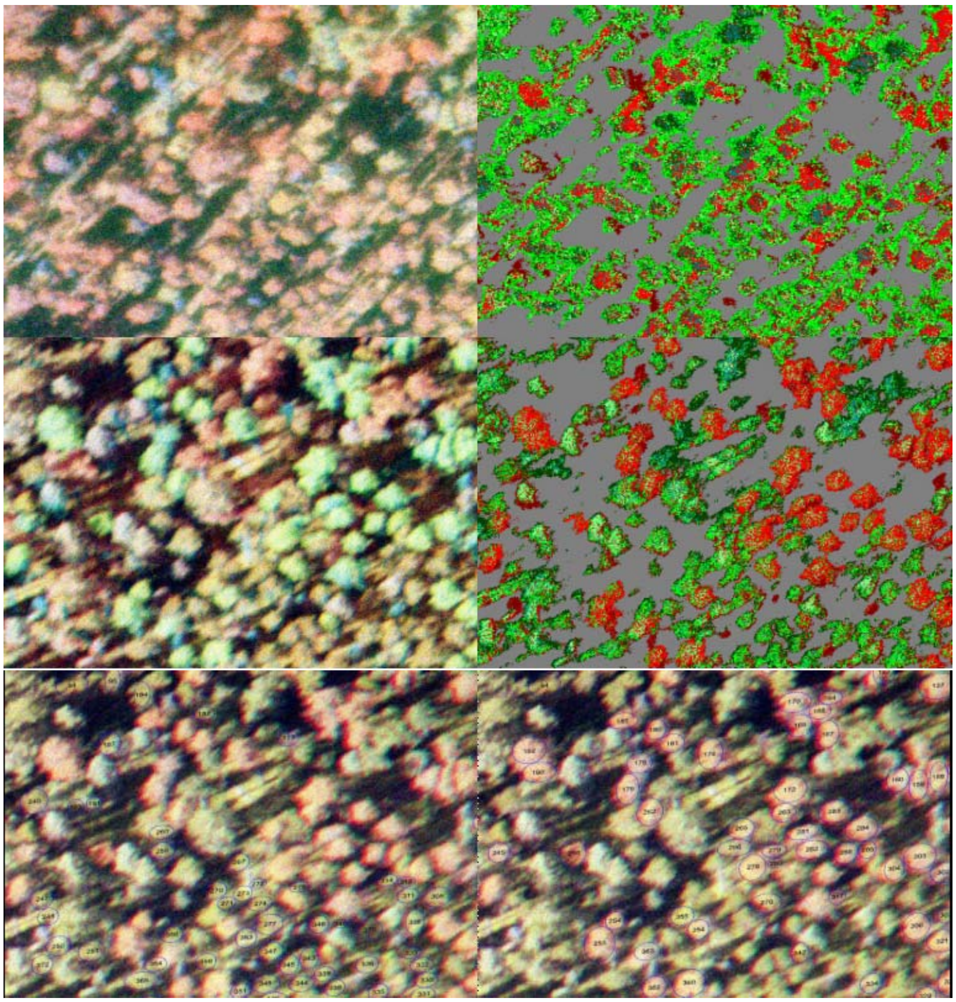
Mountain Pine Beetle Detection and Monitoring: Remote Sensing Evaluations



FII Operational Report with Reference to Recipient Agreement R2003-0205
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Cover Image: June 12, 2002 & August 14, 2002. Two multispectral images with supervised classifications from the Blackwater site: Top – June 12: false colour infrared composite with new reds as yellow, healthy trees as pink/orange and old reds as blue; right: results from supervised classification showing new red attack trees as bright red, healthy trees in different shades of green and old reds as dark red. Middle – Aug. 14: false colour infrared composite with new reds as green, healthy trees as pink/orange and old reds as blue; right: results from supervised classification showing new red attack trees as bright red, healthy trees in different shades of green and old reds as dark red. Bottom – Aug. 14: left - normal colour composite with heavily attacked trees ground truthed in 2001 circled & numbered, new red attack trees as red, healthy trees as green and old reds as grey; right - normal colour composite with new red attack trees as red, healthy trees ground truthed in 2001 circled & numbered, healthy trees as green and old reds as grey.

ABSTRACT

This report covers the first year of a five year study in the development of an applied remote sensing strategy for resource management of BC forests and forest health, involving airborne remote sensing for monitoring and control of mountain pine beetle infestations. This project addresses the most efficient and reliable remote sensing strategies for identifying and mapping, in a practical and cost effective manner, early infestation stages (current attack) of MPB and subsequent advanced stages including detection and mapping of "red attack" and monitoring infestation spread across time.

Digitally converted multispectral aerial photography was found to perform best for early detection of current attack and mapping and monitoring red attack. Results indicate that a spreading current attack can be reliably detected between mid May and early June at our sites. For mapping red attack a scale of 1:16000 is recommended at this time. For early detection experiments the 1:8000 imagery was superior but the 1:16000 imagery would be operationally effective. Aerial photography (multispectral and digitally converted) is clearly the remote sensing imaging system that can most accurately and cost effectively addresses this critical MPB problem. Of equal importance is the capability of aerial photography being implemented in a timely fashion by both government and the private sector in a business environment using competitive tendering.

KEYWORDS

mountain pine beetle, remote sensing, detection, monitoring, mapping, forest health, lodgepole pine, current attack, red attack, digital multispectral aerial photography

INTRODUCTION

This report outlines particulars regarding the second phase of a pilot study to acquire, process and evaluate digitally converted aerial photographic imagery for the detection and monitoring of mountain pine beetle (MPB) infestations. This project was jointly funded by the BC Ministry of Forests, West Fraser Mills Ltd. and Forestry Investment Innovation. FII supported airborne data acquisition in the summer and fall, fall ground truth, analogue to digital data conversion, imagery registration and enhancement, imagery classifications, variance analyses and GIS evaluation. Without this research support this project would not have been possible and the authors gratefully acknowledge this assistance.

The overall study developed and refined an applied remote sensing strategy for resource management by the MoF, West Fraser and the SFU/FII research team. It involves monitoring and control of MPB infestations. This project addresses the most efficient and reliable remote sensing strategy for investigating the possibility of identifying and mapping early infestation stages (current attack) of MPB in lodgepole pine forests in a practical and cost effective manner. In addition the project recommends optimum strategies for identifying and mapping advanced MPB attacks (red and gray attacks).

An additional aspect of the study is to evaluate applied RS tools for the general monitoring and control of forest pathogens and pests as well as related procedures that can be used for other environmental monitoring practices: e.g. riparian vegetation, erosion, logging practices, suspended sediment concentrations, stream morphology and habitat.

This research evaluation and remote sensing study was planned to specifically enhance knowledge by identifying and evaluating the remote sensing imaging systems and analytical procedures that most accurately and cost effectively address this critical MPB problem. This study provides a strategic framework with short, medium and long-term considerations of the role of remote sensing in forest resource management.

Over the past decade MOF has engaged in a series of research projects to evaluate the potential for orbital and airborne electronic sensor systems to contribute to forest health resource management. Although substantial financial and personnel resources have been committed to these projects. The results have been generally inconclusive at best and often clearly disappointing.

Satellite imagery suffers from: (1) availability problems due to cloud cover and orbital periodicity, and (2) inadequate spatial resolution for forest health issues that require a suitable spectral image for individual tree crowns.

The use of airborne imaging spectrometers (e.g. CASI) and multispectral scanners (e.g. GERS) has proved disappointing. There have been no satisfactory results for reliable early (current attack) detection of MPB and other forest pests. Secondly these airborne line-imaging systems are not good mapping instruments in comparison with aerial photography. This inevitably drives up the costs for any operational project.

An obvious gap in remote sensing research, related to these forest health problems, has been the almost complete lack of experimentation (and comparison) with digitally converted colour, colour infrared and multispectral aerial photography. In particular it is recommended that all experimental studies be evaluated against this standard in terms of: (i) mapping accuracy, (ii) potential for automated spectral interpretations and (iii) cost effectiveness. Aerial photography is the "gold standard" in terms of mapping.

Of concern is the continuing assertions by the contractors, undertaking MOF MPB remote sensing projects over several years of testing, that their results were "promising" and indicated "operational potential". This is further outlined by the "positive spin" that has been placed on apparently unreliable results evaluated in some of these reports. The results, in contrast, clearly indicate that no reliable remote sensing signal for predicting early current MPB attack under the tested conditions has been detected.

Related to this concern is the fact that the scientific "particulars" were often not available for evaluation: specifically with many CASI studies there was no adequate information, throughout the sequence of experiments over the past few years, regarding the: (i) spectral image bands used, (ii) analytical procedures and (iii) statistical verification. At no point was adequate information made available by the contracting companies in order to permit scientific validation of the conclusions presented in their reports.

Additionally, the processed imagery used in many of the analyses was not made available in order to permit independent examination and evaluation. All of this could have been done without violation of "proprietary" agreements in contracts.

If predictive classifications are tested in the future, future operational trials should include rigorous trial designs and utilize rigorous and independent blind testing. All scientific and analytical procedures should be made available for independent evaluation. All imagery used in the analyses should be made available for independent examination and evaluation.

The current provincial visual overview flight program should evaluate the utility of incorporating an increased use of aerial photography for detection and mapping of "red attacked" trees. It should be a point of evaluation to determine if this will be less expensive and/or more comprehensive. In addition to detection and mapping there is considerable potential for objectively and comprehensively monitoring the spread of this infestation by mapping the red attack and/or, for the late spring early summer months, mapping the spreading current attack.

For general forestry applications conventional aerial photography should be used as much as possible. For forest health issues the use of digitally converted colour and colour infrared aerial photography is recommended for detection and mapping of forest health conditions that require the capability to clearly distinguish individual tree crowns. In circumstances where it is desirable to have greater spectral detail (e.g. for early detection of forest health problems) the use of a multispectral photographic camera system (4 spectral bands: b, g, r & nir) or twin camera system (colour and infrared film in two synchronized cameras: b, g, r & nir) and digital image conversion is recommended.

For large area evaluations, that do not require the ability to resolve individual tree crowns, a variety of satellite imagery can also be considered.

The continuation of a suitable aerial photography program to meet the BC forest health needs in terms of recurrent mapping for infestation detection and spread is essential. The development of a computer assisted spectral image interpretation and mapping procedure, using the digital aerial photography, becomes the next logical step. Investigation into the suitability of using colour infrared and/or multispectral aerial photography for current attack detection of MPB infestations and other forest health early-detection applications should be undertaken.

Long-term considerations involve the melding of an operational digital aerial photography detection and mapping program with an experimental program. The experimental program should utilize airborne & orbital platforms and electro optical systems (digital frame cameras and imaging spectrometers) in support of the "operational" digital photography. This should not be considered as a primary investigative technology until the utility is clearly demonstrated. An important aspect will be to monitor and evaluate the need, at some time in the future, to phase out the use of aerial photography and replace that operational program with new generation direct digital frame or line imaging electro optical systems.

REMOTE SENSING EVALUATIONS

There is a large body of forestry related remote sensing research in the academic literature (e.g. in the *International Journal of Remote Sensing* this has accounted for approximately 10% of the studies). Most of these studies have involved the use of orbital imagery to undertake small-scale (large area) analyses. In comparison, very few studies involving airborne data have been published (<1%).

In British Columbia over the past decade there has been a sequence of studies investigating the utility of orbital and airborne electro optical remote sensing related to forestry health.

Prior to this a number of authors (Heller, 1968; Hobbs and Murtha, 1984; Hall and Maher, 1985; Murtha, 1985; Murtha and Wiart, 1989) evaluated colour infrared photography for signs of early infestation detection. Ahern (1988) and Runnesson (1991) undertook ground based spectroscopic analyses with some conflicting results.

Case Studies

Gimbarzevsky et al 1992:

Gimbarzevsky et al (1992) undertook to evaluate colour and colour infrared aerial photography, at a variety of image scales, and a multispectral scanner system for mapping MPB infestations in support of the aerial overview sketch mapping program. They used 2 RC10 mapping cameras imaging at 1:56000, 1:19000 and 1:8000 with simultaneous 11 channel scanner imagery. These images were flown on August 11 & 12, 1981. They subsequently flew 1:2000 and 1:6000 70mm colour photography over sketch mapped damage areas. They also used oblique 35mm colour slides and compared Landsat 6 imagery from August 16, 1981. All of their interpretations were visual from the photography and prints of the scanner and digitally enhanced Landsat images.

They concluded that colour and colour infrared aerial photography was considerably superior to the multispectral scanner and Landsat imagery and that the use of aerial photography would enhance the aerial sketch mapping program.

Henderson, 1994:

On September 10, 1993 3.5 m pixel resolution CASI imagery was flown using 12 spectral imaging bands across the spectrum from blue to NIR to permit an evaluation of the utility of CASI imagery for the detection of Douglas-fir beetle infestations (Henderson, 1994). Henderson reported that three spectral image bands (NIR: 745-755nm, R: 672-684nm, G: 540-558nm) showed the greatest differences in response between healthy and red/grey attacked trees. He also reported that a principal component analysis (PCA) was effective in reducing the total image variance from 12 bands to 6 components. Unfortunately the loadings for these PCA components were not given. The principal objective of this project was to determine if CASI imagery could be used to separate beetle attacked trees from healthy trees. The only positive result indicated the ability to separate a combined category of red and grey attacked trees from healthy and green attacked trees. The only significant spectral differences were on a red band (#8: 672-684nm) and a NIR band (#11: 745-756nm). This was determined on the reflectance differences between red attacked trees and healthy trees. Henderson was not able to separate red attacked trees from grey attacked trees and green attacked trees from healthy trees.

These results are inferior to normal colour photography in that they were not able to discriminate between red trees and grey trees.

Connery et al, 1994:

In 1994 Aero Sense (Connery et al, 1994) undertook an evaluation of CASI 6.5 m and 3m pixel resolution imagery for forest health detection of spruce budworm and spruce bark beetle. The imagery was flown August 25 and 26, 1994 using two different spectral band combinations. The number of spectral image bands was constrained by aircraft altitude, speed and sensor head readout rate. In general a number of near infrared (NIR), red (R), green (G) and blue (B) spectral bands were selected. Analyses consisted of "supervised classifications" using a maximum likelihood classifier. It was not specifically stated if the entire 13 or 8 spectral band data sets were used in these analyses. From the results this seems to have been the case: e.g. "...spruce bark beetle severity map resulting from further classification of the eight band Geobotany band set". No stepwise or data reduction procedures were reported. Their results indicate that medium levels of spruce bark beetle damage can be separated from areas with nil or low damage on the basis of albedo (image brightness) across the entire spectrum imaged. There was no specific spectral wavelength or combination of wavelengths that was reported as specifically contributing to the damage separation. Their attempts to detect spruce budworm damage were inconclusive.

These "damage" detection results could have been easily achieved through visual inspection of colour aerial photography.

Itres, 1997:

In May and October 1996 Itres (1997) flew (0.6m spatial resolution) CASI imagery to evaluate the potential for detection of root rot in conifers. Because of difficulties of imaging with snow cover, their analyses were restricted to the October 7, 1996 imagery. Although their report provided no details regarding the spectral image bands analyzed, they concluded that the "root rot health classes cannot be readily distinguished in the visible portion of the spectrum". Even though they concluded that the "IR portion of the spectra was related to health class", they point out that "while a trend is apparent between mean IR and health classes the standard deviation of the mean… indicates that the health classes are not statistically separable". When they ratioed the IR with a red band they determined that variations in this ratio related to intensity of IR reflectance and could be used to separate the healthy from the infected trees as a result of reduced IR reflectance from the attacked trees.

They determined these results to be "extremely promising" although no comparisons were undertaken with a blind sample dataset or with infrared aerial photography. It is equally probable that colour infrared aerial photography would produce results at least as successful.

Reich and Price, 1998:

Reich and Price undertook to evaluate the performance of the October 7, 1996 CASI imagery that was flown for the detection of root rot in spruce. This was the same imagery reported by Itres (1997) and the 8 spectral image bands were specified but there was no detailed description or evaluation of the spectral procedures and performance (undertaken by Itres) beyond the mention of the green spectral region being used to define conifers and the use of an unspecified IR/R ratio procedure to determine health classes. The general healthy classes of severe, moderate and light were based upon visual ground observations of discolouration and needle loss in the infested stand. The CASI data were able to detect the severely discoloured and damaged trees reliably but there were substantial errors and confusion between the moderate light and healthy classes. Although there were no comparisons made with aerial photography, the indications are that colour and/or colour infrared aerial photography would have performed at least as well in the spectral classifications and with considerable greater accuracy and reduced cost for the mapping. This was one of the few studies where the results were clearly laid out for performance evaluation.

Leckie et al, 1998:

On September 27 1996 (60cm spatial resolution) CASI imagery was obtained over a Douglas-fir stand to evaluate the imagery for potential to detect root rot (Leckie et al, 1998). Eight spectral bands covering portions of the B, G, R and NIR spectrum were acquired. They concluded that the red (656nm) spectral band had the best correlation with percent needle loss, "followed by the blue and then near-infrared bands". They determined that NIR/R ratio procedures gave the strongest linear correlation with needle loss. Although no data reduction techniques were reported, they deleted one of the image bands (438nm) from classification due to noise. The results of a maximum likelihood classification using the other seven image bands indicated an overall classification accuracy of 77% with dead, severe and moderate needle loss classes having the best results and 12-27% confusion in light needle loss and healthy classes (including 13% of healthy trees being classified as having moderate needle loss damage). They also cautioned that these results may not replicate with the same reliability as they used the same trees in the classification as were used to generate the "classification signatures".

They concluded that these results are promising but there was considerable confusion in the light and healthy classifications. Their best results were with dead trees and trees showing severe to moderate needle loss. These results are similar to the previous Itres study with NIR/R ratios producing the best correlations. As with the Itres study, there was no "blind" verification or comparison with near infrared aerial photography.

Davison et al, 1998:

In early October 1996 Itres flew (60cm spatial resolution) 8 band multispectral imagery for (1) forestry land classification, (2) stem densities, (3) crown closure, (4) forest health/stress estimates. They concluded that their classifications could "successfully… separate deciduous trees, water, gravel & roads, open areas and conifers". Their results for stem densities, crown closure and forest health were not successful although they indicated that the NIR and R spectral regions produced the best results for forest health.

Although they felt these results were "encouraging" they conducted no "blind" plot evaluations and did not undertake any comparisons with aerial photography. In general, the use of colour and colour infrared aerial photography provides superior interpretative results.

Spatial Mapping 1998/99

Spatial Mapping Limited determined that 30m spatial resolution Landsat data could identify and map large areas with predominantly MPB red attacked trees. Although this can show the extent of extremely severe old attacks it does not offer any potential for early detection of current MPB attacks.

Price and Jakubauskas, 1998:

Price and Jakubauskas (1998) used July 1991 Landsat 30m TM imagery to identify red attacked lodgepole pine in Yellow Stone National Park. They concluded that attacked trees have a spectral shift from green to red with an overall increase in image "brightness". As with the Spatial Mapping study, this can show the extent of extremely severe old attacks but it does not offer any potential for early detection of current MPB attacks.

Norquay and Murtha, 2000:

Norquay and Murtha, (2000) used September 12, 1999 Landsat 30m TM imagery to locate stands of trees in the red attack stage from MPB. They were not successful in locating red attacked areas with image classifications, although their supervised classifications performed a little better than their other classification procedures. They also employed a sub-pixel analysis that provided about 67% accuracy for identifying red attack when compared to aerial photography. Their omission errors were 33% but their commission errors were very large: 58 of the 87 red attacked trees were correctly identified but 495 trees that did not show red attack on the aerial photography were classified as red attack.

Clearly the aerial photography was considerably superior (it was employed as the comparison standard). Bortolot and Murtha (1999) obtained similar results using an August 23, 1998 TM 30m image to locate areas of MPB attack and verified their results against 1:2000 scale aerial photography.

Itres, 2000:

Itres (2000) used October 1, 1999 (60cm spatial resolution) 36 spectral band CASI imagery to determine if there were spectral indicators for green attack by MPB in lodgepole pine in early October. After extensive analyses they found that their selected band ratio procedures were not productive and that their best separation results indicated a slight "blue shift" in the spectral reflectance of green attacked trees along the "red edge", as opposed to the healthy lodgepole pine trees examined. They indicated that a ratio on the red edge slope (722/706nm) could be manipulated to produce successful results. Their sample, from the single site tested, included a small sample of individually selected trees and consisted of "only 15 green stage trees and 9 healthy pines". This was an exceptionally small sample, considering the area imaged and the critical fact that no "blind" confirmation procedure was employed.

Their recommendations for future success were to use an improved CASI instrument examining at least 3 spectral bands along the "red edge" (presumably approximately 700-725nm according to this study). Any form of "broad band" sensor was considered to be inadequate for this type of study and no comparisons were made with any type of aerial photography.

Heath, 2001:

Heath (2001) used September 29, 1999 (60cm spatial resolution) 36 spectral band CASI imagery to determine if there were spectral indicators and analytical procedures that would separate green attack by MPB in lodgepole pine from healthy lodgepole pine. He used a sample of 24 green attack trees and 25 healthy trees for comparisons.

Using the 60cm data, two of the 36 spectral bands, G (540nm) and NIR (706nm), were indicated by the stepwise inclusive discriminant analysis as the only spectral bands that contributed to separating the green attack and healthy samples. His best result, from a number of procedures, indicated that 79% of the green attack and 68% of the non-attack trees were correctly re-classified after being discriminated on the basis of the same sample. A subsequent discriminant analysis using the same data and procedures but with spatial resolution averaged to 1.2m pixels indicated that B (465nm) was the strongest contributor followed by B-G (494nm) and finally G (509nm). None of the other 33 spectral bands contributed to the spectral separation. Most importantly the only two bands (540nm & 706nm) that gave a separation with the 60cm "raw" data made no contribution.

Heath also points out that only one band ratio was significant in separating the samples, although other tested ratios showed some slight separation. The one exception was the ratio (722nm/706nm) indicated in the Itres (2000) study (indicated by Itres as the only spectral data contributing to their separation of green attack and healthy trees). For Heath, this ratio showed no separation between the samples.

When Heath's 36 spectral image bands were individually analyzed for statistical significance for separating the two samples (24 green attack trees and 25 healthy trees), only one of the 36 spectral bands showed significance at 0.05 probability level (one chance in 20 that the result is random). That band was a NIR (830nm) band that was not indicated by any of his discriminant analyses as contributing to separating the samples.

Furthermore Itres (2000) reported a "blue" shift on the "red edge" for their green attack population (showing an increase in red reflectance with attacked trees) and Heath reported a conflicting "infrared shift" with his averaged (1.2m) data (showing an increase in NIR reflectance).

In Heath's study no comparisons were made with any form of aerial photography. Heath's imagery was flown two days prior to the Itres (2000) imagery in the same site area (Tyee Lake) using the same platform, sensor, spectral data and basic calibration. The Itres-Heath results are in complete conflict and Heath's 1.2m averaged data are in conflict with his 60cm raw data.

Finally, Heath analyzed 36 spectral image bands to see if there was any statistically significant differences at the 0.05 probability level for these bands when used to separate the 24 selected green attack trees and the 25 selected healthy trees. Because this is a one in twenty chance probability, we would expect that if 20 evaluations were run one would show significance at this level. In fact, 36 were run with one spectral band (that made no contribution to either study) showing "significance". These CASI data (Heath, 2001 and Itres, 2000) and the related analyses are clearly not detecting any spectral signal that will separate these populations other than at a level of chance. Heath pointed out that there were no visual indicators for separating healthy and attacked trees on any of the image bands, band ratios or any other processed images.

Itres, 2001:

In September 2000 Itres flew new imagery for early MPB detection but reported that a critical spectral imaging band had not been included, so they returned to re-analyze the 1999 Tyee Lake imagery further. They stated that their "previous study on a single test area in Tyee Lake used the wavelength of the inflection point of the red edge to identify mpb green stage attack. This methodology was found to be inadequate to handle the much larger range of stand vigor, tree size and illumination conditions".

They proceeded to carefully select suitable trees for a new test sample in the Tyee Lake study area. This involved examination of each tree and selective acceptance/rejection based upon how well they felt the trees suited their categories. Such a procedure inevitably produces a biased sample. In the three study site areas they used manually selected lodgepole pine samples of 22, 27 and 20 with the healthy/GA proportions as follows: 8/14, 17/10, 12/8. All of their "successful" MPB related classifications seem to have been related to their NIR band 20 (722nm). They report an overall accuracy of 80% for MPB green attack detection using variations in NIR illumination on this one spectral image band. They point out that: "These accuracies may overestimate the levels that will be achieved operationally due to the use of the same dataset for both developing the analysis parameters and testing the accuracy".

Their results are suspect and misleading under the most favourable circumstance and, more realistically, totally unreliable considering:

(1) the extensive care that was taken by Itres in selecting a small number of specific trees for use in their analyses,
(2) their very small sample sizes (N = 22, 27 & 20),
(3) their previous conflicting results with small samples,
(4) their inadequate provision of data and detail to permit independent scientific verification and evaluation of their measures and procedures for statistical validity, and,
(5) the complete lack of comparative criteria like colour or colour infrared aerial photography.

Leckie et al, 2001:

Leckie et al (2001) principally used July 17, 1999 Landsat TM imagery to detect defoliation in white spruce. These results were also evaluated using other selected Landsat imagery from August 28, 1994, August 24, 1996, August 4, 2000 and January 29, 2000. In general they found substantial spectral variability but were able to separate healthy/light white spruce defoliation from moderate/severe defoliation with accuracies from 70-75%. They recommend that the use of higher resolution orbital (IKONOS) and airborne (CASI) imagery would likely be more successful. Although they had access to a sample of 60cm spatial resolution CASI imagery for the region, they stated that "it was not appropriate for analysis within the time frame of this study". They used both supervised maximum likelihood and unsupervised classifications. They found that "both methods produced useful results for broad levels of defoliation… However, detailed defoliation classes could not be reliably differentiated".

Although they did not evaluate any airborne imagery, they recommend the use of higher resolution airborne imagery for future research. They seemed to only consider CASI imagery and made no attempt to compare, evaluate or consider any form of aerial photography.

Whitehead and Smith, 2001:

Whitehead and Smith (2001) used Ikonos and Landsat imagery from the following dates to attempt to detect MPB attack: Ikonos: July 16 & 17, September 26 & October 4 and October 23, 2000; Landsat TM: 1999 & 2000. The July Ikonos imagery was used for an evaluation of mapping potential for red attack detection and the October 23 Ikonos imagery for green attack detection. The October 4, 2000 imagery could not be used because of cloud problems. They had reasonable success with detecting red attack from the Ikonos imagery with results varying from 78-100% when compared with oblique aerial photographs. They had no satisfactory results with the detection for green attack as a result of using a number of unspecified analysis and classification procedures.

They considered the results to be "encouraging" although they had no success with green attack. They indicated that they "found a statistical difference between healthy, red, and green attack trees" but they did not specify these values or provide any measure of confidence. Clearly aerial photography was superior as they were using it as a source of validation for their red attack mapping.

In summary there have been no studies that have been able to reliably detect current attack in lodgepole pine from MPB. The few studies undertaken often have conflicting "promising" results that subsequently are not confirmed by further research. Many studies have not provided adequate information to permit scientific validation of their results and, on a number of occasions, have provided inadequate information regarding basic procedures and spectral data. With the detection of red attack the results were surprisingly poor in many cases. Although colour aerial photography can routinely image red attack there was often significant errors with both orbital and airborne (CASI) imagery. In general, with satisfactory spatial resolution, most systems could have a reasonable level of success with detecting red attack. There were no discussions of cost-benefit considerations for these studies but clearly aerial photography would be quite favourable.

STRATEGIC PLAN

The current MPB infestation has provided an urgent incentive to address a strategic plan for remote sensing of forest health in British Columbia. Although this proposed plan directly addresses the present MPB problem, most aspects relate to other forest health problems. It is considered to be a template for future investigations into the suitability of using remote sensing for a specific problem (MPB) and the development of cost effective operational procedures. Under all circumstances the suitability for knowledge transfer from research studies to operational conditions has been considered. Of equal importance is the cost effectiveness of the procedure and the degree that it can be implemented in a business environment involving private competition. Finally, of paramount importance is the need for a "patent" treatment of all investigative research. It is essential that all experimental studies be conducted with full disclosure of data characteristics, research procedures and analytical results. The essential criteria must be sufficiently transparent such that the reviewers can replicate if necessary. If proprietary procedures are considered to be involved then the use of non-disclosure agreements will provide the necessary access to the detailed scientific components of the research while maintaining confidentiality.

Short Term

The province of British Columbia faces a number of immediate and pressing forest health problems. Paramount among these is the MPB problem. A short term remote sensing strategy to assist with addressing these health problems is urgently needed. Although a plan needs to be implemented immediately it still needs to be suitably operational and cost effective. The undertaking of expensive research without an obvious immediate value needs to be “staged” with adequate critical review to ensure that the research is proceeding appropriately and warrants further investigation. An appropriate strategic plan must have the potential for immediate operational benefits as well as an investigative aspect for future benefits.

The current provincial overview flight program is designed to identify and map established MPB infestations. By nature this program is fast and subjective with unspecified levels of human error. Unfortunately these data cannot be used for other purposes. The objective of this overview program is to map the existing infestation on the basis of identification of “red attack” in lodgepole pine trees.

A clear improvement would be the availability of additional procedures that can assist this program. Essential criteria would include:

- affordable cost,
- greater objectivity,
- more consistent data,
- the ability to provide comprehensive records of infestation spread over time and space, and
- the potential for further alternate MOF resource management uses (i.e. other uses for the aerial photography).

The use of colour aerial photography should be of comparable or less expense in terms of flight operations than the current provincial overview flight program. The photography will be easily capable of identifying discoloured trees and will provide an objective mapping record that will be useful for many other purposes.

Colour infrared (CIR) aerial photography will achieve the same results at the same cost but will also have greater potential to detect and map trees that are in earlier stages of stress (“current attack”) and could provide more information regarding the spread of the infestation.

Multispectral photography, using four optically filtered spectral bands (NIR, red, green and blue) provides black and white, normal colour and false colour infrared images for each exposed frame. This imagery is slightly more expensive than colour and CIR aerial photography but provides superior spectral separation and has greater interpretational flexibility. It is more likely to be able to detect earlier stages of vegetation stress from the current attack than colour or CIR photographic imagery since it has superior and adjustable spectral properties.

Airborne electro optical spectral imaging systems (digital frame cameras, multispectral scanners and imaging spectrometers) are more for experimental rather than operational use and should only be investigated in conjunction with digitally converted photographic systems that make an obvious and cost effective contribution and can be used for performance comparisons. Orbital systems are constrained by spatial resolution and periodicity problems and are most appropriately used for small scale (large area) mapped overviews.

The recommended short term remote sensing strategy, for addressing a variety of forest health issues, is an immediate evaluation of colour and/or colour infrared aerial photography (with digital image conversion (scanning) to photogrammetric mapping standards) to assist and supplement the overview program. This should be undertaken in conjunction with a direct comparison study with multispectral digitally converted aerial photography to determine if the improved spectral information and performance warrants the increased expenditure. Considering the superior performance of such multispectral digital photography, this is a likely outcome and should produce earlier MPB current attack detection.

Medium Term

The medium term strategy should involve:

(1) The continuation of a suitable aerial photography imaging program to meet the MOF forest health needs in terms of recurrent mapping for infestation detection and spread. This will most likely be either colour infrared or multispectral aerial photography with photogrammetric digital conversion for interpretation and mapping.

(2) The development of a computer assisted spectral image interpretation and mapping procedure using the imaged aerial photography. This procedure will be specifically intended to provide identification and classification of trees that are in several stages of infestation (e.g. red attack, current attack).

(3) Investigation into the suitability of using colour infrared and/or multispectral aerial photography for potential early current attack detection of MPB infestations and other forest health early detection applications. The initial approach will relate to the potential to remote sense MPB current attack in lodgepole pine prior to the new generation "hatching" and flying. There is a pressing need to see if this can be operationally achieved. An empirical approach is recommended where areas of anticipated spreading infestation will be recurrently imaged. This will be done such that an approximately bi-weekly record will be made across the complete cycle from healthy trees to spreading infestation through the current and red attack phases. This will permit the tracing back from dead red attack trees to provide a objective evaluation as to when the first reliable trace of the infestation can be visually detected on the imagery.

(4) This should be followed up with a computer classification study of the digitally converted imagery from the above cross-time empirical study. The purpose will be to evaluate: (1) the potential of computer assisted classifications to assist with the visual detection and mapping, and; (2) to evaluate the potential for computer enhancement and classification, of multispectral imagery, to provide superior early detection over the visual interpretation.

Long Term

Long term considerations involve the melding of an operational digital aerial photography detection and mapping program with an experimental program. The experimental program will be required to monitor and evaluate the need, at some time in the future, to phase out the use of aerial photography and replace the operational program with direct digital frame or line imaging systems and procedures.

Secondly the experimental program should investigate and address technical advances in electro optical multispectral imaging and related computer identification and classification procedures. This experimental program should at all times be subject to evaluation in terms of cost effectiveness and scientific validity. All imagery and procedures must be subject to detailed evaluation and review.

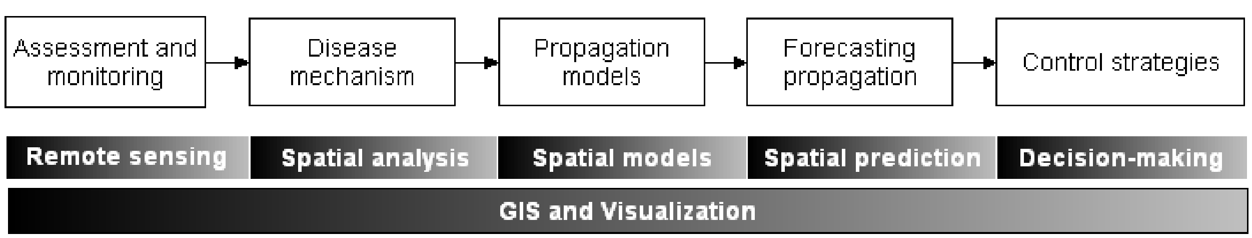
A further item for future consideration will be for real-time imaging of forest health problems. It clearly would be advantageous to have not only adequate early detection of MPB spreading but to have this in a manner that would permit airborne imaging to be transmitted to ground crews at the time of imaging. This of course would have to be cost effective but multispectral video transmission is now possible and affordable. If a suitable robust and simple spectral detection procedure can be developed this could become a consideration at some time in the future.

ENVIRONMENTAL CONTEXT AND GIS: TOWARDS A PREDICTIVE MPB MODEL

Forests represent a significant economic and ecological asset that must be managed in a sustainable way for the benefit of society. Timber, non-timber forest products, shelter and habitat, carbon sequestration, protection to soil and water resources, and biodiversity are some of the many goods and services provided by forests. However, over-logging, agricultural expansion, socio-economic pressures, political interests, and disease infestations are imposing radical changes on many global forest ecosystems. The need to effectively manage and monitor forests has now placed greater demands on spatially integrating technologies such as geographic information system (GIS) and remote sensing. The advent of the MPB infestations across forests in western North America has lead to a greater awareness of the utility of GIS and remote sensing technologies for monitoring, predicting, and mitigating MPB infestations and spread. This section provides a discussion of the potential uses of GIS techniques coupled with environmental data to providing support for inventorying and change detection, data integration and management, visualization, spatial analysis, modeling and forecasting, and stakeholder input in MPB management and control.

A geographic information system (GIS) is considered as a tool consisting of an organized collection of computer hardware, software, and trained personnel designed to efficiently capture, store, manipulate, visualize, and analyze geographically referenced data to provide information to solve unstructured management and planning problems. Remote sensing is defined as the detection, recognition or evaluation of objects by means of controlled electromagnetic interactions between the object and sensors that are not in direct physical contact. The integrated process is data intensive, and gathering data on forest attributes is a challenge due to rugged terrains, extensive areas, physical limitations of the landscape, and human resource shortages among other factors.

GIS and Remote Sensing in Forest Disease Management



This flow chart shows the GIS-based process for developing a modeling strategy to address MPB disease infestations and propagation. Aerial photography and satellite data will provide initial base conditions for understanding disease propagation mechanisms in the study regions. GIS and visualization assessments will aid in model development and testing, spatial forecasting, and evaluating decision control strategies.

Remote Sensing and Change Detection

GIS and remote sensing plays an important role in determining forest structure and patterns. Image analysis techniques applied to forest classification analysis, the development of vegetation indices, temporal and spatial analysis of vegetation dynamics, and species occurrences have been widely used. Spatial heterogeneity is a natural characteristic and forests metrics based on ecotopes, ecotones, and corridors are used to derive quantitative measures to study the spatial structure of forests. In addition, attributes such as age and species composition are usually determined by ground surveys.

The relative unavailability of continuous fine spatial and temporal resolution satellite data suitable for disease monitoring has been a source of concern among forest managers. However these data usually require validations, corrections for topographic shadows, minimization of atmospheric influences and cloud cover. Recently, improved procedures in image fusion across spatial and temporal resolutions are providing new ways of enhancing remote sensing data.

Change detection is the process of using spatial analytical methods to characterize the nature and magnitude of change events between two or more time periods for an object of interest. In monitoring forest resources, detecting that a change has occurred, identifying the nature of the change, quantifying attributes of the change, and assessing spatial patterns are important in characterizing the change.

A number of digital change detection methods available for studying forest ecosystems. These include image differencing, image ratios, regression methods, change vector analysis (CVA), class differencing, and principal components analysis (PCA). Change detection methods are based on the idea that if errors due to sensors, geometry, and the environment are minimized, and the images are registered to each other and undergoes identical pre-processing analysis, and the images are acquired from sensors with identical characteristics, then image changes will be due to changes in the radiance values of the same ground area between the different time periods.

Change detection methods have been used to track biomass changes at the forest/clearing interface. One technique employed is Markov modeling which uses an empirically defined transition probability matrix to detect changes in the land cover classes over time. In the development of these transition matrices, remote sensing data produces less biased transition probabilities in comparison to traditional field measurements since it incorporates the entire study area. Also, forest seasonality changes is a significant component of dynamics studies as it regulates many processes such as those related to primary productivity, water and gas exchanges.

Data Integration and Management

In forest planning GIS has been widely used for data management, planning, visualization, and spatial analysis whereas remote sensing has been used primarily as a data source for monitoring and assessment. Remote sensing is a relatively costly technology, but accurate and timely data about the spatial composition of forest resources are needed for modeling changes such as disease infestations that occur within small time windows. Although a number of high-resolution satellite sensors are available, the most viable option for local scale changes has been to use low altitude aerial photography together with ground surveys.

The inherent capability to store and quantify spatial data has made GIS technology an appropriate tool to facilitate data integration and management in developing information infrastructures for forest disease control. At an organizational level, a decentralized GIS approach can have many advantages for improved data access, communications and decision-making in forest management. Moreover, the GIS facilitate both the integration and separation of data by using data selection, query, buffering, and overlays.

By using geographical referencing, disparate data sets can be integrated into a common GIS database thereby providing many opportunities for integrated analysis. Forest disease infestations have complex dynamics and solutions demand integrated approaches. Moreover, the spatial integration effort not only provides a comprehensive database, but also facilitates holistic management as compared to stand and individual species management using traditional methods.

Natural disturbances such as MPB infestations have also been studied spatially by including attributes such as canopy structure in the analysis. In addition, variables such as weather, wind direction, temperature, rainfall, sunshine hours, humidity and moisture, slope, altitude and soil nutrients have been show to influence MPB disease infestations. In this study, the availability of a wet and a dry site will allow these factors to be effectively tested. Management regimes such as cutting areas, regions of protection, locations and times and duration of cutting, de-barking sites, and trail networks have an impact on the MPB disease. The environmental and management data can be obtained from existing records and the topographic data from digital elevation models, with all these integrated into a GIS framework.

Integrating data from a wide variety of sources has often been cited as one of the significant benefits of implementing a GIS. But these approaches require a commitment in addressing data ownership, copyright, data protocols, administrative, and training issues. Further, integrating spatial data and producing meaningful results is dependent on our understanding of the errors involved in each stage of the integration process. Hence, quantitative and qualitative error management and accuracy assessments are usually implemented to understand the quality of maps, compare results, and minimize risks in modeling and decision-making.

Data Visualization

As the volume of digital data increases, more reliance will be placed on visualization techniques to reveal underlying patterns and trend in multidimensional data. The objective of visualization is to transform raw data using graphics and multimedia into information that is readily amenable to understanding by the human perceptual system. GIS and image processing techniques are used to support the interactive display and presentation of spatial information for a variety of purposes and audiences. GIS normally depicts spatial data as 2-dimensional relief or gray-scale maps with an overhead view and in some cases the possibility of using draped images. Visualization has also been used to explore indexed and archived data, preview temporal changes, allow public access to data, and support political decision-making. Virtual reality techniques have extended GIS visualization to now represent 3-dimensional perspective views of landscape models. Recently, there has been growing interest in web-based GIS frameworks to support visualization, public participation in decision-making, and widespread access to GIS capabilities. Access to any developed MPB database, sharing and visualization of spatial data can be made easily through Web-based GIS tools.

Spatial Analysis

The assessment of forest functions are based on spatially distributed point and patch data measured at a variety of spatial and temporal scales. Homogeneous units of soil attributes traditionally delineated from aerial photographs and ground surveys are normally used as the basis to derive forest ecosystem interactions and processes. Extending the analytical capabilities of conventional GIS has largely been achieved through coupling mechanisms with mathematical and simulation models. Studies on spatial model integration and GIS in forest management are becoming increasingly available. For example, the range, habitat and distribution of species are key components in understanding forests and a variety of related model-based GIS studies are available. The models have included logistic regression models for species distribution, spatial multi-criteria models and spatial optimization for habitat suitability, predictive least squares models for habitat monitoring, and Bayesian models for habitat mapping. In a comparison of three GIS-based models for habitat evaluation it was concluded that wherever possible, a variety of models should be implemented and their results compared. Modeling approaches have also been used to generate data for use in forest management. The availability of baseline data strongly influences our capacity to investigate issues and hypotheses surrounding any problem of interest. In the absence of extensive baseline data sets, modeling tools can provide critical support for generating more useful information in a variety of decision-making processes.

Spatial Modeling and Forecasting

Spatial modeling using landscape complexity measures derived from vegetation patch characteristics (richness, frequency, and shape for example), patch type contiguity index, and physiography, have been used to identify and categorize diverse landscapes. These methods depend heavily on GIS analysis and remote sensing data. Metrics such as diversity, shape, texture and juxtaposition measures are area-based and can be derived during GIS-based analysis.

Forest processes are driven by variables that are controlled by physical properties such as topography, slope, elevation, and aspect. Topographic analysis can be performed in GIS analysis through the generation of 3-dimensional surface models of the landscape using contour maps. Slope and directional analysis has been used in GIS analysis to define watershed units and simulate the location, direction and quantity of surface water flows. Disturbances are also modeled using elevation data within a GIS. Species density and diversity maps have been developed using gradient modeling of environmental variables to predict vegetation and species occurrence. Also, statistical modeling between vegetation and topography can be used to study vegetation patterns and distribution.

Stakeholder Input

Stakeholders and groups with vested interests are recognized as essential components of the decision making process on all aspects of forest management. The inclusion of First Nations opinions and values are a significant necessity. Forestry issues involve a variety of stakeholders and decision makers with conflicting values and preferences making it difficult to achieve optimal management solutions. The integration of social, physical and values factors involved in forest management has provided a heuristic means of achieving consensus. However, this integration can result in delays, confrontation, and conflict in the decision making process. Tools such as GIS-based spatial decision support systems (SDSS) are providing valuable assistance in achieving compromise solutions that incorporate social issues through consensus building. The use of web-based GIS is also developing into a useful tool to elicit stakeholder opinions, communicate modeling results and share forestry data.

GIS and remote sensing can generally provide support for inventory, change detection, data integration, classification and management, visualization, spatial analyses, modeling, forecasting, and stakeholder input in MPB management and control.

RESEARCH IMAGERY

The evaluated remote sensing data in this research study included:
digitally converted multispectral aerial photography providing normal colour, colour infrared and two groups of false colour infrared composite images;
digitally converted colour negative aerial photography;
digitally converted colour infrared aerial photography;
digitally converted black & white infrared aerial photography;
combined 6 band colour and colour infrared imagery, and;
combined 4 band colour and B&W infrared imagery.

Imagery acquisition

Site-specific MPB infestation imagery was flown on April 3, May 15, June 3, June 12, June 13, August 14, October 11 and October 16, 2002. Imagery was acquired at scales of 1:8000 and 1:16000. In addition a series of imaging flights were undertaken to test film exposures, filter combinations and twin camera synchronized colour and near infrared imagery. These imaging flights occurred on February 20, March 2, March 17, May 16, June 12, June 13, June 14, August 14, August 15, October 15, October 17, October 24, and November 1, 2002. Figure 1 shows one of the 65 flight line maps that were generated for each site showing the specific location imaged. All flight line maps are posted on our FTP site. A total of 21 imaging flights, producing 476 test images, 3611 MPB infestation images and 832 forestry habitat images, were undertaken. All flight line maps and imagery are posted on the SFU Remote Sensing FTP site: 142.58.173.39 (ID: anonymous; password: email address of user; note: use only binary transfer for imagery). Figure 2 shows one of the FTP site “maps” indicating the structure of the site and location of the images. These FTP “site maps” are also posted on the FTP site.

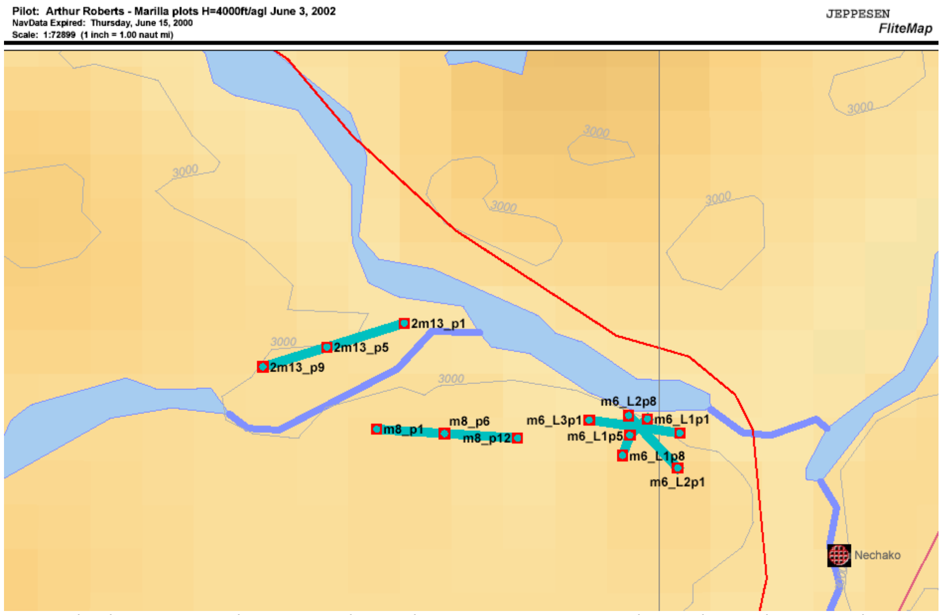


Figure 1: Digital aerial navigation chart showing imaging flight lines over Marilla area sites on June 3, 2002.

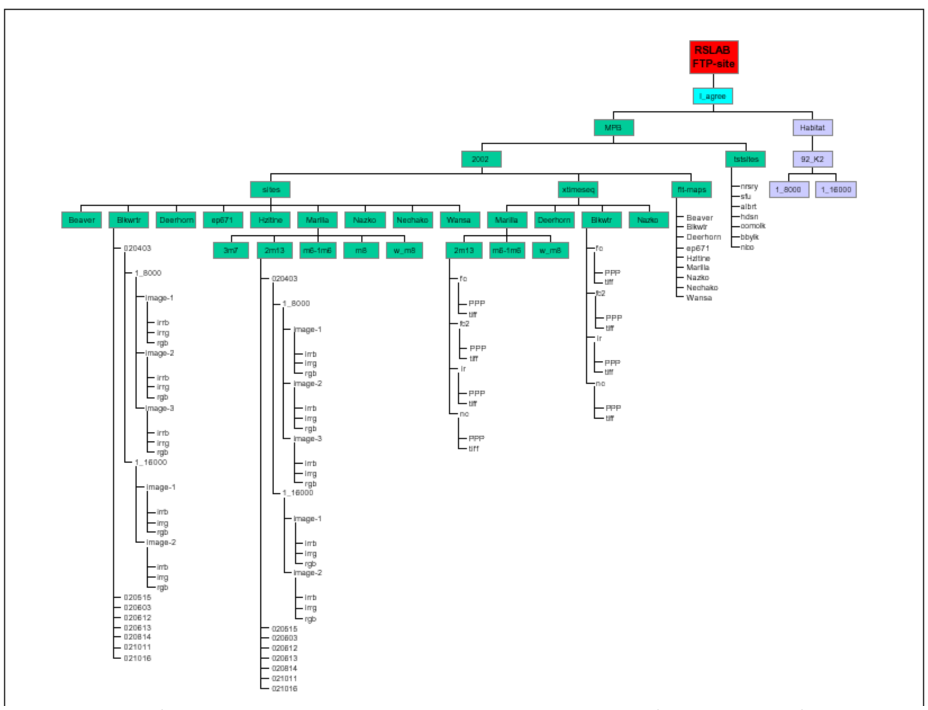


Figure 2: Schematic "map" of the SFU Remote Sensing FTP site containing all project imagery.

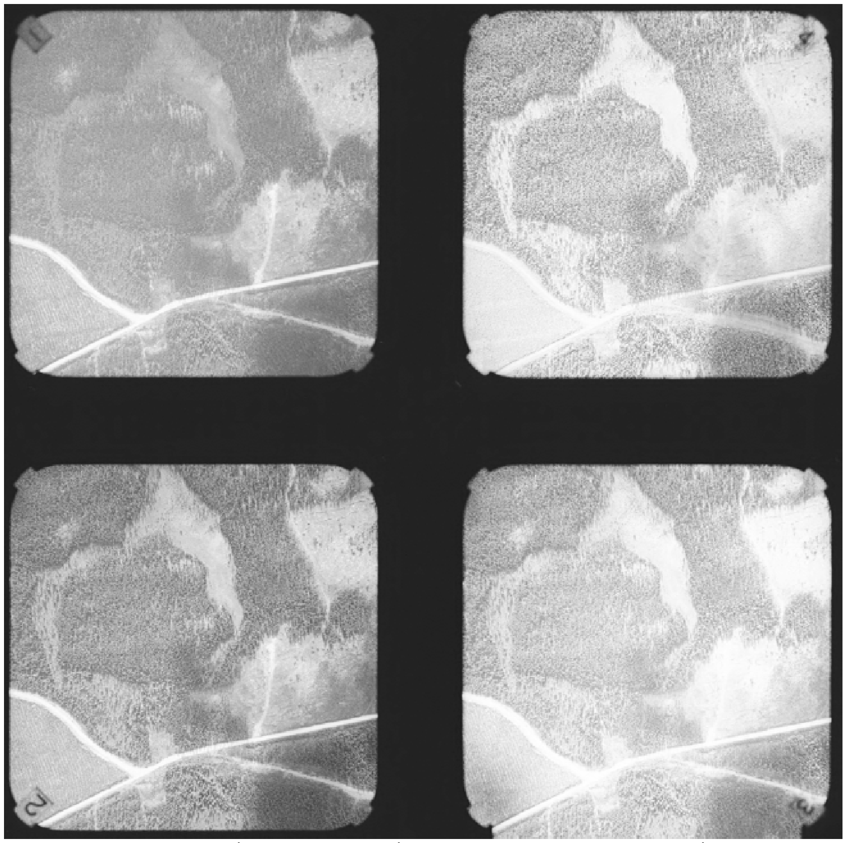


Figure 3: Four band multispectral image of Deerhorn site, August 14, 2002. Image 1: blue; Image 2: green; Image 3: red; Image 4: nir.

Each multispectral image (Figure 3) contains four spectral bands (near infrared (NIR), red, green and blue) that were combined digitally into 4 colour composites: (Figure 4) normal colour, colour infrared and two false colour infrared images for visual and computer analysis and classification. The twin camera imagery consisted of two images: (Figure 5) colour with colour infrared and colour with B&W infrared. These data were digitally converted and evaluated to determine varying levels of interpretational utility and spatial resolution performance for forestry health parameters. In addition the colour and false colour digitally converted aerial images were used as a comparative baseline to assist with the performance evaluation of the multispectral imagery.

Imagery Registration

Both the multispectral and twin camera imagery required registration of each individual image to a single image. For the multispectral imagery the NIR, red and blue images were registered to the green image. With the twin camera imagery the infrared imagery (colour IR and B&W IR) was registered to the normal colour imagery. This cross-image spectral band registration created sets of 4 band and 6 band multispectral imagery for enhancement, interpretation and classification. In all instances one of the images was left unaltered to permit precision photogrammetric mapping.

A second group of images were registered across time (same site from different imaging dates) to permit forward and backward evaluation of colour changes in MPB infested trees. This registration resulted in

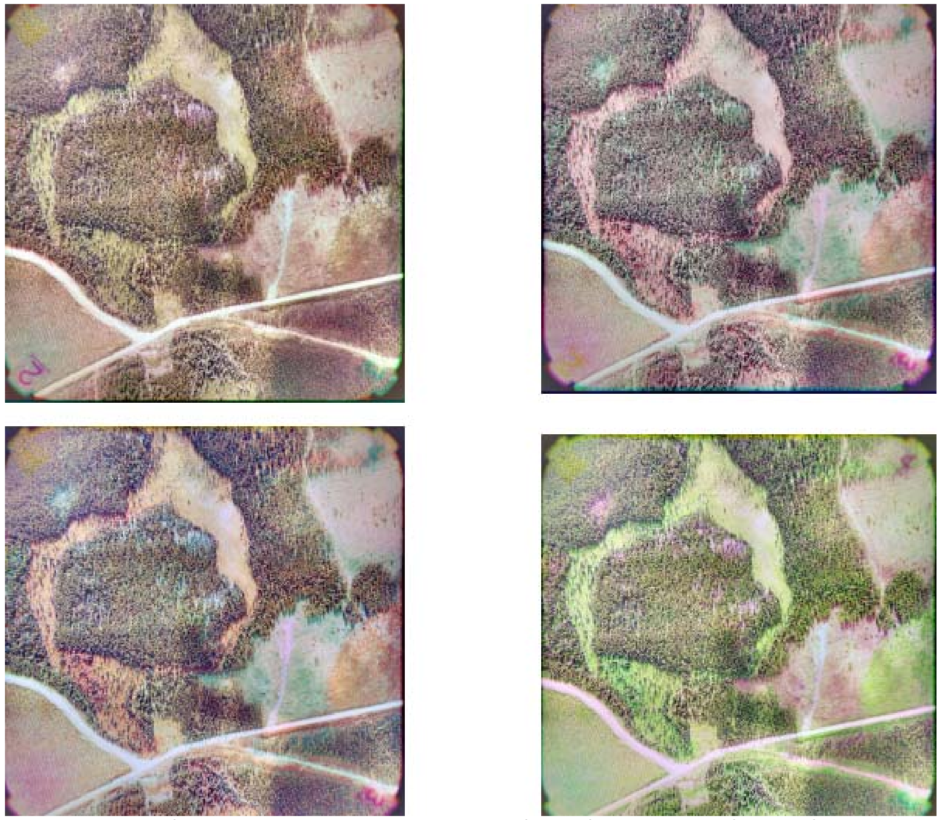


Figure 4a: Four different colour composite images using Figure 3 spectral bands. Top L: RGB; Top R: IRRG; Lower L: IRRB; Lower R: RIRB.

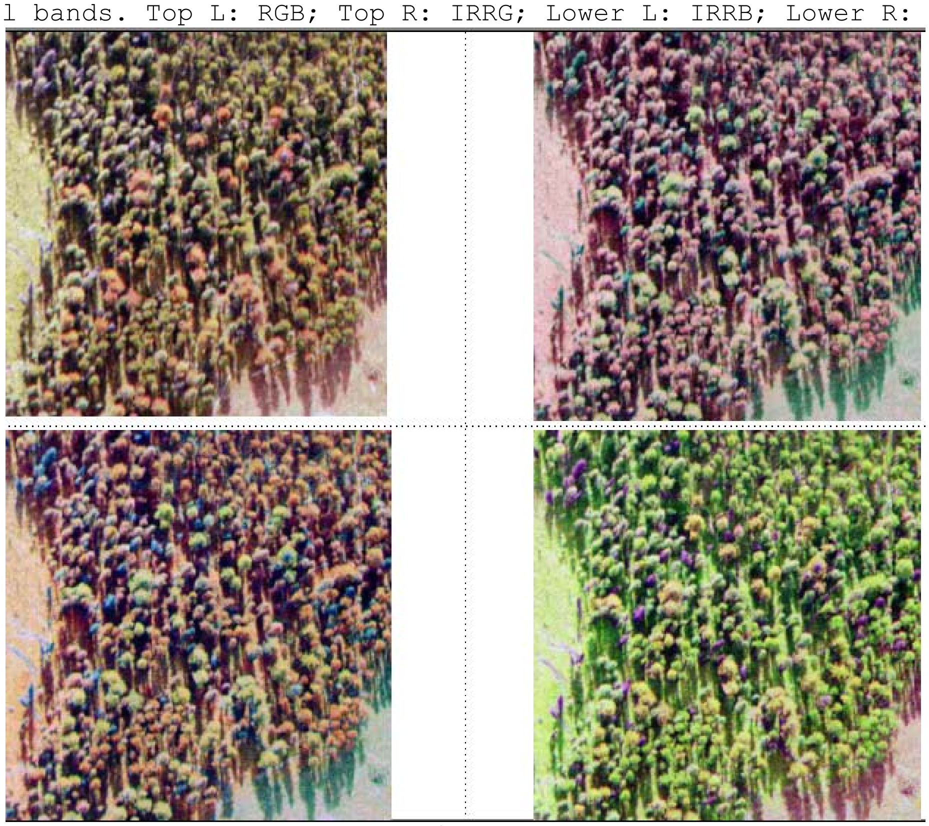


Figure 4b: An enlarged area from Figure 4a. Red attack trees are red on RGB & RIRB and green on IRRG & IRRB. TL:RGB; TR:IRRG; LL:IRRB; LR:RIRB.

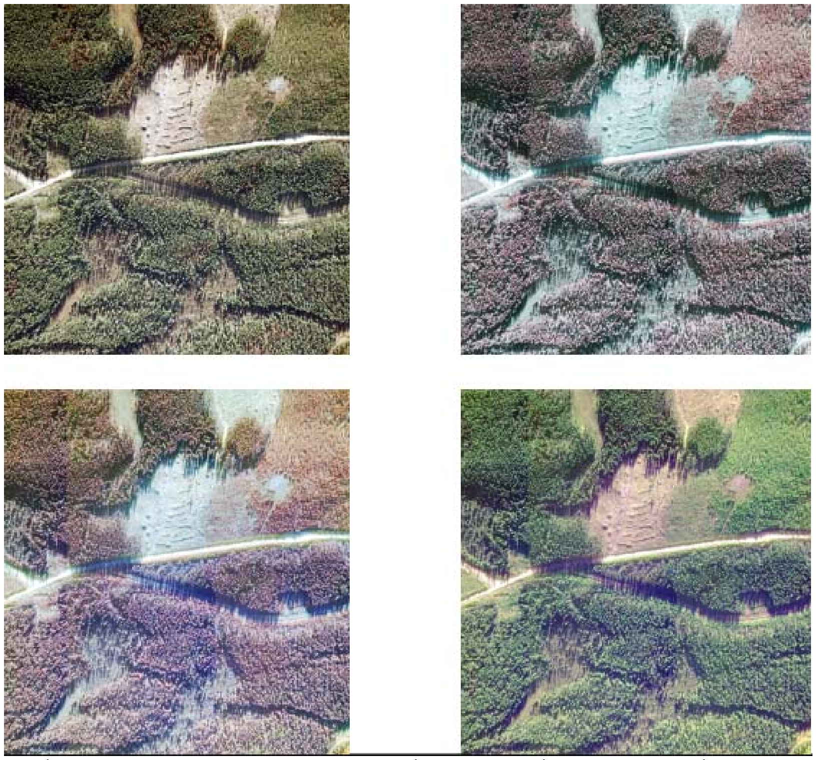


Figure 5a: Twin camera colour composite multispectral imagery: Deerhorn site, October 16, 2002.TL:RGB; TR:IRRG; LL:IRRB; LR:RIRB.

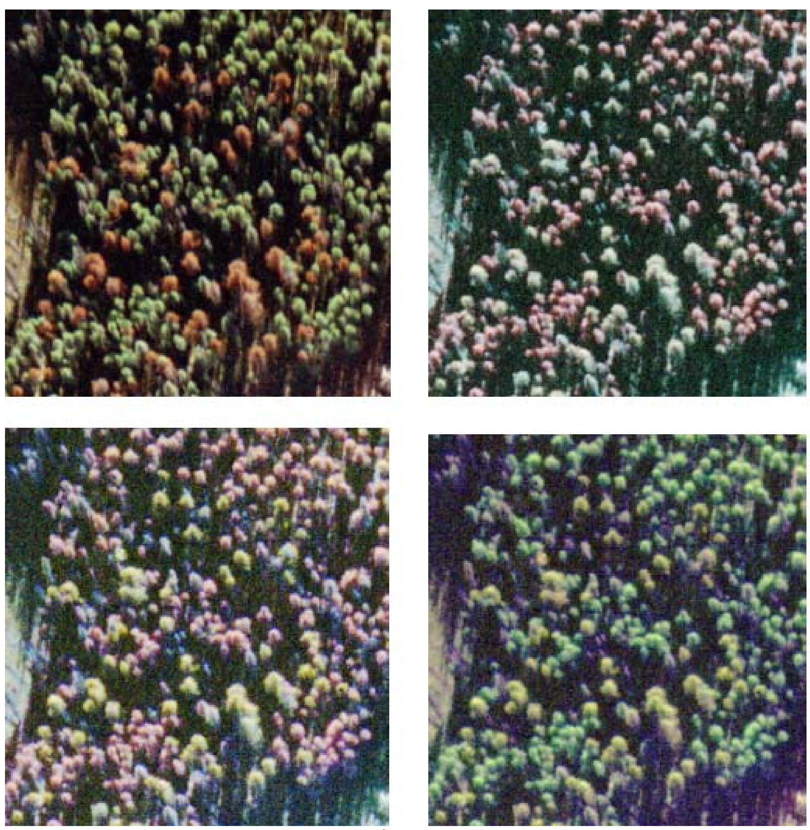


Figure 5b: An enlarged area from Figure 5a. Red attack trees are red on RGB & RIRB and green on IRRG & IRRB. TL:RGB; TR:IRRG; LL:IRRB; LR:RIRB.

large “single” image files containing up to 33 separate images across the period from April to October, 2002.

Imagery registration is a somewhat time consuming activity requiring approximately one hour per image. Cross time images take substantially longer as image rotation and scaling issues complicate the registration: assuming that the multiband (4 and 6 band) images making up these data sets are already registered, a single cross time image will take one to two man weeks. All image registration was undertaken at SFU in the SFU Remote Sensing Laboratory using ER Mapper image processing software.

Imagery Evaluation

Six areas of mountain pine beetle (MPB) infestation, to the west and southwest of Prince George, were sequentially imaged by the SFU Remote Sensing Laboratory between April and October, 2002. These sites were established by MOF as test sites for the evaluation of experimental remote sensing systems and procedures. The extent of MPB current attack was mapped, by field survey at the individual tree level, in the fall and winter of 2001 and the fall of 2002 (see Appendix A). All indicated trees are numerically keyed to data tables (see for example Table A1). A total of six sites were ground truthed by MOF and SFU/MOF combined. The total number of trees examined was 2890.

There was an apparent change in most of these currently infested trees at these six sites over the 2002 season (a small percentage of these 2001 infested trees had still shown no visible change by November 2002). On our April 3, 2002 imagery, the previous year's dead trees were clearly visible as red standing dead trees. The 2001 ground truthed current beetle attack was not detectable by visual examination on any of this early April imagery. On the later May 15th and June 3rd, 12th and 13th imagery, the currently infested trees increasingly became visible through colour changes on the various composite multispectral images.

By August 14th most of the 2001 attacked trees had changed from a green to red colour. This continued through the fall such that by October a larger percentage of the previously infested trees had continued changing colour to red. The August (and later) imagery then became another form of “ground truth” (verification data) such that we could trace back to trees that were green in April from trees that had changed to red by August. This colour shift showed these trees had died and we worked back through the June and May imagery to determine the earliest detectible “signal”. Appendix B contains a sample from a small area of a registered time sequence from one of these six sites.

These visible changes were most pronounced on the infrared false colour composites but were also detectible on the normal colour composites to a lesser degree. The colour changes are the result of reflectance changes on the trees in both the visible and near infrared spectral regions. Our results clearly indicate that early detection of “current” MPB infestations is possible.

RESULTS

Aerial imagery was acquired at two different imaging scales (1:8000, and 1:16000) for six different MPB research sites and eight different imagery test sites. The MPB sites were imaged from April 4th to October 16th, 2002 using 4 and 6 band multispectral imaging systems.

Image Processing: The acquired aerial photography was developed in Vancouver (B&W photography), Calgary (colour infrared photography) and Dayton, Ohio (colour and colour infrared photography). Imagery was developed and scanned throughout the study period with the film being developed as soon as possible following exposure to minimize deterioration. The digital film conversion (scanning) was undertaken in Vancouver by three separate companies: McElhanney, Triathalon and Silver Sands. Scanning resolution varied for test purposes however the B&W imagery was scanned at 12, 16 and 18 microns and the colour imagery was scanned at 18, 20 and 21 microns.

Image quality is generally excellent, although the colour infrared imagery processed in Ohio was not test processed, as a result it was underdeveloped producing a darker than normal image. The generally excellent quality of the imagery includes film exposure, developing and digital conversion. Colour enhancements and spectral combinations are adjustable and the imagery can be custom enhanced to assist with the interpretation of the different environmental parameters. Although some understory areas could not be imaged in direct sun due to vegetation overhang most of the selected sites have been imaged with good sun illumination.

Specific objectives set for the analytical phase of this study indicated that the following needed to be determined more precisely:

Spectral Parameters

The spectral parameters examined were limited by the spectral sensitivity of the films used and the spectral transmission of the various filters. Generally we used "broad band" imaging in the blue, green, red and near infrared.

The B&W film (Agfa 200 PE 1) used with 301a infrared cut-off for the visible bands and specific numbered Kodak Wratten filters produced the following broad spectral bands:

- blue (47 + 301a: 400nm – 500nm)
- green (40 + 301a: 475nm – 580nm)
- red (24 + 301a: 580nm – 680nm)
- nir (89b: 680nm – 740nm).

The colour negative film (Agfa N400) produced the following broad spectral bands:

- blue (400nm – 475nm)
- green (525nm – 580nm)
- red (600nm – 660nm).

The false colour infrared film (Kodak 2443 & 1443), used with a 520nm yellow filter, produced the following broad spectral bands:

- green (520nm – 580nm)
- red (625nm – 675nm)
- nir (620nm – 850nm).

The B&W film (Agfa 200 PE 1) used with a 600nm red filter produced the following broad spectral band:

- nir (600nm – 740nm).

The colour film was used in conjunction with the two nir sensitive films to produce a 4 or 6 band multispectral image using a twin mapping camera configuration.

Our results from the 2002 imaging indicate that: (1) the multispectral camera produced more distinct separation of reds and current attack than did the twin camera package; (2) the false colour combination of nir, red and blue provided the best visual separation of trees for mapping both red attack and spring current attack (see Appendix B). Both the nir and blue spectral bands improved visual mapping and classification in comparison with the other spectral combinations (rgb & irrg).

Timing of Onset

Seasonal "timing" of the onset of visibly detectable current attack (when the first spectral alterations become clearly visible) on this imagery varied between our six sites. At the Blackwater and Marilla sites we had clearly detectible evidence of current attack by May 15th at the Nazko site we did not obtain distinct separation until June 3rd. Taken as a whole it is safe to say that a spreading current attack is clearly visible by late May early June. Further analyses and refinement with more comprehensive imaging, seasonal and environmental data may enable earlier reliable detection (ca. early to mid May). Although some changes in specific trees could be detected on some of the April 3rd imagery there is no indication that this can be considered reliable.

Image Processing

Analytical procedures to enhance and objectively identify "red attack" and spreading infestations ("current attack") consist of preprocessing, visual interpretation and classification. Preprocessing is potentially the most complicated as it involves enhancements during image scanning, histogram trimming and viewing enhancements and image modification to improve classifications. During the scanning process we had little control over enhancements. With our contractors who provided this service we established a procedure that altered the image as little as possible. In general default manufacture recommended settings were used without any additional contrast enhancement. Our preference was for a simple linear transform but due to the logarithmic nature of the image density a straight linear conversion did not provide adequate analog to digital conversion. Although we obtained very good quality image scans this is an area that requires further investigation to determine optimum procedures for digital conversion of film products to be used in multispectral digital image processing.

Reliability

With red attack trees we can clearly detect and map all trees that have changed colour to red. In this sense the reliability (detection accuracy) is close to 100%. With digital image classification this is slightly reduced since some of the reds are shaded and are classified as shade areas. This is very minor and percent success remains around 99%. The issue becomes more complicated when the reliability addresses successful detection of all trees that were attacked in the previous year. Most of the heavily attacked trees (75 – 100% attack in our ground truth classification) can be reliably detected in August at the red attack stage. However many of the less heavily attacked trees (<50% attack in 2001) did not change colour by August and a number had still not changed colour in the fall (November). These trees were not detectible and if included as a statistical component would cause the detection reliability to vary considerable from location to location depending upon degree of attack and other undetermined factors.

For this reason our reliability concerns dealt primarily with attacked trees that died and turned red by August. While we are aware that more trees will have changed in September and October, problems with aspen birch and other deciduous trees undergoing senescence altered clear detection of reds as attacked pine.

From a point of view of percentage correct classification Tables 1 and 2 indicates the classification performance of new reds/current attack vs. healthy vs. old reds for two of our six sites. The Blackwater Site was our "earliest" site while the Nazko Site was our "latest" site. At Blackwater we have a clear current attack detection signal by May 15th while at Nazko we do not have clear detection until June 3rd.

In August we classified 140 trees that were ground truthed as heavily attacked in fall 2001. Of the 140 trees 129 (92.1%) were classified as new reds and 11 were classified as healthy. Of the 11 "new reds" (2001 attack) classified as healthy all were still green while the 129 classified as new red had turned red. So we were able to classify 100% of the actual new red trees as "new red". In the previous months we continued to classify using all 2001 heavily attacked ground truth trees even though 9% of them were still green in August, therefore; our indicated percent successful classifications are lower than our actual ability to detect trees that are dying and have turned red in August. On June 3rd we showed 79% 2001 attack but this was 81% of the trees that turned red in August.

On May 15 at Blackwater we show 58.9% of 2001 attacked trees classified but our classification of actual new reds is 64.4% (76 of the 118 2001 attacked trees that turned red in August). This is still a clear strong signal. In April the story is different. Our classification of 2001 attacked trees is 18.4% and random assignment across the three categories would be one in three (33%): these classification results are meaningless from a predictive point of view and the health and 2001 attack classes blend.

Nazko Site was the latest of our six sites to develop an identifiable current attack. In August 104 of the 134 2001 attacked trees ground truthed had turned red and they were all correctly identified. On Table 2 this shows as 77.6% of the 2001 attacked trees. On June 12th we have 64.9% of the 2001 attack (but 83.6% of the trees that had turned red in August). On June 3rd we have 58.2% of the 2001 attack (but 75.0% of the trees that had turned red in August). However on May 15th we have 25.3% of the 2001 attack (but 32.7% of the trees that had turned red in August): this is a random result and indicated no detection of current attack on May 15th.

Our evaluations of the detection of current attack on our June, May and April imagery were based completely upon heavily (75 – 100%) attacked trees in 2001. As a result we had generally reliable detection of these trees in June and May both visually and through image processing classification procedures (see Figures 6a – 6d).

Table 1: Blackwater Site confusion matrix of supervised classifications.

August 14/02	2001 attack	healthy	old red	Total
2001 attack	129 92.1 %	11 7.9 %	0 0 %	140 100 %

healthy	13 5.4 %	229 94.6 %	0 0 %	242 100 %
old red	0 0 %	0 0 %	9 100 %	9 100 %
total	142 36.3 %	240 61.4 %	9 2.3 %	391 100 %
June 12/02	**2001 attack**	**healthy**	**old red**	**Total**
2001 attack	108 82.4 %	23 17.6 %	0 0 %	131 100 %
healthy	28 13.1 %	186 86.9 %	0 0 %	214 100 %
old red	0 0 %	0 0 %	9 100 %	9 100 %
total	136 38.4 %	209 59.1 %	9 2.5 %	354 100 %
June 06/02	**2001 attack**	**healthy**	**old red**	**Total**
2001 attack	104 78.8 %	28 21.2 %	0 0 %	132 100 %
Healthy	16 7.2 %	207 92.8 %	0 0 %	223 100 %
old red	0 0 %	0 0 %	9 100 %	9 100 %
total	120 33.0 %	235 64.6 %	9 2.4 %	364 100 %
May 15/02	**2001 attack**	**healthy**	**old red**	**Total**
2001 attack	76 58.9 %	53 41.1 %	0 0 %	129 100 %
healthy	23 11.4 %	180 88.6 %	0 0 %	203 100 %
old red	0 0 %	0 0 %	8 100 %	8 100 %
total	99 29.1 %	233 68.5 %	8 2.4 %	340 100 %
April 03/02	**2001 attack**	**healthy**	**old red**	**Total**
2001 attack	23 18.4 %	102 81.6 %	0 0 %	125 100 %
healthy	24 12.6 %	167 87.4 %	0 0 %	191 100 %
old red	0 0 %	2 100 %	0 0 %	2 100 %
total	47 14.8 %	271 85.2 %	0 0 %	318 100 %

Table 2: Nazko Site confusion matrix of supervised classifications.

August 14/02	**2001 attack**	**healthy**	**old red**	**Total**
2001 attack	104 77.6 %	30 22.4 %	0 0 %	134 100 %
healthy	6	572	0	578

	1.0 %	99.0 %	0 %	100 %
old red	0 0 %	0 0 %	46 100 %	46 100 %
total	110 14.5 %	602 79.4 %	46 6.1 %	758 100 %
June 06/02	**2001 attack**	**healthy**	**old red**	**Total**
2001 attack	87 64.9 %	47 35.1 %	0 0 %	134 100 %
healthy	20 3.5 %	558 96.5 %	0 0 %	578 100 %
old red	0 0 %	0 0 %	46 100 %	46 100 %
total	107 14.1 %	605 79.8 %	46 6.1 %	758 100 %
June 12/02	**2001 attack**	**healthy**	**old red**	**Total**
2001 attack	78 58.2 %	56 41.8 %	0 0 %	134 100 %
healthy	7 1.3 %	571 98.7 %	0 0 %	578 100 %
old red	1 2.2 %	0 0 %	45 97.8 %	46 100 %
total	86 11.4 %	627 82.7 %	45 5.9 %	758 100 %
May 15/02	**2001 attack**	**healthy**	**old red**	**Total**
2001 attack	34 25.3 %	100 74.7 %	0 0 %	134 100 %
healthy	16 2.8 %	562 97.2 %	0 0 %	578 100 %
old red	0 0 %	0 0 %	46 100 %	46 100 %
total	50 6.6 %	662 87.3 %	46 6.1 %	758 100 %
April 03/02	**2001 attack**	**healthy**	**old red**	**Total**
2001 attack	30 22.3 %	104 77.7 %	0 0 %	134 100 %
healthy	8 1.4 %	570 98.6 %	0 0 %	578 100 %
old red	0 0 %	0 0 %	37 100 %	37 100 %
total	38 5.1 %	674 90.0 %	37 4.9 %	749 100 %

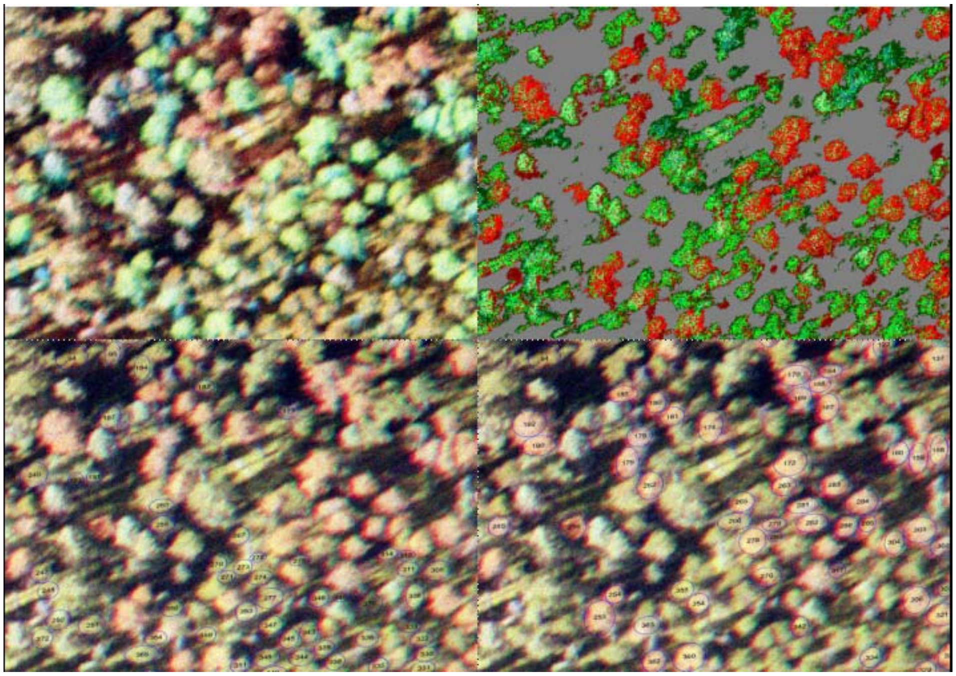


Figure 6a: August 14, 2002. Four sub-images from the Blackwater multispectral imagery:

Top Left - IRRB false colour infrared composite with new red attack trees as green, healthy trees as pink and orange and old reds as blue;
Top Right – results from a supervised classification showing new red attack trees as bright red, healthy trees in different shades of green and old reds as dark red;
Bottom Left - normal colour infrared composite with heavily attacked trees ground truthed in 2001 circled & numbered, new red attack trees as red, healthy trees as green and old reds as grey;
Bottom Right - normal colour infrared composite with new red attack trees as red, healthy trees ground truthed in 2001 circled & numbered, healthy trees as green and old reds as grey.

Cost Effectiveness

Evaluation of the cost effective aspects of these procedures is partially constrained by the fact that we did not commercially contract our imagery acquisition, registration and processing. Within the university environment return on capital investment (equipment costs etc.), profit and job security were not a budgetary issue. Our expenses were constrained by the immediate operating and personnel costs. This of course considerably reduces the expense of conducting this type of research and the acquisition and processing costs. However, there is little doubt that aerial photography is substantially less expensive than any other airborne imaging systems. The increased resolution and generally interpretative utility of aerial photography provides data detail, mapping accuracy and imaging flexibility that is not available with orbital sensors.

Knowledge Transfer

Central to this type of resource management is the determination of an effective and reliable procedure that can be implemented through competitive bidding by private sector companies. There is little applied utility if it is not practical to implement the findings of this research to assist with management of this acute forest health problem. For this reason we have initiated experiments in imaging with a twin mapping camera setup to simulate our multispectral imaging system (see Figure 5). Although this was only undertaken very late in the imaging season we have results that show satisfactory comparative results and reasonable confidence that integrated multispectral RGB & NIR imaging can be undertaken by many photo survey companies. This will permit

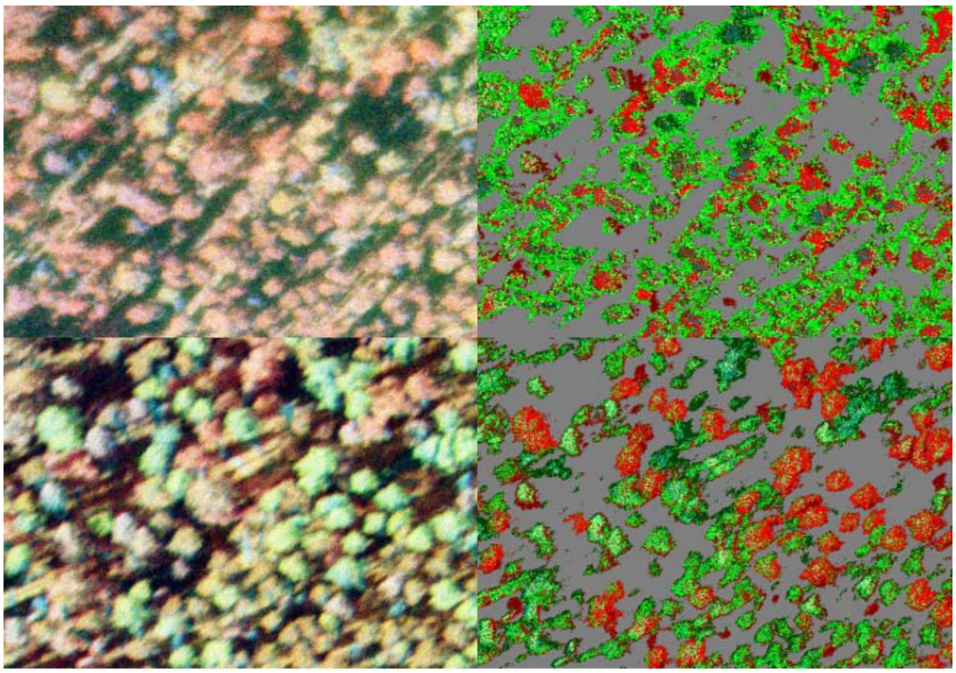


Figure 6b: June 12, 2002 & August 14, 2002. Two sub-images with supervised classifications from the Blackwater multispectral imagery:

Top Left – June 12: IRRB false colour infrared composite with new reds as yellow, healthy trees as pink/orange and old reds as blue;
Top Right – June 12: results from a supervised classification showing new red attack trees as bright red, healthy trees in different shades of green and old reds as dark red;
Bottom Left – Aug. 14: IRRB false colour infrared composite with new reds as green, healthy trees as pink/orange and old reds as blue;
Bottom Right – Aug. 14: results from a supervised classification showing new red attack trees as bright red, healthy trees in different shades of green and old reds as dark red.

knowledge and procedural transfer in a competitive context that can be operational more or less immediately.

CONCLUSIONS

Within the context of this study, airborne remote sensing of forest environments for forest health determinations (MPB) is most suitably undertaken using multispectral aerial photography at scales of 1:8000 for early detection of current MPB attack and 1:16000 for mapping and sequential monitoring of red and grey attack.

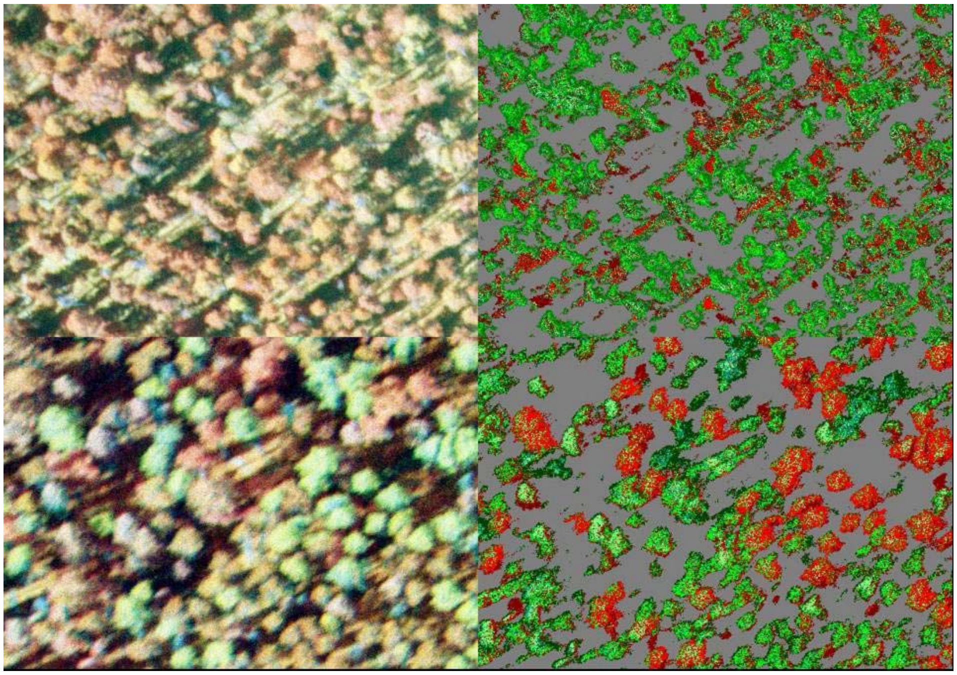


Figure 6c: June 3, 2002 & August 14, 2002. Two sub-images with supervised classifications from the Blackwater multispectral imagery:

Top Left – June 3: IRRB false colour infrared composite with new reds as yellow, healthy trees as pink/orange and old reds as blue;
Top Right – June 3: results from a supervised classification showing new red attack trees as bright red, healthy trees in different shades of green and old reds as dark red;
Bottom Left – Aug. 14: IRRB false colour infrared composite with new reds as green, healthy trees as pink/orange and old reds as blue;
Bottom Right – Aug. 14: results from a supervised classification showing new red attack trees as bright red, healthy trees in different shades of green and old reds as dark red.

From an "operational" perspective, the use of a twin mapping-camera setup with colour and B&W infrared film will provide the best approximation of the multispectral imagery with near comparable performance in a competitive private sector context (open bidding). The most suitable scales for contracted imagery would be optimized in terms of cost and performance by using 1:10000 imagery for early detection of current attack and 1:20000 for red attack mapping and monitoring.

Digital conversion of aerial photography for MPB detection and monitoring should be undertaken at 16 to 20 microns for B&W imagery and 18 to 24 microns for colour and colour infrared imagery. Image enhancements should not be added to any of this imagery in the scanning process. All enhancements should be undertaken as second-generation imagery such that they can be removed or modified.

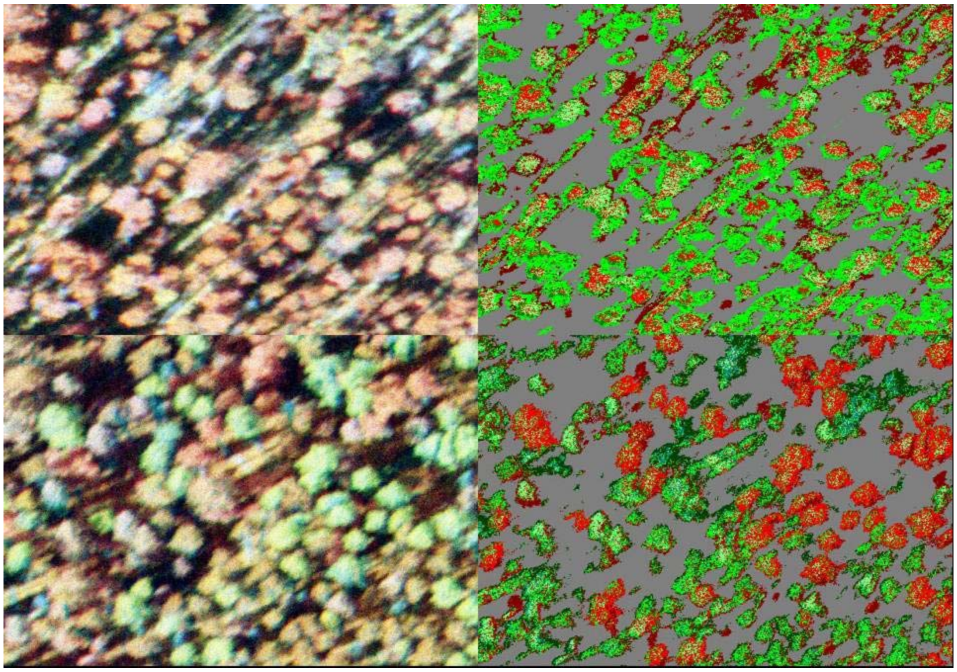


Figure 6d: May 15, 2002 & August 14, 2002. Two sub-images with supervised classifications from the Blackwater multispectral imagery:

Top Left – May 15: IRRB false colour infrared composite with new reds as yellow, healthy trees as pink/orange and old reds as blue;
Top Right – May 15: results from a supervised classification showing new red attack trees as bright red, healthy trees in different shades of green and old reds as dark red;
Bottom Left – Aug. 14: IRRB false colour infrared composite with new reds as green, healthy trees as pink/orange and old reds as blue;
Bottom Right – Aug. 14: results from a supervised classification showing new red attack trees as bright red, healthy trees in different shades of green and old reds as dark red.

This study has developed and recommended an operational remote sensing strategy for BC involving MPB as well as other forest pathogens, pests and environmental problems. This includes:

1. optimum strategies for identifying and mapping advanced Mountain Pine Beetle attacks (current and red attacks);
2. an evaluation of RS strategies involving other forest health considerations;
3. a strategy for the most efficient and reliable remote sensing investigation of the possibility for identifying and mapping early infestation stages (current attack) of mountain pine beetle in lodgepole pine forests;
4. potential for extrapolation of these early detection strategies to other forest health applications, and;
5. a determination of the operational capability, cost effective performance and knowledge transfer potential in resource management for the remote sensing procedures evaluated.

This study has critically considered traditional and new remote sensing tools and methods for the control of forest pathogens and pests as well as related procedures that can be used for other environmental monitoring practices: e.g. riparian vegetation, erosion, logging practices, suspended sediment concentrations, stream morphology and habitat.

This research evaluation and remote sensing study was planned to specifically enhance and transfer knowledge by identifying and evaluating the remote sensing imaging systems and analytical procedures that will most accurately and cost effectively address the current critical mountain pine beetle problem. It has provided a strategic framework with short, medium and long-term considerations of the role of remote sensing in forest resource management.

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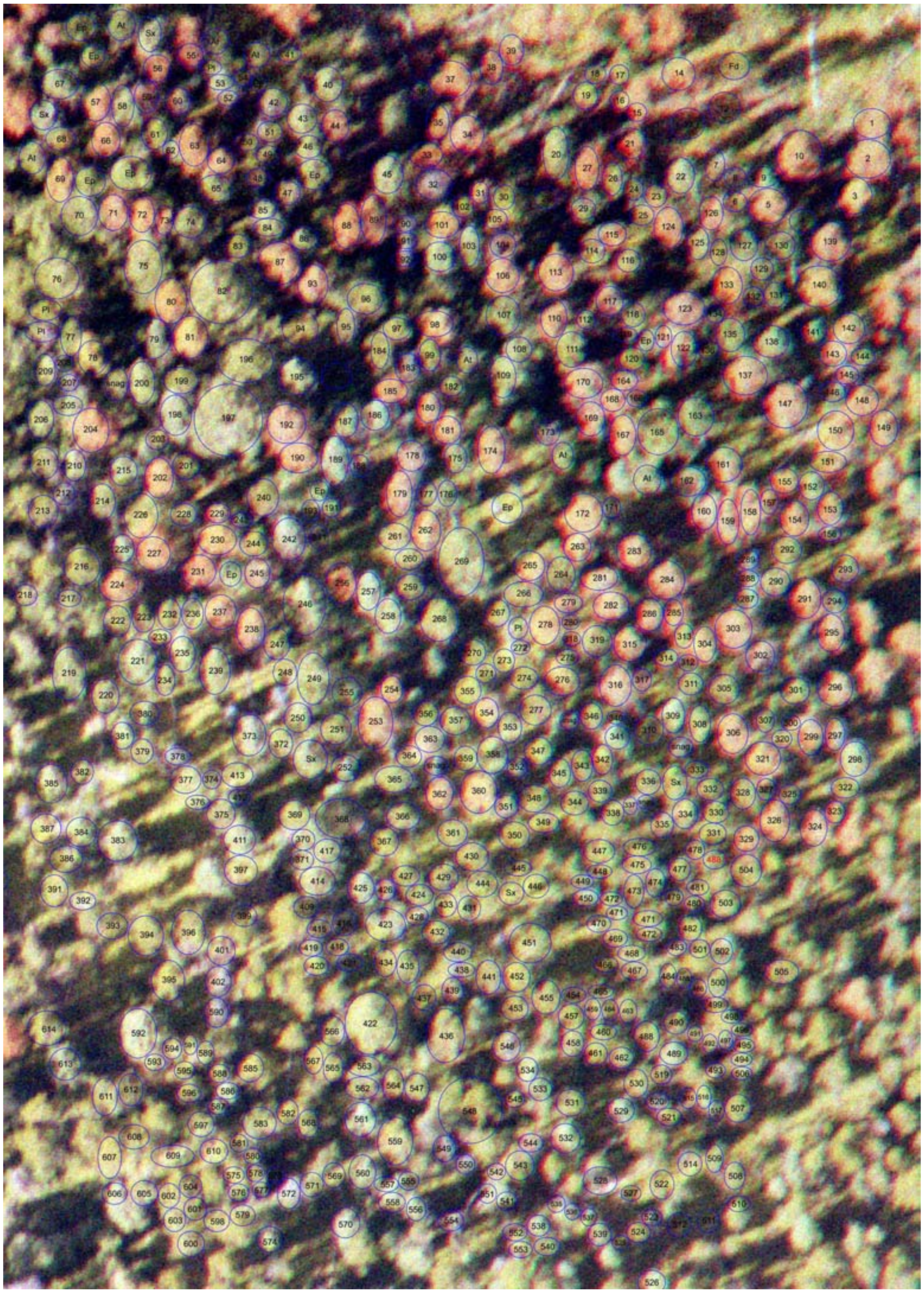
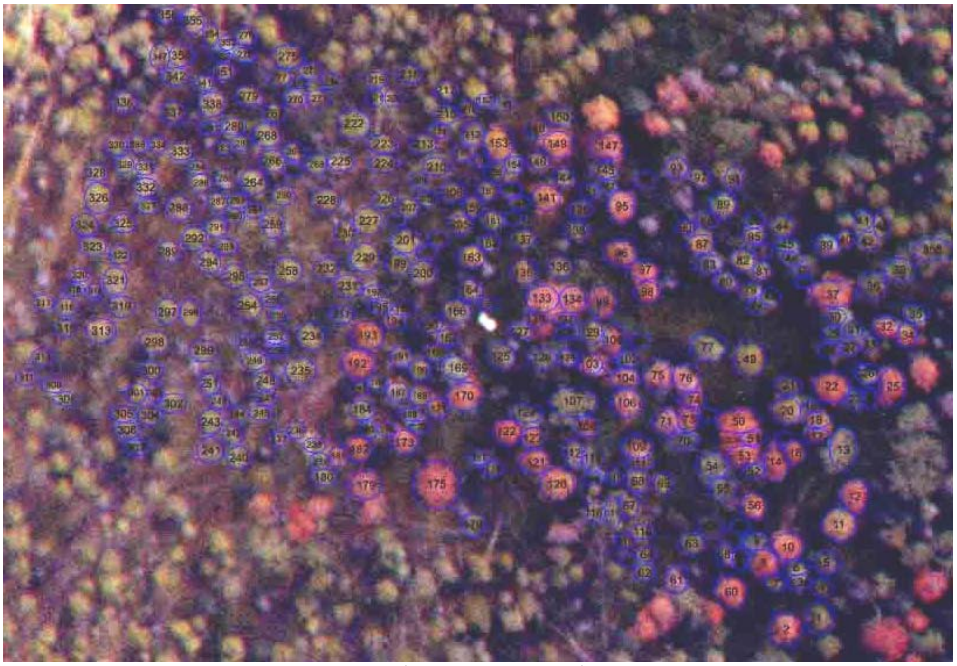
Appendix A

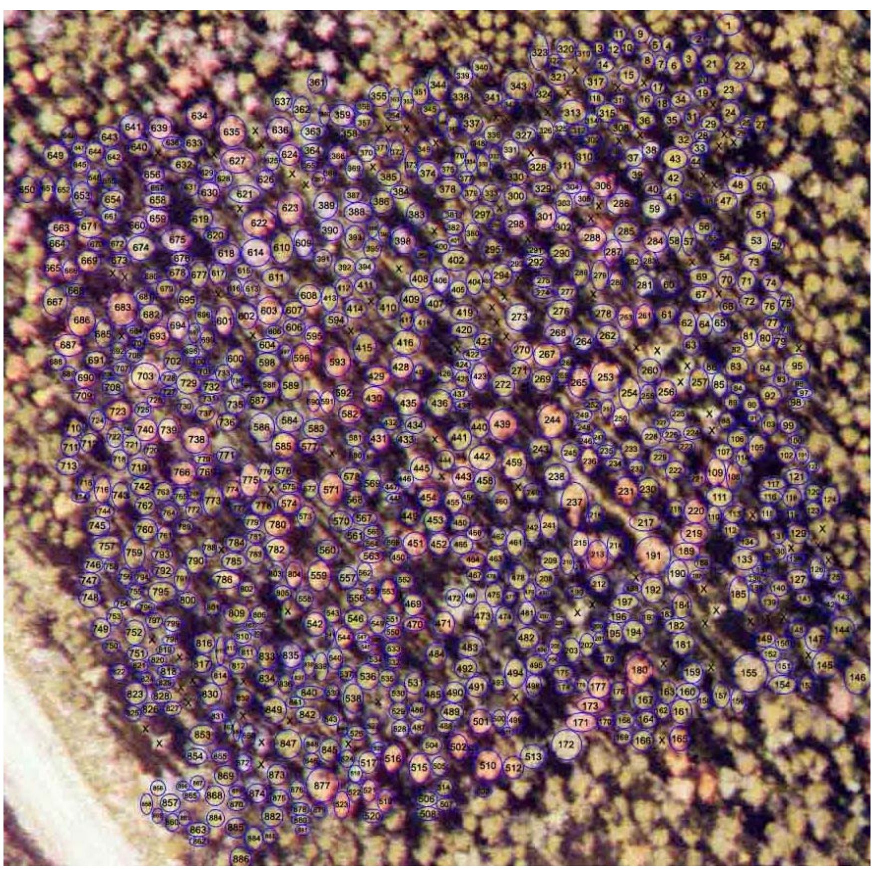
Ground truth trees displayed on remote sensing images for four of our six sites. All images are normal colour composites and all trees examined and marked in the field have their crowns circled and numbered. These numbers are keyed to appropriate tables (e.g. see Table A1).



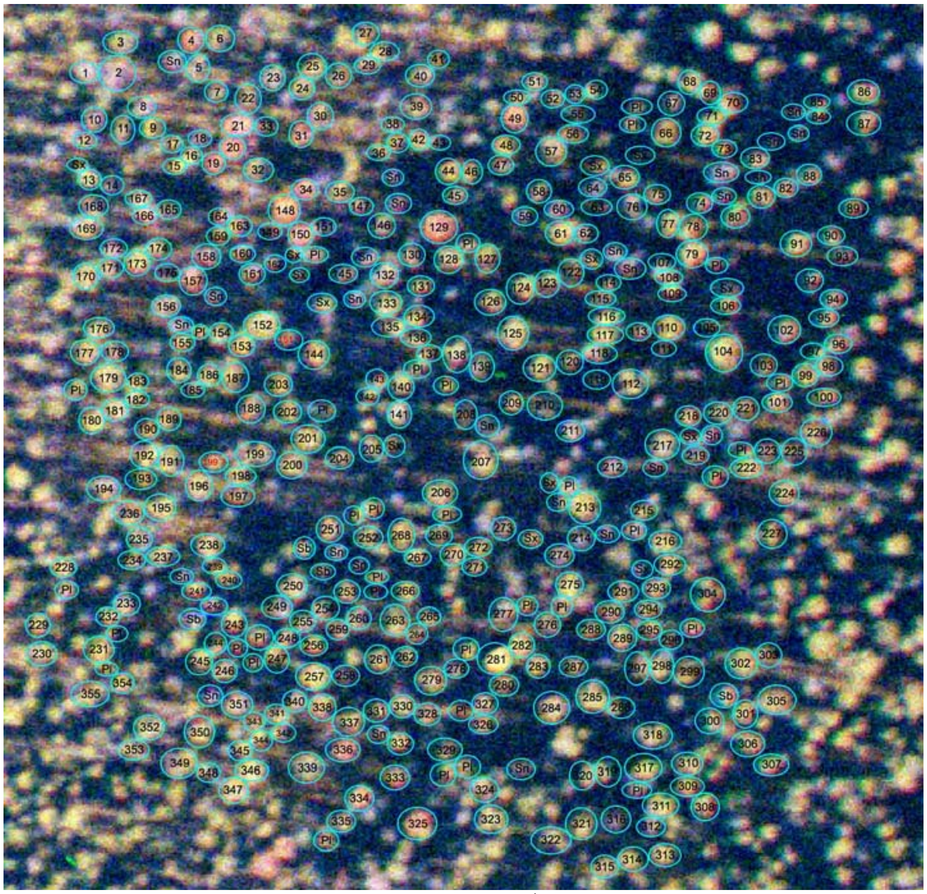
Ground truthed trees at the Blackwater site. All ground truthed trees are circled, numbered and keyed to a table. Ground truth was undertaken by MOF in November-December 2001 and SFU/MOF in November 2002.



Ground truthed trees at the Marilla 2M13 site. All ground truthed trees are circled, numbered and keyed to a table. Ground truth was undertaken by MOF in November-December 2001 and SFU/MOF in November 2002.



Ground truthed trees at the Nazko site. All ground truthed trees are circled, numbered and keyed to a table. Ground truth was undertaken by MOF in November-December 2001 and SFU/MOF in November 2002.



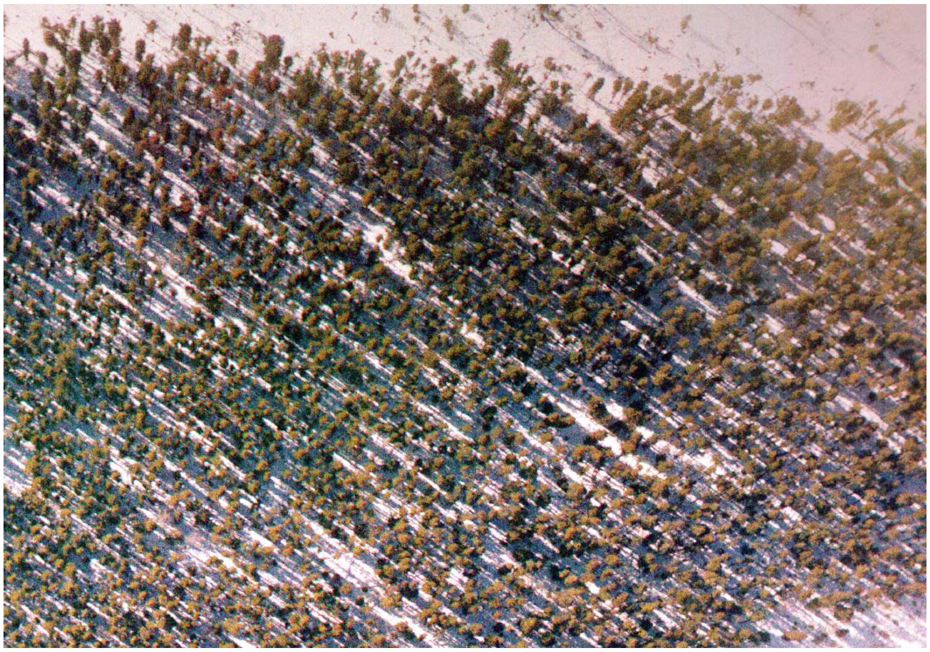
Ground truthed trees at Nechako Canyon site. All ground truthed trees are circled, numbered and keyed to a table. Ground truth was undertaken by MOF in November-December 2001 and SFU/MOF in November 2002.

Tree No.	Spp	2001 Bark Beetle Code	2001 Attack Severity	2002 Bark Beetle Code	2002 Attack Severity	DBH Class	Crown Class	Pitch Out	Late Attack	Develop Stage	Blue Stain	Surface Area Factor	Comments	is crown visible	Actual (Yes equals attacked)	CASI prediction (r = red dc y = yellow dot, or nd no dot))
1	Pl	1	D	3	D	42	D		NO	LARVAE	YES	11.6		yes	Yes	y
2	Pl	1	D	3	D	37	D		NO	LARVAE	YES	9.4		yes	Yes	y
3	Pl	1	D	3	D	32	D		YES	EGGS	YES	7.1		yes	Yes	r
4	Sx					32	C						blowdown	yes	No	y
5	Pl	1	D	3	D	37	D		NO	LARVAE	YES	9.4	Larvae 1st Instar	yes	Yes	y
6	At					27	C							At	No	y
7	Pl	1	D	3	D	27	C		YES	EGGS	NO	5.3		yes	Yes	y
8	Sx					32	C							yes	No	y
9	At					22	C							At	No	y
10	Pl	1	D	3	D	37	D		YES	EGGS	YES	9.4		yes	Yes	y
11	Sx					22	I						Witches broom on spruce. 2002 blowdown	shade	No	n
12	Pl	0				32	C							yes	No	y
13	Fd					27	C						blowdown, now leaning on tree #7	shade	No	n
14	Pl	1	D	3	D	32	C		YES	EGGS	YES	7.1		yes	Yes	y
15	Pl	1	D	3	D	32	D		YES	EGGS	YES	7.1		yes	Yes	r
16	Fd					22	C							no	No	n
17	Pl	0				27	C						unsure of crown (merged with #16)	yes	No	y
18	Pl	0				22	C							yes	No	y
19	Sx					32	C						Broken top., blowdown	shade	No	n
20	Sx					37	D							yes	No	y
21	Pl	1	D	3	D	32	C		YES	EGGS	YES	7.1		yes	Yes	y
22	Sx					42	D							yes	No	y
23	Pl	1	D	3	D	27	C		YES	EGGS	NO	1.65		yes	yes	y

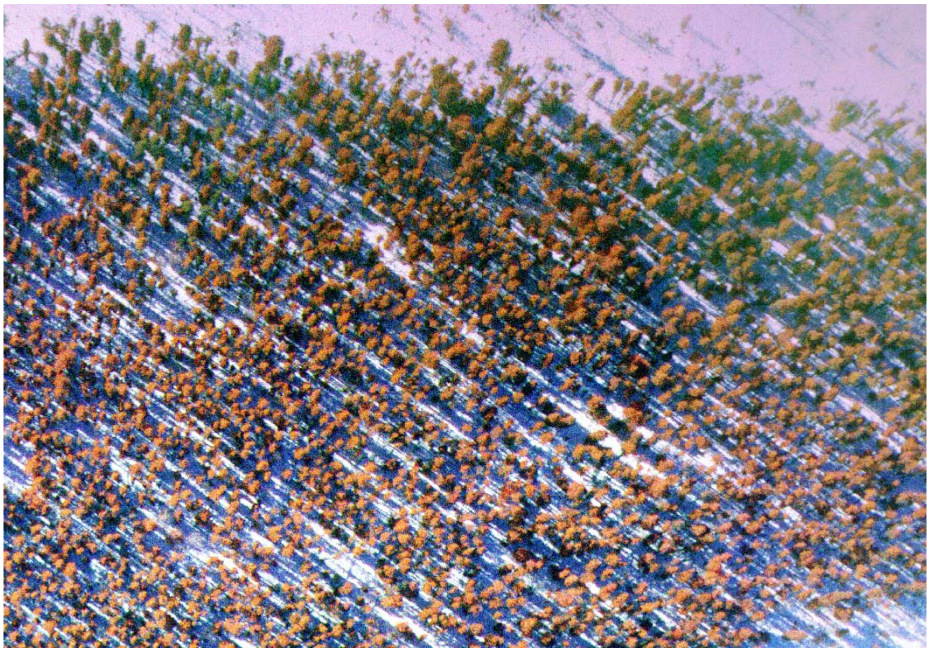
Table A1: Ground truth data for the first 23 trees from the Blackwater site. A total of 614 trees were ground truthed at this site.

Appendix B

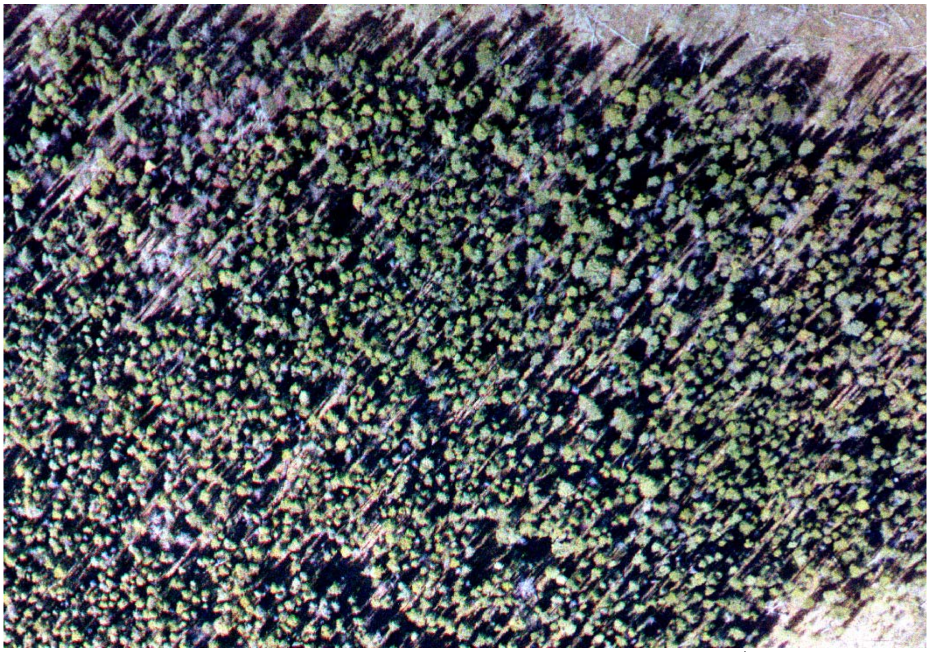
Sample MPB detection and monitoring imagery for the Blackwater Site, 2002. Imagery taken with International Imaging Systems multispectral camera using 89b (NIR), 25 (R), 46 (B) and 57 (G) filters and Agfa 200 PE 1 extended red film scanned at 16 microns. All imagery was flown at 1:8000. Normal colour (R G B) and false colour (NIR R G) are shown for each date. Note that on the false colour images the healthy trees appear red and the attacked trees appear as fading to green or green.



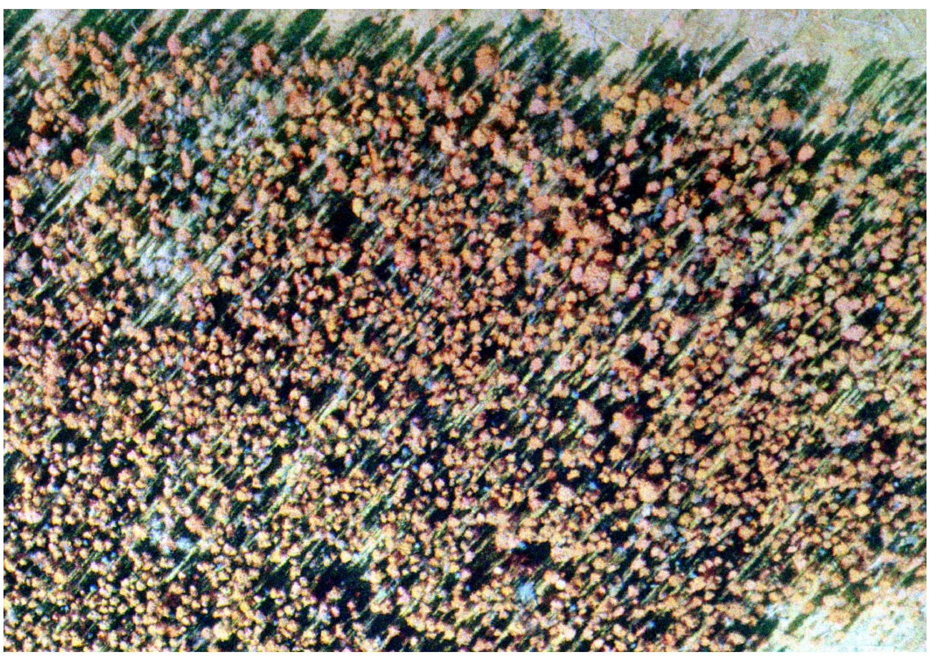
April 3, normal colour: snow on ground, old reds attack in upper left.



April 3, false colour: snow on ground, old reds attack in upper left.

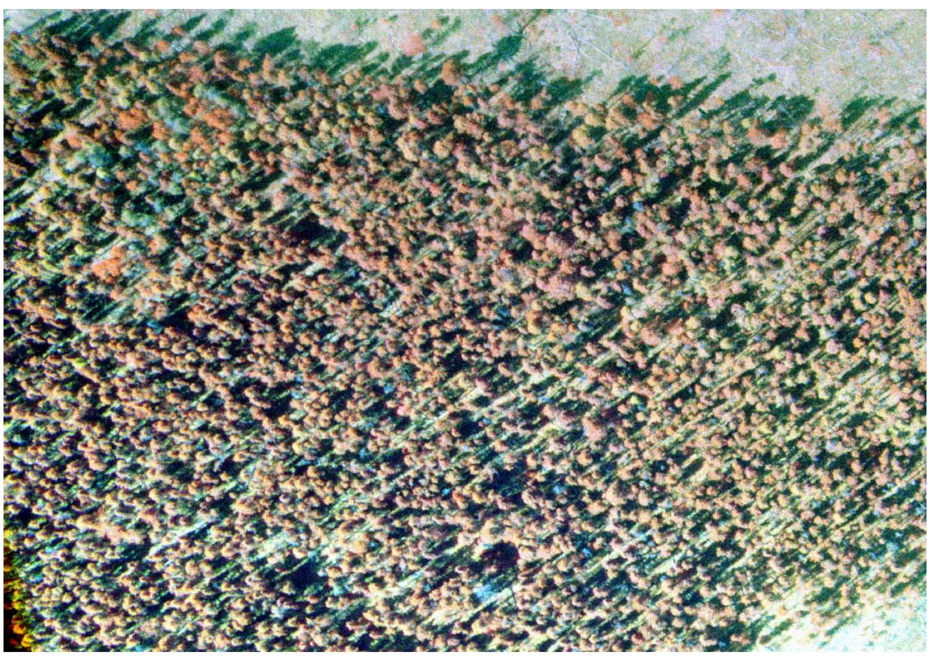


May 15, normal colour: old red attack upper left, fading current attack.

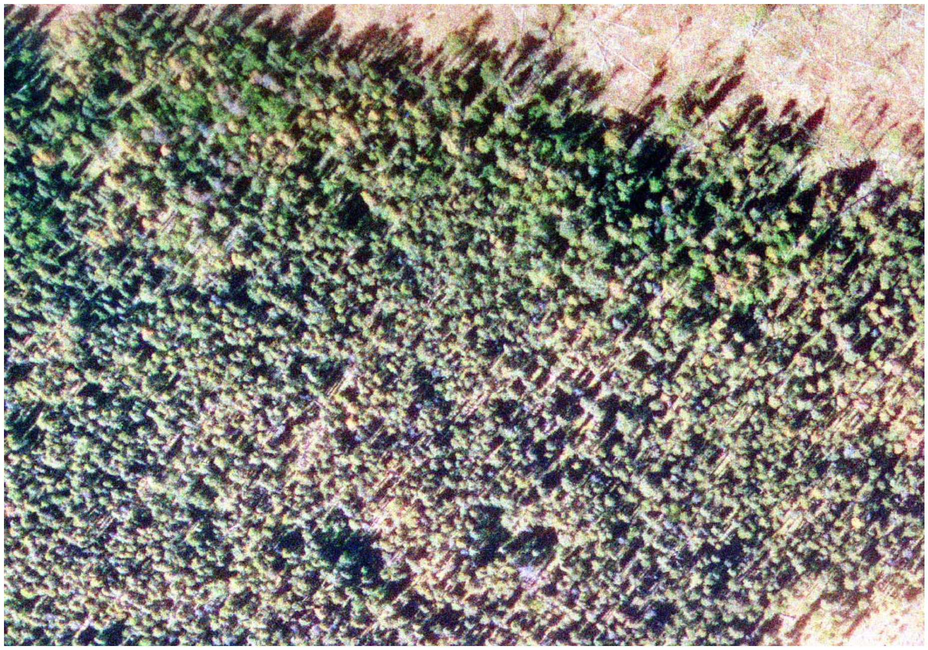


May 15, false colour: old reds are green upper left, current attack trees are yellow.

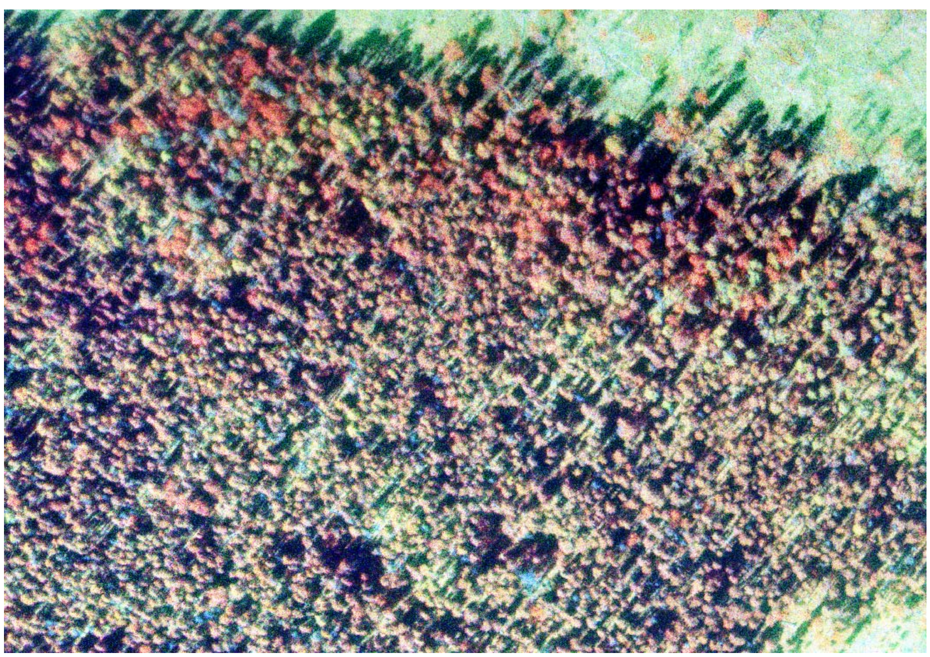
June 3, normal colour; upper left: old reds; current attack are fading & yellowing.



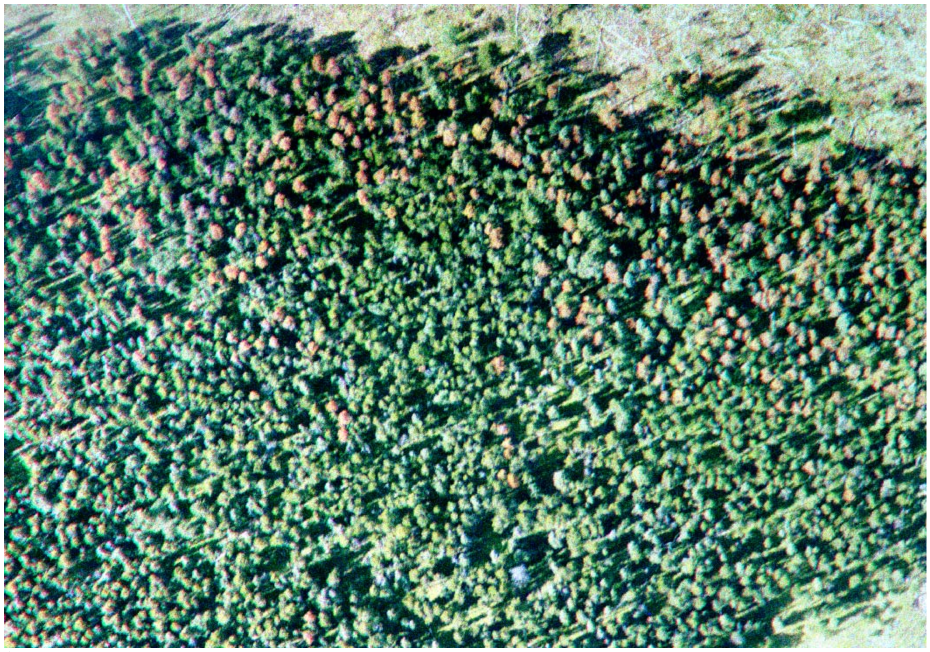
June 3, false colour; upper left: old reds (green-blue); current attack are yellow.



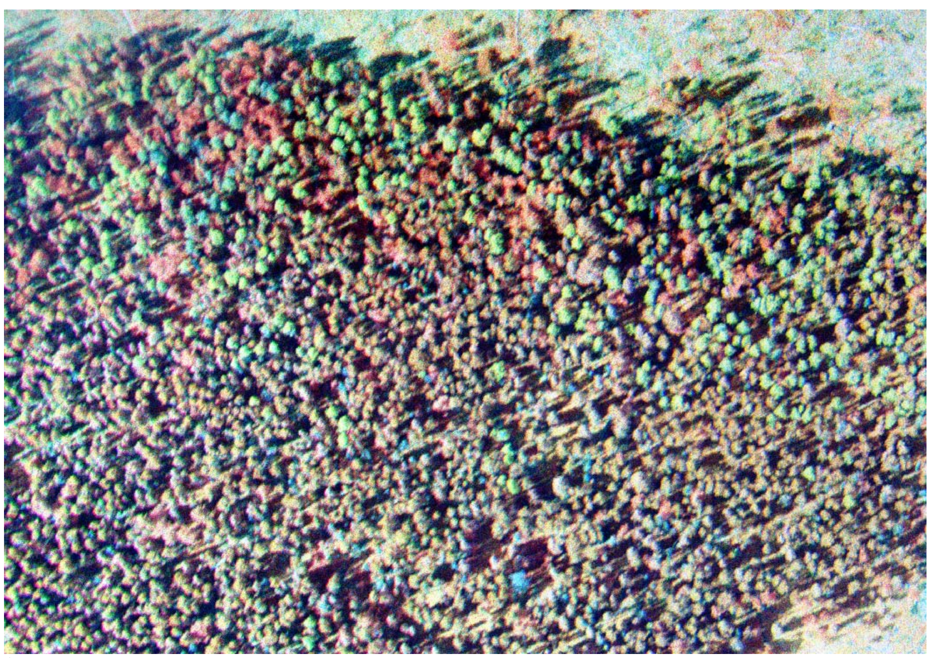
June 12, normal colour; upper left: old reds; current attack are fading & yellowing.



June 12, false colour; upper left: old reds (blue); current attack are yellow-green.



August 14, normal colour; upper left: old reds; current attack are red, fading & yellowing.



August 14, false colour; upper left: old reds (blue); current attack (bright green & yellow).