Working paper: Monitoring tree-level insect population dynamics with multi-scale and multi-source remote sensing

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Abstract

Long-term monitoring of the rate of change of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) populations requires detailed tree-level information over large areas. This information is used to assess the status of an infestation (e.g., increasing, stable, or decreasing), and to select and evaluate mitigation approaches. In this research project, we develop and demonstrate a prototype monitoring system, which enables the extrapolation of tree-level estimates of beetle damage from field data to a larger study area using a double sampling approach, and multi-scale, multi-source, high spatial resolution remotely sensed data.

Key words: high spatial resolution, QuickBird, digital aerial photography, insect, monitoring, mountain pine beetle

Résumé

La surveillance à long terme du taux de variation des populations de dendroctone du pin ponderosa (*Dendroctonus ponderosae* Hopkins) nécessite de l'information détaillée à l'échelle de l'arbre pour de grandes zones. Cette information est utilisée afin d'évaluer l'état d'une infestation (p. ex., croissante, stable ou décroissante) ainsi que pour choisir et évaluer les méthodes d'atténuation. Ce projet de recherche nous donne l'occasion de mettre au point et d'expérimenter un prototype de système de surveillance qui permet de faire des estimations à l'échelle de l'arbre des dommages causés par les dendroctones à partir d'une zone d'étude plus grande en utilisant une méthode à double échantillonnage ainsi que des données de télédétection à haute résolution spatiale à plusieurs échelles provenant de plusieurs sources.

Mots-clés : haute résolution spatiale, QuickBird, photographie aérienne numérique, insecte, surveillance, dendroctone du pin ponderosa

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1 Introduction

Over large areas, information on the location, extent, and severity of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) damage is required to determine the resources needed to address the infestation and, subsequently, allocate those resources effectively. Landscape-level (i.e., a management unit approximately 1 million ha in size) information is used to direct the location and intensity of more detailed surveys, which are designed to satisfy operational information needs and allow successful mitigation through accurate detection, location, and enumeration of individual infested trees. Similarly, tree-level (i.e., individual trees or small groups of trees) information is critical for a range of activities, including sanitation logging, the implementation of silvicultural regimes designed to reduce the susceptibility of host trees, as well as direct control treatments. Tree-level data of mountain pine beetle damage can be difficult and expensive to acquire; however, statistical sampling approaches may be used whereby samples of detailed data are used to calibrate damage estimates generated from less expensive and less detailed (but spatially extensive) data.

For mountain pine beetle monitoring in a country such as Canada, with vast tracts of forested land (and potential host species), it is necessary to have detailed tree-level information over very large areas (i.e., greater than several million hectares). Unfortunately, data sources suitable for characterizing mountain pine beetle infestations over large areas do not provide sufficient spatial resolution to generate tree-level information. (These data sources can provide a reliable estimate of the total area impacted, but cannot provide specific details regarding the number or precise location of individual infested trees.) However, by collecting a sub-sample of detailed data that does provide tree-level information, statistical methods can extrapolate estimates of the number of infested trees at the landscape-level. These estimates will not provide information on precise locations of the trees, but can give estimates on the rate of change in the mountain pine beetle population. For example, field measures may be combined with high resolution remotely sensed data (e.g., aerial photography, QuickBird, IKONOS) using double sampling with regression (Wear et al. 1966). This method of double sampling assumes that field measurements of damage or mortality relate to damage information interpreted from the remotely sensed data. A regression-based approach is used to link the field data to the satellite data, thereby providing a means by which damage or mortality estimates can be extrapolated to the landscape-level.

1.1 Goal and objectives

The research presented in this paper is a component of a larger, ongoing project initiated to develop and create a prototype of a monitoring system to provide tree-level estimates of mountain pine beetle caused mortality across a large area, thereby allowing forest managers to determine appropriate management strategies that minimize forest losses and reduce the risk of future infestations (Figure 1). Such a monitoring system provides information essential for determining the status of the infestation, monitoring the long-term impact of the infestation on forest structure, assessing the efficacy of mitigation measures, and reducing the future risk of mountain pine beetle attack. This communication provides details on the methods developed to extrapolate field measurements of tree-level mountain pine beetle red attack damage across a larger area using high spatial resolution remotely sensed data.

2 Background

2.1 Mountain pine beetle

The current mountain pine beetle outbreak in western Canada is of historically unprecedented proportions. In 2006, the area affected by the outbreak was estimated to be 9.2 million ha (Westfall 2007) and, by 2013, it is projected that the beetle will have killed 80% of the mature pine in British Columbia (Eng et al. 2006). The mountain pine beetle's range expansion has been facilitated by large areas of susceptible host species (as a consequence of stand management and fire suppression) and successive years of favourably warm climatic conditions, which enable brood development and survival (Logan and Powell 2001, 2003; Carroll et al. 2004, 2006).

When attacked by mountain pine beetle, a tree's foliage will initially remain visibly unchanged; however, signs of attack will be present on the stem (green attack stage). As the tree's foliage fades from green to yellow, the tree is referred to as a fader. Approximately one year following attack, the foliage will turn red (red attack stage) and, finally, when the tree loses its foliage, it is considered to be in grey attack stage (Amman 1982; Henigman et al. 1999; British Columbia Ministry of Forests 1995). Surveying methods and image analysis protocols exploit the visible distinctness of the red attack stage for detection and mapping of infestation location and severity (Wulder et al. 2006a).

2.2 Survey of mountain pine beetle

A variety of survey methods are used to collect information on the location, size, and severity of mountain pine beetle populations, ranging from satellite or aerial platforms, to a tree by tree basis on the ground. Thus, the area covered by a survey can vary greatly, as can the level of detail. Each survey method is applicable to different management. A comprehensive description of the survey hierarchy used to detect and map mountain pine beetle in British Columbia is detailed in Wulder et al. (2006b).

Field surveys of mountain pine beetle are conducted annually to determine population trends, by estimating the ratio of green attack to red attack trees (G:R) in a forest stand. A ratio greater than one indicates an increasing population, while a ratio less than one indicates a declining population. The G:R ratio is often estimated from a subsample of trees along randomly located transects (Safranyik and Carroll 2006). This rate of change information is one of the factors used to determine the management strategy (i.e., suppression, salvage, monitoring) for forest management units in British Columbia (British Columbia Ministry of Forests 1995). The best possible information is used to ensure that the management practices selected are appropriate for the situation; if an incorrect management approach is used, suppression may take longer, or a population that is pre-epidemic may become epidemic and suppression may no longer be possible.

2.3 Remote sensing of mountain pine beetle

Remotely sensed data provides unique options for information collection and monitoring to address mountain pine beetle information needs. By capturing the location and extent of mountain pine beetle red attack at different scales and with different levels of accuracy and precision (Wulder et al. 2006b), remotely sensed data thereby augments existing survey methods. The three most important aspects to consider when using remotely sensed data to determine the location and extent of the mountain pine beetle are the spatial, temporal, and spectral characteristics of an attack (Wulder et al. 2006a).

3 Methods

3.1 Study area

The project study area encompasses over 6 million ha and is located at the leading edge of an ongoing mountain pine beetle epidemic along the provincial border between British Columbia and Alberta, Canada (Figure 2). Nine sample locations, each with an area of 6400 ha, were selected within the study area. High spatial resolution remotely sensed imagery and field data were acquired within these sample locations (Figure 3) These sample plots were strategically placed in areas of high risk to mountain pine beetle attack based on a susceptibility rating outlined by Shore and Safranyik (1992), and using forest inventory data (i.e., stand age and density, diameter at breast height--dbh, species composition, location, and elevation). The methods presented herein were developed and tested on Site 9 (Figure 3).

Approximately 72% of the study area (south and west) is in the Montane Cordillera ecozone. The remaining 28% of the study area to the north and the east is the Boreal Plains ecozone. Tree species of the forests within the region are predominately lodgepole pine (*Pinus contorta* Dougl ex Loud. Var. latifolia Engelm.), with small proportions of alpine fir (*Abies lasiocarpa* Nutt.), Engelmann spruce (*Picea engelmannii* (Parry) Engelm.), white spruce *(Picea glauca* (Monech) Voss), black spruce (*Picea mariana* (Mill) BSP), jack pine (*Pinus banksiana* Lamb.), and tamarack (*Larix laricina* (Dr Roi) K. Kock).

Located in the Dawson Creek Timber Supply Area (TSA) of British Columbia and the Northwest Boreal Forest Management Unit in Alberta, the study area also includes provincial and federal parklands. These areas represent high-value, high-profile stands, which may be subject to aggressive direct control measures such as yearly sanitation harvesting and single tree treatments, such as those that have become commonplace in other regions impacted by mountain pine beetle. The study area has no recorded history of mountain pine beetle infestation, while areas to the northwest and southwest of the study area are currently at endemic infestation levels. Due to the abundance of large-diameter lodgepole pine in the study area, an increasing trend in the beetle population is anticipated.

3.2 Data

3.2.1 Field data

Field data was collected by ground crews from August 9th to 29th, 2006, and again from July 27th to August 12th, 2007. Measurements of individual trees included stem diameter, crown dimensions, tree height, tree species, and mountain pine beetle health status. Stand-based measurements included slope, aspect, and the geographic location of plot centre. In 2006, 26 field plots were visited across all nine sample sites; however, only one plot was found to have red attack damage. In 2007, 27 field plots were visited, again across all sites, with 164 red attack trees identified. In Site 9, four field plots were sampled in 2006 and no red attack was identified; in 2007, nine field plots were sampled and 61 red attack trees were located (Table 1).

3.2.2 Forest inventory

Forest inventory data for the portion of the study area located in British Columbia was obtained from the Ministry of Forests and Range and conforms to the standards for Vegetation Resources Inventory (VRI) in British Columbia (British Columbia Ministry of

Sustainable Resource Management 2002). Forest inventory for the portion of the study area located in Alberta was obtained from Weyerhaeuser for their FMA area, and from the Alberta Sustainable Resource Development agency for the other areas of the forest management unit, including designated wilderness areas and reserves. The Alberta inventories were compiled according to Alberta Vegetation Inventory Standards (Alberta Sustainable Resource Development 2005).

3.2.3 High-spatial resolution remotely sensed data

Annual high spatial resolution satellite images, such as those obtained from QuickBird, provide the mechanism to detect and extrapolate tree level information on mountain pine beetle red attack damage. QuickBird imagery contains four multispectral bands with a 2.5 m spatial resolution: 0.45-0.52 μm (blue); 0.52-0.60 μm (green); 0.63-0.69 μm (red); 0.76-0.90 μm (near infra-red); and a panchromatic band (0.45-0.90 μm), with a 0.68 m spatial resolution (Birk et al. 2003). QuickBird imagery was ordered in 2006 and 2007 for Site 9; however, persistent cloud cover prevented successful image acquisition in 2007. The 2006 QuickBird image was acquired on July 20th, with a sun elevation angle of 54.41 degrees and the off-nadir view angle of 11.26 degrees. The QuickBird imagery was orthocorrected to Terrain Resource Information Management II (TRIM II) aerial photography (British Columbia Ministry of Sustainable Resource Management 1997) and a Digital Elevation Model (DEM) from Canadian Digital Elevation Data (CDED) provided by GeoBase at a scale of 1:50,000. All processing used a satellite orbital model (after Toutin 2004) with cubic convolution resampling in PCI Geomatica V9.1.8. The panchromatic and multispectral bands were orthorecitifed individually and had root-mean-square (RMS) errors of 1.24 pixels (0.74 m) and 0.3 pixels (0.73 m), respectively.

To mitigate the lack of a satellite-based source of high spatial resolution imagery in 2007, 40 cm digital aerial photography was acquired over the sample sites in September, 2007, using the same camera and acquisition parameters as the 10 cm photos.

In 2006 and 2007, digital colour aerial imagery was collected prior to the commencement of field surveys. Imagery was acquired with a Canon EOS-1Ds Mark II camera (with a focal length of 85 mm), mounted on a fixed wing aircraft flying at 1100 m (Terrasaurus, Vancouver, British Columbia, Canada). Images were collected over the centre point of each plot, resulting in 10 cm spatial resolution. Imagery was orthorectified to a UTM NAD 83 projection with each photograph covering an area of approximately 0.14 km^2 (0.44 km x 0.31 km, 4850 x 3110 pixels). Imagery was recorded in three channels representing the spectral ranges: 0.6 – 0.7 µm (red), 0.5 – 0.6 µm (green), and 0.4 – 0.5 µm (blue).

The orthocorrected panchromatic QuickBird image was used as the reference image to which all other aerial images were registered. The registration was done using a third order polynomial and cubic convolution re-sampling algorithm. The final RMS error for the 10 cm images was 10.87 pixels (1.09 m) and for the 40 cm aerial image, the RMS error was 3.84 pixels (1.54 m).

3.2.4 Image analysis

The analysis procedures implemented are outlined in Figure 4 and described in the following sections.

3.2.5 Image masks

Forest inventory data were used to generate the pine mask of forest stands that contained greater than or equal to 50% pine. These masks were then applied to the 2006 QuickBird imagery to constrain subsequent analyses to those stands that contain pine, thereby reducing the total area analyzed, as well as reducing the spectral variability of the area subject to analysis (Rogan and Miller 2006). An additional mask was generated to remove cloud and cloud shadow areas within the sample site.

3.2.6 Image segmentation

Since the aerial and satellite imagery were acquired on different dates, there are differences in viewing geometry and illumination conditions. These factors, combined with the potential for error in co-registration of multiple scales and dates (Weber et al. 2008), made tracking the health status of individual trees through the different data sources and years a challenge. To mitigate this potential source of error, segmentation of the 2006 QuickBird multispectral imagery was used to provide a context for tracking tree sub-populations through time (Wulder et al. 2008). Segments were generated using all four QuickBird multispectral bands in eCognition software (Definiens GmbH, Munchen, Germany) in two passes with equal weights for all bands. The first pass used the following parameters: scale = 15; shape = 0.5; colour = 0.5; compactness= 0.75; smoothness = 0.25, while the second pass used: scale = 15; shape = 0.9; colour = 0.1; compactness = 1.0; smoothness = 0.

3.2.7 Stem counts

First, individual tree crowns were manually delineated on the 10 cm air photos. This provided a useful information source for validating stem counts generated from the QuickBird data, and for enumerating the number of red attack trees identified on the 10 cm photos. In order to generate stem counts for the entire sample site, a local maxima (LM) filter (Wulder et al. 2000) was applied to the 2006 panchromatic QuickBird image. When a LM filter is applied to high spatial resolution imagery, individual trees can be identified as local regions of relatively higher reflectance (in appropriate spectral channels, such as near infrared or panchromatic) (Dralle and Rudemo 1997). The LM filter passes over all pixels in an image, and identifies those that have a reflectance within a threshold range equal to or higher than the surrounding pixels. This requires that the image resolution is finer than the crown size of the trees, so that each tree crown is represented by multiple pixels. The LM filter has a bias towards large tree crowns, and a higher error of omission regarding smaller tree crowns; however, the impact of this bias is minimal for this project, because trees with smaller crowns are generally younger and not typically as susceptible to mountain pine beetle attack (Shore et al. 2000).

For this study, a 3- by 3-pixel LM filter was applied to identify individual tree crowns. The identified LM pixels were then converted to a vector point data set representing individual stems. The LM stems and the image segments generated from the 2006 QuickBird imagery were used for the 2007 analysis, as it was assumed that the number of stems and segments would be consistent over the two years. The LM tree counts were validated against manual tree counts from the 10 cm imagery. A calibration factor was derived from the relationship between the 10 cm and QuickBird stem counts, and this factor was then applied to the QuickBird stem counts to generate a final, calibrated stem count estimate for the entire sample site.

3.2.8 Red attack detection on 10 cm aerial imagery

Red attack trees that were identified in the 2007 field surveys were identified and manually delineated on the 10 cm aerial photography. To identify red attack trees outside of the field plot areas on the 10 cm aerial imagery, a red-green index (RGI) was calculated by dividing the red image channel by the green image channel using a similar approach developed by Coops et al. (2006) to identify red attack damage from QuickBird imagery. Once the RGI was calculated for each of the 10 cm images of 2007, a RGI threshold range was generated using the known red attack trees from the field plots. Pixels with a RGI within this range were identified as red attack in a bitmap layer. To reduce false positive red attack identification, the bitmap layer was converted into vector polygons, and those polygons with an area less than 1.44 m^2 (corresponding to an area 1.2 m by 1.2 m, or four QuickBird panchromatic pixels) were eliminated. This cut-off corresponds roughly to the crown area that is identifiable using the LM filter approach. The remaining areas identified as red attack were each visually assessed, and those that were deemed not to be red attack trees were eliminated. Individual red attack trees were enumerated. The result of this process was a calibration and validation layer of red attack trees on the 10 cm imagery that can be used to calibrate and verify red attack detection from coarser image sources.

3.2.9 Red attack detection on 2006 QuickBird and 40 cm air photos

The RGI approach used for red attack detection on the 10 cm imagery was also applied to the 2006 QuickBird multispectral data, and to the 40 cm photos collected in 2007, which provide the surrogate for the 2007 high spatial satellite resolution imagery. The RGI was calculated for the 40 cm aerial imagery of 2007 under the pine mask and a threshold range was developed using those areas identified as red attack on the 10 cm imagery. As with the 10 cm imagery, the resulting bitmap layer was converted into vector format and those polygons with an area less than 1.44 m^2 were eliminated.

The point layer representing the individual tree stems was then overlaid with the red attack areas and those stems found within a corresponding red attack area were labelled as red attack. Trees that are red attack in 2007 are assumed to have been green attack in 2006, facilitating an estimate of the G:R ratio for 2006.

3.2.10 Calibration and validation

Both stem counts and red attack detection estimates generated with the 40 cm photos were calibrated and validated using corresponding estimates from the 10 cm photos (Figure 5).

3.2.10.1 Stem counts

In order to assess stem counts generated from the LM filter, manual stem counts were conducted on the 10 cm digital imagery within 40 randomly selected segments. The relationship between the LM-derived stem counts and the manual stem counts was assessed using a simple linear regression and an adjustment factor was calculated. T-tests were used to assess if the stem counts generated from the QuickBird and the 10 cm photos were significantly different prior to and following the application of the adjustment factor.

3.2.10.2 Red attack

Estimates of red attack generated from the field data and from the 10 cm photos were used to iteratively modify the threshold range of RGI values used to identify red attack pixels from the 40 cm photos. To calibrate the threshold range, the results of the thresholding were visually compared to the 10 cm images to assess the effectiveness in terms of success at correctly identifying red attack while minimizing false positive identification. The threshold range was iteratively adjusted to improve the red attack estimates, and the results were assessed again until an optimum threshold range was identified. After the optimum threshold range was selected, the red attack area was identified and the LM-derived stems were overlaid with the red attack layer to assign attack status to the stems. Red attack estimates from the 10 cm photos were also used in a double sampling with a regression approach to calibrate broad estimates of red attack damage for Site 9 made from the 40 cm photos.

3.3 Double sampling

Double sampling with stratification is an established method for integrating remotely sensed data with ground samples (USDA Forest Service 1992). Selected classes (such as red attack trees) are randomly re-sampled at a higher level of detail to provide more information about that class (Frayer and Furnival 1999). A regression between the high accuracy ground data and lower accuracy remotely sensed data is used to adjust the estimates over the entire area (Bickford 1952). The advantage of double sampling is that expensive data collection methods, such as field sampling, are minimized, while the estimates from lower cost, broader area data sources, such as satellite imagery, are optimized. In this project, the double sampling strategy is applied in using the field data to correct the high resolution aerial estimates of red attack trees, which in turn are used to correct the estimates of red attack trees from the high resolution satellite imagery.

In this study, double sampling was used to extrapolate tree-level estimates of red attack damage across a larger study area. The high resolution 10 cm imagery was used to calibrate the LM-derived stem counts to provide a more accurate segment based tree count covering the entire study site. The resulting calibration factor was applied to the entire study site to provide an adjusted red attack count extrapolated over the entire area of Site 9.

4 Results and Discussion

4.1 Image segmentation

The number of segments generated for Site 9 was 41,119; however, only those segments that had their centroid within the pine mask area were used for further analysis, resulting in 19,297 segments. For the 2007 calibration and validation data, 510 segments that had corresponding coverage with the 10 cm photography were used for both stem counts and red attack detection (Table 2).

4.2 Validation of stem counts

To validate the LM-derived stem counts, 40 segments were selected at random and the stem counts were compared to the manual stem counts. Table 3 contains a summary of stem count results. Although the stem counts were very similar (Figure 6, R^2=0.94), there was a significant difference between the manual segment stem count generated from the 10 cm photos and the segment stem count generated from the LM filter applied to the QuickBird panchromatic image ($\alpha = 0.95$, $p = 0.006$).

To account for the difference in stem counts, a simple linear regression was used to generate an adjustment factor to calibrate the LM-derived stem counts to the manual stem counts (Figure 6). The adjustment factor for the LM tree counts was:

$$LM_{adj} = 1.209018 * LM_{QB}.$$

After application of this adjustment to the stem counts in each segment, no significant difference between the two stem count estimates was found ($\alpha = 0.95$, $p = 0.85$).

4.3 Calibration and validation of red attack detection

To obtain red attack counts for the 510 segment subset used as calibration and validation data, the trees identified as red attack in the 2007 field visits were used to derive a threshold range for the RGI values generated from 10 cm photos. The threshold range was identified as digital numbers (DNs) from 1.1 to 1.9 and pixels identified in this range were then manually assessed for red attack status (Table 4). Only ten segments had five or more red attack trees, and the maximum number of trees per segment was 14. The results of the 2007 RGI red attack mapping using the 10 cm photos were manually compared to the red attack trees identified in the 2007 field plots, and of the 220 trees that had a health status recorded in the field, only one tree on the 10 cm photo was incorrectly identified as red attack, while four red attack trees identified in the field were omitted on the 10 cm image mapping. The four omitted trees had small crowns, or were immediately adjacent to other red attack trees. The RGI was calculated for the 10 cm imagery of 2006; however, in 2006 the field surveys had found no evidence of red attack, and based on the results of the RGI and manual assessments of the 10 cm imagery, there was no red attack evident in that year.

The RGI approach described above was applied to the 40 cm photos acquired in 2007. The threshold was determined iteratively, based on red attack identified on the 10 cm imagery as DNs from 1.0 to 1.9. The 40 cm imagery was taken late in the year, and some of the hardwoods had already started to change colour. This was a source of commission error. In future, care must be taken to acquire the imagery early enough to avoid this problem again. Applying the threshold range resulted in a total red attack area for the 510 segments of 1650 m^2. When the LM-derived stems were overlaid on the red attack areas, a total of 139 trees were identified as red attack, to which the LM adjustment factor was applied. The same approach was then applied to the remaining 18,797 segments (Table 4).

4.4 Double sampling

Double sampling with regression was used to combine the estimates of red attack damage from the 40 cm photos with the red attack estimates from the field data and the 10 cm photos (Ciesla 2000). The objective is to refine the estimates generated from the 40 cm photos and to quantify estimation error for the sample site. Double sampling with regression uses two stages: the first stage requires a large sample collected via remote sensing (i.e., 40 cm photos), while the second stage requires a sub-sample of the first stage where more detailed data is collected (i.e., 10 cm photos). Of the 75 segments that had red attack identified from the 10 cm photos, 22 had red attack identified on the 40 cm photos. These 22 segments were used for the double sampling approach. A linear regression is used to determine the relationship between the estimates of red attack acquired from the 10 cm and 40 cm photos. The final estimate of red attack for the larger area is achieved by using the regression to adjust the estimates from the first stage (Ciesla 2000).

Following Wear et al. (1966) and Ciesla (2000), the first step was to generate the mean red attack count for the large sample (40 cm; n=2399 segments), which was 2.2 (Table 4). The second step was then to generate the mean red attack count for the 10 cm and 40 cm photos for the small sample (n=22), which were 3.8 and 3.18 respectively, and determine the linear regression of 10 cm red attack counts over 40 cm red attack counts for the small sample (Figure 7):

$$y = 1.22 + 0.815x$$

This regression was found to be significant at the 99-percent level (F=16.34 which is > 8.1 at 1 and 20 degrees of freedom), with an R^2=0.45 ($p < 0.001$, standard error=2.5 red attack trees). This regression was used to generate a revised estimate of the number of red attack trees within Site 9 as follows (Ciesla 2000):

$$RA_{40cm(adj)} = RA_{10cm} + b(RA_{40cm(LS)} - RA_{40cm(SS)}).$$

where RA_{10cm} is the mean red attack count from the 10 cm photos (3.8; n=22); $RA_{40cm(LS)}$ is the mean red attack count from the 40 cm photos for the large sample (LS) (2.2; n=2399); and, $RA_{40cm(SS)}$ is the mean red attack count for the photos from the small sample (SS) (3.18; n=22):

$$\begin{aligned} RA_{40cm(adj)} &= 3.8 + 0.815(2.2 - 3.18) \\ &= 3.01 \text{ red attack trees/segment} \end{aligned}$$

Applying this relationship, the total number of red attack trees in Site 9 for 2007 is estimated to be 7240. Using the method outlined by Ciesla (2000), the sampling error rate for the developed model was estimated to be 0.055% or ± 397 trees.

The results of this study suggest that some level of stratification by attack level can be effective in improving the success of the double sampling approach. Low levels of red attack, as seen in this study site, may be more difficult to calibrate compared to high levels of red attack. With higher levels of attack, the RGI threshold range used to identify red attack areas can also be optimized to reduce the error of commission, since small groups of trees will be more easily identified than single trees. At low levels of attack, where the dominant scenario is a single red attack tree per segment, a single incorrectly identified red attack tree can have a significant impact on the error, making it difficult to build a single model that captures the variability in attack conditions throughout the study site.

4.5 Estimating the G:R for 2006

Counts of individual trees attacked in successive years provide an indication of beetle population growth and dynamics. To facilitate an estimate of G:R, the amount of red attack observed in 2007 is back-cast as green attack in 2006. In 2007, the total amount of red attack estimated over the sample site was 7240 trees, distributed over 2399 segments. If these trees were green attack in 2006, the G:R for Site 9 is estimated at 3.01:0. As would be expected in an area that is on the leading edge of an epidemic, the rate of increase is high, due to an influx of beetles from external populations as opposed to an in situ population explosion. A G:R ratio was calculated for the 510 segment subset using the 10 cm photos resulting in a ratio of 3.16:0. This G:R closely corresponds to the ratio generated using the adjusted totals of red attack for the larger area from the double sampling approach.

In the Peace Forest District (Figure 2), where the majority of the project's larger study area is located, the average G:R was 12:1, with a maximum of 163:1 and a minimum of 1.1:1 (Westfall 2007). Generally, the absolute maximum possible G:R is believed to be 10:1 (British Columbia Ministry of Forests 1995), with the acceptable biological limit being 5:1 (Westfall 2007). It should be reiterated that these G:R are based on the assumption of in situ population growth rather than immigration and must therefore be interpreted with caution. Our estimated G:R is reflective of the unique conditions in this area (Carroll 2007).

5 Conclusions

In British Columbia, the spatial extent of the current infestation is such that information needs are now focused on monitoring the areas on the leading edge of the infestation, and efforts are directed towards minimizing mountain pine beetle population growth and avert spread into the boreal forest (Carroll et al. 2006; Logan and Powell 2001). A sample-based large area monitoring for forest health status is desired to track the infestation population status and dynamics, as well as track the impacts of mitigation upon these populations. Monitoring of tree-level health status is required to provide sufficiently detailed information for tracking infestation population status and dynamics. Using a range of approaches, we have integrated spatial and spectral information from differing data types to create a prototype of a tree-level monitoring program. Individual trees may be identified, insect attack status can be produced (from different image sources); these can be combined over time to produce information on mountain pine beetle population and change. Based upon the findings of this monitoring system prototype, we have demonstrated that tree-level monitoring of health status is possible, even when using differing image types (from airborne and satellite sources) in a multi-year monitoring program.

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Table 1. Summary of trees identified in the field plots (2007) and on the 10 cm imagery.

Health Status	Total # of trees
Dead	10
Healthy	146
Green attack	3
Red attack	61
Total	220

Table 2. Summary of segmentation results.

	Number of segments	Minimum segment size (m^2)	Maximum segment size (m^2)	Average segment size (m^2)
Site 9	41,119	52	16,214	1,547
Masked image area	19,297	52	12,200	1,677
Calibration/validation	510	121	7,010	1,606

Table 3. Summary of LM filter tree count results.

	Number of segments	Minimum tree count	Maximum tree count	Average tree count/segmen t
Masked image area	19,297	0	1,373	142
Calibration/validation	510	0	876	146
LM calibration set	40	5	998	175

Table 4. Summary of red attack counts.

Data	Number of segments	RA count by area	RA count Final	Segments with RA	Average RA per segment
10cm	510	-	237	75	3.16
40cm	510	139	168	54	3.11
40cm	18,797	4376	5291	2399	2.2

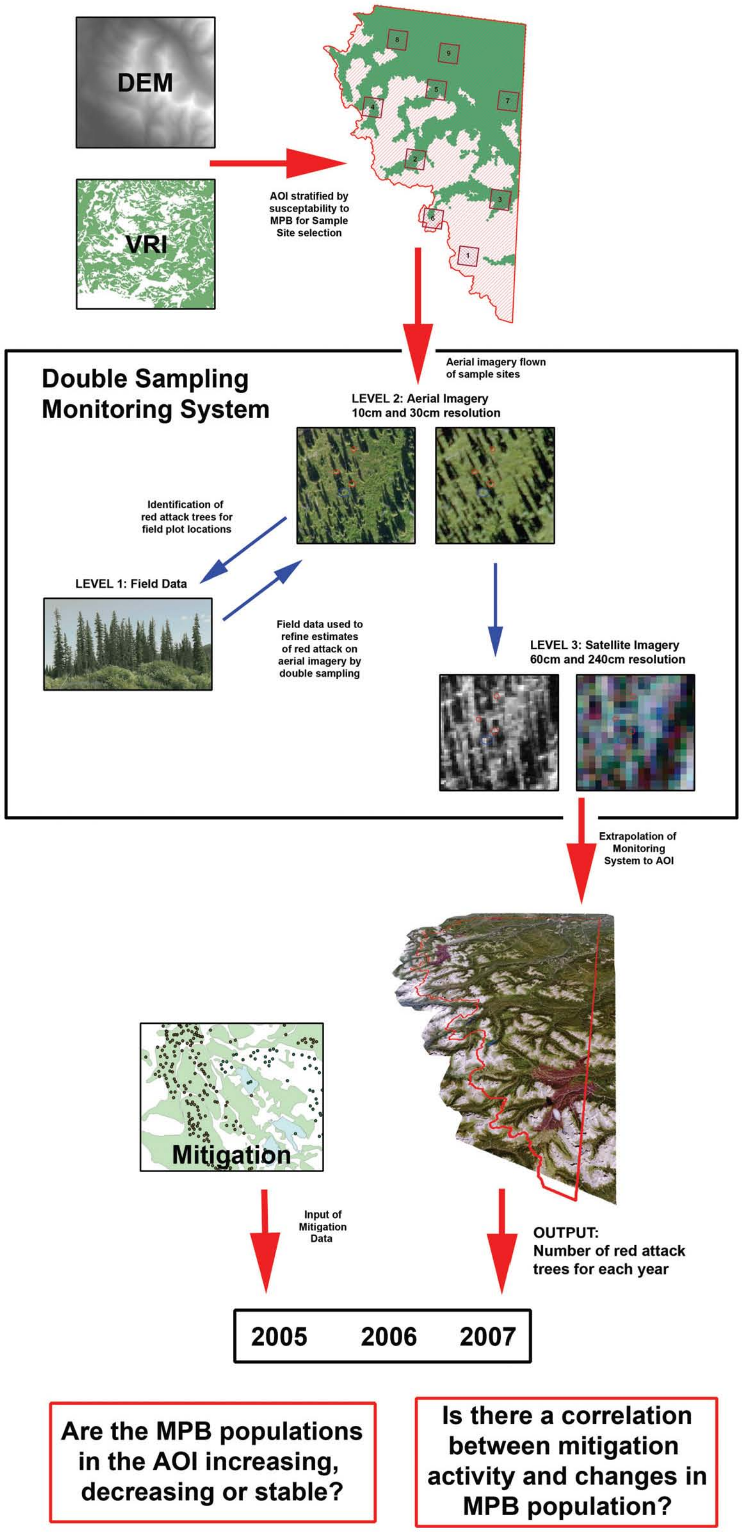

Figure 1. Theoretical design of multi-scale, tree-level mountain pine beetle monitoring program.

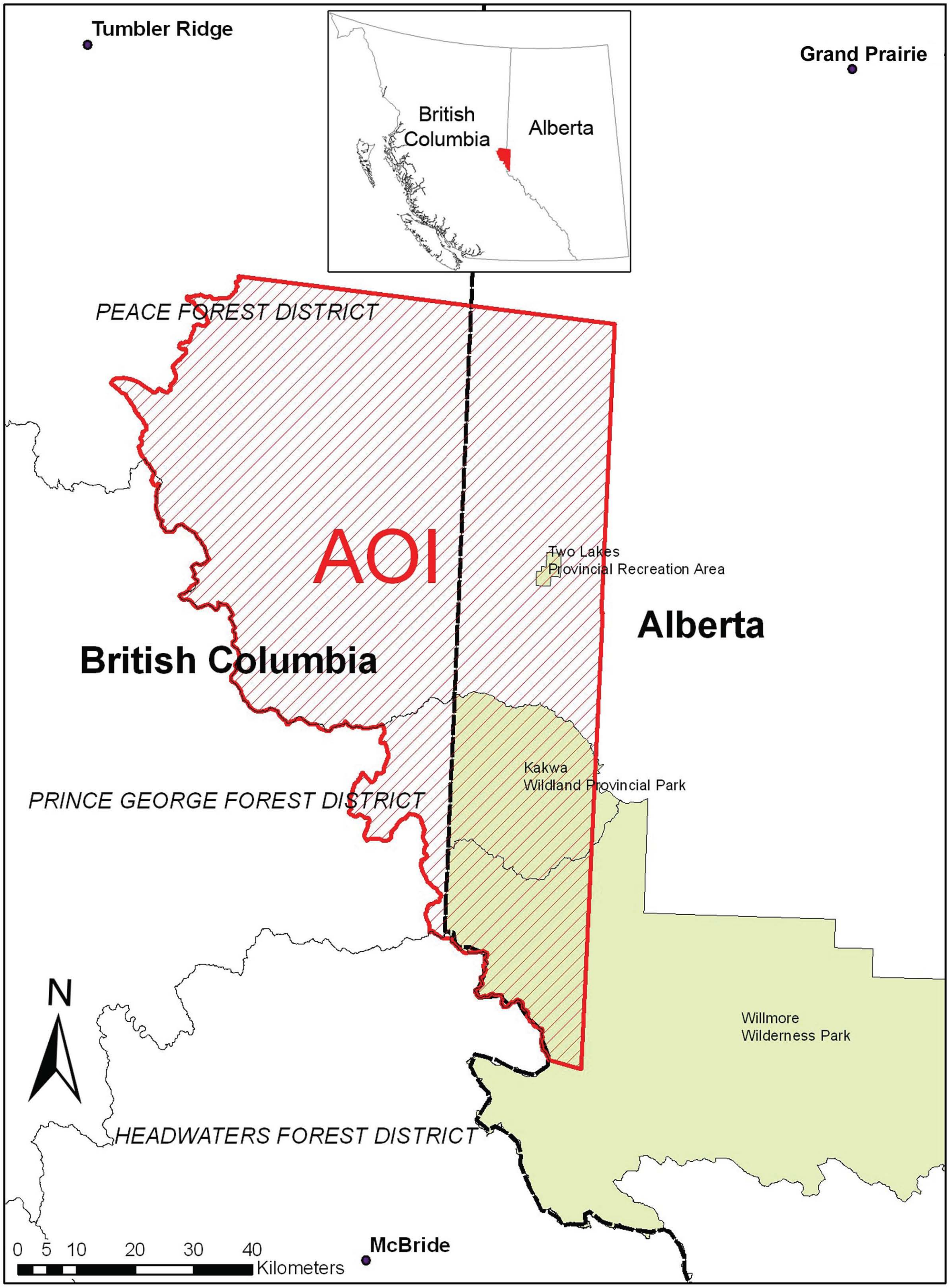

Figure 2. Study area on border of British Columbia and Alberta, Canada.

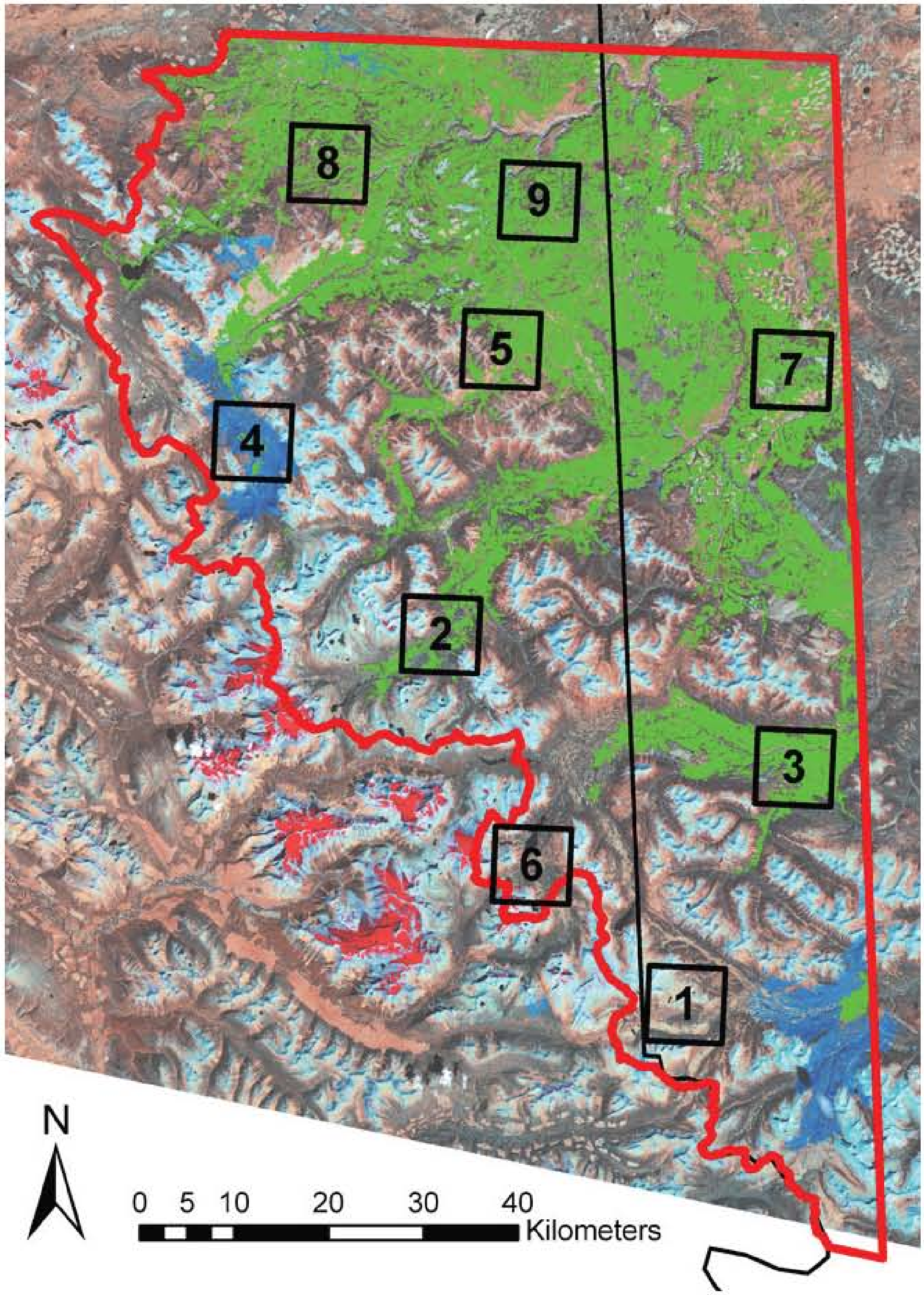

Figure 3: Area of interest, showing sample site locations and pine/elevation mask over Landsat image (path 47, row 22) backdrop.

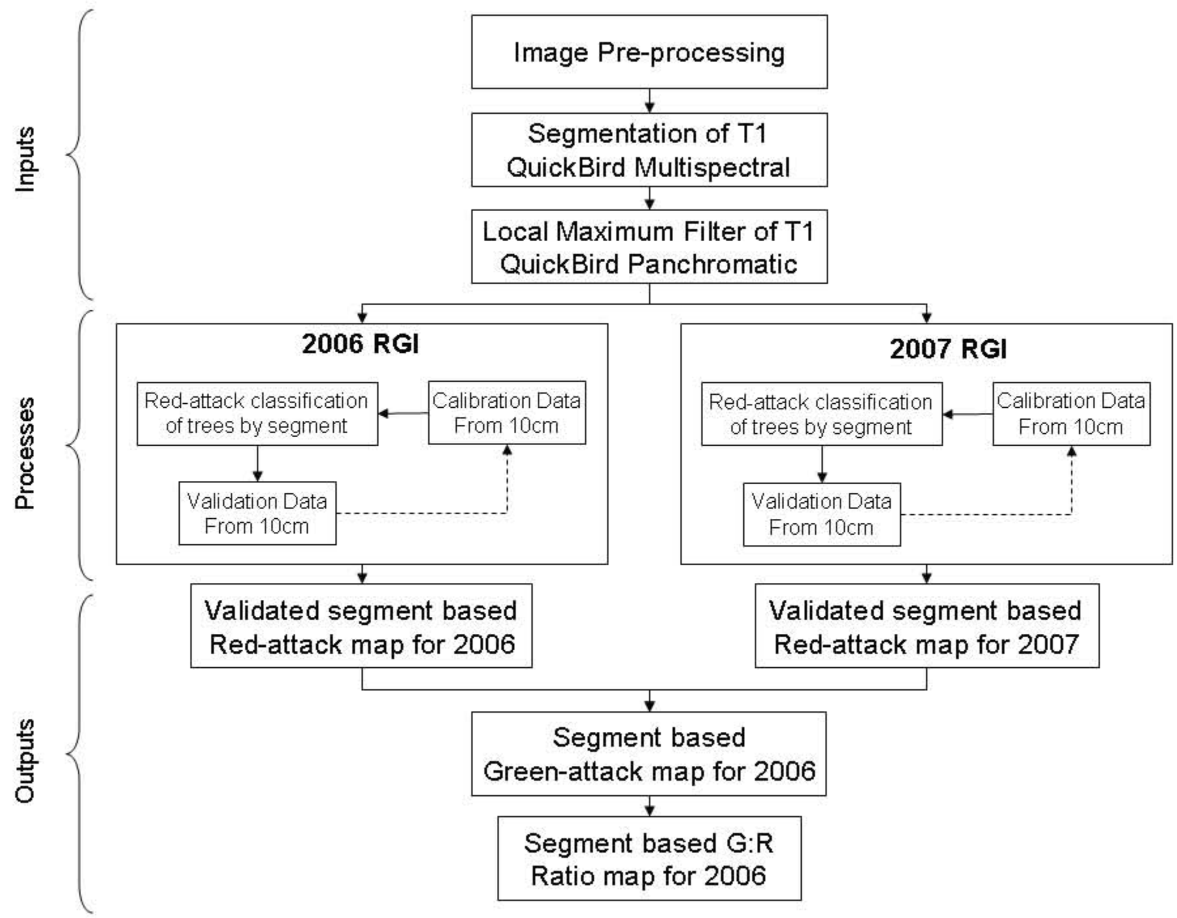

Figure 4. Processing workflow.

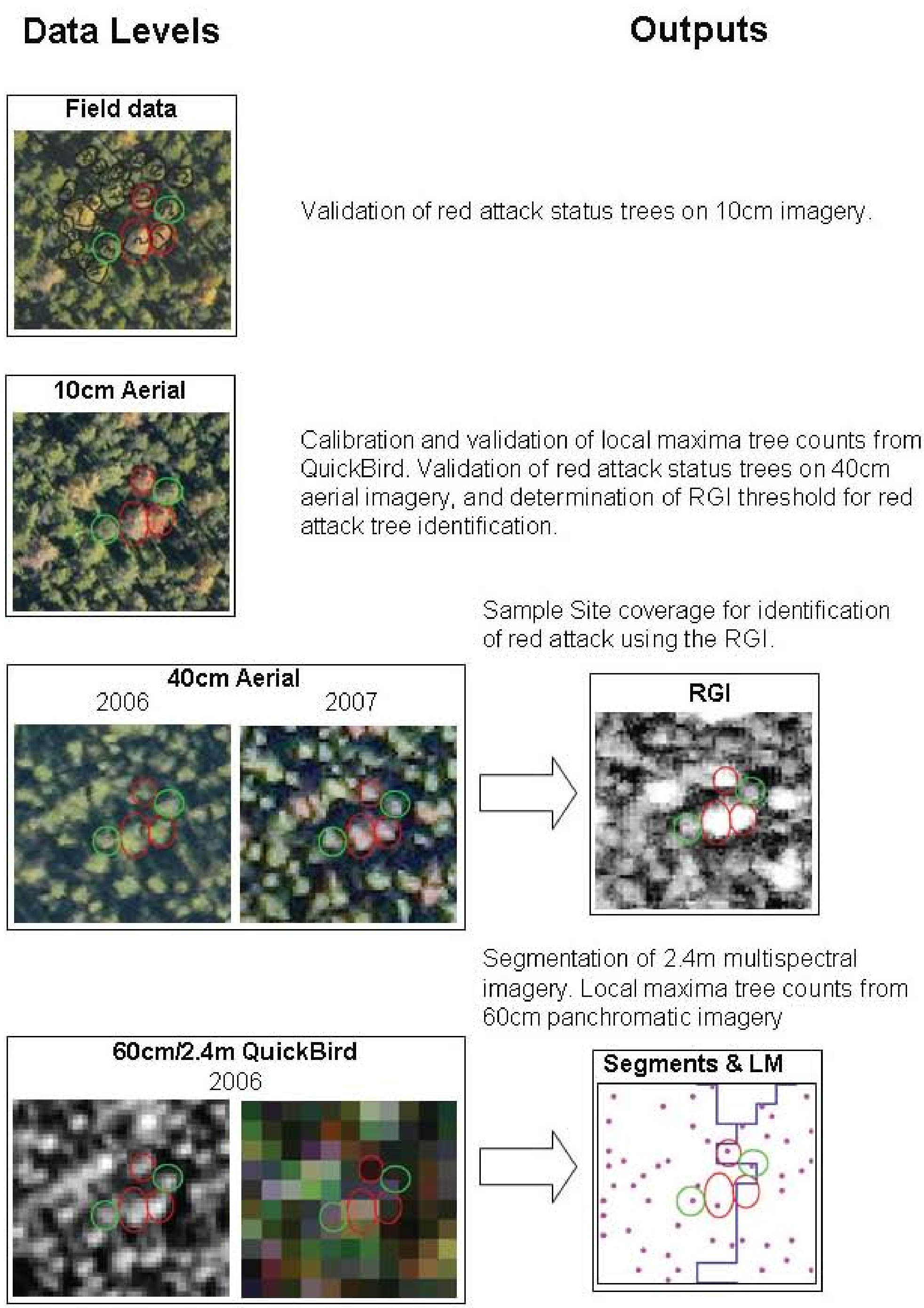

Figure 5. Available imagery showing the impact of resolution differences. The same individual red attack tree crowns are circled in red, and healthy trees are circled in green.

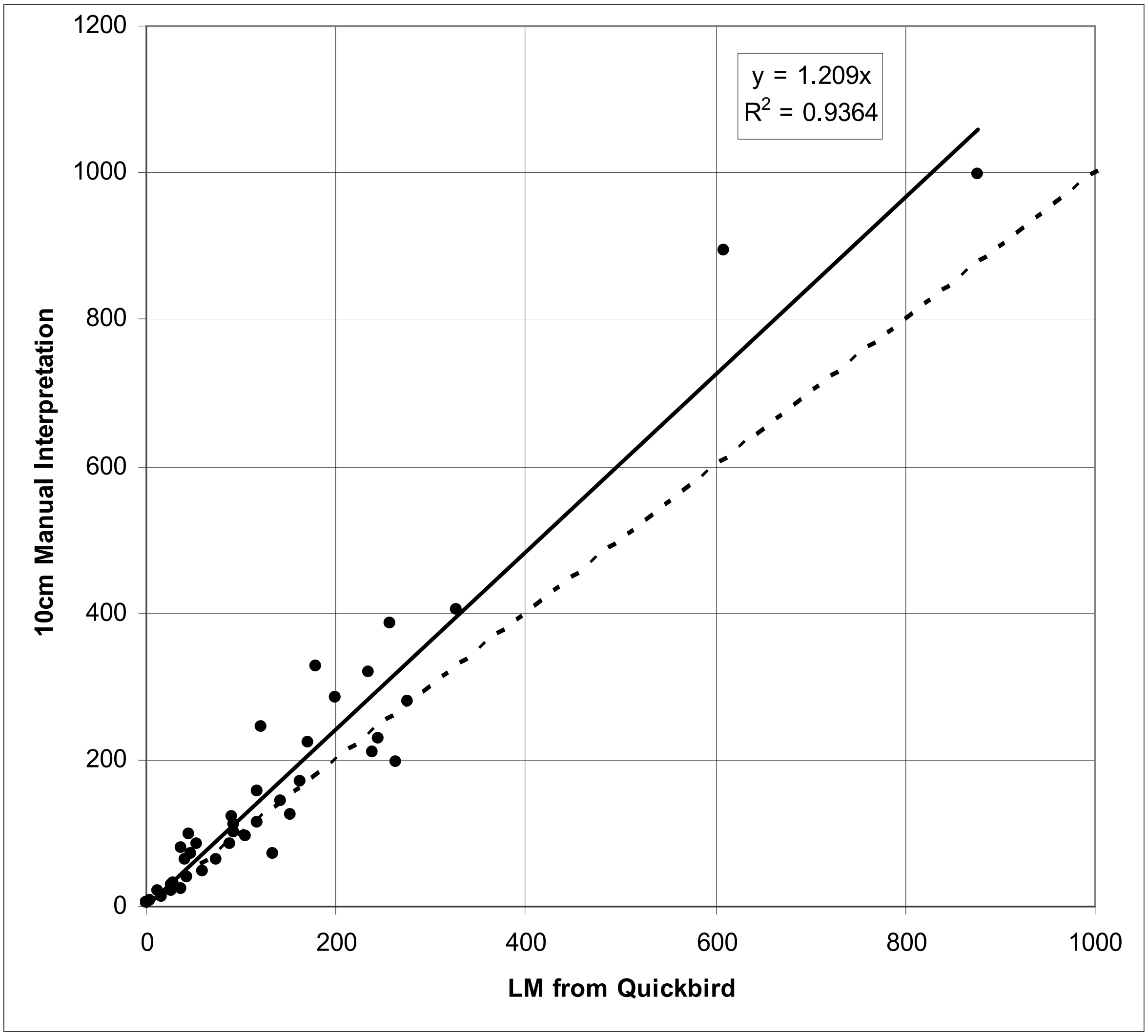

Figure 6. Stem counts/ha estimated via manual interpretation of 10 cm imagery related to stem counts from LM filter of QuickBird panchromatic imagery (*n*=40).

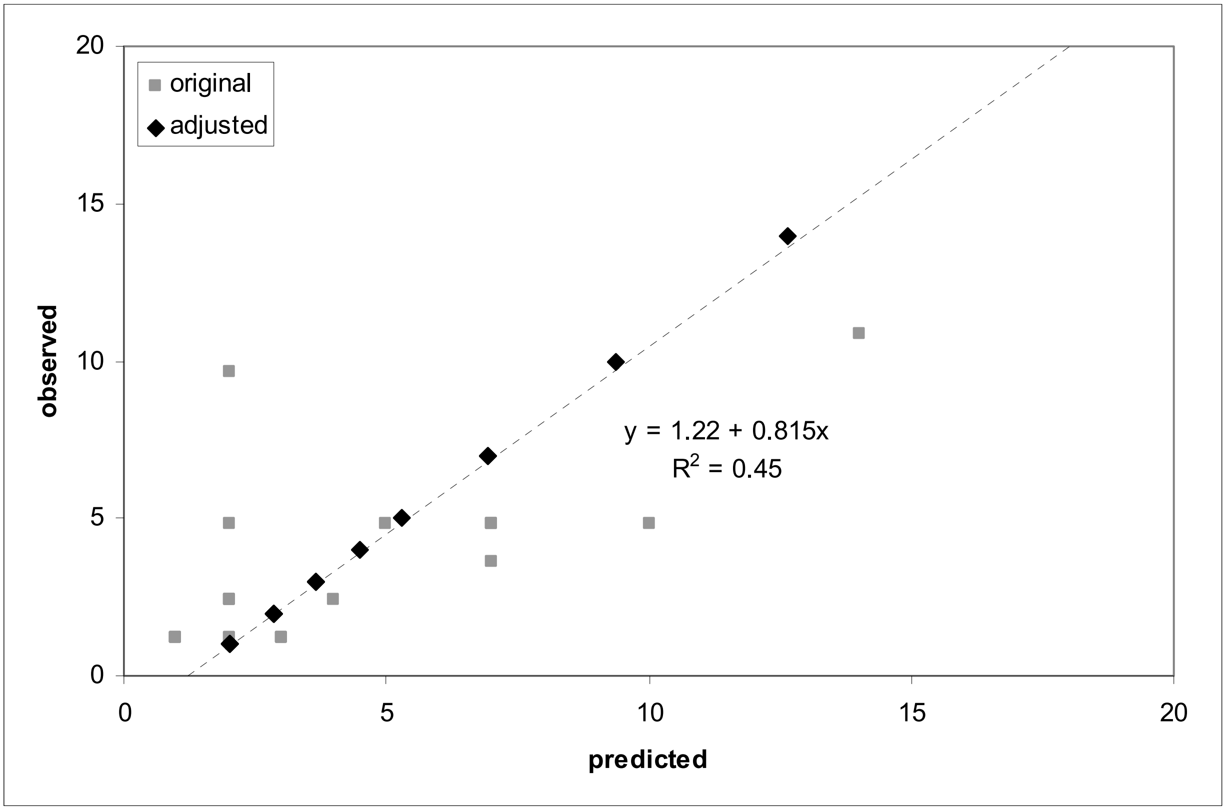

Figure 7. Number of trees identified as red attack through manual interpretation of 10 cm imagery related to red attack predictions from 40 cm imagery, with LM adjustment factor applied (*n*=22).