

Resilience of Satellite-Based Measures of Greenness to Fire Decreases with Aridity in Sagebrush-Steppe Rangelands

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ABSTRACT

Satellite measures of greenness were measured in regions differing in synoptic climate, floristics, fire history, and livestock grazing in sagebrush steppe of the upper Snake River Plain of the Great Basin USA. We hypothesized that resilience to fire, as indicated by recovery of greenness to pre-fire levels, would vary among two sagebrush community types that differ in climate, and also with livestock grazing. Study areas were in and around three large areas burned in Wyoming big sagebrush (*Artemisia tridentata* spp. *wyomingensis*) communities, and 13 smaller burn areas in a wetter and cooler region that included higher elevations and a greater occurrence of mountain big sagebrush (*A. t. spp. vaseyana*; also having *A. tripartita*) communities. Grazing effects were evaluated in and around a long-term livestock enclosure in Wyoming sagebrush region. The modified soil-adjusted vegetation index (MSAVI₂) was calculated from one Landsat scene per year to assess greenness at about the time of peak biomass and greenness, from 1984 to 2004. MSAVI₂ was about 50% lower in the Wyoming compared to mountain sagebrush communities, and had transient increases following fire in Wyoming but not mountain sagebrush communities. More persistent effects of fire were apparent in the variability of MSAVI₂ among pixels within a scene, and in relationships of this variability to annual precipitation patterns. Variability in MSAVI₂ increased for several years following fires in the Wyoming sagebrush region, due to increased sensitivity to annual precipitation ($r^2 = 0.47$ to 0.70). In contrast, variability in MSAVI₂ decreased following fires in the mountain sagebrush region, and was not correlated to annual precipitation. The time required for variability in MSAVI₂ to recover to pre-fire levels was greater in grazed compared to ungrazed areas of the Idaho National Laboratory study area, but there were otherwise no detectable impacts of grazing on MSAVI₂. The less resilient Wyoming sagebrush communities had greater and more enduring changes in greenness after fire. The climatic and biogeographic differences examined here may span a threshold for ecosystem resilience to fire.

KEYWORDS: *fire, geographic information systems, grazing, MSAVI, precipitation, remote sensing, sagebrush-steppe, spectral vegetation indices.*

INTRODUCTION

Sagebrush (*Artemisia*) steppe ecosystems throughout western North America experience combinations of natural and anthropogenic impacts, such as altered fire regimes and domestic livestock grazing, in addition to natural variation in precipitation (Anderson and Inouye 2001). Fire and livestock grazing cause changes in population and community structure and ecosystem processes that could modify climate-productivity relationships over the vast sagebrush-steppe biome in the Great Basin, USA. The separate effects of fire or grazing disturbances on semiarid rangeland function have been studied (Anderson and Holte 1981, Hosten and West 1994, Anderson and Inouye 2001, Wambolt et al. 2001, Diaz-Delgado et al. 2002, Washington-Allen et al. 2004), but studies of the multiple, potentially interacting effects of such disturbances are scarcer (Valone 2003, Geiger and McPherson 2005). Additionally, ecosystem responses to disturbance have mostly been studied at the small-scale, plot level (e.g., Anderson and Holte 1981, Hosten and West 1994, Anderson and Inouye 2001, West and Yorks 2002), therefore, little quantitative information exists over large spatial and temporal scales (e.g., Washington-Allen et al. 2004) to help address the potentially complex effects of multiple disturbances on ecosystem structure and function. Large scale, landscape-level assessments of the separate and combined effects of weather variation, fire, and livestock grazing disturbances are needed to better match the scale at which rangeland management occurs.

Remote sensing can provide periodic measures of vegetation over large areas that exceed the measurement capabilities of traditional, ground-based assessments (Washington-Allen et al. 2004). Previous studies derived spectral vegetation indices (SVI's) from remotely sensed ratios of red and near-infrared reflectance as a measure of the earth's greenness, which can indicate abundance of rangeland vegetation (e.g., Graetz and Gentle 1982, Pickup and Foran 1987, Graetz et al. 1988, Smith et al. 1990, Pickup et al. 1993, Senseman and Bagley 1996, Elmore et al. 2000, McGwire et al. 2000, Ramsey et al. 2004, Wallace et al. 2004), particularly as it varies in time in response to precipitation and land-use (Paruelo and Lauenroth 1998, Paruelo et al. 2001, Washington-Allen et al. 2004).

This study utilized a 20-year archive of Landsat data to determine how ecosystem greenness responds to fire in two regions that differ in climate on the Upper Snake River Plain of the Great Basin, USA. Both regions are dominated by big sagebrush steppe (*Artemisia tridentata*), but with the mountain big sagebrush (*A. t. ssp vaseyana*) and some three-tip sagebrush (*A. tripartita*) community types dominating the relatively cooler and wetter region compared to Wyoming big sagebrush (*A. t. ssp tridentata*) communities dominating the warmer and drier region. A lack of recovery following wildfire is perceived to be causing rapid losses of Wyoming sagebrush habitat, whereas mountain sagebrush communities are considered to be more resilient - although few studies have attempted to quantitatively substantiate perceived differences in the functioning of these community types (eg. Chambers et al. 2007). Larger burn areas of fires are increasingly occurring in the Wyoming sagebrush communities, recently attaining about 400 K ha (2007 Murphy Complex Fire in W N America). Widespread acceleration of fire frequencies and corresponding loss of fire-sensitive native perennials such as sagebrush is well known to occur with invasion by exotic annuals such as cheatgrass (*Bromus tectorum*). The fire-cheatgrass cycle can decrease resilience of species assemblages, sometimes altering succession to the extent of causing type conversion from perennial shrub steppe to near monocultures of annual grasses. The subject region has not yet experienced this degree of invasion by cheatgrass, thus providing a rare opportunity to examine fire effects independent of cheatgrass. We also wished determine how domestic livestock grazing, the most extensive land use of the region, affects recovery of greenness following fire in the warmer and drier region. Water availability in these semi-arid rangelands is limited and highly variable in time (Anderson and Inouye 2001), and primary production is linked to variation in rainfall (LeHouerou et al. 1987). Thus, we anticipated variability in greenness to be an important indicator of ecosystem stability. We hypothesized that post-fire recovery of greenness to levels observed in burned areas would occur more quickly in the wetter and cooler region, and in areas in which grazing had been excluded.

Furthermore, we hypothesized that variability in SVI's resulting from fire would result from a greater coupling of vegetation greenness to precipitation patterns.

METHODS

Areas with different fire and grazing histories since 1939 were identified from US Bureau of Land Management (BLM) Geographic Information Systems (GIS) data for lands within or nearby two adjacent regions of the Upper Snake River Plain (Idaho; Figures. 1, 2); the Idaho National Laboratory (INL) and the U.S. Department of Agriculture Sheep Experiment Station (USSES). Both areas were ideal for this study because of their relatively flat topography and large homogenous management units (livestock grazing allotments) where wildfires have occurred frequently over the last two decades. Additionally, both areas have experienced similar livestock grazing. The two study areas are also unique from each other because of their geographic locations; with the USSES situated approximately 100 km north of the INL on the northernmost extent of the Upper Snake River Plain, it is higher in elevation (approx. 1500 – 1950 m) and experienced greater amounts of average yearly precipitation over the 20-year study period ($300.5 \text{ mm} \pm 75.1$) compared to the INL (approx. 1480 – 1600 m; $192.7 \text{ mm} \pm 60.4$; $F_{1,40} = 26.28$, $P = 0.000$; Figure 3).

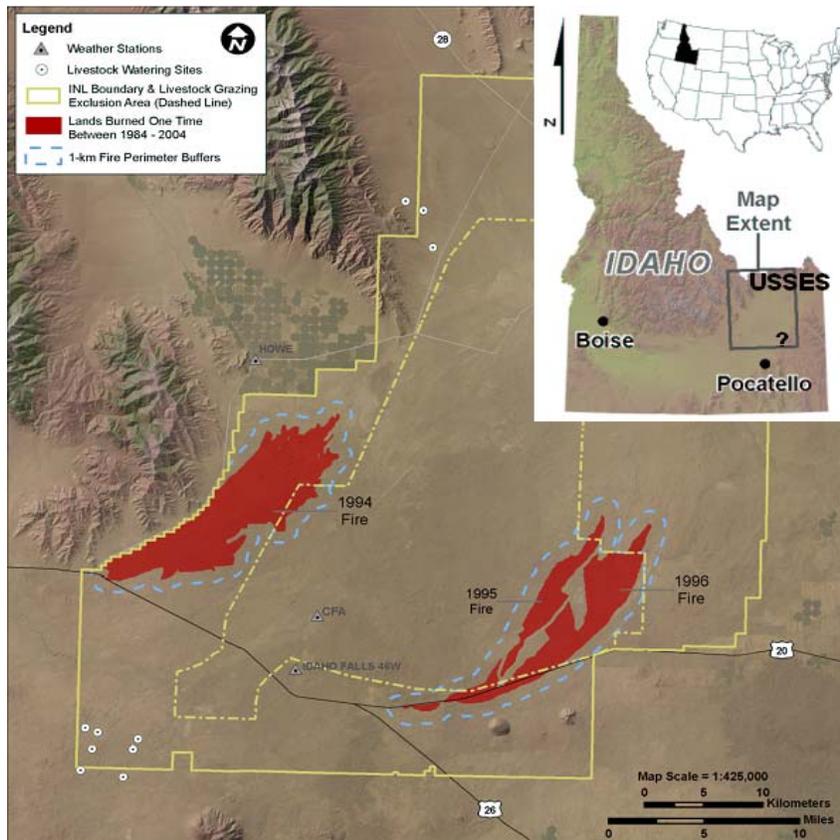


Figure 1. Map of the Idaho National Laboratory (INL) with disturbance history lands for the 1994, 1995, and 1996 fires indicated in red. Dashed blue lines show 1-km fire buffers. Solid yellow line indicates INL boundary with lands closed to livestock grazing since 1950.

Areas within 1 km buffers of wildfire perimeters were categorized as follows: 1) unburned areas where livestock grazing has been excluded since 1950; 2) areas having livestock grazing, in allotments administered by the BLM and referred to here as pasture; 3) ungrazed areas that have been burned once during the study years and not any other time since 1939; and 4) grazed and burned lands. Whereas the INL region offered replicate areas having all of these conditions, there were no ungrazed areas in the USSES region. No pixels within 90 m of boundaries of burn or grazed areas were measured, to avoid

edge effects. Fire years were 1994, 1995, or 1996 on the INL and in 1986, 1988, 1994, or 1998 on the USSSES. These burns encompassed significant variation in annual precipitation, and provided 6 – 18 years of recovery from fire. BLM summer stocking rates of domestic grazers (cattle and sheep) varied little over the last 20 years and ranged from 12.4 to 33.5 acres/active animal unit months (AUM). Grazing was excluded from burned areas for two years following fire.

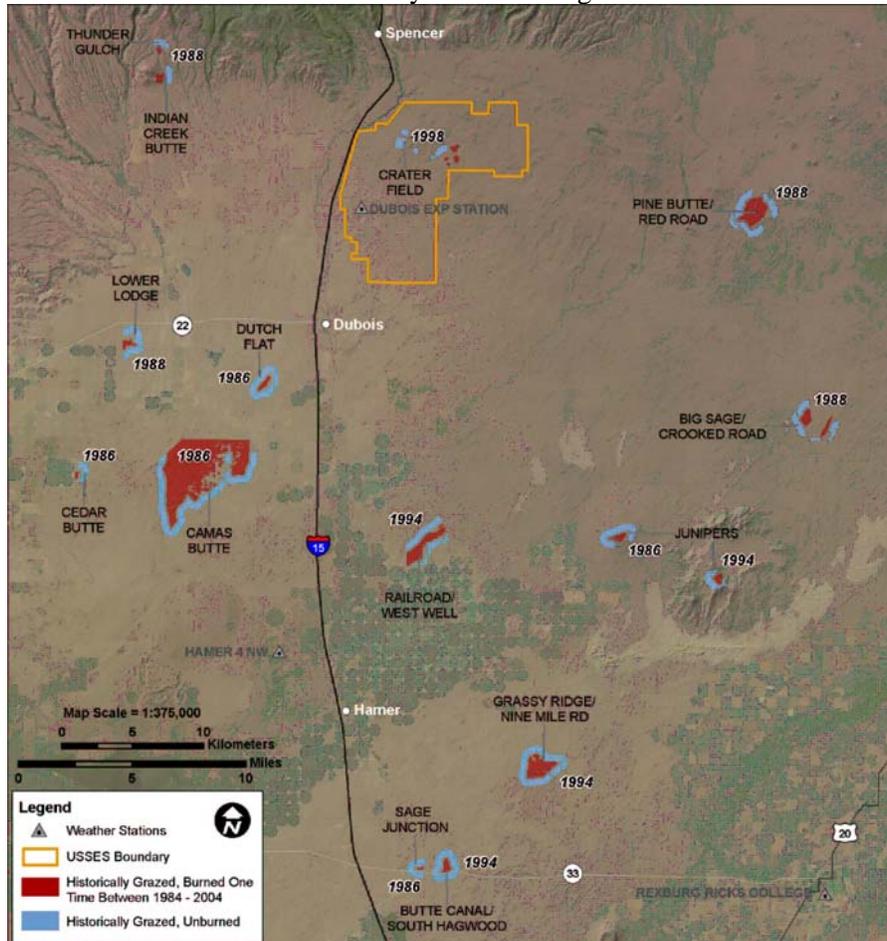


Figure 2. Map of the U.S. Sheep Experiment Station (USSSES) located on the northern Upper Snake River Plain (Idaho) with grazed lands that were burned one time by fire in either 1986, 1988, 1994, or 1998 fires indicated in red. Solid blue areas show 1-km fire buffers for historically grazed, unburned areas.

We examined spatial and temporal variability in cloud-free Landsat 5 Thematic Mapper (TM) or 7 Enhanced Thematic Mapper (ETM+) image per year. Image sampling dates were selected for 19 of the years from 1984 – 2004, in a 30-day window centered on 27-June. We were unable to use more sampling dates per year, due to cloud cover or data gaps, and therefore, adjusted our inquiry to avoid complications due to phenological variability among years. The 30-day window evaluated was roughly equivalent to the peak summer growing season for sagebrush-steppe, as estimated by Paruelo and Lauenroth (1995 and 1998) using the maximum normalized difference vegetation index (NDVI) derived from Advanced Very High Resolution Radiometer (AVHRR) data. Pixels (30 m resolution) were converted to at-satellite reflectance, coregistered, and radiometrically normalized with relative corrections for atmospheric attenuation using the empirical, multiple-date, regression method (Jensen 1996).

The second modified soil-adjusted vegetation index (MSAVI₂) was calculated to quantify the abundance of sagebrush-steppe vegetation. MSAVI₂ increases the dynamic range of the vegetation signal and minimizes soil background influences by enhancing the red (band 3, 630-690 nm) and near-infrared (band

4, 750-900 nm) reflectance ratios (Qi et al. 1994). It was calculated using the equation developed by Qi et al. (1994):

$$MSAVI_2 = \frac{2*(\text{band } 4) + 1 - \sqrt{(2*(\text{band } 4) + 1)^2 - 8*(\text{band } 4 - \text{band } 3)}}{2}$$

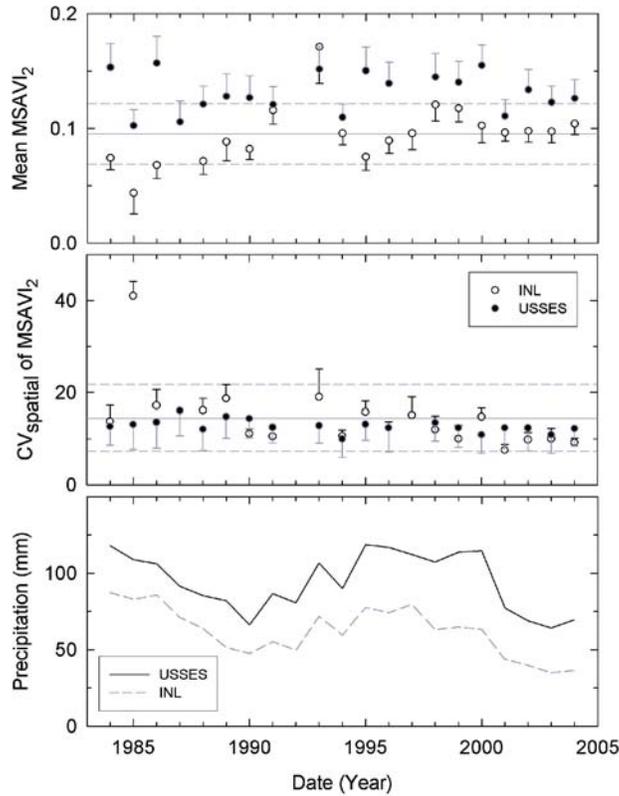


Figure 3. Mean MSAVI₂ (+ or - SD) and mean CV_{spatial} of MSAVI₂ (+ or - SD) for unburned, grazed pixels of INL (open symbols) and the USSES region (closed) from 1984 - 2004, and sliding, three-year averages of cumulative yearly precipitation (mm) during the study period. Solid lines represent INL group means and dashed lines show ± 1 SD for all years combined (n = 19 years).

Total vegetation cover is commonly less than 50% or even 25% of ground area in sagebrush-steppe at the INL (Anderson and Inouye 2001, R. Blew, unpublished data). MSAVI has been used to quantify sparse vegetation cover in arid and semi-arid rangelands, and significantly correlates to field measures of canopy and areal ground cover (Senseman and Bagley 1996, Purevdorj et al. 1998, McGwire et al. 2000). In arid environments with less than 25% vegetation cover, MSAVI had a higher and more constant sensitivity over the full range of plant cover compared to other soil-adjusted SVI's (Rondeaux et al. 1996). Other soil-adjusted SVI's require constant, empirically defined, soil adjustment factors to minimize soil influences on canopy spectra (e.g., SAVI, TSAVI), and are therefore difficult to apply in assessing impacts of disturbances that alter soil exposure (Rondeaux et al. 1996). Defining an appropriate soil adjustment factor for pixels across an entire image, where the quantity and type of vegetation and soil is not constant, is likely to cause non-systematic errors in estimates of variation in SVI's among pixels that differ in soil exposure due to disturbance regime or variation in precipitation. MSAVI₂, a variant of MSAVI avoids this problem by using a dynamic, inductive soil adjustment factor that varies inversely with the amount of vegetation present in each pixel (Qi et al. 1994). MSAVI₂'s increased sensitivity to vegetation is important for assessing the year-to-year variability of disturbed sagebrush-steppe rangelands

where the total cover of vegetation is relatively low and soil exposure varies considerably with disturbance and precipitation.

Our analyses focused on calculations of mean MSAVI₂, the coefficient of variation (CV) of MSAVI₂ among years (“CV_{temporal} of MSAVI₂”; $CV = SD / \text{mean} * 100$), and CV of MSAVI₂ among pixels with a year (i.e. within one image, “CV_{spatial} of MSAVI₂”). Fire effects on MSAVI₂ were determined by comparing post-fire mean and CV of MSAVI₂ in both burned and non-burned (i.e. grazed) lands the first and subsequent growing seasons after fire. Distances to livestock watering troughs had no effects on MSAVI₂, as assessed by examining variation in MSAVI₂ among areas that were either within 30 m, or were 30 m to 100 m, 100 m to 500 m, or 500 m to 1000 m from watering troughs (Figure 1). Thus, we examined all pixels within grazing allotments for assessments of disturbance history impacts.

To estimate the potential for shifts from shrub to grass dominance to explain fire effects on MSAVI₂, we compared mean and CV of MSAVI₂ between lands with history of wildfire and those lands that were not burned and only grazed, and either contained sagebrush or had no sagebrush and were dominated by grasslands. Vegetation communities were identified from previous field surveys and existing vegetation classifications of the INL (Kramber et al. 1992) and USSES (Hanser et al. 2005).

Statistical Analyses

Areas in and around each complex of fires occurring in a year were our unit of replication, with $n = 3$ blocks for the INL sites burned in either 1994, 1995, or 1996; and $n = 4$ sets of burn areas lumped together for the USSES region fires of 1986, 1988, 1994, or 1998 (Figure 1). Background differences in mean and CV_{spatial} of MSAVI₂ in unburned pasture between regions, and between pasture and ungrazed areas at INL, were determined over all study years using repeated measures MANOVA. Differences in CV_{temporal} of MSAVI₂ among the study regions were determined using one-way ANOVA.

Fire effects were assessed using separate ANOVAs for each region, because they could not be consolidated into one experimental design. At the INL, differences in mean and CV_{spatial} of MSAVI₂ were determined using ANOVA with grazing, fire, and year as main factors. In the USSES region, the factors were fire and year. Fire effects on CV_{temporal} of MSAVI₂ at INL were evaluated with a two-way ANOVA with fire and grazing as main factors, and with a one-way ANOVA in the USSES region.

The significance of relationships between precipitation (PPT) and inter-annual mean MSAVI₂ and CV of MSAVI₂ were determined using linear least squares regression. Relationships were examined using sliding, three-year averages of yearly PPT (cumulative from January to image date), which had higher correlations with MSAVI₂ (higher r^2 values) than did water-year PPT (cumulative from October to image date) and growing season PPT (cumulative from April to image date). Precipitation was determined from historical climate summary data (Western Regional Climate Center, Desert Research Institute, Reno NV) obtained at nearby weather stations ($n = 3$ each) for the INL (CFA, Howe, and Idaho Falls 46W; Figure 1) and USSES (Dubois Experimental Station, Hamer 4NW, and St. Anthony 1WNW; Figure 2). Three-year sliding averages were calculated by averaging precipitation in the current year up to image dates with that in the two preceding years, respectively, to test for lag effects in vegetation responses to precipitation (Anderson and Inouye 2001). Over the study period, three-year averages of yearly PPT ranged from 246.7 mm to 77.34 mm on the INL and from 394.1 mm to 217.6 mm for the USSES region (Figure 3). One-way ANOVA and Kruskal-Wallis tests were used to detect differences in mean slopes of the relationships between PPT and mean MSAVI₂ or CV of MSAVI₂ burned and unburned pasture in the INL and USSES regions, using the slope for each replicate burn area at the INL, or clusters of burns for a year at the USSES, as replicates.

RESULTS

Background differences among regions

Mean MSAVI₂ in unburned pastures was 28% greater and about 50% less variable among years in the USSES (0.132 ± 0.02 SE, 13.3% CV_{temporal}) compared to INL region, over the 20-year period (0.095 ± 0.03 , 29.6% CV_{temporal}; $P < 0.000$; Figure 3). Variation in MSAVI₂ among years (CV_{temporal} of MSAVI₂) in the INL region was similar among undisturbed sagebrush (29.6%) and grasslands (31.6%); and ungrazed (29.6%) and grazed (27.8%) areas at INL. CV_{spatial} of MSAVI₂ (variation in MSAVI₂ among pixels within each image) varied in the INL region from 6.8% to 48.3% among the study years in ungrazed and unburned areas (Figure 3; $P < 0.0001$), and marginally from 7.6% to 41.0% in unburned pasture ($P = 0.11$). In pastures of the USSES region, CV_{spatial} of MSAVI₂ (variation in MSAVI₂ among pixels within each image) varied from 9.9% to 16.1% among study years (Figure 3; $P = 0.025$). Thus, MSAVI₂ tended to be greater and less variable in space and time in the USSES compared to the drier INL region.

Fire effects

There were no differences in mean MSAVI₂ (\pm SD) over all growing seasons after fire, but MSAVI₂ increased as much as 39% in the second post-fire year at the INL ($F_{1, 18} = 28.31$, $P < 0.0001$) in grazed and non-grazed pixels, compared to background increases of 14% in unburned areas (Figure 4; $P = 0.0008$). There was no statistical support for increases in MSAVI₂ after fires at the USSES.

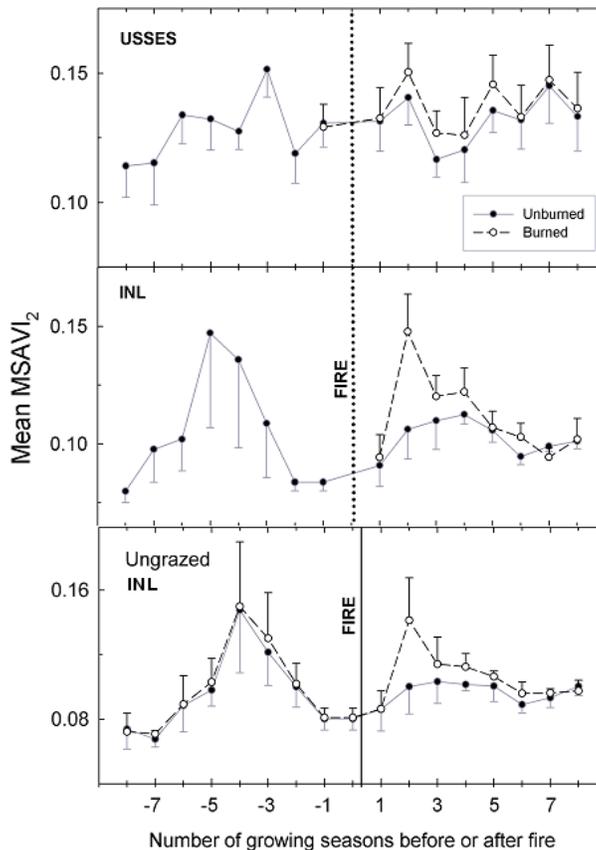


Figure 4. Comparisons of mean MSAVI₂ (\pm 1 SE) from 11 June to 17 July for grazed lands between the USSES (top panel) and INL groups (bottom panel) before or after fire. Vertical line shows time of fire in mid-to-late summer of 1994, 1995, or 1996 for the INL and either 1986, 1988, 1994, or 1998 for the USSES. Scale on the x-axis is year relative to year of fire. Burn-year blocks were $N = 3$ and $N = 4$, respectively for the INL and USSES.

As a result of the fire-induced changes in mean MSAVI₂, inter-annual variability (CV_{temporal}) of MSAVI₂ following INL fires was up to 2-fold greater in burned (16%), compared to unburned areas (7%; calculations for Figure 4; $P = 0.04$). In contrast, CV_{temporal} of MSAVI₂ following USSES-region fires was similar among burned (7.2%) compared to unburned pasture (6.8%; Figure 4).

Mean CV_{spatial} of MSAVI₂ increased 37% in the first post-fire year on INL pastures (Figure 5; $P = 0.09$) and then decreased over years to levels observed in unburned pasture. In contrast, CV_{spatial} of MSAVI₂ in the USSES region decreased following fire, and the only statistically supported changes were 35% decreases in years 4-5 following fire ($P = 0.013$). At INL, CV_{spatial} of MSAVI₂ recovered to levels observed in unburned areas more quickly in ungrazed areas compared to pasture.

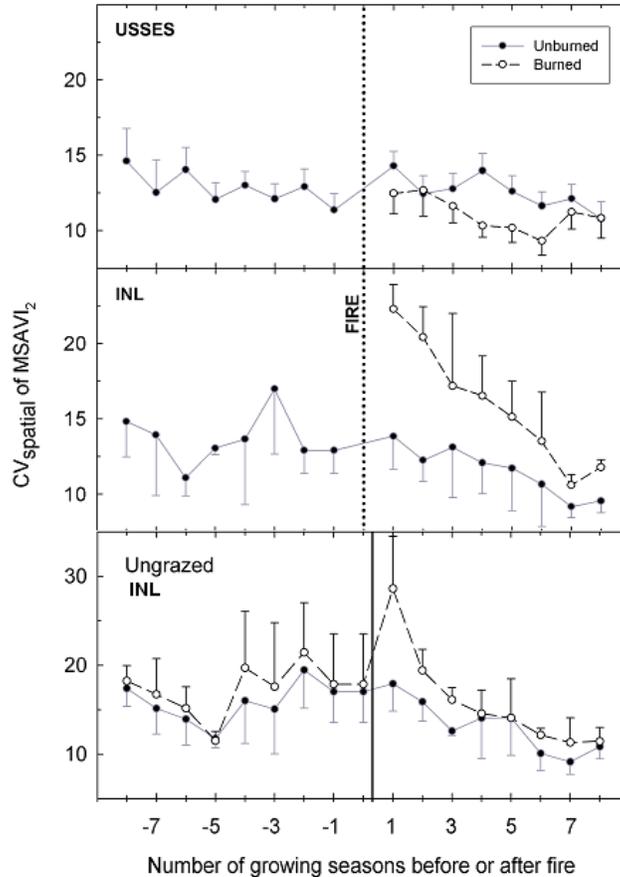


Figure 5. Comparison of mean CV of MSAVI₂ (+ or - 1 SE) among pixels (CV_{spatial}) of historically grazed lands on the USSES (top panel) and INL (bottom panel) study areas before or after fire. See Fig. 4 for plotting details. $N = 3$ burn-year blocks for INL and $N = 4$ for USSES.

Relationships to precipitation

No relationships of mean MSAVI₂ and yearly PPT were significant at the 0.05 level (not shown). In the USSES region, CV_{spatial} of MSAVI₂ was mostly not correlated with annual precipitation, with the exceptions being small slopes of the relationship in 1994 for both burned and unburned sites (Figure 6, Table 1). In contrast, the slope of the relationship between CV_{spatial} and PPT nearly doubled following fire on pastures at the INL ($F_{3, 11} = 10.80$, $P = 0.03$, Fig. 6, Table 1). The relationship between CV_{spatial} and PPT was significantly for all burn sites on INL, with mean slopes of 0.132 on pasture compared to 0.123 on ungrazed areas. In contrast, the relationship on unburned areas, as well as overall unburned areas of INL was only significant in 1994, and moreover had small slopes (Table 1).

that had no shrubs, the slopes (mean = 0.154) were greater than on areas with the greatest abundances of sagebrush (mean = 0.109; $P < 0.000$, Table 1).

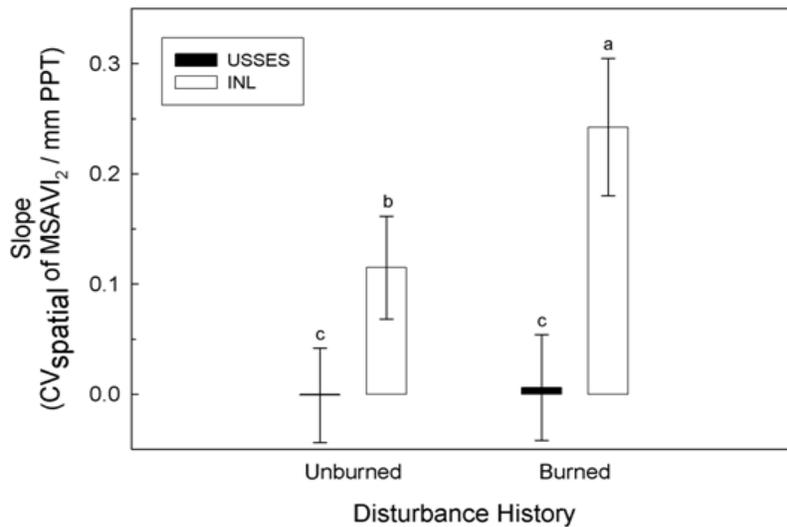


Figure 6. Mean slopes (+ or – 1 SD) of relationships between sliding three-year averages of cumulative yearly precipitation (PPT, from April 1 to image date) and post-fire CV_{spatial} of $MSAVI_2$ among pixels to 2004, for unburned and burned pastures. Replicates were the three INL burn blocks, for areas burned in 1994, 1995, and 1996; and four clusters of burns in the USSES region, including areas burned in 1986, 1988, 1994, or 1998. Letters denote significantly different slopes according to MANOVA.

Table 1. Correlations of sliding three-year averages of cumulative yearly precipitation (from January to image date) and post-fire CV_{spatial} of $MSAVI_2$ among pixels. N indicates the number of post-fire years up to 2004 included in regression analyses.

Region	Condition	Burn	r^2	P	Slope	N		
USSES	Grazed	1986	0.0275	0.695	0.016	16		
		1988	0.1406	0.360	-0.039	14		
		1994	0.6764	0.052	0.012	9		
		1998	0.1609	0.431	-0.039	6		
	Grazed/Burned	1986	0.0017	0.922	-0.004	16		
		1988	0.0389	0.640	-0.024	14		
		1994	0.609	0.022	0.077	9		
		1998	0.1678	0.420	-0.025	6		
		INL	Grazed	1994	0.647	0.005	0.058	10
				1995	0.080	0.460	0.015	9
1996	0.064			0.545	0.014	8		
Grazed/Burned	1994		0.701	0.003	0.124	10		
	1995		0.465	0.043	0.086	9		
	1996		0.556	0.034	0.186	8		
Ungrazed/Burned	1994		0.631	0.006	0.080	10		
	1995		0.568	0.019	0.105	9		
	1996	0.556	0.034	0.186	8			
Ungrazed/Unburned	1994	0.466	0.030	0.057	10			
	1995	0.355	0.091	0.075	9			
	1996	0.456	0.066	0.064	8			
Ungrazed/Unburned Sagebrush	1994	1994	0.545	0.015	0.104	10		
		1995	0.440	0.051	0.098	9		
	1996	1996	0.633	0.018	0.124	8		
		1994	0.505	0.021	0.149	10		
	Grassland	1995	0.392	0.071	0.137	9		
		1996	0.576	0.029	0.175	8		

DISCUSSION

Sagebrush steppe of lower elevations that are warmer, drier, and dominated by the Wyoming big sagebrush community type are commonly perceived to be more vulnerable than higher and wetter mountain big sagebrush communities to grazing and fire impacts. Whereas some field studies point to this assertion (e.g., Seefeldt et al. 2007), there have been few quantitative comparisons of fire effects in the two sagebrush types. Our findings that SVIs were greater, less variable, and quicker to recover following fire in mountain big sagebrush than Wyoming big sagebrush thus stands uniquely as evidence of less destabilizing effects of fire in smaller patches it occurs in, in the higher and cooler communities. Significantly, SVIs were constant among annual precipitation variations, nearly irrespective of fire occurrence, in the mountain big sagebrush. These findings indicate the possible existence of an ecosystem threshold in resilience and resistance to fire in this sagebrush biome, in which the drier Wyoming sagebrush appears to have strong responses to fire, but these responses (e.g., increased coupling of productivity to annual precipitation) are absent in the mountain big sagebrush.

Many studies have measured mean changes in plant cover of sagebrush-steppe in response to wildfire or grazing disturbances (e.g., Laycock 1967, Brotherson and Brotherson 1981, Humphrey 1984, Hosten and West 1994, Wambolt 2001, West and Yorks 2002). However, we found that variability in MSAVI₂, rather than average trends in MSAVI₂, was more sensitive to disturbance than mean MSAVI₂, for 8 – 10 years following fire. The immediate responses to fire in initial post-fire years were consistently observed despite climate variations among the burn years. In addition to these shorter-term responses, longer-term variability following fire for INL study areas appeared to result from increased coupling of CV_{spatial} of MSAVI₂ to inter-annual changes in precipitation. Fire and grazing influenced the stability or spatio-temporal constancy of MSAVI₂ measures in sagebrush-steppe, in ways that were more persistent than their direct, immediate effects of vegetation removal. In contrast, we observed no changes in mean MSAVI₂ in any years following fire, and moreover observed variability to decrease post-fire and to be relatively insensitive to yearly precipitation in the USSES region.

Although mean MSAVI₂ significantly increased among burned lands the second growing season following fire on the INL, it appeared to recover to levels similar to nearby unburned lands by the third growing season after fire, irrespective of study area. These results contrast previous findings of post-fire vegetation recovery in Mediterranean oak-pine ecosystems, where NDVI derived from Landsat decreased substantially following fire but recovered to pre-fire levels after about a decade (Diaz-Delgado et al. 2002). Post-fire increases in SVI's in sagebrush-steppe compared to decreases in forests may be attributable to greater standing biomass and corresponding leaf area before fire in forests. In sagebrush-steppe ecosystems, resprouting species, especially herbs, tend to increase in abundance in response to fire (Humphrey 1984, Hosten and West 1994, West and Yorks 2002), probably in compensation to overall reductions of dominant sagebrush, a non-resprouting species that recovers slowly after fire. The lack of significant differences in MSAVI₂ after fire in the USSES region may reflect greater constancy in herb production, as would be expected with more reliable and abundant precipitation. Our observations of greater mean MSAVI₂ among grassland compared to sagebrush pixels, and in burned compared to unburned pixels agree with previous findings of greater SVI values in grassland compared to sagebrush communities (Kremer and Running 1993, Paruelo and Lauenroth 1995, Weiss et al. 2004, Bradley and Mustard 2005).

Increased variability in burned areas might reflect exclusion of shrubs and site dominance by herb cover. MSAVI₂ in sites dominated by sagebrush was less responsive to inter-annual variations in precipitation, compared to herb-dominated communities. Similarly, NDVI variability in time was greater in areas dominated by annual grass compared to shrubs (Bradley and Mustard 2005). Long-term field plots on the INL with higher shrub densities tended to exhibit less inter-annual variability in cover than plots with low shrub densities over 45 years (Anderson and Inouye 2001). Additional ground-based studies demonstrate that Wyoming big sagebrush cover varies less than herbaceous or annual species in response to drought

(estimated from data in Passey et al. 1982 and West and Yorks 2002). Less spatio-temporal variability of MSAVI₂ in sagebrush compared to herb dominated communities could result from the evergreen habit of sagebrush, which enables the plant to produce leaf area during favorable conditions and retain the foliage during less favorable periods. Thus, increased temporal and spatial variability (i.e. lower stability) among fire-disturbed lands on the INL could be partly due to reductions of shrub cover and compensating increases in herbaceous, and especially grass cover. While in contrast, decreased temporal and spatial variability (i.e. higher stability) among fire-disturbed lands on the INL could be partly due to reduced responses of herbaceous and grass cover.

Increases in CV_{spatial} of MSAVI₂ after fire on INL pasture were more persistent than fire effects on ungrazed lands, and may be attributable to more than conversion of shrubs to grasses alone. Greater standing crop results from promotion of shrub over grass cover, leading to greater fuel loads and amplified intensity and severity of fire (DeBano et al. 1998). Increased fire severity may lead to greater site alterations (e.g. changes in soil physical properties) rather than just exclusion of shrubs and could thereby contribute to greater spatial and temporal variability in MSAVI₂. Interactions of fire and grazing thus appear to affect sagebrush-steppe communities in ways that are not detectable by simple assessments of mean responses, and moreover, cannot be predicted from linear combinations of the separate effects of grazing and fire.

Our data suggest that fire and grazing can have synergistic effects on the stability of vegetation indices in sagebrush-steppe, primarily by increasing the sensitivity of communities to variability in precipitation, especially in more arid regions where the amount and frequency of precipitation is less consistent. Burning on the INL influenced the long-term response of vegetation in grazed lands differently from ungrazed lands by causing greater increases in the variability of MSAVI₂ with increased precipitation. However, this relationship was not observed in grazed lands that burned on the USSES. There was no coupling of MSAVI₂ to precipitation, possibly a result of more reliable pre-summer wetting in the USSES region compared to the INL. It is likely that the INL findings could result from pre-fire alterations of community composition by livestock that tend to decrease variability in MSAVI₂ until after fire, when variability in MSAVI₂ becomes even greater than in burned areas that were not grazed before fire. While changes in precipitation occur due to climate change, the response of sagebrush-steppe rangelands to changes in precipitation may be particularly dependent upon the history of fire and grazing, especially for lands that experience significantly less annual precipitation, such as the INL. Our results indicate that studies seeking to determine fire and grazing impacts should encompass multiple years, consideration of different levels of variation in spatial heterogeneity among sites with different histories of disturbance, and precipitation in sampling among years. Similarly, large-scale assessments linking climate variability and ecosystem productivity will likely reflect disturbance legacies.

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