Evaluating Satellite Imagery for Estimating Mountain Pine Beetle-Caused Lodgepole Pine Mortality: Current Status

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Abstract

Spatial accuracy in the detection and monitoring of mountain pine beetle populations is an important aspect of both forest research and management. Using ground-collected data, classification models to predict mountain pine beetle-caused lodgepole pine mortality were developed for Landsat TM, ETM+, and IKONOS imagery. Our results suggest that low-resolution imagery such as Landsat TM (30 m) is not suitable for detection of endemic level populations of mountain pine beetle. However, good results were obtained for pixels with groups of red beetle-killed lodgepole pine (> 25 trees killed per 30-m pixel), implying that Landsat imagery is most suited to detection of populations at the building or epidemic phase. Preliminary results using high resolution IKONOS imagery (4 m) suggest that detection of individual or small groups of red beetle-killed lodgepole pine can be accomplished with a relatively high accuracy.

Introduction

The mountain pine beetle (*Dendroctonus ponderosae* Hopkins Coleoptera: Scolytidae) is one of the most important drivers of vegetation change in lodgepole pine (*Pinus contorta*) forests. Outbreaks of these insects can be truly impressive events, with annual losses that are often greater than fire or any other natural disturbance. Mountain pine beetle populations can erupt rapidly, resulting in large increases in tree mortality within a few years. Timely forest management is contingent upon population monitoring and detection of beetle-caused tree mortality. Mountain pine beetle populations persist at endemic levels in single attacked trees scattered across a landscape. Population monitoring at this level can be difficult. Given appropriate weather and stand conditions, beetle success increases and groups of trees begin to be attacked. At the outbreak level, thousands of hectares with up to 70% mortality can occur. One promising avenue for detection of tree mortality caused by mountain pine beetles at various population levels is the use of remotely sensed data.

Remotely sensed data can be used for detecting visual, and through the near infrared bands, non-visual physiological changes in vegetation. Numerous studies have investigated the use of satellite-based digital remote sensing for the characterization of forest ecosystems and changes that occur within

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these systems [see Lunetta and Elvidge (1998) and Cohen and Fiorella (1998) for reviews]. Pixel-wise transformations of spectral values are often used to enhance particular vegetative qualities. Ratios of spectral bands and the Normalized Difference Vegetation Index, which are based on known spectral interactions in green vegetation canopies, are examples of techniques that result in vegetation indices. Derived vegetation indices generally have a stronger relationship to the phenomena of interest in the scene than do any single spectral band. The tasseled-cap transformation, originally developed using Landsat Multispectral Scanner (80 m resolution) data (Crist and Cicone 1984), is another technique which can be used to extract physical/biological characteristics from the spectral features to develop more sensitive vegetation indices. The tasseled-cap procedure produces an orthogonal transformation of the original six-channel data to a new, three-dimensional space that creates axes that describe scene brightness, greenness, and wetness. This technique was adapted to Landsat 5 Thematic Mapper data (TM) (30 m resolution) (Crist and Cicone 1984) and Landsat 7 Enhanced Thematic Mapper data (ETM+) (30 m resolution) (Huang et al. 2002) providing an invariant transformation for comparing both TM and ETM+ scenes.

The tasseled-cap technique has proven useful in many situations as an indicator of forest vegetation change (Cohen and Fiorella 1998; Price and Jakubauskas 1998), including predictions of bark beetle-caused mortality in California (Collins and Woodcock 1996; Macomber and Woodcock 1994). Using change detection techniques and percent basal area killed per multi-pixel stand over a 3-year period as the basis for analysis, up to 73% accuracy was obtained for stands with a 20% mean change (N=50) that was attributed to bark beetle-caused mortality (Collins and Woodcock 1995; 1996). Similarly, an earlier study suggested groups of infested trees needed to be large, at least 1.5 ha (17 pixels) in size, to be detected using TM data (Renez and Nemeth 1985). In a recent Canadian study using Landsat TM imagery and a combination of helicopter and ground crew collected data, Franklin et al. (2003) predicted pixel-wise presence/absence of mountain pine beetle-killed lodgepole pine with an overall accuracy of 73%. Stratification of the image prior to classification is one technique used by Franklin et al. (2003) to increase the per pixel accuracy of detecting red-attacked versus green trees. We define red-attacked trees as trees that were attacked and killed by bark beetles the flight season prior to the current year. Lodgepole pine foliage typically turns red approximately 10 months after the initial mass attack.

In addition to the low resolution TM data, several recently launched satellites collect data at a higher resolution of 4 m and 1 m. Little work on detecting red beetle-killed trees has been conducted with these data. Our main objective of this paper is to relate the status of research aimed at evaluating Landsat TM, ETM+ and IKONOS (4 m) satellite data for detecting levels of red mountain pine beetle-killed trees in lodgepole pine stands in the United States.

Methods

Study Site and Ground Data Collection

Landsat

The study area was located in a mountainous region of the Lolo National Forest in central Montana (Fig. 1).

Elevation within the study area ranged from 940 m to 1524 m. Forest conditions were mixed conifer, although all ground plots were taken in areas with predominantly lodgepole pine (*Pinus contorta*). Other species included subalpine fir (*Abies lasiocarpa*), mountain hemlock (*Tsuga mertensiana*), western hemlock (*Tsuga heterophylla*), larch (*Larix occidentalis*), grand fir (*A. grandis*) and Douglas-fir (*Pseudotsuga menziesii*). Based on aerial detection survey (ADS) information (USDA Forest Service, Forest Health Protection, Region 1) mountain pine beetle populations were active within the study area beginning in 1994.

Ground data was collected from August through September in 2000, 2001 and 2002. In 2000, data were collected using variable radius plots (20 Basal Area Factor) on a 3 x 3 grid, with plot centers every

30 m. A 30 m plot size was used to correlate with the area covered by a TM pixel. In 2001, each site consisted of nine plots, again in a 3 x 3 grid pattern, but a 100% survey was taken within each 30 m x 30 m plot (0.09 ha) instead of variable radius plots as in 2000. In 2002, sampling intensity at each site was reduced to facilitate an increase in the number of sites across the study area. The grid size of plots at each site was reduced to 2 x 2 (4 total plots) with a 100% survey taken within each 30 m x 30 m plot. In addition, plots on the ground were oriented in a north-south direction to more closely align with the Landsat image pixels. At each plot, all years, diameter at breast height (dbh) was measured for all trees, and each tree was assigned a species and attack code: 1) live and not currently infested, 2) current mountain pine beetle attack, 3) mountain pine beetle-attacked the previous year, 4) mountain pine beetle-attacked two years previous, or 5) mountain pine beetle-attacked more than two years previous. At each site, GPS positions were acquired to relate the survey sites to the digital imagery. Points were taken in the center of each plot in 2000 and in the four corners and center of each site in 2001 and 2002. A total of 58 sites and 380 plots were surveyed from 2000-2002: 15 sites and 143 plots in 2000, 13 sites and 117 plots in 2001, and 30 sites and 120 plots in 2002. To increase the sample size of live, non-beetle infested trees, areas of green lodgepole pine were located on aerial photos of the study area taken in 2000. These areas where then overlaid on the 2000 ETM+ image to extract spectral digital values for green lodgepole pine.

IKONOS

The Sawtooth National Recreation Area (SNRA) is located in central Idaho (Fig. 1). Elevation at the valley floor is approximately 2000 m. Forest conditions within the study area were mostly pure lodgepole pine, with transition areas of Douglas-fir and subalpine fir as elevation increased on the valley slopes. Mountain pine beetle populations began building in the northern section of the SNRA in 1997, and by 2002 were at outbreak levels throughout the valley (USDA Forest Service, Forest Health Protection, Region 4, ADS). Ground data collection for classification of IKONOS imagery was conducted in September 2002 and

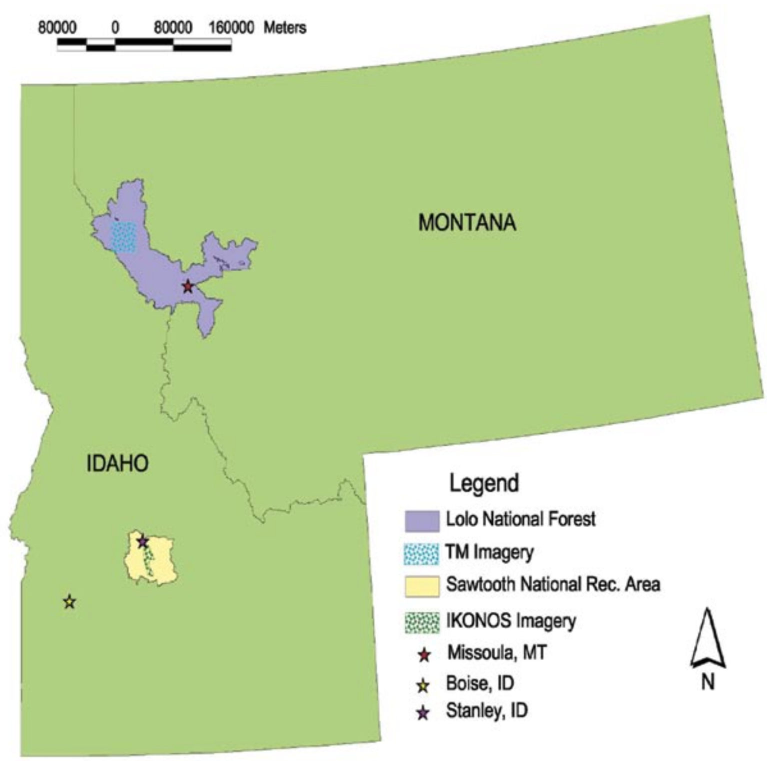


Figure 1. Study locations within Montana (Landsat) and Idaho (IKONOS).

consisted of identifying individual trees and assigning a trees species and attack code: 1) live and not currently infested, 2) current mountain pine beetle attack, 3) mountain pine beetle-attacked the previous year, or 4) mountain pine beetle-attacked two years previous. The geographic location of each tree was recorded with a GPS. Other classes including water, roads, dirt, agriculture, and sagebrush were identified from the IKONOS image. The training data contained 699 observations in 10 classes (Table 1).

Table 1. Number of observations in each class of the training data used for developing classification models for the 2001 IKONOS image.

Vegetation Class	Number of Points	Vegetation Class	Number of Points
Agriculture	106	Red trees	68
Dirt	53	Road	68
Douglas-fir	66	Sagebrush	29
Grass	15	Shadow	84
Green lodgepole pine	55	Water	155

Image Acquisition and Processing

Landsat

Landsat imagery (Path 42, Row 27) was acquired for the following dates: October 4, 1993; August 31, 1998; August 26, 1999; August 28, 2000; August 15, 2001; and August 18, 2002. The 1993 and 1998 images were from the Landsat 5 Thematic Mapper (TM) sensor, and the 1999-2002 images were from the Landsat 7 Enhanced Thematic Mapper (ETM+) sensor. All five images were re-projected to UTM coordinates, Zone 11N, and NAD27 datums, and geo-rectified to the 1993 image. The images were cropped to focus on the area in which ground data were collected. After preliminary processing, several corrections and enhancements were performed on all images including dark pixel atmospheric correction (Chavez 1975), and calibration to radiance values and conversion to reflectance values (NASA Landsat 7 Science Users Handbook http://ltpwww.gsfc.nasa.gov/IAS/handbook/handbook_toc.html; Canada Centre for Remote Sensing Calibration/Validation, http://www.ccrs.nrcan.gc.ca). After a specific correction procedure, a tasseled cap transformation was performed using a 6 x 6 matrix of coefficients, specific for each sensor (Tables 2 and 3). This value was then multiplied by 1023 to increase the range of digital values.

Table 2. Tasseled-cap coefficients for the TM sensor (Crist and Cicone 1984).

Index	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6
Brightness	0.3037	0.2793	0.4743	0.5585	0.5082	0.1863
Greenness	-0.2848	-0.2435	-0.5436	0.7243	0.0840	-0.1800
Wetness	0.1509	0.1973	0.3279	0.3406	-0.7112	-0.4572
Fourth	-0.8242	0.0849	0.4392	-0.0580	0.2012	-0.2768
Fifth	-0.3280	0.0549	0.1075	0.1855	-0.4357	0.8085
Sixth	0.1084	-0.9022	0.4120	0.0573	-0.0251	0.0238

Table 3. Tasseled-cap coefficients for the ETM+ sensor (Huang et al. 2002)

Index	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6
Brightness	0.3561	0.3972	0.3904	0.6966	0.2286	0.1596
Greenness	-0.3344	-0.3544	-0.4556	0.6966	-0.0242	-0.2630
Wetness	0.2626	0.2141	0.0926	0.0656	-0.7629	-0.5388
Fourth	0.0805	-0.0498	0.1950	-0.1372	0.5752	-0.7775
Fifth	-0.7252	-0.0202	0.6683	0.0631	-0.1494	-0.0274
Sixth	0.4000	-0.8172	0.3832	0.0602	-0.1095	0.0985

Stand survey data within a GIS database (USFS, Timber Management Control Handbook Region 1 Amendment 2409.21e-96-1) were used to stratify the landscape by creating a mask layer that was applied to each image. Included in the mask layer were stands in which lodgepole pine comprised the plurality of the stocking and was also the primary species of the stand component based on plurality of basal area stocking. In addition, only stands that had not been harvested within the past 50 years were included. Following image enhancements and transformations, spectral values for each survey plot within each site were assigned using area of interest layers. Using the GPS points collected in the field, ground-collected plot data from each site were overlaid on each transformed image. Area of interest layers were created surrounding all pixels encompassed in each plot and any adjoining pixels that could influence the overall mean spectral value of a plot. A mean digital value was calculated for each band, within each area of interest. The spectral digital values were combined with the ground data (describing the amount of mountain pine beetle activity in the plot) into a database for statistical analysis.

IKONOS

IKONOS satellite imagery was acquired for 26 August 2001 and 3 September 2001 for the 299-km^2 study area within the SNRA. The IKONOS multi-spectral imagery has four bands: blue (0.45 µm—0.52 µm), green (0.52 µm—0.60 µm), red (0.63 µm—0.70 µm), and near infrared (0.76 µm—0.85 µm) at a resolution of 4 m. The imagery was purchased ortho-rectified with eight bits per pixel, and geo-referenced to metadata layers obtained from the Sawtooth National Recreation Area and ground control points (e.g., major road intersections) obtained with a GPS.

Statistical Analyses

Landsat

Ground data collected in 2001 and 2002 were used to develop a model for classifying the TM and ETM+ images. Because trees that were beetle-killed the previous year and two years previous had a very similar foliage color, these trees were merged into one category identified as Red. Trees beetle-killed more than two years before the date of the image were placed into a separate category identified as Grey. All live trees (all species) and trees beetle-infested the year of the image date were merged into one category identified as Green. A variety of metrics were calculated for each plot to test appropriate measures for correlating vegetative ground data with the pixel spectral value on Landsat images. These included trees per acre Red, trees per acre Green, trees per acre Grey, basal area Red, basal area Green, basal area Grey, number of trees Red, number of trees Green, and number of trees Grey. Ground data were also summarized, per plot, into one of three classes: 0-9 trees Red, 10-24 trees Red, and > 25 trees Red.

To develop a model for classifying the amount of beetle-caused tree mortality within Landsat image pixels, the relationship between 254 ground points and the corresponding spectral value of the image was analyzed using a variety of statistical algorithms including regression trees, linear discriminant analysis, quadratic discriminant analysis, and k's Nearest Neighbor (SAS Institute, Splus®). A 10-fold cross-validation estimate of the error rate was computed, and one thousand random permutations of the data were generated. Each permutation was then split into two pieces, with the first 90% of the observations being assigned to be a training data set and the remaining observations comprising a test data set. The four classifiers were then fit to the training data, evaluated on the test data, and the predictive error rates averaged over all 1000 samples. Using the derived model, all images were classified. The 2001 and 2002 image classifications were assessed using ground data collected for those years and site-specific error was assessed using a confusion matrix and a weighted kappa statistic (Campbell 1996). Model-predicted classified images were also compared to polygons of mountain pine beetle-killed trees developed from digitized aerial detection surveys (USFS, Forest Health Protection Region 1; McConnell et al. 2000).

IKONOS

Training data collected on the ground (Table 1) were combined with the associated pixel spectral values on the image. The same four statistical classification algorithms used to develop models for Landsat imagery were tested with the IKONOS multi-spectral data for classification model development. A 10-fold cross-validation estimate of the error rate was computed using each method, and one thousand random permutations of the data were generated. Each permutation was then split into two pieces, with the first 90% of the observations being assigned to be a training data set and the remaining observations comprising a test data set. The four classifiers were then fit to the training data, evaluated on the test data, and the predictive error rates averaged over all 1000 samples. Using the derived model, all pixels of the IKONOS image were classified and assessed using the same training data set.

Results and Discussion

Of the four models tested, cross-validation revealed that the lowest overall misclassification rate (37.67%) for Landsat imagery was achieved using the linear discriminant analysis-derived model and non-transformed values of tree counts. Class 2 had the highest misclassification rate (62.02%), while classes 1 and 3 had lower rates (21.14% and 33.70%, respectively). The addition of Green and Grey tree counts per pixel did not significantly increase the power of the model. The linear discriminant model resulted in the following equations that can be used to create a classified Landsat image based on 3 classes of mountain pine beetle-killed trees (Class 1: 0-9 trees Red, Class 2: 10-24 trees Red, and Class 3: > 25 trees Red):

$$\text{CLASS 1} = -83.45386 + (B1\times-1.03769) + (B2\times1.65584) + (B3\times-0.90812) + (B4\times3.27962) + (B5\times-2.19315) + (B6\times2.08431)$$

$$\text{CLASS 2} = -85.12807 + (B1\times-1.05044) + (B2\times1.62908) + (B3\times-0.94684) + (B4\times3.38405) + (B5\times-1.86218) + (B6\times1.95214)$$

$$\text{CLASS 3} = -84.82084 + (B1\times-1.13747) + (B2\times1.64929) + (B3\times-1.07066) + (B4\times3.31968) + (B5\times-1.45134) + (B6\times2.42476)$$

The Bn values are the individual bands of the tasseled-cap transformed TM image for a given pixel. The equation that generates the largest value is coded to its respective class value. This model was applied to all images, then masked with two layers to remove areas of bare ground, water, non-lodgepole pine stands, and stands that had been harvested. The classification accuracy assessment using 2001 and 2002 ground data revealed an overall accuracy of 59% with a weighted kappa of 45.6% (Table 4).

Class 3 had the greatest predicted classification accuracy when compared to ground data (79%).

Cross-validation revealed that the lowest overall misclassification rate (11.68%) for the IKONOS image was achieved using quadratic discriminant analysis. Over 95% of the mountain pine beetle-killed trees (Red trees) were correctly classified (Table 5).

Green lodgepole pine and Red trees were misclassified less than 0.01%. Misclassification of Douglas-fir as green lodgepole pine and vice versa accounted for the largest amount of error. Transformation of spectral values using tasseled-cap or the Normalized Difference Vegetation Index did not increase the power of the model.

When applied to the 1993 Landsat TM image, taken prior to the start of the mountain pine beetle outbreak within the study area, the Landsat TM model predicts more areas of beetle-caused mortality than are shown in the Aerial Detection survey for that year (Fig. 2).

These predictions are somewhat expected based on the poor accuracy of vegetation Classes 1 and 2 (Table 4). At endemic population levels, mountain pine beetle-caused tree mortality most likely will not cover an entire 30 m pixel. However, model predictions of the 2002 ETM+ image, during the peak of the mountain pine beetle outbreak in the study area, correlate well with the mortality estimated by Aerial Detection Surveys for that year (Fig. 3).

Although we have not yet quantified differences in IKONOS model predictions and observed mortality in the Sawtooth National Recreation Area, patterns of mortality in a small area of the image are consistent with our ground observations (B. Bentz unpublished data) (Fig. 4). Validation data collection in the Sawtooth National Recreation Area is ongoing.

Table 4. Error matrix of 2001 and 2002 ground data and predictions based on 2001 and 2002 ETM+ Landsat images. Red trees are trees killed by mountain pine beetle 1 and 2 years prior to the image date.

	0-9 Red trees	10-24 Red trees	>25 Red trees	Total
Class 1				
Frequency	74	22	4	100
Percent	58%	25%	9.5%	
Class 2				
Frequency	47	44	5	96
Percent	37%	52%	12%	
Class 3				
Frequency	6	19	33	58
Percent	0.05%	22%	79%	
Total	**127**	**85**	**42**	**254 (59%)**

Table 5. Partial error matrix for vegetation classes predicted on the 2001 IKONOS image.

	Grass	Green lodgepole pine	Douglas-fir	Red trees	All other classes
Grass	27.6%	0.3%	6.1%	4.8%	61.2%
Green lodgepole pine	3.9%	56.1%	40.0%	0.0%	0.0%
Douglas-fir	1.4%	23.8%	74.8%	0.0%	0.0%
Red trees	1.3%	0.01%	0.0%	95.8%	2.9%
All other classes	0.4%	0.2%	0.2%	0.6%	98.6%

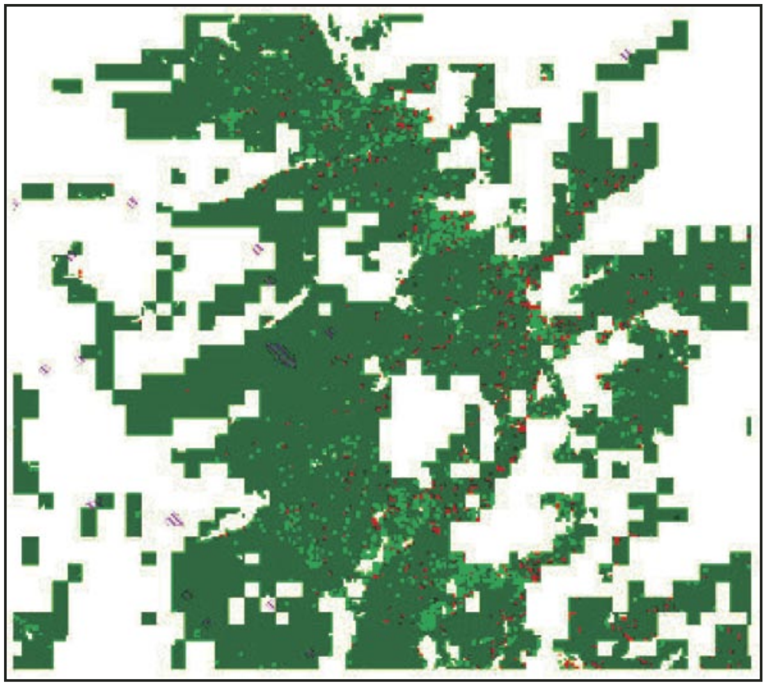


Figure 2. Model predictions of mountain pine beetle-killed lodgepole pine in 1992 (prior to the mountain pine beetle outbreak) on the Lolo National Forest using 1993 Landsat TM imagery. Red pixels are predicted to have > 25 beetle-killed trees per 30-m pixel, light green pixels are predicted to have 10-24 beetle-killed trees per 30-m pixel and dark green pixels indicate 0-9 beetle-killed trees per 30-m pixel. White areas are non-lodgepole pine dominated stands. Purple cross-hatched polygons are areas predicted to have beetle-killed trees based on 1993 Aerial Detection Surveys.

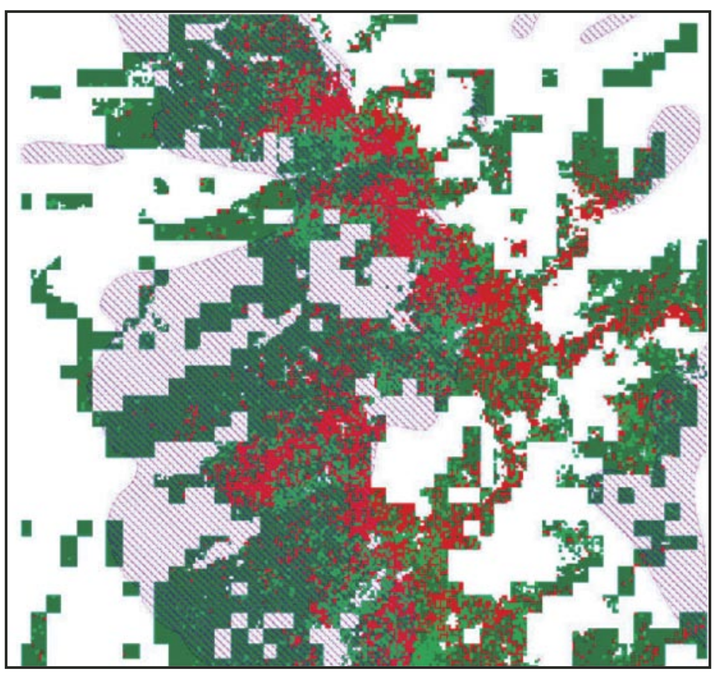
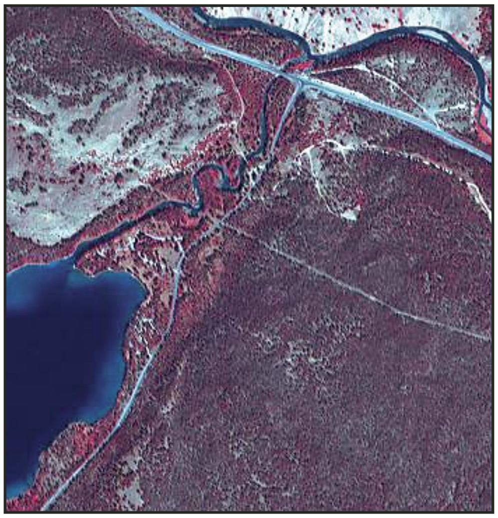


Figure 3. Model predictions of mountain pine beetle-killed lodgepole pine in 2001 (at the peak of the mountain pine beetle outbreak) on the Lolo National Forest using 2002 Landsat ETM+ imagery. Red pixels are predicted to have > 25 beetle-killed trees per 30-m pixel, light green pixels are predicted to have 10-24 beetle-killed trees per 30-m pixel and dark green pixels indicate 0-9 beetle-killed trees per 30-m pixel. White areas are non-lodgepole pine dominated stands. Purple cross-hatched polygons are areas predicted to have beetle-killed trees in 2001 based on 2002 Aerial Detection Surveys.



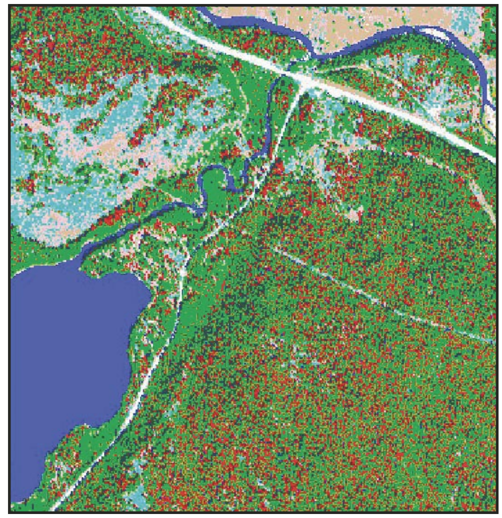


Figure 4. A portion of the 2001 IKONOS image from the Sawtooth National Recreation Area (A), and the image classified using quadratic discriminant analysis (B). Red pixels represent mountain pine beetle-killed trees, light green pixels are live lodgepole pine and dark green pixels are Douglas-fir trees. Cyan, pink, blue and white are predictions of grass, sagebrush, water, and roads, respectively.

Conclusions

Discriminant analysis algorithms provided the best overall statistical fit between mountain pine beetle-killed trees identified on the ground and both Landsat TM, ETM+, and IKONOS pixel spectral values. One of the largest sources of error in model development was correlating the spatial location of ground data (e.g., individual trees or stands of trees) with the correct pixel spectral signal of the images. Our results from the Lolo National Forest suggest that Landsat TM and EMT+ data may be better suited to detection of beetle-killed trees after the population has expanded to killing groups of trees that will dominant the spectral signal of a 30 m pixel. The spectral signal of individual or small patches of red beetle-killed trees, which are indicative of endemic populations, will be difficult to identify with the low-resolution imagery. However, when populations reach the building or outbreak level, models developed for Landsat TM and ETM+ data can provide increased spatial accuracy of groups of red beetle-killed trees compared to current methodology including Aerial Detection Surveys. A more accurate spatial representation of mountain pine beetle infested trees will facilitate both management and research aimed at landscape-scale disturbance processes. Preliminary results in the Sawtooth National Recreation Area suggest that high-resolution imagery, such as IKONOS, show promise for detection of small groups of trees or individual trees killed by the mountain pine beetle. Remotely sensed imagery can be a valuable tool for forest managers, although the specific product to use should correspond with the appropriate beetle population level and specific land management objectives and budget.

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