Disturbance histories increase variability in remotely sensed indices of sagebrush-steppe over the past ca. 20 years.

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Abstract

Many studies have investigated the separate effects of drought, fire, or livestock grazing on semiarid rangeland function, however, most sagebrush-steppe rangelands are likely to experience multiple, potentially interacting combinations of these disturbances. Little quantitative information exists over large spatial and temporal scales to help address the effects of multiple disturbances on ecosystem function. Remote sensing and Geographic Information Systems (GIS) were used to investigate spatial and temporal variability of disturbed and undisturbed sagebrush-steppe communities in southeast Idaho from 1984 – 2003. Lands disturbed by livestock grazing and/or wildfire were selected from existing GIS data and combined with modified soil-adjusted vegetation indices ($MSAVI_2$) derived from yearly Landsat data to examine temporal and spatial responses of sagebrush-steppe to variation in precipitation, grazing, and/or fire. Long-term disturbance effects were most apparent in the spatial variability of $MSAVI_2$ within and between years, rather than in mean responses of $MSAVI_2$. The coefficient of variation (CV) of $MSAVI_2$ among pixels within one sampling date (i.e. within one Landsat image) increased in the first few years following fire. Fire, or the combination of both grazing and fire, resulted in greater correlations and steeper relationships between the CV of $MSAVI_2$ in one image and cumulative annual PPT ($r^2 = 0.76 – 0.81$; mean increase of 0.33 in $CV_{spatial}$ of $MSAVI_2$ / mm PPT) than grazed-only ($r^2 = 0.60$; mean increase of 0.08 in $CV_{spatial}$ of $MSAVI_2$ / mm PPT) and undisturbed lands ($r^2 = 0.62$; mean increase of 0.16 in $CV_{spatial}$ of $MSAVI_2$ / mm PPT). These data suggest that higher disturbance levels decrease the stability of vegetation indices in sagebrush-steppe, primarily by increasing the sensitivity of communities to variability in precipitation. Conversion of vegetation type from shrub to grassland can explain higher variability in $MSAVI_2$ following fire alone, but cannot explain even greater variability in

sites disturbed by both fire and grazing. Interactive effects of grazing and fire may cause more fundamental changes in site properties that are more readily detected in spatial and temporal variations rather than mean values of vegetation indices.

Introduction

Sagebrush (*Artemisia*) steppe ecosystems throughout western North America experience combinations of natural and anthropogenic disturbances, such as altered fire regimes and domestic livestock grazing, in addition to natural variation in precipitation (Anderson and Inouye 2001). Disturbance here refers to events that cause abrupt change in ecosystem processes, or population and community structure, by altering resource availability or other aspects of the physical environment (Pickett and White 1985, Begon et al. 1996). Many studies have investigated the separate effects of disturbance on semiarid rangeland function (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), however most rangeland ecosystems are likely to experience multiple, potentially interacting disturbances (Valone 2003). 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 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. Evaluations at larger scales are also important because ecological measures have been shown to vary at different scales (Stohlgren et al. 1999, Small and McCarthy 2003). Assessments of disturbance impacts are best done in light of comparisons to natural, background variability (Magnuson et al. 1991, Paruelo and Lauenroth 1998).

Remote sensing provides the data necessary to examine large-scale spatial and temporal variability of sagebrush-steppe by obtaining periodic measures of vegetation over areas that exceed the capabilities of traditional ground-based assessments (Washington-Allen et al. 2004). Previous studies have used spectral vegetation indices (SVI's), derived from remotely sensed ratios of red and near-infrared reflectance, to examine the abundance of rangeland vegetation (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; Washington-Allen et al. 2004). These indices provide estimates of seasonal and inter-annual variations in vegetation in response to precipitation changes and anthropogenic disturbances (Paruelo and Lauenroth 1998, Paruelo et al. 2001, Washington-Allen et al. 2004) and can be used to detect broad-scale landscape changes related to ecosystem condition, independent of the phenological events of specific plants (Reed et al. 1994).

The modified soil-adjusted vegetation index (MSAVI) enhances the red and near-infrared reflectance ratio in low vegetation cover by increasing the dynamic range of the vegetation signal and minimizing soil background influences (Qi et al. 1994). MSAVI has been used to quantify sparse vegetation cover in arid environments, and significantly correlates to field measures of canopy and areal ground cover (Senseman and Bagley 1996, Purevdorj et al. 1998, McGwire et al. 2000). Other soil-adjusted SVI's require constant, empirically defined, soil adjustment factors to minimize soil influences on canopy spectra. 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 vegetation indices among pixels within or between images. $MSAVI_2$, a variant of MSAVI avoids this problem by replacing the constant, empirical, adjustment factor for soil with a dynamic, inductive one 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 sagebrush-steppe rangelands where the total cover of vegetation is relatively low. In our study area from 1983 to 2001, total cover was 23% +/- 2.4% SD, shrub cover was 19% +/- 3.9 SD, and grass cover was 5% +/- 1.8 SD (Anderson and Inouye 2001, R. Blew, unpublished data). In arid environments with less than 25% vegetation cover, MSAVI had a higher and more constant sensitivity over the full range of cover compared to other soil-adjusted SVI's (Rondeaux et al. 1996).

This study utilized a 17-year archive of Landsat data to determine the interactive effects of fire, grazing, and precipitation change on the spatial and temporal variability of $MSAVI_2$ in sagebrush-steppe. The Idaho National Laboratory (INL; Fig. 1), situated on the Eastern Snake River Plain, was ideal for this experiment because of its relatively flat landscape and large homogenous management units (livestock grazing allotments) where wildfires have occurred frequently over the last two decades. Some studies have shown a strong relationship between precipitation and variability in shrubland productivity (Le Houerou et al. 1988, Lauenroth and Sala 1992, Milchunas and Lauenroth 1993, Pareulo and Lauenroth 1995, Paruelo and Lauenroth 1998), whereas others detected no relationship (West et al. 1979, Passey et al. 1982, Anderson and Inouye 2001). We hoped to gain a better understanding of landscape-scale responses of disturbed and undisturbed sagebrush steppe rangelands to variability in precipitation. In addition, we were interested in testing the sensitivity of remote sensing to evaluating long-term effects of different disturbances on sagebrush-steppe ecosystem function.

Our research addressed the following questions: 1.) How much spatial and temporal variability occurs in $MSAVI_2$ among lands undisturbed by grazing and fire? 2.) How do natural and anthropogenic disturbances, such as livestock grazing, and/or fire influence spatial and temporal variability in $MSAVI_2$ among sagebrush-steppe communities? 3.) How spatial and temporal variability among these lands differs during years of precipitation change (i.e. drought years)? We hypothesized that landscapes with histories of multiple disturbances, such as livestock grazing and/or fire, would exhibit relatively higher amounts of variation in $MSAVI_2$ during years of varying precipitation than sites with fewer disturbances. In addition, we hypothesized that burned lands would show increased spatial and temporal variability measured by $MSAVI_2$ in years immediately following fire. These hypotheses were based on theoretical predictions that high levels of disturbance decrease biodiversity (Muldavin et al 2001, Ludwig et al 2004), and that resulting decreases in biodiversity should lead to less stability in ecosystem function (Frank and McNaughton 1991, Tilman 1996, Lavorel 1999, Anderson and Inouye 2001, Ludwig et al. 2004), measured here as year-to-year variability in $MSAVI_2$.

Methods

Lands dominated by Wyoming Big Sagebrush (*Artemisia tridentata wyomingensis*) with different fire and grazing histories since 1939, were identified from Bureau of Land Management (BLM) Geographic Information Systems (GIS) data within the INL. Lands within 1 km buffers of wildfire perimeters were categorized as follows (Fig. 1): 1) *Control*, undisturbed lands where no fires have occurred and livestock grazing has been excluded since 1950; 2) *Grazed*, lands within BLM grazing allotments that have been actively grazed since 1950; 3) *Burned*, non-grazed lands that have been burned once from 1994 – 1996 and not any other time since 1939;

and 4) *Grazed/burned*, lands within BLM grazing allotments that have been actively grazed since 1950 and burned once from 1994 – 1996. We focused our study on lands that burned in 1994, 1995, or 1996 because they encompassed years of significant variation in precipitation, and provided 7 – 9 years of recovery from fire. More current fires occurred on the INL during our 17-year study period, but were too recent to allow for assessment of temporal variation in $MSAVI_2$ following 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 fire-disturbed areas for two years following fire.

To examine spatial and temporal variability in $MSAVI_2$ among lands with different disturbance histories, we used one cloud-free Landsat 5 Thematic Mapper (TM) or 7 Enhanced Thematic Mapper (ETM+) image per year. Image sampling dates were selected for 17 of the previous 20 years from 1984 – 2003, in a 30-day window centered on 27-June (Table 1). 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 shifts. 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). $MSAVI_2$ was calculated from red (band 3, 630-690 nm) and near-infrared (band 4, 750-900 nm) reflectance using the equation developed by Qi et al. (1994):

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

Our analyses focused on calculations of mean $MSAVI_2$, the coefficient of variation (CV) of $MSAVI_2$ among years ("$CV_{temporal}$ $MSAVI_2$"; CV = SD / mean * 100), and CV of $MSAVI_2$ among pixels with a year (i.e. within one image, "$CV_{spatial}$ $MSAVI_2$"). Fire effects on $MSAVI_2$ were determined by using only post-fire $MSAVI_2$ in both burned and non-burned (i.e. control) lands. 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 (Fig. 1). Thus, we did not place any qualifiers on which lands to use for assessment of grazing impacts. In addition, the effect of community type on $MSAVI_2$ was examined by comparing mean $MSAVI_2$ between undisturbed areas of sagebrush and grasslands, identified from previous vegetation classifications of the INL (Kramber et al. 1992). One and two-factor analysis of variance (ANOVA) were used to compare mean $MSAVI_2$ and mean CV of $MSAVI_2$ among years, and between pixels with different disturbance histories.

We compared mean and CV of $MSAVI_2$ of lands with different disturbance histories between "wet" and "dry" years with the greatest and least amount of precipitation (PPT) during the study period. Wet years consisted of years when cumulative annual PPT was greater than one SD above the mean PPT over the study period, and dry years were years when cumulative annual PPT was lower than one SD below the mean. These years were determined from sliding, three-year averages of growing season PPT (cumulative from April to image date), which showed higher correlations with $MSAVI_2$ (higher r^2 values) than did water-year PPT (cumulative from October to image date) and yearly PPT (cumulative from January to image date). Precipitation was determined from data obtained from the INL Central Facilities Area station (Western Regional Climate Center, Desert Research Institute, Reno NV). 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). Relationships between precipitation and inter-annual mean $MSAVI_2$ and CV of $MSAVI_2$ for disturbance history lands and community types were examined using linear least squares regression.

Results

Mean $MSAVI_2$ of undisturbed lands fluctuated significantly over the 20-year period, ranging from 0.03 in 1985 to 0.l6 in 1993 (Fig. 2; $F_{16, 84} = 66.57$, $P < 0.0001$). The greatest amount of change in mean $MSAVI_2$ over the 17-years occurred between 1993 and 1994, when mean $MSAVI_2$ decreased by 0.07 (44%).

Grazed/burned pixels had 18% greater mean $MSAVI_2$ compared to undisturbed lands over all 7 – 9 growing seasons following the 1994 fire ($F_{3, 31} = 3.24$, $P = 0.03$), but no differences were observed following the other fires (Fig. 3). However, $MSAVI_2$ increased as much as 61% ($F_{1, 71} = 28.32$, $P < 0.000$) in the second growing season following fire, for all fire years in grazed and non-grazed pixels alike, compared to background increases of 20% across the same years, in undisturbed control pixels (Burned: 0.142 ± 0.020 Standard Error (SE); Burned-grazed: 0.140 ± 0.012 SE; Grazed: 0.089 ± 0.008 SE; Control: 0.105 ± 0.010 SE; Fig. 4; $F_{1, 71} = 5.21$, $P < 0.008$). For grazed-only lands, there were no differences in mean $MSAVI_2$ as the distance from livestock watering sites increased. Inter-annual variability ($CV_{temporal}$) of $MSAVI_2$ following all fires combined was up to 2-fold greater in pixels of burned and grazed/burned lands compared to control and grazed-only lands (Fig. 4).

Mean $CV_{spatial}$ of $MSAVI_2$ (variation in $MSAVI_2$ among pixels within each image) of increased following fire, especially in the first and second growing seasons (Fig. 5).

Specifically, in the first growing season following fire, mean $CV_{spatial}$ of $MSAVI_2$ was 27% higher in burned compared to control pixels and 30% higher in grazed/burned compared to grazed pixels (Fig. 6; $F_{1, 71} = 7.55$, $P = 0.008$). In the second growing season, $CV_{spatial}$ of $MSAVI_2$ increased 75% among grazed/burned pixels (CV = 29.6% ± 4.6 SE) compared to among grazed pixels (CV = 16.9% ± 0.9 SE; $F_{1, 72} = 4.19$, $P = 0.04$; Fig. 6). $CV_{spatial}$ of $MSAVI_2$ decreased to different extents for all lands during the study period, irrespective of disturbance history, though rates of decrease were at least two-fold greater for sites recovering from fire, and especially for grazed/burned lands (Fig. 6).

$CV_{spatial}$ of $MSAVI_2$ among pixels with no fire or grazing disturbance was correlated with sliding three-year averages of growing season precipitation, PPT ($r^2 = 0.62$, $P = 0.02$), but the highest correlations occurred in grazed ($r^2 = 0.79$, $P = 0.02$) and non-grazed ($r^2 = 0.81$, $P = 0.002$) lands that burned (Table 2). Following fire, the slope of the relationship between $CV_{spatial}$ of $MSAVI_2$ and PPT in grazed/burned lands (mean increase of 0.33 in $CV_{spatial}$ of $MSAVI_2$ / mm PPT) was over two times greater than burned lands (mean increase of 0.17 in $CV_{spatial}$ of $MSAVI_2$ / mm PPT), and especially undisturbed, control lands (0.16 increase in $CV_{spatial}$ of $MSAVI_2$ / mm PPT), and five times greater than grazed lands (0.08 increase in $CV_{spatial}$ of $MSAVI_2$ / mm PPT). For grassland communities, the slope of the relationship between $CV_{spatial}$ of $MSAVI_2$ and PPT was almost two times higher (mean increase of 0.32 in $CV_{spatial}$ of $MSAVI_2$ / mm PPT) compared to sagebrush communities (mean increase of 0.18 in $CV_{spatial}$ of $MSAVI_2$ / mm PPT). In addition, there was a marginal difference in the interaction between PPT and

$CV_{spatial}$ of $MSAVI_2$ between grazed and grazed/burned lands ($F_{15,\,1}$ = 3.49, *P* = 0.08; Table 2 and Figure 7).

Post-fire variability in $CV_{spatial}$ of $MSAVI_2$ increased up to nearly three times in years of high compared to low precipitation (Fig. 8). In drought years, no differences in $CV_{spatial}$ of $MSAVI_2$ were detectable among pixels (Fig. 8). In wet years, post-fire $CV_{spatial}$ among pixels of lands that had been grazed/burned was 20% higher than in control lands, 44% higher than grazed-only lands, and 23% higher than in burned-only lands (Fig. 8; $F_{3,\,19}$ = 6.08, *P* = 0.009). Overall, grazing and fire appeared to have an almost additive, positive effect on $CV_{spatial}$ of $MSAVI_2$ in high precipitation years.

Discussion

Many studies have measured mean changes in plant cover of sagebrush-steppe in response to wildfire and/or grazing disturbances (e.g. Brotherson and Brotherson 1981, Humphrey 1984, Hosten and West 1994, Wambolt 2001, West and Yorks 2002). However, we found that changes in the variability of remotely sensed indices of cover (Fig. 6) were more responsive than mean responses of vegetation indices (Fig. 4) for assessing long-term disturbance effects. Differences in $MSAVI_2$ within a sampling date ($CV_{spatial}$), and between years ($CV_{temporal}$) emerged as more sensitive response variables than mean $MSAVI_2$, over longer time scales. Mean $MSAVI_2$ increased only in the second growing season following fire, but mean $CV_{spatial}$ of $MSAVI_2$ was greater in fire-disturbed lands for nearly a decade (Table 2), most apparently due to greater sensitivity of $CV_{spatial}$ of $MSAVI_2$ to years with above average precipitation (Fig. 7). Greater mean $MSAVI_2$ and mean $CV_{spatial}$ of $MSAVI_2$ observed following fire and grazing/fire compared to undisturbed lands demonstrated that fire and the interaction of fire and grazing can strongly influence the stability or constancy of $MSAVI_2$ measures in sagebrush-steppe (Figs. 4 and 6).

Although mean $MSAVI_2$ significantly increased among burned and grazed/burned lands the second growing season following fire, it appeared to recover to near pre-fire levels by the third growing season after fire. Many studies report that reductions in sagebrush cover due to fire are compensated for in total community biomass/cover by disproportionate increases of perennial and annual grasses and forbs (Humphrey 1984, Hosten and West 1994, West and Yorks 2002). Typically, grassland communities have higher vegetation index measures compared to the sagebrush or other shrub communities (Kremer and Running 1993, Paruelo and Lauenroth 1995, Weiss et al. 2004). In some years, we found $MSAVI_2$ to be as much as 0.07 higher among undisturbed lands dominated by grasslands compared to sagebrush. Our study provides an indication that flushes of over-compensating herbaceous and grass cover in sagebrush-steppe following fire may not occur until the second growing season following fire.

Grazing has been shown to significantly alter species composition and cover characteristics at the plot level (Brotherson and Brotherson 1981, West and Yorks 2002) and landscape level in sagebrush-steppe (Anderson and Inouye 2001, Washington-Allen et al. 2004). Grazing, along with climate change and fire, is considered to be a primary control of vegetation response in sagebrush-steppe landscapes (Laycock 1991, West and Young 2000, Washington-Allen et al. 2004). We did not detect significant differences in spatial and temporal variability in $MSAVI_2$ among grazed lands compared to non-grazed lands. However, grazing appeared to interact with fire in a way that increased the heterogeneity of plant cover, resulting in higher post-fire CV of $MSAVI_2$ among grazed/burned pixels within a sampling date compared to control, grazed-only, and burned-only pixels.

Increases in spatial heterogeneity of $MSAVI_2$ in disturbed compared to undisturbed lands, and in grassland compared to sagebrush communities, became more evident in wet compared to dry years (Fig. 7 and Table 2). In dry years, CV of $MSAVI_2$ among lands with different disturbance histories may have decreased because the amount of live cover was relatively low due to decreased growth potential (Lauenroth and Sala 1992). Drought appeared to decrease the vegetation index potential of pixels to common, low values. This is further supported by stronger correlations of spatial variability and growing season precipitation for fire-disturbed or undisturbed grassland pixels compared to non-burned or undisturbed sagebrush pixels. These results indicate that studies seeking to determine fire and grazing impacts should encompass multiple years, and consideration of variation in spatial heterogeneity in sampling among years.

We speculate that increased temporal and spatial variability for pixels with higher levels of disturbance may be partly attributable to increases in abundances of annual and perennial grasses, and forbs, which, compared to sagebrush (evergreen/deciduous), tend to express a tighter linkage of $MSAVI_2$ and variation in PPT (Table 2). Annual grasses tend to be the major cover component on burned sites for at least the first few years following fire, with steady increases of perennial grasses in remaining years up to a decade, as described in nearby sagebrush-steppe (West and Yorks 2002). Wyoming big sagebrush cover appeared to vary less than herbaceous or annual species in response to drought (Passey et al. 1982, West and Yorks 2002). Also, long-term field plots on the INL with higher shrub densities tended to exhibit less variability in cover than plots with low shrub densities over 45 years (Anderson and Inouye 2001). Thus, it is likely that increased temporal and spatial variability (i.e. lower stability) among fire-disturbed lands could be due to reductions of shrub cover and compensating increases in herbaceous and, especially grass cover.

The greater variability in grazed/burned compared to burned-only lands, however, appears to be due to more than conversion of shrubs to grasses alone. Grazing appears to increase the amount of shrub cover relative to herbaceous and grass cover, resulting in higher densities of sagebrush that may persist for long periods (Anderson and Inouye 2001). Indeed, our measurements of less variability in $MSAVI_2$ in grazed-only compared to undisturbed, control lands, could be explained by greater relative abundances of shrubs (Figs. 4 – 7). Greater standing crops of shrubs compared to grasses should raise fuel loads, due to increased shrub cover, amplifying the intensity and severity of fire (DeBano et al. 1998), resulting in greater site alterations (e.g. changes in soil physical properties) rather than just changes in floristics. We speculate that these changes contribute to greater spatial and temporal variability in large-scale satellite-based measurements of vegetation. 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 only.

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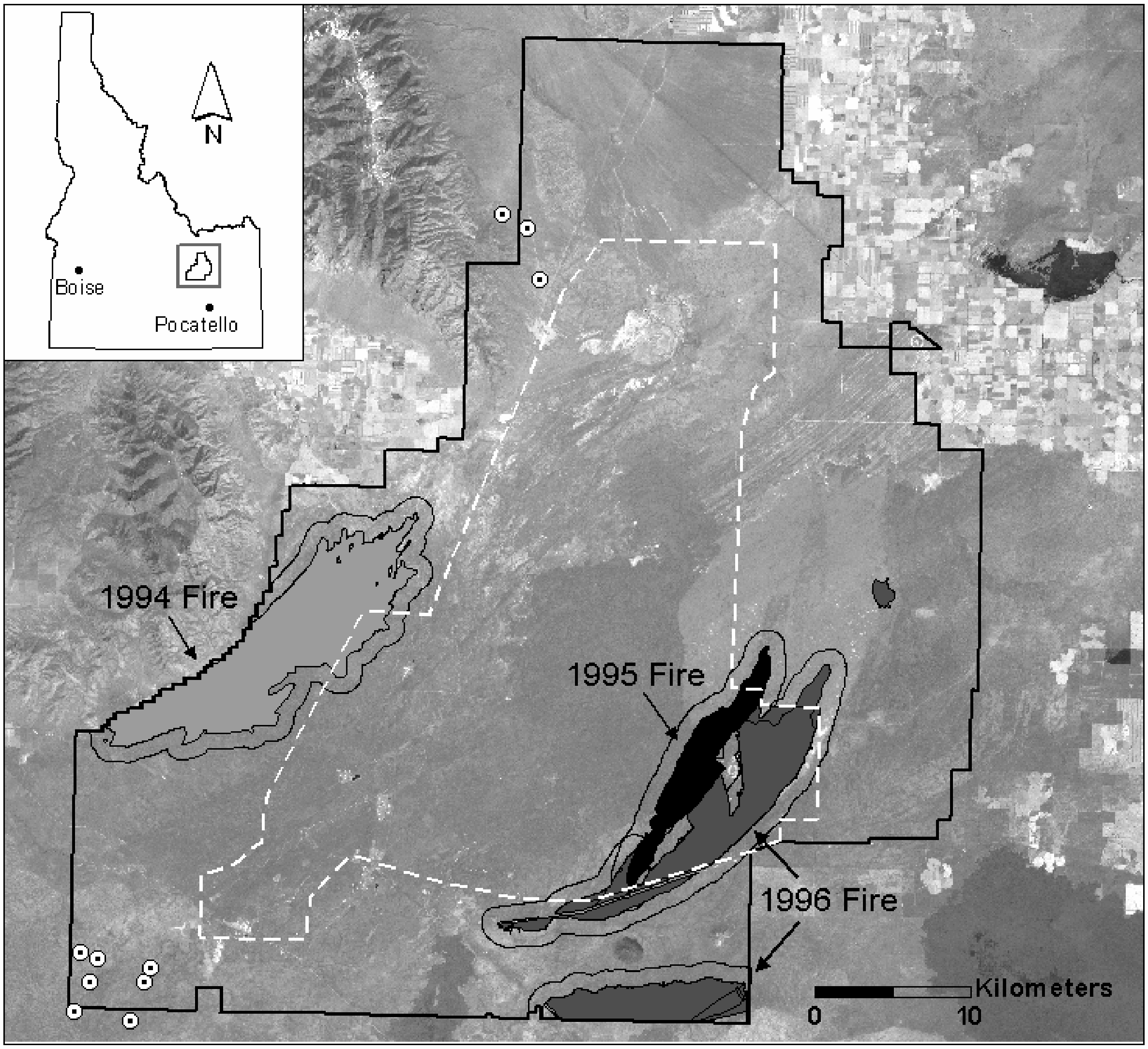

Figure 1. Map of the Idaho National Laboratory (INL) located on the Upper Snake River Plain (Idaho) with disturbance history lands for the 1994, 1995, and 1996 fires indicated. Black line indicates INL boundary with lands closed to livestock grazing since 1950 inside the dashed white line. White circles indicate livestock watering sites for two grazing allotments on the INL.

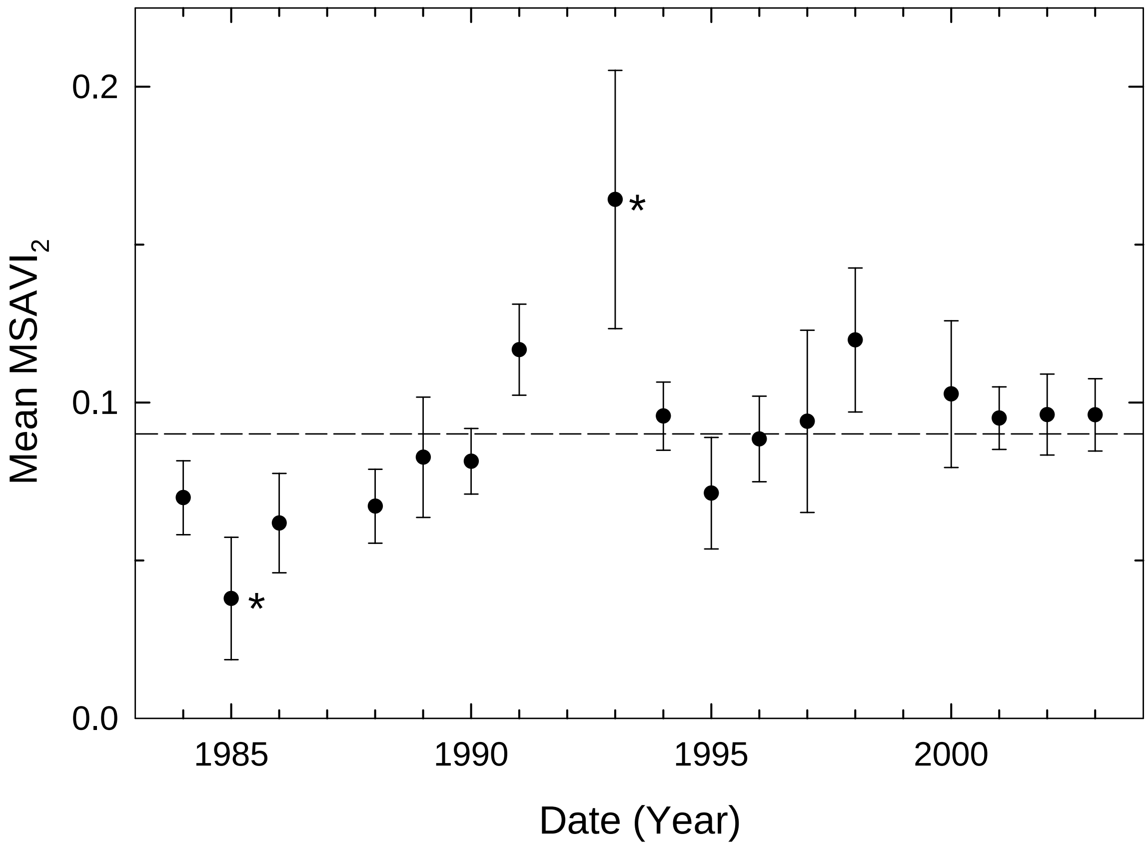

Figure 2. Mean $MSAVI_2$ (+/- 1 SD) for pixels of undisturbed, control lands on the INL from 1984 - 2003. Dashed line indicates mean of $MSAVI_2$ for all years combined (n = 17 years) and * indicates significant differences from all years (Tukey, P = 0.05).

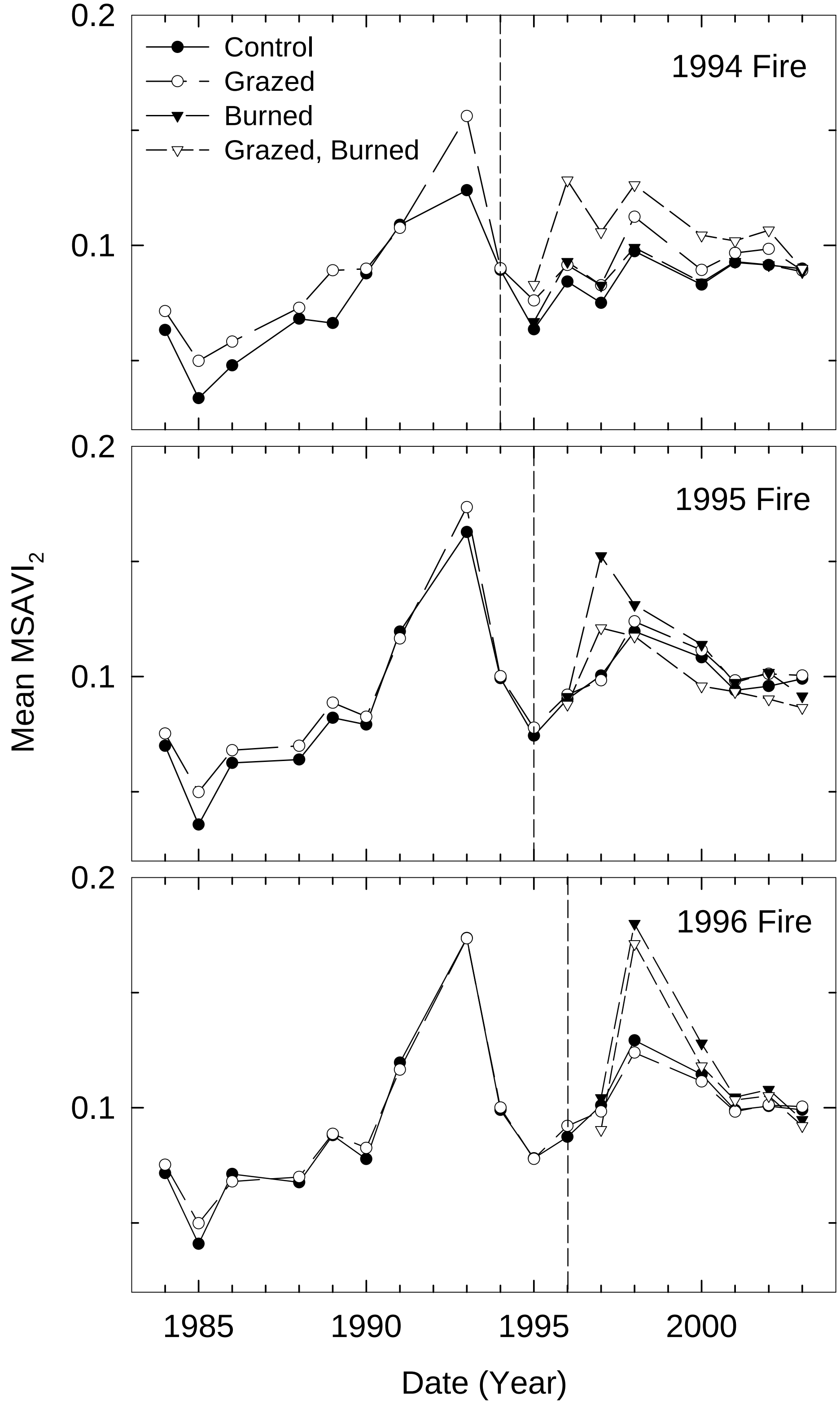

Figure 3. Mean MSAVI$_2$ among disturbance history lands following the 1994, 1995, and 1996 fires. Vertical dashed lines represent the year fires occurred.

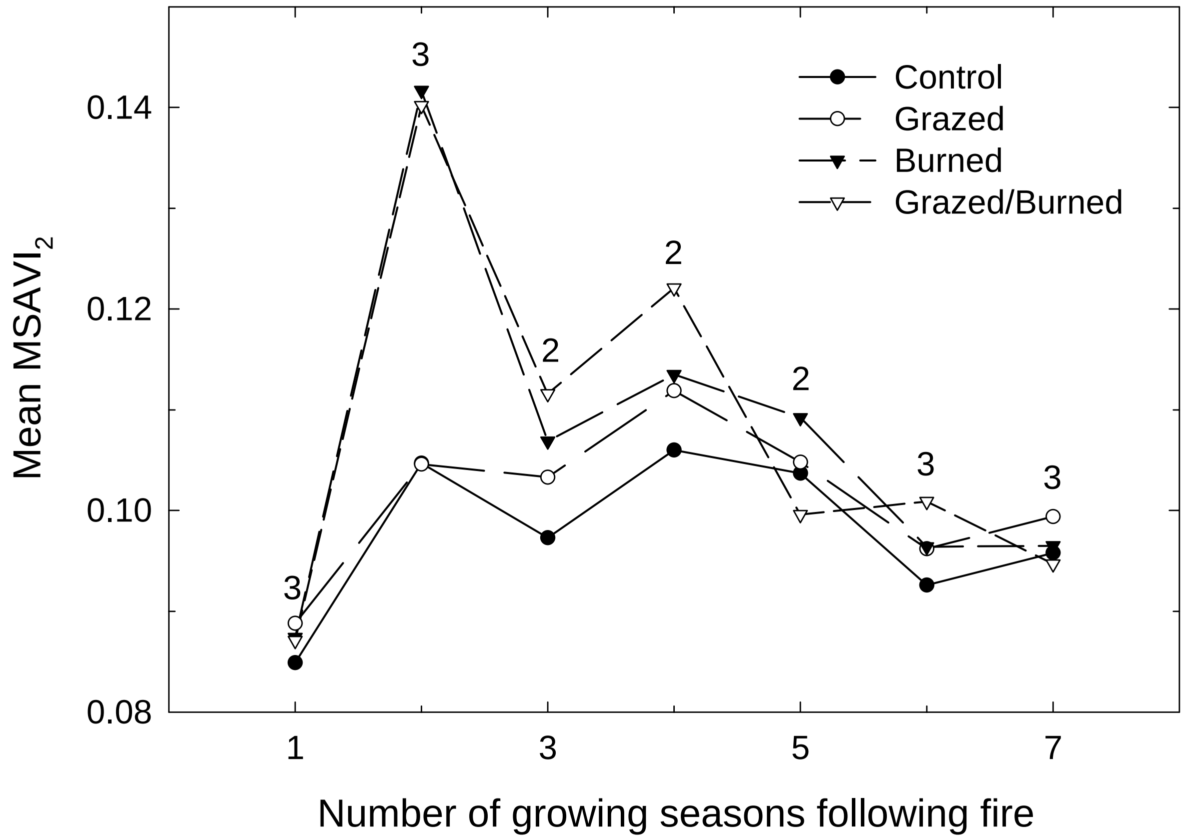

Figure 4. Grouped comparisons of mean $MSAVI_2$ among disturbance history lands following the 1994, 1995, and 1996 fires. The number of burned sites included in grouped post-fire year calculations is indicated above line graphs.

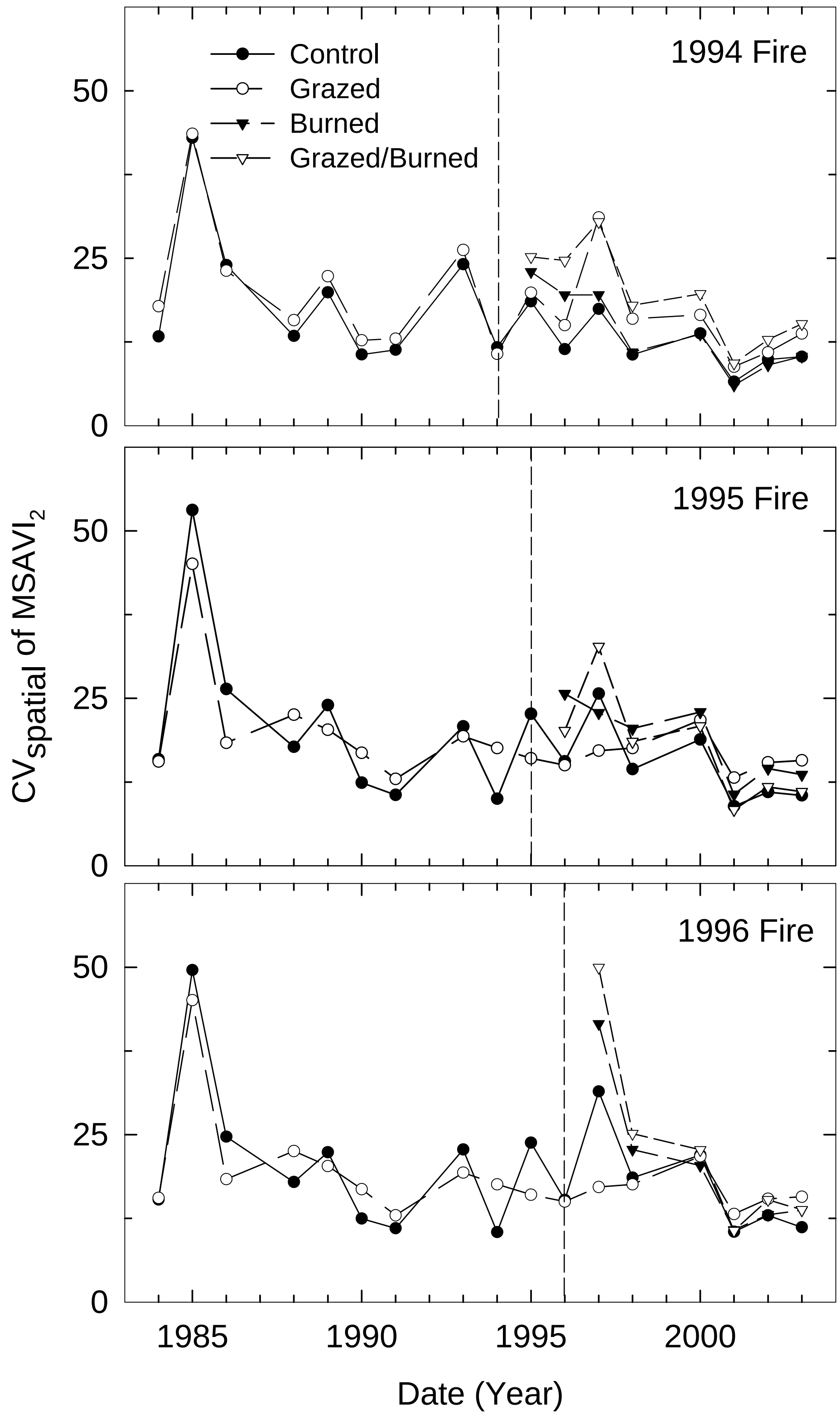

Figure 5. Mean CV of $MSAVI_2$ among pixels for disturbance history lands following the 1994, 1995, and 1996 fires. Vertical dashed lines represent the year fires occurred.

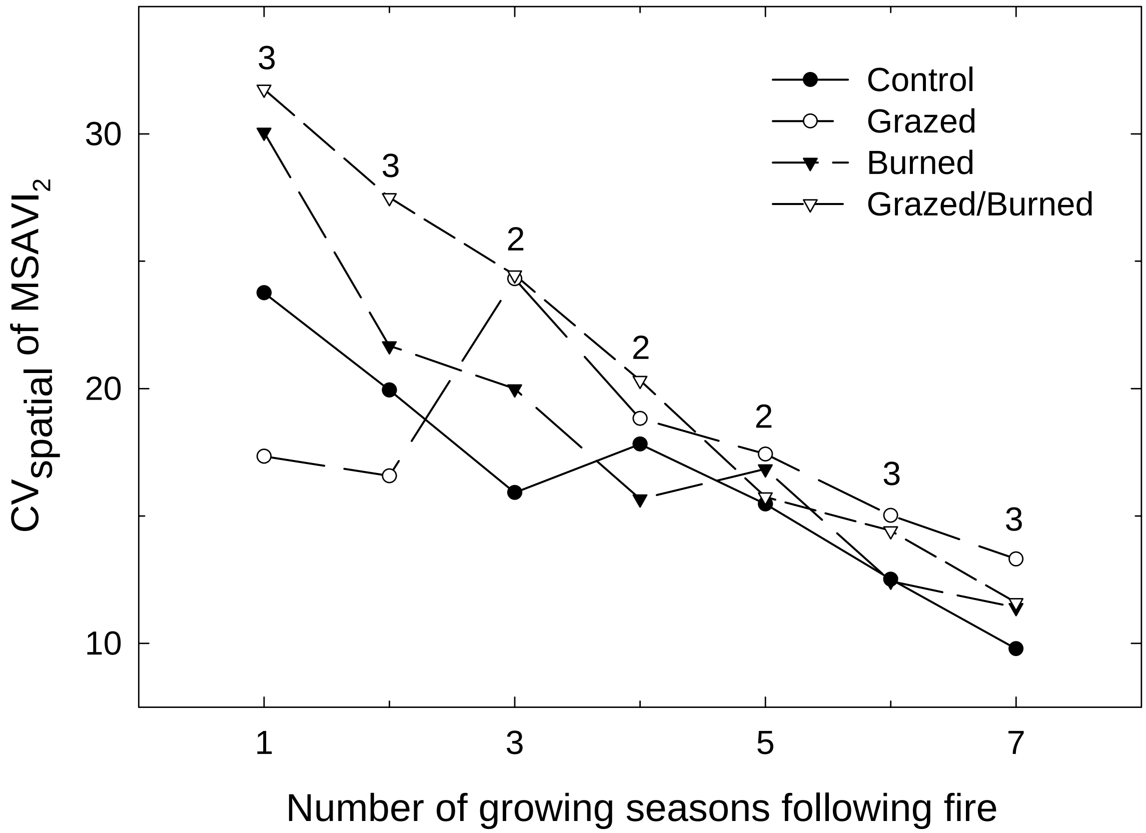

Figure 6. Grouped comparisons of mean CV of $MSAVI_2$ among pixels for disturbance history lands following the 1994, 1995, and 1996 fires. The number of burned sites included in grouped post-fire year calculations is indicated above line graphs.

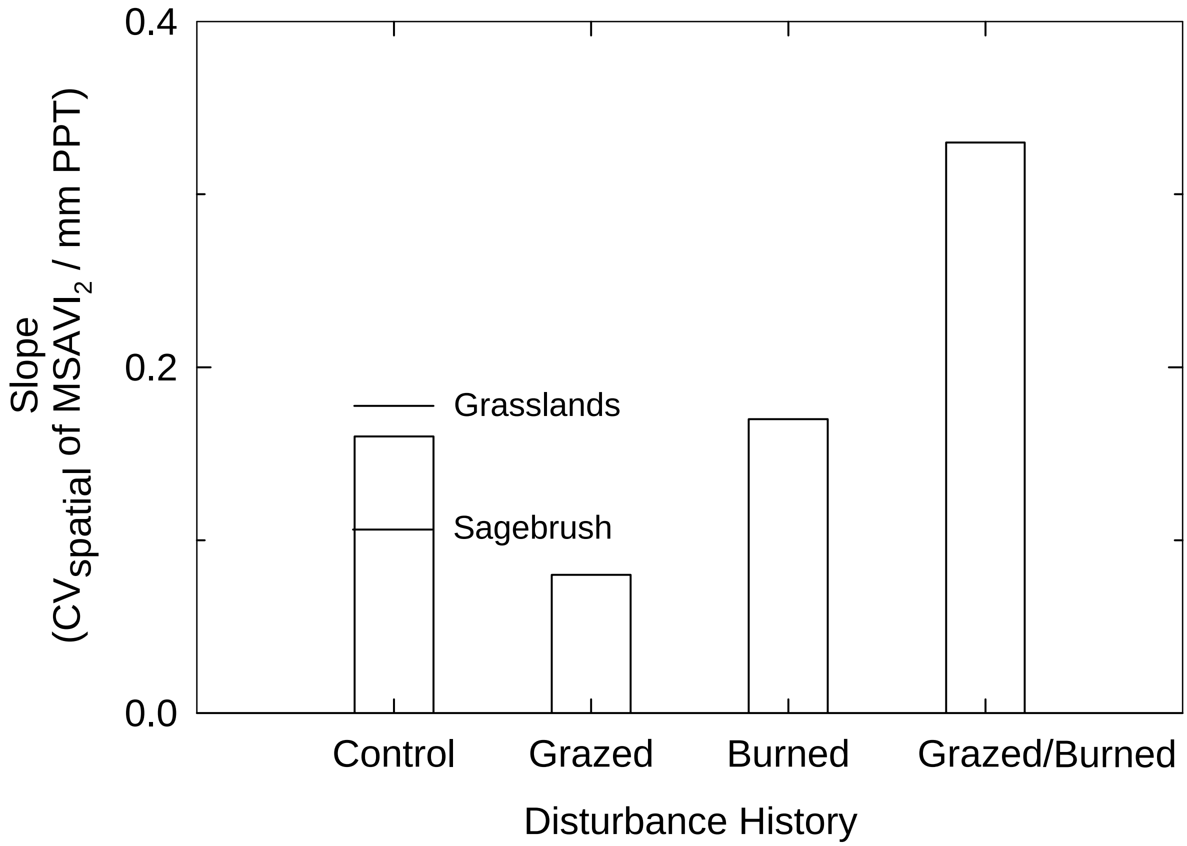

Figure 7. The slopes of the relationships between sliding three-year averages of cumulative annual growing season precipitation, PPT (from April 1 to image date), and post-fire $CV_{spatial}$ of $MSAVI_2$ among pixels of lands with different disturbance histories and undisturbed community types (sagebrush and grasslands). See Table 2 for regression statistics.

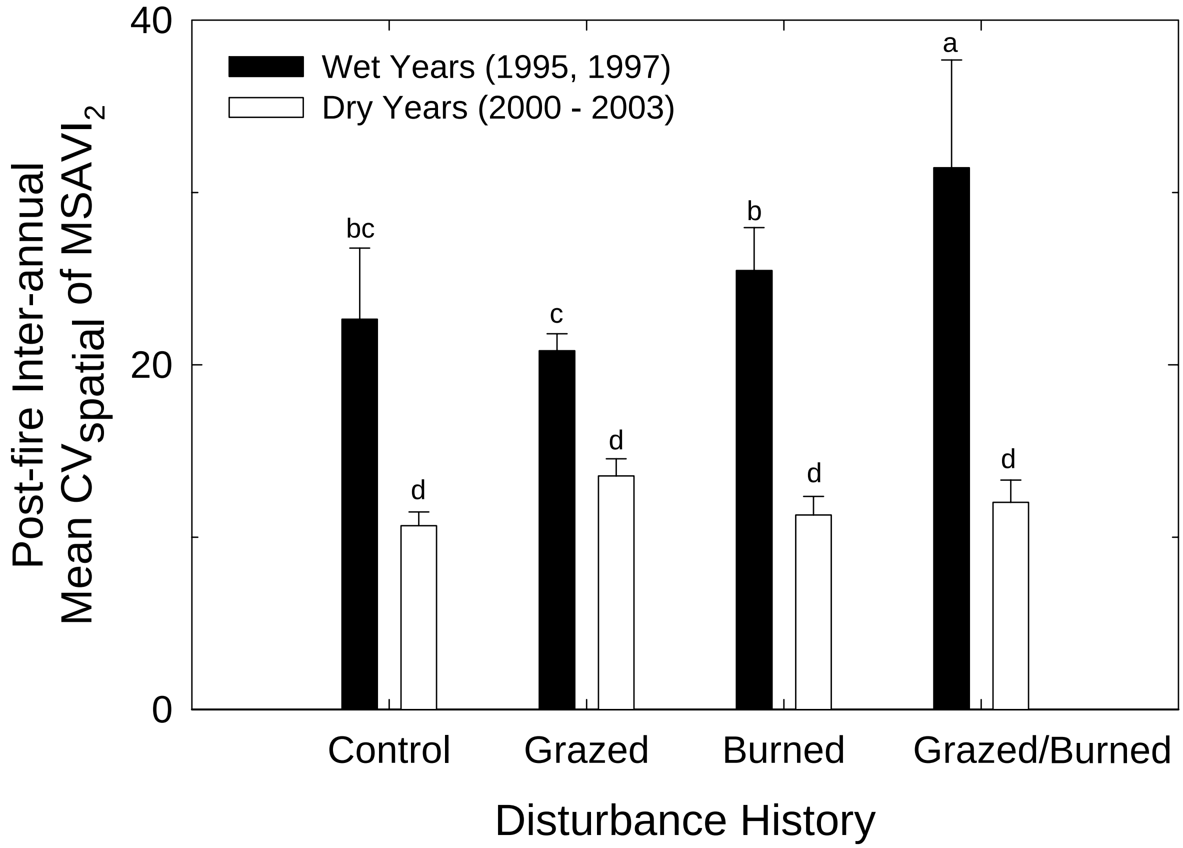

Figure 8. Mean $CV_{spatial}$ of $MSAVI_2$ (+/- 1 SE) during years of varying precipitation for undisturbed (control), grazed-only, burned-only, and grazed/burned lands. Wet years (n = 2 years) and dry years (n = 3 years) were years when the sliding three-year average of annual cumulative growing season precipitation (mm) was +/- 1 SD from the 20-year mean (1984 - 2003). Letters denote significant differences (P = 0.05).

Table 1. Inter-annual Landsat image acquisition dates from 1984 – 2003.

Image Date	DOY	Sensor Type
07/02/84	183	Landsat 5 TM
07/05/85	186	Landsat 5 TM
06/23/86	174	Landsat 5 TM
06/11/88	162	Landsat 5 TM
06/30/89	181	Landsat 5 TM
07/03/90	184	Landsat 5 TM
06/20/91	171	Landsat 5 TM
06/25/93	176	Landsat 5 TM
06/28/94	179	Landsat 5 TM
07/17/95	198	Landsat 5 TM
06/17/96	168	Landsat 5 TM
06/20/97	171	Landsat 5 TM
07/09/98	190	Landsat 5 TM
06/20/00	171	Landsat 7 ETM+
07/01/01	182	Landsat 7 ETM+
07/12/02	193	Landsat 7 ETM+
07/07/03	188	Landsat 5 TM

Table 2. Correlations of sliding three-year averages of cumulative growing season precipitation (from April 1 to image date) and post-fire $CV_{spatial}$ of $MSAVI_2$ among pixels of lands with different disturbance histories. N indicates the number of years prior to 2003.

Disturbance History	r^2	F	*P*	Slope	DF	N
Control	0.615	9.598	0.021	0.160	6	8
Control	0.378	9.099	0.008	0.237	15	17
Undisturbed Sagebrush	0.316	6.919	0.019	0.176	15	17
Undisturbed Grasslands	0.411	10.463	0.006	0.318	15	17
Grazed-only	0.597	8.906	0.025	0.078	6	8
Grazed-only	0.267	5.457	0.034	0.139	15	17
Burned 1994	0.814	26.279	0.002	0.159	6	8
Burned 1995	0.741	17.195	0.006	0.178	5	7
Burned 1996	0.780	16.709	0.009	0.166	4	6
Grazed, Burned 1994	0.758	15.701	0.011	0.238	6	8
Grazed, Burned 1995	0.787	14.767	0.018	0.341	5	7
Grazed, Burned 1996	0.765	13.027	0.022	0.425	4	6