Post-fire Recovery of Sagebrush Communities: Assessment using SPOT5 and Very Large-Scale Aerial Imagery

Temuulen Tsagaan Sankey, GIS Training and Research Center, Idaho State University, 921 South 8th Avenue, Stop 8104, Pocatello, ID 83209 (sankteki@isu.edu)

Corey Moffet, Research Rangeland Scientist, USDA-ARS, U.S. Sheep Experiment Station, Dubois, Idaho 83423

Keith T. Weber, GISP, Idaho State University, GIS Training and Research Center, 921 S. 8th Ave., Stop 8104, Pocatello, Idaho 83209-8104 (webekeit@isu.edu)

ABSTRACT

Much interest lies in the long-term recovery rates of sagebrush communities after fire in the western USA as sagebrush communities comprise millions of hectares of rangelands and important wildlife habitat. Little is known about post-fire changes in sagebrush canopy cover over time, especially at a landscape scale. We studied post-fire recovery of shrub canopy cover in sagebrush-steppe communities using spectral mixture analysis. Our study included 16 different fires that burned between 1937-2005 and one unburned site at the U.S. Sheep Experiment Station in eastern Idaho. Spectral mixture analysis was used with September 2006 SPOT5 satellite imagery to estimate percent shrub canopy cover within pixels, an approach that has not been commonly used in sagebrush studies. Very large-scale aerial (VLSA) imagery with 2-cm resolution was used for training and validation. SPOT5 imagery classification was successful and the spectral mixture analysis estimates of percent shrub canopy cover were highly correlated with the shrub canopy cover estimates in the VLSA imagery (R^2= 0.91; p<0.0001). This successful application of spectral mixture analysis has important implications for the monitoring and assessment of sagebrush-steppe communities. Using the percent shrub canopy cover estimates from the classified SPOT5 imagery, we examined shrub canopy recovery rates since different burn years. Using piecewise regression, it was determined that shrub cover in mountain big sagebrush (*Artemisia tridentata* Nutt. ssp. *vaseyana* [Rydb.] Beetle) communities was recovered in 27 years after fire. The recovered shrub cover was 38.6 %. These results are consistent with other field-based studies in mountain big sagebrush communities.

KEYWORDS: Remote sensing, rangelands, photogrammetry

INTRODUCTION

Sagebrush (*Artemisia* spp) communities constitute the largest temperate semi-desert in North America (Anderson and Inouye 2001) and approximately 60 million hectares of rangelands in the western US (Watts and Wambolt 1996). In the Great Basin, sagebrush-steppe occupies approximately 450,000 km^2 area of the Columbia and Snake River Plateaus and provide important habitat for many wildlife species such as sage grouse (Anderson and Inouye 2001). Hundreds of thousands of acres were burned in the Great Basin (Blaisdell and Mueggler 1956) over the latter half of the last century to eradicate sagebrush (Wambolt et al 2001). More recently, the sagebrush-steppe management objectives and values changed and land managers are now concerned about post-fire recovery of sagebrush communities. Meanwhile, fire was suppressed in other areas of the Great Basin and land managers now use prescribed fire as a tool to restore sagebrush communities (Wambolt et al 2001). In both cases, much interest lies in the long-term recovery rates of sagebrush communities after fire. However, little is known about post-fire changes in sagebrush canopy cover over time (Lesica et al 2007), especially at a landscape scale.

Wildfires might have had much larger effects on pre-settlement sagebrush communities than other biotic and abiotic factors (Lesica et al 2007). Post-fire sagebrush recovery has been used as an indicator of pre-settlement fire frequency and to estimate natural fire rotation in sagebrush communities (Baker 2006). Pre-settlement fire return interval varied in sagebrush communities between 12-25 years on more mesic sites and 200 years on more xeric sites (Crawford et al 2004). Pre-settlement fire return intervals were estimated to be 12-25 years for mountain big sagebrush (*Artemisia tridentata* Nutt. ssp. *vaseyana* [Rydb.] Beetle) communities, 30-100 years for Wyoming sagebrush (*Artemisia tridentata* spp. *wyomingensis* Rydb.) communities, and 100-200 years for low sagebrush (*Artemisia arbuscula* Nutt.) communities (Crawford et al 2004). Post-settlement fire regime in sagebrush steppe has been spatially variable, but largely resulted in two common patterns: 1) fire suppression followed by increased shrub cover and tree encroachment by juniper and pinyon species, and 2) annual grass invasion by species such as cheatgrass (*Bromus tectorum*) leading to increased fire frequency (Crawford et al 2004) and a fire-grass feedback loop (Baker 2006). Post-fire sagebrush canopy recovery has been inconsistent among sites and the estimated length of time for recovery has varied greatly among different studies. The documented estimate of time required for canopy cover recovery spans a broad range between 35-100 years for mountain big sagebrush and 50-120 years for Wyoming big sagebrush (Baker 2006). This is partly because post-fire sagebrush recovery can be highly variable in space (Crawford et al 2004) and among species (Lesica et al 2007). Post-fire sagebrush establishment may also be dependent on distance to seed source, availability of viable seed reservoir, availability of moisture, and post-fire weather conditions (Crawford et al 2004). Recovery can also depend upon fire intensity and post-fire land use treatment such as grazing (Baker 2006).

Most sagebrush studies have been based on field measurements and ground observations. Remote sensing and image analysis techniques have not been commonly used. Previous remote sensing-based studies have used AVIRIS data (Kokaly et al 2003) and NOAA/AVHRR data (Kremer and Running 1993) for thematic classification (i.e., a single cover type is assigned to each pixel), and LiDAR data to determine sagebrush presence/absence and height within pixels (Streutker and Glenn 2006). An important research question is whether sagebrush canopy cover can be estimated within pixels using moderate-resolution satellite imagery such as SPOT5. Pixels in SPOT5 imagery are 100 m^2 (10 m x 10 m) in size and thus frequently have a mix of bare ground, herbaceous plants, and shrub in sagebrush-steppe communities. This mix of cover types within pixels poses a fundamental challenge in classifying pixels, since the spectral characteristics of the mixed pixels do not represent any single land cover type (Lillesand and Kiefer 2000). Spectral mixture analysis techniques have been developed to allow estimates of how much of a pixel is comprised by different land cover types (Adams et al 1986; Small 2004; Xiao and Moody 2005). Spectral mixture analysis is most suited when there are a limited number of land cover types and when the spectral properties of these cover types can be assumed to be relatively constant. Spectral mixture analysis characterizes the spectral signatures as a mix of land cover types in each pixel rather than assigning a single land cover type to

each pixel. Each land cover type within the mix is known as a separate "endmember" (Rencz 1999). Once "pure" endmembers (i.e., pure pixels of each cover type) are determined within imagery, endmember fractions or abundance of each cover type within each pixel can be estimated as a mixture (Rencz 1999). A mixture represents a linear combination of the endmembers, weighted by the areal coverage of each endmember in a pixel (Adams et al 1986). The result is an estimate of how much of a given pixel is comprised of different cover types.

We studied sagebrush-steppe communities and their post-fire canopy recovery across the U.S. Sheep Experiment Station's (USSES) Headquarter property in eastern Idaho using SPOT5 satellite imagery and spectral mixture analysis, an approach that has not been used to our knowledge in sagebrush studies. Our objectives were to: 1) determine if spectral unmixing techniques could be used with SPOT5 imagery to estimate percent shrub cover within pixels, and 2) describe post-fire shrub canopy recovery over time using the canopy cover estimates from the classified SPOT5 imagery. We studied 16 fires that burned in different years between 1937-2005 and one site that has not been burned since before 1936 (Table 1). We chose SPOT5 imagery from September 27, 2006. In the sagebrush-steppe of eastern Idaho, grass and forb growth is completed by the beginning of July (Seefeldt and Booth 2006) and herbaceous species are senescent by September. Sagebrush species, however, still actively photosynthesize in September (Billings and Morris 1951; DePuit and Caldwell 1973) and show a second peak in greenness (Kremer and Running 1993) due to overwintering-leaf growth after the ephemeral-leaf drop at the end of the growing season (Bilbrough and Richards 1993). We expected this difference in phenology to allow more prominent spectral discrimination of the shrubs in September, although some shrubs in arid and semi-arid environments have been thought to be spectrally indeterminate from other plant cover types during the growing season (Okin et al 2001).

Table 1. Description of the 16 fires studied.

Burn years	Years since last burn as of 2006	Burn season	Type of fire
0	>70		No fire
1937	69	Unknown	Prescribed
1938	68	Unknown	Unknown
1939	67	Unknown	Unknown
1947	59	Unknown	Prescribed
1974	32	Unknown	Wild
1977	29	Spring	Prescribed
1979	27	Summer	Prescribed
1981	25	Summer	Wild
1990	16	Spring	Prescribed
1993	13	Unknown	Prescribed
1995	11	Fall	Prescribed
1998	8	Fall	Prescribed
1999	7	Fall	Prescribed
2002	4	Fall	Prescribed
2003	3	Fall	Prescribed
2005	1	Summer	Prescribed

METHODS

Study Site Description

The study site is the northwest portion of the USSES headquarters (44º14'44"N, 112º12'47"E) rangeland which has been used for spring and fall grazing by the USSES for more than 70 years. The area is dominated by mountain big sagebrush (*Artemisia tridentata* Nutt. ssp. *vaseyana* [Rydb.] Beetle) with subdominant shrubs of antelope bitterbrush (*Purshia tridentata* [Pursh] DC.), spineless horsebrush (*Tetradymia canescens* DC.), and yellow rabbitbrush (*Chrysothamnus viscidiflorus* [Hook.] Nutt.). The understory is cool season grasses and forbs including bluebunch wheatgrass

(*Pseudoroegneria spicata* [Pursh] A. Löve), Sandberg bluegrass (*Poa secunda* J. Presl), and arrowleaf balsamroot (*Balsamorhiza sagittata* [Pursh] Nutt.). Mean annual precipitation at the nearest weather station is 326 mm. The soils are a complex of sandy loam aeolian deposits of varying depth over lava flows.

Portions of the headquarters property have been subjected to prescribed burning for research since 1936 and these prescribed fires as well as wildfires on the property have been documented. The fire boundaries have been digitized and made available for use in Geographic Information System (GIS) software. We selected 16 different fires (Figure 1) that burned between 1937-2005 (Table 1). We also included one site for which there is neither evidence nor record of fire since the establishment of the USSES and where minimum fire effects were expected.

Imagery and Shrub Classification

SPOT5 images have four spectral bands, centered at 0.55 µm (green), 0.65 µm (red), 0.85 µm (near infrared), and 1.67 µm (middle infrared), and have a spatial resolution of 10 m. The SPOT5 imagery we used was acquired on September 27, 2006, georectified, and corrected for atmospheric effects using Idrisi's ATMOSC module. A subset of this image was used for this project. A set of four very large-scale aerial (VLSA) images were used for training and an independent set of eleven VLSA images were used for validation. The VLSA images were acquired on June 16 and 17, 2006. All VLSA images had 2-cm resolution and each VLSA image was approximately 100 m x 70 m in dimension (approximately 70 SPOT5 pixels). The SPOT5 image subset and VLSA images were both projected in Idaho Transverse Mercator, NAD 83 projection and datum. The VLSA imagery were all co-registered to the SPOT5 imagery (root mean squared errors <1m).

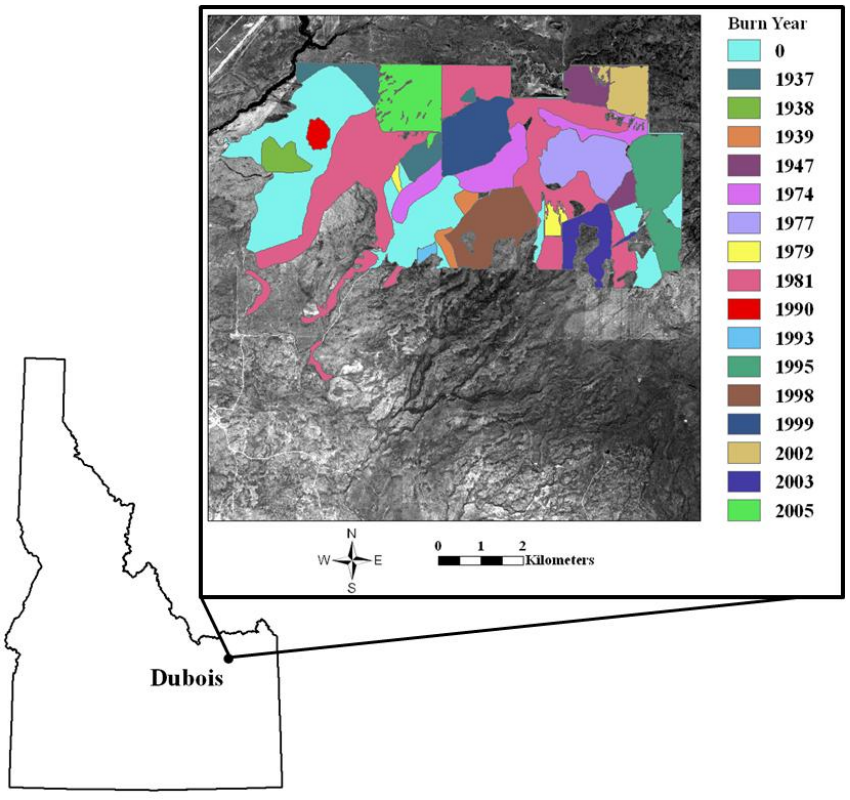

Figure 1. The study site in Idaho showing polygons of mountain big sagebrush ecological sites with fire history defined.

The Matched Filtering Spectral Unmixing technique was used to classify shrubs in the SPOT5 imagery (ENVI Version 4.3, ITT Industries Inc, 2006, Boulder, CO). The Matched Filtering Spectral

Unmixing approach detects a user-defined target cover type in the imagery, while suppressing the spectral signatures of other cover types. Classification training requires identification of pure pixels of the cover class of interest as well as pure pixels that do not have the cover class of interest (i.e., pixels of other cover types). In our case, the target cover type of interest was shrubs, while the other cover types to be suppressed were bare ground and herbaceous cover. Using the four VLSA images, we selected in the SPOT5 imagery 32 pure shrub pixels (shrub endmember) and 30 other pure pixels that clearly had no shrubs (no-shrub endmember), but bare ground and herbaceous cover. A spectral unmixing model was then developed for the SPOT5 image subset to estimate shrub endmember fractions or percent cover of shrubs within each pixel. If constrained to 1, spectral unmixing results produce values ranging 0-1, where 0 indicates 0 percent shrub canopy cover and 1 indicates 100 percent. However, values <0 and >1 are possible when Matched Filtering spectral unmixing technique is used with no constraints. Values <0 and >1 were replaced with 0 and 1, respectively, in our classification model. The accuracy of the resulting classification model was assessed using a linear regression model (Figure 2) and 71 random SPOT5 pixels and 71 windows, 10 m x 10 m in size, placed at the corresponding locations in the eleven VLSA images set aside for validation. The 71 pixel locations were randomly selected using Hawth's tool in ArcMap 9.1. At each random pixel location, an ocular estimate of percent shrub canopy cover was made in the 10 m x 10 m windows placed over the VLSA images. The spectral unmixing model estimates of percent shrub canopy cover within the 71 SPOT5 pixels were extracted from the classified SPOT5 imagery. The two sets of estimates were then correlated in a linear regression model for accuracy assessment.

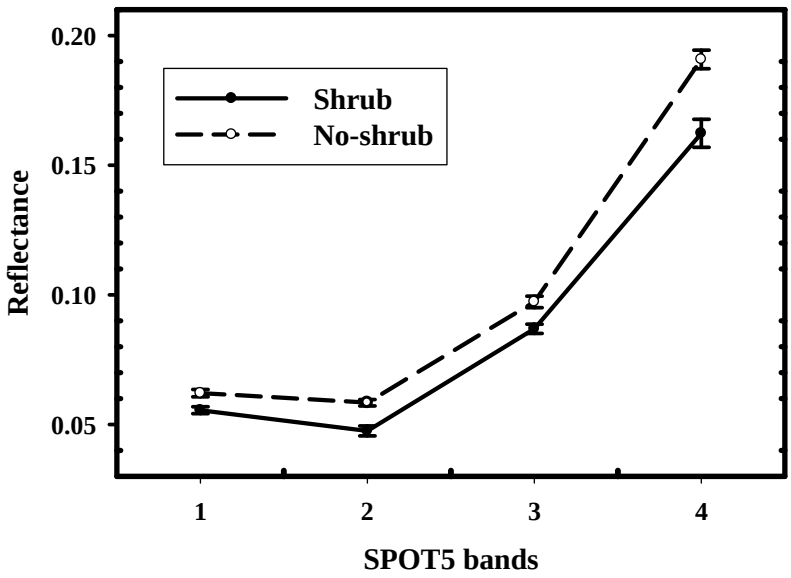

Figure 2. Mean spectral reflectance (+/-1SE) of pure pixels of shrub (n=32) and no-shrub (n=30) endmembers in SPOT5 imagery band 1 (Green), band 2 (Red), band 3 (Near Infrared), and band 4 (Middle Infrared).

Statistical Analysis

The selected 16 fires and one unburned site were represented by 17 sets of polygons. We overlaid the polygons on the classified SPOT5 imagery and generated 100 random points within each polygon to extract the shrub cover estimates from the corresponding 100 pixels in the classified SPOT5 image. The mean of these 100 random pixels were used in the analysis. We used two regression approaches to describe how shrub canopy cover changes with number of years since last burn. The first approach was to model the data with a polynomial regression and the 2nd approach was to model the data with a continuous piecewise regression. For the polynomial regression, we considered linear, quadratic, and cubic terms and selected the lowest order model for which a significant improvement was made by adding the term. The continuous piecewise regression modeled two post-fire phases as follows:

$$\hat{Y} = b_0 + b_1 X_1 + b_2 (X_1 - R) X_2 \quad \textbf{[1]}$$

where $\hat{Y}$ is the predicted shrub canopy cover, X_1 is the number of years since last burn, R is the post-burn year which separates the two phases, X_2 is 1 if $X_1 > R$ and 0 otherwise, b_0 is the predicted shrub cover in the year of a burn, b_1 is the predicted annual increase in shrub cover in phase 1 (recovery), and ($b_1 + b_2$) is the predicted annual increase in shrub cover during phase 2 (recovered). For the piecewise regression, all possible breakpoints (R) were considered and the breakpoint that resulted in a model that fit the data best was selected. The metric used to select the breakpoint for the best piecewise model was the Akaike Information Criterion (AIC) (Akaike 1974). Regardless of the regression approach, we evaluated the normality assumption with the Shapiro-Wilk test on the model residuals and in all cases the data did not warrant rejecting the hypothesis that errors were normally distributed.

RESULTS

Performance of Shrub Classification Model

The spectral reflectance of SPOT5 imagery pixels having shrubs was distinct from pixels that had no shrubs (Figure 2). In all four bands of SPOT5 imagery, the spectral reflectance of pixels having no shrubs was greater than that of pixels having shrubs. The SPOT5 spectral unmixing model performed well when validated using the VLSA image estimates of shrub canopy cover (adjusted $R^2 = 0.91$; $p < 0.0001$; mean error = 0.006 ($\pm$0.10SD) (Figure 3).

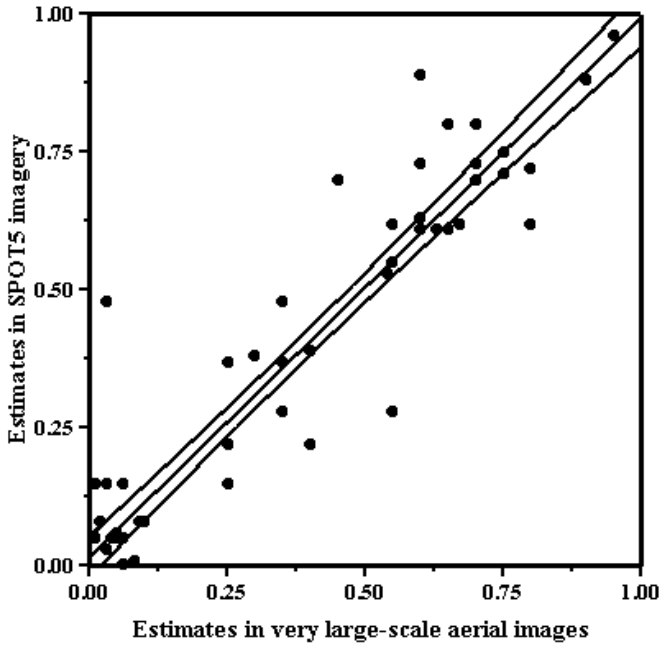

Figure 3. Linear regression of percent shrub cover estimates in SPOT5 and very large-scale aerial images with 95% confidence interval (mean error = 0.006 ($\pm$0.10SD); $R^2 = 0.91$; n = 71).

Post-fire Shrub Canopy Recovery

The 2005 (1 year since last burn) polygon mean was excluded in all analyses performed to describe the relationship between shrub cover and year since last burn, because it was clear that mean shrub cover estimated for this polygon was not a reasonable estimate of the shrub cover.

The piecewise model that best fit the data had a breakpoint at 27 years (Figure 4). The model predicted that shrub cover in the year of burn (year = 0) was 0.47% which was not significantly different from 0. A significant, 1.45 % per year, increase in shrub cover was predicted during phase 1. In phase 2, shrub cover was predicted to decrease by 0.06 % per year, but this estimate was not significantly different from 0. The peak shrub cover at the breakpoint was 38.6 %.

The quadratic model fit the data slightly better than the piecewise regression model on the basis of the AIC and R^2. The R^2 for the best piecewise regression was 0.71, whereas the R^2 for the quadratic model was 0.73. The quadratic regression model had a residual standard error of 8.86 %, whereas the best continuous piecewise regression model had a residual standard error of 9.05 %. The fitted quadratic model was:

$$\hat{Y} = -3.36 + 2.04X - 0.02X^2 \quad \textbf{[2]}$$

where X is the number of years since last burn (Fig 4). This model predicts a negative shrub cover in the year of burn and shrub cover does not become positive until 1.7 years after the burn. Shrub cover increases each year after the burn, but at a decreasing rate, until peak shrub cover of 45 % is reached in year 47. After year 47, shrub cover is predicted to decrease, and is predicted to be less than the cover in year 27 by year 68. In general, the quadratic model and piecewise regression model showed very good agreement in the 0-30 years range after fire and again at around 69 years after fire (Figure 4). The two models had poor agreement between 40 to 50 years after fire where there is no data. The year since last burn was not known for the unburned polygon except that there was no record of fire for the polygon and the first fire records began in 1936, so we arbitrarily assigned it a value of 71 as the number of years since last burn. The model that best fit the data was sensitive to the choice of years since last burn assigned to the unburned polygon. When the value was changed to 91 years, the piecewise regression was the best model. Regardless of the number of years since last burn (>70 years) assigned to the unburned polygon, the fit breakpoint and slopes ahead of and beyond the breakpoint were robust. For the quadratic approach, parameter estimates were not robust to these changes in the years since last burn of the unburned polygons.

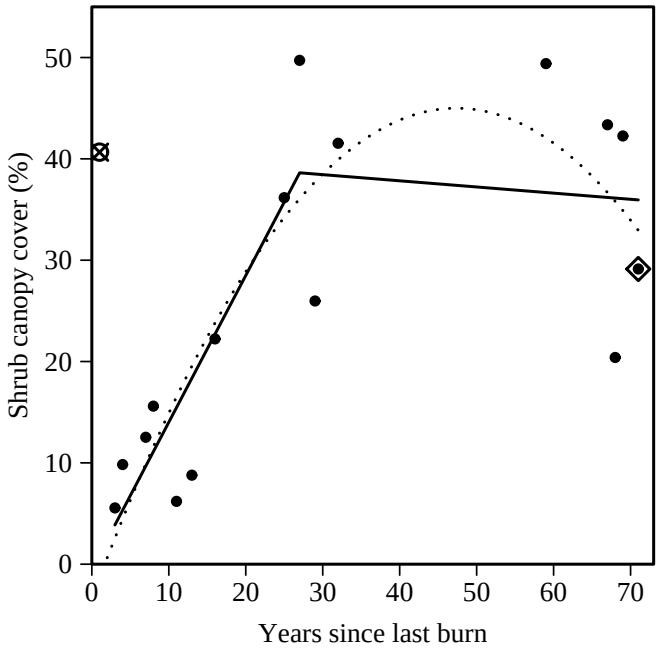

Figure 4. Mean cover estimates from 100 classified SPOT5 pixel samples in each of 17 areas with a different number of years since last burn. The best continuous piecewise regression relationship (solid line) and quadratic relationship (dotted line) are shown. The 1 year since last burn point is shown (⊗) but was not included in the analysis. The >70 years point (• inside the diamond) was plotted at 71 years, but in reality we only know that it is greater than 70.

DISCUSSION

Suitability of SPOT5 and VLSA Imagery for Shrub Classification

The application of SPOT5 imagery in sub-pixel classification of shrubs in sagebrush-steppe communities was successful. The spectral reflectance of shrubs was distinct compared to bare ground and senescent herbaceous cover in the imagery. In all four bands of the SPOT5 imagery, shrub canopy appeared darker than the bright-colored bare ground and herbaceous cover (Fig. 2). We used

a SPOT5 image subset from September because we expected to better distinguish shrubs spectrally in the fall. While herbaceous species are senescent at our study site at this time of the year, shrubs have green leaves year-round. Shrubs produce ephemeral leaves in early spring, which senesce during the growing season, and overwintering leaves later in the growing season, which senesce the following spring (Bilbrough and Richards 1993). Furthermore, sagebrush green vegetation index has been previously shown to be stable between August and October (Chen et al 1998).

Our validation model indicated that the application of spectral mixture analysis in estimating shrub canopy cover within pixels was also successful. The estimated percent shrub canopy cover in the SPOT5 imagery were well correlated to the estimates based on the VLSA imagery. However, there were exceptions. Using visual assessment of the classified SPOT5 imagery and local knowledge, we identified some areas where classification results appeared incorrect. Many pixels with low percent cover of shrubs were classified as having 0 percent shrub cover, when we examined the classified imagery and histogram distribution of pixel values. This pattern supports Okin et al.'s (2001) conclusion that spectral mixture analysis does not provide accurate estimates of vegetation cover, when vegetation cover within a pixel is less than 30 percent. In our observation, shrub cover of less than 15 percent appeared to be commonly classified as having 0 percent shrub cover. Spectral mixture analysis, therefore, might be more appropriate to use in sagebrush-steppe communities, where average shrub cover within pixels is at least greater than 15 percent, if not 30 percent. Furthermore, the estimated shrub canopy percent cover from the SPOT5 imagery within the 2005 fire polygon was unexpectedly high. We suspected this might be due to a high amount of ash on the soil or a high percent cover of velvet lupine (*Lupinus leucophyllus* Dougl. ex Lindl.) in the year following fire. The velvet lupine appeared to have a similar spectral characteristic to sagebrush in the imagery and even appeared similar to sagebrush in the VLSA imagery. Our local familiarity with the site and a field visit to the 2005 fire polygon confirmed this observation.

Availability of the 2-cm-resolution VLSA imagery proved very useful in this study. The VLSA imagery provided accurate and detailed point data that could be used as samples for SPOT5 image training and validation. The results of this successful application of SPOT5 and VLSA imagery in shrub classification have important implications for monitoring and assessment of millions of hectares of sagebrush-steppe in the western United States. Field-based approaches to monitoring post-fire sagebrush canopy cover changes provide highly accurate and valuable results, but they can be labor-intensive, time-consuming, and limited in the spatial extent they can cover. In comparison, the application of remote sensing methods can be more cost-effective and timely due to the large areal extent they cover. Digital imagery also provides opportunities for more robust and comprehensive analysis of change, as the imagery can be easily integrated with other sources of digital data such as maps of fire boundaries and land use.

Post-fire Shrub Canopy Recovery

The best fit regression model considered in this analysis was a quadratic equation, but interpretation of this model made less biological sense than the continuous piecewise regression model. The second order regression model indicated that shrub canopy recovery might continue for 47 years after which shrub cover would decrease. The predicted shrub cover at 47 years after fire would peak at 45 %. The dominant shrub in these sites is mountain big sagebrush and Lesica et al. (2007) reported that mean mountain big sagebrush cover in unburned areas was 28 ± 2 % and that this level of cover was reached by 32 years after fire. Our interpretation of the continuous piecewise regression model that shrub cover was recovered by 27 years after fire was similar to the 32 year mountain big sagebrush recovery period reported by Lesica et al. (2007). Although we didn't consider non-linear regression approaches, Watts and Wambolt (1996) reported that Wyoming big sagebrush cover after fire and other control treatments followed a sigmoid relationship with time. In that study, Wyoming big sagebrush cover had reached >95 % of the expected long-term cover by 30 years. We found the rate of shrub cover increase to be constant during the recovery phase, but Lesica et al. (2007) reported a better fit from a log-linear model where sagebrush cover increased at an increasing rate with time.

Management Implications
Shrub cover in mountain big sagebrush communities is an important attribute for guiding management. This study demonstrated a successful application of SPOT5 imagery, VLSA images, and classification methods in estimating shrub canopy cover. The classification approach described here could enable a more rapid estimate of shrub canopy cover across large areas compared to ground-based measurements, which are both costly and time-consuming. Our results indicated that active shrub canopy recovery might continue for up to 27 years in mountain big sagebrush communities. Using similar methods, post-fire canopy changes in other sagebrush communities can be assessed. Once shrub cover and its changes are estimated, managers can apply post-fire recovery rates to aid their decision making.

ACKNOWLEDGEMENTS

We would like to acknowledge the Idaho Delegation for their assistance in obtaining the grant that supported this work funded through the National Aeronautic and Space Administration (NASA NNG05GB05G).

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