Postfire Recovery of Sagebrush Communities: Assessment Using SPOT-5 and Very Large-Scale Aerial Imagery

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Abstract

Much interest lies in long-term recovery rates of sagebrush communities after fire in the western United States, as sagebrush communities comprise millions of hectares of rangelands and are an important wildlife habitat. Little is known about postfire changes in sagebrush canopy cover over time, especially at a landscape scale. We studied postfire recovery of shrub canopy cover in sagebrush-steppe communities with the use of spectral mixture analysis. Our study included 16 different fires that burned between 1937 and 2005 and one unburned site at the US Sheep Experiment Station in eastern Idaho. Spectral mixture analysis was used with September 2006 Systeme Pour l'Observation de la Terre-5 (SPOT-5) satellite imagery to estimate percent shrub canopy cover within pixels. Very large-scale aerial (VLSA) imagery with 24-mm resolution was used for training and validation. SPOT-5 image 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 ($R^2 = 0.82$; $P < 0.0001$). Additional accuracy assessment of shrub classification produced 85% overall accuracy, 98% user's accuracy, and 78% producer's accuracy. This successful application of spectral mixture analysis has important implications for the monitoring and assessment of sagebrush-steppe communities. With the use of the percent shrub canopy cover estimates from the classified SPOT-5 imagery, we examined shrub canopy recovery rates since different burn years. With the use of linear-plateau regression, it was determined that shrub cover in mountain big sagebrush (*Artemisia tridentata* Nutt. subsp. *vaseyana* [Rydb.] Beetle) communities recovered approximately 27 yr after fire, with an average shrub cover of 38%. These results are consistent with other field-based studies in mountain big sagebrush communities.

Resumen

Mucho interés radica en las tasas de recuperación a largo plazo de las comunidades de triguillo crestado después del fuego en el oeste de los Estados Unidos de America ya que las comunidades de triguillo crestado cubren millones de hectáreas de pastizales y un importante hábitat de vida salvaje. Muy poco se sabe sobre los cambios posteriores a los fuegos en la cobertura de dosel del triguillo crestado a lo largo del tiempo, especialmente a escala del paisaje. Nosotros estudiamos la recuperación posterior al fuego de la cobertura de dosel arbustivo en comunidades de estepas de triguillo crestado usando análisis espectral mixto. Nuestro estudio incluyo 16 diferentes fuegos que quemaron entre 1937 y 2005 y un sitio sin quemar en la Estación Experimental de Oveja en el este de Idaho. Se utilizó el análisis espectral mixto con la imagen satélite de Septiembre 2006 del Sistema para la observación de la tierra (Système Pour l'Observation de la Terre-5; SPOT-5) para estimar el porcentaje de cobertura del dosel arbustivo dentro de los pixeles. Imágenes aéreas de gran escala (VLSA) con 24 mm de resolución fueron utilizadas para el entrenamiento y la validación. La clasificación de la imagen SPOT-5 fue exitosa y las estimaciones del análisis espectral mixto del porcentaje de cobertura de dosel arbustivo estuvieron altamente correlacionadas con las estimaciones de la cobertura del dosel arbustivo en la imagen VLSA ($R^2 = 0.82$; $P < 0.0001$). La evaluación adicional de precisión adicional que se hizo en la clasificación del arbusto produjo 85% en la precisión general, 98% de precisión del usuario y 78% de precisión del productor. Esta aplicación exitosa del análisis espectral mixto tiene importante implicaciones para el monitoreo y la evaluación de las comunidades de estepas de triguillo crestados. Utilizando las estimaciones del por ciento de cobertura arbustiva de la clasificación de la imagen SPOT-5, nosotros examinamos las tasas de recuperaciones de la cobertura del dosel arbustivo en los diferentes años quemados. Utilizando la regresión lineal de Plateau, se determino que la cobertura arbustiva en comunidades montañosas grande de triguillo crestados (*Artemisia tridentata* Nutt. subsp. *vaseyana* [Rydb.] Beetle) se recuperó en aproximadamente 27 años después del fuego, con una cobertura de dosel arbustivo promedio de 38%. Estos resultados son consistentes con otros estudios basados en el campo en comunidades montañosas grande de triguillo crestado.

Key Words: classification accuracy, GIS, mountain big sagebrush, remote sensing, shrub canopy cover, spectral mixture analysis

INTRODUCTION

Sagebrush (*Artemisia* spp.) communities constitute the largest temperate semidesert ecosystem in North America (Anderson and Inouye 2001) and approximately 60 million hectares of rangelands in the western United States (Watts and Wambolt 1996). Sagebrush steppe occupies approximately 450 000 km^2

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of the Columbia and Snake River Plateaus and provides 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), especially over the latter half of the last century, to eradicate sagebrush (Wambolt et al. 2001). However, more recently sagebrush-steppe management objectives and values have changed and land managers are now concerned about postfire 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, there is much interest in the long-term recovery rates of sagebrush communities after fire. However, little is known about postfire changes in sagebrush canopy cover over time (Lesica et al. 2007), especially at a landscape scale.

Wildfires may have had much larger effects on presettlement sagebrush communities than other biotic and abiotic factors (Lesica et al. 2007). Postfire sagebrush recovery rates have been used as an indicator of presettlement fire frequency and to estimate natural fire rotation in sagebrush communities (Baker 2006). Presettlement fire return intervals varied in sagebrush communities between 12 yr and 25 yr on more mesic sites and 200 yr on more xeric sites (Crawford et al. 2004). Presettlement fire return intervals were estimated to be 12–25 yr for mountain big sagebrush (*Artemisia tridentata* Nutt. subsp. *vaseyana* [Rydb.] Beetle) communities, 30–100 years for Wyoming big sagebrush (*Artemisia tridentata* subsp. *wyomingensis* Rydb.) communities, and 100–200 yr for low sagebrush (*Artemisia arbuscula* Nutt.) communities (Crawford et al. 2004). The postsettlement 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).

Postfire recovery of sagebrush canopy has been inconsistent among sites, and the estimated length of time for recovery has varied greatly among different studies. The documented estimates of time required for recovery spans a broad range between 35 yr and 100 yr for mountain big sagebrush and 50–120 yr for Wyoming big sagebrush (Baker 2006). This is partly because postfire sagebrush recovery can be highly variable in space (Crawford et al. 2004) and among species (Lesica et al. 2007). Postfire sagebrush establishment may be dependent on distance to seed source, availability of viable seed reservoir, availability of moisture, and postfire weather conditions (Crawford et al. 2004). Recovery can also depend upon fire intensity and postfire land use treatment such as grazing (Baker 2006). For the purposes of this study, recovery is defined as the time period required for a site to return to the estimated percent shrub canopy cover characteristic of an unburned site. We use canopy cover estimate as an indicator, because this is one variable that can be measured using remote sensing tools. The unburned site(s) in this study area have approximately 25% shrub cover and are dominated by sagebrush.

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 Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data (Kokaly et al. 2003) and National Oceanic and Atmospheric Administration/Advanced Very High Resolution Radiometer 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). In addition, Weber (2006) used multispectral sensors (Quickbird, September 2006 Systeme Pour l'Observation de la Terre-5 [SPOT-5], and Landsat) to evaluate the separability and classification accuracy of various land-cover types in sagebrush-steppe rangelands, including various sagebrush cover assemblages. Spectral mixture analyses have not been used in the cold desert shrub steppe of Idaho to estimate sagebrush canopy cover within pixels with the SPOT-5, although several studies have used spectral mixture analysis methods in warm desert chapparal and sage scrub communities in California with AVIRIS and Landsat images (Roberts et al. 1998; Elmore et al. 2000; Riano et al. 2002; Rogan et al. 2002). Pixels in SPOT-5 imagery are 100 m^2 (10×10 m) in size and thus typically contain a mix of land-cover types, known as "endmembers" (Rencz 1999), such as bare ground, herbaceous plants, and shrubs in sagebrush-steppe communities. This mix within pixels poses a fundamental challenge in classifying pixels, because the spectral characteristics of the mixed pixels do not represent any single land cover type (Roberts et al. 1998; Small 2004).

Spectral mixture analysis techniques have been developed to allow estimates of how much of a pixel is comprised by different endmembers (Adams et al. 1986; Small 2004; Xiao and Moody 2005). Spectral mixture analysis is most suitable when there are a limited number of endmembers (fewer than the number of bands) and when the spectral properties of these endmembers can be assumed to be relatively constant (Small 2004). 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 land cover types.

We studied mountain big sagebrush-steppe communities and their postfire canopy recovery across the portion of the US Sheep Experiment Station's (USSES) Headquarters property that supports mountain big sagebrush, with the use of SPOT-5 satellite imagery and spectral mixture analysis. Our objectives were 1) to estimate percent shrub cover within pixels with the use of spectral mixture analysis with SPOT-5 imagery, and 2) to describe postfire shrub canopy recovery over time with the use of the canopy cover estimates from the classified SPOT-5 imagery. We studied 16 fires that burned in different years between 1937 and 2005 and one site that has not been burned since before 1936 (Table 1). We chose SPOT-5 imagery from 27 September 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-

Table 1. Description of the 16 fires and the unburned site.

Year burned	Years since last burn as of 2006	Burn season	Type of fire
Unburned	> 70	Not applicable	Not applicable
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

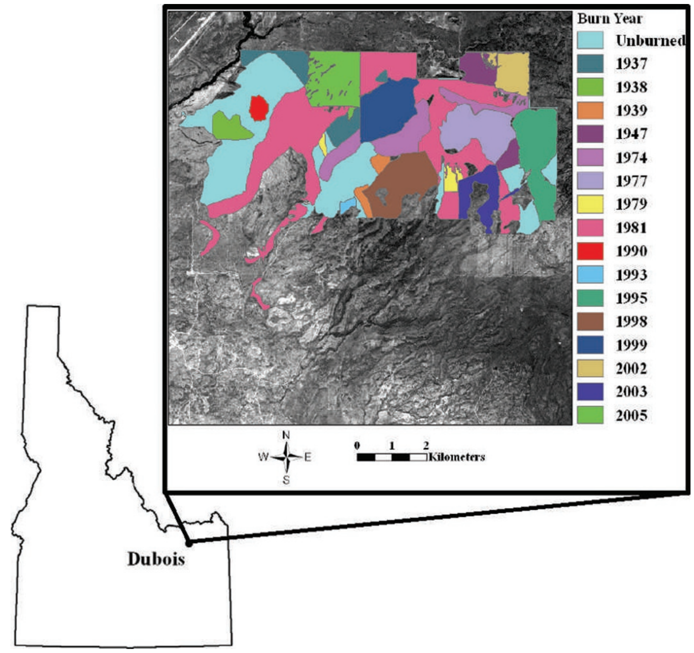

Figure 1. The study site in Idaho and polygons of mountain big sagebrush ecological sites and their fire history.

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 semiarid environments are thought to be spectrally indeterminate from other functional groups, such as herbaceous plants during the growing season (Okin et al. 2001).

Many factors influence shrub recovery following fire. In this study, space has been substituted for time as in many other chronosequence-based sagebrush studies (Wambolt et al. 2001; Crawford et al. 2004 and references therein; Baker 2006 and references therein). Some factors that influence the rate of recovery, such as weather and soil moisture conditions before and after the fire, have varied among sites, but all efforts were made to minimize the confounding effects that could be controlled. For example, the composition of soils and grazing management were the same among sites.

METHODS

Study Site Description

The study sites were confined to soil mapping units in the northwest portion of the USSES headquarters (lat 44°14′44″N, long 112°12′47″E), where the dominant shrub of the historic climax plant community is mountain big sagebrush (Fig. 1). The study sites were limited to these soils to remove variation in postfire recovery rate associated with differences in site potential and to assure that the unburned areas were ecologically similar to the burned areas. The study sites have all been used for moderate to light spring and fall grazing for more than 70 yr. The area is dominated by mountain big sagebrush with subdominant shrubs of antelope bitterbrush (*Purshia tridentata* [Pursh] DC.), spineless horsebrush (*Tetradymia canescens* DC.), and yellow rabbitbrush (*Chrysothamnus viscidiflorus* [Hook.] Nutt.). The herbaceous understory is comprised of cool-season grasses and forbs including bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] A. Löve), Sandberg bluegrass (*Poa secunda* J. Presl), parsnipflower buckwheat (*Eriogonum heracleoides* Nutt.), bushy bird's beak (*Cordylanthus ramosus* Nutt. ex Benth.), and tailcup lupine (*Lupinus caudatus* Kellogg). Mean annual precipitation is approximately 326 mm. The soils on the study sites were a complex of three soil series, all of which are formed in aeolian deposits overlying lava flow bedrock, but vary in depth to bedrock. The soil series are Akbash (fine–loamy, mixed, superactive, frigid Calcic Pachic Argixerolls), Maremma (fine–loamy, mixed, superactive, frigid Calcic Pachic Haploxerolls), and Pyrenees (loamy–skeletal, mixed, superactive, frigid Typic Calcixerolls).

Portions of the headquarters property have been subjected to prescribed burning for research since 1936 and the extent, nature, and timing of these prescribed fires as well as wildfires on the property have been well documented. The fire boundaries have been digitized and made available for use in Geographic Information System software. We selected 16 different fires (Fig. 1) that burned between 1937 and 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

SPOT-5 images have four spectral bands, centered at 0.55 μm (green), 0.65 μm (red), 0.85 μm (near infrared), and 1.67 μm (shortwave infrared), and have a spatial resolution of 10 m. The SPOT-5 imagery we used was acquired on 27 September 2006, georectified, and corrected to top-of-the-atmosphere reflectance values with the use of the Chavez (1996) cos(*t*) model in Idrisi's ATMOSC module. No other conversions or resampling were performed. A subset of this image was used for this project. A set of 4 very large-scale aerial (VLSA) images

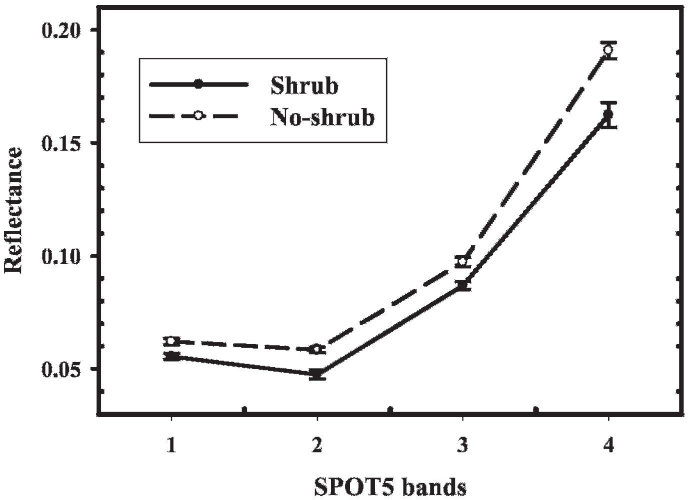

Figure 2. Mean spectral reflectance (± 1 SE) of pure pixels of shrub ($n = 32$) and no shrub ($n = 30$) in SPOT-5 imagery band 1 (Green = 500–590 nm), band 2 (Red = 610–680 nm), band 3 (Near Infrared = 780–890 nm), and band 4 (Shortwave Infrared = 1 580–1 750 nm).

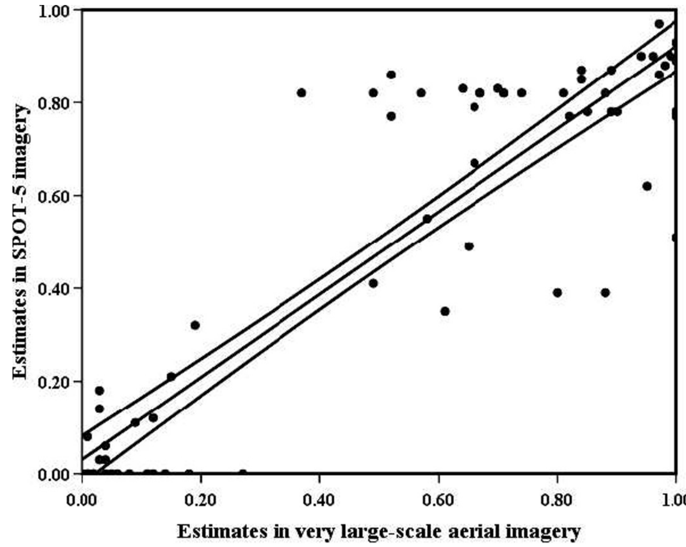

Figure 3. Linear regression of shrub fractional cover estimates in Systeme Pour l'Observation de la Terre-5 and very large-scale aerial images with 95% confidence interval (mean error = 0.021 [± 0.019 SE]; $R^2 = 0.82$; $n = 71$).

were used for training and an independent set of 11 VLSA images were used for validation and accuracy assessment. The VLSA images were acquired on the mornings of 16 and 17 June 2006, from an altitude of 250 m above ground level. The VLSA images were captured with an 11-megapixel digital camera configured with a 100-mm focal length lens (Booth and Cox 2006). The image resolution was approximately 24 mm and each VLSA image covered a ground area that was approximately 100×70 m in dimension (approximately 70 SPOT-5 pixels). For a more complete description of the VLSA imaging system see Booth and Cox (2006). The SPOT-5 image subset and VLSA images were both projected in Idaho Transverse Mercator, North American Datum 83 projection, and datum. The VLSA images were all coregistered to the SPOT-5 imagery (all root-mean-squared errors < 10 m).

A matched filtering spectral mixture analysis technique was used to classify shrubs in the SPOT-5 imagery (ENVI Version 4.3, ITT Industries Inc., 2006, Boulder, CO). The matched filtering spectral mixture analysis 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. In our case, the target cover type of interest was shrubs, and the other cover types to be suppressed were bare ground and herbaceous cover. With the use of four VLSA images, we selected in the SPOT-5 imagery 32 pure shrub pixels for shrub endmember training (Fig. 2). The training pixels had at least > 80% shrub cover. They also had shadow and bare ground present within them, which were not spectrally separated from shrub. In addition, 30 other pure pixels that clearly had no shrubs (no-shrub endmember) but bare ground, herbaceous cover, and shadow were selected (Fig. 2). The pure pixels of each class were then combined to generate spectra for training. The spectra representing the endmembers were also compared with spectra from an Analytical Spectral Devices (ASD) spectroradiometer to understand better the signal received by the SPOT-5 sensor. Many targets, including both sagebrush and bare ground, were characterized with the use of an ASD FieldSpec Pro handheld spectroradiometer during the summer of 2006 to develop a library of spectra characteristic of the sagebrush-steppe vegetation in southeastern Idaho. These spectra were recorded at ± 1 h of solar noon and 15 observations were made for each vegetation class of interest. The data were downloaded and analyzed for this project by first calculating the mean reflectance ($n = 15$) per wavelength band (350–2 500 nm, 251 bands), and then simulating the response at the SPOT-5 satellite by finding the mean reflectance within the same wavelengths occupied by the SPOT-5 sensor (i.e., green = 500–590 nm, red = 610–680 nm, near infrared = 780–890 nm, and shortwave infrared = 1 580–1 750 nm).

A spectral unmixing model was then developed for the SPOT-5 image subset to estimate shrub endmember fractions or percent cover of shrubs within each pixel. If endmember fraction sum is constrained to 1, spectral unmixing results produce values ranging from 0 to 1, where 0 indicates 0% shrub canopy cover and 1 indicates 100% shrub cover. However, values < 0 and > 1 are possible when matched filtering spectral unmixing technique is used with no constraints. Values < 0 and > 1 indicate none-to-low and high percent shrub canopy cover, respectively. These values were replaced with 0 and 1, respectively, to simplify the procedure for management purposes. The accuracy of the resulting classification model was assessed with the use of a linear regression model (Fig. 3). The regression model correlates percent shrub canopy cover estimates from 71 randomly selected (Hawth's tool in ArcMap 9.1) SPOT-5 pixels with estimates from 71 windows, 10×10 m in size, placed at the corresponding locations in the 11 VLSA images set aside for validation and accuracy assessment. Within each 10×10 m window, a point grid method was used to estimate percent shrub canopy cover. A grid with 100 points was drawn over each 10×10 m area of the VLSA in Corel Paint Shop Pro Photo XI software (2006, Corel Corporation, Ottawa, Canada)

Table 2. Shrub and no-shrub classification accuracy in SPOT-5 imagery.

Classification data	Training data		Row total	User's accuracy	Producer's accuracy	Overall accuracy
	Shrub	No shrub				
Shrub	39	1	40	98%	78%	—
No shrub	11	29	40	72%	97%	85%
Column total	50	30	—	—	—	—

and grid points that hit shrub canopy were counted. In addition, the accuracy of the classification model was assessed by calculating user's, producer's, and overall accuracies for shrub and no-shrub classes based on 80 other randomly selected points.

Statistical Analysis

The 16 selected fires and one unburned site were represented by 17 polygons. The polygons were overlaid on the classified SPOT-5 imagery and 100 random points were generated within each polygon (Hawth's tool in ArcMap 9.1) to extract shrub cover estimates from the corresponding 100 pixels in the classified SPOT-5 image. The mean of these 100 random pixels were used in the subsequent analysis. We used a linear-plateau regression approach to describe how shrub canopy cover changes with the number of years since fire (Anderson and Nelson 1975). This approach modeled two postfire phases as follows:

$$\hat{Y}_i = b_0 + b_1[\min(X_i, R)], \quad [1]$$

where $\hat{Y}_i$ is the predicted shrub canopy cover, X_i is the number of years since last burn, R is the postburn year that separates the two phases, 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 the model assumes a constant shrub cover for years since fire greater than R (i.e., the recovered phase). The value of R was selected by iteratively fitting the model described in Equation 1, substituting all observed years since last fire for R and choosing the value that resulted in the smallest residual mean square. A second equation:

$$\hat{Y}_i = b_0 + b_1[\min(X_i, R)] + b_2[\max(X_i, R) - R], \quad [2]$$

was fitted to determine if the shrub cover was changing linearly with increasing number of years since fire greater than R. 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 the Shrub Classification Model

The spectral reflectance of SPOT-5 imagery pixels having shrubs was distinct from pixels that had no shrubs (Fig. 2). In all four bands of SPOT-5 imagery, the spectral reflectance of pixels having no shrubs was significantly greater (P values < 0.05) than that of pixels having shrubs. In the ASD-based spectra, sagebrush reflectance values in the near infrared (NIR) band were greater than those in the shortwave infrared (SWIR) band, which was the expected pattern in the SPOT-5 image spectra. However, the sagebrush reflectance values in the SPOT-5 image spectra were lower in the NIR band compared to the SWIR band. Still, the SPOT-5 spectral unmixing model performed well when validated with a regression model and the VLSA image estimates of shrub canopy cover (adjusted $R^2 = 0.82$; $P < 0.0001$; mean error = 0.021 (± 0.019E; Fig. 3). The SPOT-5 spectral unmixing model also performed well when assessed with the use of a classification error matrix (Table 2). Its overall accuracy was 85%. Producer's accuracies were 78% and 97% for shrub and no-shrub classes, respectively, whereas user's accuracies were 98% and 72% for shrub and no-shrub classes, respectively. Most of the classification errors were found in pixels with low shrub cover.

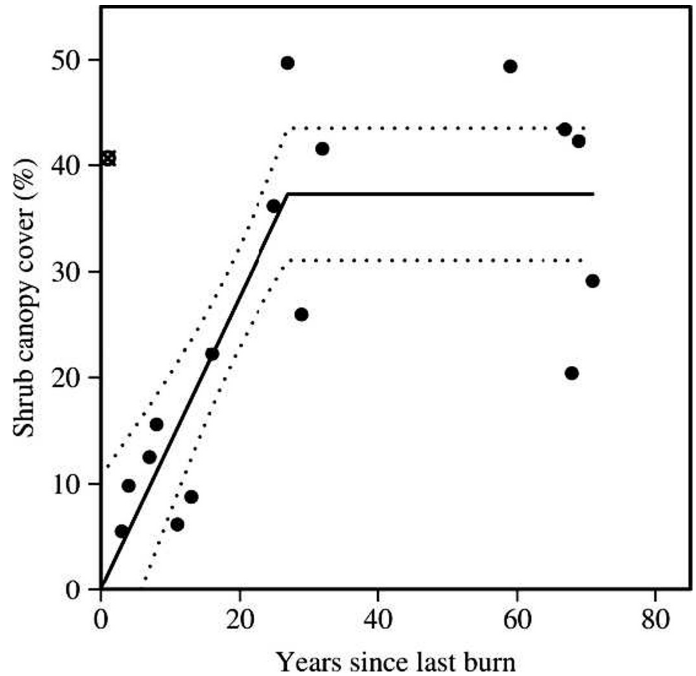

Figure 4. Mean shrub cover estimates from 100 classified Systeme Pour l'Observation de la Terre-5 pixel samples in each of 17 polygons with different numbers of years since fire. The best linear-plateau regression relationship (solid line) with upper and lower 95% confidence intervals (dotted lines) are shown. The 1 yr since fire point is shown (open circle with an x), but was not included in the analysis.

Postfire Shrub Canopy Recovery

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

The linear-plateau model that best fit the data had a breakpoint at 27 yr (Fig. 4). The model predicted that mean shrub cover in the year of burn (year = 0) was 0.11%, which was not significantly different from 0. A significant increase, 1.38% per year, in mean shrub cover was predicted during the recovery phase. Mean shrub cover was predicted from

Equation 2 to decrease by 0.06% per year, but this estimate was not significantly different from 0. The two models (Equations 1 and 2) were not significantly different. Mean shrub cover reached a plateau at 38%.

DISCUSSION

Suitability of SPOT-5 and VLSA Imagery for Shrub Classification

The application of SPOT-5 image in subpixel classification of shrubs in sagebrush-steppe communities was successful at our study site. The spectral reflectance of pixels with shrubs was distinct compared to the pixels of bare ground and senescent herbaceous cover in the imagery. In all four bands of the SPOT-5 image, shrubs and their shadows appeared darker than the bright-colored bare ground and herbaceous cover (Fig. 2), which might be expected because of the bright soil albedo effects and senescent herbaceous cover in the no-shrub endmember that had low moisture content. We used a SPOT-5 image subset from September because we expected that shrubs could be distinguished spectrally better in the fall. Although 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). We note that the spectral separation of shrub versus bare ground and herbaceous cover might not be applicable to other times of year and other regions with different background vegetation. In addition, we note that the shrub endmember at our study site showed greater reflectance values in the SWIR band compared to the NIR band, which was not expected. This might be largely associated with the presence of bare ground in the selected pixels and the substantial woody component of the shrubs, which oftentimes are greater than the photosynthesizing leafy component. The woody component, which also has very little moisture content, would be expected to behave similarly to nonphotosynthetic vegetation. Indeed, our shrub pixel spectra show similar patterns as the nonphotosynthetic vegetation in the Numata et al. (2007) study.

The validation model and classification error matrix indicated that the application of spectral mixture analysis in estimating shrub canopy cover within pixels was successful at our study site. The estimated percent shrub canopy cover in the SPOT-5 image was well correlated to the point grid estimates derived from the VLSA imagery. Shrub and no-shrub classes were classified with adequate accuracy. However, there were exceptions. Using the root-mean-squared error image of the classified SPOT-5 image, the validation regression model, 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% shrub cover when we examined the classified imagery and histogram distribution of pixel values. This pattern supports the Okin et al. (2001) conclusion that spectral mixture analysis does not provide accurate estimates of vegetation cover when vegetation cover within a pixel is less than 30%. In our observation, shrub cover of less than 20% appeared to be commonly classified as having 0% 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 20%, if not 30%. Meanwhile, high shrub percent covers at many locations were classified as having 100% shrub cover. The estimated shrub canopy percent cover from the SPOT-5 imagery within the 2005 fire polygon was unexpectedly high. We suspected this might be due to high percent cover of velvet lupine (*Lupinus leucophyllus* Dougl. ex Lindl.) in this polygon 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. Furthermore, the validation regression results indicate that some of the pixels having 40–65% shrub canopy cover were overestimated. Collectively, our results might indicate that spectral mixture analysis can be more appropriately used to estimate ranges of shrub canopy cover (i.e., categorical classes associated with ranges such as 0–30%, 30–60%, etc.) or to estimate mean shrub canopy cover for an area. Such estimates of ranges or means might be more practical for management purposes. We also used a constraint of 0 (corresponds with 0% shrub canopy) and 1 (corresponds with 100% shrub canopy) in our spectral mixture analysis results, rather than values < 0 and > 1, to make the application of this method simpler.

Availability of the 24-mm-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 SPOT-5 image training, validation, and accuracy assessment. The results of this successful application of SPOT-5 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 postfire sagebrush canopy cover changes provide highly accurate and valuable results. However, field-based methods can be labor-intensive, time-consuming, and limited in the spatial extent they 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.

Postfire Shrub Canopy Recovery

The linear-plateau regression model indicated that the mean recovered shrub canopy cover at our study sites is 38% and it took our sites approximately 27 yr to reach this recovery. Our interpretation of the linear-plateau regression model and recovery period estimate was similar to a recovery period reported by Lesica et al. (2007). Lesica et al. (2007) reported that mean mountain big sagebrush cover in unburned areas was $28 \pm 2\%$ and that this level of cover was reached by 32 yr after fire. Although we did not consider nonlinear 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 yr. 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 SPOT-5 imagery, VLSA images, and classification methods in estimating shrub canopy cover. Such approach 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 yr in mountain big sagebrush communities. With the use of similar methods, postfire canopy changes in other sagebrush communities can be assessed. Once shrub cover and its changes are estimated, managers can apply postfire recovery rates to aid their decision making.

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