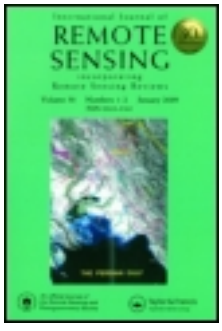


International Journal of Remote Sensing
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tres20

# Assessing long-term variations in sagebrush habitat - characterization of spatial extents and distribution patterns using multi-temporal satellite remote-sensing data

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Available online: 18 Oct 2011

*International Journal of Remote Sensing*
iFirst, 2011, 1–25

# Assessing long-term variations in sagebrush habitat – characterization of spatial extents and distribution patterns using multi-temporal satellite remote-sensing data

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(*Received 9 June 2010; in final form 9 May 2011*)



An approach that can generate sagebrush habitat change estimates for monitoring large-area sagebrush ecosystems has been developed and tested in southwestern Wyoming, USA. This prototype method uses a satellite-based image change detection algorithm and regression models to estimate sub-pixel percentage cover for five sagebrush habitat components: bare ground, herbaceous, litter, sagebrush and shrub. Landsat images from three different months in 1988, 1996 and 2006 were selected to identify potential landscape change during these time periods using change vector (CV) analysis incorporated with an image normalization algorithm. Regression tree (RT) models were used to estimate percentage cover for five components on all change areas identified in 1988 and 1996, using unchanged 2006 baseline data as training for both estimates. Over the entire study area (24 950 km$^2$), a net increase of 98.83 km$^2$, or 0.7%, for bare ground was measured between 1988 and 2006. Over the same period, the other four components had net losses of 20.17 km$^2$, or 0.6%, for herbaceous vegetation; 30.16 km$^2$, or 0.7%, for litter; 32.81 km$^2$, or 1.5%, for sagebrush; and 33.34 km$^2$, or 1.2%, for shrubs. The overall accuracy for shrub vegetation change between 1988 and 2006 was 89.56%. Change patterns within sagebrush habitat components differ spatially and quantitatively from each other, potentially indicating unique responses by these components to disturbances imposed upon them.

## 1. Introduction

Sagebrush shrublands provide critical habitats for many wildlife species (Connelly *et al*. 2000, Davies *et al*. 2006) and play a vital role in semi-arid ecosystems in the western USA by affecting biodiversity, water resources and regional climate conditions (Berlow *et al*. 2003, Perfors *et al*. 2003). The extent and quality of sagebrush ecosystems have dramatically decreased since European settlement, and the remaining sagebrush is undergoing further fragmentation and degradation (Berlow *et al*. 2002, Connelly *et al*. 2004, Schroeder *et al*. 2004), leading to the decline of many sagebrush-dependent species. For example, sage grouse have experienced an approximately 2%

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*International Journal of Remote Sensing*
ISSN 0143-1161 print/ISSN 1366-5901 online © 2011 Taylor & Francis
http://www.tandf.co.uk/journals
http://dx.doi.org/10.1080/01431161.2011.605085

overall annual population decline since 1965 (Connelly *et al*. 2004). Invasive species, fire, grazing, oil and gas development, climate change and other factors continue to degrade sagebrush ecosystems (Knick *et al*. 2003, Aldridge *et al*. 2008). Developing adequate scientific knowledge to understand, analyse, manage and monitor these large landscapes is a great challenge. Natural gas energy extraction activities in western Wyoming have significantly impacted sagebrush communities in the region (Sawyer *et al*. 2006, Walston *et al*. 2009) and will continue to have impacts as development increases. Understanding historical trends of change areas across sagebrush ecosystems is critical to modelling and monitoring the magnitude of disturbance trends and impacts to ecosystem processes. These processes are the focus of land managers who need trend information on current and historical distributions of sagebrush components to properly manage habitats of key species such as sage grouse (*Centrocercus* spp.) within an adaptive management framework (Aldridge *et al*. 2004). Furthermore, spatially explicit measures of sagebrush components could potentially be directly related to landscape-scale process models that include and/or predict budgets of water, biogeochemistry and energy (Smith *et al*. 2008), improving understanding of feedback loops among vegetation characteristics, biogeochemical fluxes, carbon storage and climate variation.

Rigorous spatial tools and models that accurately assess sagebrush habitats consistently over large areas, but that retain local detail, are still unavailable (Connelly *et al*. 2004, Homer *et al*. 2009, 2010). Given the vast geographic extent of sagebrush ecosystems, a cost-effective approach is needed. Remote-sensing information has been widely used for monitoring vegetation conditions and variations in other ecosystems. Remotely sensed imagery can provide spatially explicit, continuous and extensive data on the composition and condition of sagebrush ecosystems (Ramsey *et al*. 2004, Stow *et al*. 2008). Medium-resolution remote-sensing data sources, that is 30 m Landsat imagery, have been employed to characterize the spatial distribution of sagebrush ecosystems (Graetz and Gentle 1982, Tueller 1987, Homer *et al*. 1993, Seefeldt and Booth 2004, Underwood *et al*. 2007). Maps of sagebrush canopy cover (as a continuous variable) or categories of sagebrush vegetation according to sagebrush canopy density have been developed using Landsat-scale remotely sensed information with direct application for management activities (Homer *et al*. 2009, Sivanpillai *et al*. 2009).

However, challenges exist for characterizing sagebrush habitat components using remotely sensed data because of the semi-arid nature of these ecosystems. Conditions of sparse vegetation, large amounts of bare ground and high albedo usually make accurate classification difficult. On the other hand, recent advances in remote-sensing technology, methods and analytical approaches provide new opportunities to more successfully characterize vegetation structure attributes from individual plant to multiple species (Smith *et al*. 2008, Waser *et al*. 2008) and derive vegetation structure across a range of local and regional scales. Homer *et al*. (2009, 2010) used multiple remote-sensing images and field measurements to stratify sagebrush habitat into eight components as continuous cover fields across Wyoming: four primary components (bare ground, herbaceous, litter and shrub) and four shrub secondary components (sagebrush, big sagebrush, Wyoming sagebrush and shrub height). This research was designed to develop a rigorous regional sagebrush habitat characterization and monitoring framework to provide products for multiple applications across large spatial areas while retaining local detail.

Remote-sensing data can also provide spatially explicit, continuous and extensive data on the composition and condition of habitats over time, a key requirement for assessing and monitoring the health of these habitats because they link to wildlife populations (Stow *et al*. 2008). A time series of repeated remote-sensing data records from the early 1970s to the present are available and represent valuable sources to understand decadal vegetation shifts that can accompany land-use and land-cover change, either from direct (i.e. removal of habitat due to cultivation or energy development) or indirect (i.e. vegetation composition or quality shifts due to climate change) consequences. To monitor long-term variation in sagebrush ecosystems, time sequential remote-sensing imagery can be used to map baseline characteristics of sagebrush and then monitor changes over time. The potential of remote-sensing-based monitoring of sagebrush ecosystems has been explored in several studies (Longmire and Stow 2001, Ramsey *et al*. 2004, Stow *et al*. 2004, Witztum and Stow 2004). For example, Stow *et al*. (2008) used image segmentation and classification processes applied to the bitemporal layer of airborne multispectral imagery to determine fine-scale shrub change (a net 5% loss) for 1998–2005 in Southern California. Ramsey *et al*. (2004) used three dates of Landsat images to develop predictions for percentage cover of vegetation (total cover) and bare ground for a large area. Their result demonstrated that medium-resolution remotely sensed imagery can monitor vegetation cover on semi-arid rangelands. Sivanpillai *et al*. (2009) further demonstrated that Landsat spectral bands can be used to distinguish sagebrush vegetation into broad categories through stepwise regression analysis. However, results of change monitoring for sagebrush ecosystems for relatively short time intervals (one to several years) will be unable to detect persistent slow landscape change manifested over many years. Thus, decadal monitoring is necessary for assessing sagebrush ecosystem variations induced by natural and anthropogenic disturbances.

The objective of this study was to develop a monitoring prototype using medium-resolution remote-sensing data to assess long-term variations of sagebrush habitats over a large area. Methods were developed to test the ability of these approaches to detect changes in sagebrush habitat components for the periods 1988–1996 and 1996–2006 in southwestern Wyoming. Percentage cover of sagebrush habitat components including bare ground, herbaceous, litter, shrub and sagebrush was developed using 2006 estimations (Homer *et al*. 2009) derived from multispectral and multisource imagery and representing baseline conditions for this change analysis. Algorithms designed and implemented for the US Geological Survey (USGS) National Land Cover Database (NLCD) 2006 updating method (Xian *et al*. 2009, Xian and Homer 2010) were applied for change detection across five habitat components. Changes between 1988 and 2006 were investigated to reveal relevant component patterns and provide insight on change trajectories and drivers.

Overall, we used the approach in an attempt to (1) determine whether medium-resolution satellite imagery (e.g. 30 m Landsat images) combined with other ancillary data sets can be used to accurately reveal long-term sagebrush habitat change over a large area and to (2) quantify long-term sagebrush habitat change over large spatial extents to understand the patterns of long-term change. The purpose of this article is to summarize sagebrush habitat distribution and change. The results will be used for further causality analysis and will be presented in a subsequent article.

## 2. Data and methods

### 2.1 *Study area*

The study area, which encompasses one Landsat scene (path 37 and row 31) with a spatial extent of approximately 30 500 km$^2$, is located primarily in southwestern Wyoming, but it also includes small portions of northeastern Utah and northwestern Colorado (figure 1). This area includes a wide range of sagebrush habitats and is subject to a variety of natural and anthropogenic disturbances.

The terrain within the study area ranges from 1600 to 3500 m in elevation with many steep slopes. The climate of the area is typical of semi-arid and high plains ecosystems with mean maximum temperatures in July ranging between 29.5°C and 35.0°C and mean minimum temperatures in January ranging from –15.0°C to –12.0°C. Precipitation varies a great deal across the study area. The period of maximum precipitation occurs in the spring and early summer and is greater over the mountain ranges at higher elevations, but elevation alone is not the predominant influence. For most of the northwestern mountain portion, where the elevation ranges from 1980 to 2600 m, annual precipitation varies from 177 to 250 mm. At lower elevations over the northeastern portion and along the eastern border, where elevations are mostly in the range from 1200 to 1670 m, annual mean precipitation varies from 304 to 404 mm. The relatively dry portion is a high plateau nearly surrounded by mountain ranges. Our research focused on lower elevations of the study area below 2377 m, dominated by sagebrush shrubland and intermingled with salt desert shrubland, and grassland. Areas of forestland, water, agricultural land and urban areas were excluded from analysis and not counted in the change comparisons. Thus, the study area that contains sagebrush habitat components below 2377 m is approximately 24 950 km$^2$.

### 2.2 *Baseline sagebrush habitat characterization in 2006*

The spatial distributions of five components of sagebrush habitat including bare ground, herbaceous, litter, sagebrush and shrub in 2006 were estimated in southwest Wyoming, USA, using a new method that includes field measurements and 2.4 m QuickBird (QB) imagery to predict each component with Landsat 30 m imagery using regression tree (RT) models (see Homer *et al*. (2010) for details). Briefly, this approach used eight QB images (8 km × 8 km) from 2006 and 2007 representing a reasonable sample of landscape diversity. Second, QB imagery was segmented into image objects (polygon patches) using Definiens eCognition software to identify sites for potential field sampling using a hierarchical and regional merging technique based on spectral colour and shape homogeneity. Segmented patches were then intersected with an unsupervised clustering from the QB imagery to identify the majority cluster class in each patch. A total of 60 field sample patches for each QB image were selected using restrictions that included the size of the patch (>5000 m$^2$), adjacency to roads (within 1 km), land ownership access, maximizing spatial distribution on the image and ensuring equal distribution across polygon majority classes. Third, vegetation characteristics were sampled at seven 1 m$^2$ quadrats along each of two 30 m transects for 14 quadrats per sample polygon. The mean value for each of the variables of interest was calculated across all fourteen 1 m quadrats within a polygon. These values were assigned to all pixels occurring within the transect sampling area for each polygon. Fourth, the proportion of each of the five components on a per-pixel basis occurring within all QB images was estimated independently using the RT algorithm, Cubist, which is similar

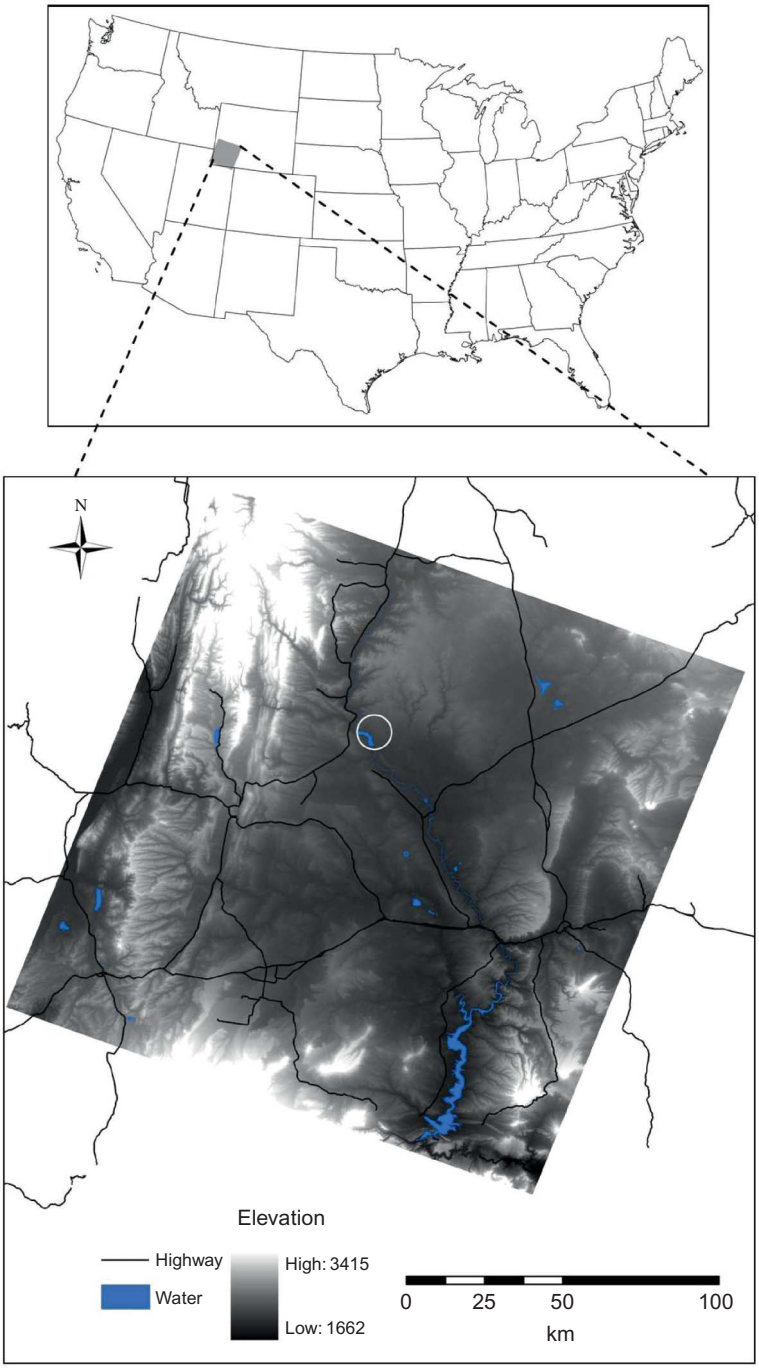


Figure 1. The extent of the study area represented with a digital elevation image. The elevation values are in metres. The circled location is the Fontenelle Reservoir.

to the NLCD 2001 percentage tree canopy calculation (Homer *et al*. 2004). Fifth, component predictions from all eight QB scenes were rescaled from 2.4 to 30 m using the nearest neighbour algorithm to provide training data for Landsat predictions. Finally, RT models were created to estimate sagebrush components using QB training data on 2006 Landsat imagery and ancillary data sets. The average root mean square error for all five components was 9.28% (Homer *et al*. 2010).

### 2.3 *Image preprocessing and change detection*

Landsat imagery in 1988, 1996 and 2006 was acquired for image change detection and sagebrush change estimation using the 2006 sagebrush distribution as a baseline. The approach is similar to the prototype method developed for updating the USGS NLCD 2001 to 2006 for land cover classification (Xian *et al*. 2009) and continuous variable impervious surface estimation (Xian and Homer 2010). Landsat images in path 37 and row 31 were collected from three dates in 1988, 1996 and 2006 (table 1). Images for the three different years were selected in the same months, May, June and September for most years except in June 1996 due to cloud cover, to minimize seasonal differences and obtain optimal normalizations. These images also represented regional landscape conditions in spring, summer and fall. All Landsat images were corrected using the Multi-Resolution Land Characteristics Consortium image protocol, which standardizes imagery to at-satellite reflectance (Chander *et al*. 2009). The corrected images were then further normalized to reduce seasonal phenology and atmospheric effects between the two-date images. The normalization procedure was accomplished using a linear regression algorithm that relates each pixel of the subject image to the reference image. Each band was compared across years using least-squares regression to achieve the normalization values (Xian *et al*. 2009). Overall, three 1988 images were first normalized to three 2006 images across the same months to produce three normalized images for comparison. Then, three 1996 images were normalized to three 2006 images. Three 1988 images were also normalized to three 1996 images to obtain an additional image pair. The 1988–1996 and 1996–2006 image pairs were used to enhance change detection between these dates.

Normalized and reference images from the same month were used to calculate a change vector (CV) image that represented spectral feature differences that contain potential land cover change between the two dates. Generally, a greater value of the CV indicates a higher probability of land cover change, and a specific threshold needs to be determined to identify pixels of change or no-change. The CV analysis focused on

Table 1. Landsat images in path 37 and row 31 used for the study.

| Year | Month | Day |
|---|---|---|
| | 5 | 12 |
| 1988 | 7 | 15 |
| | 9 | 1 |
| | 6 | 3 |
| 1996 | 7 | 21 |
| | 9 | 7 |
| | 5 | 14 |
| 2006 | 7 | 17 |
| | 9 | 3 |

multivariate change detection for the two-date images. The CV ($\rho(i,j)$) was calculated from the spectral differences between a two-date image pair in the same or close to the same month for all spectral bands as $\rho(i,j) = \sqrt{\sum_{n=1}^{6}\left[R(i,j)_{n,\mathrm{r}} - R(i,j)_{n,\mathrm{s}}\right]^2}$, where $R$ represents the spectral value in the image, either early year or late year, as shown by the subscripts r and s, respectively; $i$ and $j$ are coordinates of a pixel; and $n$ represents the number of reflectance bands of Landsat imagery. All Landsat bands except the thermal band were used to calculate CV. A CV image was obtained by calculating a $\rho$ value for each pixel from bi-date normalized and reference images in the same month. Altogether, three CV images accompanying bi-date images for all 3 months were derived.

A multi-threshold approach was used to determine pixels of change or no-change from a CV image by connecting a specific threshold to each land cover type (Xian *et al*. 2009). The NLCD 2001 land cover product was recategorized into eight classes according to the Anderson Level I classification to simplify the class legend during threshold calculations. The magnitudes of SD and mean for a CV that belonged to a specific land cover type were calculated to serve as the threshold for pixels in the land cover type. The threshold is defined as

$$C_k(i,j) = \begin{cases} \text{change} & \text{if} \quad \rho_k(i,j) \geq \overline{\rho_k} + a_k\sigma_k, \\ \text{no-change} & \text{if} \quad \rho_k(i,j) < \overline{\rho_k} + a_k\sigma_k, \end{cases} \tag{1}$$

where $k$ represents a land cover class; $\overline{\rho_k}$ is the mean of CV ($\rho_k$) for the land cover type $k$; $C_k(i,j)$ represents a change pixel; $\sigma_k$ is the SD of $\rho_k$; and $a_k$ is an adjustable parameter. The range of $a_k$ was dependent on the land cover type and was retained from 0.0 to 1.5, which has been shown to be optimal for change detection (Xian *et al*. 2009). After all pixels were labelled as change or no-change, they were combined to create a binary image to serve as a mask for pixel change determination. Three mask images were produced from the corresponding three CV images for the three separate month periods in each 2-year image pair. To ensure that a consistent change mask was used for the 1988 and 1996 predictions, a restriction was implemented to retain change pixels. Areas were defined as changed only if pixels were identified as having changed in two out of three change mask images in each of the 2-year time intervals. After change masks were obtained for the three time intervals, 1988–1996, 1996–2006 and 1988–2006, they were reconciled to remove false changes that might be included from image noise introduced from phenology variations, atmospheric effects and image quality especially in geo-registration using the restrictions in the following expressions.

For $P_{i,j}(t) \in \{0,1\}$ and $t \in \{k,m,n\}$,

$$\left.\begin{array}{l} P_{i,j}(t) = P_{i,j}(k) = P_{i,j}(m) = 1, \text{ or } P_{i,j}(t) = P_{i,j}(k) = 1, P_{i,j}(m) = 0, \ P_{i,j}(t) \text{ is kept as changed,} \\ P_{i,j}(t) = P_{i,j}(k) = P_{i,j}(m) = 0, \text{ or } P_{i,j}(t) = P_{i,j}(k) = 0, P_{i,j}(m) = 1, \ P_{i,j}(t) \text{ is kept as unchanged,} \end{array}\right\}, \tag{2}$$

where $P_{i,j}(t)$ is the magnitude of a pixel ($i,j$) in a change mask image at time $t$. Variables of $k$, $m$ and $n$ are intervals of 1988–1996 ($t$), 1996–2006 ($k$) and 1988–2006 ($m$). After this step, three binary images that contained pixels defined as changed or unchanged were retained to serve as change mask images for further model prediction.

### 2.4 *Modelling sagebrush variables*

Previous results from the 2006 baseline sagebrush habitat mapping demonstrated that the percentage cover of sagebrush components could be estimated using RT models, Landsat images and ancillary data. We assumed a similar approach could be used to estimate the proportion of habitat components in 1988 and 1996. We also assumed that (1) the 2006 distribution maps for habitat components accurately represented baseline (current) conditions and (2) landscape changes detected by image spectral change and determined by CV represented landscape changes associated with the five habitat components between 1988 and 2006. Therefore, an RT modelling approach similar to that used to predict the 2006 baseline distributions, except for the training data set protocol, could be used to estimate the proportion cover change of each component in 1988 and 1996. Furthermore, the training data sets were prepared using 2006 baseline habitat components after first excluding change pixels from training consideration by using a binary change mask to identify them. Training samples containing all ranges of percentage cover for each component were generated from the unchanged pixel base to produce a total of five training data sets.

The RT model used here is identical to the approach used for creating the 2006 baseline and is constructed by using the training data sets as dependent variables and linearly establishing the relationship with the independent variables. RT modelling uses a partitioning algorithm that builds the trees by recursively splitting the training samples into smaller subsets. A set of rules was produced for predicting a target variable, for example, per cent sagebrush vegetation, based on training data. Each rule set defined the condition under which a multivariate linear regression model was established for prediction. Each rule includes three parts: statistical descriptions of the rule containing the number of cases used to build the rule and error range in the rule; conditions used to determine whether the rule can be applied by using a magnitude range of independent variables as thresholds; and a linear model in which independent variables were used to calculate the dependent variable. Generally, the model can be expressed as

Rule $i$
If condition(s) for $x_1, x_2, x_3, \ldots, x_n$ is (are) true then

$$y_i = F(x_1, x_2, \ldots, x_m) = a_i + \sum_{j=1}^{m} b_j x_j, \tag{3}$$

where $i$ is the $i$th rule; $x_n$ are independent variables and $n$ is the number of these variables; $y_i$ is the dependent variable under the $i$th rule; $a_i$ and $b_j$ are constants; and $m$ is the number of independent variables used in the $i$th rule and varies in each rule. The linear model is a simplified equation that fits the training data covered by the rule. Models based on the RT algorithm provide a proposition logic representation of these conditions in the form of tree rules. The main advantages of the RT algorithm include the simplification of complicated non-linear relationships between predictive and independent variables into a multivariate linear relationship and accepting both continuous and discrete variables as input data for continuous variable prediction.

The RT model provides several parameters to measure the model's predictive performance. These include average error, which is the average of the absolute difference between model-predicted value and true value, and the correlation coefficient, which

measures the agreement between the actual values of the target attribute and those values predicted by the model.

To estimate the percentage cover of habitat components in 1988, all three seasonal Landsat images from 1988 and ancillary data sets (similar to variables used to create the 2006 base) were input as independent variables in the RT. After RT models were produced for a specific sagebrush habitat component, they were used to calculate percentage cover of the component in each pixel for the entire study area. However, values were only retained in areas identified as having undergone spectral changes from the initial change detection analysis. The same procedures were repeated for all five sagebrush habitat components to produce their predictions for 1988. Similarly, the percentage cover of five sagebrush habitat components in 1996 was estimated using all three seasonal Landsat images from 1996 and ancillary data sets, with 2006 estimates also used as a baseline.

Changes were labelled as a decrease if the magnitudes of 1988 percentage cover for a component were larger than those in 2006, as an increase if the magnitudes were smaller in 1988 than in 2006, or as unchanged if both estimates were the same. Similar comparisons were also implemented for the 1996 and 2006, and the 1988 and 1996 estimates.



### 2.5 *Strategy for evaluating model estimates*

Historical satellite images provide a valuable and useful source for monitoring long-term variations of sagebrush habitat components over a large area. However, challenges remain to reliably validate model results across a 20-year span. Generally, validation should focus on whether spectral changes from CV analysis represent true landscape changes that are properly quantified. Our previous study, which looked at land cover change across the continental USA using similar methods, suggested that the majority of changes associated with land cover variations were detected by satellite imagery (Xian *et al*. 2009). With the use of baseline sagebrush information and RT models, we quantified the decadal changes of the five components. However, the verification of this change requires either adequate 1988 field measurements or historical high-resolution images capable of inferring reliable component percentage cover estimates for 1988. Unfortunately, neither of these types of data were available to support validation. Hence, our validation strategy encompassed two alternative approaches. First, a simplified approach was used to focus on validating whether change or no-change estimates associated with habitat components were accurate. Second, an *in situ* survey in 2009 for selected change areas was conducted. The first validation strategy depended on visually comparing change maps with historical aerial photos from the 1980s with high-resolution images from 2006, and the second strategy depended on ground truth information collected from 2009 fieldwork.

The first assessment approach used aerial photos from 1989 provided by the National Aerial Photography Program (NAPP) and orthoimagery from 2006 to verify landscape variations. The NAPP images were scanned from cartographic quality aerial photography from 1989 to a standard format 1 m pixel resolution. The quality of the scanned images did not allow for quantitative comparison of spatial cover of sagebrush habitat components. However, most of the 1989 colour-infrared NAPP imagery and 2006 0.6 m orthoimagery were clear enough for visual interpretation and qualitative assessment of gross changes.

The change validation was also conducted to quantitatively verify changes associated with a more general classification of shrub vegetation (independent of species). The shrub vegetation change was evaluated because those changes are the easiest components to detect by aerial interpretation of NAPP images from 1989 and orthoimages from 2006. The interpretations were compared with RT model estimates and applied to examine the accuracy of modelling results. The shrub vegetation change estimated from RT models between 1988 and 2006 was compared with colour-infrared NAPP photos and orthoimages. The validation procedures included (1) the selection of random samples from the change map; (2) recording comparison results of agreement on no-change, decrease or increase labels; and (3) calculating statistical scores for change agreements.

The second approach involved an *in situ* survey in 2009 targeting areas that were not covered by high-resolution NAPP photos and orthoimages. On each site, 1988 and 2006 Landsat images were used to compare with current ground observations to confirm whether changes associated with sagebrush habitat components estimated from the RT model were likely. The evaluation determined how likely the change would occur by comparing current ground conditions, potential change extent and two-date satellite images. If apparent changes were observed, for example, caused by fire or oil/gas well developments or vegetation regrowth from previous disturbances, the site was marked as highly likely for change. Otherwise, if changes could not be determined, for example, the ground did not have apparent vegetation removal or no change was apparent or could be inferred, the site was labelled as either no-change or uncertain.



## 3. Results

### 3.1 *Change detections*

To demonstrate how change pixels are incorporated into the change mask image, Landsat red, green and blue false colour images, displayed as bands 4, 3 and 2 in 1988, 1996 and 2006, and the change mask images near Fontenelle Reservoir located in the north central part of the study area are presented in figure 2. A few oil/gas wells are observed in the 1988 Landsat image (figure 2(*a*)), but after 1988, the number of oil/gas wells increased, and they are detectable in the 1996 (figure 2(*b*)) and 2006 (figure 2(*c*)) Landsat images. Corresponding spectral changes and potential changes associated with variations of land cover are identified correctly as changed areas in the binary image. Figure 2(*d*) displays changes between 1988 and 1996 when a large number of oil/gas wells were built on the eastern side of the reservoir. A few more wells were added between 1996 and 2006 and were captured in the change mask (figure 2(*e*)). The change mask for 1988–2006 contains persistent changes associated with these anthropogenic disturbances and other land cover variations (figure 2(*f*)).

### 3.2 *Sagebrush habitat change estimates*

Five sagebrush habitat components and their spatial distributions in 1988 and 1996 were extrapolated from five modelling results. The modelling accuracies for all sagebrush habitat components were achieved by retaining average error values that were less than 6% from the training data set and correlation coefficients greater than 0.90, which were calculated directly using cross-validation from the RT model and through sensitivity tests, respectively, for both 1988 and 1996 estimations. Changes of

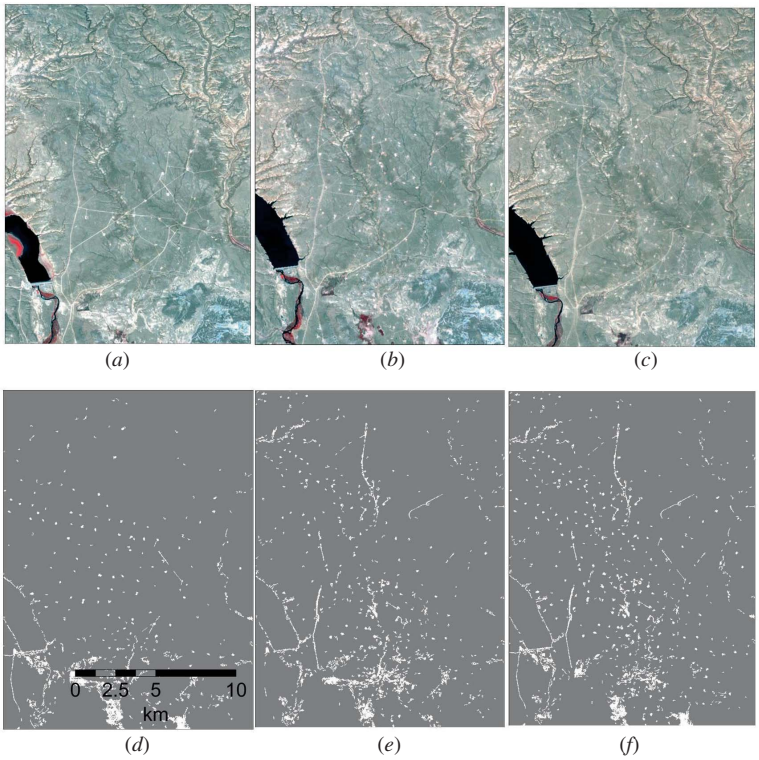


Figure 2. 1988 (*a*), 1996 (*b*) and 2006 (*c*) Landsat images near Fontenelle Reservoir displayed as red, green and blue (RGB) false colours by bands 4, 3 and 2. The changed (white colour) and unchanged areas (grey colour) from the binary change mask are represented for the periods 1988–1996 (*d*), 1996–2006 (*e*) and 1988–2006 (*f*).



those components from 1988 to 1996 and from 1996 to 2006 were determined by comparing 1988 with 1996 predictions and 1996 predictions with 2006 baseline conditions. The spatial distributions of sagebrush habitat components and associated changes are displayed in figure 3. The first row of figure 3 shows 1988 bare ground (figure 3(*a*)), changes between 1988 and 1996 (figure 3(*b*)) and changes between 1996 and 2006 (figure 3(*c*)). The second to fifth columns are 1988 herbaceous and associated changes (figure 3(*d*)–(*f*)), 1988 litter and associated changes (figure 3(*g*)–(*i*)), 1988 sagebrush and associated changes (figure 3(*j*)–(*l*)) and 1988 shrub and associated changes (figure 3(*m*)–(*o*)).

The central part of the study area exhibited relatively low percentage cover for all habitat components but relatively high cover for bare ground. Relatively high cover estimates for the other vegetation components were predicted on the southwest, northeast and southeast regions where higher elevation terrain exists. However, most changes occurred on the southern and western portions of the study area after 1996. Bare ground predictions show many positive changes for change amounts (green colour in the change map), indicating increases in bare ground cover. Other components show both positive and negative (red colour in the change map) trajectories for their cover changes.

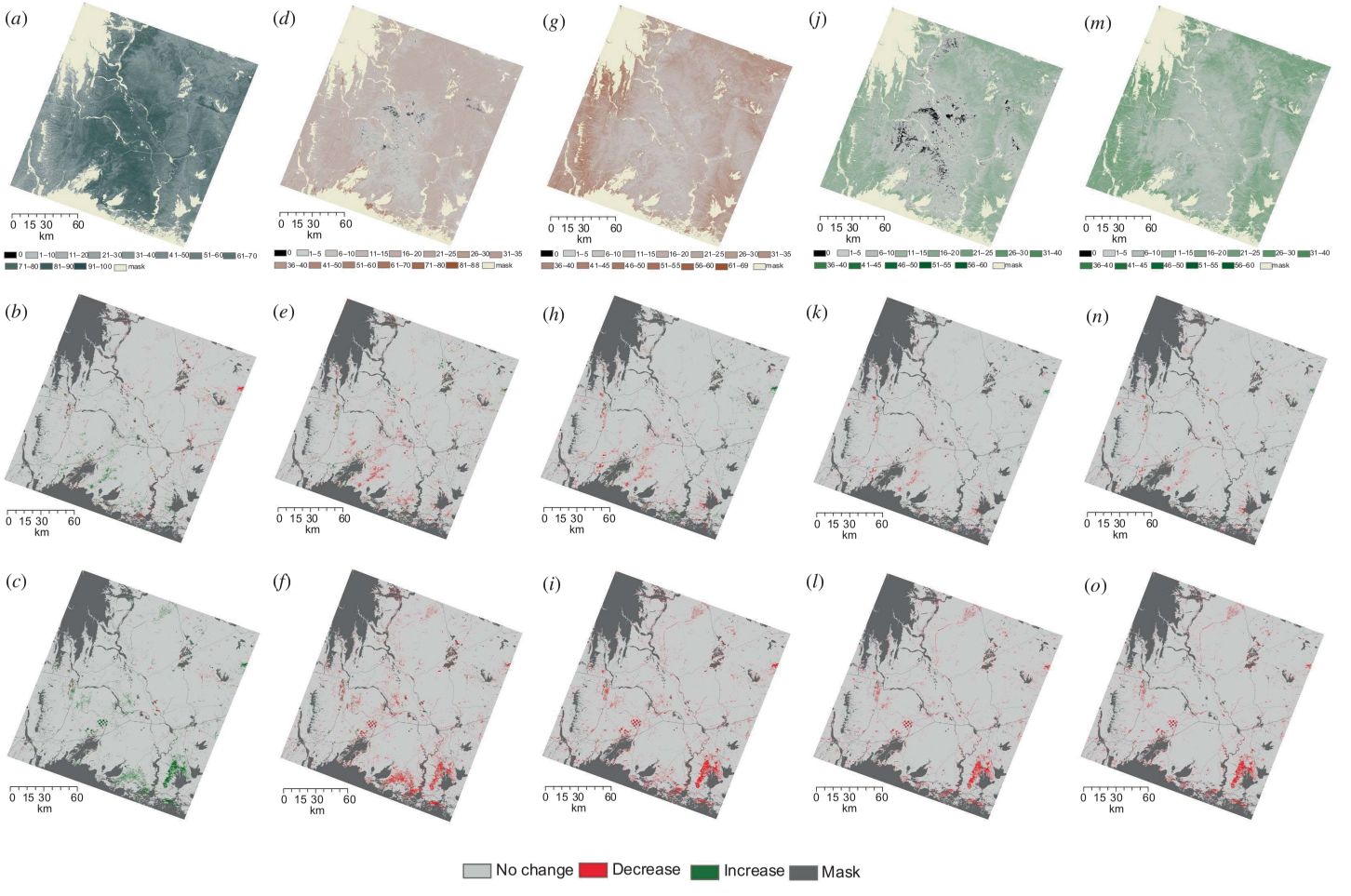


Figure 3. All five sagebrush components including the component in 1988, changes between 1988 and 1996 and changes between 1996 and 2006 in the study area. Each row from top to bottom represents spatial distributions of each component (*a*, *d*, *g*, *j*, *m*) and its changes from 1988 to 1996 (*b*, *e*, *h*, *k*, *n*) and from 1996 to 2006 (bottom row). Each column from left to right includes bare ground (*a*)–(*c*), herbaceous (*d*)–(*f*), litter (*g*)–(*i*), sagebrush (*j*)–(*l*) and shrub (*m*)–(*o*). The legends under (*a*), (*d*), (*g*), (*j*) and (*m*) represent percentage covers from 0% to 100% for bare ground, herbaceous, litter, sagebrush and shrub, respectively. The mask represents the area not containing any sagebrush components.

The details of spatial distribution changes of sagebrush habitat components for a specific location are shown in figure 4, which displays five components and their density changes for the periods 1988–1996 and 1996–2006 in the area near Fontenelle Reservoir, the same location displayed in figure 2. Most positive changes of bare ground cover from 1996 to 2006 were associated with oil/gas well developments in the region. The construction usually removed natural surface vegetation cover and increased bare ground cover. The herbaceous component both increased and decreased in the area, likely due to the quick response to disturbance by herbaceous vegetation. Additionally, the increase in herbaceous on the eastern side of the reservoir was associated with decreases in litter, sagebrush and shrub, likely because shrub removal left room for herbaceous regrowth. The sagebrush component, which had similar change patterns with litter and shrub, had little change and large areal decreases in the periods 1988–1996 and 1996–2006, respectively, in the area.



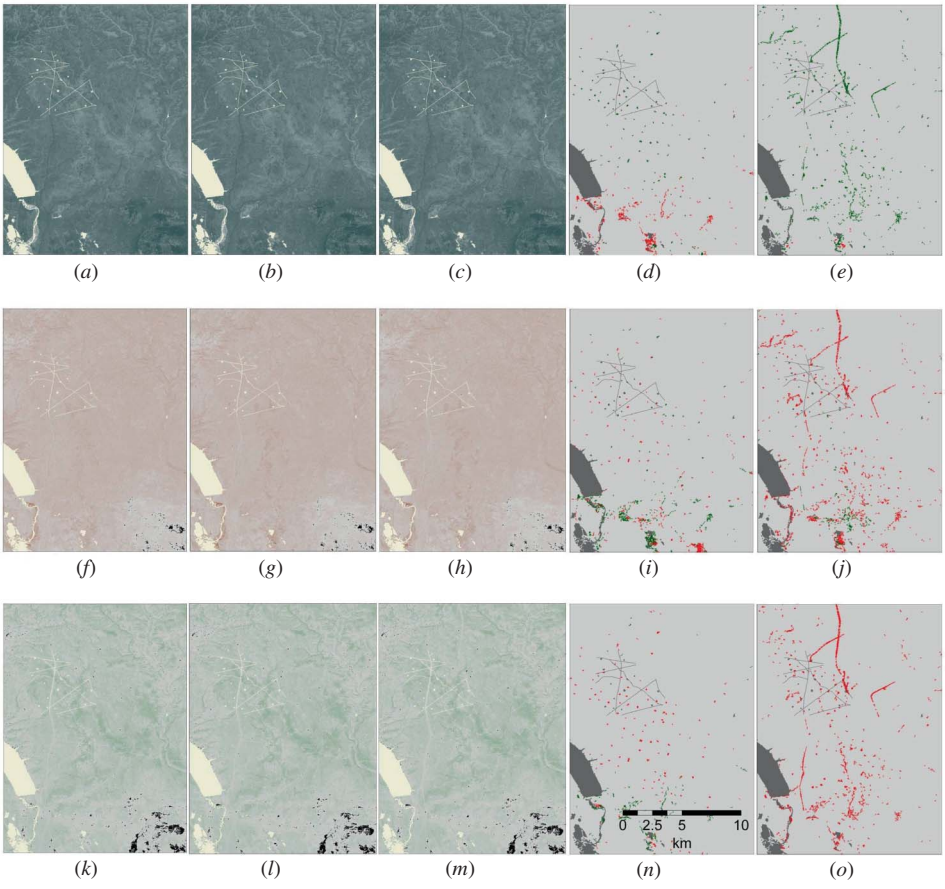


Figure 4. From left to right in each panel are sagebrush habitat components in 1988, 1996, 2006 and corresponding change from 1988 to 1996 and from 1996 to 2006. From top to bottom are bare ground and its changes (*a*)–(*e*), herbaceous and its changes (*f*)–(*j*) and sagebrush and its changes (*k*)–(*o*). The location is the same as in figure 2 and colour legends are the same as in figure 3.

### 3.3 *Spatial variation of sagebrush habitat components*

Percentage cover estimates of sagebrush habitat components were also used to quantify the spatial extent and change amounts for each component. Table 2 lists the areal changes. Areal cover is calculated by multiplying the percentage cover of a component in the pixel by the total area of a pixel, and subsequently totalling all pixels containing the component for the entire area. Changes in percentiles of each component between 1988 and 2006 are also presented. Figure 5 presents areal changes for all five components during the periods 1988–1996, 1996–2006 and 1988–2006.

Table 3 reports the overall change proportion of each sagebrush ecosystem component between 1988 and 2006 in southwestern Wyoming, including the number of decreasing and increasing pixels as a proportion of overall change. Change proportions do not include areas of water, forest, urban and agricultural land within the study area.



Table 2. Area proportions of sagebrush habitat components in 1988, 1996 and 2006 for southwestern Wyoming.

| Component | 1988 ($km^2$) | 1996 ($km^2$) | 2006 ($km^2$) | Areal change ($km^2$) | Change rate (%) |
|---|---|---|---|---|---|
| Bare ground | 14 664.00 | 14 680.16 | 14 762.83 | 98.83 | 0.67 |
| Herbaceous | 3 316.90 | 3 351.81 | 3 296.73 | −20.17 | −0.61 |
| Litter | 4 167.38 | 4 186.00 | 4 137.22 | −30.16 | −0.72 |
| Sagebrush | 2 176.70 | 2 175.82 | 2 143.89 | −32.81 | −1.51 |
| Shrub | 2 729.86 | 2 725.93 | 2 696.52 | −33.34 | −1.22 |

Notes: Areal proportional change from 1988 to 2006 and change rates over 18 years for each component are listed. All change calculations consider 1988 as the base year, and changes are shown chronologically (from 1988 to 2006).

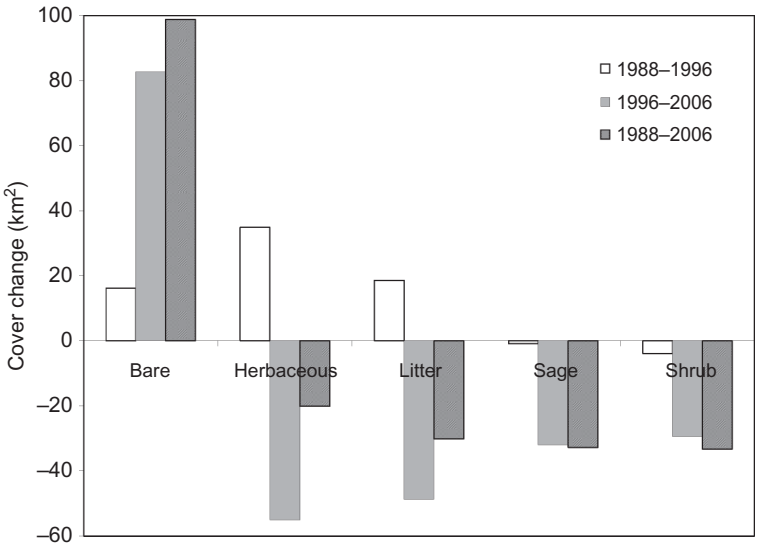


Figure 5. Total coverage changes for each of five sagebrush habitat components from the periods 1988–1996, 1996–2006 and 1988–2006.

Table 3. Number of pixels showing decrease and increase between 1988 and 2006 for each sagebrush habitat component in southwestern Wyoming.

| Component | Decreased pixels (percentage of total change) | Increased pixels (percentage of total change) | Total changed pixels (percentage of total pixel) |
|---|---|---|---|
| Bare ground | 56 598 (6.66) | 793 339 (93.34) | 849 937 (3.07) |
| Herbaceous | 990 416 (87.66) | 139 435 (12.34) | 1 129 851 (4.08) |
| Litter | 799 420 (94.13) | 49 831 (5.87) | 849 251 (3.06) |
| Sagebrush | 657 190 (95.82) | 28 667 (4.18) | 685 857 (2.47) |
| Shrub | 671 917 (94.63) | 38 139 (5.37) | 710 056 (2.56) |

Notes: The percentages of decreased and increased pixels relative to the total changed pixels are listed. The total changed pixels and their percentages compared with the study area are also listed. 'Total pixels' (and similar) means 'total number of pixels'; 'decreased pixels' means 'number of pixels showing a decrease'; 'increased pixels' means 'number of pixels showing an increase'; and 'total changed pixels' means 'total number of pixels showing a change'.



**3.3.1 Bare ground.** Bare ground has the largest spatial coverage among the five components in 1988, 1996 and 2006. The total area of bare ground was 14 664 km$^2$ in 1988, 14 680 km$^2$ in 1996 and 14 763 km$^2$ in 2006, indicating a net increase of approximately 99 km$^2$, or a 0.7% increase from 1988 to 2006. The ratio of bare ground to the entire study area increased from 58.8% in 1988 to 59.2% in 2006. Additionally, 849 937 pixels, or 3.07% of the 1988 total, were labelled as changed between 1988 and 2006. Among change pixels, 6.66% experienced bare ground decrease and 93.34% had an increase between 1988 and 2006. The change proportions indicate the majority of variations represent bare ground increases.

**3.3.2 Herbaceous.** Herbaceous vegetation covered approximately 3317 km$^2$ in 1988, 3352 km$^2$ in 1996 and 3297 km$^2$ in 2006, indicating a net decrease of approximately 20 km$^2$, or a 0.6% decline from 1988 to 2006. The ratio of herbaceous vegetation to the entire area declined from 13.3% in 1988 to 13.2% in 2006. Furthermore, 1 129 851 herbaceous pixels, or 4.07% of the 1988 total, were identified as changed between 1988 and 2006. In other words, of the five components, the herbaceous component had the largest number of pixels that experienced disturbance. Among change pixels, 87.66% experienced herbaceous vegetation decrease between 1988 and 2006 and 12.34% had an increase.

**3.3.3 Litter.** Litter cover included 4167 km$^2$ in 1988, 4186 km$^2$ in 1996 and 4137 km$^2$ in 2006, indicating a 30 km$^2$ net reduction, or a 0.7% decline from 1988 to 2006. The ratio of litter coverage to the entire area declined from 16.7% in 1988 to 16.6% in 2006. Overall, 849 251 litter pixels, or 3.1% of the 1988 total, were labelled as changed between 1988 and 2006. Among change pixels, 94.1% were categorized as decreases between 1988 and 2006 and 5.9% had an increase. The number of changed pixels for litter was similar to the bare ground amount, but bare ground had a much larger spatial extent.

**3.3.4 Sagebrush.** Sagebrush covered approximately 2177 km$^2$ in 1988, 2176 km$^2$ in 1996 and 2144 km$^2$ in 2006, indicating a 32 km$^2$ net reduction, or a 1.5% decline from 1988 to 2006. The ratio of sagebrush vegetation to the entire area declined from 8.7% in 1988 to 8.6% in 2006. Overall, 685 857 sagebrush pixels, or 2.5% of the 1988 total, were labelled as changed between 1988 and 2006. Among change pixels between 1988 and 2006, 95.8% were categorized as decreases and 4.2% as increases. When compared with other components, sagebrush vegetation had both the smallest spatial extent and the fewest pixels labelled as change between 1988 and 2006.

**3.3.5 Shrub.** Shrub vegetation covered approximately 2730 km$^2$ in 1988, 2726 km$^2$ in 1996 and 2697 km$^2$ in 2006, representing a 33 km$^2$ net reduction, or a 1.2% decline from 1988 to 2006. The ratio of shrub vegetation to the entire area declined from 10.9% in 1988 to 10.8% in 2006. Overall, 710 056 shrub pixels, or 2.6% of the 1988 total, were labelled as changed between 1988 and 2006. Among change pixels between 1988 and 2006, 94.6% were categorized as decreases and 5.4% as increases. The number of shrub pixels labelled as change from 1988 to 2006 was similar to sagebrush change patterns.

### 3.4 *Percentage cover changes of sagebrush habitat components*

The changes in spatial extents of sagebrush habitat components were also associated with variations of their density distributions. Figure 6 displays percentage cover distributions of all five components in change areas by three time periods, including 1988–1996, 1996–2006 and 1988–2006.

**3.4.1 Bare ground distribution.** The 1988 bare ground distribution is characterized by two peaks of cover proportions around 40% and 80% (figure 6(*a*)). The percentage cover distributions in changed areas show that bare ground in 1988 had a peak cover proportion around 70%, which shifted to around 40% in 1996 and 85% in 2006, leading to the mean density of bare ground changing from 51% in 1988 to 64% in 2006. In other words, the increase of spatial extent of bare ground between 1988 and 2006 was achieved by a moderate increase in bare ground cover in areas that already contained bare ground.

**3.4.2 Herbaceous distribution.** The 1988 herbaceous distribution had a narrow density distribution with most pixels having percentage cover varying from 1% to 25% (figure 6(*b*)). The peak of canopy cover in 1988 appeared around a 20% coverage. The percentage cover in changed areas exhibits different patterns in 1988, 1996 and 2006. The 1988 herbaceous vegetation in 1988 and 2006 change areas has a peak of percentage cover around 20% and a mean density of 15.6%. The peak remained the same in 1996 but shifted to around 5% cover in 2006, representing a decline in the mean density to 13.6% in 2006.

**3.4.3 Litter distribution.** The 1988 litter distribution had a relatively widespread pattern for its density with most pixels having percentage cover varying from 1% to 50% (figure 6(*c*)). The most common litter cover in 1988 emerged around 10% cover. The percentage cover distribution in changed areas displays similar distribution patterns in 1988, 1996 and 2006. In changed areas, 1988 litter had a peak areal cover

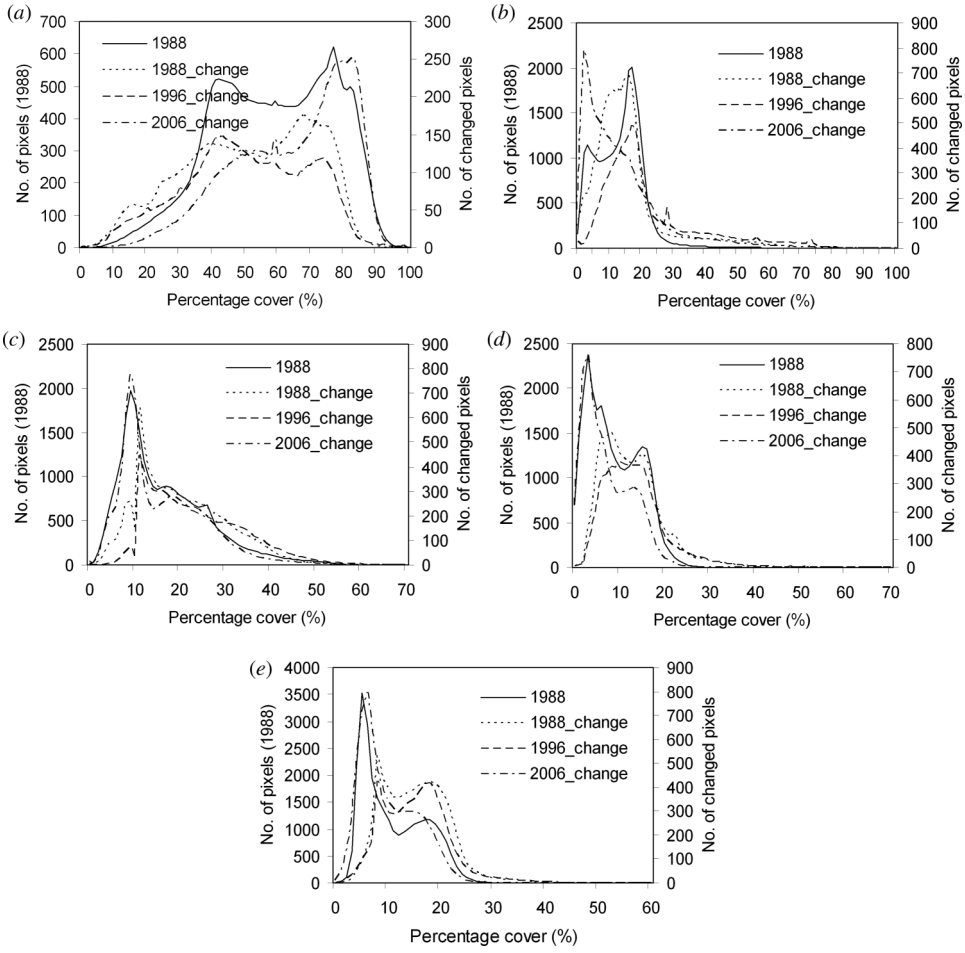


Figure 6. Percentage covers of sagebrush components in 1988 and their distributions in changed areas for bare ground (*a*), herbaceous (*b*), litter (*c*), sagebrush (*d*) and shrub (*e*). The numbers of pixels in 1988 and numbers of changed pixels shown in all graphics are divided by 1000 and 100, respectively. Solid lines are for sagebrush habitat components in 1988. Short dash lines labelled as 1988_change are 1988 components in changed areas. Long dash lines labelled as 1996_change are 1996 components in changed areas. The dash-dot lines labelled as 2006_change are 2006 components in changed areas.

around 11%, with a similar peak in 1996 and then shifting to around 8% in 2006. This leads to the mean percentage cover changing from 20.0% in 1988 to 16.0% in 2006.

**3.4.4 Sagebrush distribution.** The 1988 sagebrush distribution had a pattern of relatively narrow density with most pixels having percentage cover varying from 0% to 30% (figure 6(*d*)). Two percentage cover peaks appeared in the 1988 sagebrush distribution, with the larger one around 4% and a smaller one around 18%. The percentage cover distributions in changed areas display two peaks, one around 8% and another at 18% in 1988, one peak around 12% in 1996 and one peak around 4% in 2006. The 1996_change is slightly different from its 1988_change line with only one peak near

10% cover. This pattern indicates that most sagebrush reduction occurred in areas with less than 10% cover during this time. The shift of density peaks leads to a decline of mean density from 12.5% in 1988 to 7.2% in 2006.

**3.4.5 Shrub distribution.** The 1988 shrub distribution had a pattern of relatively narrow density with most pixels having percentage cover varying from 1% to 30% (figure 6(*e*)). The percentage cover distribution of shrub vegetation, as expected, was not substantially different from the pattern of sagebrush vegetation. Two cover peaks of shrub vegetation at 8% and 20% occurred in 1988, with large and small numbers of pixels, respectively. In changed areas, the percentage cover distributions possessed similar patterns; the 1988 shrub peak had a large number of pixels around a density of 10.0%, and a second peak had a moderate number of pixels around 20%. These two peaks remained in the same densities in 1996 and were shifted to 8% and 18% in 2006. The shifts of density reduced mean density from 15.2% in 1988 to 10.0% in 2006.

### 3.5 *Evaluations of model estimate*

Figure 7 displays an overall example of visual resources available for interpretation of changes associated with sagebrush ecosystems through the first assessment approach using NAPP, orthoimagery and Landsat imagery. The figure contains Landsat images from 1988 (*a*), 1996 (*b*) and 2006 (*c*); changes of bare ground in 1988–1996 (*d*) and 1996–2006 (*e*); changes of sagebrush vegetation in 1988–1996 (*f*) and 1996–2006 (*g*); and examples of validation imagery in 1989 (*h*) and 2006 (*i*). Landsat images show no significant spectral change between 1988 and 1996, but significant spectral changes occur between 1996 and 2006 in the area. The images of 1988–1996 change for bare ground and sagebrush demonstrate a few change patches in the area. The images of 1996–2006 change present large patch increases for bare ground and decreases for sagebrush for the area. The 1989 NAPP photo for the area outlined by the white rectangle in the figure reveals sagebrush abundance in the area. The 2006 orthoimage, however, discloses removal of sagebrush vegetation and emergence of bare ground in the area. Areal changes and change patterns associated with other sagebrush habitat components were found consistent with RT model estimates.

Overall, 20 NAPP frames and orthoimages were used with 7–18 randomly selected samples in each frame for a total of 680 samples. Omission errors for shrub vegetation were 12.98% for no-change, 7.19% for decreased change and 11.54% for increased change. The commission errors were 6.80% for no-change, 11.44% for decreased change and 36.11% for increased change. The overall accuracy was 89.56%.

Overall, 40 sampling sites were randomly selected and visited following the protocol of the second validation approach. Figure 8 presents Landsat images from 1988 (*a*), 1996 (*b*) and 2006 (*c*); bare ground changes for 1988–1996 (*d*) and 1996–2006 (*e*); sagebrush vegetation changes for 1988–1996 (*f*) and 1996–2006 (*g*); and photos taken on selected sites (*h*) and (*i*). Patches associated with spectral variations are observed on the southeastern portion of the Landsat images in 1996 and 2006. The change map derived from our modelling results shows several large patches where bare ground increased and sagebrush vegetation decreased between 1988 and 1996, overlapping with change areas visually observed in 1996 Landsat images. A small patch of bare ground reduction is also observed in the change map of 1996–2006 and the 2006 Landsat image. Corresponding to the same location with decreasing bare ground, a small patch of increasing sagebrush is also detected in the sagebrush change

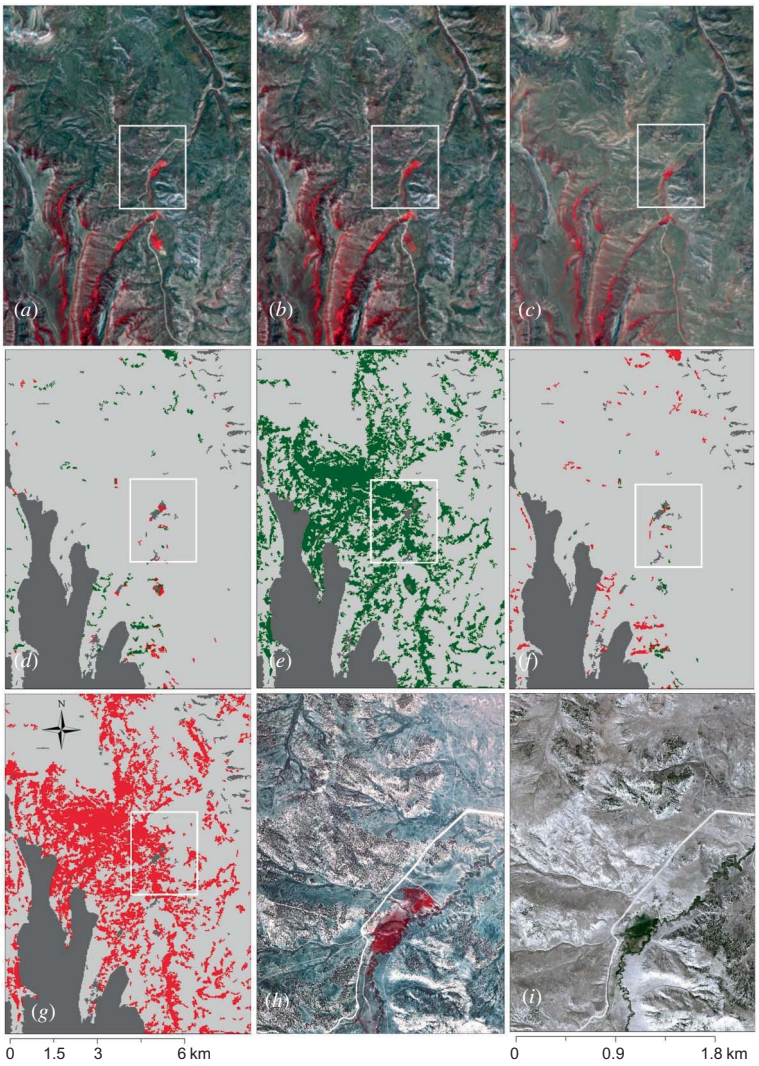


Figure 7. Landsat images, changes of bare ground and sagebrush and high-resolution aerial photos in a subset area in the southeastern part of the study area in southwestern Wyoming. From left to right, top to bottom are Landsat imagery in the summer of 1988 (*a*), 1996 (*b*) and 2006 (*c*); changes of bare ground in the periods 1988–1996 (*d*) and 1996–2006 (*e*); and changes of sagebrush vegetation in the periods 1988–1996 (*f*) and 1996–2006 (*g*). For change maps, green, red and light grey are for increasing, decreasing and unchanged areas, respectively. A small area defined by a white rectangle is enlarged to show aerial photos from 1989 (*h*) and orthoimagery from 2006 (*i*) used for validation.

map between 1996 and 2006. Our on-site survey reveals that surface vegetation was removed by the building of utility facilities in the area. The photos taken from both unchanged (figure 8(*h*)) and changed (figure 8(*i*)) sides reveal variations of disturbed and undisturbed landscapes associated with change maps of bare ground and sagebrush vegetation, providing an example where our change analyses could correctly

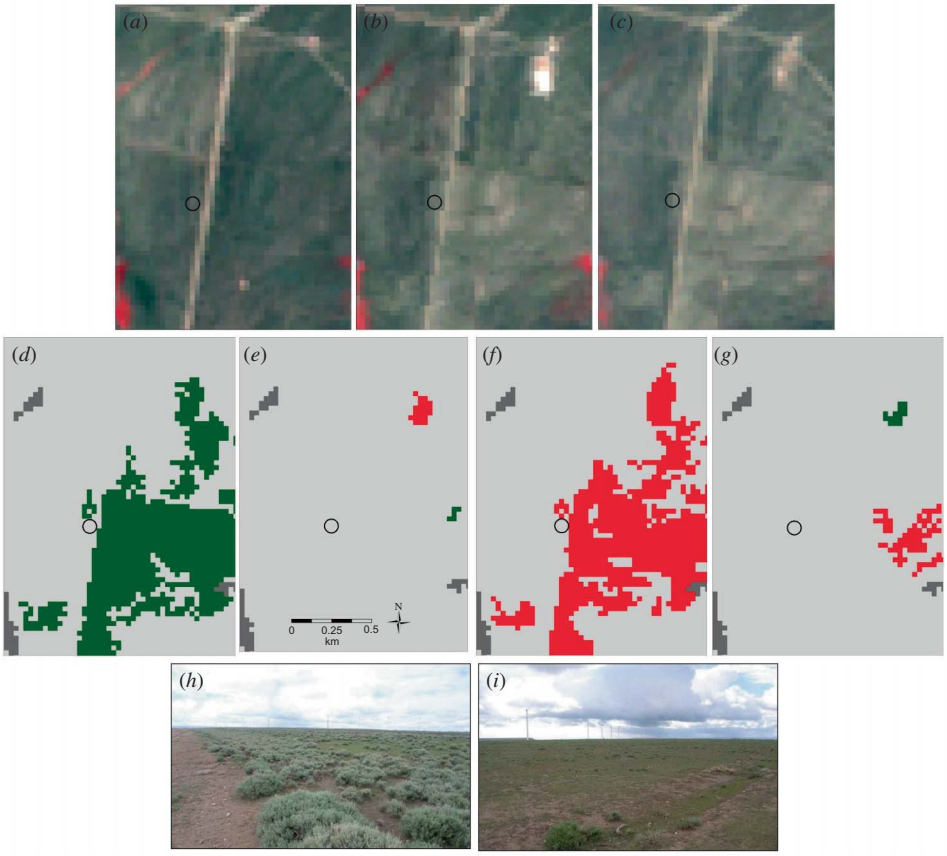


Figure 8. The top panel has Landsat images displayed as red, green and blue (RGB) false colours by bands 4, 3 and 2 in a subset area in the southwest part of the study area in 1988 (*a*), 1996 (*b*) and 2006 (*c*). The middle panel is changes of bare ground from 1988 to 1996 (*d*), 1996–2006 (*e*), sagebrush vegetation from 1988 to 1996 (*f*) and 1996–2006 (*g*), in which light grey, green and red are for unchanged, increasing and decreasing areas, respectively. The bottom panel shows examples of unchanged (*h*) and changed (decreasing in sagebrush (*i*)) areas taken from a field survey in 2009. Photos were taken facing south from the position marked by black circles in (*a*)–(*g*).

capture change. Overall, 60% of the change estimates could be confirmed as highly likely change using field information collected from the on-site survey.

## 5. Discussion

We developed an image change detection and RT modelling approach which successfully identified changes in sagebrush habitat components, highlighting the potential to use these approaches for long-term monitoring of changes in sagebrush ecosystems. Image change detection and percentage cover estimate procedures were applied to a bitemporal composite of medium-resolution Landsat image data from 1988, 1996 and 2006 to directly identify changes in individual components. Estimates of percentage cover for sagebrush habitat components in 1988 and 1996 were made only in changed areas using imagery and ancillary data. The 2006 baseline data were retained in unchanged areas for previous years' assessments to minimize effort and reduce

potential biases caused by image noise and modelling errors. Identification and use of high-quality bi-date image data sets for comparison minimized noise caused by scene registration and phenology and our robust classification approach could label change quantities across five sagebrush habitat components. Overall, change results were relatively consistent.

While our sagebrush habitat monitoring approach was successful, it has both advantages and disadvantages relevant to both the bi-date image change detection and RT modelling aspects. The strength of the bi-date image change detection is that resultant habitat change objects represent landscape patches that have undergone either the changed or unchanged state but not both, allowing a land cover transition sequence to be explicitly determined. However, the image CV approach only develops the magnitude of radiometric change, so ambiguities can result from identification of land cover transitions other than targeted sagebrush habitat changes. We focused change analysis on sagebrush habitat changes by using a land cover mask based on NLCD 2001 land cover (Homer *et al*. 2004), assessing potential change within grass, shrub and bare ground classes only. Additionally, using change detection based on multiple pairs of images from multiple seasons helped to further minimize substantial amounts of change image noise. This image change detection approach avoids the need for *a priori* knowledge of the location of landscape changes for selecting training sample objects that represent habitat loss or increase, as has been required for change detection analysis in other studies (Davies *et al*. 2006).

Our RT training approach depended on stratified sampling from the unchanged portions of the baseline data set. We assumed these baseline data were accurate enough to produce reliable component predictions over change candidate areas. While this assumption may occasionally be violated, we assumed the robust nature of RT prediction could overcome small proportions of erroneous training from the base. Using multi-date and medium-resolution Landsat imagery to generate estimates of component cover is economically feasible and useful over relatively large areas (Homer *et al*. 2010), and it benefits our approach better. In addition, this approach has advantages in using multiple regression equations to include all Landsat imagery bands in different seasons to estimate fractional covers of different sagebrush habitat components over a large geographic area. Other previous research has initially demonstrated success with sagebrush cover estimation in a relatively small area using single stepwise regression equations to estimate percentage total vegetation cover and bare ground for sagebrush-dominated landscapes with limited Landsat imagery bands and normalized difference vegetation index (NDVI) (Ramsey *et al*. 2004). We were successfully able to monitor changes in several different sagebrush habitat components across a large spatial extent and across a broad time period. Products such as these can enable cost-effective and practical application to management applications for long-term and large-scale assessment (Anderson and Mccuistion 2008, Chambers and Pellant 2008).

Despite the success of our change detection results, some cautions are still warranted. For instance, image change detection between two time periods only represents a paired trend and not a long-term pattern. Using additional sequential images in a formal trend analysis would likely allow for more accurate detection of even more subtle changes occurring on the ground, especially given the difficulty of detecting this type of change with the high variability of vegetation phenology and productivity that can exist within moisture-limited sagebrush ecosystems (Verbesselt *et al*. 2010). Changes from 1988 to 2006 in our study without considering the 1996 imagery would

have clearly resulted in some different interpretations of local trends. The additional time series imagery improved change detection for sagebrush habitat components. Our field survey conducted in 2009 shows that change was visually observed for at least 60% of sagebrush ecosystems components. Other changes that could not be visually verified were associated with either the increase or decrease of component change in density and were subtle rather than abrupt changes. It is very difficult to visually determine those variations without using either long-term field measurements or time series of high-quality and high-resolution imagery. Neither of these are available for the study area. Therefore, capturing similar phenology and moisture conditions across years is important to increase the accuracy of detecting real change and limiting variance due to seasonal variability.

Our results detected differences between two discrete periods and quantified both spatial extent and density of component change. Our change estimates showed 32 and 33 $km^2$ decreases for sagebrush and shrub, respectively, between 1988 and 2006 from their 1988 totals, respectively. Among pixels identified to have undergone change over this time, there was a 5.4% increase for shrub pixels compared with 1988, which was slightly higher than 4.2% for sagebrush. The increasing shrub areas likely provide some offset to the more widespread trend of decreasing shrub vegetation but are included in the overall estimate of shrub decrease. Similarly, bare ground pixels show a 6.7% decrease between 1988 and 2006 from its 1988 total, although it had a 99 $km^2$ net increase. The net increase of bare ground almost matches the total decreases of herbaceous, sagebrush and shrub. When evaluating these numbers, it is important to realize that some change trajectory differences may also be the result of borderline change areas that occur within the uncertainty threshold of the regression model error margin.

Even with the limitations of our approach, this quantification of sagebrush habitat component change provides an important step towards a framework for the long-term monitoring of regional ecosystem change. Information provided from 3 years of image change can both quantify density changes and determine trends between decades for sagebrush habitat components. Areal change and density distribution patterns can now be used for further assessment into the major drivers of these changes and to investigate impacts of potential anthropogenic or natural disturbances on variations of sagebrush habitat components. Coupling our data with an analysis of driving forces of change would allow for other application assessments correlating habitat component changes with other time series data sets, such as the impact of changing habitat components on wildlife populations, the effect of long-term grazing or the impact of changing temperature and precipitation trends over time. Ultimately, this framework would provide land managers important insight and feedback on various aspects of sagebrush ecosystem changes, and further understanding of the potential impacts of their decisions.

## 6. Conclusions

Image change detection derived from a CV analysis using multi-date Landsat images from 1988, 1996 and 2006 realistically delineated most land cover change across sagebrush habitat. Using multi-date CVs with the restriction of retaining change for areas registering at least two out of three change pairs yielded more accurate potential change areas. Having the 2006 sagebrush habitat component data set as the training base for RT modelling provided an objective and semi-automated way for training data selection for such a large-area change assessment. The estimate of component percentage of cover in 1988 and 1996 and associated change maps agreed closely with reference data from high-resolution orthoimages. Further, the RT modelling accuracy

was high, with the retention of relative error less than 6.0% and correlation coefficients greater than 0.9 for all components. The overall validation from comparing ground truth information collected from on-site surveys suggested that 60% of changes associated with the five sagebrush components were confirmed as highly likely changes. The overall accuracy for shrub vegetation change was very high (89.56%) based on a comparison of change predictions with 1989 NAPP aerial photos and 2006 orthoimages. Generally, the most uncertainty was associated with trying to determine areas where shrub vegetation had increased rather than decreased.

Overall, we observed a net 0.7% increase (98.8 $km^2$) of bare ground cover from 1988 to 2006 across the study area. Comparatively, we saw net losses in the spatial extents of the other four components we measured. Shrub vegetation had the largest net loss of 33.3 $km^2$, or a decrease of 1.2%. Herbaceous vegetation and litter increased between 1988 and 1996, but this trend reversed to show decreases from 1996 to 2006, leading to net losses for these two components from 1988 to 2006. The other three components did not have alternate trends between paired years but kept a consistent trend of reduction for the 1988–1996 and 1996–2006 time frames. Finally, the distribution features of habitat cover density varied with different components, with their change patterns consistent with variations of their spatial extents.

Our results reveal that basic Landsat spectral information, image change detection and the RT models can support estimation of per cent cover change across five sagebrush habitat components over 18 years. Changes in density variation and net loss in spatial extent of habitat components are well quantified. Hence, we conclude this approach validates the potential for using these methods as part of a monitoring system for sagebrush ecosystems. We anticipate such information can provide relevant input for habitat analysis and management decision making, especially when coupled with field observations to validate modelling results. Ideally, long-term field sampling and high-resolution imagery acquisition protocols could supplement our modelled results and bolster the accuracy of predictions and overall model performance. While this approach to sagebrush habitat change delineation and identification is promising, future research is needed to analyse patterns of habitat change, understand the drivers of this change and ultimately understand our ability to measure, monitor and predict these changes over large ecosystems in the future. To this end, current additional monitoring research is under way, collecting repeated field and image measurements annually to more precisely determine patterns and rates of change.

**Acknowledgements**

We thank Debbie Meyer for selecting and providing Landsat imagery and certain GIS data layers. We thank Greg Fox, Austin Krcmarik, Chris Mahony, Katie Moon, Roger Pearce, Tracy Perfors, Sarah Rehme, John Severson and Greg Wann for their tireless efforts to collect all the field data, and Spencer Shell for his extraordinary efforts in the field. We also thank Dan Neubaum and Diana Keck for coordination of field crews. The Wyoming State office and the Lander Bureau of Land Management field office were instrumental in supporting this project, both logistically and financially. Specifically, we thank T. Rinkes, R. Vigil, K. Henke and D. Simpson for their support and interest in this research. We thank the USGS Central Region Office and all individuals involved with the Central Region Integrated Science Proposals and the Central Region's DOI on the Landscape Program for financial support. Drs James Vogelmann and Robert Klaver are also thanked for their suggestions to improve this article. Two anonymous reviewers are thanked for their constructive suggestions. Work by George Xian was performed under USGS contract 08HQCN0007.

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