ASSESSING LAND COVER CHANGES USING STANDARDIZED PRINCIPAL COMPONENT AND SPECTRAL ANGLE MAPPING TECHNIQUES

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ABSTRACT

This paper reports a practical application of digitally enhanced Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) data coupled with principal component analysis (PCA) and spectral angle mapping (SAM) techniques to assess changes in vegetation and land condition within the U.S. Army installation at Fort Bliss, Texas. Fort Bliss is located in a semi-arid desert environment where the vegetation is sparse, diverse and highly sensitive to climatic variability. Despite the widespread use of vegetation indices to map vegetation cover in arid and semi-arid environments, we believe that in an area like Fort Bliss, the non-photosynetic plant tissue may be a better indicator of ecosystem health than photosynthetic active vegetation. Results of this study indicate that the main drivers for both temporal and spatial change are climate and various types of disturbance, such as fire, livestock grazing and military training activities.

INTRODUCTION

This paper reports a practical application of digitally enhanced Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) data coupled with principal component analysis (PCA) and spectral angle mapping (SAM) techniques to assess changes in vegetation and land condition within the U.S. Army installation at Fort Bliss, Texas. Fort Bliss, an area of approximately 1.17 million acres, is geographically located in far-west Texas and south-central New Mexico on the northern edge of the geographic province known as the Chihuahuan Desert (Figure 1). The ecosystems that exist within Fort Bliss are diverse and highly affected by climatic variability and human activities. Disturbance of the natural landscape and ecosystems within this installation is usually associated with a decrease in vegetation and an increase in soil erosion. The satellite data and remote sensing methodology discussed in this paper is being utilized by Program Managers from the Fort Bliss Directorate of Environment to assess and monitor vegetation cover and land condition within the installation in support of the U.S. Army training mission. The U.S. Army is charged with maintaining its ranges in a condition suitable for training and able to support the natural biotic communities that exist within the range boundaries.

Rationale and Objective

Many remote sensing studies of vegetation in arid and semi-arid lands have focused on the study of vegetation condition using various vegetation indices, such as normalized vegetation index (NDVI), soil adjusted vegetation index (SAVI) and modified soil adjusted vegetation index (MSAVI) (Huete, 1988; Price, 1987). These vegetation indices, which are closely related to vegetation biomass, leaf area index and fractional canopy cover are not very useful for mapping in environments where the vegetation coverage is typically low, where leaves have drought-adapted morphology and/or where the vegetation is often dormant. There is evidence tosuggest that brightness indices are more related to woody canopy cover than vegetation indices in semiarid savannahs (Yang and Prince, 1997). Dry grasslands at Fort Bliss are dormant for approximately nine months each year, with photosynthetic activity generally confined to the months of July, August and September. While dry grassland cover has been estimated using AVIRIS hyper-spectral data, there is no accepted methodology for estimating dry grassland biomass

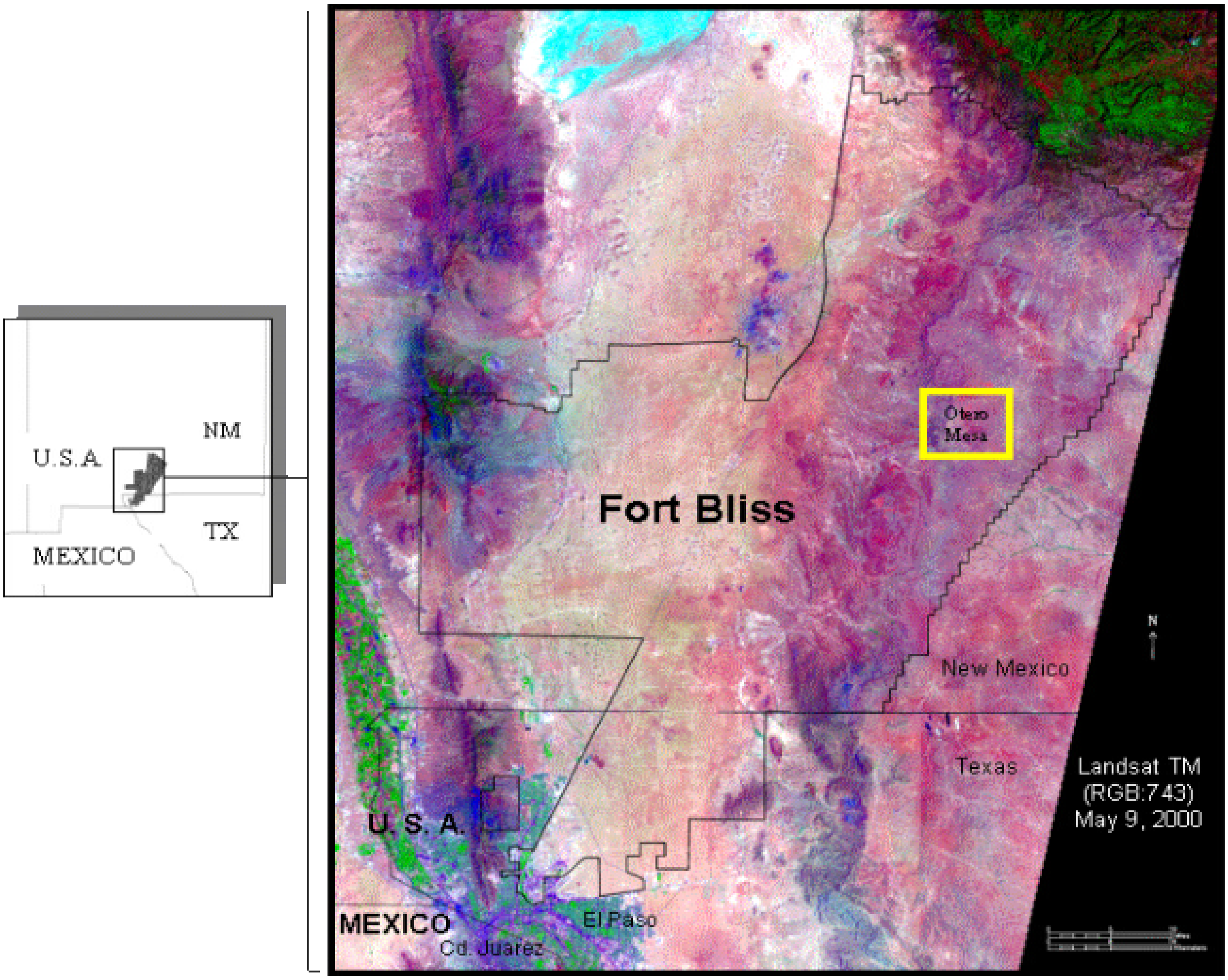


Figure 1 Landsat TM false-color composite image showing the location of Fort Bliss, Texas and New Mexico. The image data discussed in this paper applies to a selected military training area highlighted in yellow and referred to as Otero Mesa.

using Landsat TM imagery. We propose the use of Landsat thematic imagery coupled with the Tasseled Cap transformation, using the Gram-Schmidt sequential orthogonalization technique (Jackson, 1983), to develop an index for dry grass cover in semi-arid rangeland. Soils in the area are highly reflective due to their low organic matter content and the presence of carbonates. Soils tend to dominate reflectance, when the vegetation cover is less than 30 percent. Any assessment of training range conditions requires a technique capable of separating soil from the green and dry vegetation reflectance.

The objective of our study is to map land cover and ecosystem changes via remote sensing change detection technique using Landsat muti-temporal data. We have selected an approach that uses standardized PCA and SAM techniques to accomplish our objective. The overall goal is to use Landsat TM and ETM+ data to help monitor and assess the cumulative effects that impact the natural landscape within Fort Bliss. This paper demonstrates our approach as it applies to a selected training site located on a plateau known as Otero Mesa.

Background and Dimensionality of the Landsat Thematic Data

The phenology, composition and structure of the natural land cover that exists within Fort Bliss are highly variable and present particularly difficult problems for remote sensing studies of vegetation distribution and abundance. The major scene components include patchy mixtures of grasses, shrubs, succulents, shrubby trees, litter, rock and bare soil. Much of the vegetation is often dormant and limited in reflectance. Bare soil and non-photosynthetic standing dead litter are highly visible through the sparse vegetation canopies and constitute as much as 90 percent of the total land cover. For these reasons, we believe that non-photosynthetic plant tissue may be as important as photosynthetic active vegetation.

Precipitation is probably the most important climatological factor for vegetation in this area where the maximum temperatures of over 32.2ºC (90ºF) are exceeded for approximately 105 days of each year. The mean annual precipitation is 225 mm (8.5 inches). The summer months, June through August, receive approximately 73% of the maximum temperatures and 59% of the annual precipitation (Schmidt, 1986). Precipitation varies greatly from year-to-year and from month-to-month At Orogrande (adjacent to Fort Bliss) 22.55 inches fell in 1905 and 2.93 inches in 1934 (USDA, 1978). The study of vegetation is hampered by the fact that the vegetation is sparse, diverse and highly sensitive to climatic variability.

The main drivers for temporal change are climate and various types of disturbance, such as fire, grazing and military training activities. Although both natural and man induced changes are important, it is vital distinguish between them. Climate is one of the most important drivers of natural ecosystem change and in an effort to understand the role of climate in driving ecosystem change; we have plotted changes in average band reflectance against the New Mexico Climatic Division and Palmer Modified Drought Severity Index (PMDSI) for the years 1991-2002. The PMDSI is a soil moisture algorithm calibrated for relative homogeneous regions so that comparisons using this index could be made over time and between months (Palmer, 1965). The PMDSI varies roughly between –6.0 and +6.0 and the classification scale is provided in Table 1. Graphic comparisons of PMDSI and average band reflectance for TM bands 1, 2, 3, 4, 5 and 7 are provided in Figure 2. Pearson Product Moment Correlation Scores for thematic bands versus PMDSI scores indicated a rather strong relationship in our data (Table 2).

Palmer Classification	
4.0 or more	Extremely wet
3.00or 3.99	Very wet
2.00 or 2.99	Moderately wet
1.00 to 1.99	Slightly wet
0.50 to 0.99	Incipient wet spell
0.49 to -0.49	Near normal
-0.50 to -0.99	Incipient dry spell
-1.00 to -1.99	Mild drought
-2.00 to -2.99	Moderate drought
-3.00 to -3.99	Severe drought
-4.00 or less	Extreme drought

Table 1. Palmer Classification Scale.

TM Band	1	2	3	4	5	7
PPMC	-.46	-.60	-.66	-.50	-.56	-.67

Table 2. Pearson Product Moment Correlation (PPMC) between average TM band reflectance and Palmer Modified Drought Severity Index.

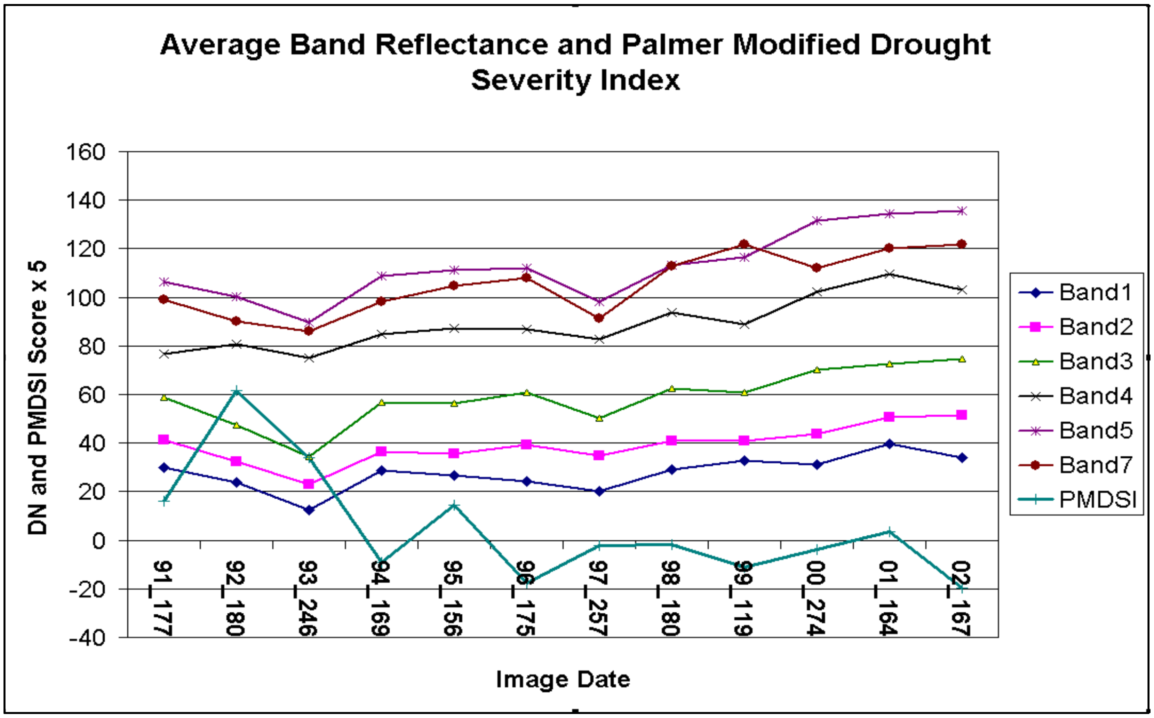


Figure 2. Graphic comparison of Palmer Modified Drought Severity Index and average band reflectance for Landsat TM bands 1, 2, 3, 4, 5 and 7.

METHODOLOGY

The following change detection methodology is currently being utilized to detect and monitor the environmental effects that activities such as training exercises and fires pose on the natural landscape and resources of Fort Blis s. The Landsat thematic data provides an ideal supplement to field surveys when attempting to characterize and monitor changes in vegetation and land condition at a broad scale and level of detail. We have Landsat (30 meter spatial resolution) coverage of the installation and surrounding region for the time period of 1991 thru 2002. Coverage includes both dry-season and wet-season imagery. To detect change and assess trends, we have orthorectified the data, standardized the data to reflectance, generated time series images using principal component one, generated orthogonal indices for green-vegetation and dry-vegetation using the Gram-Schmidt (Tasseled Cap) process and applied spectral angle mapping techniques for change quantification and establishing change thresholds. An illustration of the process flow is provided in Figure 3.

Principal Component Analysis

Principal component analysis (PCA) undertakes a linear transform of a set of image bands to create a new band set or images that are uncorrelated and are ordered in terms of the amount of variance explained in the original data. Most commonly, principle component transformations are designed to remove or reduce redundancy in multi-spectral data by compressing all the information contained in the original *n-channel* data into fewer than *n -new channels* or *components* (Fung and LaDrew, 1987). The new components are than used in lieu of the original data because the new component images are more interpretable than the original images. Eastman and Fulk (1993) indicate that the standardized PCA approach is more effective than unstandardized PCA in the analysis of change in multi-temporal image data sets. With standardized PCA the eigenvectors are computed from the correlation matrix and the effect is to force each band to have equal weight in the derivation of the new component images. The standardized PCA approach converts all image brightness values to standard scores (by subtracting the *mean* and dividing by the *standard deviation*) and computing the unstandardized principle components of the results. The first principal component explains 91.93 percent of all the variability in the Landsat TM and ETM+ data sets.

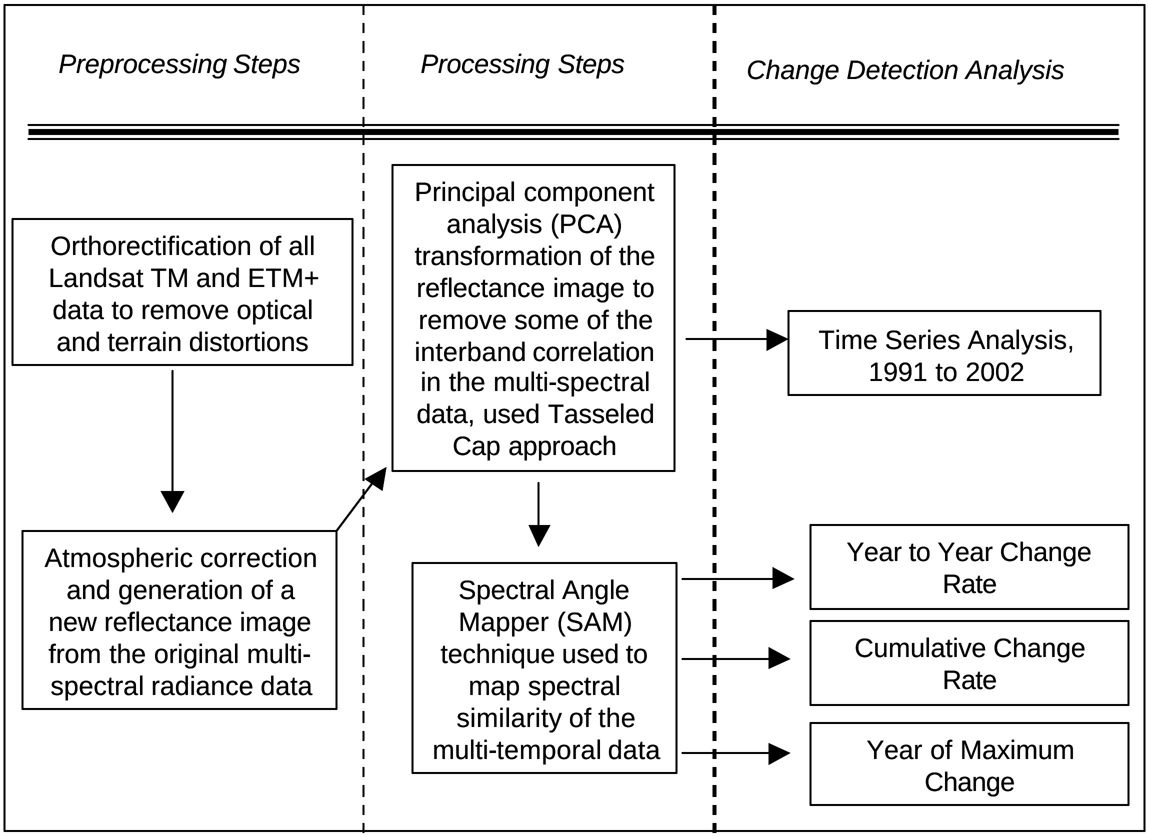


Figure 3. Diagram illustrating the process flow used to standardized all the multi- temporal Landsat TM and ETM+ data used in this study.

Gram-Schmidt Analysis

Because principal components 2 through 6 are not directly related to scene components, we have used the Gram-Schmidt process (Jackson, 1983) to develop indices related to green vegetation and dry vegetation (litter), using PC1 as the first index. This procedure develops orthogonal indices for green vegetation and litter without requiring detailed knowledge of soil brightness, which is quite variable over time and in a large area such as Fort Bliss. The eigenvectors developed by this process are shown in Table 3.

TM Band	PC1	Green	Litter
1	0.12256	-0.25032	-0.26798
2	0.21783	-0.27278	-0.40495
3	0.37307	-0.41124	-0.51339
4	0.40111	0.81951	-0.38641
5	0.55669	0.00015	0.34290
7	0.57233	-0.14899	0.48345

Table 3. Eigenvectors obtained for principal component one (PC1), green vegetation (green) and dry vegetation (or litter).

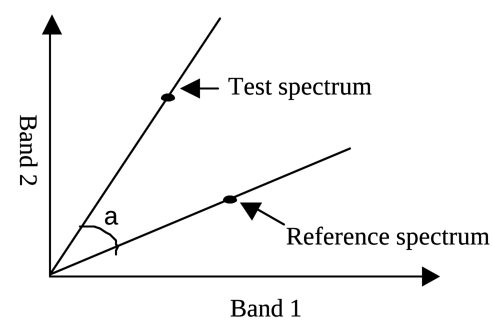
Spectral Angle Mapping

Spectral angle mapping (SAM) is a technique that allows for rapid mapping of the spectral similarity of image spectra to a reference spectrum (Kruse et al., 1993). The reference spectrum can be either laboratory spectra, field spectra or spectra extracted from the image. The SAM algorithm determines the spectral similarity between two spectra by calculating the "angle" between the two spectra, treating them as vectors in a space with dimensionality equal to the number of bands (*nb*). A simplified explanation of SAM can be given by considering a reference spectrum and a test spectrum from two-band data represented on a two-dimensional plot as two points (Figure 4). The lines connecting each spectrum point and the origin contain all possible positions for that material, corresponding to the range of possible illuminations. Poorly illuminated pixels will fall closer to the origin than pixels with the same spectral signature but greater illumination. The angle between vectors is the same regardless of the length of the vector. The calculation consists of taking the arccosine of the dot product of the spectra. SAM determines the similarity of a test spectra *t* to a reference spectrum *r* by applying the following equation (Kruse et al., 1993):

$$\cos^{-1}\left(\frac{\vec{t}\cdot\vec{r}}{\|\vec{t}\|\cdot\|\vec{r}\|}\right)$$

For each reference spectrum chosen, the spectral angle a is determined for every image spectrum, and this value, in radians or degrees, is assigned to that pixel in the output SAM image. A unique spectral range may be chosen for each reference spectrum. This allows the algorithm to focus on spectral regions that are significant for a particular reference spectrum. The derived spectral angle maps form a new data set with the number of bands equal to the number of image dates in the temporal sequence. SAM can be used to evaluate change between a reference year (1991 in this study) or from the previous year and a year in the series to develop a sequence.

Figure 4. Plot of reference spectrum and test spectrum for a two-band image. The same materials with varying illumination are represented by the vectors connecting the origin (no illumination) and projected through the points representing the actual spectra. By measuring the angle between two vectors, one determines the relationship between the vectors. If the angle between the vectors is 90 °, then they are orthogonal and there is no correlation between the vectors. If the spectral angle is greater than 90 °, the cosine has negative values. The cosine is -1, when the angle is 180°. Correlation between vectors increases as the angle between them is reduced, until, at 0°, they have a correlation coefficient of 1, and are indistinguishable. The cosine is independent of the brightness values being compared



Change Analysis

Change analysis was accomplished using two forms of SAM techniques: 1) using 1991 as the reference spectrum for all the years included in this study and 2) using the previous year as reference spectra for 1991 through 2002. These techniques provide insight into two different dynamics, the trend in relation to the first year in the series and the year-to-year change. Examples of images used in our change analysis are provided in Figure 5.

Trend Analysis

Trends are visualized by plotting standardized scores of PC1, green index and litter index over time. Trend analysis is accomplished by vector analysis techniques to calculate magnitude and direction of difference vectors. The magnitude of the difference is indicative of the degree of change and the vector direction indicates the direction of movement in the PC1, green and litter indices space. Graphs showing trends are provided in Figure 6.

RESULTS

The images shown in Figure 5 and the graphs presented in Figure 6 and Figure 7 illustrate the results of our study. The control area (blue boxes in Figure 5) is situated in a pasture used for grazing livestock in a rest-rotation pattern with 18 months grazing followed by a period of 9 months rest or recovery. The burned area (yellow boxes in Figure 5) is located in an adjacent pasture, which has a similar grazing regime, but has been subject to frequent low intensity fires. The fires are both natural and man-made (result of military training exercises). This area was burned in 1993, 1995, 1997 and 2000. The temporal patterns observed in the SAM change detection reveal some important differences in disturbance regime. The vegetation in both areas consists of Mesa Grassland Black Grama-Blue Grama (Banana Yucca) (U.S. Army, 1996).

The graph in Figure 6a reveals that the control sample site is characterized by low amplitude fluctuations with an approximate four-year periodicity. The maximum spectral angle for both, the year-to-year change and the change referenced to 1991, is 43 degrees. After initial divergence the year-to-year change curve converges with the 1991 reference curve. This indicates that there is no overall trend with reference to 1991. Therefore, we think that this area is in a stable oscillating state. The pattern observed in Figure 6b, in the burned area, is characterized by higher amplitude fluctuations and higher spectral angles. The maximum spectral angle for both, the year-to-year change and the change referenced to 1991, is 79 degrees. After initial convergence the year-to-year SAM curve and the 1991 reference SAM curve diverge with the 1991 reference SAM curve fluctuating between 40 and 80 degrees while the year-to-year SAM curve is relatively stable between 20 and 30 degrees. This indicates a trend toward a relatively stable state that is significantly different than in 1991. The change threshold is a controlling boundary used to establish conditions that identify significant change in contrast to normal fluctuations. Examination of these data indicate that a change threshold of 55 degrees will identify most fires and significant training impacts while screening out background fluctuations in these grasslands.

The differences in trend between the burned area and the control area are the result of ecological response to disturbance regime (Figure 7). The burned plot is higher in PC1, green index and litter index than the 1991 reference spectrum. The control plot is lower in PC1 and green index, but higher in litter index than the 1991 reference spectrum. Increase in PC1 score and green index follows fire in the burned area, but the litter index response is more ambiguous, showing no clear response following fires. This anomaly may be a result of low intensity fires that fail to consume all of the litter, or it could be a result of the response of the litter index to ash or organic material in exposed soil. However, it should be noted that the litter index was generally lower in the burned plot than in the control plot. The behaviour of these data suggests the pattern of ecological response to disturbance. PC1 increases following disturbance, followed by increase in green index as vegetation responds to disturbance through growth from rootstocks or germination of weedy species. Litter index follows a pattern less responsive to disturbance except in cases of severe disturbance, such as land clearing. PC1 in undisturbed areas tends to fluctuate within a relatively narrow range and is probably responsive to moisture, plant cover, and plant physiological status. Green index and litter index tend to be negatively correlated with respect to time in undisturbed areas. This may be a result of plant response to moisture where cover is relatively constant (Figure 8).

We recognize that both the PCA, SAM, and trend analysis techniques have limitations. For example, SAM does not indicate the direction of change, only the magnitude in reference to a standard spectrum. PCA allows us to view areas that are changing, but does not indicate the exact cause or direction of change. However, these techniques together provide insight into patterns of ecological dynamics and can identify areas that are undergoing change so that we can focus on those areas with further investigations. The Landsat data also provides a historical database that can be used for more detailed studies of ecological change on Fort Bliss training areas.

CONCLUSIONS

It is apparent that there are a number of techniques that can be applied to Landsat thematic data in order to detect changes in land cover and land conditions. The selection of particular technique depends very much on the type of environment being investigated. This study has shown that, standardized PCA coupled with SAM techniques and trend analysis appears to be a useful tool for the analysis of general and isolated changes as well as trends in land surface conditions in semi-arid grassland. The Landsat data not only allows us to build a historical record of the natural resources and land conditions within the study area, but also allows us to identify those areas that are under going change so that we can conduct further investigations. There are many avenues of research that could be followed using these techniques including correlation of PC1 and indices to vegetation condition and cover, the role of soil moisture and composition on spectral response, and the relationship of change measurements to ecological processes. As a result of this study, Program Mangers at Fort Bliss, have a systematic and cost-effective procedure for monitoring cumulative environmental impacts using time series image data.

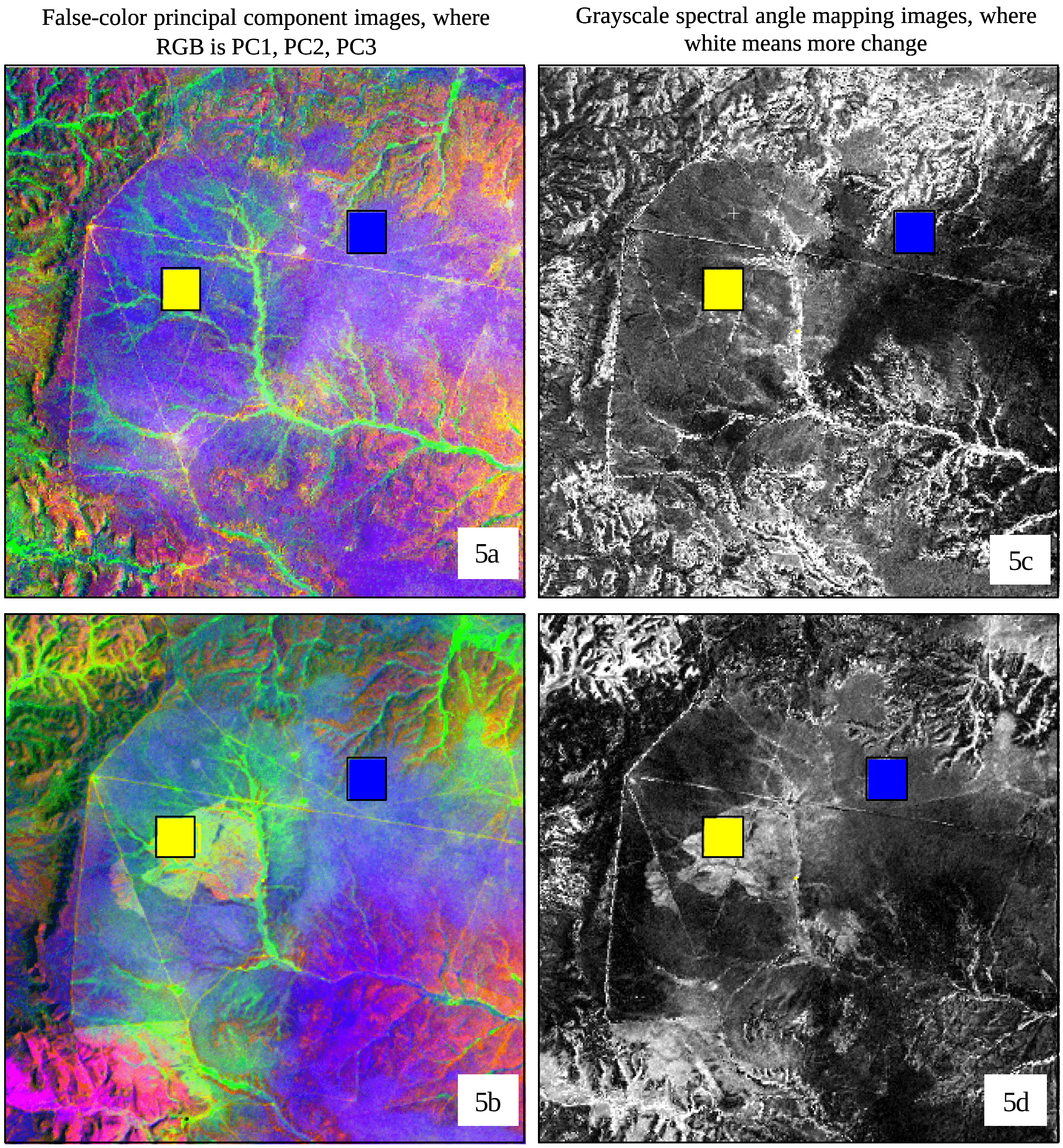
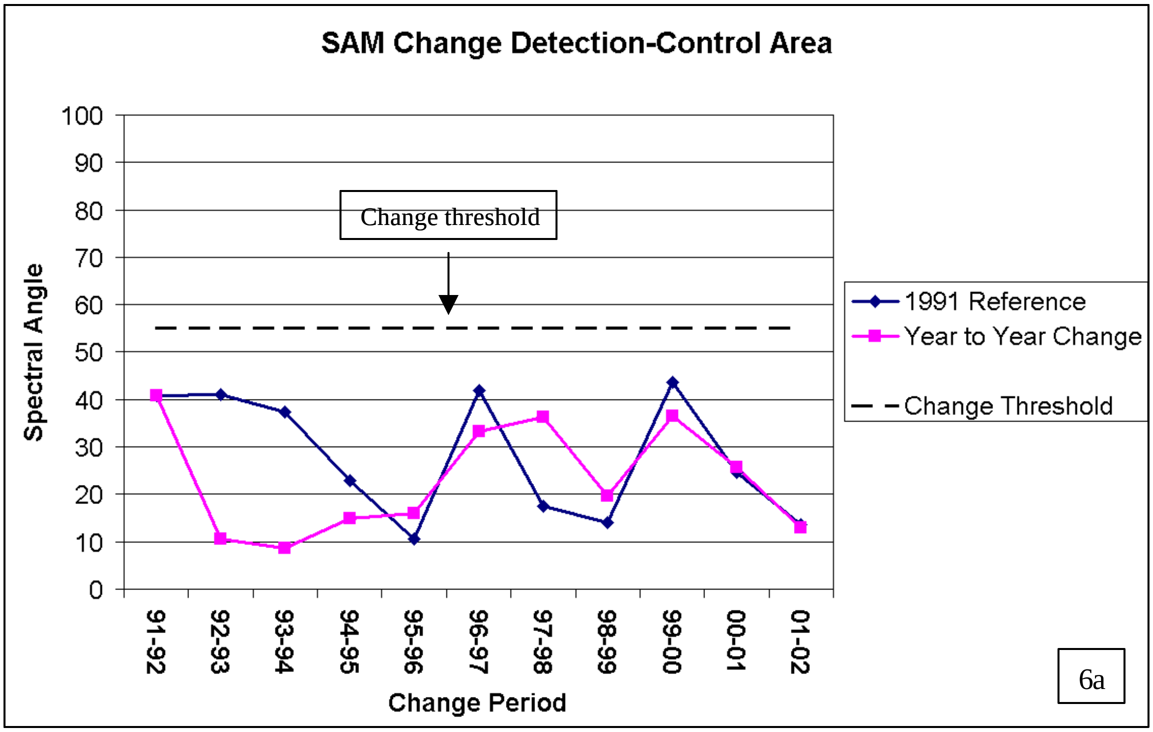


Figure 5. Examples of false-color principal component and grayscale spectral angle mapping images generated for Otero Mesa. Principal component images for 1992 (5a) and 1993 (5b) were generated from PC1, PC2 and PC3. Spectral angle mapper images using two dates of data were generated for 1991-1992 (5c) and 1992-1993 (5d). The area under the yellow boxes in images (5a) through (5d) represents a training site that was burned in 1993. The area under the blue boxes in images (5a) through (5d) represents a controlled site where disturbance has been limited. The total area of coverage in each image (5a through 5d) is 16 square kilometers and the distance between the sample sites (blue and yellow boxes) is 2,900 meters. Graphs displaying the data in the sample sites are provided in Figure 6.



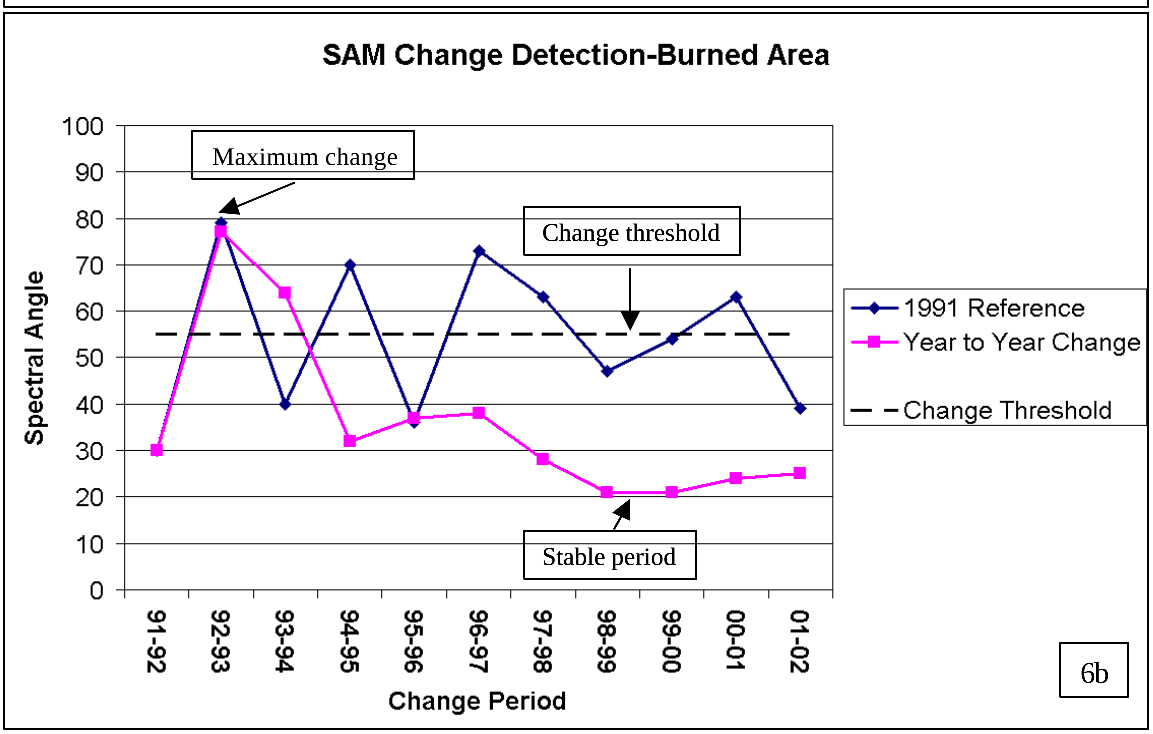


Figure 6. Graphs showing SAM with 1991 reference spectrum and year-to-year reference spectra for (6a) control area (blue boxes in figure 5) and (6b) burned area (yellow boxes in figure 5).

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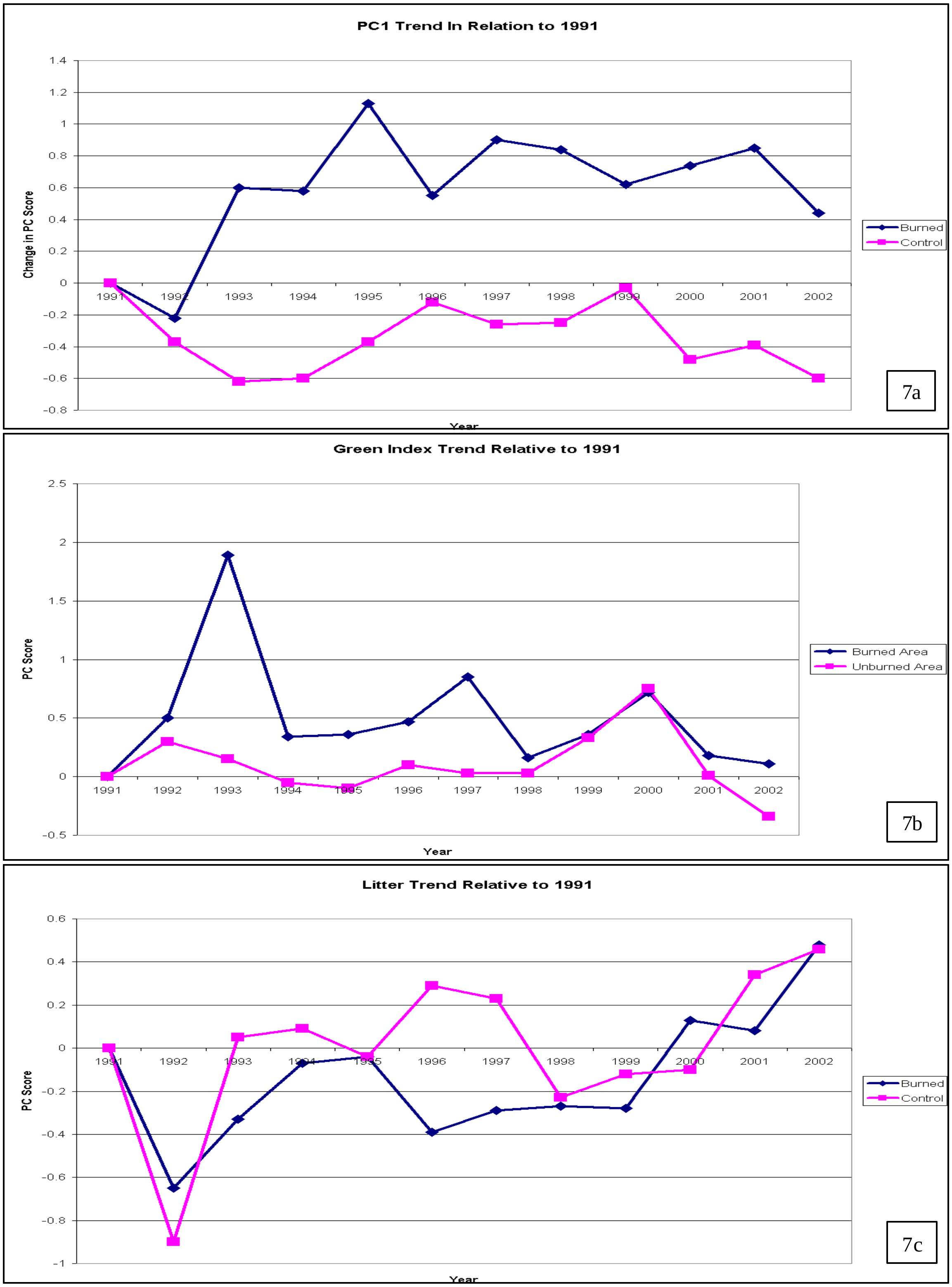

Figure 7. Graphs showing difference in trends between PC1 (7a), green (7b) and litter (7c) in the control area relative to reference year 1991.

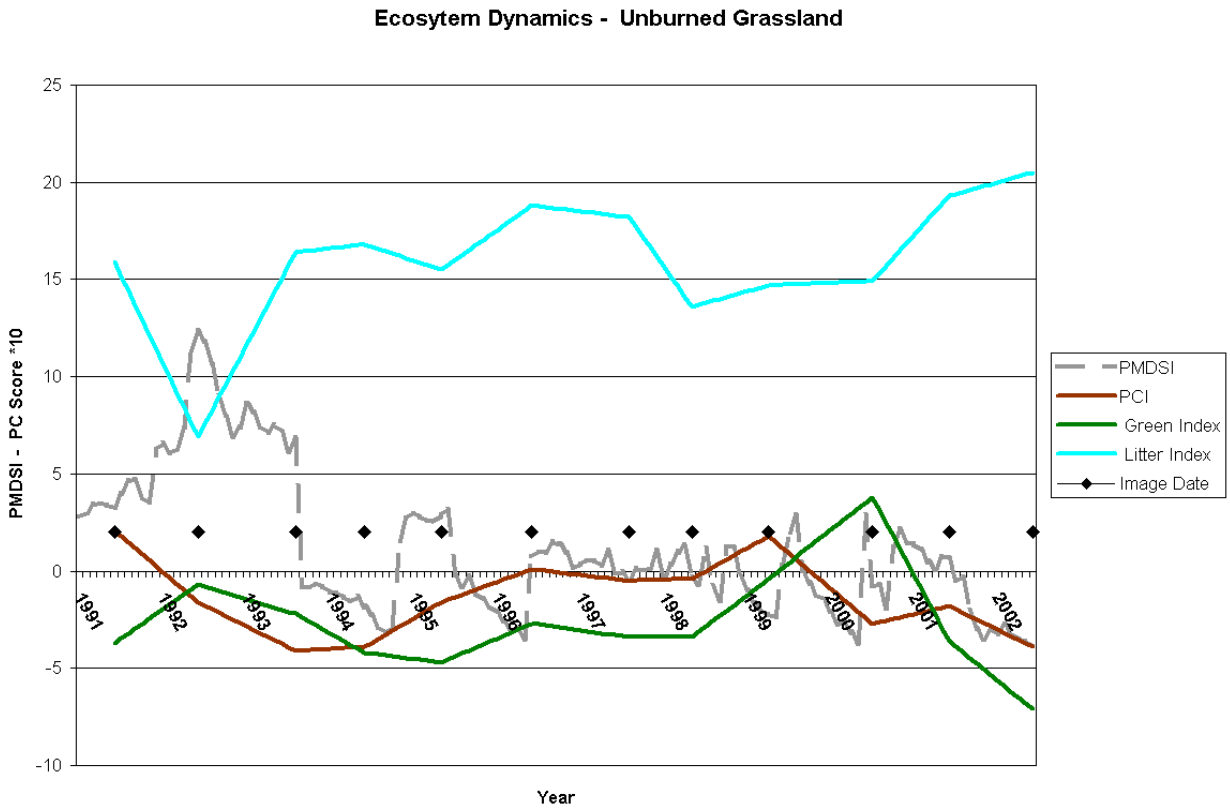

Figure 8. Response of PC1, Green Index, and Litter Index to Palmer Modified Drought Severity Index.

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