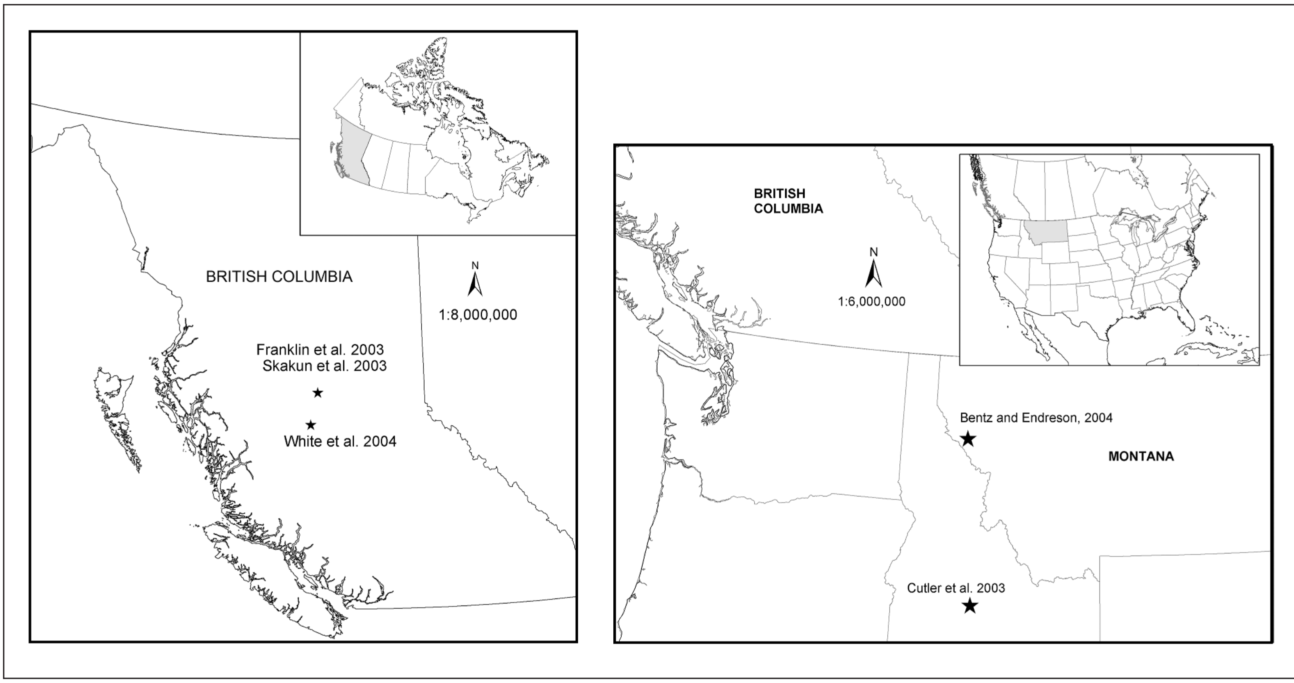

Fig. 3. Location of study sites in British Columbia (left) and Montana, USA (right).

Table 3. Accuracy assessment results for a single image date classification using Landsat Thematic Mapper data (Franklin et al. 2003). A supervised maximum likelihood classification was used and the accuracy for both the red-attack class and areas that were not attacked are presented. The overall classification accuracy was 72.3%.

		Validation Data				
		No attack	Red-attack	Total	User's	Commission
	No attack	71.1	26.7	98	72.6%	27.4%
Classified	Red-attack	28.9	73.3	102	71.8%	28.2%
Image	Total	100	100	200		
	Producer's	71.1%	73.3%		Overall Accuracy	
	Omission	28.9%	26.7%		72.3%	

Franklin *et al.* (2003) reported an overall classification accuracy of 72.3%; red-attack locations were detected with 73.3% accuracy, while accuracy for non-attack locations was 71.1% (Table 3). These results must be considered in the context of the infestation in the study area; stands in the red-attack stage had a heterogeneous spatial distribution, and many of the patches of infestation were small. For example, 82% of the field and aerial survey points had less than 10 trees infested (within a 50-metre radius plot). Stratification of the calibration sites was critical for constraining the spectral variability associated with forest stands, and enhancing the separation between red-attack and non-attack locations. In the case of the healthy forest, calibration and validation data were extracted from the GIS forest inventory — more robust training data for healthy forest obtained by aerial observation or direct field validation, in a manner comparable to that for the red-attack calibration and validation data, may have improved results. The final product was a map showing the location and extent of mountain pine beetle red-attack in the study area (Fig. 4).

A similar study using single date Landsat imagery for red-attack mapping was recently completed in the mountainous region of the Lolo National Forest in central Montana, United States (Fig. 3) (Bentz and Endreson 2004). Although forest species in the area were mixed conifer, field data collection was restricted to areas dominated by lodgepole pine. Mountain pine beetle infestations began in the area in 1994. Field data were collected in 2000, 2001, and 2002. A total of 380 plots across 15 different sites were surveyed; each plot was 30 m by 30 m in size, corresponding to a single Landsat pixel. Data was collected for every tree within each plot; attributes included species, diameter at breast height, and attack code (1, live and not currently infested; 2, current attack; 3, attacked the previous year; 4, attacked two years previous; 5, attacked more than two years previous). The sample size for live and not currently infested stands was increased with air photo interpretation.

The Landsat ETM+ image used in this study was acquired on August 18, 2002. A dark pixel atmospheric correction was

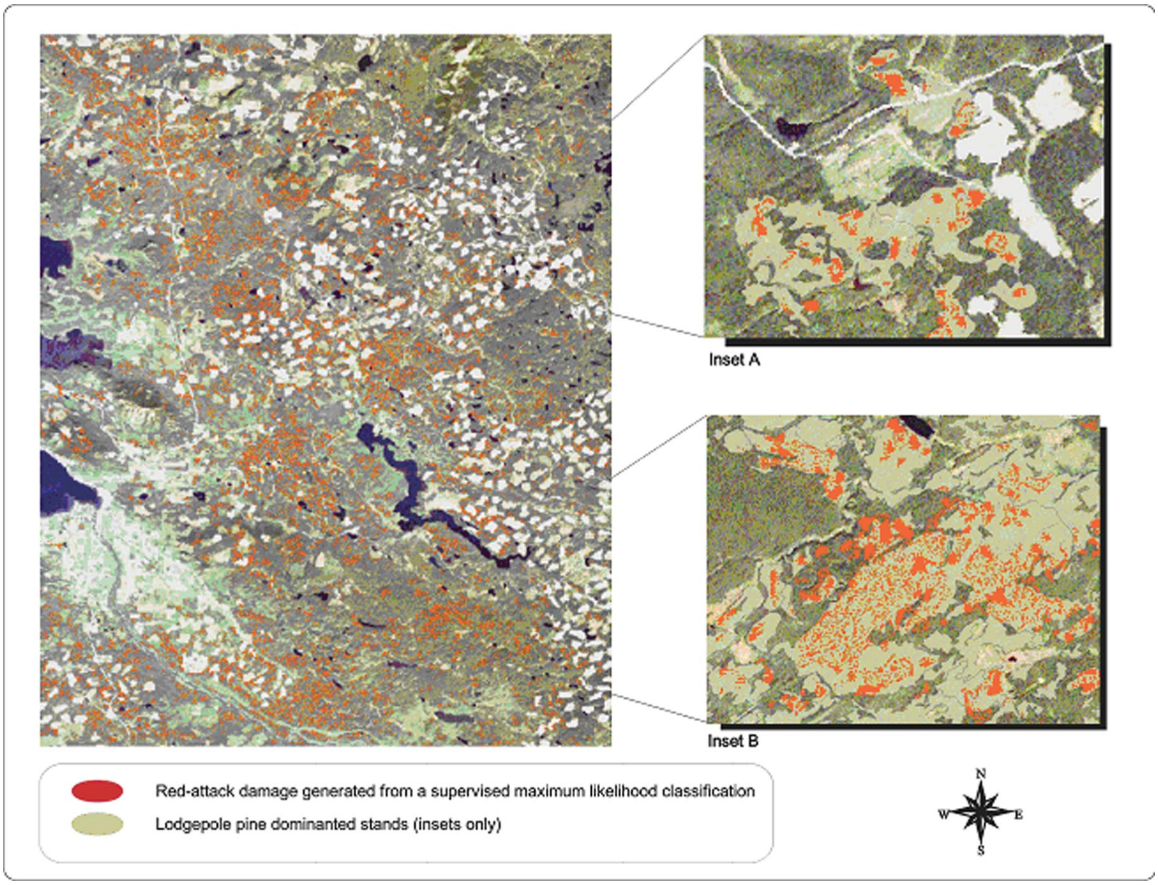

Fig. 4. Location and extent of mountain pine beetle red-attack as identified with single date Landsat imagery (Figure reproduced with permission, the American Society for Photogrammetry and Remote Sensing, Franklin et al.(2003)).

applied to the imagery, which was then calibrated to radiance, and converted to reflectance (Chavez 1997). Finally, a Tasseled Cap Transformation was performed to generate three outputs that highlight the brightness, wetness, and greenness information content in the six optical Landsat bands (Crist and Cicone 1984). Using a similar approach to that of Franklin *et al.* (2003), the forest inventory was used to stratify the calibration and validation data into suitable areas that were dominated by lodgepole pine and that had not been harvested in the past 50 years. A mean reflectance value for each Landsat band was calculated for each plot, along with mean values for each of the Tasseled Cap components. These values were subsequently exported to a database for further statistical analysis and model development.

It was not expected that it would be possible to discriminate between red-attack for the current year and red-attack from previous years. Therefore, the five attack classes identified in the field data were generalized to three classes: green (not infested and current attack); red (attacked in previous year and previous two years); and grey (attacked more than two years previous). Development of a classification algorithm focussed solely on the identification of red-attack. Several classification methods were tested; however, the lowest overall misclassification rate was generated using linear discriminant analysis. Validation data for the red-attack locations were stratified for three levels of red-attack intensity: plots with 0–9 red-attack trees, 10–24 red-attack trees, and more than 25 red-attack trees. Using the classification approach described above, the overall accuracy for red-attack was 59%; however, accuracy for plots with greater than 25 red-attack trees was 79%.

Multi-date Landsat imagery

Skakun *et al.* (2003) used multi-temporal Landsat 7 ETM+ imagery from the years 1999, 2000, and 2001 to identify locations of mountain pine beetle red-attack in a study area near Prince George, British Columbia (Fig. 3). Known locations of red-attack were collected by a helicopter GPS survey in July 2001. Previous studies have suggested that change over time, as measured with the Tasseled Cap Transformation, may be useful for mapping insect disturbance (Cohen *et al.* 1995, Price and Jakubauskas 1998, Franklin *et al.* 2001, Sharma and Murtha 2001). The image data were geometrically and atmospherically corrected, and the Tasseled Cap Transformation was used to generate brightness, greenness, and wetness components (Crist and Cicone 1984). Stand stratification was used in a manner similar to Franklin *et al.* (2003) in order to reduce variability in the calibration and validation data. In total, 120 samples per class were selected, with half of the samples being retained for independent validation. The target

Table 4. Accuracy assessment results for a multi-date image date classification using Landsat ETM+ data (Skakun et al. 2003). Discriminant analysis was used to classify the (A) 2000/2001 EWDI image and the (B) 1999/2001 EWDI image. A stratified random samples of non-attacked forest (n = 60) and different levels of red-attack damage (n = 60 for each level) were input to the model. The overall classification accuracy for both classification outputs was 74%.

A. 2000/2001 EWDI

		Validation Data					
		1	2	3	Total	User's	Commission
Classified Image	1	48	11	8	67	72%	28%
	2	8	40	7	55	73%	27%
	3	4	9	45	58	78%	22%
	Total	60	60	60	180	–	–
	Producer's	80%	67%	75%	–	Overall Accuracy = 74%	
	Omission	20%	33%	25%	–		

1 = Non-attacked forest
2 = Group of 10–29 red-attack trees
3 = Group of 30–50 red-attack trees

B. 1999/2001 EWDI

		Validation Data					
		1	2	3	Total	User's	Commission
Classified Image	1	46	14	8	68	68%	32%
	2	8	41	5	54	76%	24%
	3	6	5	47	58	81%	19%
	Total	60	60	60	180	–	–
	Producer's	77%	68%	78%	–	Overall Accuracy = 74%	
	Omission	23%	32%	22%	–		

1 = Non-attacked forest
2 = Group of 10–29 red-attack trees
3 = Group of 30–50 red-attack trees

categories for the classification included non-attacked forest, forest stands with 10–29 red-attack trees, and forest stands with 30–50 red-attack trees.

Analysis was completed using image pairs: 1999 and 2001; and 2000 and 2001. The wetness components generated for each image date were then differenced, for each image pair. The wetness difference output was then enhanced and thresholded, creating an Enhanced Wetness Difference Index (EWDI) image for the 1999–2001 image pair and for the 2000–2001 image pair. The threshold value corresponding to red-attack was selected through an iterative process; the range of EWDI values was correlated to calibration data of known red-attack tree locations. Discriminant functions were then applied to the EWDI images in order to classify each pixel in the image to one of the three aforementioned classes. The classification was completed for the 1999–2001 EWDI image and the 2000–2001 EWDI image. Each of the classification outputs contained three classes: non-attacked forest, forest stands with 10–29 red-attack trees, and forest stands with 30–50 red-attack trees. The outputs were evaluated using the retained independent validation data, with the overall classification accuracy for the two output maps equalling 74% (Table 4). It is noteworthy that for both classifications, stands with 30-50 red-attack trees had higher accuracies than those stands with only 10–29 red-attack trees. This indicates that larger numbers of red-attack trees per site will generate a stronger pattern of red-attack reflectance.

Potential and limitations

These examples illustrate that both single-date and multi-date Landsat imagery may be used to map red-attack damage, with overall accuracies ranging from 59% to 81%. When considered in the context of red-attack magnitude, accuracies for stands with greater numbers of red-attack trees ranged from 73% to 81%, and these results emphasize the suitability of these medium spatial resolution data sources to areas with larger, more widespread infestations. The output maps generated from these image classifications provides an efficient and accurate representation of the distribution of red-attack damage across the landscape. This digital output may be easily integrated into existing GIS-based forest inventory systems (Wulder *et al.* 2005).

Once integrated into the forest inventory using polygon decomposition, the red-attack information could be used by forest managers to prioritize areas for more detailed survey, to facilitate the comparison of similar products produced over several years, and as a means to assess mountain pine beetle population and tree damage trends (both spatial and temporal) over the landscape. Landsat data are cost-effective ($0.02 to $0.03 per square kilometre for data collection — costs for processing and analysis will vary but should also be considered) — however, in some areas it may be difficult to acquire cloud free imagery in the desired time frame, as the sensor passes over any given area only twice per month. Multi-date techniques, which capitalize on the dramatic change in reflectance exhibited by red-attack damage, show promise for achieving greater accuracy than methods using single-date imagery. An extensive archive of Landsat imagery data is available to facilitate this type of analysis, and for longer-term retrospective type analyses.

In areas with outbreak levels of infestation, Landsat data could provide a more specific and precise estimate of red-attack damage, in comparison to the broader information and spatial resolution of the aerial overview survey. The utility of the Landsat data, however, would be in a retrospective analysis, since analysis of the Landsat imagery could not be completed within the temporal and fiscal constraints, which are currently only met by the aerial overview sketch mapping. The results of the examples presented above, and other studies that have been completed, indicate that Landsat data, and other sensors with comparable spatial and spectral resolutions, are best suited to strategic (and perhaps some tactical) information requirements. Generally, the identification of red-attack with Landsat imagery is somewhat dependent on the size and nature of the infestation. This data source tends to be most successful in areas where the infestation is large and growing (i.e., epidemic), and somewhat less effective when the infestation is small and dispersed across the landscape (i.e., endemic).

High spatial resolution Data: IKONOS

Sensor specifications, data cost and availability

The availability of commercially delivered, high spatial resolution satellite data offers a potential source for the cost-effective collection of accurate, consistent, and timely data regarding mountain pine beetle red-attack. The spatial resolution for high spatial resolution sensors that are currently operational ranges from 0.67-metre (panchromatic) and 2.44-metre (multispectral) for QuickBird, to 1-metre (panchromatic) and 4-metre (multispectral) for IKONOS. The spectral properties of the QuickBird and IKONOS sensors are provided in Table 5. The average bandwidth of the multispectral bands on these sensors is approximately 80 nm. In contrast, the panchromatic bands have a bandwidth of 403 nm. The large bandwidth of the panchromatic channel results in a lower spectral sensitivity. The implications of this are that this band has limited utility for detecting mountain pine beetle red-attack, although fusion of this band with the multispectral bands could be useful for the visualization of red-attack areas.

To purchase archived imagery with both the panchromatic and multispectral bands together as a bundle, the cost for IKONOS is approximately $12.74/km^2, and for the QuickBird is $31.20/km^2. These costs are more comparable than they initially seem, since the minimum order size for IKONOS is 49 km^2 ($625 for minimum order) and for QuickBird is 25 km^2 ($780 for minimum order). The advantage of these two sensors is an ability to collect data over a specific area of interest and within a specified date range; the disadvantage is that unlike Landsat, these sensors are not continuously collecting data over the entire earth's surface. Costs for acquiring new imagery, or for purchasing archive imagery are provided in Table 2. Although QuickBird has a higher spatial resolution, the smaller minimum order area required makes this data source less expensive than IKONOS — for study areas less than 64 km^2. Prices and minimum order sizes change regularly, and end-users are advised to fully evaluate these factors before purchasing. High spatial resolution remotely sensed data provides a promising option for the detection of red-attack at both local and landscape scales. The imagery has a high level of spatial detail, and a large image extent (IKONOS and QuickBird images have spatial extents of 121 and 272.25 square kilometres, respectively). IKONOS 4-metre multispectral data have been used to map red-attack in areas of low to moderate levels of infestation (Cutler *et al.* 2003, Bentz and Endreson 2004, White *et al.* 2004).

Table 5. Spectral properties of IKONOS and QuickBird sensors

Sensor	QuickBird	IKONOS
	Panchromatic	
Spectral Bands (nm)	445–900	526-929
Spatial Resolution	61 cm (at nadir)	1 m (at nadir)
	Multispectral	
Blue	450–520	445–516
Green	520–600	506–595
Red	630–690	632–698
Near Infra Red	760–900	757–853
Spatial Resolution	2.44 m (at nadir)	4 m (at nadir)

Application examples

An investigation into the merits of using IKONOS 4-metre multispectral data was recently completed at a study site near Prince George, British Columbia (Fig. 3). IKONOS provides global coverage, a consistent acquisition schedule, and near-nadir viewing angles. The spatial resolution of the sensor is suitable for high-accuracy photogrammetric processing and mapping applications (Tao *et al.* 2004). In addition, the IKONOS 4-metre multispectral bands have similar spectral properties in the visible and near infrared wavelengths as Landsat ETM+ multispectral data (Goward *et al.* 2003). This project examined the use of an unsupervised clustering of image spectral values to detect mountain pine beetle red-attack at susceptible sites (i.e., with known risk factors for infestation), which were considered to be lightly infested (1% to 5% of trees red-attacked) or moderately infested (greater than 5% and less than 20% trees red-attacked).

A mask was generated from the IKONOS image to exclude potential areas of confusion from the classification process (e.g., large water bodies, cutblocks). An unsupervised classification (ISODATA), which included all four IKONOS spectral bands, was used to identify red-attack trees. The unsupervised approach was used to diminish the requirement for training data (Franklin *et al.* 2003). Independent calibration and validation data were collected from 1:30 000 scale aerial photography. The calibration data were used to verify the correspondence of spectral clusters to known red-attack locations, and the validation data were used to assess the accuracy of the resulting red-attack map. The independent calibration data consisted of four 1-ha sites where red-attack trees were delineated and detailed stem maps were created. Three of the calibration sites were medium attack and one was low attack. The calibration data had 274 red-attack trees. The validation data included nine sites for the low damage class (127 red-attack trees) and 10 sites for the medium damage class (510 trees).

A 4-m buffer (analogous to a single IKONOS pixel) was applied to the red-attack pixel identified on the IKONOS imagery in order to account for positional error. When compared to the independent validation data collected from the aerial photography, it was found that 70.1% (lightly infested sites) and 92.5% (moderately infested sites) of the red-attack trees existing on the ground were correctly identified through the classification of the remotely sensed IKONOS imagery. Analysis of red-attack trees that were missed in the classification of the IKONOS imagery indicated that detection of red-attack was not effective for smaller tree crowns (diameter < 1.5 m), which were more than 11 m from other red-attack trees.

Another application example using 4-m multispectral IKONOS data for mapping red-attack damage was recently completed in an area dominated by lodgepole pine in the Sawtooth National Recreation Area in central Idaho, United States (Fig. 3) (Cutler *et al.* 2003). Mountain pine beetle populations started building in the northern section of the study area in 1997, and by 2002 were at outbreak levels throughout the study area. The IKONOS imagery was purchased orthorectified with an 8-bit radiometric resolution. Additional GIS layers and field points were co-registered to the imagery. The field data, collected in 2002, identified the location of individual trees with a GPS and assigned the trees an attack code: 1, live and not currently infested; 2, current attack; 3, attacked the previous year; 4, attacked two years previous; 5, attacked more than two years previous. Samples were also collected from five other land cover classes in the area (water, roads, dirt, agriculture, and sagebrush). In total, there were 699 observations for the 10 different target classes. A discriminant function, which included the four multispectral bands of the IKONOS, was calibrated and used to classify each pixel in the image into one of the ten target classes. Validation data were used to assess the accuracy of the classification; 95% of the red-attack trees identified from the classification of the IKONOS image were verified as being red-attack from the validation data. Measures of commission error were not reported for this study.

Potential and limitations

At the local level in British Columbia, management of the mountain pine beetle has shifted to the detection and mitigation of sites with minimal levels of infestation in order to reduce or contain the outbreak to a size and distribution that can be handled within the capacity of the existing forestry infrastructure. There is an operational need for an efficient and cost-effective method to identify red-attack trees in areas with low levels of infestation. Errors of commission must be minimized; from an operational perspective, the deployment of field crews to sites falsely identified as red-attack has greater consequence than sites where red-attack trees are located, but where every single red-attack tree may not be identified. The use of imagery for this scale of red-attack mapping provides a permanent record of the survey, which can subsequently be used by field crews who need to assess not only the exact location of the red-attack, but also the extent and shape of the red-attack stands and their relative position in the landscape.

With high spatial resolution data, the greatest challenge for model development lies in correlating the spatial location of measured ground data points to the corresponding pixel in the image. GPS systems will have an error associated with the position information, and the rectified imagery will likewise have an associated error. Similarly, the high spatial resolution of the IKONOS and QuickBird imagery magnifies positional errors that exist in much of the standard topographic base information — most of which is collected at scales of 1:20 000 or 1:50 000 (this base information is frequently used to geocorrect or orthorectify imagery). Overall, the results of the examples presented here indicate that IKONOS is well suited to the detection of small groups of red-attack trees, while detecting individual red-attack trees can be more problematic due to the errors discussed above. In addition, very little pre-processing of the image data used in these examples was required to successfully identify red-attack trees. Both QuickBird and IKONOS have rapid revisit rates, returning to the same location every one to three days. The trade-off for this rapid revisit rate is that the imagery is not always collected at nadir, and detection and mapping algorithms can be sensitive to off-nadir view angles. Users can specify the viewing geometry they require when ordering either QuickBird or IKONOS imagery. High spatial resolution imagery is well suited to the information requirements at the tactical or operational level; however, it is more expensive to acquire than medium spatial resolution imagery. When warranted by high value stands, high spatial resolution imagery can provide spatially explicit data on both red-attack and live trees for input to models that describe the evolution of spatial and temporal patterns of mountain pine beetle attack. Once integrated into the forest inventory using polygon decomposition, the red-attack information could be used by forest managers to identify stands for direct control and to plan salvage logging activities.

Integration of RS/GIS technology

Methods

Remotely sensed data can be used to generate maps that depict the spatial location and extent of mountain pine beetle red-attack. This information is of greatest value to forest managers when it is effortlessly integrated directly into a pre-existing forest inventory. Polygon decomposition is an analysis technique that facilitates this integration (Wulder and Franklin 2001), providing a link between outputs from remotely sensed image classification and the stand records (polygons) in the inventory. For example, the EWDI output described earlier can be linked to the inventory to provide information on the total area of the stand that is red-attack, and the location of the red-attack within the stand (Wulder *et al.* 2005). Polygon decomposition is a method that is well

Table 6. Polygon decomposition results for aerial overview sketch map, helicopter GPS survey points, and Landsat EWDI.

Forest Inventory Data			
	Sketch Map	Helicopter GPS Survey Points	Landsat EWDI
Number of polygons with red-attack	648	783	857
Total area of polygons with red-attack (ha)	11 461.3	24 554.3	28 782.6
Aerial Overview Sketch Map	Area of aerial sketch map = 6 256.1 ha		
Helicopter GPS Survey Points	Count of aerial survey points = 2 128 Number of trees = 17 430		
Landsat EWDI	Area of EWDI pixels = 4 961.79 ha		

suited to a hierarchy of data sources: estimates of red-attack from many different data sources, such as aerial overview survey, helicopter GPS survey, and high spatial resolution remotely sensed data can be integrated at the stand level. This provides a common unit to compare the magnitude and extent of red-attack estimated by each of these sources, providing valuable inputs for modellers and illustrating the importance of matching the data source to the management objective. For instance, polygon decomposition allows the attributes of the attacked stands to be analyzed quickly and may provide the manager with some context for the biological or economic impact of the infestation (Table 6).

Summary and Conclusions

Maps of the location and extent of mountain pine beetle infestations drive mitigation and prediction activities. For example, the placement of field crews relies on accurate detection of insect activities over large areas. Similarly, output from decision support models are improved through the inclusion of accurate maps of attack conditions. All levels of planning require information on the location and extent of mountain pine beetle red-attack damage. This information is also used to parameterize models and validate the assumptions used to generate the models. The integration of red-attack information with existing forest inventories in a GIS environment generates value-added information for forest managers. In turn, the forest inventory provides a context for, and source of, validation data for the information extracted from the remotely sensed data (Wulder and Franklin 2001, Wulder *et al.* 2005). The augmentation of forest inventory data provides enhanced baseline data for models that predict the extent and impacts of future mountain pine beetle infestations. Satellite-based remotely sensed data can provide information that complements existing data sources and can be integrated into the existing hierarchy of available survey data.

The objective of this paper was to provide practical guidelines to potential users of satellite-based remotely sensed imagery, who are interested in identifying the location and extent of mountain pine beetle red-attack damage. Examples, using both medium and high spatial resolution satellite remotely sensed imagery were presented, along with methods for pre-processing, classification, and validation. The use of aerial overview sketch mapping (or relatively inexpensive, low spatial resolution satellite based remotely sensed data) to provide a synoptic view of mountain pine beetle red-attack damage at the landscape level, and then subsequently to guide the acquisition of higher spatial resolution, more costly data, is one example of how a data hierarchy can be a cost-effective and efficient tool. The importance of matching the information requirement to the appropriate data source is emphasized as a means to reduce the overhead associated with data collection and processing.

The nature of the infestation (i.e., endemic, incipient, epidemic) should guide the selection of an appropriate data source. Medium spatial resolution data, such as Landsat TM and ETM+, are better suited to mapping epidemic and outbreak levels of infestation. High spatial resolution data, such as IKONOS and QuickBird, are suitable for identifying small clusters of red-attack trees; however, the consistent detection of individual red-attack trees remains challenging. The relative costs, availability, and processing requirements of the various data sources are all important considerations for the end user. In contrast to conventional survey methods, the costs of remotely sensed options (beyond the cost of imagery) are not well documented; costs associated with processing the imagery are variable and must be acknowledged when choosing between survey options.

The concept of an information requirement hierarchy was introduced to demonstrate how different levels of forest inventory, planning, and modeling have different requirements in terms of the timeliness and precision of mountain pine beetle red-attack estimates. This hierarchy of information requirements is matched by a hierarchy of different data sources, and each data source provides a different level of detail on the location and extent of the mountain pine beetle red-attack damage. Research has demonstrated that remotely sensed data (with varying spatial resolutions) can be used to successfully detect and map red-attack and as a result, should be considered part of this data hierarchy. An understanding of the information content of a range of data sources results in the ability to judiciously select the most appropriate data source to populate the information hierarchy.

Matching the appropriate data source to the information requirement reduces the complexity of data collection and processing, and ensures that the required level of detail is provided to address the management objectives specific to that level of the hierarchy. Furthermore, a data hierarchy is cost-effective; low spatial resolution, relatively inexpensive data sources may be used to guide the acquisition of more costly, higher spatial resolution data. Satellite remotely sensed data cannot supplant existing methods of red-attack detection; however, it does provide information that can augment and complement conventional methods, filling spatial or temporal gaps in other data sources.

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