Available online at www.sciencedirect.com

SCIENCE DIRECT®

Remote Sensing of Environment 96 (2005) 340 – 351

Remote Sensing of Environment

www.elsevier.com/locate/rse

Detection of red attack stage mountain pine beetle infestation with high spatial resolution satellite imagery

Joanne C. White[a,1], Michael A. Wulder[a,*], Darin Brooks[b,2], Richard Reich[c,3], Roger D. Wheate[d,4]

[a]Canadian Forest Service, Pacific Forestry Centre, 506 West Burnside Road, Victoria, BC, Canada V8Z 1M5
[b]Kim Forest Management Ltd., 1985 Garden Drive, Prince George, BC, Canada V2M 2V9
[c]British Columbia Ministry of Forests, 1011 4th Avenue, Prince George, BC, Canada V2L3H9
[d]University of Northern British Columbia, Natural Resources and Environmental Studies, 3333 University Way, Prince George, BC, Canada V2N 4Z9

Received 6 August 2004; received in revised form 1 March 2005; accepted 9 March 2005

Abstract

The on-going mountain pine beetle outbreak in British Columbia, Canada, has reached historic proportions. There is an operational need for efficient and cost-effective methods to identify red attack trees in these areas. In this paper, we examine the use of an unsupervised clustering 4-m multispectral IKONOS imagery for the detection of mountain pine beetle red attack at sites with low and medium levels of attack. Independent validation data were collected from aerial photography and were used to determine the accuracy with which mountain pine beetle red attack could be detected using the multispectral IKONOS imagery. Concentric buffers, in 1-m increments to a maximum of 4 m, were applied to red attack pixels to characterize attribute accuracy as a function of positional accuracy. When a one-pixel buffer (4 m) is applied, the accuracy with which mountain pine beetle red attack could be detected using the multispectral IKONOS imagery was 71% (low attack) and 92% (medium attack). Analysis of red attack trees that were omitted in the analysis of the multispectral IKONOS image indicated that detection of red attack was most effective for larger tree crowns (diameter >1.5 m) that were less than 11 m from other red attack trees. These results demonstrate that the unsupervised classification of mountain pine beetle red attack using multispectral IKONOS imagery is an operationally viable approach.

Keywords: Mountain pine beetle; IKONOS; IAccuracy assessment

1. Introduction

The mountain pine beetle (*Dendroctonus ponderosae*) is the most destructive insect of mature pine forests in western North America (Wood, 1963). Populations of mountain pine beetle in the central interior region of British Columbia, Canada, have been increasing since 1994. The rates of spread and attack intensity have increased especially dramatically in the past few years. From 2002 to 2003, the mountain pine beetle infestation doubled, increasing from approximately 2.0 to 4.2 million hectares (Ministry of Forests, 2003a). Preliminary projections estimate that the area affected by mountain pine beetle increased to 7.0 million hectares in 2004 (Ministry of Forests, 2005).

The extent of the current mountain pine beetle outbreak, and the associated economic impacts, have prompted research into new techniques and data sources for reconnaissance and mapping of the infestation. Management efforts at the local level have shifted from attempting

* Corresponding author. Tel.: +1 250 363 6090; fax: +1 250 363 0775.
E-mail addresses: joanne.white@nrcan.gc.ca (J. White), mwulder@nrcan.gc.ca (M. Wulder), kfmgis@telus.net (D. Brooks), Richard.Reich@gems4.gov.bc.ca (R. Reich), wheate@unbc.ca (R. Wheat).
[1] Tel.: +1 250 363 0751; fax: +1 250 363 0775.
[2] Tel.: +1 250 564 3808; fax: +1 250 564 4427.
[3] Tel.: +1 250 565 6203; fax: +1 250 565 6671.
[4] Tel.: +1 250 960 5865; fax: +1 250 960 5538.

0034-4257/$ - see front matter.
doi:10.1016/j.rse.2005.03.007

to address all levels of infestation across the landscape, to the detection and mitigation of sites with minimal levels of infestation. The objective of this shift in management efforts is to reduce or contain the outbreak to a size and distribution that can be handled within the capacity of the existing forest industry infrastructure. Detection and mapping of current impact enables planning and mitigation activities, and serves as a driver for parameterizing models of beetle spread which are designed to reduce future risks and impacts.

In general, mountain pine beetles in British Columbia reproduce at a rate of one generation per year (Safranyik et al., 1974). Adult beetles typically 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 defenses 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 (gray attack) (Ministry of Forests, 1995). Generally, the foliage fades from green to yellow to red over the spring and summer following attack (Amman, 1982; Henigman et al., 1999). The leaves gradually desiccate and the pigments break down; initially the green chlorophyll pigments are lost, then the yellow carotenes and red anthocyanins (Hill et al., 1967). Slowly, the needles drop until the tree is completely defoliated.

Knowledge of the spatial locations of mountain pine beetle infestations is required for a range of management activities. The identification of mountain pine beetle red attack occurs at three different scales in British Columbia, Canada: province-wide, landscape, and local. Over the entire province, the Ministry of Forests is primarily interested in the detection of red attack stage trees, as opposed to green or gray attack (Wiart, 2003). Red attack indicates mortality, and at the provincial scale, the amount of mortality caused by mountain pine beetle has implications for strategic planning (e.g. allocation of mitigation funding) and timber supply analysis.

At landscape scales, estimates of mountain pine beetle impact are used for expediting the deployment of field crews to areas which are eligible for suppression activities, or which require sanitation harvesting. Surveys at this scale are typically completed using a helicopter with a global positioning system (GPS). Another method of detecting and mapping mountain pine beetle red attack at this scale is with 1:30,000 aerial photography. At local scales, field crews complete surveys of red attack trees for the purposes of designing logging and sanitation plans. The locations of red attack trees are also used to aid in the determination of the probable locations of green-attack trees in support of strategic planning and suppression activities.

2. Using remotely sensed data for red attack mapping

The three critical data collection requirements for the detection and mapping of mountain pine beetle red attack are (Wiart, 2003):

- Accuracy (e.g. Is the resolution of the acquisition appropriate for the task?)
- Consistency (e.g. Can the detection method be replicated with a sufficient level of confidence over a variety of stand and biogeoclimatic conditions?)
- Timeliness (e.g. Can the detection method be used to acquire and deliver large amounts of data to satisfy beetle management plan timelines for probing, layout, and treatment?)

These three critical factors cannot be considered without also weighing the costs associated with data acquisition. Several remotely sensed data sources are currently used operationally to detect and map red attack. Detection and mapping of red attack have also been demonstrated with other sources of remotely sensed data such as medium and high spatial resolution satellite imagery; these data sources may provide information where operational methods are unavailable, logistically difficult to execute (e.g. weather, accessibility), or where retrospective analyses are required and historical data has not been collected.

2.1. Existing detection and mapping methods

In order to gather synoptic information on forest health at the provincial scale, an aerial sketch-mapping program is conducted on an annual basis. This broad survey encompasses several pests and forest health issues, including mountain pine beetle red attack (Westfall, 2003). 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 (Ministry of Forests, 2003b). In addition, this information is used to adjust the annual allowable cut and timber supply forecasts (Ministry of Forests, 2003a). Due to its cost effectiveness and the speed with which the data can be collected and made available to forest managers, aerial overview sketch mapping is unparalleled in the broad, provincial-scale detection and mapping of mountain pine beetle red attack damage.

At the landscape scale, helicopter GPS surveys are used to identify red attack trees in areas that are eligible for suppression activities (e.g. areas with low levels of infestation). The helicopter is positioned over a cluster of red attack trees and GPS location information is collected at the centroid of the infestation cluster. For each cluster, the number of infested trees is estimated and the infesting insect species recorded. The size of the clusters may vary; however, the maximum cluster size is considered to have a radius of 100 m. Cluster area, shape, and compactness are not recorded (Nelson et al., 2004). Field crews will subsequently use the position of cluster centroids to conduct large sweeps (approximately 100 m wide) for identifying green-attack trees. These green-attack trees will then be removed in an effort to mitigate the infestation.

Both aerial overview sketch mapping and helicopter GPS surveys rely heavily on the interpreter's ability to make instantaneous decisions regarding tree species, damage agent, location, and severity of observed disturbances. These survey approaches are subjective and the accuracy with which red attack damage may be detected and mapped can vary considerably based on the interpreter's experience and preferences (Ministry of Forests and Canadian Forest Service, 2000). In addition, the collected data cannot easily be statistically analyzed due to the nature of the attributes collected (e.g. qualitative or estimated quantitative), and in the case of aerial overview sketch mapping — the coarse nature of the polygon delineation.

Aerial photography is also used to detect and map mountain pine beetle red attack at the landscape scale. There are several advantages to the use of air photos for red attack mapping. Firstly, air photos provide a permanent record of the survey, so unlike other survey methods (i.e. overview surveys and helicopter GPS), the data (image) is captured and then the attack interpreted. In this way, the air photos facilitate historical analysis, or additional interpretation and validation by multiple interpreters. Secondly, aerial photography can be collected at a specified scale and the photos can be geometrically controlled to provide more spatially precise estimates of beetle location and extent. The photos are then available for other forestry and non-forestry related applications, and for subsequent use by field crews for navigation and validation. In 2004, the British Columbia Ministry of Forests encouraged the widespread use of 1:30,000 scale color aerial photography for red attack detection and mapping in areas identified for suppression activities in the provincial mountain pine beetle strategic action plan.

2.2. Emerging detection and mapping methods

Research into the use of medium resolution satellite imagery (Landsat TM and ETM+) for red attack detection and mapping at the landscape scale has yielded promising results. Using a single-date Landsat TM image and a supervised classification approach, the accuracy with which areas of red attack could be identified was approximately 73% (Franklin et al., 2003). Red attack detection accuracies resulting from the use of discriminant functions on multi-date TM and ETM+ images ranged from 67% to 78% (Skakun et al., 2003). In both of these studies, stratification of the imagery with existing GIS forest inventory information was

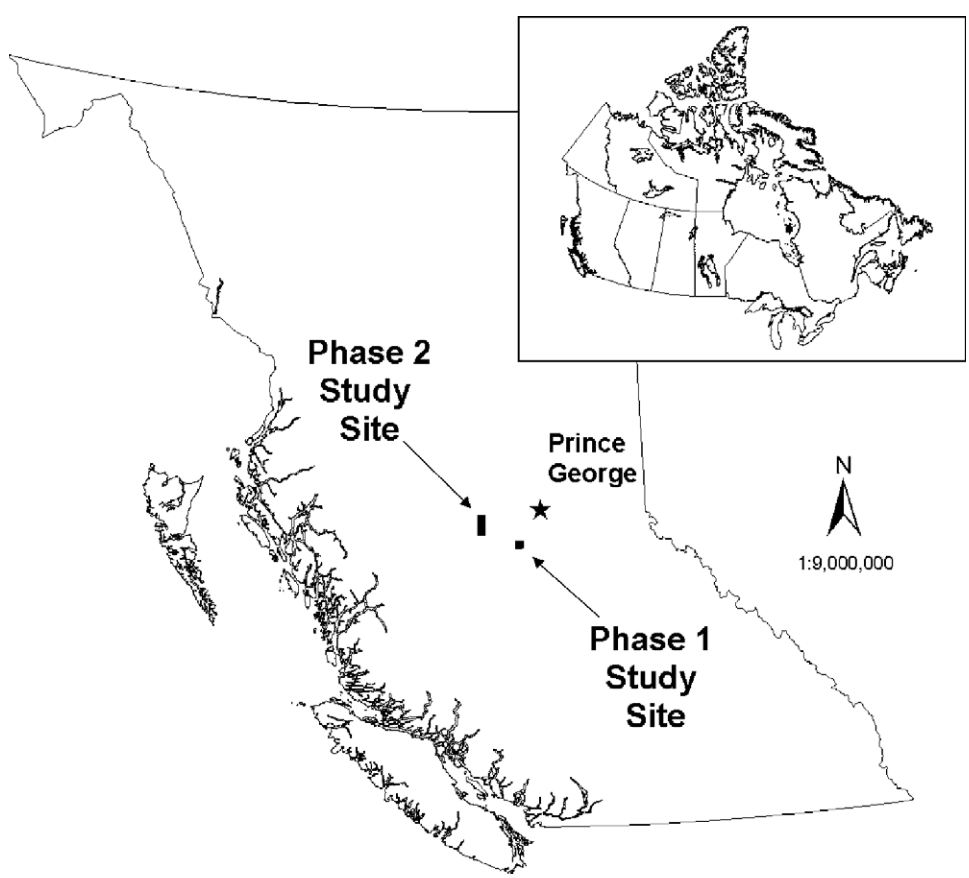

Fig. 1. Location of phase 1 and phase 2 study areas in British Columbia, Canada.

used to constrain the natural variability in the stand, thereby reducing spectral edge effects occurring along cut-block, road, river, and lake edges, and enhancing the difference in spectral response between red attack and non-attack. The 30-m spatial resolution of Landsat TM/ETM+ resulted in more accurate detection of larger areas of red attack; however, while smaller, dispersed patches of red attack were also detectable with a reasonable level of accuracy (Franklin et al., 2003; Skakun et al., 2003), these results indicate that a higher spatial resolution data source could be more effective at identifying small and dispersed areas of red attack damage.

The availability of commercially delivered, high spatial resolution satellite data offers a potential source for cost-effective collection of accurate, consistent, and timely data regarding mountain pine beetle impacts at both landscape and local scales. The imagery has a high level of spatial detail combined with a large spatial extent. For example, the spatial extent of IKONOS and QuickBird images are 121 and 272 km^2 respectively, compared to a spatial extent of 47 km^2 for a 1 : 20,000 air photo. Unsupervised classification algorithms may be used to isolate red attack damage, reducing issues of inconsistency in photo interpretation. High spatial resolution imagery (e.g. 4-m multispectral IKONOS) has smaller pixels than medium resolution imagery (e.g. 30-m Landsat TM/ETM+); these smaller IKONOS pixels are closer to the size of the target object of interest (individual tree crowns). Fewer objects (trees) are found within each multispectral IKONOS pixel, reducing the effect of mixed pixels. A 30-m Landsat pixel will encompass multiple tree crowns (at various stages of infestation), resulting in a weakened spectral response when the red attack occurs in small patches dispersed across the landscape. In contrast, a single multispectral IKONOS pixel may contain only two or three tree crowns, depending on the size of the tree crowns.

Some of the high spatial resolution sensors, including IKONOS, have robust positional accuracy (Tao et al., 2004). Furthermore, unlike helicopter GPS surveys, 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.

The purpose of this study is to assess the accuracy of the 4-m multispectral IKONOS imagery for mapping mountain pine beetle red attack. Accuracy is the first of the three critical data collection requirements for mapping mountain pine beetle red attack. The red attack areas identified using the 4-m multispectral IKONOS imagery are compared to the red attack areas interpreted from 1 : 20,000 color aerial photography. A rigorous accuracy assessment protocol is followed: independent calibration and validation data sets are used; only the attribute specific accuracy (true positive rate) is reported; confidence intervals are provided for all reported accuracy values.

3. Study area

The study area is located in the central interior of British Columbia, Canada. The ecosystem in this area is dominated by the Sub-Boreal Spruce (SBS) biogeoclimatic zone, with a minor component of the Engelmann Spruce Sub-Alpine Fir (ESSF) biogeoclimatic zone occurring in higher elevations areas to the east (Medinger & Pojar, 1991). Two separate areas (Fig. 1) were used in this study: the first area (phase one) is 13 by 11 km, centered at 123°15′ west and 53°21′ north, approximately 75 km southwest of Prince George; the second area (phase two) is 13 by 33 km, centered at 124°18′

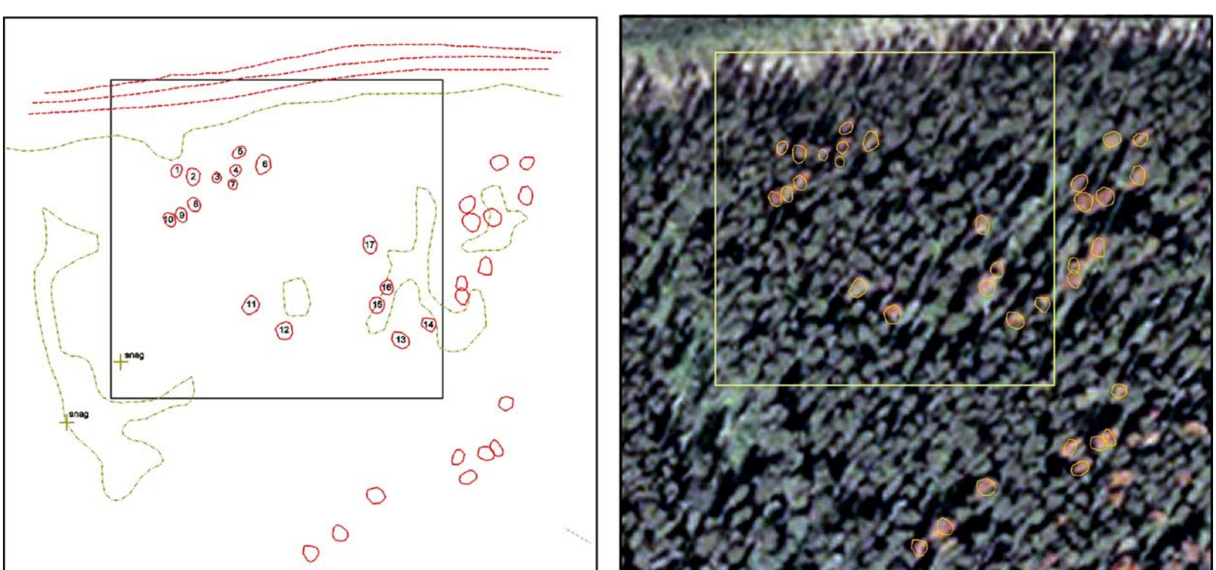

Fig. 2. Detailed stem map (left) generated from 1 : 20,000 colour photography (right).

west and 53°39′north, approximately 120 km west of Prince George. Elevations in the first area range from 640 to 1280 m, while elevations in the second area range from 850 to 1500 m.

The provincial forest inventory data indicates that the leading species in both study areas are dominated by mature lodgepole pine (*Pinus contorta*), which comprises 77% of the productive forest area. The second most common leading species is spruce (*Picea* spp.), comprising 19% of the productive forest area. Other minor leading species include alpine fir (*Abies lasiocarpa*) (at higher elevations) and aspen (*Populus tremuloides*). The lodgepole pine stands are characterized by an average age of 105 years, an average height of 19 m, and an average crown closure of 48%. Average stand density for these lodgepole pine stands is 1600 stems per hectare, with an average stand volume of 171 m^3, or a total volume of 270,857 m^3.

4. Data

4.1. Field data

Field crews were dispatched to validate the location and confirm the status of each of the red attack trees delineated on the photo interpreter's detailed stem map. Six field sites were visited; two of the sites were surveyed on April 28, 2003 and the remaining four sites were surveyed on May 12, 2003. For each tree at each test site, field crews collected the following information: tree species, species of bark beetle present, attack severity, diameter at breast height, and foliage color. Errors of omission (red attack trees missed by the photo interpreters) and commission (trees erroneously identified as red attack that were not red attack) were also noted by the field crew.

4.2. Aerial photography

Standard color aerial photography, at 1:20,000 scale, was used as a source of validation data in this project. The color aerial photography was collected on October 16, 2002. The aerial photography was orthorectified using an automated aerotriangulation process (ImageStation Automatic Triangulation).

4.3. High spatial resolution remotely sensed data

The high spatial resolution remotely sensed data used for this project was the 4-m multispectral IKONOS data, acquired the same day as the aerial photography (October 16, 2002). The multispectral IKONOS image was a georeferenced product with a positional accuracy of 15 m (Dial et al., 2003). The IKONOS satellite, launched in 1999, collects 1-m panchromatic and 4-m multispectral images concurrently. The IKONOS instrument has global coverage, a consistent acquisition schedule, and the capability to acquire imagery with near nadir viewing angles. The resolution of the sensor is suitable for high accuracy photogrammetric processing and mapping applications (Tao et al., 2004). With the robust geometric accuracy of the IKONOS sensor, 1:10,000 scale mapping can be produced without ground control and 1:2400 scale mapping with ground control (Dial et al., 2003). The 4-m multispectral data has similar spectral properties in the visible and near infrared wavelengths as Landsat ETM+ (Goward et al., 2003). With these spectral and spatial properties, IKONOS offers potential for natural resource applications (Goetz et al., 2003; Hurtt et al., 2003).

5. Methods

The project was completed in two phases, with each phase conducted in a separate geographic area (Fig. 1). The phase one area was used to confirm that 1:20,000 color aerial photography was a suitable surrogate for ground data for validating the presence of mountain pine beetle red attack. In the phase two area, a 4-m multispectral IKONOS image was classified, and areas of red attack were identified. The red attack areas identified from the IKONOS image were then validated against detailed stem maps of red attack trees, which were generated by photo interpreters using 1:20,000 color aerial photography.

5.1. Phase 1: Aerial photography as a surrogate for field data collection

The first phase of the project assessed the suitability of 1:20,000 color aerial photography to serve as a surrogate for ground validation data. A strong correspondence between the number and location of red trees identified by ground survey, and the number and location of red trees identified through the interpretation of air photos would greatly reduce the costs and time associated with the collection of validation data. (Field surveys cost approximately $11.00 CAD/ha, while surveys using 1:30,000 air photos cost approximately $0.15 CAD/ha.) Six 1-ha test sites were selected at random using a numbered grid overlaid on the phase one study area. A map of the six test site locations, and the air photos associated with each test site, were provided to an independent third party photogrammetric specialist (with extensive experience in air photo interpretation and local knowledge of the study area). Red attack tree crowns were identified and delineated with stereo pairs of air photos using DiAP Viewer, a Microstation compatible digital photogrammetric system. Each attacked tree was given a unique identifier and a distance and bearing from a known feature in the test site. With this method, a detailed stem map was compiled for each of the six test sites (see example in Fig. 2). The photo interpreter was certified and had local knowledge of the study area.

Fig. 3. 1:20,000 colour aerial photography superimposed on IKONOS 4-m multispectral imagery.© Space Imaging LLC, all rights reserved.

5.2. Phase 2: Identifying red attack trees using multispectral IKONOS imagery

The second phase of the project compared the classification of red attack generated from the multispectral IKONOS data to the detailed stem maps of red attack trees generated from 1:20,000 color aerial photography. The phase two area (Fig. 1) was split into two halves due to the lack of availability of air photos for the entire area; however, for the random selection of samples, the photos were treated as one dataset (Fig. 3). The phase two study area encompassed a wide range of infestation intensities. Infestation intensities were categorized into four distinct damage classes: non-attacked susceptible stands (zero); lightly infested susceptible stands with 1% to 5% of trees red attacked (low); moderately infested susceptible stands with greater than 5% and less than 20% trees red attacked (medium); and heavily infested susceptible stands with greater than 20% of trees red attacked (high).

The damage class for each site was determined by counting the number of live green and red stems within each test site; the ratio of red attack trees to live green trees determined the appropriate damage class for each site. Sites were selected at random and assigned a damage class. This process continued until ten 1-ha sites were selected for each of the zero, low, and medium damage classes. One of the low damage class sites was labeled incorrectly and was later dropped; therefore, analysis proceeded for the low damage class with only nine test sites. Non-attacked areas with no red attack trees (zero) were identified in order to test for false positives (errors of commission where a red attack tree is identified, but no red attack tree exists). High damage class sites (sites where greater than 20% of the trees in the stand were red attack) were not assessed because the infestation in these areas was too widespread to be considered for operational suppression treatments. The

Fig. 4. Exclusionary mask superimposed on IKONOS image. The areas under the mask were not included in the classification.

Table 1
Parameters used for unsupervised clustering algorithm (ISODATA)

Parameter	Value
Mask	Exclusionary mask
Desired number of clusters	255
Minimum number of clusters	255
Maximum number of clusters	255
Maximum iterations	10, 50, 100, 200, 500, 1000
Movement threshold	0.01
Lumping threshold	1
Number of samples	262144

objective of the detection and mapping exercise presented in this paper was to identify small, scattered infestations suitable for suppression activities. The process for generating the detailed stem maps from the stereo air photo pairs was identical to that described in under the methods for phase one of this project.

An image mask was generated from features in an ancillary GIS database. The mask was designed to exclude features such as logged areas, water bodies, and cloud cover from the classification (Fig. 4). The purpose of using the mask was to reduce the spectral variability inherent to forest stands (Franklin et al., 2003). An unsupervised classification (ISODATA) of the multispectral IKONOS imagery was then used to delineate the red attack trees. The unsupervised approach was selected to diminish the requirement for training data (Franklin et al., 2003). The parameters used in the clustering algorithm are provided in Table 1. An independent set of calibration data was used to identify which clusters corresponded to red attack locations. The calibration data consisted of four 1-ha sites where red attack trees were identified and detailed stem maps were created — as per the phase one component of this study. Three of the calibration sites were of the medium damage class and one was of the low damage class. The four calibration sites had a total of 274 red attack trees. Fig. 5 illustrates an example of the red attack trees identified by photo interpretation and those red attack trees identified by the unsupervised clustering of the multispectral IKONOS imagery.

5.3. Accuracy assessment

In order to account for slight differences in spatial location and to facilitate the accuracy assessment process, the air photos were spatially adjusted to match the IKONOS data. Landscape features were used to align the two data sources to a sufficient level of spatial correspondence to facilitate comparison of the photo-derived vectors (stem maps) and the red attack pixels identified from the IKONOS image. To further compensate for positional errors and differences in spatial resolution between the aerial photography and the multispectral IKONOS data, a series of buffers were generated around the 4-m multispectral IKONOS pixels identified as red attack (Fig. 6). Buffers, increasing in size by 1-m increments to a maximum of 4 m, were generated to characterize attribute accuracy as a function of positional accuracy.

From an operational perspective, a buffer corresponding to the dimensions of a single pixel (for multispectral IKONOS imagery, this distance is 4 m) is a logical choice for characterizing attribute accuracy. The consideration of buffers greater than 4 m in size is not practical (this suggests gross misregistration errors and results in unrealistic estimates of accuracy). Since accuracy will continue to increase with increasing buffer size, the estimates of accuracy for buffer sizes greater than the image pixel size will be impractical and may misrepresent the efficacy of the both the classification methods and the data source itself.

Three accuracy measures were used to enumerate the correspondence between the red attacked trees identified in the aerial photography and those identified with the

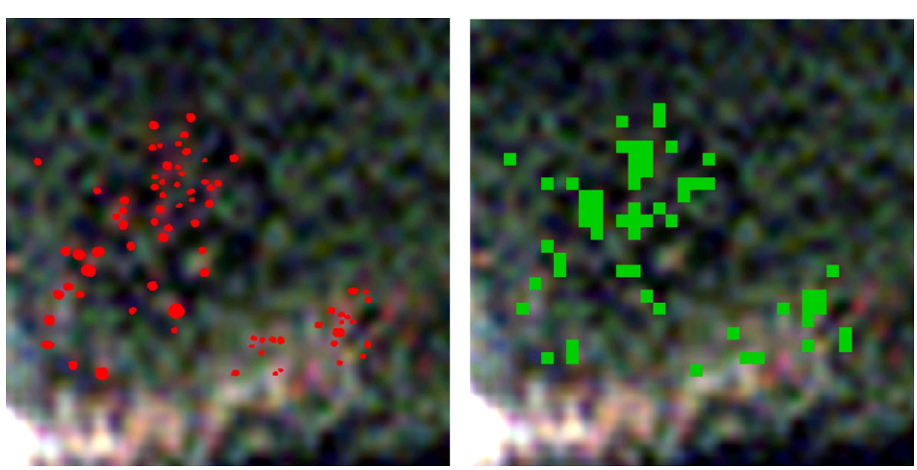

Fig. 5. Red attack tree crowns delineated from aerial photographs (left) and IKONOS pixels identified as red attack trees by the unsupervised clustering process (right).

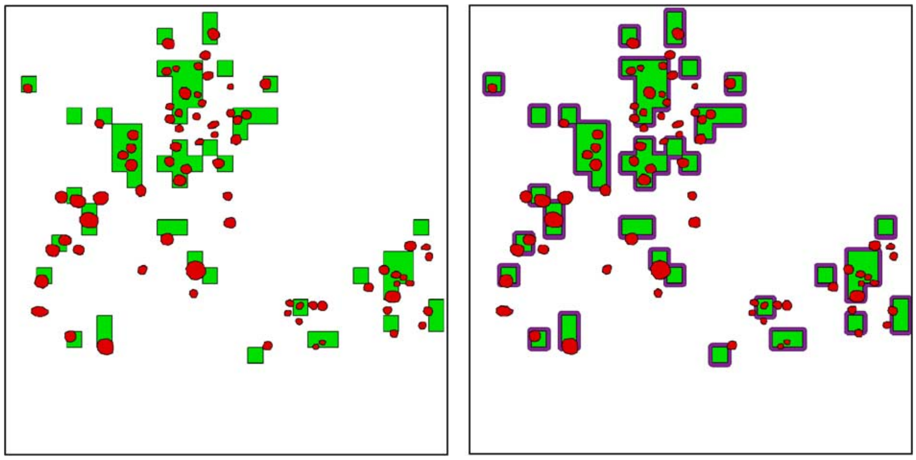

Fig. 6. Red attack crowns from photos (red) merged with red attack pixels from IKONOS (green) (left). 1-m buffer added to pixels for accuracy assessment (right). Additional buffers, in 1-m increments, were applied; accuracy measures were calculated for each buffer increment (see Table 2 for results).

clustering of the multispectral IKONOS data: true positive, omission and commission (Fig. 7). True positive is defined as red attack trees, identified on the aerial photography, which fall within the buffer applied to the red attack pixels identified in the multispectral IKONOS data. In the context of accuracy assessment for remote sensing, errors of omission are traditionally defined as the proportion of pixels incorrectly excluded from a particular class. However, in the context of this analysis, errors of omission are defined as the number of red attack trees, identified on the aerial photography, which are found outside the buffer surrounding the IKONOS red attack pixels. Similarly,

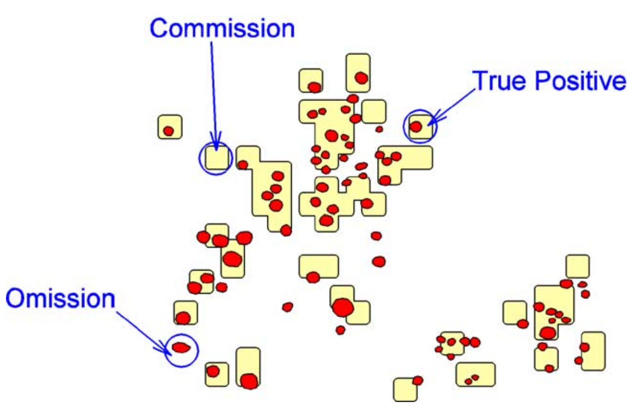

Fig. 7. Measures of correspondence between the red attack trees identified in the IKONOS image and the aerial photography: true positive, omission, commission. True positive accuracy is defined as red attack trees, identified on the aerial photography, which fall *inside* the buffer applied to red attack pixels identified on the IKONOS image (true positive pixels/total red attack trees (air photos)). Errors of omission are defined as the number of red attack trees, identified on the aerial photography, which fall *outside* the buffer applied to red attack pixels identified on the IKONOS image (omission/total red attack trees (air photos)). Errors of commission are defined as the number of buffers surrounding red attack pixels that have no red attack trees (as identified on aerial photography) *inside* them (commission/total red attack pixels (IKONOS image)).

errors of commission are traditionally defined as the proportion of pixels incorrectly assigned to a particular class, which actually belong to another class. In the context of this analysis; however, commission errors are defined as the number of buffers surrounding red attack pixels that have no red attack trees within them (as identified in the aerial photography). Confidence intervals for the accuracy proportions, at $\alpha = 0.05$, have been calculated to represent the confidence of the estimates for true positive rates and levels of omission and commission Table 2). Confidence intervals were calculated using standard methods that are appropriate for proportions (i.e. binomial distribution) (Czaplewski, 2003).

6. Results

6.1. Phase 1: Aerial photography as a surrogate for field data collection

A field crew validated each of the stem maps; every field site was visited and the location and status of each red attack tree, as identified on the stem map, was confirmed. Discrepancies with the stem map were recorded, as were any red attack trees omitted by the photo interpreters. A total of 210 trees, in the six 1-ha test sites, were identified as red attack by the photo interpreters. Of these identified red attack trees, only 1 tree was incorrectly identified as red attack (commission). Thus, 99.5% of the trees identified on the photos as red attack were red attack in the field. However, the field crews identified 23 additional red attack trees that were omitted from the detailed stem map derived from the aerial photos; the photo-interpretation therefore missed approximately 10% of the red attack trees located in the test sites.

The majority of these omitted trees were found in close association with other red attack trees and were difficult to distinguish as separate crowns on the air photos. In

Table 2
Validation results for low and medium damage class sites*

Low density attack sites				
Buffer size	1 m	2 m	3 m	4 m
Total red attack trees (air photos)	127	127	127	127
Total red attack pixels (IKONOS)	73	73	73	73
True positive (pixel count)	69	79	85	90
True positive (%)[a]	54.33	62.20	66.93	70.87
Lower 95% confidence interval (%)	45.27	53.37	58.35	62.57
Upper 95% confidence interval (%)	63.39	71.03	75.51	79.17
Omission (tree count)	58	48	42	37
Omission (%)[b]	45.67	37.80	33.07	29.13
Lower 95% confidence interval (%)	36.61	28.97	24.49	20.83
Upper 95% confidence interval (%)	54.73	46.63	41.65	37.43
Commission (buffer count)	9	8	8	7
Commission (%)[c]	12.33	10.96	10.96	9.59
Lower 95% confidence interval (%)	4.10	3.11	3.11	2.15
Upper 95% confidence interval (%)	20.56	18.81	18.81	17.03
Medium-density attack sites				
Buffer size	1 m	2 m	3 m	4 m
Total red attack trees (air photos)	510	510	510	510
Total red attack pixels (IKONOS)	389	389	389	389
True positive (pixel count)	398	439	457	471
True positive (%)[a]	78.04	86.08	89.61	92.35
Lower 95% confidence interval (%)	70.45	79.67	83.91	87.33
Upper 95% confidence interval (%)	85.63	92.49	95.31	97.37
Omission (tree count)	112	71	53	39
Omission (%)[b]	21.96	13.92	10.39	7.65
Lower 95% confidence interval (%)	14.37	7.51	4.69	2.63
Upper 95% confidence interval (%)	29.55	20.33	16.09	12.67
Commission (buffer count)	25	16	13	8
Commission (%)[c]	6.43	4.11	3.34	2.06
Lower 95% confidence interval (%)	3.86	2.01	1.43	0.52
Upper 95% confidence interval (%)	9.00	6.21	5.25	3.60

*Results included totals for all test sites for LOW (9 sites) and MEDIUM (10 sites) damage classes.

[a] True positive accuracy is defined as red attack trees, identified on the aerial photography, which fall *inside* the buffer applied to red attack pixels identified on the IKONOS image (# of true positive pixels/total # of red attack trees *on air photos*).

[b] Errors of omission are defined as the number of red attack trees, identified on the aerial photography, which fall *outside* the buffer applied to red attack pixels identified on the IKONOS image (omission count of trees/total red attack trees *on air photos*).

[c] Errors of commission are defined as the number of buffers surrounding red attack pixels that have no red attack trees (as identified on aerial photography) *inside* them (commission count of buffers/total # of red attack pixels on IKONOS image).

addition, it is possible that some of the omitted red attack trees identified by the field crew had turned red subsequent to the collection of the aerial photography. The photography was collected in October 2002; however, the field data was not collected until April and May 2003. Based on the results of phase one, 1:20,000 color aerial photography was accepted as a suitable surrogate for field data in detecting and mapping mountain pine beetle red attack. In phase two, detailed stem maps generated from 1:20,000 color aerial photography were used to validate the unsupervised classification of the 4-m multispectral IKONOS image.

6.2. Phase 2: Identifying red attack trees using multispectral IKONOS imagery

The ten sites examined for the zero damage class (non-attacked susceptible stands) had no red-attack areas identified on the IKONOS image. There were also no red attack trees identified by the photo interpreters in any of these ten sites; therefore no true positive or omission rates could be determined. The commission error for these sites was 0%, with no red-attack trees erroneously identified in the IKONOS image (no false positives). The results in these ten zero-damage sites suggest that the spectral signal of mountain pine beetle red attack damage was not confused with any other spectral responses in the study area, and that the image mask was effective in reducing the within-image variability in spectral response.

The results for the low damage class sites are presented in Table 2 and Fig. 8. Nine test sites were examined in the low test site damage class dataset (lightly infested susceptible stands with 1% to 5% red attack). The true positive values (using the 1-m buffer) indicated that red attacked trees in areas of low-density attack were detected and delineated with 54% accuracy. With the additional buffers, true positive accuracy ranged from 62% (2-m buffer) to 71% (4-m buffer). The omission results ranged from 46% (1-m buffer) to 29% (4-m buffer). The commission results ranged from 12% (1-m buffer) to 10% (4-m buffer).

The results for the medium damage class are presented in Table 2 and Fig. 9. Ten test sites were examined in the medium test site damage class dataset (moderately infested susceptible stands with greater than 5% but less than 20% red attack) and these results are presented in Fig. 9. The true positive values (using the 1-m buffer) indicated that red attacked trees in areas of medium-density attack were detected and delineated with 78% accuracy. True positive accuracy ranged from 86% (2-m buffer) to 92% (4-m buffer). The omission results ranged from 22% (1-m buffer) to 8% (4-m buffer). The commission results ranged from 6% (1-m buffer) to 3% (4-m buffer). For both low and medium damage classes, the confidence intervals indicate that as the buffer size

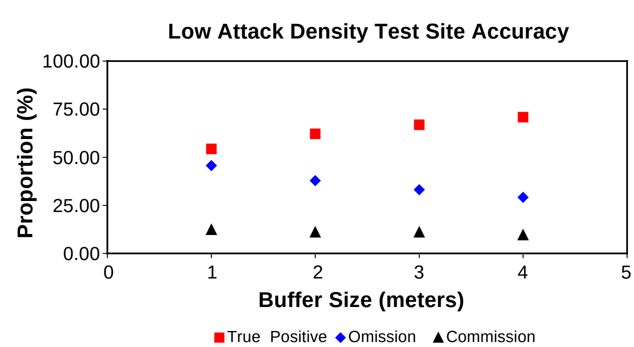

Fig. 8. Validation results for low damage class sites.

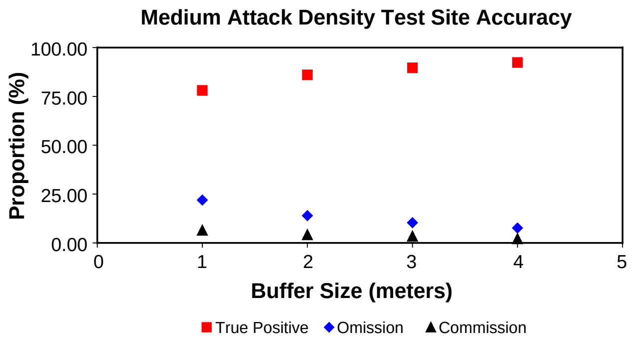

Fig. 9. Validation results for medium damage class sites.

increases, the true positive rate increases and the confidence interval narrows.

7. Discussion

This study was specifically designed to examine the potential of 4-m multispectral IKONOS imagery for red attack detection and mapping in areas identified for suppression by the British Columbia Ministry of Forests (Ministry of Forests, 2003b). These suppression areas have minimal levels of mountain pine beetle infestation, and the management objective in these suppression areas is to reduce or contain the outbreak to a size and distribution that can be handled within the capacity of existing forest industry infrastructure.

In the context of suppression activities associated with mountain pine beetle infestations, commission errors are much more problematic than errors of omission when detecting and mapping red attack. From an operational perspective, the deployment of field crews to sites falsely identified as red attack (as a result of commission error) has greater consequence than sites where red attack trees are located, but where every single red attack tree may not be identified on the photo. Therefore, based on the results of the phase one investigation and the importance of low commission errors, 1:20,000 color aerial photography was determined to be a suitable surrogate for ground data.

The spatial resolutions of the multispectral IKONOS image and the aerial photography are different, and therefore the objects discernable in the two image sources are also different. In addition to the differences in spatial resolution, positional errors must also be accounted for. Foody (2002) highlighted the need to incorporate positional tolerance into thematic accuracy assessments and suggested that an assumption of perfect co-registration between the two data sources should therefore not be made. The buffers used to characterize the change in accuracy with increasing distance from identified red attack pixels from the 4-m multispectral IKONOS imagery are one method of accounting for positional ambiguity.

The results of this study indicate that a one pixel (4-m) buffer is a reasonable size to account for potential positional errors from both the multispectral IKONOS imagery and the aerial photography. When a one pixel buffer (4-m) was applied to the red attack pixels, the true positive rates of red attack detection were 70.1% (low attack) and 92.5% (medium attack). These results indicate that the unsupervised classification of mountain pine beetle red attack using multispectral IKONOS imagery is an operationally viable approach. In addition, the generation of independent calibration data using aerial photography was instrumental in identifying the spectral clusters corresponding to red attack trees.

Phase one of this project indicated that there was a relationship between the detectability of red attack trees and both the size of a red attack tree crown and the association of the red attack tree with other adjacent red attack trees. Generally, the red attack trees that were missed by the photo interpreters were small crowns directly adjacent to other, larger red attack trees. The average tree crown diameter of all 637 trees in the study dataset was 2.9 m. Similar to the patterns of omission observed in phase one, properties of omitted red attack trees were analyzed to determine the relationship between tree crown diameter and the distance (or proximity) of red trees to other red trees. It was observed that red trees with an average tree crown diameter of 1.5 m or less were omitted when they occurred an average distance of 11.3 m or greater from another red tree. When red trees that exceed a diameter of 1.5 m occur singularly or in groups and are located within 11.3 m of the next nearest red tree(s), they are accurately detected with 54% to 78% accuracy (for low and medium damage classes).

As outlined earlier, accuracy, consistency, and timeliness are the three critical data collection requirements for mountain pine beetle detection and mapping at landscape and local scales. It has been demonstrated through this study that 4-m multispectral IKONOS data can provide accurate and consistent detection and mapping of mountain pine beetle red attack, even in sites with relatively low levels of infestation. Processes for acquiring IKONOS imagery are timely, although they are subject to cloud cover conditions (as are other remote sensing methods — including aerial overview surveys and helicopter GPS surveys). However, the monetary costs of IKONOS data should be considered relative to other survey methods currently in use, as cost may be an operational constraint to the widespread use of IKONOS imagery for mountain pine beetle red attack detection and mapping.

Aerial overview surveys cost approximately \$0.01 CAD/ha, whereas helicopter GPS surveys cost \$0.15 CAD/ha and 1:30,000 air photo surveys cost \$0.21 CAD/ha. Field surveys typically cost \$11.00 CAD/ha. These cost estimates include all aspects of the survey-from data acquisition to production of the final deliverables. Costs for IKONOS imagery vary; to purchase archive 4-m multispectral imagery costs approximately \$0.09/ha, while tasking the satellite to acquire data in a specific area of interest costs approximately \$0.23 CAD/ha. These costs for IKONOS imagery are only the data costs and do not include costs for processing, classification, or creation of the final deliverables. This summary of survey costs indicates that there may be an operational niche for IKONOS data where aerial photography or helicopter GPS survey data has not, or cannot be collected, and where the level of detail provided by a field survey is not required by the management objective under consideration. In addition, archive IKONOS imagery can be extremely useful in retrospective analyses for detection and mapping of mountain pine beetle red attack in previous years where no other high spatial resolution data source was collected.

8. Conclusion

Spatially-explicit information on mountain pine beetle activities (as indicated by red attack location) is required for areas identified for suppression activities. This information is used to plan treatment activities designed to contain or reduce the mountain pine beetle infestation (through selective harvest), to a level that can be managed within logistical constraints, such as harvesting and milling capacities. Therefore a strong operational need exists to have an efficient and cost-effective method to identify red attack trees in these suppression areas. High resolution remotely sensed data provides a potential source for accurate, consistent, and timely data for this application.

This investigation has demonstrated that 4-m multispectral IKONOS data may be successfully used for the detection and mapping of mountain pine beetle red attack, under certain conditions. Sites with low levels of infestation present problems for detection with 4-m multispectral IKONOS imagery due to the disperse nature of this level of infestation and the weak spectral signal generated by single, red attack trees. As the buffer size increased from 1 to 4 m, the detection accuracy also increased, ranging from 54% (low damage class) for the 1-m buffer to 93% for the 4-m buffer (medium damage class). In addition, the commission error results for both of these damage classes were low and decreased further with increasing buffer size. The reporting of accuracy by buffer size (Figs. 8 and 9) can be used to reflect different management or treatment objectives. For example, for mapping purposes where spatial locations of red attack are paramount, a more conservative estimate of accuracy may be appropriate and a smaller buffer size, and consequently a lower level of accuracy, selected. Alternatively, for other applications where omission errors are more significant (e.g. suppression), it may be appropriate to adopt an estimate of red attack with lower omission errors and a correspondingly larger buffer size (as field crews would want to remove as many red attack trees as possible, in addition to identifying any potential green-attack trees at the site).

Acknowledgements

This research is the result of a collaboration of the Canadian Forest Service, the British Columbia Ministry of Forests, the University of Northern British Columbia, and Kim Forest Management Ltd. (KFM), where KFM undertook the data collection, photo interpretation, and the subsequent image analysis. This work was funded by the Province of British Columbia's Forestry Innovation Investment Program and by Canadian Forest Products Ltd. The early contributions of Dr. Pranesh Kumar (University of Northern British Columbia) are gratefully acknowledged. Elements of this project were funded by the Government of Canada through the Mountain Pine Beetle Initiative, a six-year, $40 million program administered by Natural Resources Canada, Canadian Forest Service (http://mpb.cfs.nrcan.gc.ca).

References

Amman, G. D. (1982). The mountain pine beetle—identification, biology, causes of outbreaks, and entomological research needs. *Proceedings of the joint Canada/USA workshop on mountain pine beetle related problems in western North America* (pp. 7–12). Victoria, British Columbia: Canadian Forestry Service.

Czaplewski, R. L. (2003). Accuracy assessment of maps of forest condition. In M. A. Wulder, & S. E. Franklin (Eds.), *Remote sensing of forest environments: Concepts and case studies* (pp. 115–140). Boston: Kluwer Academic Publishers.

Dial, G., Bowen, H., Gerlach, F., Grodecki, J., & Oleszczuk, R. (2003). IKONOS satellite, imagery and products. *Remote Sensing of Environment*, *88*, 23–36.

Foody, G. M. (2002). Status of land cover classification accuracy assessment. *Remote Sensing of Environment*, *80*, 185–201.

Franklin, S., Wulder, M., Skakun, R., & Carroll, A. (2003). Mountain pine beetle red attack damage classification using stratified Landsat TM data in British Columbia, Canada. *Photogrammetric Engineering and Remote Sensing*, *69*, 283–288.

Goetz, S. J., Wright, R. K., Smith, A. J., Zinecker, E., & Schaub, E. (2003). IKONOS imagery for resource management: Tree cover, impervious surfaces, and riparian buffer analysis in the mid-Atlantic region. *Remote Sensing of Environment*, *88*, 195–208.

Goward, S. N., Davis, P. E., Fleming, D., Miller, L., & Townshend, J. R. (2003). Empirical comparison of Landsat 7 and IKONOS multispectral measurements for selected Earth Observation System (EOS) validation sites. *Remote Sensing of Environment*, *88*, 80–99.

Henigman, J., Ebata, T., Allen, E., Holt, J., & Pollard, A. (Eds.) (1999). *Field guide to forest damage in British Columbia*. Victoria: British Columbia Ministry of Forests, Victoria, British Columbia.

Hill, J. B., Popp, H. W., & Grove Jr., A. R. (1967). *Botany: A textbook for colleges* (4th edition). Toronto: McGraw-Hill Book Co.

Hurtt, G., Xiao, X., Keller, M., Palace, M., Asner, G. P., Braswell, R., et al. (2003). IKONOS imagery for the large scale biosphere–atmosphere experiment in Amazonia (LBA). *Remote Sensing of Environment*, *88*, 111–127.

Medinger, D., & Pojar J. (Eds.) (1991). Ecosystems of British Columbia. *Special Report Series*, *vol. 6*. Victoria, British Columbia: Research Branch, British Columbia Ministry of Forests.

Ministry of Forests. (1995). *Bark beetle management guidebook (forest practices code)*. Victoria, British Columbia: Forest Practices Branch.

Ministry of Forests. (2003a). *Timber supply and the mountain pine beetle infestation in British Columbia*. Forest Analysis BranchVictoria, British Columbia: .

Ministry of Forests. (2003b). *Provincial bark beetle management technical implementation guidelines*. Victoria, British Columbia: Forest Practices Branch.

Ministry of Forests. (2005). 2004 aerial overview survey estimates (preliminary). Available online. Site accessed January 24, 2005. URL: http://www.for.gov.bc.ca/ftp/HFP/external/!publish/Aerial_Overview/2004/2004_overviewFeb23.xls.

Ministry of Forests and Canadian Forest Service. (2000). *Forest health aerial overview survey standards for British Columbia, version 2.0 The B.C. Ministry of Forests adaptation of the Canadian Forest Services's FHN Report 97-1 "Overview of aerial survey standards for British Columbia and the Yukon"*. Victoria, British Columbia: Resources Inventory Committee.

Nelson, T., Boots, B., & Wulder, M. A. (2004). *Point-based, aerial surveys of mountain pine beetle infestations: Exploring survey accuracy and data representation*. Victoria, British Columbia: Mountain Pine Beetle Initiative Report.

Safranyik, L., Shrimpton, D., & Whitney, H. (1974). *Management of lodgepole pine to reduce losses from the mountain pine beetle*. Victoria, British Columbia: Environment Canada, Forestry Service.

Skakun, R. S., Wulder, M. A., & Franklin, S. E. (2003). Sensitivity of the thematic mapper enhanced wetness difference index (EWDI) to detect mountain pine needle red attack damage. *Remote Sensing of Environment*, *86*, 433–443.

Tao, C. V., Hu, Y., & Jiang, W. (2004). Photogrammetric exploitation of IKONOS imagery for mapping applications. *International Journal of Remote Sensing*, *25*, 2833–2853.

Westfall, J. (2003). *2002 Summary of forest health conditions in British Columbia*. Victoria, British Columbia: Forest Practices Branch.

Wiart, R. J. (2003). *Detecting and mapping mountain pine beetle infestations: Defining the role of remote sensing and establishing research priorities. Workshop Summary Report, June 26–27, 2003. Vancouver, British Columbia*. Victoria, British Columbia: R.J. Wiart and Associates.

Wood, S. L. (1963). A revision of bark beetle genus *Dendroctonus* Erickson (Coleoptera: Scolytidae). *Great Basin Naturalist*, *23*, 1–117.