Relationship between sagebrush species and structural characteristics and Landsat Thematic Mapper data

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Keywords
Regression models; Remote sensing; Sage grouse; Semi-arid; Transformed bands; Vegetation indices

Nomenclature
Dorn (2001)

Abstract

Questions: Do the spectral patterns recorded by Landsat Thematic Mapper (TM) for various sagebrush species differ from each other? Could ancillary data derived from topographic variables (elevation, slope and aspect) strengthen the relationship between sagebrush and spectral characteristics?

Location: Rawlins, Wyoming, USA.

Methods: Field data on sagebrush species and structural characteristics collected in 2005 were regressed against spectral values and transformed indices derived from Landsat TM data. Step-wise regression methods were used to build (1) a combined model that ignored species and physical differences in sagebrush, and (2) four different models that took those differences in account. Parsimonious models were selected with significant independent variables that accounted for the largest amount of the ground-measured variation in cover.

Results: In the combined model, a subset of Landsat bands and topographic values accounted for 65% ($P < 0.001$) of variance in sagebrush canopy cover. However, when separate regression models were fitted based on species type (big and low sagebrush) and height (for big sagebrush only), Landsat data accounted for 71–85% ($P < 0.001$) of the ground measured variance.

Conclusions: Spectral patterns of sagebrush species and their physical characteristics were distinguishable with Landsat TM data. Transformed indices derived from Landsat data accounted for more variance than the original spectral bands. Future research should focus on testing the relationship between Landsat TM data and sites where sagebrush is present with other vegetation to facilitate landscape and regional mapping of changing sagebrush ecosystems.

Introduction

Sagebrush steppe ecosystems cover large geographic areas worldwide and provide key ecosystem services, including carbon and water cycling, and habitat for endangered species and livestock (Knight 1994; Wambolt et al. 2001; Frisina & Wambolt 2004). These types of semi-arid to arid closed to open shrublands cover over 14% of the terrestrial surface (Loveland et al. 2000). In the western US these ecosystems cover ca. 630,000 km$^2$ (West 1983) and serve as habitat for species such as sage grouse (Centrocercus urophasianus) and livestock (James et al. 2003). Currently, these ecosystems and their services are threatened by exotic species invasion, changing fire regimes, urbanization and natural resource extraction (Knick et al. 2003; Baker 2006). Conservation of these ecosystems is of paramount importance for sustaining the wildlife and environmental and economic services that are dependent on them. Natural resource management agencies and private land managers require updated information on sagebrush distribution by species and structural characteristics. For example, different sagebrush species and subspecies have different impacts on ecosystem function (Kolb & Sperry 1999; Wang et al. 1999). It is also important to monitor these changes occurring in this ecosystem due to natural or anthropogenic factors, since they can impact biodiversity (Brooks et al. 2002). Several studies have quantified the impacts of these threats but have relied on plot-level field studies and experiments of limited spatial extent (Dodd & Lauenroth 1997).

Remotely sensed data are widely used for generating land-cover and vegetation maps, however, remote sensing of shrubland vegetation poses challenges due to the sparse nature of vegetation resulting in a mixed signal response...
from sagebrush, grasses, forbs and bare ground (Tueller 1987; Okin et al. 2001). Estimating or mapping sagebrush ecosystem structural properties with remotely sensed data requires detailed analyses of the relationship between the sagebrush characteristics driving ecosystem properties measured on the ground and the spectral values recorded by satellite sensors (Anderson et al. 1993). Such analyses should take into account the differences in spectral values as a result of terrain and environmental conditions, e.g. soil colour, and should provide insights regarding the potential and limitations of satellite remote data for distinguishing sagebrush species types and certain structural characteristics.

Studies have reported the utility of active remote sensing data such as RADAR (Walker et al. 2007) and LIDAR (Streutker & Glenn 2006; Su & Bork 2007) for mapping vegetation characteristics in arid environments. However, the costs associated with acquiring active remote sensing data for large geographic areas can be high, and complex algorithms and software are required to process these data. The cost can escalate further if data are to be acquired repeatedly for periodic monitoring. The spatial, spectral and temporal resolutions of optical remote sensing data collected from Landsat, SPOT and IRS satellites are attractive since they periodically collect data for large geographic areas. However, the characteristics of data collected by these sensors (spatial, spectral and temporal) are different, therefore combining data from more than one sensor would require careful evaluation of the input data.

Previous studies have tested the utility of Landsat and other moderate resolution satellite data for improving the vegetation mapping in sagebrush steppe ecosystems. These studies have combined different plant life forms (shrubs, grasses and forbs, or different species of sagebrush (Ustin et al. 1986; Ramsey et al. 2004; Sivanpillai & Booth 2008). Ramsey et al. (2004) estimated the total vegetation cover in a south-central Utah rangeland using Landsat data. Sivanpillai & Booth (2008) used a combination of transformed vegetation indices derived from Landsat data and topographic variables for estimating rangeland vegetation in Wyoming.

Fewer studies have mapped or characterized the spectral values recorded by satellite sensors based on individual sagebrush species types. Reiners et al. (1989) determined that spectral discrimination of Wyoming big sagebrush (Artemisia tridentata Nutt. subsp. wyomingensis Beetle & Young) and black sagebrush (Artemisia nova A. Nels.) was poor, based on the Landsat spectral values. Jakubauskas et al. (2001) predicted the big and low sagebrush cover in the Grand Teton National Park (Wyoming, USA) using SPOT satellite data. Spectral bands of the SPOT data accounted for some of the ground-measured variability in the big and low sagebrush cover and bitterbrush (Purshia tridentata (Pursh) DC], an often co-occurring shrub in these ecosystems. The predictive abilities of these models, though significant, were <50% (Jakubauskas et al. 2001). The predictive ability of these models has to be improved before Landsat or similar satellite data are used for mapping sagebrush distribution. The first step towards that would be to test the relationship between the structural characteristics of sagebrush and their spectral values recorded by Landsat. Data on different species of sagebrush and percentage cover must be compared against the spectral values recorded by satellite sensors. These models have to be extended for sites where sagebrush is found with other vegetation, such as grass and forbs.

The goal of this study was to analyse the relationship between field-measured sagebrush characteristics (species type and percentage canopy cover) and remotely sensed data (Landsat – Thematic Mapper) in south-central Wyoming. First, a mixed species model was fitted that combined different species of sagebrush and their physical characteristics (tall and short) for estimating percentage canopy cover using the spectral values of Landsat data. Next, individual models were fitted for each species to test the utility of Landsat data to estimate percentage canopy cover. These results could provide valuable insights for evaluating the utility of Landsat data for mapping different species of sagebrush and their physical characteristics.

Methods

Study area

The study sites were located south and southwest of Rawlins, Wyoming (Fig. 1) and are part of the sagebrush steppe ecosystem (West 1983). Vegetation in this part of Wyoming is dominated by various types of sagebrush, mixed with grasses and forbs – sagebrush steppe (Beetle & Johnson 1982; Knight 1994). Topography of the study area is rugged and elevation at the sample sites ranged between 2012 m and 2199 m a.s.l. Mean monthly temperature varies between 29.6 °C (max) and 10.2 °C (min) in July, and 0.7 °C (max) to −10.8 °C (min) in January. Mean annual precipitation is 24.74 cm; monthly averages vary between 3.78 cm (May) and 1.24 cm (December). Historically, the various species of sagebrush are known to exist in broadly predictable habitats based on soil type, elevation and competition (Knight 1994). For the big sagebrush species, these habitats are further segregated by subspecies genetics (Wang et al. 1997) that broadly correlate with water availability (Kolb & Sperry 1999). Recently, many of these broad relationships have been altered by changes in fire return intervals in big sagebrush ecosystems (Baker 2006), invasive species such as cheatgrass (Miller & Eddleman 2000) and disturbance due to resource extraction (Walston et al. 2009).
Field data

Field data used in this study were collected as part of another project that attempted to map the land cover for the Wyoming Game and Fish Department (WGFD), Rawlins District (Rodemaker & Driese 2006). Data were collected through field surveys consisting of teams of vegetation experts. Crews sampled large homogenous areas (>1 ha) to ensure good association between field and Landsat data. Sites were randomly distributed throughout the project area and information pertaining to vegetation and terrain characteristics was recorded at each site. Experts, who were trained and cross-calibrated, used ocular estimation techniques (Anderson 1986) and assigned values for percentage sagebrush, grass and forb cover. Sagebrush was categorized either as big (subspecies of *Artemisia tridentata* Nutt.) or low, consisting of black or birdfoot (*Artemisia pedatifida*). Preliminary visual analysis of the study sites indicated that the big sagebrush characteristics varied based on its height. Shrub height was assigned as either ≥ 46 cm (tall sagebrush hereafter) or less (short sagebrush hereafter) as a proxy for ‘decadent’ sagebrush (Anderson & Inouye 2001). Tall big sagebrush were likely older and had a complex stand structure consisting of dead branches and twigs, whereas short big sagebrush were likely younger and had less structural variability. Field photos were obtained in four directions, along with the geographic location (Trimble Navigation Ltd, Sunnyvale, CA, USA) of the site centre. From this data set, a subset of sites (*n* = 47) that contained Wyoming big, basin big (*Artemisia tridentata* subsp. *tridentata*), black or birdfoot sagebrush was selected for the present study. These sites had mostly sagebrush and no or very few grasses and forbs.

Using field-recorded data and photos, geographic boundaries of these sites were manually interpreted from 1-m colour infrared photographs obtained from the Wyoming Geographic Information Science Center, and stored as an ArcGIS Shapefile (ESRI, Redlands, CA, USA). This process enabled us to check the quality of field data, including the impact of half-a-pixel (15 m) positional error associated with the Landsat image. This process also screened for anomalies such as rock outcrops or water bodies in each site. Geographic areas of study sites (*n* = 47) ranged between 463 and 33 286 m². Given the fact that

![Fig. 1. Geographic location of the study sites in south-central Wyoming, USA.](image)
this area witnessed minimal human disturbance, it was possible to find large areas of near homogenous sites. Percentage cover values for Wyoming and basin big sagebrush ranged between 10% and 60%, whereas the corresponding values for black and birdfoot sagebrush ranged between 10% and 30%.

Remotely sensed and terrain data
A Landsat image (Path 35 Row 31), acquired on 17 July 2005, was obtained from the US Geological Survey – EROS Data Center, Sioux Falls, SD, USA. This mostly cloud-free Landsat image (30-m resolution) was rectified and geo-referenced to UTM (zone 13) and WGS84 datum, and the RMS error associated with geo-referencing was <1 pixel. The six multispectral bands were imported to a single ERDAS Imagine file (ERDAS Inc., Atlanta, GA, USA). Since we did not compare remotely sensed data from multiple dates or sensors, we used the digital numbers to describe the relationship between the spectral and field data sets. A digital elevation model (DEM) at 30-m spatial pixel resolution was obtained from Wyoming Geographic Information Science Center (WyGISC) to derive slope and aspect values for each pixel. Aspect values were grouped into eight directions.

The geographic boundary of each sampling site (in shapefile format) was overlaid on the Landsat image to assess the geographic agreement between the two data sets, screened for the presence of clouds, and the average spectral values were extracted. Eight transformed bands (Table 1) were computed from these spectral values. Transformed bands are indices that are derived from linear combinations or ratios of Landsat bands and can be related to vegetation conditions, such as vigour and health (Archibald & Scholes 2007). The normalized difference vegetation index (NDVI) is widely used for mapping vegetation vigour based on the information content in the infrared and red bands (Aragon & Oesterheld 2008), while mid-infrared values or their derived indices are used for distinguishing vegetation types and status based on leaf water content (Trombetti et al. 2008). Mean elevation, slope and aspect values were extracted from the DEM since these variables influence the establishment and growth of vegetation through temperature, soil moisture content and the amount of sunlight received. Aspect (0–360°) values were grouped in eight categories based on directions, such as north, northeast, etc. All derived variables (slope and aspect) were combined with the satellite spectral values and field data such as percentage cover and shrub height.

Relating sagebrush characteristics and Landsat spectral values
Percentage sagebrush cover (dependent variable) was regressed against Landsat spectral bands, transformed indices and terrain characteristics data as independent variables, first using simple linear regression of each independent variable (Appendix S1) and then using step-wise regression modelling techniques. Regression algorithm was selected for describing the association between the field and image data (Montgomery & Peck 1992). Bork et al. (1999) reported that multiple regression models had advantages over other modelling methods for predicting abundant cover components. An appropriate model for each instance was selected based on overall significance of the model (P < 0.05) and individual significance of each independent variable (P < 0.05). First, we tested the predictive ability of satellite and terrain data to estimate overall sagebrush cover (Fig. 2). Percentage sagebrush cover values were regressed against (1) Landsat multispectral data, (2) Landsat multi-spectral and terrain (elevation, slope and aspect) data, (3) Landsat transformed bands (Table 1), and (4) Landsat transformed bands and terrain data. This resulted in four regression

Table 1. Transformed bands and indices derived from Landsat (TM) data that were used in this study.

<table>
<thead>
<tr>
<th>Name</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple ratio vegetation index (SR); TM4/TM3</td>
<td>Tasseled cap brightness: 0.44 TM1 + 0.54 TM2 + 0.46 TM4 + 0.07 TM5 + 0.01 TM7</td>
</tr>
<tr>
<td>Mid-IR/Red reflectance index (MIRi); TM7 – TM3/TM7 + TM3</td>
<td>Tasseled cap greenness: –0.22 TM1 – 0.20 TM2 – 0.35 TM3 + 0.88 TM4 – 0.04 TM5 – 0.05 TM7</td>
</tr>
<tr>
<td>Normalized difference vegetation index (NDVI); TM4 – TM3/TM4 + TM3</td>
<td>Tasseled cap wetness: 0.42 TM1 + 0.18 TM2 – 0.36 TM3 – 0.05 TM4 – 0.75 TM5 – 0.31 TM7</td>
</tr>
<tr>
<td>Vegetation condition index (VCI); TM7/TM4</td>
<td>Tasseled cap wetness: 0.42 TM1 + 0.18 TM2 – 0.36 TM3 – 0.05 TM4 – 0.75 TM5 – 0.31 TM7</td>
</tr>
</tbody>
</table>

Fig. 2. Conceptual diagram outlining the different step-wise regression models that were built to evaluate the predictive ability of Landsat and terrain data for estimating sagebrush cover based on species and height differences.
models, and the parsimonious model that accounted for most of the variance ($R^2$ value) and had the best residual analyses was selected. Step-wise regression analyses were performed in Minitab version 13 (Minitab Inc., State College, PA, USA).

Results

Combined model for all sagebrush

The combined model ($n = 47$) did not take into account the differences in sagebrush species type or height. Landsat band 1 (TM1; $P < 0.01$), band 3 (TM3; $P < 0.01$), band 5 (TM5; $P < 0.05$) and band 7 (TM7; $P < 0.01$) accounted for 64% ($F = 21$, $P < 0.001$) of the variation in sagebrush cover. When ancillary data were combined with spectral data, elevation values (Table 2), and Landsat TM5 and TM7 were included, $P$-values derived from the regression model that combined all sagebrush types irrespective of their species or height.

Modelling low vs big sagebrush cover

The regression model consisting of transformed indices SR ($P < 0.01$), VCI ($P < 0.01$) and MIRI ($P < 0.01$) accounted for 85% ($F = 24$, $P < 0.001$) of the measured variance for the low (black and birdfoot) sagebrush ($n = 13$) (Table 3). The regression between measured and predicted values from the model selected for low sagebrush yielded a $R^2$ of 89% (slope = 0.89 and intercept = 1.9).

The regression model for big (Wyoming and Basin) sagebrush consisting of Landsat TM1 ($P < 0.01$), TM3 ($P < 0.01$), TM5 ($P < 0.01$) and TM7 ($P < 0.01$) accounted for 55% ($F = 11$ and $P < 0.001$) of the variance ($n = 34$). When ancillary data were combined with spectral data, Landsat TM1 ($P < 0.01$) and TM3 ($P < 0.01$) and elevation values ($P < 0.05$) accounted for 57% ($F = 16$, $P < 0.001$) of the variance (Table 2), and Landsat TM5 and TM7 were not significant. This result indicates that the spectral inter-

![Fig. 3. Plot of the ground-measured sagebrush cover and predicted values derived from the regression model that combined all sagebrush types irrespective of their species or height.](image)

Modelling short vs tall big sagebrush

When two different models were built for short ($n = 18$) and tall ($n = 16$) big sagebrush types, the relationship between Landsat spectral and terrain data and ground-measured percentage cover values improved in comparison to a single model for all big sagebrush. For the big sagebrush that were short (<46 cm), a model consisting of transformed bands MR ($P < 0.05$), SR ($P < 0.05$), VCI ($P < 0.05$) and MIRI ($P < 0.01$) and elevation ($P < 0.05$) accounted for 71% ($F = 10$, $P < 0.001$) of the measured variance. A plot of the measured and predicted values from this model yielded a $R^2$ of 79% (slope = 0.79 and intercept = 3.46). Another regression model consisting of transformed indices VCI ($P < 0.01$), MIRI ($P < 0.01$) and tasseled cap brightness ($P < 0.01$), greenness ($P < 0.01$) and wetness ($P < 0.05$) accounted for 80% ($F = 13$, $P < 0.001$) of the measured variance in the big sagebrush that were tall ($\geq 46$ cm; Table 3). The regression between measured and predicted values from this model yielded a $R^2$ of 86% (slope = 0.86 and intercept = 3.81).

Table 2. Relationship between Landsat spectral bands and sagebrush characteristics, such as shrub height and species type.

<table>
<thead>
<tr>
<th>Model</th>
<th>Independent variables</th>
<th>$F$-value</th>
<th>Adjusted $R^2$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Constant Elevation</td>
<td>TM1</td>
<td>TM2</td>
</tr>
<tr>
<td>All sagebrush</td>
<td>-139</td>
<td>0.07</td>
<td>1.45</td>
</tr>
<tr>
<td>Big sagebrush*</td>
<td>-158</td>
<td>0.08</td>
<td>1.73</td>
</tr>
</tbody>
</table>

TM1: Blue; TM2: Green; TM3: Red; TM4: Near-infrared; TM5: Near-infrared; TM7: Shortwave infrared.

*Big sagebrush includes both tall ($\geq 46$ cm) and short (<46 cm) shrubs.

***$P < 0.001$. 

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Models based on sagebrush species and height

Figure 4 compares the relationship between field-measured sagebrush cover and the corresponding values predicted from the three different regression models that were based on differences in species type and shrub height. Plot of the measured and predicted values from these models yielded a $R^2$ of 89% (slope = 0.86 and intercept = 2.06). In absolute terms, the $R^2$ value increased by 22% (from 67% to 89%) when three separate models were built based on sagebrush species and height.

Landsat spectral and transformed bands

Transformed Landsat bands accounted for more variation in percentage cover when sagebrush were separated based on species type and shrub height (Table 1). Inclusion of transformed bands derived from Landsat TM7 (mid-infrared), TM4 (near-infrared) and TM3 (red) in all three regression models demonstrates the importance of the infrared and red bands for vegetation characterization. Raw Landsat bands were better predictors of shrub cover when species type and height were ignored, whereas the transformed bands were better predictors when these characteristics were incorporated into the models. Elevation values improved the relationship between the spectral values and big (Wyoming and Basin) sagebrush ($R^2 = 71\%$) that were also short (<46 cm). Models without elevation values accounted for only 53% (original Landsat bands) and 49% (transformed Landsat bands) of the variance in the big sagebrush canopy cover. Inclusion of elevation values did not improve the relationship between the Landsat spectral values and in the low sagebrush and big sagebrush that were also tall (>46 cm). In comparison, the adjusted $R^2$ values of the simple linear models were less than the adjusted $R^2$ values associated with the multiple regression models.

Discussion

Spectral values recorded by Landsat TM bands varied based on sagebrush species type and their physical characteristics (tall vs short) for big sagebrush. In other words, separate models are necessary for adequately characterizing sagebrush using Landsat data. The relationship between transformed Landsat spectral values and sagebrush characteristics improved significantly when differences in species type and shrub height were taken into account. Spectral interaction of sagebrush varied based on their species type and height, and incorporating this information could improve sagebrush characterization using moderate resolution satellite data. When different vegetation types were combined as total vegetation cover, Landsat spectral and elevation values accounted for 65% of the variability in shrub cover. However, Landsat spectral bands 1, 3, 5 and 7 accounted for 64% of the ground-measured variability, demonstrating the value of moderate resolution satellite data for mapping sagebrush cover. Results obtained in this study demonstrate that Landsat spectral values vary based on sagebrush species type and structural (percentage cover and height) characteristics. This information can be used for future mapping of sagebrush cover using spectral unmixing techniques, where spectral values of different

### Table 3. Relationship between Landsat transformed indices and sagebrush characteristics, such as shrub height and species type.

<table>
<thead>
<tr>
<th>Model</th>
<th>Independent variables</th>
<th>$F$-value</th>
<th>Adjusted $R^2$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low sagebrush</td>
<td>Constant Elevation SR MR MIRI NDVI TCB TCW VCI</td>
<td>$-1588$</td>
<td>$85$</td>
</tr>
<tr>
<td>Big and tall sagebrush*</td>
<td>3201 -1608 3636</td>
<td>$-603$</td>
<td>$80$</td>
</tr>
<tr>
<td>Big and short sagebrush*</td>
<td>548 1098 -1.89 -9.5 -3.13</td>
<td>$-1965$</td>
<td>$71$</td>
</tr>
<tr>
<td>Low sagebrush</td>
<td>4141 0.11 2335 -550 -5181</td>
<td>$1608$</td>
<td>$71$</td>
</tr>
</tbody>
</table>

SR, simple ratio vegetation index; MIRI, Mid-IR/Red reflectance index; MR, Mid-IRRatio; NDVI, normalized difference vegetation index; TCB, tasseled cap brightness; TCG, tasseled cap greenness; TCW, tasseled cap wetness; VCI, vegetation condition index.

*Big and tall sagebrush included shrubs that were $>46$ cm, and Big and short sagebrush included shrubs that were $<46$ cm.

***$P<0.001$. 

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stands were leaf area indices increased predictably with age until the Ewers & Pendall (2008) found that sagebrush cover and the threshold value (46 cm) could be a surrogate for age. Sagebrush height is not available. It is conceivable that that young and old might be an alternative if information on old sagebrush stands, and separating big sagebrush sites as cover and leaf area would alter the spectral interaction of which changes the relationship between plant cover and increased amounts of dead or dying branches and shrubs, complex structure. Old sagebrush stands often have dead material, whereas older stands have relatively more dead material, whereas older stands have relatively more

Results reported here demonstrate that precise models for estimating percentage sagebrush cover can be developed using the spectral interaction patterns recorded by Landsat. Information content in mid-infrared (TM7) was essential for estimating sagebrush cover, since transformed bands derived from the mid-infrared band were included in all three regression models (Table 1). Landsat TM7 is used for deriving equivalent water thickness that contributes to spectral absorption at the leaf level (Trombetti et al. 2008). Results obtained in this study highlight the importance of mid-infrared bands for future sagebrush mapping. An earlier study aimed at mapping sagebrush categories as low, medium and high also reported the importance of mid-infrared bands (Sivanpillai et al. 2009). Most other moderate resolution satellites do not collect information in this spectral region, which might limit their ability for deriving such precise information. Jakubauskas et al. (2001) reported that combinations of near-infrared, red and green spectral bands of SPOT satellite accounted for 26%, 44% and 46%, respectively, of the variability in big sagebrush, low sagebrush and bitterbrush cover. These results also highlight the fact that spectral information (or resolution) is also important for characterizing vegetation in sagebrush steppe ecosystems. Imagery collected by the Advanced Land Imager contains additional spectral bands (Lobell & Asner 2003), which might be valuable for estimating sagebrush cover.

Spectral values of sagebrush were not influenced by variations in slope and aspect of the study sites. These somewhat unexpected results may be due to several factors. One could be due to errors in the DEM used for deriving aspect and slope (van Neil et al. 2004; Bader & Ruijten 2008). The scale of 30 m may not be optimal for some small-scale variation in sagebrush ecosystems, such as the known response to snow depth (Kwon et al. 2008), which will vary due to snow drifting. However, our study focused on larger spatial patterns so the scale of 30 m is appropriate for our study, as has been found previously (Ramsey et al. 2004). Methods to overcome or minimize such errors could be to measure these variables directly at each site, or by deriving these values from newer DEM models derived from the Shuttle RADAR Topographic Mission (Prates-Clark et al. 2008). Other factors could be that the sampling scheme employed in this study did not adequately capture the variability in these physiographic variables, or that sagebrush does not respond to them. However, we consider the latter extremely unlikely in these semi-arid ecosystems (Burke et al. 1989).

Combining different species of sagebrush under a single shrub category or ignoring the differences in height for certain sagebrush species will result in less precise information, which might limit the ability to scale plot-level ecosystem processes or services to regional scale and beyond through future sagebrush mapping. In future, procedures used in this study can be extended to sites where different types of sagebrush are found with other vegetation, such as forbs and grasses, prior to extending them other semi-arid shrublands. Accounting for differences in the interaction of vegetation types with electromagnetic radiation would enable more precise spatial characterization of vegetation in sagebrush steppe ecosystems, enabling ecologists and land managers to gain insights into the vegetation distribution in these ecosystems.

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Supporting Information

Additional supporting information may be found in the online version of this article:

**Appendix S1.** Results obtained when the shrub cover, as dependent variable, was regressed against each (a) Landsat Thematic Mapper bands and (b) transformed Landsat Thematic Mapper bands as independent variables.

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