Linking survey detection accuracy with ability to mitigate populations of mountain pine beetle

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ABSTRACT
In 2007, the mountain pine beetle impacted an estimated 10.1 million hectares of pine forest in British Columbia, Canada. Surveys to detect the location, size, and impact of infestations are conducted from field, airborne, and satellite perspectives. Importantly, the differing survey approaches characterize the infestation over dissimilar spatial scales (i.e., trees, stands, landscapes), and with varying levels of detection accuracy. In this communication, we provide background for understanding differing survey approaches, the nature of the information generated, the resultant detection accuracies that may be expected, and the link between survey accuracy and the ability to mitigate a given mountain pine beetle infestation. A detection accuracy of 100% implies that all infested trees could be mitigated; however, no survey method achieves this level of detection accuracy, and therefore some residual infestation will persist, facilitating further population expansion if other environmental factors are conducive. Based upon this understanding, we model the number of years of mitigation effort required to maintain endemic beetle population levels, as a function of the survey approach used and the expected detection accuracy.

Key words: mountain pine beetle, survey, detection, remote sensing, accuracy, mitigation, insect, Landsat, QuickBird, aerial overview survey, heli-GPS

RÉSUMÉ
Au cours de la période allant de 1999 à 2006, le dendroctone du pin ponderosa (*Dendroctonus ponderosae* Hopk.) a infesté plus de 10,1 millions d'hectares de pinède en Colombie-Britannique au Canada. Les sondages effectués pour détecter la localisation, l'étendue et le niveau d'infestation sont entrepris à partir du sol, des airs et de l'espace. À noter cependant, ces approches distinctes de sondage répertorient l'infestation en fonction d'échelles spatiales différentes (par ex., arbres, peuplements, écosystèmes) et selon des niveaux variables de précision de détection. Dans cet article, nous présentons les raisons permettant de comprendre les approches distinctes de sondage, la nature de l'information générée, la précision résultante en matière de détection à laquelle on peut s'attendre, et le lien entre la précision du sondage et la capacité de mitiger les effets d'une infestation donnée de dendroctone du pin. Une précision de détection de 100% implique que tous les arbres attaqués peuvent être récupérés; cependant aucune méthode de sondage ne permet d'atteindre ce niveau de précision de détection et, par conséquent, une certaine infestation résiduelle demeurera en place, facilitant l'expansion accrue des populations dans le cas où les autres facteurs environnementaux s'y prêteraient. En fonction de la compréhension de ces faits, nous avons modélisé le nombre d'années requis d'efforts de mitigation pour maintenir les populations de dendroctones à un niveau endémique, sous forme de fonction du mode de sondage utilisé et de la précision de la détection attendue.

Mots clés : dendroctone du pin ponderosa, sondage, détection, télédétection, précision, mitigation, insecte, Landsat, QuickBird, sondage aérien, GPS héliporté

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Introduction

The natural range of the mountain pine beetle occupies much of the province of British Columbia. Overview surveys indicate that the beetle affected 164 000 hectares of lodgepole pine forest (*Pinus contorta* var. *latifolia* Doug. Ex. Loud) in 1999 (BCMFR 2000), which increased to 10.1 million hectares by 2007 (Westfall and Ebata 2008). The area infested has approximately doubled each year between 1999 and 2004, with the highest increase in infested area experienced in 2000 (BCMFR 2001). Large tracts of susceptible forests and a lack of sufficiently cold winters, among other factors, have favoured population growth and resulted in an expansion in the mountain pine beetle's range northward to higher elevations in British Columbia (Safranyik and Carroll 2006, Taylor *et al.* 2006), and in increasing numbers, eastward into Alberta, where 2.8 million trees were surveyed as attacked by the beetle in 2006 (Alberta Sustainable Resource Development 2007). Infestations occur largely in lodgepole pine forests, but there is increasing concern beetles may successfully reproduce in jack pine (*Pinus banksiana* Lamb) forests (Logan and Powell 2001, Carroll *et al.* 2004), enabling further eastward expansion into the vast Canadian boreal forest.

Mountain pine beetle attack is commonly described as occurring in 3 stages that sequentially manifest (albeit at a variable rate) over a 3-year period. Infestation of trees initially occurs between late July and early August when adult beetles emerge from beneath the bark of attacked trees and commence flight in search of new host trees. Initially, attacked trees are referred to as green-attack because beetles have attacked the stem of trees and have begun to form egg-laying galleries beneath the bark; however, at this stage, the tree's foliage remains green. The following year, foliage becomes desiccated and fades from green to yellow to red. The fade is the result of a combination of factors, including gallery development and fungal inoculation that impacts the ability of the tree to translocate nutrients (Safranyik and Carroll 2006). While fade rates are variable, it can be expected that 90% of attacked trees will have red needles one year after attack (Wulder *et al.* 2006a), followed by shedding of needles from the branches, resulting in the final stage known as grey-attack (Wulder *et al.* 2006b).

Usually, beetles exist as endemic populations (Table 1) attacking small groups of trees, and are controlled by lethal cold winter temperatures that cause mortality to beetles (Maclauchlan and Brooks 1998) acting to either maintain or decrease population levels. The lethal low temperature changes according to the time of year, whereby if beetle larvae have not fully developed mortality is caused at lower temperatures. Maximum cold-hardiness is achieved in December–January and large larvae can potentially survive short exposures to -38°C during this period. During the fall and spring when beetles are more susceptible to extreme cold, unseasonably low temperatures (less than -26°C) can cause widespread mortality (Safranyik and Linton 1991). Indeed, the last extensive infestation in British Columbia occurred on the Chilcotin Plateau during the early 1980s and was eventually halted by low temperature events in 1984 and 1985 where sustained low temperatures caused significant mortality and halted the infestation in 1987. In 1984, temperatures of -26°C were experienced on October 31, which further decreased to -43°C by December 30 (Safranyik and Linton 1991). In 1985, lethal low temperatures ranged from -27.5°C on November 11 decreasing to -43°C on November 27 and remaining below -30°C until December 2 (Safranyik and Linton 1991). Recent climate records for British Columbia indicate temperatures have been warming steadily over the past decade, enabling beetle populations to survive winters (Carroll *et al.* 2004) and increase to epidemic population levels (BCMFR 2006). In instances where natural control of beetle populations is ineffective, anthropogenic controls are typically initiated.

A range of survey methods are used to detect mountain pine beetle infestations and these methods can be considered in the context of an information hierarchy, whereby each method provides greater detail over a smaller spatial extent (Wulder *et al.* 2006c). There are generally 3 scales of observation for surveying mountain pine beetle damage: regional (coarse), landscape (medium), and local (fine) (Wulder *et al.* 2006b). Regional-scale surveys are conducted on an annual basis by trained specialists in aircraft, who delineate broad areas of infestation on topographic maps (e.g., aerial overview surveys or sketch-mapping) (Wulder *et al.* 2006a). Landscape-scale surveys typically utilize data generated by digital remotely sensed data (e.g., Landsat Thematic Mapper sensor) that can provide large spatial coverage with low per unit area image costs (Franklin *et al.* 2003) and can supply quantitative information on the extent of infestations (Wulder *et al.* 2004). Local-scale surveys are used to detect single infested trees or small groups of infested trees by helicopter-GPS surveys (heli-GPS), 1:30 000 scale (or larger) colour aerial photographs, and high-spatial resolution satellite imagery (<1-m pixel size) and are augmented and validated with targeted field observations. Each scale of observation will satisfy a specific information need; for example, regional-scale surveys are able to capture provincial-level infestation status, whereas local-scale surveys capture fine detail in specific areas. The survey intensities and the information required differs, consequently a given survey may cover large or small areas and the information returned is governed by the scale of observation (Wulder *et al.* 2004).

Ground crews locate red-attack (RA) trees and associated green-attack trees by conducting walkthrough surveys or "probes" (Machlauchlan and Brooks 1998). These surveys obtain data on the proportion of green attack in forest stands and the amount of remaining susceptible host material (Machlauchlan and Brooks 1998). Walkthroughs are ground-based surveys completed prior to probes to locate attack and provide general estimates of the severity and extent of infestations. Probes are systematic, strip-type surveys that provide highly detailed information on the extent of the infestation, the susceptibility of stands to further attack, and identify potential constraints to harvesting (British Columbia Ministry of Forests 1995, Machlauchlan and Brooks 1998).

This hierarchy of survey data sources can be used to reduce the cost and time required to collect detailed information on beetle infestations; regional-scale data may be used to identify broad areas of infestation and guide the acquisition of landscape-scale data, which in turn may be used to guide local-scale data acquisition and the deployment of field crews. Each survey method has limitations relating to the timeliness of data acquisition and the results provided, data cost, capacity to detect red-attack damage, the spatial extent of the survey, and the speed with which the survey can be completed

Table 1. Characteristics associated with the population states of mountain pine beetle and the likely rate of population expansion associated with each population state (adapted from Wulder et al. 2004)

Population state	Population characteristics	Likely population expansion rate
Endemic	• Widespread in mature pine forests; however, they are restricted to weakened and decadent trees. • Frequently found in trees attacked by secondary bark beetle species. Trees containing mountain pine beetles can be very difficult to locate on the ground and even from the air since many of the trees will be in the intermediate to suppressed crown classes, the faded crowns of which are partially hidden below the crowns of taller, uninfested trees. • Currently attacked trees are often not located near brood trees. • There is no obvious relationship between the probability of attack and tree diameter. • Yearly tree mortality is normally less than volume growth.	R = <2
Incipient epidemic	• Most infested trees are in the larger diameter classes. • Clumps of infested trees are scattered and confined to some stands. • The infested clumps vary considerably in size and number from year to year but tend to grow over time. • Frequently, the groups of infested trees first appear in the following situations; draws and gullies, edges of swamps or other places with wide fluctuations in the water table; places where lodgepole pine is growing among patches of aspen, perhaps indicating the presence of root disease; dry, south and west-facing slopes.	R = >2
Epidemic	• Resilient to large proportional losses through natural mortality. • Generation mortality is usually in the range of 80–95%, corresponding to potential rates of population increase of 2- to 8-fold. The usual rate of increase, however, is 2- to 4-fold when measured over the entire epidemic area. • Infestations are widespread and exist at the landscape level. • There are usually large annual increases in both infested areas and numbers of infested trees.	R = 4 or 5

Adapted from Wulder et al. (2006b).

and information provided to forest managers (Wulder *et al.* 2006b). For example, it is critical to deploy ground crews to conduct mitigation based on data collected during recent surveys so that the full extent of the infestation is realised and appropriate control methods can be used. In general, it is not economically feasible to use local-scale surveys over large areas and therefore regional-scale and landscape-scale surveys have an important role to play to efficiently and cost-effectively stratify the area of interest and identify general locations of infested forest stands.

Local-scale surveys are preferred for the detection of individual infested trees; however, high spatial resolution imagery typically has a limited spatial extent and is significantly more expensive than regional- or landscape-scale surveys (Wulder *et al.* 2006c). This is problematic when small, isolated groups of infested trees (which are not detectable with coarser data sources) are scattered over large areas, as these spot infestations may remain undetected until they expand and coalesce with other similar spots and cause extensive mortality. Furthermore, surveys are subject to errors of commission (trees incorrectly classified as red-attack) and omission (red-attack trees missed during image interpretation), with higher error rates associated with coarse-scale survey approaches and lower error rates with local-scale approaches (Nelson *et al.* 2006).

Detection of red-attack stage trees is used as a primary means for locating green-attack stage trees (Wulder *et al.* 2004). Red-attack trees may be identified relatively consistently and accurately, following both digital or manual approaches (Wulder *et al.* 2006b). Based upon an understanding of mountain pine beetle spread, green-attack stage trees are known to be found in close proximity to existing red-attack trees. Thus, the use of remotely sensed data to map green attack trees in the proximity of red attack trees provides little operational gain over existing practices. Locating green-attack trees not in proximity to red-attack stage trees (i.e., seeking locations of infestation due to long-range transport), is limited by biological, environmental, geographic, temporal, economic, and technological considerations that limit the operational utility of remotely sensed data for green attack detection. As such, locating green-attack trees using remotely sensed data, from an operational point of view, is currently not realistic (Wulder *et al.* 2006b).

Green-attack trees are the primary target of mitigation activities. Several mitigation methods exist, which can be implemented either on individual trees or small groups of trees (Maclauchlan and Brooks 1998). In large infestations, mitigation tactics include: sanitation harvesting, where standard silvicultural practices such as clearcutting, shelterwood, and selective cutting are utilized to remove infested trees; salvage logging, where dead trees are removed and processed for lumber; high-hazard host removal, where the stands deemed at highest risk from mountain pine beetle attack are removed to decrease the risk of attack to the forest; and, a harvest priority rating system, where forest stands with the heaviest beetle concentrations are removed first.

Mitigation tactics for smaller infestations can be grouped into direct control methods that involve removing infested trees to reduce current and future population levels, and indirect methods, which attempt to prevent trees from becoming infested (i.e., stand thinning, pesticides). Common mitigation tactics include: felling and removing single trees or patches of trees (i.e., infestations less than 1 ha in size are removed); felling and burning of individual trees; applying pesticides to individual infested trees to either prevent beetles from boring beneath the bark or to cause mortality of beetles already beneath the bark; and, baiting areas with synthetic pheromones to aggregate beetles into areas that are subsequently harvested or treated. There has only been one documented incident of successful mitigation, which occurred near Banff, Alberta in the early 1940s (Hopping and Mathers 1945); with the use of aggressive and persistent mitigation tactics, an outbreak of mountain pine beetle was declared extinct 3 years after initial infestation (Carroll *et al.* 2006). Persistent mitigation, completed annually, has the potential to slow infestations or even cause localised extinction; however, if the accuracy of red-attack detection is limited, infestations may continue to spread.

Objectives

In this paper we present the implications of survey detection accuracies on mitigation activities designed to control mountain pine beetle populations. First, we provide background on the use of conventional forest health survey data and digital remotely sensed imagery for the detection of mountain pine beetle infestations. Each of the scales of observation currently used for detecting mountain pine beetle red-attack in British Columbia are linked to the scale of measurement and described according to the inherent accuracy of the data source at detecting the status of mountain pine beetle infestations. Second, we follow with a complementary discussion of how detection accuracies of a range of survey techniques can be utilized to provide mitigation data to slow the progress of infestations. The ramifications of undetected infested trees on forest stands are then presented. Finally, we conclude by calculating the number of trees that must be removed to maintain populations at endemic levels and prevent an infestation from spreading, and estimating the period of time required to monitor infested stands, as a function of detection accuracy, to ensure all infested trees are removed.

Review of Current Methods for Red Attack Detection

Following the nomenclature of Wulder *et al.* (2006c) 3 scales of observation of mountain pine beetle detection can be defined: regional, landscape, and local (Table 2). A literature search was conducted to compile studies investigating mountain pine beetle infestation that had a reported a range of red-attack detection accuracy and that were conducted in a similar manner (Table 2). From these studies we produced an assessment of the documented range from each of the 3 scales and used 2 studies to demonstrate the efficacy of detection data to drive mitigation activities. We provide examples of recent studies that supply red-attack detection accuracy statements in the sections below.

Regional scale

Aerial overview surveys, also known as sketch mapping, are primarily used for regional-scale detection of infestations across federal, provincial, and state government jurisdictions (Wulder *et al.* 2004). In British Columbia, the main objective of aerial overview surveys is to monitor and record the extent, severity, and general location of insect infestations in forests on an annual basis (Westfall and Ebata 2008). The surveys provide a broad overview at map scales between 1:100 000 to 1:250 000 (Wulder *et al.* 2006b). In comparison to other survey methods, acquiring data from aerial overview surveys is considered to be an effective, low-cost detection and mapping method (Wulder *et al.* 2006c). To date, no rigorous accuracy

Table 2. Data sources for remote sensing of mountain pine beetle red attack mapping including sources and detection accuracies

Scale	Technology	Source (date)	Reported detection accuracy
Regional	Aerial overview survey	To date, no rigorous accuracy assessment has been conducted for this data.	N/A
Landscape	**Single date** Landsat TM	Franklin *et al.* (2003)	73% (± 7%)
	Multiple date Landsat TM (TCT and EWDI)	Skakun *et al.* (2003)	73% (± 12%) (groups of 10–29 RA trees) 81% (± 11%) (groups of 30–50 RA trees)
	Landsat ETM+ (TCT and EWDI)	Wulder *et al.* (2006d)	86% (± 7%)
Local	Heli-GPS	Nelson *et al.* (2006)	92.6% (± 10 infested trees)
	IKONOS	White *et al.* (2005)	71% (± 8%) (lightly infested stands; 1–5% RA) 92% (± 5%) (moderately infested stands; 5–10% RA)

assessment has been conducted for this data source; however, there are issues related to positional and attribution accuracy (Aldrich *et al.* 1958, Nelson *et al.* 2004). Errors that may occur in aerial overview survey data have been attributed to off-nadir viewing, distortions due to lighting conditions, interpreter fatigue, and level of experience (Aldrich *et al.* 1958; Leckie *et al.* 2005; Wulder *et al.* 2006a, b). Interpreter variability has been tested by conducting a comparison between the numbers of infested trees observed from the aerial overview surveys against the number of infested trees counted on aerial photographs (Harris and Dawson 1979). Estimates were found to vary widely, with interpreters varying by -42% to 73%, with a mean deviation of 7% for experienced interpreters and an 8% deviation for inexperienced interpreters.

Landscape scale

Detailed surveys conducted at the landscape scale can provide spatially explicit estimates of the number of infested trees and the volume of timber affected. The information generated from these surveys provides information for tactical plans, which provide methods to implement the broad objectives outlined in a forestry strategic plan and specify areas that require more detailed ground surveys. Recently, landscape-scale information of forest condition has been derived from the Landsat satellite, which has shown utility in detecting mountain pine beetle infestations (Skakun *et al.* 2003, Franklin *et al.* 2003, Wulder *et al.* 2006d). For example, Franklin *et al.* (2003) found that when using single-date Landsat TM imagery with a 30-m pixel size over areas of 0.2 ha, it was possible to generate a red-attack detection accuracy of 73.3% ± 6.7%, $p = 0.05$.

Multi-date imagery, one prior to, and one following, attack can also be used to monitor forest change due to mountain pine beetle infestations. These approaches typically include image transformations that utilize specific Landsat band combinations designed to enhance a range of forest conditions. The Tasselled Cap Transformation (TCT) was used to process multi-date imagery to obtain wetness indices and the Enhanced Wetness Difference Index (EWDI) was used to interpret spectral patterns in stands with confirmed red-attack (Skakun *et al.* 2003). This approach produced an accuracy of 76% (± 12%, $p < 0.05$) for groups of 10 to 29 infested trees, and 81% (± 11%, $p < 0.05$) for groups of 30 to 50 infested trees. To reduce the reliance upon the application of change thresholds, Wulder *et al.* (2006d) used the Enhanced Wetness Difference Index (EWDI) in conjunction with slope and elevation surfaces. These data were analyzed using a logistic regression approach to map red attack damage in the Lolo National Forest in Montana, USA. With this method, red-attack was mapped with 86% accuracy (± 7%).

In addition, new generation satellite sensors such as Hyperion, onboard EO-1, offer improved spectral sensitivity over existing systems (White *et al.* 2007); a single date of Hyperion imagery to generate 6 moisture indices, which were compared to the proportion of each Hyperion pixel that was independently surveyed as red-attack stage. Results indicated that moisture indices incorporating the shortwave-infrared and near-infrared regions were significantly correlated to levels of damage ($r^2 = 0.51$; $p < 0.001$). This study demonstrated that Hyperion data may be used to map low-level infestations of mountain pine beetle red-attack at the landscape scale.

Local scale

Local-scale surveys detect low infestation levels and have traditionally included surveys conducted with a helicopter where the geographic location of infestation centres are recorded with a global positioning system (a process otherwise known as heli-GPS) and fine-scale aerial photographs (1:30 000). Heli-GPS points are a rapid and accurate means for detailed mapping of mountain pine beetle red-attack. Using this method, tree clusters or individual tree counts, and damage severity are identified. Nelson *et al.* (2006) assessed the spatial accuracy of 100 heli-GPS points delineated during aerial surveys and compared them to ground data. Results were calculated for several error ranges and indicated that 17.4% of points correctly identified the number of infested trees when comparing heli-GPS estimates to field data, but contained high errors of commission and omission (Nelson *et al.* 2006). Heli-GPS data were shown to be 92.6% accurate with an error of ±10 trees, which provides sufficient detail and accuracy for regional planning and management purposes.

An additional survey method used to provide local-scale data is aerial photography. Fine-scale aerial photographs, acquired at a scale of 1:30 000, enable identification of areas with low infestation levels and provide data that support mitigation activities by supplying geographic locations and number of trees infested (Wulder *et al.* 2006c). The photographs are digitized (scanned) and infested trees are visually interpreted using digital photogrammetric software. To date, no objective accuracy assessment has been conducted for this data source.

Detailed surveys at the stand level can also be undertaken using high-spatial-resolution remotely sensed imagery with a pixel size of <5 m. High-spatial resolution digital satellite imagery is available to supply detection information for insect infestations. IKONOS is a high-spatial-resolution satellite that can be used to detect mountain pine beetle infested trees, has a multispectral pixel size of 4 m (White *et al.* 2005). An unsupervised clustering of image spectral values was used to detect mountain pine beetle infestations in lightly or moderately infested trees near Prince George, British Columbia. When 1% to 5% of a forest stand contained infested trees, infestations were categorized as light. Similarly, moderate infestations were defined as those where >5% to <20% of the forest stand contained attacked trees. To account for positional error, a 4-m (one pixel) buffer was applied to red-attack control data for comparison with the image classification. When compared to independent validation data collected from aerial photography, the accuracy of red-attack detection from IKONOS imagery was shown to be 71.0% for lightly infested stands and 92.5% for moderately infested stands.

Effects of Mitigation on Mountain Pine Beetle Infestations

To facilitate discussion on how mitigation can affect mountain pine beetle infestations, we used population-scale modelling scenarios (Carroll *et al.* 2006) to predict the impact of management tactics on beetle populations. In this discussion we suggest a theoretical framework for the suppression of mountain pine beetle infestations using mitigation driven by detection accuracy statements. This framework uses mountain pine beetle population dynamics in a population-scale model to predict the level of mitigation required to bring populations under control, the extent of mountain pine beetle damage following a single mitigation event, and the number of years mitigation must continue to suppress infestations.

Population-scale models consider the interactions between a forest disturbance agent (e.g. mountain pine beetle) and its host species to predict the spread of infestation over time. For instance, models can estimate the current population size based on the previous year's population (Barclay *et al.* 1985, Thompson 1991) and use mathematical functions to predict population fluctuations, based on numerous parameters, such as weather and host conditions (Mitchell and Preisler 1991, Thompson 1991, Beukema *et al.* 1997, Malmström and Raffa 2000). Modelling scenarios allow us to examine the effects of mitigation driven by detection accuracies to suppress beetle populations, assess the extent of an infestation following a single mitigation event and, finally, estimate the length of time required to suppress infestations given differing levels of detection accuracy.

It is important to consider the role played by detection accuracies in an ongoing mitigation program where the objective is to halt the infestation or stabilize beetle populations. Table 1 provides examples of the likely rates of population expansion associated with various population states of the mountain pine beetle. In northern British Columbia it is common for the rate of beetle population increase to double on an annual basis (BCMFR 2002) and then remain at a constant rate for a number of years. To maintain a static population level when the population is doubling, at least 50% of infested trees must be detected and removed before the annual flight period. To reduce the population when the rate of growth is 2 (population is doubling), more than 50% of infested trees must be removed, provided the rate of population increase remains constant. However, populations regularly increase 4-fold and can be as high as 5-fold in areas of southern British Columbia, but rarely exceed this level (BCMFR 2002). Under these growth scenarios a high proportion of infested trees must be treated in order to reduce the population. The proportion (P) of trees requiring mitigation according to the rate of population increase is defined as (Carroll *et al.* 2006):

[1] $P = 1-1/R$

where (R) is the rate of population expansion. Detection accuracy data can be incorporated into Eq. [1] when used as a surrogate for the proportion of trees requiring mitigation (P). We utilize 3 detection accuracies in 3 population-based modelling scenarios to demonstrate mitigation efficacy (assuming mitigation is 100% effective) and estimate the subsequent effects on mountain pine beetle populations. For the modelling scenarios it is pertinent to include only survey methods that are suited to spatially detailed detection of mountain pine beetle infestations. It is unlikely that regional-scale data would be used to guide mitigation because although these survey methods are critical for broad classification of the severity and extent of infestations on the landscape, they lack the spatial and attribute accuracy necessary to guide mitigation efforts. Therefore, finer-scale data sources, such as those available at the landscape and local scales, are used to supply spatial and attribute data to guide mitigation crews. Landscape-scale data such as Landsat has a 30-m by 30-m pixel, which may contain an amalgamation of several forest elements typical of a pine stand, e.g., trees, shadowing, and understorey (Wulder *et al.* 2006b). This amalgamation may dilute the appearance of red-attack tree crowns in each pixel and make detailed mapping of red-attack difficult because patches of infestation will become clear only when the majority of trees within a pixel become infested. Local-scale infestations do detect individual infested trees and also a range of infestation severity.

In order to complete the modelling we used generic detection accuracies at 70%, 80%, and 90% (Table 3), which represent the range of accuracies reported in Table 2. The results of Eq. [1] are graphically represented in Fig. 1. The modelling demonstrates the potential effect detection accuracies have on a beetle population assuming a single detection activity over the duration of an infestation. Carroll *et al.* (2006) indicate that if mountain pine beetle populations increase by a factor of 2 (R = 2), starting with 1 undetected infested tree in year 1, then by year 10 that stand will contain 512 infested trees, which is estimated to be 2% of the trees contained within a 20-ha area (Carroll *et al.* 2006). Hypothetically, infestations of this magnitude could escape detection for some time depending on the scale of observations utilized and whether the infestation is scattered throughout the stand or is clumped in a single infestation. However, if in year 4, a proportion of infested trees is removed, infestations expand to lower levels

Table 3. Number of years (t) required to suppress infested stands of mountain pine beetle using a range of initial infestation (N_0) and a range of detection accuracies representative of the survey methods discussed

	Scale of observation				
Detection accuracy	1000	2000	5000	10 000	100 000
70%	13.5	14.9	16.7	18.0	22.5
80%	7.5	8.3	9.3	10.1	12.6
90%	4.3	4.7	5.3	5.7	7.2

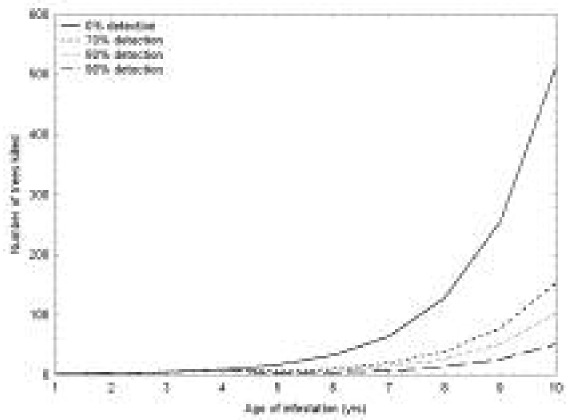

Fig. 1. Prediction of the number of trees killed using a range of detection accuracies.

than previously experienced. This implies that when mitigation is completed on 70% of infested trees 5 trees are correctly identified, resulting in the remaining population expanding to 154 infested trees by year 10. If 80% of infested trees are removed, 3 infested trees would remain in the stand and by year 10, the infestation will have expanded to cause mortality of 102 trees. Lastly, if 90% of infested trees are correctly identified in year 4, 7 trees would be detected and by year 10, 51 trees would be infested (Fig. 1).

Two examples of survey methods that detect moderate to low levels of infestation are provided and include accuracies generated from high-spatial-resolution satellites and heli-GPS data (Fig. 2). First, the satellite IKONOS was used to detect mountain pine beetle red-attack in forest stands with low (1% to 5% of stand infested) and moderate levels (>5% to 20% of stand infested) of infestation (White *et al.* 2005). The study was designed to examine the potential of 4-m multispectral IKONOS imagery to detect red-attack and map areas suitable for suppression. Results show that imagery detected 93% (± 5%) of red-attack trees when identifying >5% to 20% of the stand as infested and 71% (± 8%) of attacked trees when 1% to 5% of the stand is infested (White *et al.* 2005).

In incipient epidemic conditions, populations triple annually (R = 3) and can be suppressed using a detection accuracy above 71% (Fig. 2A and 2B). In epidemic conditions where population expansion rates can be R = 5, mitigation driven by detection accuracies of 92% (Fig. 2A) is able (assuming 100% mitigation success) to reduce the population to less than populations observed in previous years. Similarly, using a detection accuracy of 71% results in population reduction at expansion levels of R = 4 (Fig. 2B). These examples indicate that a decrease in detection accuracy causes a decrease in the proportion of attacked trees removed from an infestation. If undertaking mitigation with an accuracy lower than 70%, suppression becomes even less possible. When considering the margin of error associated with accuracy statements (as shown in Fig. 2A and 2B), the efficacy of resulting mitigation may be decreased further. The lower error bar in each of the examples provided in Fig. 2 infers a decrease in the proportion of attacked trees detected and subsequently removed. When providing mitigation for a doubling population (R = 2) detection accuracies of 50% are adequate; however, if it less than 50% mountain pine beetle populations will be able to rapidly increase each year when residual infestation is fuelling future expansion.

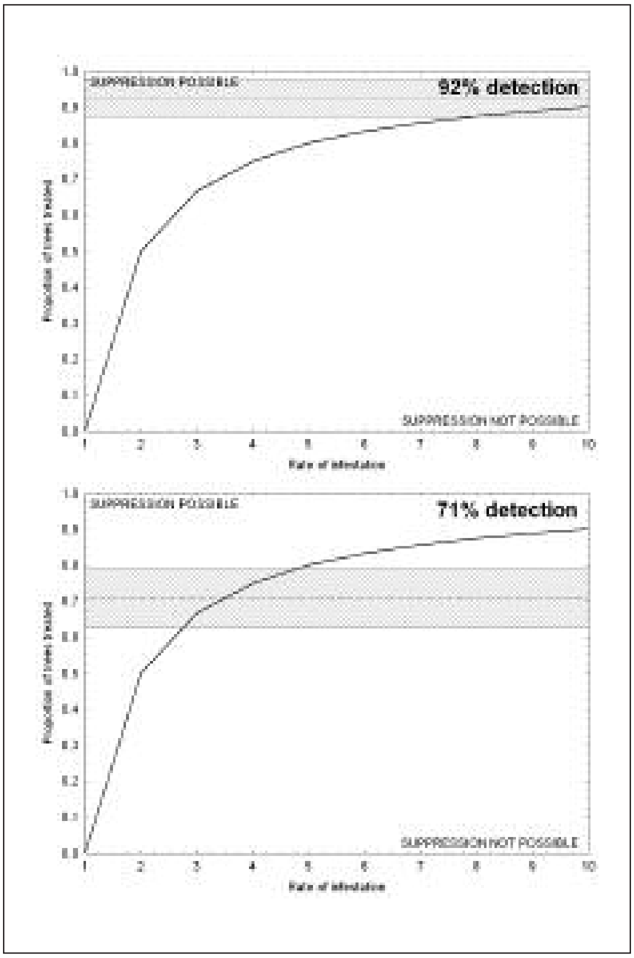

Fig. 2. Generalized prediction of the effect of 2 detection accuracies provided by recent research; 92% (A) and 71% (B).

The final scenario calculates the length of time required for ongoing detection, monitoring, and mitigation to bring a given infestation under control. In order to effectively control and reduce populations a proportion of infested trees should be removed each year as part of a persistent mitigation program (Carroll *et al.* 2006). During an outbreak, the number of trees killed annually can often be in the millions and may cover hundreds of thousands of hectares. Due to the magnitude of these infestations, management tactics to reduce the entire population remain futile even though populations may only increase at the same rate as low-level expansion (R = 2) (Carroll *et al.* 2006). For example, Carroll *et al.* (2006) describe an outbreak of 300 000 ha with R = 2, where 150 000 ha of infested trees must be mitigated each year to ensure the infestation remains stable. In this situation, removing such a large number of infested trees would be impossible if attempting a single mitigation activity (Carroll *et al.* 2006). Further, existing rules regarding sustainable forest management, including limitations to the landbase eligible for harvest (e.g., operability, road access, land use) and annual allowable cuts, must also be considered. Large-area infestations require persistent mitigation for several years:

$$[2] \quad N = N_0[R(1-P)]^t$$

where the number of trees initially infested (N_0), the yearly rate of increase (R), the proportion of trees treated each year (P), and the number of years (t). N is therefore an estimate of the number of trees infested in any given year. Knowledge of R and P can determine the number of years needed for continuous direct suppression as defined in Eq. [1] (Carroll *et al.* 2006). To further explore this concept, 5 examples were developed using initial infestations of 1000, 2000, 5000, 10 000, and 100 000 trees (Fig. 3). For each example it is possible to calculate the number of years needed to suppress a mountain pine beetle infestation using the data from each scale of observation (Table 3). Mitigation using a detection accuracy of 90% is estimated to bring infestations under control in the shortest time. If the initial infestation is limited to individual infestations on the landscape, mitigation may be completed within 4 years (N_0 = 1000); however, for larger infestations persistent

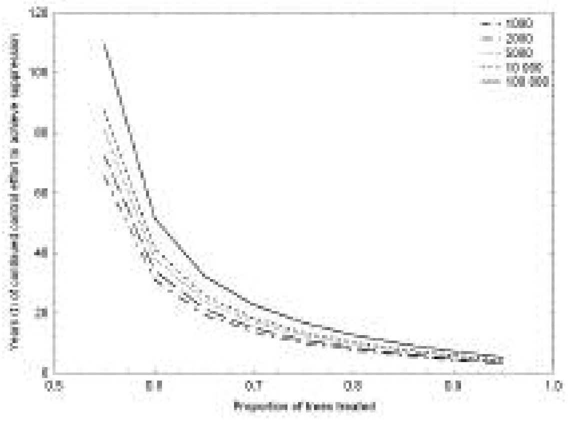

Fig. 3. Number of years required to suppress infestations of mountain pine beetle using detection accuracies (± known error) generated from remotely sensed and conventional data sources (after Carroll et al. 2006).

mitigation may be required for 7 years (N_0 = 100 000). A detection accuracy of 80% provides data to estimate that under an intensive mitigation program, infestation are controlled within 8 years (N_0 = 1000) extending to 13 years for larger infestations (N_0 = 100 000). Mitigation took longest when guided by the 70% detection accuracy to bring infestations under control, infestations are estimated to be controlled within 14 years (N_0 = 1000) and large-scale infestations within 23 years (N_0 = 100 000).

Use of Survey Data to Monitor Mountain Pine Beetle Infestations

In this study, we have assumed that mitigation is 100% effective; however, trees exhibiting evidence of infestation may be overlooked during surveys, because foliage appears to be healthy and there is no capacity to detect damage caused by attacking beetles to the bole of the tree. Mitigation efficacy has not been thoroughly assessed, although Fettig *et al.* (2007) report results from a mitigation study on the southern pine beetle. This beetle shares similar traits to the mountain pine beetle in that it is a bark beetle that aggressively attacks pine trees causing scattered, low-level mortality of forest stands that, given favourable conditions, can lead to severe infestations on the landscape. Mitigation of detected infestations reduced population expansions by 77.4% when compared to untreated controls (Fettig *et al.* 2007). In addition Coops *et al.* (2008) reviewed mountain pine beetle mitigation strategies and the effectiveness of these approaches to impacting insect population levels. In British Columbia annual mitigation techniques typically employ fall and burn strategies, which require ground crews to identify attacked trees, fall and burn trees to kill beetles beneath the bark. Other suggested techniques to control beetles include prescribed burning (landscape level), silvicultural treatments (forest stand level), and altering chemical cues received and emitted by beetles (individual tree level). The effectiveness of mitigation approaches may be monitored using a similar hierarchical approach. Forest managers face the task of deciding which treatment best suits the scale of infestation, according to the rate of population expansion and the cost associated with each type of survey method. It therefore follows that fine-scale, high-accuracy data from local-scale data are critical in individual tree level identification whereas landscape-scale surveys link to silviculturally based approaches and, finally, coarse-scale mitigation techniques such as fire are associated with regional-scale data.

When deciding on an appropriate survey method to guide mitigation it is important to consider the limitations associated with each survey method, the information required from the survey, and the time it takes to receive the survey data. For example, aerial overview surveys provide a broad measure of the severity and extent of an infestation over large areas, but can take approximately 6 months to plan, collect, and prepare data for use. Exceptions to this include when data are intended to be used to aid planning of more detailed surveys and can be made available within 2 to 3 months. Furthermore, mountain pine beetle information is usually available at the beginning of November proceeding survey completion. Heli-GPS surveys, however, provide data on individual trees in small forest stands that can be available upon completion of survey. Therefore, the type of survey utilized depends on the last known extent of an infestation or whether new infestation is being detected. If an infestation is known to be established it is more likely broad-scale technologies will be used to monitor the annual spread. If a new infestation is discovered and rapid data acquisition is important, surveys such as heli-GPS should be utilized that rapidly acquire highly accurate data to guide mitigation efforts.

The type of survey selected is also subject to financial limitations—aerial overview surveys have been estimated to cost \$0.01 per hectare, whereas heli-GPS costs \$0.15 per hectare (Wulder *et al.* 2006c). Survey costs increase according to the spatial resolution of the data used, where high-spatial-resolution satellite imagery can cost up to \$28.60 / km^2 over a minimum area of 64 km^2 (Wulder *et al.* 2006c) for a cost per hectare of \$0.26. Overall, the greater the detection accuracy utilized the more successful mitigation will be, albeit subject to the constraints mentioned above. Funds should either be allocated to supply high-accuracy detection in the short term or allow for persistent mitigation in the long term. However, long-term monitoring is needed on a continuous basis, not just when populations begin to reach incipient epidemic levels and end-users must possess the skills and capacity to utilize data when received.

Conclusion

Mitigation of mountain pine beetle populations requires timely detection followed by swift and persistent destructive mitigation. Swift mitigation enables killing of beetles prior to flight (when evident as red attack stage) or prior to development (when at green attack stage). Mitigation of the mountain pine beetle populations requires intensive and destructive means, such as falling and burning of infested trees. Further, as not all beetle infested trees are likely to be identified and subject to mitigation, additional beetle ingress may occur during the flight period, requiring continual mitigation over many years. The number of years required for suppression of a given infestation is a function of the beetle population present, the host characteristics and numbers, the rate of population increase present, the actual level of mitigation, and the accuracy with which infested trees can be identified.

Mitigation is most successful when completed on small groups or individual infested trees. We posit that survey detection accuracy has a direct impact upon mitigation success, influencing the number of infested trees requiring treatment and the duration of continued mitigation efforts. Single mitigation events will cause decreased infestation, however populations can rapidly increase and cause further infestation if mitigation is not completed persistently. To combat population increases in large infestations, persistent mitigation must be completed to reduce beetle population levels. In a doubling population, detection accuracies are required to be greater than 60% and mitigation should persist between 31 years and 52 years. If infestation rates increase, detection accuracies as high as 80% may be required to provide data to guide mitigation to suppress beetle populations. Mitigation over this timescale is an overwhelming task with respect to time and resources. To implement a persistent mitigation program to address these large infestations requires governments to invest significant resources and, most important, to maintain this level support even once infestations appear to be decreasing.

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References

Alberta Sustainable Resource Development. 2007. Beetle Bulletin [online]. Available at http://srd.alberta.ca/forests/pdf/Beetle_Bulletin_May_July.pdf.

Aldrich, R.C., R.C. Heller and W.F. Bailey. 1958. Observation limits for aerial sketch-mapping southern pine beetle in the southern Appalachians. Journal of Forestry 56: 200–202.

Barclay, H.J., L.S. Otvos., and A.J. Thomson. 1985. Models of periodic inundation of parasitoids for pest control. Canadian Entomologist. 117: 705–716.

Beukema, S.J., J.A. Greenough., D.C.E. Robinson., W.E. Kurz., E.L. Smith and B.B. Eav. 1997. The westwide pine beetle model: a spatially-explicit contagion model. *In* R. Teck, M. Moeur and J. Adams (eds.). Proceedings of the Forest Vegetation Simulator Conference. 3–7 February, Fort Collins, CO. pp. 126–130. Department of Agriculture, Forest Service, Intermountain Research Station, Gen. Tech. Rep. INT-GTR-373. Ogden, UT. 222 p.

[BCMFR] British Columbia Ministry of Forests and Range. 1995. Bark beetle management guidebook [online]. Available at http://www.for.gov.bc.ca/tasb/legsregs/fpc/fpcguide/beetle/chap3a.htm.

_____**. 2000.** 1999 Aerial overview survey summary [online]. Available at http://www.for.gov.bc.ca/hfp/health/overview/1999table.htm. Accessed 16 October 2007.

_____**. 2001.** 2000 Aerial overview survey summary [online]. Available at http://www.for.gov.bc.ca/hfp/health/overview/2000table.htm.

_____**. 2002.** What is the theoretical Maximum Green:Red? [online]. Available at http://www.for.gov.bc.ca/hfp/health/fhdata/maxbeetles.htm.

_____**. 2006.** Preparing for climate change: adapting to impacts on British Columbia's forest and range resources [online]. Available at http://www.for.gov.bc.ca/mof/Climate_Change/Preparing_for_Climate_Change.pdf.

Carroll, A.L., T.L. Shore and L. Safranyik. 2006. Direct Control: Theory and Practice. *In* L. Safranyik and B. Wilson (eds.). The Mountain Pine Beetle: A Synthesis of Biology, Management, and Impacts on Lodgepole Pine. pp. 155–172. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC, Canada. 317 p.

Carroll, A.L., S.W. Taylor, J. Régnière and L. Safranyik. 2004. Effects of climate change on range expansion by the mountain pine beetle in British Columbia. *In* T.L. Shore, J.E. Brooks, J.E. Stone (eds.). Mountain pine beetle symposium: challenges and solutions, 30–31 October 2003, Kelowna, British Columbia, Canada. pp. 223–232. Canadian Forest Service, Pacific Forestry Centre, Victoria, British Columbia, Information Report BC-X-399. 298 p.

Coops, N.C., J.A. Timko, M.A. Wulder, J.C. White and S.O. Ortlepp. 2008. Investigating the effectiveness of mountain pine beetle mitigation strategies. International Journal of Pest Management 54(2): 151–165.

Fettig, C.J., K.D. Klepzig, R.F. Billings, A.S. Munson, T.E. Nebeker, J.F. Negrón, and J.T. Nowak. 2007. The effectiveness of vegetation management practices for prevention and control of bark beetle infestations in coniferous forests of the western and southern United States. Forest Ecology and Management 238: 24–53.

Franklin, S.E., M.A. Wulder., R.S. Skakun and A.L. Carroll. 2003. Mountain pine beetle red-attack forest damage classification using stratified Landsat TM data in British Columbia, Canada. Photogrammetric Engineering and Remote Sensing 69(3): 283–288.

Harris, J.W.E. and A.F. Dawson. 1979. Evaluation of aerial forest pest damage survey techniques in British Columbia. Canadian Forestry Service, Victoria, Information Report, BC-X-198. 22 p.

Hopping, G.R. and W.G. Mathers. 1945. Observations on outbreaks and control of mountain pine beetle in the lodgepole pine stands of western Canada. The Forestry Chronicle 21(2): 98–108.

Logan, J. and J. Powell. 2001. Ghost forests, global warming, and the mountain pine beetle (Coleoptera: Scolytidae). American Entomologist. Fall: 162–172.

Leckie, D.G., E. Clooney and S.P. Joyce. 2005. Automated detection and mapping of crown discolouration caused by jack pine budworm with 2.5 m resolution multispectral imagery. International Journal of Applied Earth Observation and Geoinformation 7: 61–77.

Maclauchlan, L.E. and J.E. Brooks. 1998. Strategies and tactics for managing the mountain pine beetle, *Dendroctonus ponderosae*. British Columbia Forest Service, Kamloops Region Forest Health, Kamloops, BC. 55 p.

Malmström, C.M. and K.F. Raffa. 2000. Biotic disturbance agents in the boreal forest: considerations for vegetation change models. Global Change Biology 6(1) (Supplement): 35–48.

Mitchell, R.G. and H.K. Preisler. 1991. Analysis of spatial patterns of lodgepole pine attacked by outbreak populations of the mountain pine beetle. Forest Science 37(5): 1390–1408.

Nelson, T., B. Boots and M.A. Wulder. 2004. Spatial-temporal analysis of mountain pine beetles infestations to characterize pattern, risk, and spread at the landscape level. *In* T.L. Shore, J.E. Brooks, J.E. Stone (eds.). Mountain pine beetle symposium: challenges and solutions, 30–31 October 2003, Kelowna, British Columbia, Canada. pp. 164–173. Canadian Forest Service, Pacific Forestry Centre, Victoria, British Columbia, Information Report BC-X-399. 298 p.

Nelson, T., B. Boots, and M.A. Wulder. 2006. Large-area mountain pine beetle infestations: Spatial data representation and accuracy. Canadian Journal of Forest Research 36: 2815–2825.

Safranyik, L. and A.L. Carroll. 2006. The biology and epidemiology of the mountain pine beetle in lodgepole pine forests. *In* L. Safranyik and B. Wilson (eds.). The Mountain Pine Beetle: A Synthesis of Biology, Management, and Impacts on Lodgepole Pine. pp. 3–66. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC, Canada. 317 p.

Safranyik, L. and D.A. Linton. 1991. Unseasonably low fall and winter temperatures affecting mountain pine beetle and pine engraver beetle populations and damage in the British Columbia

Chilcotin region. Journal of the Entomological Society of British Columbia 88: 17–21.

Skakun, R.S., M.A. Wulder and S.E. Franklin. 2003. Sensitivity of the Thematic Mapper Enhanced Wetness Difference Index (EWDI) to detect mountain pine beetle red-attack damage. Remote Sensing of Environment 86: 433–443.

Taylor, S.W., A.L. Carroll., R.I. Alfaro, and L. Safranyik. 2006. Forest, climate and mountain pine beetle outbreak dynamics in western Canada. *In* L. Safranyik and B. Wilson (eds.). The Mountain Pine Beetle: A Synthesis of Biology, Management, and Impacts on Lodgepole Pine. pp. 67–94. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC, Canada. 317 p.

Thompson, A.J. 1991. Simulation of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) spread and control in British Columbia. Pacific Forestry Centre, Canadian Forestry Service, Pacific and Yukon Region, B.C. Information Report BC-X-329. 18 p.

Westfall, J. and T. Ebata 2008. 2007 Summary of forest health conditions in British Columbia. British Columbia Ministry of Forests and Range, Forest Practices Branch, Victoria, BC. 81 p.

White, J.C., N.C. Coops, T. Hilker, M.A. Wulder and A.L. Carroll. 2007. Detecting mountain pine beetle red attack damage with EO-1 Hyperion moisture indices. International Journal of Remote Sensing 28(10): 2111–2121.

White, J.C., M.A. Wulder, D. Brooks, R. Reich and R.D. Wheate. 2005. Detection of red attack stage mountain pine beetle infestation with high spatial resolution satellite imagery. Remote Sensing of Environment 96: 340–351.

Wulder, M.A., C.C. Dymond and B. Erickson. 2004. Detection and monitoring of the mountain pine beetle. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, British Columbia, Information Report BC-X-398. 24 p.

Wulder, M.A., C.C. Dymond, J.C. White and B. Erickson. 2006a. Detection, mapping, and monitoring of mountain pine beetle. *In* L. Safranyik and B. Wilson. (eds.). The mountain pine beetle: A synthesis of biology, management, and impacts on lodgepole pine. pp. 123–154. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, British Columbia. 317 p.

Wulder, M.A., C.C. Dymond, J.C. White, D.G. Leckie and A.L. Carroll. 2006b. Surveying mountain pine beetle damage of forests: a review of remote sensing opportunities. Forest Ecology and Management 221: 27–41.

Wulder, M.A., J.C. White, B.J. Bentz and T. Ebata. 2006c. Augmenting the existing survey hierarchy for mountain pine beetle red-attack damage with satellite remotely sensed data. The Forestry Chronicle 82(2): 187–202.

Wulder, M.A., J.C. White, B. Bentz, M.F. Alvarez and N.C. Coops. 2006d. Estimating the probability of mountain pine beetle red-attack damage. Remote Sensing of Environment 101: 150–166.