Interactive Effects of Fire, Grazing, and Precipitation on Long-Term Variability in Remotely Sensed Indices of Vegetation

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ABSTRACT
We evaluated the interactive effects of fire and grazing disturbances on satellite-derived measures of vegetation, particularly as they vary in space and time with yearly precipitation (PPT), over 20 years and nearly 300 km^2 of semiarid sagebrush-steppe. Some grazing systems may promote shrub cover and fire temporarily excludes dominant sagebrush species, so we also compared spatio-temporal patterns of disturbed areas with undisturbed areas with and without sagebrush within sagebrush-steppe ecosystems at the Idaho National Lab, in cold desert of the Great Basin, USA.

Remote sensing was used to calculate a soil-adjusted vegetation index ($MSAVI_2$) from Landsat satellite data, for the period of peak biomass in each year from 1984-2004. Differences in the mean or coefficient of variation (CV) of $MSAVI_2$ were determined for sites that (1) were either unburned in the previous 70 years, or burned in 1994, 1995, or 1996, and (2) either had livestock grazing excluded since 1950, or have been regularly grazed over the past century. Correlations of mean and CV of $MSAVI_2$ and 3 year sliding averages of PPT were determined for each disturbance type, for the 8-10 years following each fire. Livestock grazing did not affect mean $MSAVI_2$, and fire led to increases in mean $MSAVI_2$ in the second year after burning only. In contrast, the CV of $MSAVI_2$ among pixels within one image (i.e. spatial variation; $CV_{spatial}$) was lower in grazed compared to ungrazed areas, and increased for 1-3 years following fire. Short-term effects of fire on CV of $MSAVI_2$ were more persistent on grazed lands, and occurred irrespective of significant climate variability among burn years. Yearly $CV_{spatial}$ of $MSAVI_2$, but not mean $MSAVI_2$, was correlated with PPT ($r^2 = 0.47 – 0.70$). The slope of the relationship between $CV_{spatial}$ of $MSAVI_2$ and PPT was least positive in grazed areas, but 78% steeper (and steepest of all disturbance regimes) in grazed areas that had also burned. In undisturbed areas, mean $MSAVI_2$ and the slope of yearly $CV_{spatial}$ of $MSAVI_2$ and PPT were about 40% greater in grasslands than in areas dominated by sagebrush.

Longer-term disturbance effects are more apparent in the spatio-temporal variability of greenness as measured by $MSAVI_2$, rather than in mean responses of $MSAVI_2$. Variability in $MSAVI_2$ had complex responses to interactions of disturbances, as indicated by negative responses to grazing, positive responses to fire, but even more positive responses to the combination of grazing and fire. Conversion of vegetation type, as well as modification of responses to yearly changes in PPT, are likely ways that fire and grazing alter spatio-temporal variability of $MSAVI_2$.

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

INTRODUCTION

Like most ecosystems, sagebrush (*Artemisia*) steppe in western North America experiences combinations of natural and anthropogenic disturbances. Sagebrush steppe is affected by annual variations in precipitation, abrupt disturbances such as fire, and disturbances such as livestock grazing that occur persistently over longer periods (Anderson and Inouye, 2001). Disturbances cause changes in communities and ecosystems (Pickett and White, 1985) that could modify climate-productivity relationships over the vast areas of sagebrush steppe in which they occur. Many studies investigated separate effects of fire or grazing on semiarid rangeland function (Anderson and Holte, 1981; Anderson and Inouye, 2001; Wambolt et al., 2001; Diaz-Delgado et al., 2002; Washington-Allen et al., 2004), but less is known about interactive effects of disturbances (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; 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 assessments of effects of weather variation, fire, and livestock grazing disturbances are needed to better match the scale at which rangeland management occurs as well as for global assessment of vegetation-climate relationships. Evaluations at larger scales are also important because ecological relationships can be scale dependent (e.g., Stohlgren et al., 1999; Small and McCarthy, 2003).

Remote sensing can provide periodic measures of vegetation over large areas that exceed 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 to examine greenness of vegetation in rangeland ecosystems (e.g., Graetz and Gentle, 1982; Pickup and Foran, 1987; Graetz et al., 1988; Smith et al., 1990; Pickup et al., 1993; Elmore et al., 2000; Ramsey et al., 2004; Wallace et al., 2004). Greenness of earth surfaces, as measured by SVIs, is affected by chlorophyll concentrations and leaf abundance in the vertical plane (ie. leaf area index, "LAI", # leaf layers/unit ground area). SVIs are a valuable tool for large-scale assessment of ecosystem responses 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 the interactive effects of fire, livestock grazing, and precipitation change on the spatial and temporal variability of SVI's in sagebrush-steppe, relative to background variability in undisturbed areas. Water availability in these semi-arid rangelands is limited and highly variable in time (Anderson and Inouye, 2001), and primary production in semiarid lands can be tightly linked to variation in rainfall (LeHouerou et al., 1987). Long-term grazing tends to promote shrub cover (Laycock, 1967; Anderson and Holte, 1981; Brotherson and Brotherson, 1981; Anderson and Inouye, 2001) and fire temporarily promotes grass cover (Humphrey, 1984; Wambolt et al., 2001; West and Yorks, 2002). We hypothesized that lands with histories of grazing, fire, or no disturbance would not differ much in mean responses, but that histories of fire and grazing would lead to greater variability in SVIs in years following disturbance, due to changes in the sensitivity of SVIs to annual precipitation and conversions of community type. Thus, in addition to calculating mean SVIs, we assessed how disturbances and precipitation affected the stability of SVIs in space and time, measured as coefficient of variation of SVIs.

METHODS

Areas dominated by Wyoming Big Sagebrush (*Artemisia tridentata* Nutt ssp. *wyomingensis* Beetle and Young) with different fire and grazing histories since 1939 were identified from Bureau of Land Management (BLM) Geographic Information Systems (GIS) data within the Idaho National Laboratory (INL; Fig. 1; version 9, ArcGIS, ESRI, Redlands CA, USA). The INL is located on the Eastern Snake River Plain (Idaho), and was ideal for this study because of its relatively flat topography and large homogenous management units (livestock grazing allotments) where wildfires have occurred frequently over the last two decades. Areas within 1 km buffers of wildfire perimeters were categorized as follows: 1) *Rest*, undisturbed areas where no fires have occurred since at least 1939, and livestock grazing has been excluded since 1950; 2) *Grazed*, areas within BLM grazing allotments that have been actively grazed since 1950; 3) *Burned*, non-grazed areas that have burned once from mid-late summer in 1994 – 1996 and not any other time since 1939; and 4) *Grazed/burned*, areas within BLM grazing allotments that have been actively grazed since 1950 and burned once from 1994 – 1996. No pixels within 90 m of boundaries of burn or grazed areas were included. We focused our study on areas that burned in 1994, 1995, or 1996 because they encompassed years of significant variation in precipitation, and provided 8 – 10 years of recovery after fire. Fires occurred elsewhere on the INL during our study period, but they were too recent to allow for adequate assessment of temporal variation in SVI's following fire. BLM summer stocking rates of domestic livestock (cattle and sheep) varied little over the last 20 years and ranged from 12.4 to 33.5 acres/active animal unit month (AUM). Grazing was excluded from burned areas for two years following fire.

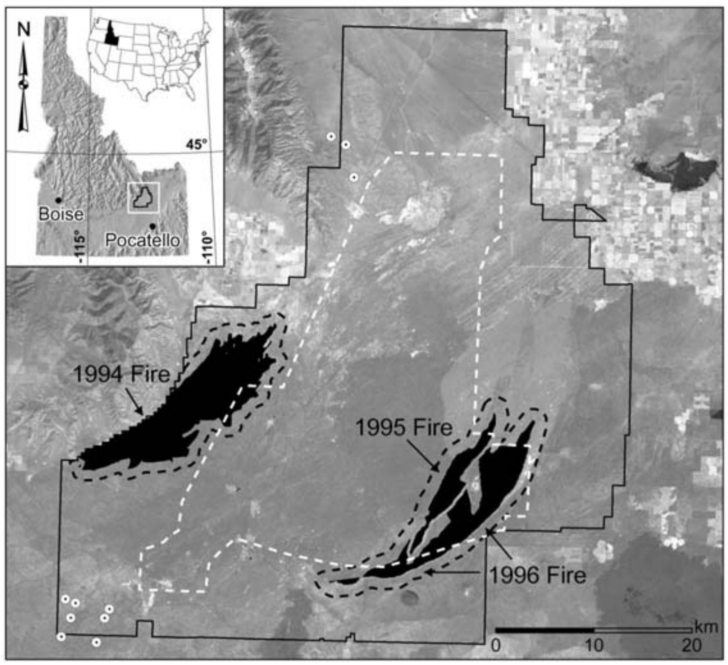

Figure 1. Map of the Idaho National Laboratory (INL, bound by solid black line) located on the Upper Snake River Plain (inset map; coordinates for Idaho) and the arrangement of four disturbance types in three replicate blocks around the 1994, 1995, and 1996 fires. Burn areas are shown in black, and livestock grazing has been excluded from area inside white dashes since 1950. Sampling areas within 1-km of burns are bound by black dashes. White circles indicate livestock watering sites for two grazing allotments on the INL. Image is derived from Landsat data.

We examined spatial and temporal variability in SVIs among lands with different histories of disturbance, in one 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 37-day window centered on 27-June. Fires in occurred from mid July through August, weeks after the Landsat sampling dates of the same years, and 11 to nearly 12 months prior to the next image acquisition. We were unable to use more sampling dates per year, due to cloud cover or data gaps. Landsat sampling dates corresponded to the peak summer growing season for sagebrush-steppe, as estimated by Paruelo and Lauenroth (1995 and 1998) for the INL 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" ($MSAVI_2$, Qi et al. 1994) was calculated to quantify the greenness of sagebrush-steppe vegetation (version 4.1, ENVI, Research Systems Inc, Boulder CO, USA). $MSAVI_2$ minimizes soil background influences on vegetation signals 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 as:

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

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, soil-adjusted vegetation index), 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. $MSAVI_2$ is a variant of MSAVI that does not rely on pre-determined soil correction factors, because soil is adjusted for inductively by a term that varies inversely with the amount of vegetation present in each pixel (Qi et al., 1994). $MSAVI_2$'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 $MSAVI_2$, the coefficient of variation (CV) of $MSAVI_2$ among years ("$CV_{temporal}$ of $MSAVI_2$"; CV = SD / mean * 100), and CV of $MSAVI_2$ among pixels with a year (i.e. within one image, "$CV_{spatial}$ of $MSAVI_2$"). Fire effects on $MSAVI_2$ were determined by comparing post-fire mean and CV of $MSAVI_2$ in both burned and non-burned (i.e. rest) lands the first and subsequent growing seasons after fire. Distances to livestock watering troughs had no effects on $MSAVI_2$, as assessed by examining variation in $MSAVI_2$ 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 (data not shown; troughs locations in Fig. 1). Thus, we examined all pixels within grazing allotments for assessments of grazing impacts.

To estimate the potential for interconversions of community type between shrub and grassland to explain disturbance effects on $MSAVI_2$, we compared mean and CV of $MSAVI_2$ between areas that were grazed, burned, or grazed/burned, to those areas that were undisturbed and either contained sagebrush or had no sagebrush and were dominated by grass. Vegetation communities were identified from previous field surveys and vegetation classifications of the INL (Kramber et al., 1992, and subsequent monitoring by R. Blew for US Department of Energy).

Statistical Analyses

Areas containing each of the four disturbance regime types (undisturbed rest, grazed, burned, and grazed/burned) around each of the 1994, 1995, or 1996 burns were our unit of replication, resulting in n=3 complete blocks of disturbance types (Fig. 1). One-way ANOVA was used to detect differences in mean or CV of $MSAVI_2$ among the four disturbance types within individual years (i.e., within one image). Repeated-measures MANOVA was used to detect differences among disturbance or community types (sagebrush or grass in undisturbed areas) when comparisons included sampling over multiple years. The significance of differences in the relationship between precipitation (PPT) and mean or CV of $MSAVI_2$ among the disturbance and community types were investigated using linear, least-squares regression. Relationships between PPT and $MSAVI_2$ over years were examined using sliding averages of PPT each the image year (cumulative from January to image date; 'yearly PPT') and total cumulative PPT in each of the two previous years. Cumulative yearly PPT had greater correlations with $MSAVI_2$ (higher r^2 values) than did water-year PPT (cumulative from October to image date) or growing-season PPT (cumulative from April to image date). Anderson and Inouye (2001) also found that ground-based measures of cover at INL were best correlated with 3-year sliding averages of yearly PPT, compared to other statistical representations of PPT. Precipitation data were from the INL Central Facilities Area station (Western Regional Climate Center, Desert Research Institute, Reno NV). Over the study period, three-year averages of yearly PPT ranged from 246.7 mm to 77.34 mm, with the highest PPT occurring in 1985 and 1995, and the lowest PPT occurring in 1990 and 2001-2004 (Fig. 2). One-way ANOVA and Kruskal-Wallis tests were used to detect differences in the slope of the relationships between PPT and mean or CV of $MSAVI_2$ among the disturbance types, with three replicates of each disturbance type, as described above.

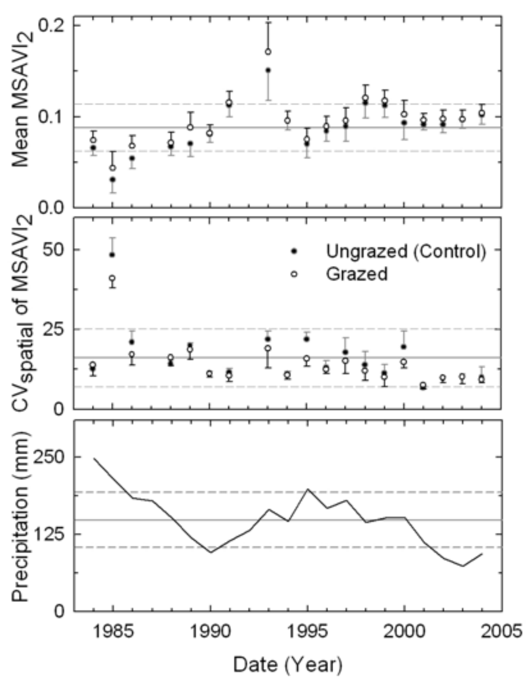

Figure 2. Mean and $CV_{spatial}$ (%) of $MSAVI_2$ for unburned pixels of ungrazed (rest, solid symbols) and grazed areas (open) on the INL from 11 June to 17 July in 1984 – 2004; and sliding, 3-yr averages of yearly precipitation during the study period. Errors for individual data points are shown as + or – 1 SD, and are not shown in ± for clarity. Solid and dashed horizontal lines show mean ± 1 SD values for rest areas over all 20 years.

RESULTS

Mean $MSAVI_2$ of undisturbed lands fluctuated significantly over the 20-year period, ranging from 0.03 in 1985 to 0.15 in 1993 (Fig. 2; $F_{18,56} = 12.60$, $P < 0.0001$). Mean $MSAVI_2$ among the 20 years ranged from 0.03 to 0.15 in sagebrush and 0.06 to 0.22 in grasslands (data not shown; $F_{1,37} = 2.94$, $P = 0.10$ for mean differences). Mean $MSAVI_2$ over the whole study period was not different between undisturbed-rest and grazed areas (Fig. 2). Variation in $MSAVI_2$ among years ($CV_{temporal}$ of $MSAVI_2$) was similar among undisturbed sagebrush (29.6%) and grasslands (31.6%); and ungrazed (29.6%) and grazed (27.8%) areas (Fig. 2, top panel). $CV_{spatial}$ of $MSAVI_2$ (variation in $MSAVI_2$ among pixels within each image) varied significantly among years in undisturbed areas (6–48%, $F_{18,56} = 32.96$, $P < 0.0001$), but varied only marginally among years in grazed areas (8–41%, $F_{18,72} = 1.82$, $P = 0.11$; Fig. 2).

History of disturbance and time since fire had a significant, interactive effect on mean $MSAVI_2$ in the second growing season after fire, only (Fig. 3; $F_{6,16} = 3.51$, $P < 0.05$). Specifically, mean $MSAVI_2$ in grazed and ungrazed areas alike increased 40% in the second growing season following fire ($F_{1,18} = 28.31$, $P < 0.0001$), compared to average background increases of 14% in pixels of unburned areas surrounding each burn (Fig. 3; $F_{1,18} = 12.96$, $P < 0.001$). There were otherwise no differences in mean $MSAVI_2$ among disturbance types over all 8-10 growing seasons after fire, with mean values ± 1 SD ranging from only 0.10 ± 0.01 in undisturbed rest areas to 0.11 ± 0.02 in grazed/burned areas. Inter-annual variability ($CV_{temporal}$) of $MSAVI_2$ following all fires combined was up to 2-fold greater in pixels in burned (15.9%) and grazed/burned areas (16.2%) compared to rest (6.6%) and grazed-only areas (7.3%; calculations for Fig. 3; $F_{3,12} = 7.63$, $P < 0.05$).

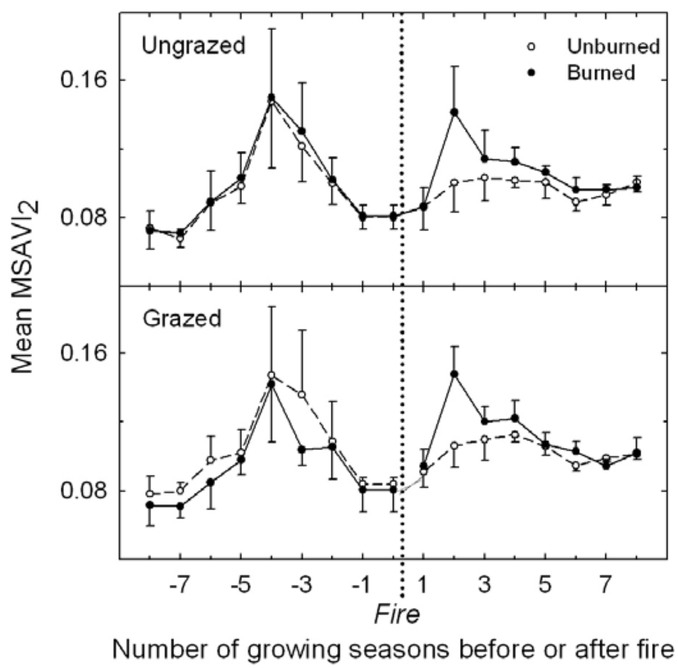

Figure 3. Mean $MSAVI_2$ (+ or – 1 SE) from 11 June to 17 July among ungrazed (top panel) and grazed lands (bottom panel) before or after fire. Solid vertical line shows time of fire in late summer of either 1994, 1995, or 1996; and scale on x-axis is year relative to year of fire. N = 3 burn-year blocks.

$CV_{spatial}$ of $MSAVI_2$ was 37% greater in burned and grazed/burned areas compared to rest and grazed-only areas in the first post-fire year (Fig. 4; $F_{3,11} = 3.12$, $P = 0.09$). Post-fire recovery (decreases) of $CV_{spatial}$ of $MSAVI_2$ to levels observed in unburned areas appeared to occur more quickly in ungrazed compared to grazed areas ($F_{3,8} = 3.10$, $P = 0.09$), and by the fourth year after fire, no significant differences in $CV_{spatial}$ of $MSAVI_2$ were detectable among disturbance types. $CV_{spatial}$ of $MSAVI_2$ of undisturbed rest areas decreased progressively following burning of neighboring areas, after 1994-1996 (Fig. 4; $F_{2,16} = 6.16$, $P = 0.01$), corresponding to a trend of decreasing yearly PPT.

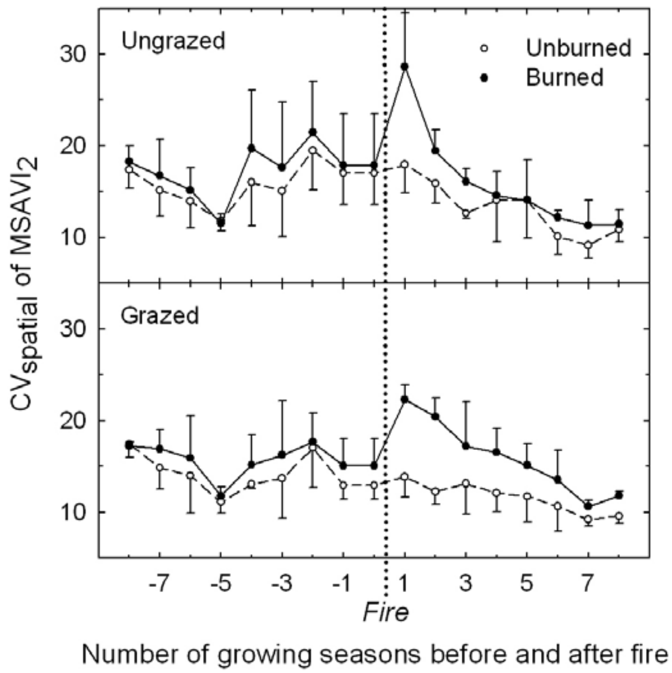

Figure 4. Mean CV of $MSAVI_2$ (+ or – 1 SE) among pixels ($CV_{spatial}$) for ungrazed (top) and grazed lands (bottom) before or after fire (N = 3 burn-year blocks). See Fig. 3 for plotting details.

Mean $MSAVI_2$ was weakly or uncorrelated with sliding, three-year averages of cumulative yearly PPT for lands in all disturbance types alike (Table 1), in contrast to greater correlations of $CV_{spatial}$ of $MSAVI_2$ and yearly PPT (Table 2). Moreover, greater correlations of $CV_{spatial}$ of $MSAVI_2$ and PPT were detected in burned areas than in undisturbed rest areas and grazed plots. Specifically, mean r^2/P values for the regressions in all burn-year blocks were 0.57/0.03 and 0.59/0.06 in grazed/burned and burned areas, compared to 0.43/0.06 in undisturbed rest areas and an insignificant 0.26/0.35 in grazed areas that did not burn (calculated from Table 2). The slope of the relationship between $CV_{spatial}$ and PPT in burned areas was 51% steeper than in rest areas, and 78% steeper than in grazed areas ($F_{3, 11} = 10.80$, $P = 0.03$, Fig. 5, Table 2). Mean ± SE slopes of the relationship between $CV_{spatial}$ and PPT in over the three undisturbed areas around each burn were 41% steeper in grasslands (0.15± 0.01) than in sagebrush (0.11± 0.01; $F_{1, 5} = 10.80$, $P = 0.03$).

DISCUSSION

Previous, ground-based studies 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; Wambolt, 2001; West and Yorks, 2002). However, we found that variability of $MSAVI_2$ was more sensitive to disturbance than mean $MSAVI_2$ for 8 – 10 years following fire. Spatio-temporal variability in greenness among 30 x 30 m units of ground area and years emerged as more responsive than average greenness over km^2 and decades. Mean $MSAVI_2$ among burned lands increased only in the second growing season following fire compared to unburned lands (Fig. 3), but mean $CV_{spatial}$ of $MSAVI_2$ was greater in fire-disturbed lands for up to three growing seasons after fire (Fig. 4). These immediate responses to fire (within 3 years) were consistently observed despite climate variations among the burn years (Figs. 2-4). In addition to these shorter-term responses, longer-term variability following fire appeared to result from increased coupling of $CV_{spatial}$ of (but not mean) $MSAVI_2$ to inter-annual changes in precipitation (Fig. 5). Thus, fire and grazing influenced the stability (or, spatio-temporal constancy) of $MSAVI_2$ measures in sagebrush-steppe in ways that were more persistent and different from effects that might result from their direct, immediate impacts of vegetation removal.

Table 1. Correlations of yearly mean $MSAVI_2$ and sliding three-year averages of cumulative yearly precipitation, in each disturbance type and burn-year block (burns in 1994, 1995, or 1996), as well as portions of undisturbed rest areas dominated by sagebrush or grassland. N indicates the number of years following each fire up to 2004 included in regression analyses.

	Burn year	**r^2**	***P***	**Slope**	**N**
Sagebrush, in rest	1994	0.186	0.214	0.000	10
	1995	0.017	0.741	0.000	9
	1996	0.002	0.903	0.000	8
Grassland, in rest	1994	0.006	0.834	0.000	10
	1995	0.073	0.483	0.000	9
	1996	0.177	0.300	0.000	8
Rest	1994	0.376	0.060	0.000	10
	1995	0.036	0.624	0.000	9
	1996	0.253	0.204	0.000	8
Grazed	1994	0.071	0.458	0.000	10
	1995	0.035	0.629	0.000	9
	1996	0.147	0.349	0.000	8
Burned	1994	0.223	0.169	0.000	10
	1995	0.343	0.097	0.000	9
	1996	0.171	0.309	0.000	8
Grazed/Burned	1994	0.025	0.662	0.000	10
	1995	0.416	0.061	0.000	9
	1996	0.281	0.177	0.000	8

Although mean $MSAVI_2$ significantly increased among burned areas in the second growing season following fire, it appeared to recover to levels similar to nearby unburned lands by the third growing season after fire. These results contrast previous findings of post-fire vegetation recovery in Mediterranean oak-pine ecosystems, where NDVI (normalized difference vegetation index) 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 may be attributable to lower standing biomass and corresponding leaf area before fire in shrubland compared to forests, which allows for relatively quicker regeneration of leaf area to equal or greater levels than pre-fire conditions in shrub steppe. Resprouting annual and perennial grasses and forbs tend to increase in abundance in response to fire in sagebrush steppe (Humphrey, 1984; West and Yorks, 2002), probably in compensation to overall reductions of dominant sagebrush, a non-resprouting species that recovers slowly after fire (>decades). Plants that initially colonize burns also can be enriched in the soil nutrients that temporarily become more available after fire, and correspondingly can have greater LAI or concentrations of chlorophyll (DeBano et al. 1998), and thereby could express more greenness to satellite sensors. Our observations of greater mean $MSAVI_2$ in burned compared to unburned pixels corresponds with greater $MSAVI_2$ and SVI values in grassland compared to sagebrush communities measured here and by others (Kremer and Running, 1993; Paruelo and Lauenroth, 1995; Weiss et al., 2004; Bradley and Mustard, 2005). Although sagebrush has greater biomass per unit ground area than grasses, much of the biomass is non-photosynthetic. Thus, short-term increases in $MSAVI_2$ after fire may result in part from conversion to grasses and intrinsically greater greenness of grasslands, though the duration and magnitude of changes of fire-induced changes in $MSAVI_2$ were less than expected if changes were entirely attributable to conversion to grassland. Progressive reductions in $MSAVI_2$ towards rest levels following the 2^{nd} post-fire year could reflect establishment of new plants on otherwise unvegetated soil, and dilution of growth resources, leaf area, and chlorophyll from a few colonizing plants to greater horizontal plant cover.

Table 2. Correlations of yearly $CV_{spatial}$ of $MSAVI_2$ and sliding three-year averages of cumulative yearly precipitation, in each disturbance type and burn-year block (1994, 1995, or 1996), as well as portions of undisturbed rest areas dominated by sagebrush or grassland. N indicates the number of years following each fire up to 2004 included in regression analyses.

	Burn year	**r^2**	***P***	**Slope**	**N**
Sagebrush, in rest	1994	0.545	0.015	0.104	10
	1995	0.440	0.051	0.098	9
	1996	0.633	0.018	0.124	8
Grassland, in rest	1994	0.505	0.021	0.149	10
	1995	0.392	0.071	0.137	9
	1996	0.576	0.029	0.175	8
Rest	1994	0.466	0.030	0.057	10
	1995	0.355	0.091	0.075	9
	1996	0.456	0.066	0.064	8
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
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
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

Our measurements of less spatio-temporal variability of $MSAVI_2$ in grazed lands compares with similar findings from ground-based studies (Adler and Lauenroth, 2000; Adler et al., 2001), but contrasts greater variability detected in $MSAVI_2$ following fire (Figs. 4-5). Less spatio-temporal variability in grazed lands might reflect removal of patches of greater herbaceous growth in wet years or patches by livestock (as suggested by Anderson and Inouye, 2001). Grazing and fire effects on spatio-temporal variability could also result partly from interconversion of community types, as discussed for mean responses of $MSAVI_2$. Specifically, relative decreases or increases in variability of $MSAVI_2$ following grazing or fire, respectively, correspond with promotion of shrubs by grazing and exclusion of shrubs by fire. Spatial variability in $MSAVI_2$ was less in undisturbed sagebrush compared to grass-dominated communities, especially in relation to annual changes in precipitation (Table 2). Similarly, NDVI variability in time was greater in areas dominated by annual grass compared to shrubs, in other regions of the Great Basin (Bradley and Mustard, 2005). Plots with higher shrub densities tended to exhibit less variability in cover from year-to-year than plots with low shrub densities, over 45 years of ground-based monitoring at INL (Anderson and Inouye, 2001). Similarly, ground measures of cover varied less for Wyoming big sagebrush than herbaceous and annual species, in response to drought (West and Yorks, 2002; also estimated from ground data in Passey et al., 1982). Less spatio-temporal variability of $MSAVI_2$ in sagebrush compared to herb-dominated communities, especially in response to variable PPT, could result from the evergreen habit of sagebrush, which enables retention of leaf area produced in favorable conditions through less favorable periods. As noted for mean responses of $MSAVI_2$, the magnitude and duration of fire-induced changes in variability in $MSAVI_2$ were not fully matched by changes that would be expected from conversion to grassland alone. Thus, other factors that we cannot identify likely contributed to changes in variability in greenness among 30 x 30 m ground areas following fire.

Figure 5. Mean slopes (± SE) of relationships between sliding 3-yr averages of cumulative yearly precipitation (PPT, from April 1 to image date) and post-fire $CV_{spatial}$ of $MSAVI_2$ among pixels, for lands with different histories of disturbance. Values are means for replicate areas matched to the 1994, 1995, or 1996 burns (n=3). See Table 2 for regression statistics.

More persistent increases in $CV_{spatial}$ of $MSAVI_2$ following fire on grazed compared to ungrazed lands may be attributable to more than conversion of shrubs to grasses (Fig. 4). Greater fuel loads result from promotion of shrub over grass cover by livestock grazing, leading hotter fires (DeBano et al., 1998). Increased fire severity may lead to greater site alterations (e.g. changes in soil physical properties) than just exclusion of shrubs, leading to greater spatial and temporal variability in $MSAVI_2$ following fire. Also, fewer herbs prior to burning should lead to fewer resprouting herbs in the first year after fire on grazed lands, and post-fire heterogeneity in establishment of new herbs could contribute to greater spatio-temporal variability in $MSAVI_2$.

SUMMARY

Semiarid shrub-grasslands cover a large portion of the global land area, and are regularly affected by fire, grazing, and variability in precipitation (Frank and Inouye 1994). Grazing and fire effects were less evident in average greenness over kilometers^2 and decades than in spatial variability of greenness at the scale of 30 x 30 m areas and yearly timesteps. Interactive effects of grazing and fire may be complex, as indicated by decreased spatio-temporal variability of greenness in response to grazing, but increases in response to fire, and especially grazing followed by fire. Patches of landscapes appear to vary in their sensitivity to fire, and the combination of fire, grazing, and precipitation. Longer-term effects of fire and grazing appear to result from modification of the linkage between spatio-temporal variability of greenness and variability in PPT. Changes in spatio-temporal variability are an important issue for efforts to utilize multispectral satellite imagery, such as Landsat, to map community types or assess responses of ecosystem productivity to climate variability. Legacies of disturbances affect the certainty of multi-spectral signatures related to vegetation, particularly as they relate to climate variability over large scales.

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