LANDSCAPE-SCALE POSTFIRE VEGETATIVE CONDITION MONITORING USING MULTI-TEMPORAL LANDSAT IMAGERY ON THE CERRO GRANDE FIRE

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ABSTRACT

The Cerro Grande Fire of May 2000 burned approximately 43,000 acres in the eastern Jemez Mountains in the vicinity of Los Alamos, New Mexico. BAER (Burned Area Emergency Response) expenditures exceeded 14 million dollars on immediate post-fire treatments. Remote sensing was used to monitor and evaluate the effectiveness of post-fire treatment prescriptions as a cost-effective tool at the landscape scale. We performed a multi-temporal normalized difference vegetation index (NDVI) analysis based on Landsat imagery acquired on several anniversary dates between 1999 and 2005. An assessment of vegetation regeneration within treatment areas was conducted by comparing inter-annual NDVI values using the normalized regeneration index (NRI). The NRI results show that certain BAER treatments helped to enhance vegetative cover over the course of our monitoring. The quickest vegetation regeneration occurred in the unit with the highest proportion of acres treated for the purpose of establishing immediate ground cover through mulching and seeding.

INTRODUCTION

Fire History of the Jemez Mountains

Fire in the Jemez Mountains is common and a natural part of the ecosystem. The Jemez Mountains have seen a number of wildfires that burned thousands of acres. Some recent large fires in the immediate vicinity of Cerro Grande include the La Mesa Fire (15,270 acres in 1977), Dome Fire (16,575 acres in 1996) and Oso Fire (6,517 acres in 1998) (WALTER, 2004).

Cerro Grande Fire Background and Details

The Cerro Grande Fire was ignited on May 4, 2000, as a prescribed burn by the National Park Service on the southwestern flank of Cerro Grande, within the Sierra de los Valles on the eastern rim of the Jemez Mountains, on May 4, 2000. A timeline of significant events in the fire is shown in table 1.

Date in 2000	Event
May 4	Prescribed fire ignition
May 5	Became wildfire
May 6/7	Initial containment
May 7	Declared out of control
May 10	Firestorm (wind event)
May 13	Declared major disaster by President Clinton
June 6	Contained
July 20	Controlled
September 22	Declared out

Table 1; Timeline of the Cerro Grande Fire

The total acreage burned as reported in the Cerro Grande Fire 2500-8 (USDA Forest Service, 2005) was 42,970 acres, of which 25,633 acres were on National Forest lands, 15,270 acres were on other federal lands, and 2,067 acres were privately owned.

Values at Risk

First and foremost was human health and safety as large upstream basins within the fire perimeter were burned. Immediate emphasis was placed on reducing potential post fire flooding, debris delivery and expected excess erosion.

Not only did about 7,600 acres burn within the boundaries of Los Alamos National Laboratory (LANL), but upstream contributing watersheds were within the fire perimeter as well. Storage of legacy waste associated with management of the area going back to the "Manhattan Project" provided significant overriding issues as potential contaminant transport from increased erosion and runoff had significant downstream implications. Threats to Los Alamos County included surface water resources, water supply wells and their infrastructure, sewage treatment facility and infrastructure, now under-sized road crossings, emergency services access /egress and localized flooding of neighborhoods. Downstream Pueblos had similar threats as well as very specific local issues. Protection of heritage resource sites was a concern for all entities (BAER, 2000).

REHABILITATION/RESTORATION EFFORTS ON THE CERRO GRANDE FIRE

Burn Severity

The burn severity assessment was conducted within the BAER assessment process and relied on local aerial reconnaissance, four-meter resolution IKONOS digital color-infrared imagery acquired on May 20, and 21, 2000, and field observations. Burn severity acreage as reported in the final Burned Area Report (FS-2500-8) was identified as: 25,034 low or unburned, 3,424 moderate and 14,512 high. The largest concentration of "high" was a single polygon of over 10,000 acres resulting from the firestorm on May 10 with entire headwater areas almost completely burned (Balice et al., 2004). The extent and depth of hydrophobic soil conditions resulted in calling many areas "high" with virtually no litter remaining on the landscape.

Post-Fire Runoff and Soil Conditions.

Prior to the fire, runoff and surface erosion from the National Forest was negligible (Lavine et al., 2005). Post-fire modeling predicted extremely high erosion potential, returning numbers that were hard to believe - until the first rain event. The reader is referred to numerous publications related to this fire, including the final Burned Area Report (USDA Forest Service, 2005). Post-fire peak flows were up to three orders of magnitude (1000 times) higher than pre-fire events and post-fire sediment deliveries were documented (Gallaher and Koch, 2004) at about 500 times higher than pre-fire conditions. Extensive treatments, including about 2,700 acres of hand-applied straw mulch, were effective at reducing some of these impacts. Precipitation patterns help explain some of the vegetation response (regeneration rates) and watershed response (erosion rates) after the fire. This landscape receives widely varied amounts of precipitation shown by the LANL weather station at 7,424’ and the Quemezon NRCS SNOTEL site at 9,500’ (figure 1).

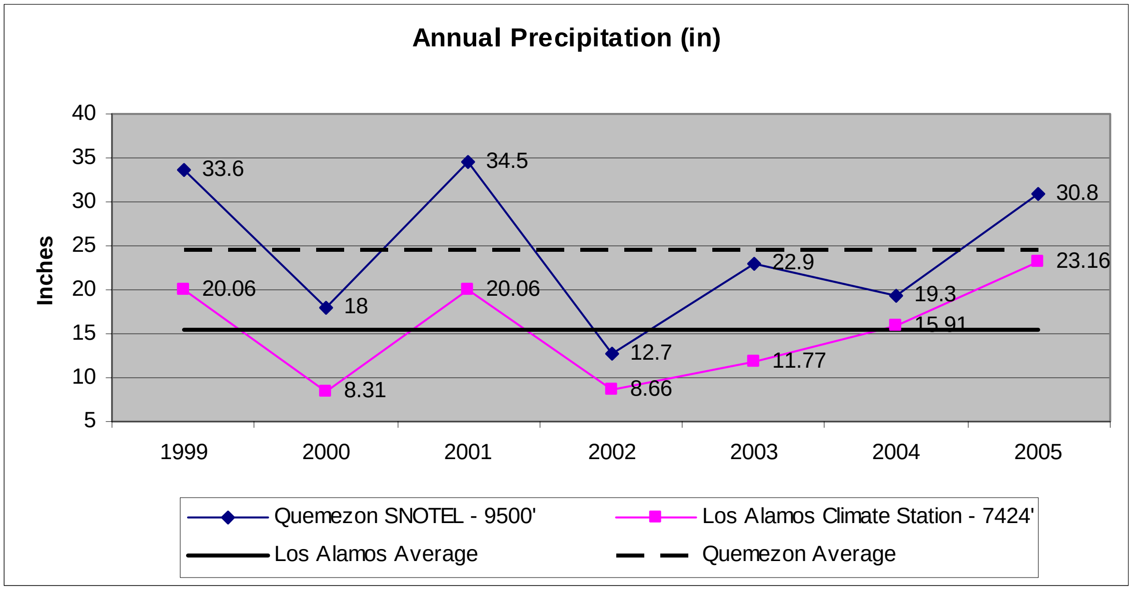


Figure 1; Annual precipitation (by water year) on the Jemez Mountains during the analysis period

BAER Treatments

Watersheds were prioritized for post-fire treatment as a function of downstream values at risk resulting from post-fire runoff events. While on-site erosion from burned areas was an issue, it was secondary to scour and transport of contaminated sediments or run-on/runoff from legacy waste areas influenced by the Laboratory. For example, Gallaher and Koch (2004, p. 59) noted that “[H]igh-volume storm runoff events in Pueblo Canyon in 2001, 2002, and 2003 contained significantly higher concentrations of plutonium-239,240.”

All moderate and high severity burned areas were immediately aerially seeded (about 21,000 acres) with many areas manually re-seeded after localized but highly damaging flood events of June 28, 2000. Key slope treatments resulted in increased cover from treatments that included 2,217 acres of hand applied straw mulch along with 1,184 acres of aerial hydromulch. These mulch treatments were completed by the end of July 2000. In 2001, 587 additional acres were covered with hand-applied straw mulch between May and August, mostly in the Pueblo Canyon watershed. These acres were concurrently reseeded by crews. In March 2002, over 600 acres in Pueblo Canyon were aerially reseeded. All treatments applied are listed in table 2. Forest Service costs alone for BAER or post-fire related treatments exceeded $14 million.

Treatment	Acreage
Aerial seeding	21,080
Aerial hydromulch	1,184
Contour felling	3,139
Straw wattles	1,265
Grade control	128
Straw mulch	2,704
Raking	112
Totals	**29,612**

Table 2; Treatments applied to burned areas of the Cerro Grande Fire

MONITORING VEGETATION REGENERATION

Methods

With fires increasingly burning extensive landscapes, resources can be stretched thin for mapping and monitoring post-fire vegetation regeneration to estimate the effectiveness of treatments. The use of airborne or spaceborne imagery to monitor vegetation trends has become an efficient and cost-effective tool available to resource managers. Correlation between BAER treatments, imagery, and image-derived products is dependent on the contiguous acreage of the treated area. For example, the effects of the many channel treatments and other linear treatments installed to reduce post-fire runoff and erosion are not likely to be visible considering the source imagery. For this project, Landsat 7 ETM+ and Landsat 5 TM imagery was acquired of the Jemez Mountains between 1999 (pre-fire) and 2005 (WRS path 34, row 35 and path 33, row 35). Each image was received in NLAPS format from USGS-EROS (Earth Resources Observation & Science) and converted to reflectance: Landsat 5 imagery was converted as outlined by Chander and Markham (2003) and Landsat 7 imagery was converted as outlined by the Landsat 7 Science Data User's Handbook (NASA, 1998). Imagery delivered in NLAPS format is terrain corrected, but when performing image differencing, coregistration between temporal dates is required. This was done by utilizing the Landsat sensor model in ERDAS Imagine 8.7, which provided favorable results (root mean square error ~20 meters).

The imagery was clipped to a rectangular shape that included the burn scar and ample land outside the burn perimeter. With atmospheric and geometric problems accounted for, the normalized differenced vegetation index (NDVI) was then performed on each year's imagery. The NDVI is a common index used to monitor the strength of photosynthetic activity in vegetation. The theoretical data range in this ratio is -1 to 1, with negative values typically representing non-vegetated surfaces, i.e., snow, clouds, water, etc. As values approach 1, photosynthetic activity becomes very strong. Typically, the highest values returned from the NDVI process are golf courses, riparian/wetland areas, and irrigated farm lands.

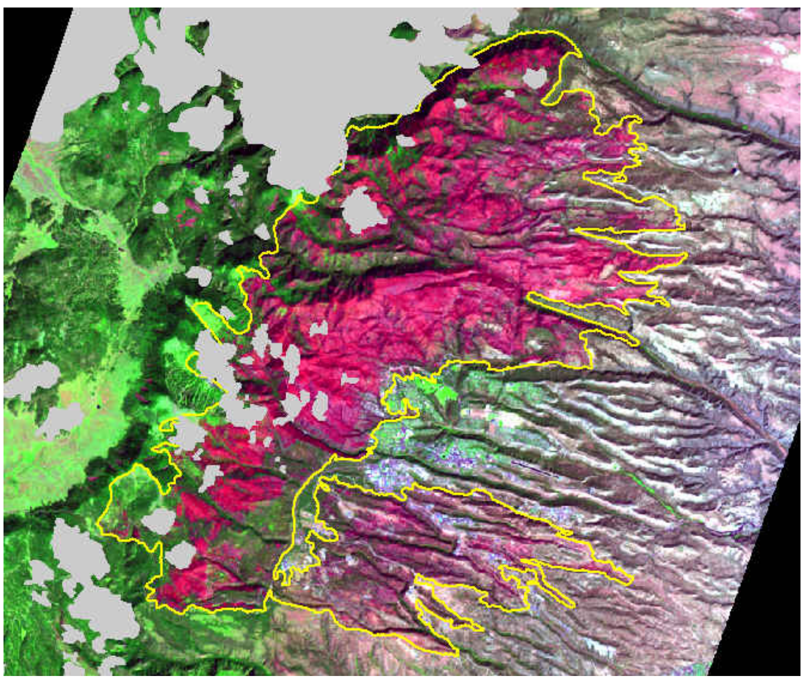


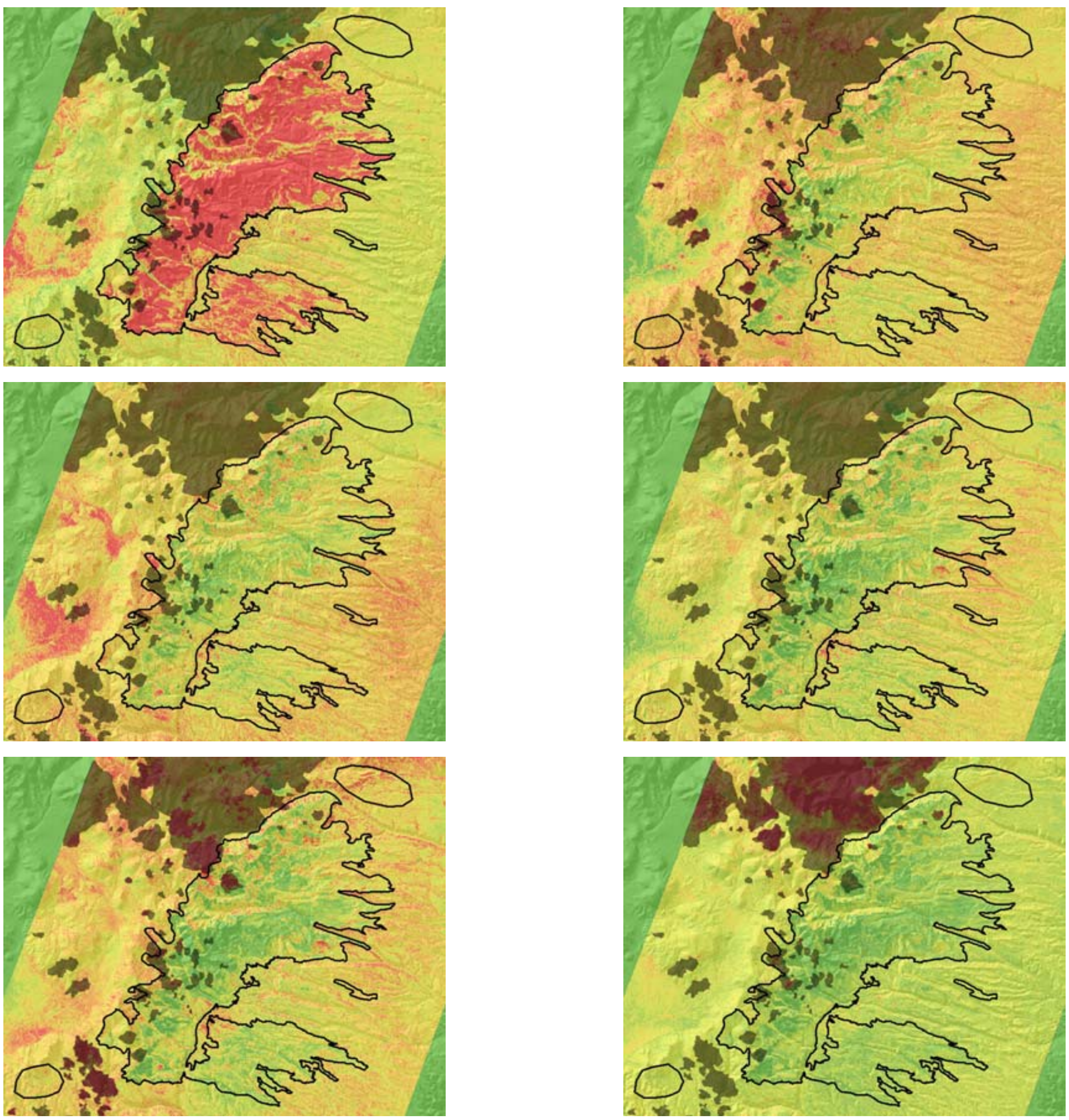
Figure 2; Landsat image (Sept. 2000) with fire perimeter and cloud mask (gray polygons) shown

As precipitation and temperature may have dramatic effects on vegetation activity, it was interesting to see the inter-annual differences in the NDVI products. As noted earlier, this area has experienced extreme variance in precipitation since the Cerro Grande Fire, which is reflected in the annual NDVI products. The annual NDVI products were computed for the whole burn scar, providing a synoptic view of the landscape.

Before performing any further analysis, we masked all clouds and cloud shadows that were visible on the imagery. These masks carried through to all dates; for example, if clouds existed on the imagery in 2001, the shape of the cloud and accompanying shadow was masked out of each NDVI image between 1999 and 2005. Of the seven images used in this project, 2001, 2004, and 2005 images contained clouds (see figure 2). The end result was a set of images for seven years that had no clouds or cloud shadows present, although each image now had "holes" where the clouds existed. The exclusion of the clouds and shadows allowed us to focus on trends in the vegetation without having to interpret anomalies in the products that would be due to clouds or cloud shadows.

The analysis included all the areas contained within the official fire perimeter, which we delineated into two zones, each with varying coverage of applied BAER treatments. The North zone is defined as Rendija Canyon Watershed and north; the South zone is defined as Pueblo Canyon Watershed and south, including lands managed by LANL. We also included three control sites to account for localized changes, such as those attributable to precipitation patterns or beetle infestations, without the effects of the fire. The three controls chosen encapsulate the land cover present in the north and South zones of the burned area. These controls included one in the north that contained a mixture of conifer and piñon-juniper woodland, one in the south that was mostly higher elevation conifer, and one on the east that contained mostly lower elevation piñon-juniper woodland. We chose three separate controls to encompass the variability of the burned landscape. The control site selection was limited by clouds, land management activities, degree of similarity among ecosystems, and fire history. A graphical representation of the zones, controls, cloud mask, and NDVI change can be seen in figure 3.

Figure 3; NDVI change maps between selected years. Controls are black-outlined polygons on north, east, and south of fire perimeter. Clouds are the semi-transparent black polygons scattered throughout the image. L to R (top): 1999 – 2000; 2000 – 2001; L to R (middle): 2000 – 2002; 2000 – 2003. L to R (bottom): 2000 – 2004; 2000 – 2005



Results

With the three controls chosen, we computed zonal statistics on the NDVI values for each region – the two zones within the fire perimeter and the three controls – and year. These statistics were exported to DBF files and then compiled into a Microsoft Excel spreadsheet and graphed (figure 4). Graphs of each zone and control's variance can be found in Appendix 1.

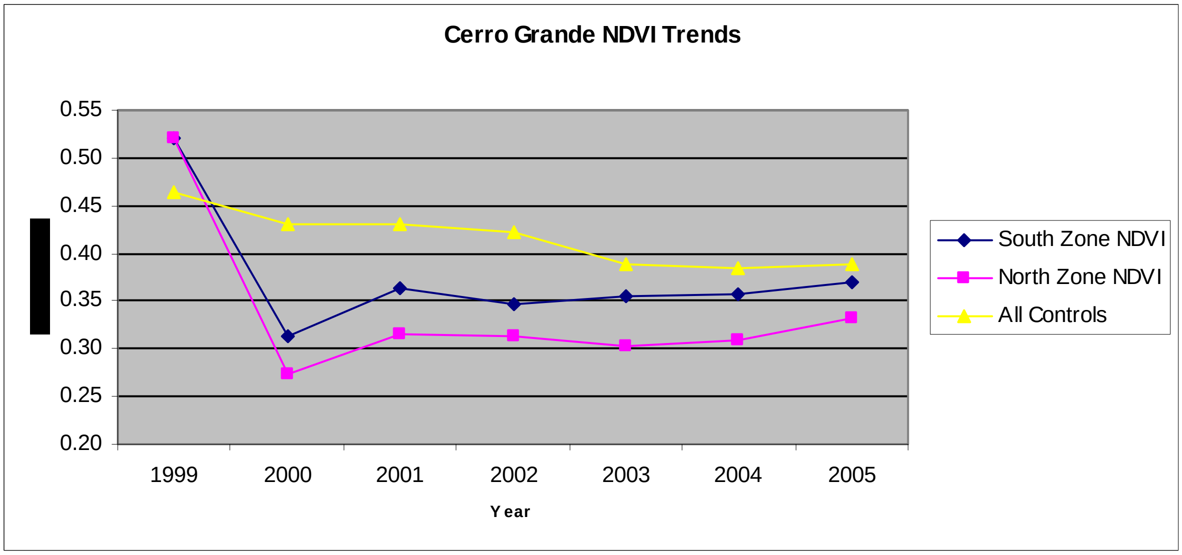


Figure 4; Graph showing NDVI values from pre-fire (1999) to present (2005)

Figure 4 shows the South zone as more productive, which is likely because it had a lesser percentage of high and moderate burn severity within the fire perimeters (34% in South zone versus 48% in the North zone; see Table 4), resulting in a smaller average NDVI drop immediately following the fire. While the North zone had no change between 2001 and 2002 (figure 5), the South zone reported a drop in overall NDVI values. The very next year, those values were swapped, with the South zone making a strong comeback, despite poor precipitation. Following 2003, the zones exhibited practically the same NDVI response, with the North zone doing better overall.

To provide some statistical analysis, the NDVI values for every 10^{th} pixel in each zone were exported to an ASCII text file and imported into Microsoft Excel. This subsampling was necessary to avoid an inherent problem noted in the central limit theorem; as the sample sizes increase, the probability of returning statistically significant differences between means continually increases. To avoid this we instead sampled one tenth of the original dataset and found differences between north and South zone NDVI means to be statistically significant for all years but 1999 (One-way ANOVA; n = 1001 for North zone; n = 837 for South zone; Table 3).

Year	F Statistic	P-Value
1999	0.0012	0.9717
2000	33.73	7.43E-09
2001	62.89	3.76E-15
2002	35.76	2.68E-09
2003	91.9	2.84E-21
2004	80.51	6.98E-19
2005	59.12	2.4E-14

Table 3; One-way ANOVA results showing significance of differences between zone NDVI means

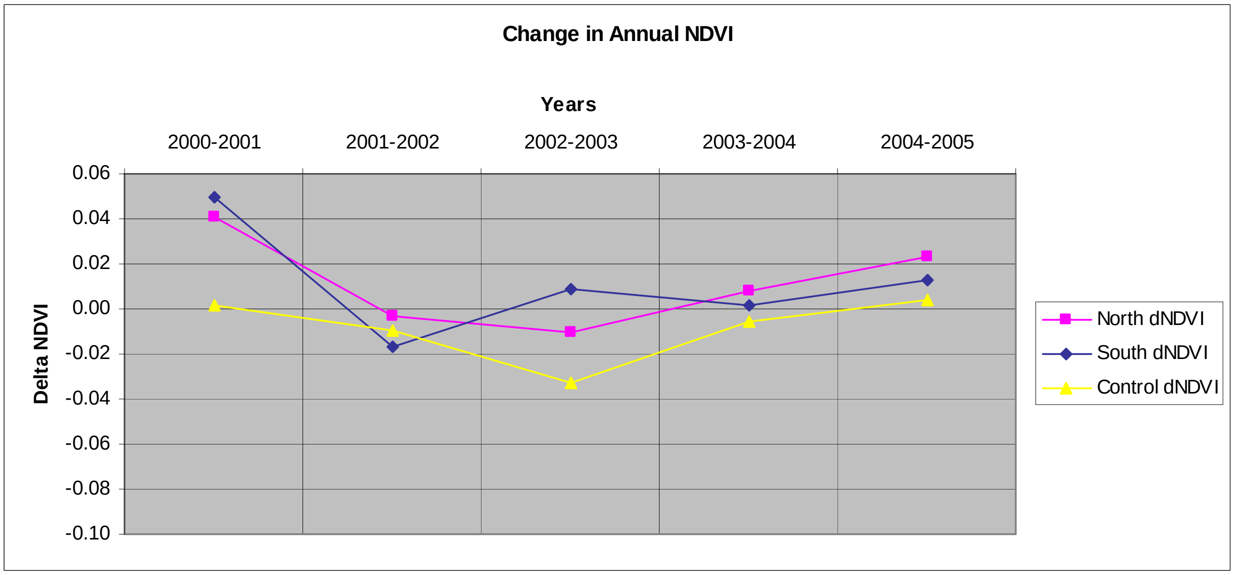


Figure 5; Change in annual NDVI values between 2000 and 2005.

Another analysis utilizes control site information when comparing the statistics of the North and South zones, in order to adjust for the effects of the regional drought. The comparison was performed using the Normalized Regeneration Index (NRI) (Diaz-Delgado et al., 1998; Riano et al., 2002). This index compares the NDVI values from within the burn scar to those within the controls. The algorithm is as follows:

$$NRI = 1 + ((NDVI_{fire} - NDVI_{control}) / (NDVI_{fire} + NDVI_{control}))$$

When the NRI values equal one, the land within the burn scar and controls are reflecting the same amount of photosynthetic activity. In theory, the pre-fire NRI value should be close to zero. As the vegetation recovers after a fire, the values will, given enough time, gradually increase to roughly one (figure 6).

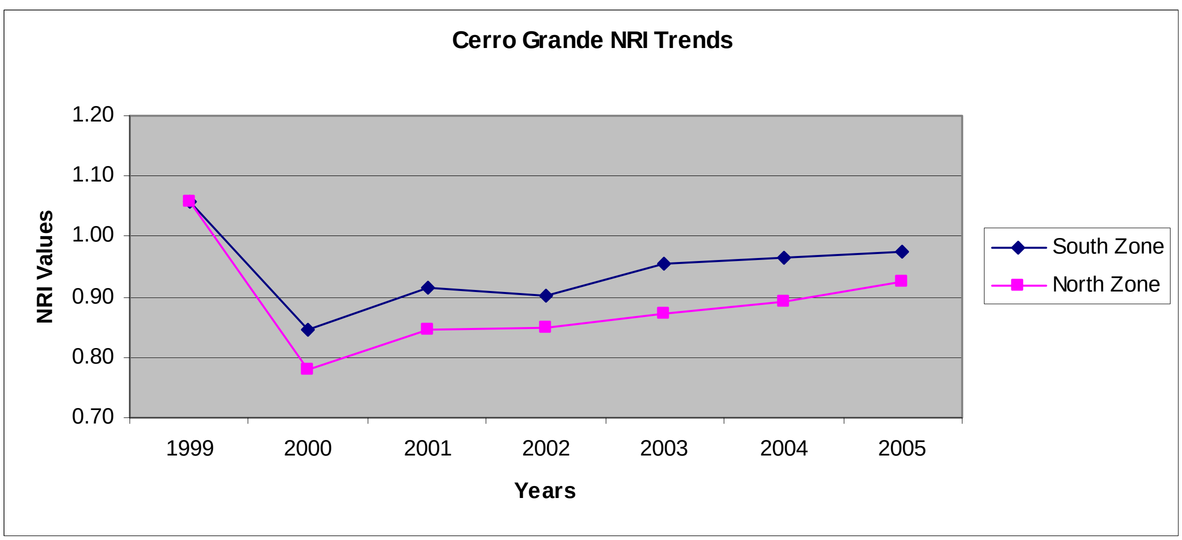


Figure 6; Graph showing NRI values for both zones

Both zones are gradually increasing toward the same level of greenness (NRI value of 1) as the control sites (figure 6). The South zone was most heavily treated by BAER teams and land management agencies following the fire, with 46% of its moderate and high burned areas receiving mulch. The North zone, least treated following the fire (only

7% of its moderate and high burned areas received mulch), still shows a lag in vegetation regeneration compared to the three controls. While equilibrium has not been achieved, the trend is positive toward vegetation regrowth within each zone. If the NRI trends from the past 3 years persist, then the South zone is projected to reach an NRI value of 1 by 2007, while the North zone is projected to reach that threshold a year later.

It is very important to note, however, that equilibrium (NRI values close to 1) does not imply recovery of pre-fire vegetation species. None of the burned mature stands of coniferous or hardwood trees have "recovered" in the five years since the fire. NDVI measures photosynthetic activity in vegetation – or greenness – regardless of species. What the NRI does show is that the vegetation growing in the two zones is producing a greenness response nearly congruous to the vegetation in the controls. Some of this is from natural recovery and can take the form of dense aspen and oak regeneration. Some of this recovery can also be explained by treatment activity in each zone following the fire. A review of treatments, this time segmented by zone, is shown in table 4.

Treatment	**South**	**North**	**Total**
Aerial seeding	>6,700	>11,200	21,080
Aerial hydromulch	515	669	1,184
Contour felling	1,823	1,316	3,139
Straw wattles	914	351	1,265
Grade control	84	44	128
Straw mulch	2,534	170	2,704
Raking	15	97	112
Totals	**12,585**	**13,847**	**29,612**
Total acreage mulched	3,049	839	3,888
Total acres within fire perimeter	~19,650	~23,450	~43,000
Acres categorized as high and moderate burn severity (H&M)	6,700	11,200	17,900
% of acreage within perimeter classified as H&M severity	34	48	42
% of H&M acreage receiving mulch	46	7	22

Table 4; Treatment acres by zone

These acreage numbers represent absolute values of treated areas and are summarized by zones in table 2. A number of treatments were concurrently implemented on the same polygon and were independently reported as accomplishments, having the effect of multiple counting of the same acres. In order to prevent such multiple counting, it was decided, for this study, to report the treatment that contributed most directly to increasing total cover. For example, an acre with raking, straw mulch and contour felling (a combination which was applied to a total of 504 acres) was reported only as "straw mulch."

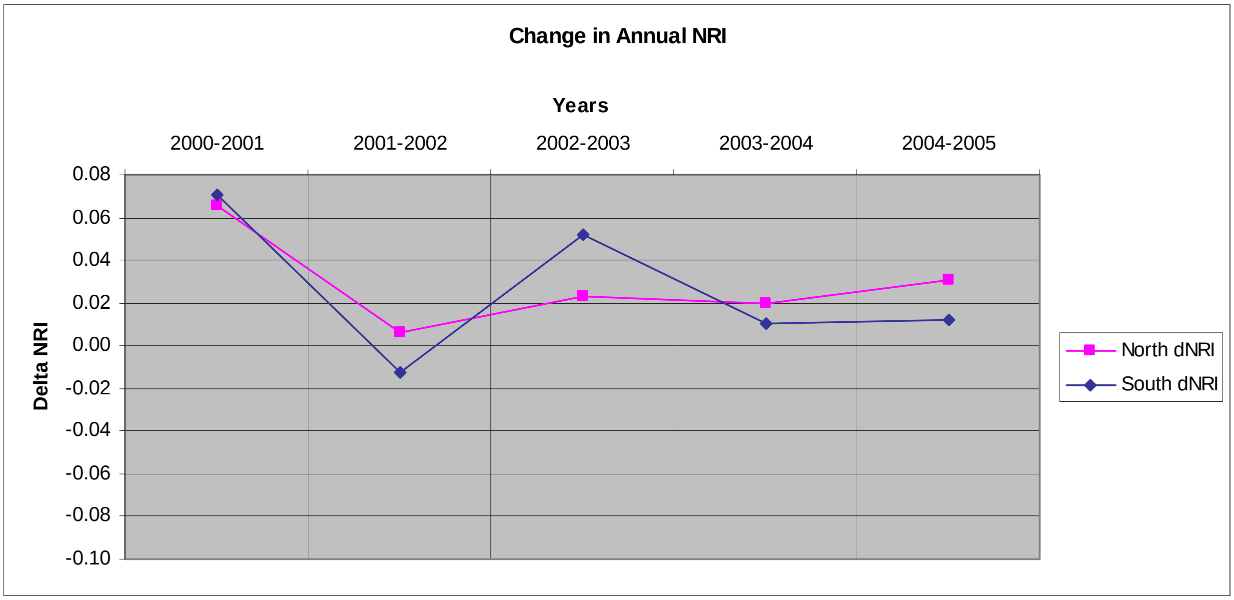


Figure 7; Graph showing change in annual NRI values from 2000 to 2005

All annual combinations after the fire, with the exception of 2001 – 2002, showed positive responses in regeneration values (figure 7). 2002 was an extremely dry year on the Jemez Mountains, perhaps severely stressing regeneration. The highest NRI values were seen between 2000 and 2001, with 2001 being an above average water year (figure 1). Between 2002 and 2003, the South zone experienced a large increase in regeneration values, possibly indicating that a slightly wetter year resulted in an immediate response to precipitation by the herbaceous cover.

CONCLUSIONS

The results from this study are promising both in terms of outcome and technique. Two important factors when monitoring landscape-scale treatments are highlighted through this study: some BAER treatments appeared to have had an immediate impact on the landscape, and local precipitation patterns are very influential in vegetation regeneration. It is also important to note that 4 years following the fire, both zones were fairly similar in regeneration trends. This leads to a preliminary conclusion that BAER treatments had an immediate impact on the landscape, but in the long run, natural recovery often performs just as well. This is being further explored in future studies (in preparation) to include polygon-specific plot and point data. Since the purpose of BAER is emergency stabilization, it seems as though the BAER efforts on the Cerro Grande Fire were successful in protecting many values at risk, while slowing some of the erosion that was to occur on the landscape during post-fire runoff events.

Using remote sensing to produce landscape-scale assessments of burned areas can provide a starting point for ground-based assessments. The NDVI images can be segmented by watersheds and analyzed for vegetation response by watershed. If, for example, a watershed continues to show low NDVI values after a few years of assessment, it could warrant field visits to examine the situation. This study did not focus on the watershed scale; it will be tested in future studies.

This process demonstrated a technique for landscape-scale characterization of vegetation recovery of burned acreage. Postfire assessment of large fires, especially, would benefit from this synoptic view of the vegetation condition over time. This study outlines a quick and cost-effective way to assess the vegetation condition through subsequent growing seasons after a fire.

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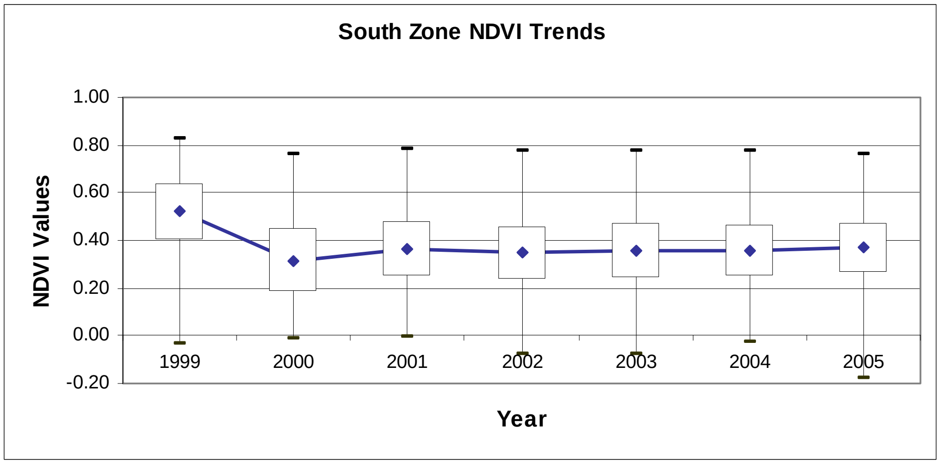
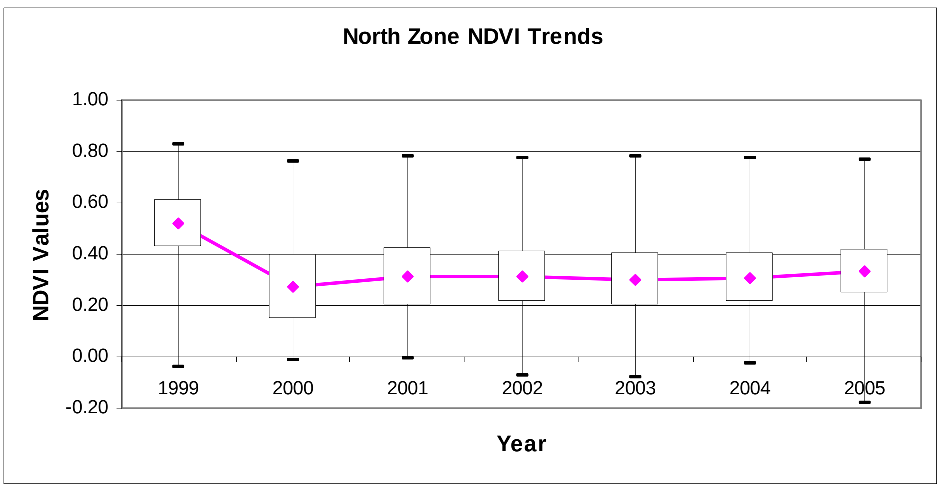
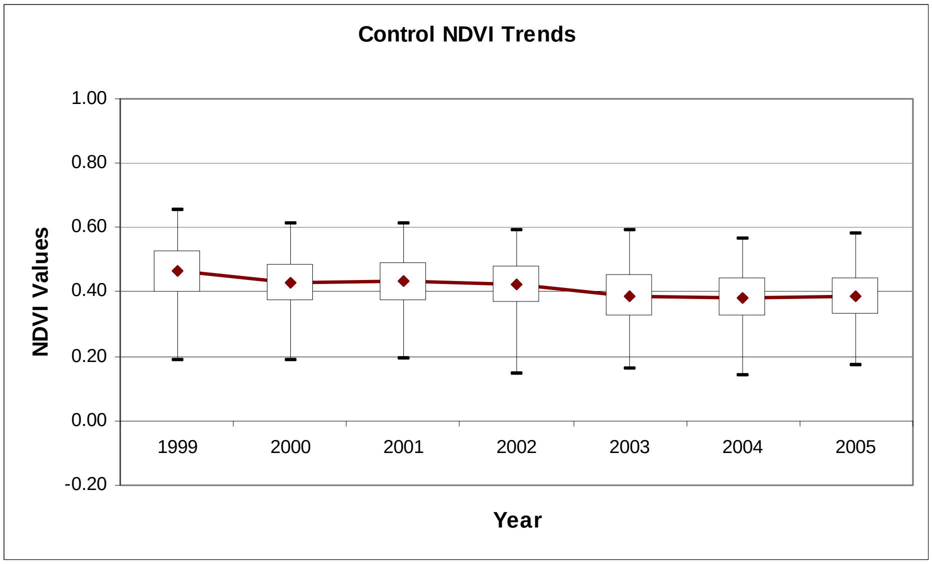
Appendix 1; Zone and Control NDVI trends with box and whisker plots showing estimated variance. The box encloses the mean NDVI value bounded by the 25th and 75th percentiles, while the whiskers indicate the minimum and maximum NDVI values.







Control NDVI Trends
NDVI Values
1.00
0.80
0.60
0.40
0.20
0.00
-0.20
1999
2000
2001
2002
2003
2004
2005
Year

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