Effects of Land Cover and Regional Climate Variations on Long-Term Spatiotemporal Changes in Sagebrush Ecosystems

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Abstract: This research investigated the effects of climate and land cover change on variation in sagebrush ecosystems. We combined information of multi-year sagebrush distribution derived from multitemporal remote sensing imagery and climate data to study the variation patterns of sagebrush ecosystems under different potential disturbances. We found that less than 40% of sagebrush ecosystem changes involved abrupt changes directly caused by landscape transformations and over 60% of the variations involved gradual changes directly related to climatic perturbations. The primary increases in bare ground and declines in sagebrush vegetation abundance were significantly correlated with the 1996–2006 decreasing trend in annual precipitation.

INTRODUCTION

Sagebrush ecosystems are important for sustaining a variety of landscape functions and provide vital ecological, hydrological, biological, agricultural, and recreational ecosystem services in arid and semiarid areas in the intermountain region of the western United States (Connelly et al., 2004; Perfors et al., 2003; Davies et al., 2007; Anderson and McCuistion, 2008). Most recognized may be the key habitats these systems provide for numerous sagebrush-obligate species, including the greater sage-grouse (*Centrocercus urophasianus*; Connelly et al., 2000). However, the quality and quantity of sagebrush ecosystems have steadily declined and the speed of the deterioration has accelerated in recent decades in the western United States. The total spatial extent of sagebrush-steppe ecosystems is estimated to have decreased by

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GIScience & Remote Sensing, 2012, **49**, No. 3, p. 378–396. http://dx.doi.org/10.2747/1548-1603.49.3.378

50%, with remaining sagebrush areas undergoing further fragmentation and degradation (Connelly et al., 2004; Schroeder et al., 2004). As a result, species dependent on sagebrush ecosystems have experienced substantial range contractions and population declines (Aldridge et al., 2008).

Given the rates of reduction of sagebrush ecosystems and the relatively slow recovery potential of these semiarid shrublands, information on ecosystem distributions and temporal variations is important for evaluating the source of change, their subsequent patterns, and the causes of change. Important progress has been made in obtaining accurate information of sagebrush distribution and variation across a large area (Sivanpillai et al., 2009; Walston et al., 2009; Homer et al., 2012). Primary external disturbances including land cover change associated with livestock grazing, exotic species invasion, conversion to agriculture, conversion to urban land use, resource development, and their impacts on sagebrush ecosystems variations in the western intermountain region of U.S. have also been addressed (Young et al., 1989; Crawford et al., 2004). Additionally, recent energy development in the region has introduced more potential ecological conflicts, especially as these activities apparently impact the quality and quantity of sagebrush (Davies et al., 2006, 2007; Aldridge and Boyce 2007; Doherty et al., 2008). A study in a small part of western Wyoming in the United States estimated that natural gas/oil development had directly impacted 2.7% of original Wyoming big sagebrush habitat, and the sagebrush habitat declined linearly at a rate of 0.2% per year between 1985 and 2006 (Walston et al., 2009). Development such as this might trigger many indirect impacts that further alter the quality as well as quantity of the remaining sagebrush habitats.

Wildland fire is another potential disturbance factor that might alter sagebrush ecosystem integrity in the western U.S. Although sagebrush is naturally adapted to fire, with fire rotations historically varying from several hundred years to several decades for most sagebrush communities (Baker, 2006), exotic species invasion, grazing practices, management activities, and other factors have significantly altered the historical fire regime in some areas with significant negative consequences to sagebrush ecosystems (Haws et al., 1990). Fire occurrence derived from remotely sensed information is necessary for isolating fire disturbance from other types of disturbance in sagebrush habitats (Knick and Rotenberry, 1997; Rollins et al., 2004).

Climate change, which results in temperature warming and alteration of precipitation regimes by affecting timing, frequency, and intensity of precipitation events (Easterling et al., 2000; IPCC, 2007), has the potential to cause major changes in terrestrial ecosystems (Vitousek, 1994; Baron et al., 1998; Schwinning and Ehleringer, 2001; Linares et al., 2009). While land cover modification directly causes many abrupt changes in sagebrush habitats, climate perturbation can produce gradual changes that are usually related to subtle and slowly occurring, within-state changes in ecosystems. Previous studies revealed that variations in precipitation strongly influence arid-land plant composition and dynamics (Branson et al., 1976; Cook and Irwin, 1992; Pelaez et al., 1994; Ehleringer et al., 1999; Reynolds et al., 2000), including sagebrush cover in the northern Great Basin (Svejcar et al., 2003). Arid and semiarid systems may be among the most sensitive to precipitation changes because of low soil moisture content in the region (Reynolds et al., 1999; Weltzin et al., 2003) and ecosystem feedback effects to climate perturbation could be intensified (Knapp et al., 2002).

Climate variation and land cover change have the potential to profoundly modify the quantity and quality of sagebrush ecosystems as concomitant stressors, making it difficult to disentangle their separate impacts. Most previous studies reporting on changes in spatial coverage of sagebrush habitats in the western U.S. attributed the majority of observed changes to either climate variation or land cover change from either individual site observations (Perfors et al., 2003; Schwinning et al., 2003; Bates et al., 2006) or a small-area study (Walson et al., 2009) so that their contributions can be identified separately. However, an important consideration in the analysis of the effects of climate and land cover on the variation of sagebrush ecosystems at a regional scale is that the systems are not in equilibrium with one type of disturbance and their current distributions were modified by historical disturbances. The uncertainty over how sagebrush ecosystems respond to different disturbance regimes restricts our understanding of the net result of biotic feedbacks to climate and land cover modifications.

To evaluate the impacts of climate and land cover on the sagebrush habitats across decades, we applied a conceptual framework that examined multi-temporal distributions and variations of sagebrush components and linked component changes to potential disturbance sources. We assumed that the sensitivity of sagebrush components to an observed disturbance was mainly determined by their adaptations to local conditions through changes in both population and spatial coverage from existing habitats. Overall, we analyzed spatial and temporal variations of four components of the sagebrush ecosystem (bare ground, herbaceousness, shrub, and sagebrush) from our previous study, carried out in a 30,500 km^2 area in western Wyoming between 1988 and 2006 (Xian et al., 2012). The area was chosen because it has experienced substantial variations in sagebrush components observed from both Landsat imagery and recent field observations. Proportions of each of four sagebrush ecosystem components across 1988, 1996, and 2006 were estimated for every 30 m × 30 m pixel in the area covered by one Landsat scene in a backward manner. The percent cover of components in 2006 were first estimated using a combination of 30 m spatial resolution Landsat Thematic Mapper (TM) imagery, 2.4 m resolution QuickBird satellite imagery, and field measurements from the same year (Homer et al., 2012). The 2006 on-site vegetation measurements used as training data were combined with 2006 QuickBird images to extrapolate sagebrush coverage at a 2.4 m scale using regression tree models. After that, the 2.4 m distribution data were converted to 30 m and used as dependent variables while 2006 Landsat imagery and other ancillary datasets were used as independent variables to create regression tree models for estimating the 2006 percentage cover of each sagebrush component. Landsat TM images in 1996 and 1988 were then acquired for identifying change areas for the periods 2006–1996 and 2006–1988 through change vector analysis to create two mask files that retain all potential changes in sagebrush components and avoid seasonal changes related to normal phenological cycles (Xian et al., 2009; Xian and Homer, 2010). The masks were then applied to the 2006 baseline information of each sagebrush component to exclude all potential changes so that information from unchanged areas was used as two training datasets with Landsat imagery in 1996 and 1988, respectively, to create regression tree models for the 1996 and 1988 estimates. The percent cover of each ecosystem component in 1996 and 1988 was estimated separately in identified change areas from the 2006 base by using regression models in two years (Xian et al., 2012).

The 2006 field measurements and historical aerial photographs in early 1990s were used to validate mapping results.

In this study, we combined datasets for the distribution of sagebrush components bare ground, herbaceousness, sagebrush, and shrub with Landsat images, elevation, and long-time climate records at 2 km resolution to determine how sagebrush ecosystems respond to different potential causal factors. Our objective was to quantify both abrupt and gradual changes in sagebrush ecosystems between 1988 and 2006 related to different types of disturbances that could alter abundances and extents of these components. The response of the sagebrush ecosystems to climate variation, for example, would likely depend on several physical factors including elevation and biogeographical setting due to their inherent vulnerability to climate effects. However, without clear identification of the spatial regimes of different stressors, their relative impacts on sagebrush ecosystems in the region were inconclusive. Our second aim was to identify the most important regional-scale climate correlates for changes in sagebrush ecosystems. Because regional land cover change could potentially lead to some of these variations, climate change also might be working to amplify the intensity of stressors.

MATERIALS AND METHODS

Study Region

The study was conducted primarily in southwestern Wyoming, United States. Figure 1 represents the spatial extent of the study region, elevation, a picture of a sagebrush habitat, and percent sagebrush distribution in 2006 in the study area. The area contains a wide range of arid, semiarid, and montane shrublands and grasslands. The terrain ranges from 1600 to 3500 m in elevation and has frequent steep slopes. Our research focused on lower elevations (below 2377 m) where the landscape is dominated by sagebrush shrubland, intermingled with salt desert shrubland and grasslands.

The climate is typical of semiarid and high plains ecosystems, with mean maximum temperatures in July ranging between 29.5 and 35°C and mean minimum temperatures in January ranging from –15 to –12°C (Curtis and Grimes, 2004). Precipitation is generally low and locally variable (Dettinger et al., 1998), with the maximum precipitation occurring in the spring and early summer (Curtis and Grimes, 2004). Much of the yearly precipitation comes as winter snowfall rather than convective storms in the summer (Chambers and Pellant, 2008).

External Disturbance Analysis

We first compared change mask pairs obtained from change vector analysis in the periods of 1988–2006 and 1996–2006 (Xian et al., 2012) with time-series Landsat imagery and ancillary information to quantify potential disturbance types by category. Spectral feature differences of Landsat imagery in different time periods represent potential land cover change between the two dates. The change vector $\rho(t)$ used to determine potential land cover changes is calculated from the normalized spectral differences between a two-date image by

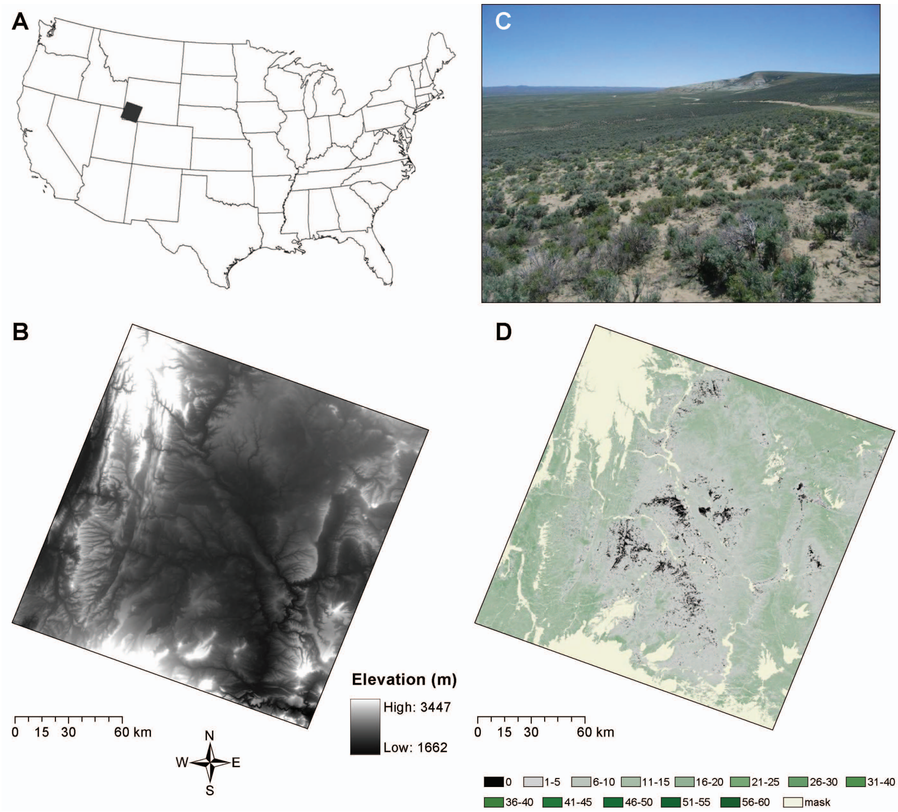

Fig. 1 Spatial extent of the study region (A), elevation (B), typical sagebrush habitat (C), and distribution of classified sagebrush cover (percent) in 2006 (D) in the southwestern Wyoming study area.

$$\rho(t) = \sqrt{\sum_{n=1}^{6} (R_{n,t} - R_{n,t-1})^2} \quad (1)$$

where n represents six spectral bands of Landsat imagery, R is the spectral radiance, and t is the time. The ρ value was calculated to determine change areas. Two types of change related to anthropogenic and natural disturbances were determined from changed areas. Most anthropogenic disturbances (AD) in this region are associated with natural gas and oil development, road construction, urban development, livestock grazing, and other agricultural activities. Oil and natural gas development and road construction were believed to be the dominant disturbances to sagebrush habitats over the last two decades in the region (Walston et al., 2009) and only road construction, urban development, and energy development were included in AD areas. Areas that had experienced AD were directly extracted from the spectral change Landsat imagery because footprints of these disturbances have distinct spatial and spectral features that usually persist for many years. Major natural disturbances in this area include those related to wildland fires and climatic variation. Areas that experienced wildland fires (WF) were extracted by using both image change information and fire history data (Eidenshink et al., 2007). Finally, we isolated areas where sagebrush component changes had occurred, but were not directly caused by anthropogenic or fire disturbances, and considered them as likely impacted by other disturbances (OD), including potential climate variations. After each change type was identified from the change mask pairs, we applied the change mask pairs containing different disturbance types to each component change map to obtain distributions of each component within different disturbance regimes.

Environmental and Climate Data Analysis

We chose Parameter-elevation Regressions on Independent Slopes Model (PRISM) climate data (Daly et al*.,* 2008) from 1988 to 2006 for regional climate change analysis. This dataset was chosen because records from individual climate stations cannot provide enough spatial detail for spatial correlation analysis. The PRISM data, with a spatial resolution of approximately 2 km, provides detailed information about spatially heterogeneous regional climates to which species usually respond (Walther et al*.,* 2002) and local scale effects of climate change that could improve the accuracy of response analysis for plant species (Pearson, 2006; Ashcroft et al*.,* 2009). We converted both precipitation and temperature records from PRISM to a geographic information system (GIS) raster and projected the data into the same projection space as sagebrush components to facilitate direct comparison.

We calculated mean annual precipitation, mean annual temperature, and their standard deviations for each grid from PRISM data. The normalized differences were also calculated as

$$\Delta x = \bar{x}_{97-06} - \bar{x}_{88-96} \quad (2)$$

$$ND = \frac{\Delta x - \Delta x_{min}}{\Delta x_{max} - \Delta x_{min}} \quad (3)$$

where $\bar{x}_{97-06}$ and $\bar{x}_{88-96}$ are averages of mean annual precipitation or temperature in periods of 1997–2006 and 1988–1996, respectively, and are the maximum and minimum values of Δx.

We also collected an additional 14 years of Landsat imagery from 1988 to 2006 to calculate the normalized difference vegetation index (NDVI). The NDVI, which is calculated from Landsat spectral reflectance measurements in the visible and near-infrared regions and scaled from 1 to 200, is a standard greenness index and has been used to detect significant changes in levels of green vegetation. The annual trend of NDVI and the standard deviation (σ_{NDVI}) from the 14-year distribution were also calculated for the entire study area and over different disturbance areas using the change mask pairs.

Correlation Analysis for Sagebrush Component Density Variations

Hypothesized influences of climate variation on sagebrush ecosystem component changes were analyzed for the area that experienced OD and also identified as the climatic-effect area (CEA); *t*-tests were conducted to evaluate differences of mean NDVI in the two periods, 1988–1996 and 1997–2006, in different disturbance areas. To test the hypothesis that the influence of climate variation is the primary causal factor for changes of sagebrush components in the CEA, we examined the relationship between changes in percent cover of sagebrush components and the respective climatic variables with correlation analysis. Percent cover of each component in 1988, 1996, and 2006 were first aggregated to 2 km spatial resolution and averaged in each 2 km grid in the CEA by

$$\sum_{t=1}^{3}\sum_{i=1}^{n} PC_{i,t}/3n \quad (4)$$

where *n* is the total number of 30 m grids with any percent cover (PC) of a sagebrush component within a 2 km grid. Spatial linear correlation analyses between the means of sagebrush components and the mean annual precipitation, or temperature, or annual trend of precipitation, or annual trend of temperature were only performed for climatic effect areas because sagebrush variations associated with AD and WF were assumed not directly related to climate forcing. Similarly, seasonal means also were calculated from PRISM data for correlation analysis. To simplify the correlation analysis, two seasons similar to the field experiment designed for evaluating precipitation timing on sagebrush (Bates et al., 2006) were considered: winter (from October to March) and summer from (April to September). To further test the hypothesis of climate influence, correlation analyses were also conducted by randomly selecting 1000 samples for sagebrush components and mean annual precipitation in unchanged areas.

RESULTS

Variation Patterns of Sagebrush Components

Direct comparison of sagebrush component distribution change reveals that extents of herbaceousness, sagebrush, and shrub had net decreases of 12, 31, and 30 km^2, respectively, while bare ground experienced a net increase of 94 km^2 from 1988 to 2006. The full spectral variations of sagebrush components under different disturbances of AD, WF, and OD are depicted in Figure 2. Anthropogenic activities enlarged the extent of bare ground at the high percent cover end (Fig. 2A1) and reduced abundances of other components in the ranges from medium to low percent cover (Figs. 2B1–2D1). Fire disturbances mostly occurred after 1996, resulting in increased bare ground cover by shifting and widening the distribution toward the high percent end (Fig. 2A2), while reducing the other components in both the middle and low percent ranges (Figs. 2B2–2D2). Climate perturbations appeared to impact sagebrush components in almost all cover ranges by increasing the extent of bare ground and shrinking the extents of other covers (Figs. 2A3–2D3). Substantial increases in bare ground and decreases in sagebrush vegetation components appear to be affected by climate variations only after 1996.

All sagebrush components had the largest change ratios in mean percent cover in the WF area (Table 1). Compared with changes in the WF and AD regimes, changes of mean percent cover in the CEA were relatively small. The mean percent cover of

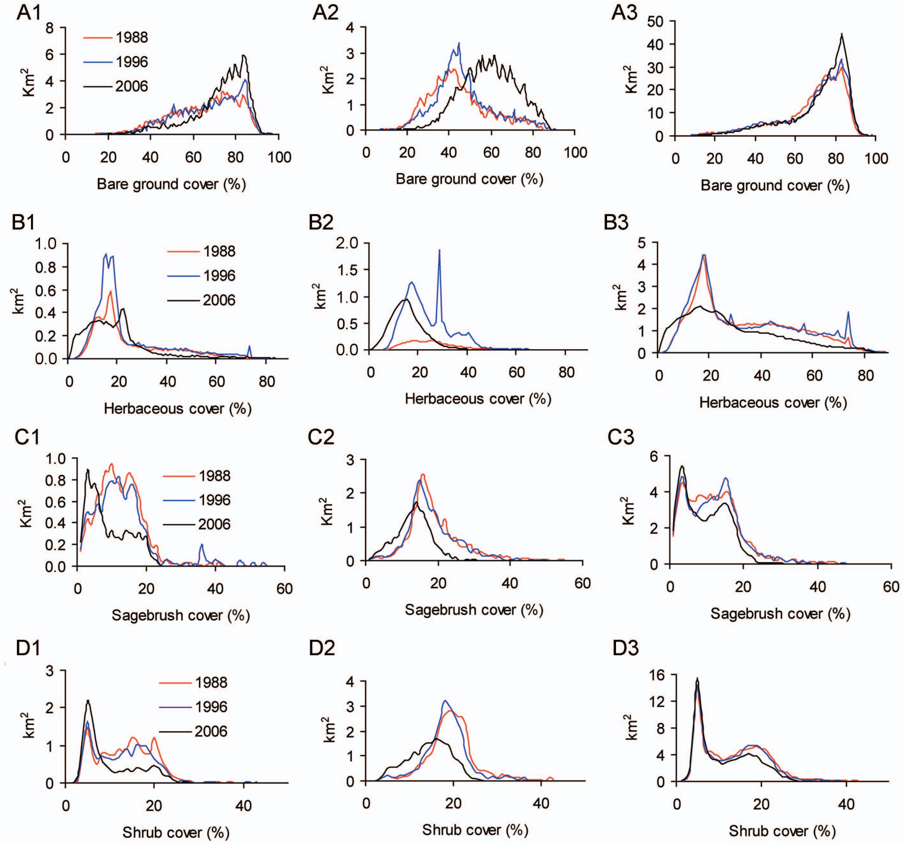

Figure 2. Percent cover of sagebrush components in different impact regimes. Panels from top to bottom are bare ground (A1–A3), herbaceousness (B1–B3), sagebrush (C1–C3), and shrub (D1–D3) in anthropogenic disturbance (column 1), wild fire (Column 2), and climatic effect (Column 3) areas.

sagebrush vegetation declined from 37.8% in 1988 to 28.8. The ratio of vegetation to bare ground also declined from 0.62 to 0.44.

Climate and Greenness Trends

The regional mean annual precipitation and temperature showed apparent and opposite trends for annual precipitation (decreasing) and temperature (increasing) between 1988 and 2006 (Fig. 3). The areal averages of annual precipitation (Fig. 3A1) were above and below the 19-year mean from 1995 to 1999 and from 2000 to 2003, respectively. Precipitation declined from 1996 to 2002, recovered close to the mean in 2003 and 2004, and declined again after that. The areal averages of mean annual temperature (Fig. 3B1) show an increasing trend after 1997. Generally, the 19-year (1988–2006) and 11-year (1996–2006) annual precipitation and temperature trends were –0.38 mm/year, –7.02 mm/year, 0.03°C/year, and 0.07°C/year, respectively,

Table 1. Mean Percent Cover of Sagebrush Components from 1988 to 2006 in Areas Experiencing Different Disturbances Across Southwestern Wyoming

Sagebrush habitat	Disturbance[a]	1988	1996	2006	Change pct. (1988–2006)
Bare ground	AD	60.1	62.2	56	14.6
	OD	61.1	62.3	65.5	7.2
	WF	40.1	42.9	68.9	39.7
Herbaceous	AD	17.4	17.1	11.7	–32.8
	OD	21.8	22.1	15.7	–28.0
	WF	21.1	19.9	12.3	–41.7
Sagebrush	AD	8.5	7.6	5.2	–38.8
	OD	6.7	6.5	5.3	–20.9
	WF	15.6	15.2	10.5	–32.7
Shrub	AD	10.4	9.5	7.3	–29.8
	OD	9.3	8.9	7.8	–16.1
	WF	17.6	16.7	12.3	–30.1

[a]AD = anthropogenic disturbance; WF = wildlife disturbance; OD = other disturbance.

for the entire study area. The decrease in precipitation and increase in temperature trends intensified after 1996. Furthermore, both precipitation and temperature trends were different over different disturbance areas, but similarly following the areal patterns. The 19-year precipitation trends were 0.52 mm/year, –1.97 mm/year, and –0.21 mm/year for the AD (Fig. 3A2), WF (Fig. 3A3), and climatic-effect (Fig. 3A4) areas, respectively. However, the 11-year trends from 1996–2006 had drying patterns, with most years occurring below the long-term average precipitation level, and a –6.94 mm/year, –8.84 mm/year, and –7.59 mm/year for these disturbance areas, respectively. Declines in precipitation across these regimes would be expected to have impacts on abundances of sagebrush components. The temperature trends displayed no obvious difference across different disturbance types, but the 11-year warming trends were substantial, 0.07°C/year for the AD area (Fig. 3B2), 0.08°C/year for the WF area (Fig. 3B3), and 0.07°C/year for the CEA (Fig. 3B4). Furthermore, no persistent seasonal shifts in precipitation and temperature were observed for the study area.

Figure 4 displays the spatial distributions of 19-year mean annual precipitation and its standard deviation (Figs. 4A–4B), mean annual temperature and its standard deviation (Figs. 4C–4D), and σ_{NDVI} and annual trend of NDVI in 14 years (Figs. 4E–4F). The spatial distributions of mean annual precipitation and mean annual temperature showed both precipitation and temperature had several patches with higher variance that emerged across the region. However, the central part of the study area was relatively dry and warm with relatively small variations in both precipitation and temperature. Areas having large magnitudes of standard deviation in either precipitation or temperature indicated places experiencing intensified climatic variations. Correspondingly, the NDVI annual trend reveals several negative areas, including the

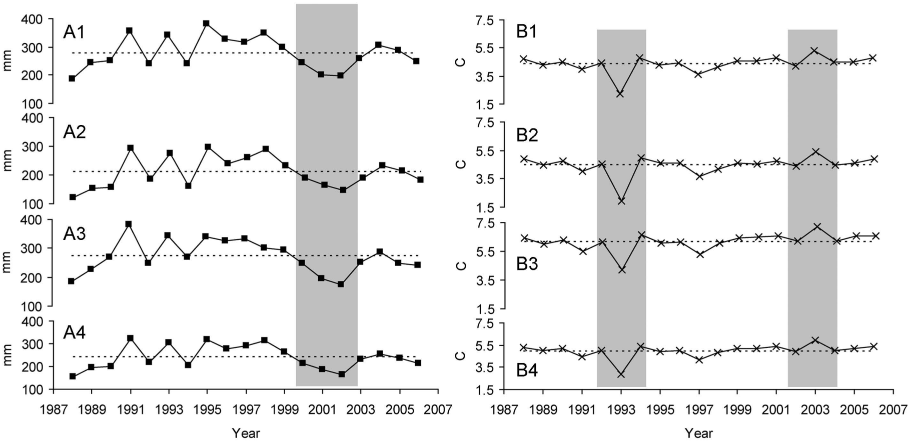

Fig. 3. Annual mean of precipitation and temperature from 1988 to 2006 for the study area using PRISM 2-km and climate station data. The x-axis is for year and the y-axis is for precipitation in A1–A5 and for temperature in B1–B5. The graphs show the temporal variation of mean annual precipitation and temperature, respectively, in areas associated with different categorical disturbances: areal mean of mean annual precipitation and mean annual temperature for the entire study area (A1) and (B1), for the area experiencing anthropogenic disturbance (A2) and (B2), for the area experiencing wildland fire (A3) and (B3), and for the area experiencing climate variation impact (A4) and (B4). The dash lines in A1–A4 and B1–B4 are the 19-year means for the set group of interest. The grey areas in both A1–A4 and B1–B4 highlight precipitation and temperature trends.

one in the southeastern corner caused by wildland fire (Fig. 4F). Most areas dominated by sagebrush habitats, however, do not have very high values of both σ_{NDVI} and NDVI annual trend; *t*-test results show that the WD area has the largest and the CEA the smallest differences in both mean NDVI and σ_{NDVI} between the 1988–1996 and 1997–2006 periods (Table 2). The significant levels of mean NDVI are 95% in AD and WD areas and 90% in CEA.

Effects of Climate Variations

Analysis of climatic variables in both climatic-effect and sagebrush-ecosystem-unchanged areas shows that climatic trends and their variations were more noticeable in the CEA than in the unchanged area (Table 3). The variability in precipitation ($\overline{\sigma}_{pmean}$) was larger in the CEA (69.2 mm) than that in the unchanged area while the $\overline{\sigma}_{tmean}$ in the unchanged area (7.0°C) was slightly larger than that in the CEA. The ND_{pmean} in the CEA (0.6 mm) is larger than that in unchanged area, suggesting an apparent deficit in precipitation in the CEA after 1996. The temperature trend, however, displayed no difference in ND_{tmean} between the CEA and the unchanged area.

Correlation and linear regression analyses, conducted in the climatic-effect area using mean annual precipitation and three-year (1988, 1996, and 2006) mean percent cover, and ND cover trends between 1997 and 2006 showed significant correlations (Table 4). The significant negative correlation between bare ground and annual

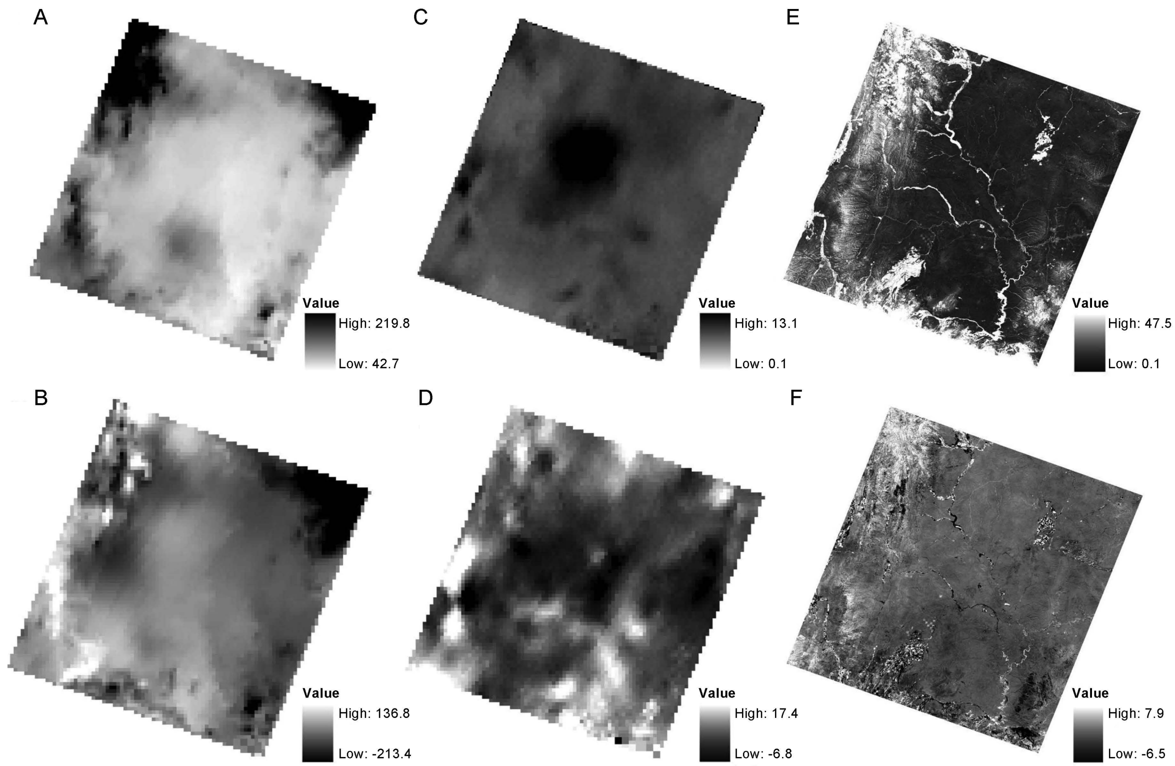

Fig. 4. Standard deviation of mean annual precipitation in mm (A), normalized difference of mean annual precipitation (B), standard deviation of mean annual temperature in °C (C), normalized difference of mean annual temperature (D), standard deviation of NDVI in 14 years (E), and annual NDVI trend (F) across the study area.

Table 2. *t*-test Results for Mean NDVI in Different Disturbance Areas in 1988–1996 and 1997–2006[a]

Disturbances	Mean/Std	1988–1996	1997–2006	Significance
AD	Mean	114.97	114.58	$p < 0.05$
	Std	8.13	7.61	
WD	Mean	124.68	120.16	$p < 0.05$
	Std	9.42	6.27	
CEA	Mean	119.64	119.60	$p < 0.1$
	Std	13.69	13.56	

[a]Significance levels of mean NDVI differences are also given.

Table 3. The 19-Year Annual Average (1988–2006), Annual Trends, and 10-Year Annual Trends of Precipitation and Temperature by Change Category for Southwestern Wyoming[a]

Variable	Climatic effect area	Unchanged area
Mean annual precipitation (mm)	240.2	277.9
88–06 precipitation trend (mm $year^{-1}$)	–0.4	–0.2
96–06 precipitation trend (mm $year^{-1}$)	–7.0	–7.6
$\overline{\sigma}_{pmean}$ (mm)	69.2	65.7
ND_{pmean}	0.6	0.5
Temperature (°C)	4.4	5.0
88–06 temperature trend (°C $year^{-1}$)	0.0	0.1
96–06 temperature trend (°C $year^{-1}$)	0.0	0.1
$\overline{\sigma}_{tmean}$ (°C)	6.8	7.0
ND_{tmean}	0.4	0.4
Elevation (m)	2133.0	2102.2

[a]Average standard deviations of mean annual precipitation ($\overline{\sigma}_{pmean}$), temperature ($\overline{\sigma}_{tmean}$), normalized differences of annual mean precipitation (ND_{pmean}) and temperature (ND_{tmean}) in both climatic-effect and unchanged areas are also listed.

precipitation suggests that increases in bare ground could be related to the reduced precipitation. Correlations of precipitation with other sagebrush components were positive and significant. The correlation analysis shows a very weak and insignificant correction between 19-year annual precipitation and mean coverage of the sagebrush component. However, the precipitation trend between 1997 and 2006 is significantly correlated with the variations of sagebrush component densities of bare ground, sagebrush, and shrub. Mean annual temperature was negatively correlated with the mean percent cover of bare ground but positively correlated with other sagebrush components. However, linear regressions indicated that all r^2 values were very small (< 0.06)

Table 4. Correlations between Means of Percent Covers of Sagebrush Components and Annual Precipitation/Mean Annual Temperature between 1988 and 2006, and Means of Percent Sagebrush Components and Annual Precipitation Trend/Mean Annual Temperature Trend between 1996 and 2006 in Climatic-Effect Area

	Bare ground	Herbaceous	Sagebrush	Shrub
r^2 of mean prec.	0.28***	0.30***	0.12**	0.22***
r^2 of mean temp.	0.02	0.06*	0.01	0.02
r^2 of prec. trend	0.34***	0.33***	0.28***	0.35***
r^2 of temp. trend	0.07*	0.03	0.00	0.04
n	59	56	52	59

[a]Values of r^2, number of samples, and significant level are included as * for $p < 0.1$, ** for $p < 0.05$ and *** for $p < 0.01$.

Table 5. Correlations between Means of Percent Covers of Sagebrush Components and Annual Precipitation/Mean Annual Temperature between 1988 and 2006 in Unchanged Areas[a]

	Bare ground	Herbaceous	Sagebrush	Shrub
r^2 for mean prec.	0.16***	0.01**	0.17***	0.18***
r^2 for mean temp.	0.01***	0.01***	0.01**	0.01**
n	961	933	944	941

[a]Values of r^2, number of samples, and significant level are included as * for $p < 0.1$, ** for $p < 0.05$, and *** for $p < 0.01$.

and none of these correlations were significant ($p > 0.05$). Mean annual temperature trend between 1997 and 2006 has very weak or no correlation with sagebrush component densities. In fact, the gradual decrease of sagebrush vegetation abundance was preceded by precipitation stress after 1996. In contrast, we identified similar but weak correlations between annual mean precipitation and sagebrush components in the unchanged area: bare ground ($r^2 = 0.16$), herbaceous ($r^2 = 0.01$), sagebrush ($r^2 = 0.17$), and shrub ($r^2 = 0.18$) (Table 5).

Mean seasonal precipitation and temperature had similar correlation patterns with mean annual variables. However, no apparent differences in r^2 values were found between the two seasons.

DISCUSSION

Our results demonstrate the utility of remote sensing time series data for detecting both abrupt and subtle changes of sagebrush ecosystems over two decades in a semi-arid environment. The findings provide useful perspectives on the spatial distributions and temporal variations of sagebrush ecosystem components resulting in the expansion of bare ground and the declines of other sagebrush components. It is noteworthy that the approach used in this study can also provide objective analyses of potential causal factors resulting in either abrupt or subtle changes in ecosystems. By connecting variations of spatial extents of sagebrush components and external disturbances, we isolated causal factors of land cover change dominated by anthropogenic activities, wildland fire, and climate variation.

Anthropogenic disturbances associated primarily with energy development were readily identified from time-series satellite imagery. For these disturbance areas, sagebrush vegetation was usually partially removed and replaced by non-vegetative materials, resulting in the loss and degradation of sagebrush vegetation, likely having negative impacts on wildlife populations such as pronghorn (Sawyer et al., 2006) and sage-grouse (Aldridge and Boyce 2007; Doherty et al., 2008). Our analysis indicates that 10 to 15% of sagebrush ecosystem changes in the area were directly related to anthropogenic disturbances.

The occurrence of wildland fire was another major change agent, resulting in abrupt changes in sagebrush ecosystems in the region. The location and extent of these changes were readily quantified using both satellite image and existing fire occurrence information. The latter data were used to ensure that fires in some herbaceous areas that leave only fleeting scars difficult to detect with remote sensing change analysis could still be captured. Overall, approximately 12–23% of the changes in sagebrush components could be directly attributed to fires. Compared with AD, wildfire caused more serious disturbances in sagebrush vegetation. In general, the sagebrush vegetation recovery rate after fire varies from 35 to over 100 years, depending on the system and species of sagebrush (Baker, 2006). Both WD and AD resulted in abrupt changes in sagebrush ecosystems by greatly shifting the mean percent cover of each sagebrush component.

Despite strong links between changes in sagebrush components and land cover change, our analyses suggest that over 60% of measured sagebrush ecosystem change was attributed to other change agents. Additional variations in sagebrush components are likely driven by factors such as livestock grazing, insect or disease outbreaks, or climate variation (Davies et al., 2007; Chambers and Pellant, 2008). We discounted insect outbreaks as a factor since there are no reports of large-area outbreaks during the period 1988–2006. Livestock grazing occurs extensively in the region (Anderson and McCuistion, 2008) and could likely factor into observed component change. However, because grazing has been a consistent factor on the landscape over the duration of our study (Connelly et al., 2004), and because most observed component changes in our study occurred after 1996, we infer normal sustained grazing would not likely produce such large reductions between 1996 and 2006 alone.

We had hypothesized that some variations in sagebrush ecosystems were primarily attributable to regional climate variation. Regional annual precipitation started declining after 1996 and reached the lowest value in 2002, 71% of the 19-year mean. Mean annual temperature exhibited a weak increasing trend after 1996, leading to warmer temperatures than the 19-year mean between 1996 and 2006. In the area designated as the CEA, sagebrush ecosystems experienced relatively moderate changes in both mean percent cover and spatial extent. Changes of sagebrush component in the CEA were more moderate compared with changes in the AD and WF areas.

Correlation analyses revealed that changes of sagebrush ecosystems in climatic effect areas were significantly related to the amount of annual precipitation. Subsequently, no apparent difference in correlation between seasonal precipitation and sagebrush ecosystem variation was observed. In addition, there was no significant correlation between mean annual temperature and variations of sagebrush components. The result agrees with other field experiments that concluded that seasonal precipitation variation would alter sagebrush ecosystems only if precipitation shifted from winter to spring and such a shift lasts more than four years (Bates et al., 2006). The moderate seasonal shifts in precipitation that do not vary greatly from historical patterns do not appear to cause major disruptions to ecosystem composition or productivity (Grime et al., 2000; Knapp et al., 2002; Svejcar et al., 2003). In addition, the resilience of sagebrush communities to climate perturbation is long, as many of the vegetation shifts tracked in our study area did not appear to begin until the fourth year after precipitation shifts were applied. Our analysis indicated that southwestern Wyoming experienced at least four consecutive years of precipitation from 1996 to 2006 that were below the 20-year average. The decline of precipitation in both winter and spring/summer seasons would be unfavorable to both shallow and deep-rooted vegetation (Schwinning et al., 2005). While increased precipitation events might be beneficial, prolonged drought conditions can cause mortalities in shallow-rooted vegetation (i.e., our herbaceous measurements), and might have reduced the average adaptive capacity of some deep-rooted species, thus increasing vulnerability of sagebrush ecosystems to climatic changes. Annual precipitation stress and its trend are likely the most influential climatic stressors affecting sagebrush ecosystem abundance.

It is noteworthy that satellite remote sensing provided repetitive and consistent observations of large areas of the terrestrial surface over time, and is capable of generating high-temporal-frequency information about conditions in sagebrush ecosystems. The image change analysis and modeling tools can provide quantitative details about the extent and spatial distribution of sagebrush components across a large area. The approaches used in the study provide objective assessments for identifying potential factors that cause both abrupt and gradual variations in sagebrush ecosystems. The information can be used to assess the impacts of both anthropogenic activities and natural disturbances, including climate variation, on long-term variations of sagebrush components. These approaches could be used as a monitoring tool for assessing long-term landscape variations in the semiarid environment.

CONCLUSIONS

We analyzed changes in sagebrush ecosystem components over two decades to quantify the relationship of these changes with potential causal factors. The use of time series remote sensing data and change analyses allowed quantification of the spatial distribution of change patterns of sagebrush components and identification of the roles of different disturbance drivers. The responses of sagebrush components to land cover and climate changes were different. Notable variations in spatial extent and mean percent cover of sagebrush components across different disturbance regimes were discovered. Abrupt changes of sagebrush components associated with the land cover change induced by human activities and fire occurrences were segregated from gradual changes induced by climatic impacts. Anthropogenic developments, wildfire, and recent drought conditions, which led to below-normal precipitation and a warming trend during the 1996–2006 period, were strongly associated with observed increases in bare ground cover and decreases in vegetation cover, including herbaceous vegetation, sagebrush, and shrub. Due to the semiarid nature of the region, sagebrush vegetation is sensitive to annual precipitation variations, which are expressed through changes in abundance and distribution that we were able to quantify. Compared with the land cover change impacts, climatic perturbation produced less change in mean percent cover but a wider range of declines in percent cover of sagebrush vegetation. Furthermore, significant correlations of precipitation with reductions in the extent of sagebrush components over time suggests that impacts of precipitation and other climatic variables on ecosystem health may persist over long time scales. Our study found that sagebrush ecosystems centered around the elevation of 2100 m, where precipitation had much higher spatial variance, vegetative cover had relatively low abundances, and most bare ground had medium to high percent cover, are most likely to be vulnerable to climate changes. Finally, our connection of medium-resolution precipitation variation to remote-sensing-based sagebrush ecosystem variation has important implications for the ability to make future predictions of climate change trajectories for sagebrush ecosystem change analysis at much larger spatial scales. The approaches could be used as a monitoring tool for assessing long-term landscape conditions and potential impact mechanisms in a semiarid environment.

ACKNOWLEDGMENTS

We would like to thank Drs. Jim Vogelmann and Lei Ji from USGS Earth Resources Observation and Science Center for their suggestions and comments for improving the manuscript. 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 of 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. George Xian's work is performed under USGS contract G08PC91508.

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