MONITORING VEGETATION REGENERATION AND DEFORESTATION USING CHANGE VECTOR ANALYSIS: MT. ST. HELENS STUDY AREA

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ABSTRACT

A sophisticated method for monitoring land-cover change in a highly disturbed landscape involved change vector analysis of multitemporal Kauth-Thomas transformation data. Landsat TM data acquired after the 1980 eruption of Mt. St. Helens (1986 and 1996) were analyzed in this study. Topographic effects from the rugged terrain were removed by regressing a generated hillshade image against each band to estimate illumination variation. The estimates were subtracted from each image to generate variation-free data. The images were then transformed into Kauth-Thomas features representing brightness and greenness to enhance landscape features and reduce data redundancy. Change vector analysis allowed for land-change classification without defined calibration sites. The technique produced images of change direction and magnitude between two dates based on the inputs of brightness and greenness. The direction of change indicated whether a landscape had experienced deforestation, reforestation, or remained persistent. Magnitude indicated to what degree the change occurred. The results of the study show that intensive vegetation regeneration occurred within the blast-zone between 1986 and 1996. The method provided a clear-cut process for classifying and quantifying vegetation change.

INTRODUCTION

Recent events at the Mt. St. Helens volcano in the Pacific Northwest of the United States have reminded us that Mother Nature is ready, at any time, to unleash her power and permanently alter the landscape she created. In October 2004, Mt. St. Helens narrowly missed an eruption that would almost certainly have resulted in a devastating impact on the landscape, none of which had been seen since the great eruption 24 years prior. The region surrounding Mt. St. Helens is considered a highly disturbed landscape (Lawrence and Ripple, 1998). Landscape perturbations have been caused by both natural events and human disruption. In May 1980, the volcano violently erupted, permanently altering the landscape and destroying hundreds of square kilometers of forest (Lawrence and Ripple, 1998, Weyerhaeuser, 2004). Vegetation in the area has also been affected by economically-driven factors, such as clear-cut logging. The human impacts, though not as uniquely catastrophic as the eruption, have been more widespread over time and space as logging has occurred throughout the region for over a century (Weyerhaeuser, 2004). As a result, the distribution of vegetation throughout the area surrounding the volcano is constantly fluctuating, so there is a need for effective monitoring of the change in this landscape.

Vegetation analysis is one of the most fundamental applications of remotely sensed satellite imagery (Lawrence and Ripple, 1999). Monitoring change in vegetation between two time periods can assess the health and vigor of forest and plant species, assess vegetation growth and regrowth following a cataclysmic event, or quantify forest loss caused by deforestation and timber harvesting (Lawrence and Ripple, 1999). Classifying these types of changes can be effectively performed using change vector analysis (CVA) (Lambin and Strahler 1994, Johnson and Kasischke, 1998, Allen and Kupfer, 2000, Lorena et al., 2002, Lunetta et al., 2004). CVA is a radiometric technique that examines corresponding pixels of two maps by comparing two bands of each map to produce images of change direction and change magnitude. These input bands can be raw satellite wavelengths or derived from a combination of these raw bands, such as Kauth-Thomas transformations (Johnson and Kasischke, 1998, Allen and Kupfer, 2000, Lorena et al., 2002, Lunetta et al., 2004) or Principal Components Analysis (PCA) (Lambin and Strahler 1994). The combination of the change direction and magnitude can produce categories of change without having to specify training sites of each classification. Identifying training sites of directional change and magnitude can be extremely difficult, time consuming, and inaccurate. CVA provides an automated alternative to this process that is sophisticated, efficient, and can be replicated for any study of vegetation change (Johnson and Kasischke, 1998).

DATA AND METHODS

Study Area

Mt. St. Helens, Washington, is located in the Pacific Northwest region of the United States. The volcano is one of many that line the ridge of the Cascade Range, which stretches from Canada southward to northern California. It is situated between the two large urban centers of Seattle, approximately 90 miles to the north, and Portland, Oregon approximately 60 miles to the southwest (Figure 1). Being situated in a mountainous region, the terrain is very rugged and sparse in human habitation. The area is heavily forested with coniferous (mountain hemlock, Pacific silver fir, Douglas fir) and deciduous forest (willows, black cottonwood) (Lawrence and Ripple, 1998). The density and variety of harvestable timber in the study area makes Mt. St. Helens attractive to timber harvesting.

Figure 1. The location of the Mt. St. Helens study area within the state of Washington, USA.

The Gifford Pinchot National Forest, operated by the United States Forest Service, occupies over 5,000 km^2 of the neighboring region and controls the permitted deforestation within its boundaries. Private logging companies own much of the remaining forested land, the largest being the Weyerhaeuser Company, which occupies large portions of land west of the volcano. In May 1980, Mt. St. Helens violently erupted, causing devastation to a 600 km^2 area surrounding the summit (Weyerhaeuser, 2004). Much of the land affected by the eruption lay north of the volcano, due to the large landslide when the summit slid down the north face. As a result, the exposed molten rock created an enormous blast, knocking down stands of trees over many hundreds of kilometers. Since the eruption, vegetation has been returning to the devastated "blast zone" through either natural recovery, managed by the post-eruption-established Mt. St. Helens National Volcanic Monument, or by controlled clearing and replanting, managed by private logging companies. Areas closer to the volcano have experienced a slower natural recovery due to the high levels of ash still present (Weyerhaeuser, 2004).

The study area represents a 5000 km^2 region surrounding Mt. St. Helens, with the volcanic crater located near the center. The entire blast zone region from the 1980 eruption is included within the study area, as well as adjacent forests not directly affected by the event. This site was selected because it is a chronically disturbed landscape and regeneration is occurring at various rates within the devastated area. Deforestation is occurring in the surrounding forests through continued harvesting for timber production. These extreme events of regeneration and deforestation offer a unique landscape that could benefit from monitoring land-cover change using remotely sensed images and techniques.

Data

Landsat TM images of the area surrounding Mt. St. Helens from two different years, 1986 and 1996, were analyzed in this study (Figure 2). The earlier image, acquired August 26, 1986, was collected six years after the eruption. The later image, acquired August 21, 1996, succeeds the earlier image by 10 years. Bands 1 (0.45 – 0.52 μm), 2 (0.52 – 0.60 μm), 3 (0.63 – 0.69 μm), 4 (0.76 – 0.90 μm), 5 (1.55 – 1.75 μm), and 7 (2.08 – 2.35 μm) from the Landsat TM5 sensor for both dates were used for the analysis. Band 6 (10.4 – 12.5 μm) was not included in the analysis because the thermal infrared wavelengths are not required for performing Kauth-Thomas transformations. A digital elevation model (DEM) of the entire study area at 30-meter resolution was included for the removal of

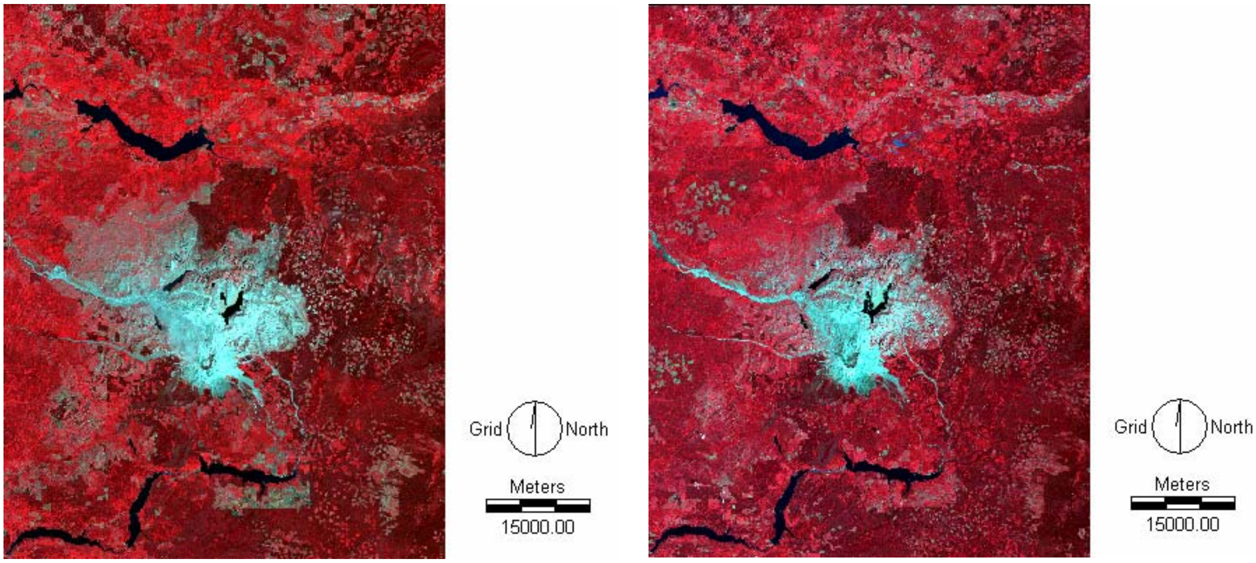

Figure 2. The Mt. St. Helens study area. The images are false color composites of Landsat TM 5 bands 2, 3, 4 for 1986 (left) and 1996 (right), which have been topographically and radiometrically corrected.

illumination effects (USGS 2004). The images were projected to the UTM 10N coordinate system. The 1986 image was georegistered to an existing georeferenced image using bilinear resampling with an RMS error of 0.21. The 1996 image was then georegistered to the 1986 image using bilinear resampling with an RMS error of 0.43. The DEM was acquired with the appropriate georegistration.

Removal of Topographic Effects and Image Preprocessing

The remotely sensed images used in this study center on a rugged region containing a high degree of terrain variation, with slopes ranging from 0˚ to 75˚, the average slope being 17˚, and 69% of the study area having slopes greater than 10˚. The topographic effects are visible in the form of shadows cast inside valleys and behind ridges and peaks throughout the scene. The shadows are an artifact of the sun angle that can lead to misclassification of the data by misrepresenting reflectance values on the image. Therefore, it is necessary to remove terrain effects from the images (Johnson and Kasischke, 1998). In order to correct for these artifacts, a new technique was used to estimate and subtract maps of illumination for each band (Figure 3).

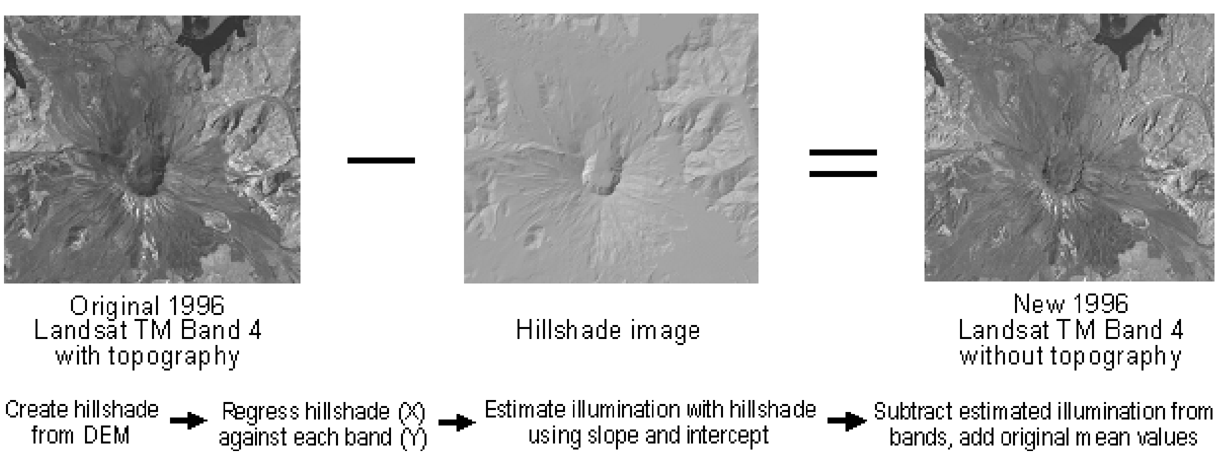

Figure 3. The procedure for removing topographic effects from satellite images.

The technique began by creating a hillshade image from a DEM of the area. The hillshade image is a simulation of the terrain insolation within the scene for the period of Landsat image acquisition. Required inputs for creating the hillshade include the sun azimuth and sun elevation angle. The hillshade (X) was then regressed against each band (Y) of the Landsat images to generate an equation of slope and intercept unique to each set of spectral wavelengths. It should be noted that the regression analysis should be restricted to land covers that are well represented in all topographic aspects. In cases where this is clearly violated, the regression should be restricted to broadly represented categories using a mask. Applying each equation to the hillshade image generated individual images of estimated illumination effects. The illumination images were then subtracted from their corresponding original band, followed by the addition of the mean value for that original band, to create new bands that contained minimal topographic effects. Following the removal of topography, the bands were radiometrically corrected using the Chavez Cos(t) model (Chavez, 1996). Haze was removed from each band and digital number values were transformed into reflectance values. This process standardizes each band so that the images can be compared without influence of atmospheric conditions or time of year.

Kauth-Thomas Transformation

In order to reduce redundancy in the data and highlight the vegetative qualities of the landscape, Kauth-Thomas Tasseled Cap transformations (Kauth and Thomas, 1976) were performed on Landsat bands 1-5, and 7. These transformations produced new image features representing greenness and brightness based on new axes associated with biophysical properties of the scene (Lorena et al., 2002). Values of brightness highlight variations in soil reflectance throughout the study area. Values of greenness represent vegetation cover. The combination of these new transformed bands offered biophysically interpretable inputs for change vector analysis.

Change Vector Analysis

CVA allows users to determine the direction and magnitude of change between two time periods. For this study, we used inputs of brightness and greenness to monitor and measure the regeneration and deforestation of the region between 1986 and 1996. The bands are observed in measurement space with brightness placed along the X-axis and greenness placed along the Y-axis.

Change direction is measured as the angle of the change vector from a pixel measurement at time 1 to the corresponding pixel measurement at time 2 (Figure 4a). Angles measured between 90° and 180° indicate an increase in greenness and a decrease in brightness. We designated this change direction to represent regeneration of vegetation (Lorena et al., 2002). Angles measured between 270° and 360° indicate a decrease in greenness and an increase in brightness. We designated this change direction to represent deforestation (Lorena et al., 2002). Angles measured between 0° and 90° and 180° and 270° indicate either increases or decreases in both bands of greenness and brightness. We designated this change to persistence, which is representative of neither an increase nor decrease in vegetation upon the landscape.

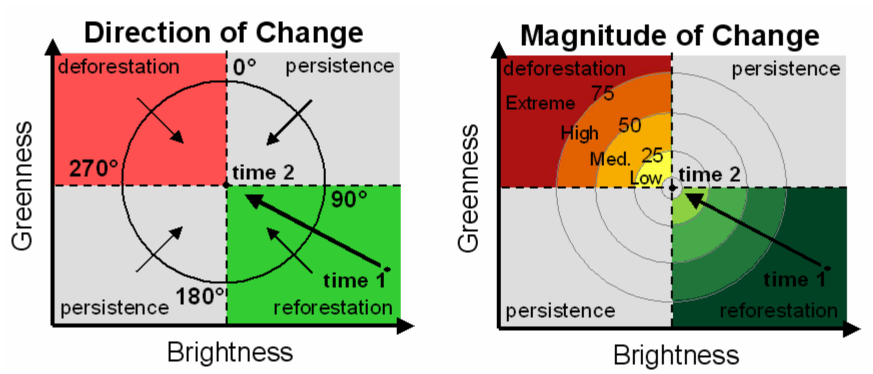

Figure 4. The process for detecting the direction of change (a) and the magnitude of change (b) within change vector analysis.

Change magnitude is measured as the Euclidean distance or length of the change vector from a pixel measurement at time 1 to the corresponding pixel measurement at time 2 (Figure 4b). Lambin and Strahler (1994) discussed how Euclidean distance can be substituted with Mahalanobis distance to explore larger data sets of more than two time inputs. For this study, however, we were only concerned with the change between two time periods. We designated four categories to represent the amount change that occurred between the two time periods. The four categories were: Low (8 to 25), Medium (25 to 50), High (50 to 75), and Extreme (75 to 100). These ranges indicate the length of the change vector of measurement space. Extreme values over 100 were considered to be outliers (0.0007% of the total number of pixels) and were reclassified into the Extreme category. Values between 0 and 8 were considered to be noise or an artifact of imperfect normalization, so the values were classified to represent persistence. The initial threshold value of 8 was selected since the chosen value should be two times the non-zero modal change magnitude value (Johnson and Kasischke, 1998). The change direction and magnitude values of the images were cross-tabulated and classified into 9 categories. These consisted of four categories of regeneration (Extreme, High, Medium, and Low), and four categories of deforestation, and persistence.

RESULTS

Figure 5 shows a map of the study area classified into the 9 categories of regeneration, deforestation, and persistence between 1986 and 1996. Surrounding the volcanic crater in the center of the image, there is a large amount of regeneration occurring, primarily to the northwest and northeast of Mt. St. Helens. Patches of regeneration and deforestation are present throughout the entire study area. Some of these patches are rectangular in shape while others form irregular shapes of various sizes. Large clusters of deforested patches are grouped mainly on the west side of the study area. Sporadic patches of deforestation in the northern part of the study area are intermixed with patches of regeneration. Large continuous patches of regeneration are located in the southern portion of the study area.

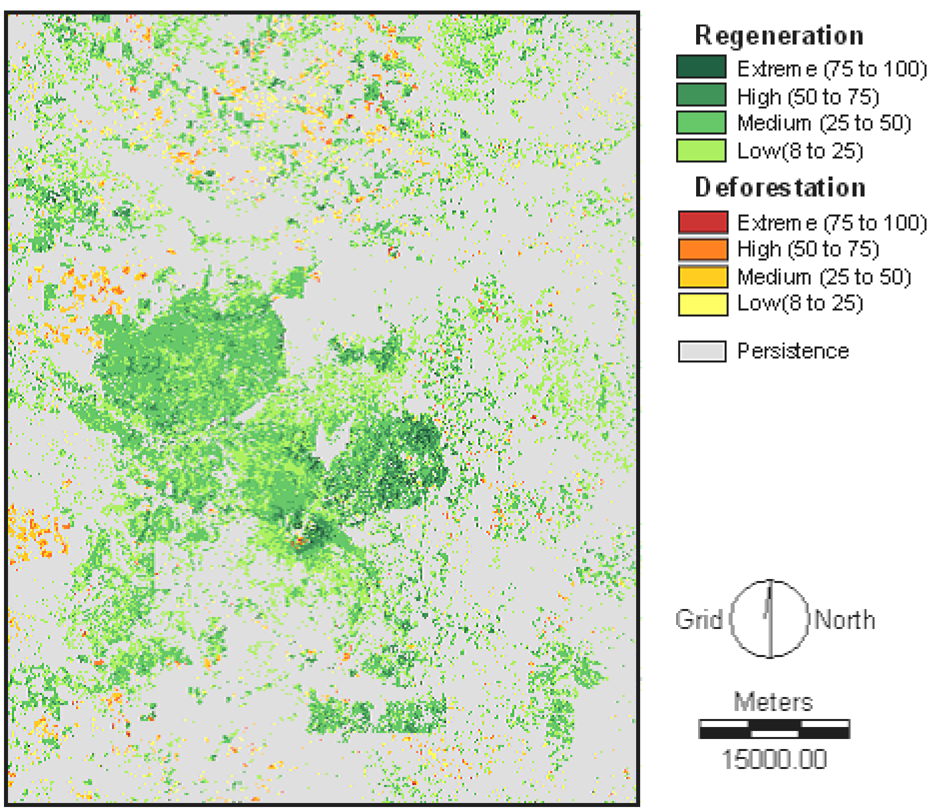

Figure 5. The classification of vegetation change between 1986 and 1996.

Table 1 displays the total area in km^2 for each category of regeneration, deforestation, and persistence, as well as the total and relative percentages of the landscape. The majority of the study area is classified as persistence, with 3,502 km^2 of the total 4,980.10 km^2 (70.32% of the landscape). Overall, there is a greater amount of regeneration than there is deforestation occurring between 1986 and 1996. Regeneration occurs in 1,308.12 sq km (26.27% of the landscape) and deforestation occurs in only 169.98 km^2 (3.41% of the landscape). Of the total landscape that is experiencing regeneration, 49.76% is occurring in the Medium range and 41.69% is occurring in the Low range. For deforestation, 41.09% is occurring in the Medium range and 42.78% is in the Low range.

Table 1. The results of the change vector analysis between 1986 and 1996 classified into categories of Regeneration, Deforestation, and Persistence.

Regeneration	Area (in sq km)	% of Landscape	% of Regeneration/ Deforestation
Extreme (75-100)	8.89	0.18%	0.68%
High (50-75)	102.93	2.07%	7.87%
Medium (25-50)	650.89	13.07%	49.76%
Low (8-25)	545.42	10.95%	41.69%
Total	1,308.12	26.27%	100.00%
Deforestation			
Extreme (75-100)	2.31	0.05%	1.36%
High (50-75)	25.11	0.50%	14.77%
Medium (25-50)	69.84	1.40%	41.09%
Low (8-25)	72.72	1.46%	42.78%
Total	169.98	3.41%	100.00%
Persistence	3,502.00	70.32%	
Total	4,980.10	100.00%	

DISCUSSION

Interpretation of the Results

Land designated as 'regenerated' contained higher levels of vegetation in 1996 than in 1986, and land designated as 'deforested' contained lower levels of vegetation in 1996 than in 1986. Because the volcano erupted six years before the first image acquisition, the majority of the deforestation that occurred between 1986 and 1996 was caused by timber harvesting and clear-cut logging. All devastation created by the 1980 Mt. St. Helens eruption occurred before 1986.

Surrounding the volcano, large patches of continuous regeneration have occurred. This area is primarily located within the blast zone where large amounts of vegetation were either buried by the landslides or blown down by the volcanic blast in 1980. On the affected land owned by the private logging companies, many of the disturbed tree stands were immediately cleared and replanted in order to return the land to its original state for future harvests. Much of the land on the newly designated National Volcanic Monument was left to regenerate naturally. As can be seen in the change image (Figure 5), even from six to sixteen years after the eruption, regeneration is a slow process since there is still a dramatic increase in vegetation years after the eruption. Since the continuous patch of land consists of mostly new and young vegetation, there has been no deforestation occurring in that area.

The majority of deforestation occurring since 1986 is clustered to the north and west of the volcano. This is because the land in these areas is privately owned and is continually clear-cut for timber harvesting. Clear-cutting is the most common practice because Douglas fir species in the region grow best when fully exposed to sunlight without other trees to create shade and hinder growth (Weyerhaeuser, 2004). Patches in the 'Extreme' deforestation category likely represent land that has been deforested within a year or two prior to 1996, the year of the latter image. Large patches of forest that belong to lower deforestation categories were likely clear cut closer to 1986 and have had a chance to regenerate vegetation, negating some of the impacts of deforestation. Some deforestation may be undetectable in this study if it has occurred after 1986 and fully regenerated before 1996.

Throughout the image, patches of various shapes and sizes of regeneration and deforestation can be seen. Outside of the blast zone, these are attributed to the patterns of timber harvesting where whole patches of timber are clear-cut. In the south, a large rectangular patch that is many km^2 in width and length has experienced heavy regeneration. In the north, patterns of rectangular grids of regeneration in square mile (1.61 km^2) blocks dominate while other areas have smaller irregular shaped patches. The slight checkerboard appearance is attributed to the patterns of land ownership between the National Forest and the private logging companies. The National Forest land tends to be persistent while private land largely experiences regeneration and deforestation. Only patches of regeneration appear to exhibit the rectangular grid pattern any deforestation that has occurred since 1986 demonstrates a more irregular pattern in close clusters.

Next Steps

Additional remotely sensed images of the study area have been obtained for the years 1975, 1990, and 1999. Incorporating the new data into the analysis will allow us to examine the direct impacts of the volcanic eruption by comparing a pre-eruption image (1975) with a post-eruption image (1986). Also, by including data from additional years, it will be possible to more closely determine when patches of land are being deforested and how the process of regeneration, both within the blast-zone and in previously deforested patches, occurs over time. The additional analysis is currently in progress and will be documented in remote sensing literature in the near future.

Further important steps to be taken include a complete accuracy assessment of the classification. A comparison of the categorized land with actual ground truth data would be possible by obtaining a map of land-cover and temporal timber harvesting. An additional map of land ownership would also offer interesting findings by analyzing the deforestation patterns of private logging companies versus the patterns occurring on federal protected lands.

CONCLUSION

For this study, CVA was used on Kauth-Thomas bands of greenness and brightness to produce maps of change direction and magnitude. The cross-tabulation of these two images produced an easily interpretable map of regeneration and deforestation without the need to designate training sites. The automated technique presented here eliminates the difficult task of manually categorizing patches of land that are either regenerated or deforested, and at their specific magnitudes (Extreme, High, Medium, Low). The sophisticated method provided a clear-cut process for classifying and quantifying vegetation change. This procedure, therefore, can be used to monitor changes in vegetation for any study site, including areas that are not as highly disturbed as the Mt. St. Helens region.

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