Satellite assessment of drought impact on native plant communities of southeastern New Mexico, U.S.A.

Albert J. Peters*, Bradley C. Reed*, Marlen D. Eve* & Kris M. Havstad†

* *Department of Geography, New Mexico State University, Campus Box MAP, Las Cruces, New Mexico 88003, U.S.A.* † *U.S. Department of Agriculture, Agricultural Research Service, Jornada Experimental Range, Las Cruces, New Mexico 88003, U.S.A.*

(*Received 15 April 1992, accepted 1 May 1992*)

Low spatial resolution imagery from a polar orbiting meteorological satellite was utilized to detect short-term drought effects on native plant communities in southeastern New Mexico, U.S.A. rangelands. A spectrally derived Vegetation Index was compared to the Palmer Drought Severity Index, Crop Moisture Index, and monthly precipitation departures for a wet year (1988) and a dry year (1989). Differences between years as well as between plant communities were assessed. Plant communities consisting primarily of grass species were the most spectrally responsive to variation in precipitation, while forested areas were least affected.

Introduction

There is little doubt that drought is a major factor in management of rangeland resources, and thus, demands a very high priority in range investigations. This is especially true in the rangelands of the southwestern United States where drought occurred during 17 of the 40 years between 1944 and 1984 (Holechek, Piper & Herbel, 1989).

Drought is often defined in either conceptual or operational terms. Conceptual definitions describe what drought is, while operational definitions are more concerned with the extent, impact, and outcome of drought (Wilhite & Glantz, 1987). Tucker & Goward (1987) define drought as a period of plant growth reduced below the historical average due to lower than average precipitation amounts. Range management professionals (Society for Range Management, 1989) have defined drought as:

(1) A prolonged chronic shorage of water, as compared to the norm, often associated with high temperatures and winds during spring, summer, and fall; and (2) A period with precipitation during which the soil water content is reduced to such an extent that plants suffer from lack of water.

Whatever the cause, the effects of drought are evident in native vegetation. Reduced biomass production, increased fire danger, and other long-term changes can often be linked to drought events. For southern New Mexico, Buffington & Herbel (1965) stated that drought has been a major contributor to the widespread conversion of desert grasslands to desert shrublands during the past 100 years.

0140–1963/93/020305 + 19 $08·00/0

Various drought indices have been developed for the purpose of monitoring the spatial extent and severity of drought conditions (e.g. Palmer, 1965). These indices have been primarily used for agricultural areas, and the information they provide may not be indicative of plant response in native ecosystems (Huete & Jackson, 1987). Therefore, the purpose of our research was to test the ability of low spatial resolution satellite imagery from the U.S.A.'s National Oceanic and Atmospheric Administration – Advanced Very High Resolution Radiometer (NOAA – AVHRR) to detect short-term spatial/temporal drought effects on native plant communities during the growing seasons of 1988 and 1989. During 1988, southeastern new Mexico experienced average to slightly above average precipitation, and in 1989, drought was indicated by meteorological data.

The objectives of this study were: (1) to assess the spectral response of native plant communities to moisture stress, and (2) to compare existing drought indices to an AVHRR-based vegetation index to identify an appropriate measure of the plant/moisture relationships within native ecosystems. If successful, a few additional years of data should be sufficient to substantiate the character of a 'normal' spectrally based drought index for native ecosystems in southeastern New Mexico. Such an index would offer the potential for significant additional information on both the temporal and spatial attributes of existing drought indices, which are derived from relatively few weather stations, and which are not usually available on a timely basis.

Climate data

Climate data used in this analysis include the Palmer Drought Severity Index, Crop Moisture Index, and precipitation departure from monthly normal. Drought information for both years of the study was obtained from the *Weekly Weather and Crop Bulletin* (U.S. Department of Commerce and U.S. Department of Agriculture, 1988; 1989). Precipitation departure from monthly normal (PDMN) is calculated as the difference between actual precipitation and the 30-year normal for each month. This information was obtained, for each climatic division in southeastern New Mexico, from the *Climatological Data Annual Summary* (NOAA, 1988; 1989).

Palmer Drought severity index (PDSI)

The PDSI developed by W. C. Palmer (1965) is the best-known and most widely used meteorological drought indicator in the United States (Wilhite & Glantz, 1987). The PDSI was developed as a tool for indicating the amount of precipitation that would be required over a given time period to maintain near-normal moisture conditions (see Appendix A for PDSI formula). According to Palmer, the question to be answered is 'how much precipitation should have occurred during a given period to have kept the water resources of the area commensurate with their established use?' Palmer's index is used primarily to evaluate prolonged periods of abnormally dry or abnormally wet weather. Index values are assigned to a condition class ranging from extreme drought to an extreme moist spell.

Crop Moisture Index (CMI)

The CMI is a short-term drought indicator developed by Palmer (1968). It uses evapotranspiration, potential evapotranspiration, location, time of year and the previous week's index to provide each week's index value (Denny & Heddinghaus, 1987). It estimates the status of moisture surplus or deficit in terms of agricultural demand, and values are assigned to a condition class similar to the PDSI (see Appendix B for CMI formula).

Vegetation response to drought

Range plants require more water than that utilized in the photosynthesis process. This additional water exits individual plants through transpiration and returns to the atmosphere (Holechek, Piper & Herbel, 1989). Many rangeland plant species have developed mechanisms to reduce transpiration losses, thereby reducing the impact of moisture shortage. Tolerance for moisture shortage varies widely among range species, causing moisture stress to be more severe in some plants than others — even under the same climatic conditions. Moisture stress causes a plant that would normally be actively growing to appear wilted and yellowish. For this reason, the effects of drought should be apparent in the vigor of a plant, and in the spectral response of plant communities as viewed from a satellite (Curran, 1980; Tucker *et al.*, 1983; Walsh, 1987).

Under normal moisture conditions, a native plant community has a characteristic phenology throughout the growing season. For southeastern New Mexico, there is a pronounced increase in vegetation vigor through the beginning of the growing season; a leveling-off or slight decline in the dry, early part of the summer; a 'green-up' and maturation when the monsoon rains begin in mid July which continues through August; then, toward the end of the growing season, photosynthetic activity decreases in connection with the seasonal senescence of vegetation. Moisture stress alters this characteristic phenologic cycle. For this reason, the spectral response of native plant communities as derived from satellite data may be a useful indicator of the spatial and temporal components of drought.

Study area

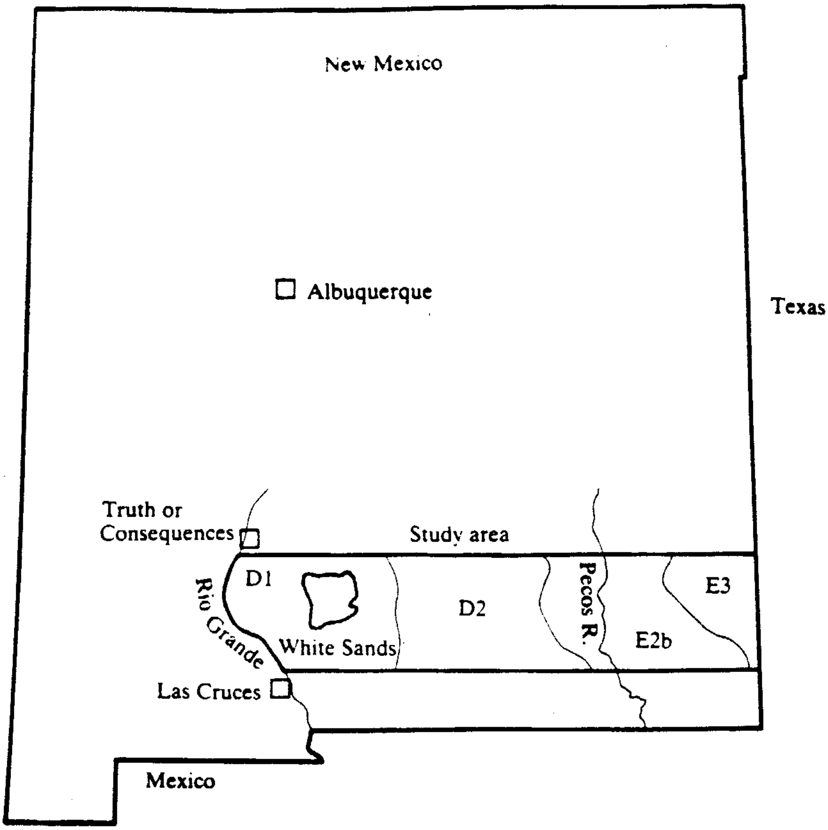
The study area is an east-west transect of approximately 75 by 340 km extending from the Rio Grande between Las Cruces and Truth or Consequences, New Mexico to the Texas border (Fig. 1). The area covers about 25,500 square km, and contains portions of the Llano Estacado and Lower Pecos Valley sub sections of the Great Plains Physiographic Province, and portions of the Mexican Highland and Sacramento Sections of the Basin and Range Physiographic Province (Hawley, 1986). The area has relatively distinct zones of vegetational diversity due to elevation, climatic, and edaphic factors.

Methodology

Satellite data

The National Oceanic and Atmospheric Administration (NOAA)operational polar orbiting satellites were designed primarily for meteorological purposes, but have become very useful for earth resource applications as well. Characteristics of the Advanced Very High Resolution Radiometer (AVHRR) system on-board these satellites include low spatial resolution (1100 m at nadir), twice-daily coverage, high radiometric resolution (1024 data levels) and synoptic view (ground swath of approximately 2400 km) (NOAA, 1991). This study utilizes High Resolution Picture Transmission (HRPT) data which are transmitted continuously in real time, in contrast to many studies which have utilized spatially and temporally composited data (e.g., Justice *et al.*, 1985; Holben, 1986). While the compositing process is useful for data reduction and cloud masking, it tends to introduce additional spatial inaccuracy and combines data from different dates and viewing angles, making detailed interpretations difficult.

This work makes use of information in the spectral-temporal domain (the change in spectral characteristics of land cover over time). So much information is carried in this domain that it overrides much of the noise inherent in variable sensor viewing geometries



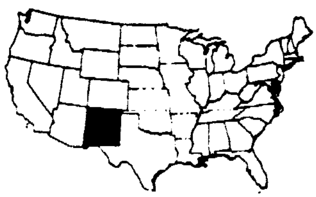


Figure 1. Study area location in New Mexico, U.S.A. and associated physiographic provinces: D1, Mexican Highland Section; D2, Sacramento Section; E2b, Lower Pecos Valley Subsection; E3, Llano Estacado.

and atmospheric distortion (Graetz, 1990). Relatively few studies of natural vegetation have made use of this domain, and even fewer with AVHRR-HRPT data (Loveland *et al.*, 1991; Peters, 1989; Tucker *et al.*, 1985; Justice & Hiernaux, 1986).

The primary method of monitoring vegetation from satellite imagery has been through the use of a vegetation index (VI). In its simplest form, a VI is a ratio of near infrared (NIR) reflectance to red (RED) reflectance. The chlorophyll in growing plants absorbs RED energy to carry on photosynthesis, and the mesophyll cells in leaves reflect NIR energy. The more active the vegetative growth, the larger the NIR/RED ratio and the higher the value of the VI. Several factors, such as atmospheric effects, soil background and soil moisture can affect these indices. Many methods of compensating for these inaccuracies have been suggested (Perry & Lautenschlager, 1984; Huete & Jackson, 1987; Huete, 1988). The VI selected for this study is the widely used Normalized Difference Vegetation Index (NDVI) which is a normalized ratio of NIR and RED reflectance. Per-pixel calculation of NDVI is as follows:

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{RED})}{(\mathrm{NIR} + \mathrm{RED})} * 100 \tag{1}$$

Image processing

Twenty one NOAA-10 AVHRR-HRPT satellite images were selected for analysis; nine from the 1988 and twelve from the 1989 growing seasons. The images were selected with near-nadir location, and minimal cloud cover. NOAA-10 has a southbound (descending) pass at approximately 07.20 a.m. local time. While the early overpass time leads to increased shadowing, it avoids increased atmospheric turbidity which occurs later in the day.

An interactive procedure involving the pixel values of the thermal-infrared (TIR) band was utilized to mask out clouds. Both the RED and NIR data sets were corrected for solar zenith angle variation and the resulting NDVI images were geographically registered. Images with greater than 20% cloud cover for an individual plant community of interest were eliminated from the analysis.

Climatic divisions

Climatic divisions in New Mexico, as defined by NOAA, are used for the computations of CMI and PDSI. These divisions are principally determined by topographic or political boundaries. The study area includes portions of New Mexico divisions five through eight. The divisions are indicated on Fig. 2. Divisions 5 (Central Valley) and 8 (Southern Desert) lie between the Rio Grande and the Sacramento Section of the Rocky Mountain Physiographic Province. Division 6, the Central Highlands, consists primarily of the Sacramento Highlands and division 7, the Southeast Plains, extends from the Sacramento Highlands to the Texas Border.

Landscape regionalization

Regionalization of the study area into land cover classes was accomplished by implementing a two-step, unsupervised spectrally based statistical classification procedure

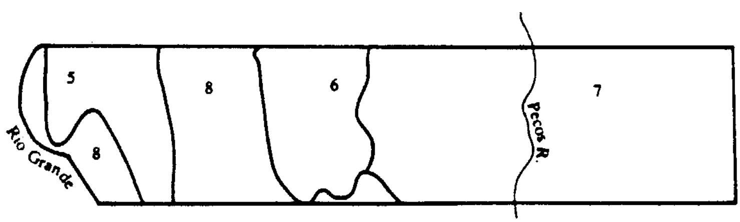


Figure 2. Climatic divisions within the study area.

on nine cloud-free images selected from the 1989 dataset. The first step in this procedure was to spectrally separate the study area into two broad categories; woodland and non-woodland. The spectral classifier could then more accurately identify sub-categories of land cover within these distinct groups.

The second step in the regionalization process involved the delineation of both the woodland and non-woodland areas into six spectrally and temporally distinct classes using the same statistical classifier. Mean NDVI values for each of the six spectral classes were plotted for each date of the study as temporal curves. The classes with the most similar temporal phenological characteristics were combined into single classes. This post-classification sorting procedure resulted in two woodland classes and four non-woodland classes.

Each class derived in this regionalization process was identified and labeled. Land cover was successfully classified at the plant community type level. The Society for Range Management Glossary of Terms (1989), defines a plant community type as an 'aggregation of all plant communities distinguished by floristic and structural similarities in both overstory and undergrowth layers.' Plant community types were identified as Desert Basins, Arid Shrublands, Arid Grasslands, Temperate Grasslands, Mixed Forests, and Coniferous Forests. The location of these plant community types is shown in Fig. 3.

Knowledge of the study area and field evaluation were utilized to verify classification accuracy. During field evaluation, it was determined that areas significantly affected by human activity (e.g. dry and irrigated crops and urban areas) should be eliminated from the analysis. White Sands National Monument (see Fig. 1) was also eliminated from the study, since it is essentially unvegetated and relatively unaffected by drought conditions.

Selection of specific plant community types for analysis

It was decided that the analysis should concentrate on the arid shrublands, temperate grasslands and coniferous forests, because those classes represent the most homogeneous native plant community types within the study area. Three plant community types were removed from the analysis due to their transition zone status (Arid Grasslands and Mixed Forest), and dominant soil background reflectance (Desert Basins). Figure 4 shows the location of the plant community types selected for analysis; the division and number of pixels for each are indicated below.

Plant community type	Climatic division	Number of pixels
Arid Shrublands	7	3179
Temperate Grasslands	7	312
Coniferous Forests	6	1337

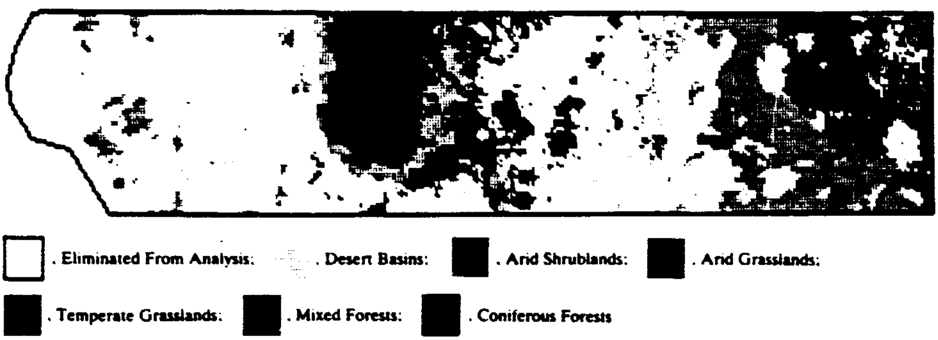


Figure 3. Study area plant community types.

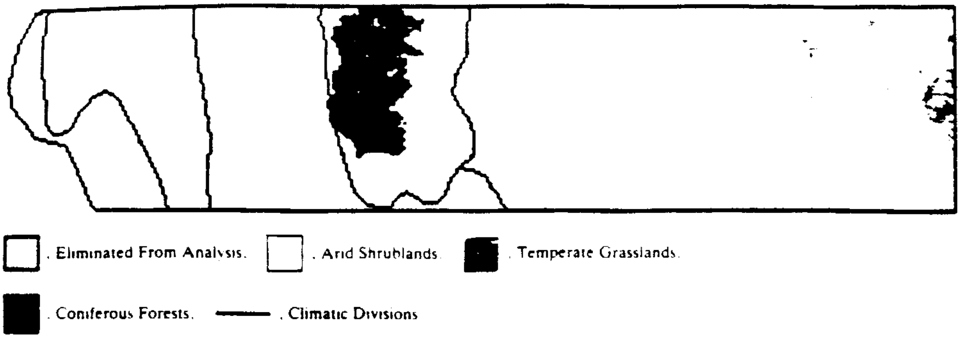


Figure 4. Native plant community types selected for analysis.

The Arid Shrublands are primarily located in the Lower Pecos Valley and the slopes of the Llano Estacado portions of the Great Plains Physiographic Province. Precipitation in this region is generally less than 30 cm per year and is highly variable. Elevation ranges from 914 to 1524 m. The dominant plants include shinnery oak (*Quercus havardii*), honey mesquite (*Prosopis glandulosa*), and several desert grasses, primarily dropseeds (*Sporobolus* spp.) (Warnock, 1974; Gay *et al.*, 1984).

The temperate grasslands are located in the Llano Estacado Section of the Great Plains Physiographic Province and along the boundary between the Great Plains and the Sacramento Section of the Basin and Range Physiographic Province. Precipitation in the Great Plains region ranges from 35 to 46 cm per year. Average elevation is between 1371 and 1524 m. This region is primarily short-grass prairie, dominated by blue grama (*Bouteloua gracilis*) and black grama (*Bouteloua eriopoda*). Also common are galleta (*Hilaria jamesii*), and species of bluestem (*Andropogon* spp.) (Gay *et al.*, 1984). Vine-mesquite (*Panicum obtusum*) and alkali sacaton (*Sporobolus airoides*) are also important plants in the landscape.

The coniferous forests are primarily located in the Sacramento Section of the Basin and Range Physiographic Province. This forest region is commonly above 1980 m and receives 50 to 76 cm of precipitation annually. Ponderosa pine (*Pinus ponderosa*) is common, and often very dense with little herbaceous understory (Gay *et al.*, 1984). Where forest cover is not as dense, Arizona fescue (*Festuca arizonica*), mountain muhly (*Muhlenbergia montana*), and blue grama are common. In subalpine meadows, fescues (*Festuca* spp.) sedges (*Carex* spp.), and rushes (*Juncus* spp.) are predominant.

Plant community response to moisture stress

The first objective: 'to assess the spectral response of native plant communities to moisture stress', was accomplished by evaluating between-year changes in the mean and variance of NDVI values for each plant community type. Mean NDVI for each date was plotted with an error bar of plus and minus one standard deviation. Assuming a normal distribution, approximately 68·26% of the population NDVI values lie within the range of the error bars. Since sample sizes (number of pixels) are large, differences in mean values are considered to be significant. However, the difference between years is most pronounced where the error bars do not overlap. This procedure illustrates the time of growing season with the greatest differences between wet and dry year NDVI values.

Comparison to climatic data

The second objective: 'to compare existing drought indices to an AVHRR-based vegetation index', was accomplished by qualitative analyses of the shapes and trends of CMI, PDSI, PDMN, and NDVI growing season curves. For instance, if NDVI responses resemble CMI responses, the argument can be made that NDVI changes are produced from shallow rooted vegetation which is responsive to short-term variations in soil moisture.

Results

Arid shrublands

Response to moisture stress. With the exception of early May, NDVI values were lower throughout the 1989 growing season than in 1988 (Fig. 5). The usual mid-season decline in NDVI occurred earlier, had lower values, and lasted longer in 1989 than in 1988. In 1988, the error bars were wider during the early season, indicating that NDVI variability was greater during initial foliage growth than during the late maturation and senescence portions of the growing season. Variability in 1989 was greatest in August during the most severe moisture stress and just before monsoon precipitation began to ease the drought; most likely a response to a more sporadic and variable precipitation pattern. Plants had remained dormant for much of 1989 because of the drought. Late summer precipitation brought about a delayed 'green-up', and an increase in spectral variability during August.

Comparison to climate data. PDSI values were consistent with the general trends in vegetation spectral response (Fig. 6). In 1988, NDVI values were high and PDSI values ranged from 'unusually moist' to 'very moist'. Monsoon precipitation caused an increase in NDVI in early July, 1988, and PDSI responded to the same precipitation in late July and early August. 'Mild' to 'severe drought' characterised 1989 PDSI values, and NDVI values were low. During 1989, the only substantial increase in monsoon season NDVI came in early September, with the corresponding increase in PDSI appearing in late September. In both years, PDSI increased about one month after NDVI began to increase,

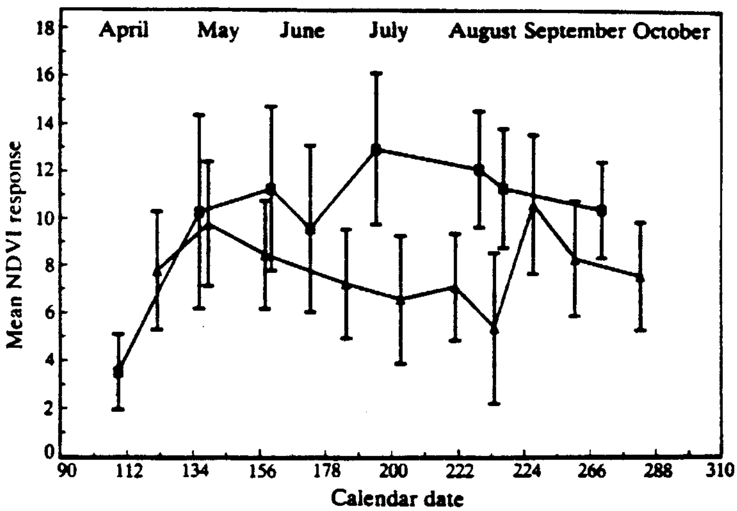


Figure 5. Arid shrublands mean NDVI of 3179 pixels for 1988, ■ and 1989, ▲ with error bars indicating one standard deviation for climate division 7.

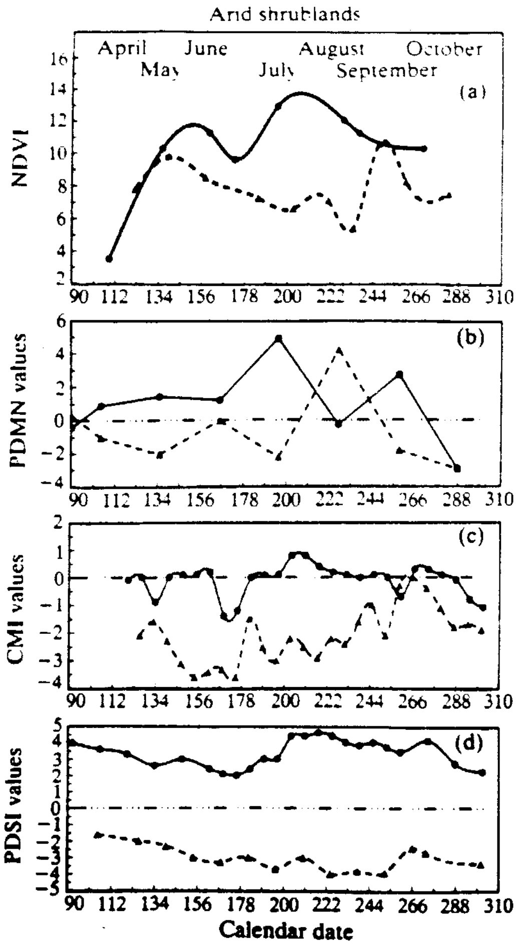


Figure 6. Mean NDVI and climate data for arid shrublands in climate division 7 – 1988, ——— and 1989, — — —. (a) Temporal NDVI means, (b) Precipitation departure (cm) from 30 year monthly normals, (c) Weekly Crop Moisture Index values, (d) Biweekly Palmer Drought Severity Index values.

providing evidence that the NDVI of the arid shrublands responds to precipitation events more quickly than does PDSI. CMI was a somewhat more responsive measure, appearing to provide information on more subtle short-term variations in precipitation.

PDMN appeared to be most closely associated with NDVI. In July 1988, NDVI increased; and precipitation was 4·95 cm above normal. In 1989, precipitation was 5·52 cm below normal between April and July, while August was 4·19 cm above normal. In late August and early September, NDVI rose significantly, indicating an increase in photosynthetic activity. Precipitation was 4·80 cm below normal over the next two months, and NDVI quickly began to drop.

Temperate grasslands

Response to moisture stress. Early season NDVI values for the temperate grasslands were lower in 1989 than those in 1988 (Fig. 7). Once August precipitation brought some relief

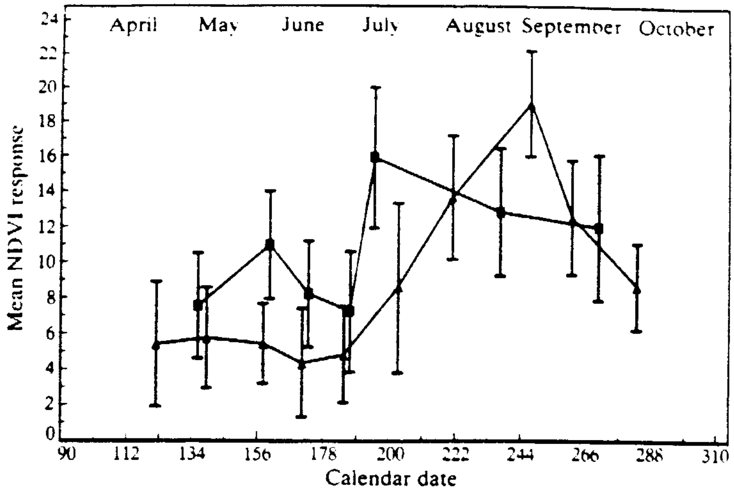


Figure 7. Temperate grasslands mean NDVI of 312 pixels for 1988, ■ and 1989, ▲ with one standard deviation error bars for climate division 7.

to the landscape, 1989 NDVI values were greater than during August 1988. In early September of 1989, NDVI was substantially higher than the previous year. The two seasons ended with approximately equal NDVI values. As with the arid shrublands, the error bars were widest during initial foliage growth, where the NDVI curves slope upward.

Comparison to climate data. Trends in PDSI had some resemblance to NDVI in 1988 (Fig. 8). While NDVI was relatively high in 1988, PDSI registered a 'moist' to 'extremely moist' growing season. In 1989, NDVI was low and PDSI recorded 'moderate' to 'severe' drought nearly the entire growing season. The CMI more strongly paralleled NDVI trends than did PDSI. Through the middle of the growing season, changes in CMI were very similar to changes in NDVI.

Temporal NDVI trends appeared to be most closely related to PDMN. When precipitation for a month was above the long-term normal, photosynthetic activity of the plant community type increased almost immediately. July 1988, and August 1989 illustrate this point. Also, early in the 1988 growing season, NDVI was higher than in 1989, coinciding with above average precipitation in 1988 and below average in 1989.

Coniferous forests

Response to moisture stress. In the coniferous forest plant community type, NDVI values for both years were nearly identical (Fig. 9). Only one date in the middle of May displayed a notable separation between the mean values for 1988 and 1989. Surprisingly, that date in 1989 had a higher NDVI than in 1988. While January through March precipitation was below normal in both years, spring 1989 NDVI values may have been in response to above normal precipitation from June through September of 1988. After early-June, 1989 NDVI values were consistently lower than those in 1988. The error bars for both years were most narrow during the very early and late portions of the growing season, and were widest during the mid-season. The coniferous forest plant community type does not display the wide error bars during initial foliage growth as observed in the more arid community types.

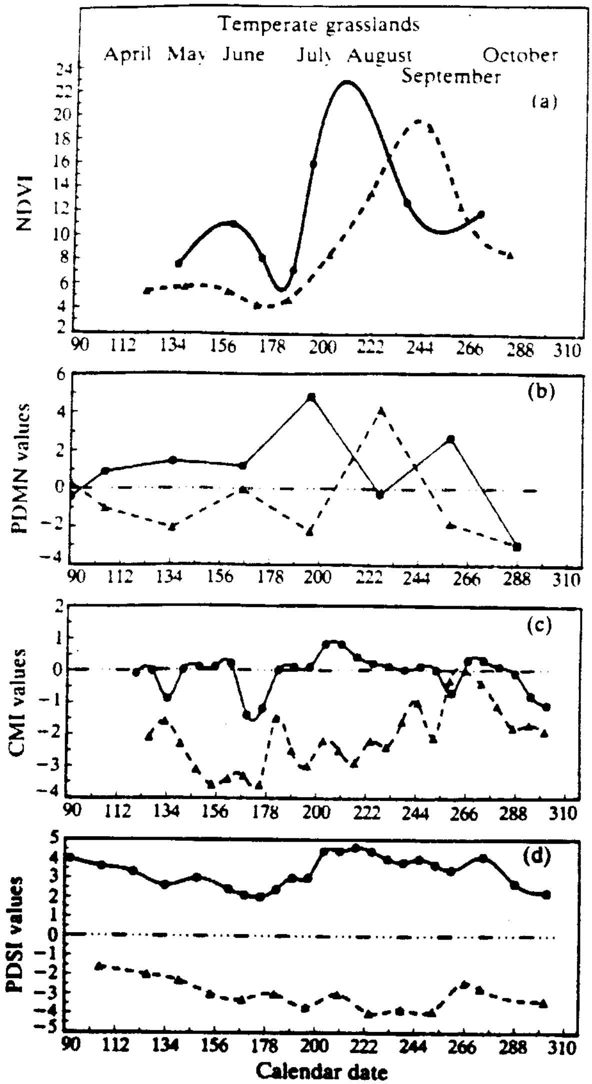


Figure 8. Mean NDVI and climate data for temperate grasslands in climatic division 7 – 1988, —— — and 1989, — — —. (a) Temporal NDVI means, (b) Precipitation departure (cm) from 30 year monthly normals, (c) Weekly Crop Moisture Index values, (d) Biweekly Palmer Drought Severity Index values.

Comparison to climate data. The PDSI registered a 'moist' to 'extremely moist' growing season in 1988; while in 1989, conditions ranged from 'severe drought' to 'near normal' (Fig. 10). There seems to be only a slight association between temporal NDVI and the climatic indicators. During the late season, the rise in NDVI in 1988 and the relative flatness of the curve in 1989 are reflected in the climate data. Also in 1989, all three indicators began to rise prior to a moderate August rise in NDVI.

Conclusions and recommendations

This study shows that the grassland plant community type was more spectrally responsive to moisture stress than shrublands or forests. Shrubland community types did not respond

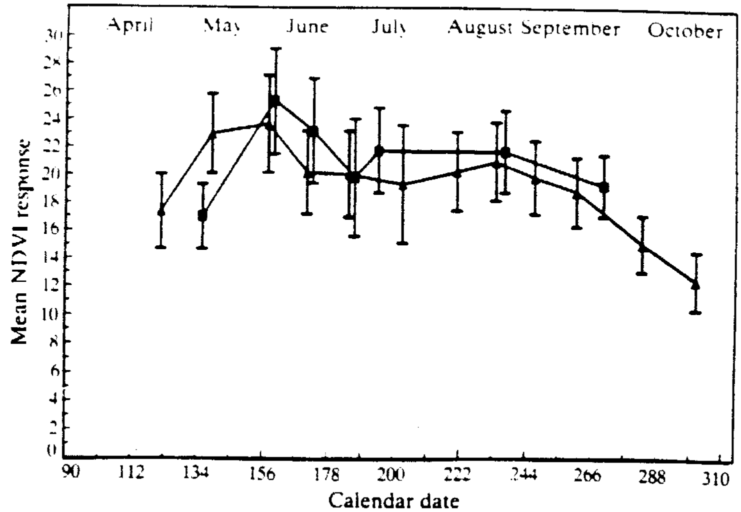


Figure 9. Coniferous forests mean NDVI of 1337 pixels for 1988, ■ and 1989, ▲ with one standard deviation error bars for climate division 6.

as strongly as grasses to short-term changes in moisture availability. Native shrubs are deep rooted plants that are very efficient water users and are not as readily affected as grasses by moisture stress. In addition, two key species, creosotebush (*Larrea tridentata*) and honey mesquite, are relatively insensitive to late summer precipitation. Creosotebush is an evergreen shrub that is responsive to winter moisture, and honey mesquite develops its leaves during spring months.

The coniferous forest showed the least spectral variability of any plant community type during the 1989 growing season. While a change in variability was noted from the wet year to the dry year, the difference was minimal due to: (1) greater annual precipitation total in the mountain highlands; (2) greater soil moisture storage; (3) lower percentage of moisture lost through evapotranspiration; (4) lower ambient temperatures, and (5) less annual variability in precipitation.

This study shows that the spectrally derived NDVI exhibits temporal trends similar to those of several climatic indicators. Of the indicators analysed, precipitation departure from monthly normal was the most closely related to spectral NDVI response. The Crop Moisture Index was more indicative of NDVI trends than was the Palmer Drought Severity Index, especially in the grassland community type.

The spectral response of individual plant community types appears to be a useful measure of drought severity. The relationship between soil moisture stress and vegetation spectral response appears to provide valuable information on range condition and drought. The establishment of long-term average NDVI curves may prove to be useful in assessing relative moisture conditions at any time during a growing season. This same information could also provide a baseline against which ecological and plant community change could be evaluated.

Appendix A

The Palmer Drought Severity Index (Palmer, 1965) uses precipitation, soil moisture, temperature, and evapotranspiration defined as Climatically Appropriate for Existing Conditions (CAFEC). The elements included in the PDSI are:

$$\hat{ET} = \alpha \hat{PE}$$

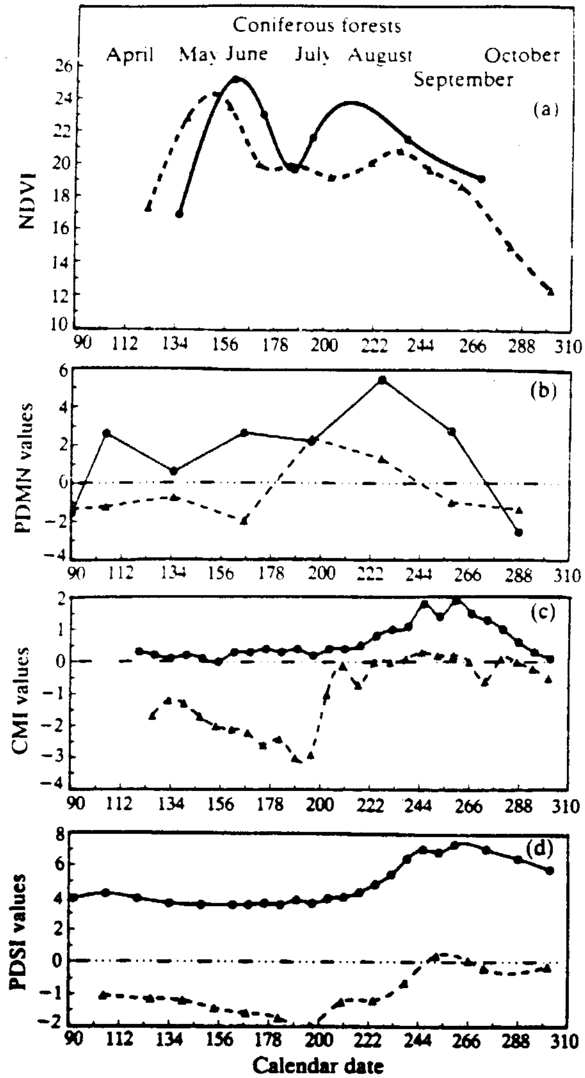


Figure 10. Mean NDVI and climate data for coniferous forests in climatic division 6 – 1988, ——— and 1989, — — —. (a) Temporal NDVI means, (b) Precipitation departure (cm) from 30 year monthly normals, (c) Weekly Crop Moisture Index values, (d) Biweekly Palmer Drought Severity Index values.

$$\hat{R} = \beta \hat{PR}$$
$$\hat{RO} = \tau \hat{PRO}$$
$$\hat{L} = \delta \hat{PL}$$

where ET is evapotranspiration, PE potential evapotranspiration, R recharge, PR potential recharge, RO runoff, PRO potential runoff, L soil water loss, and PL potential soil water loss. The CAFEC values (denoted by ^) are reported for individual stations then averaged over an entire climatic division. The constants (α, β, τ, and δ) are computed monthly and are based on thirty-year means. A combination of the CAFEC quantities give the hydrological water balance:

$$\hat{P} = \hat{ET} + \hat{R} + \hat{RO} - \hat{L}$$

where P is precipitation. Measured P is compared to P to define moisture excess or deficit (d):

$$d = P - \hat{P}$$

The moisture anomaly index is calculated as

$$Z = dK$$

where K is a weighting factor, unique for each month and division, based on moisture supply and demand. PDSI is then defined as:

$$X_t = X_{t-1} + Z_t/3 - 0{\cdot}103\ X_{t-1}$$

where t is the PDSI for week t.

Appendix B

CMI is calculated as:

$$Y_i = 0{\cdot}67_{i-1} + 1{\cdot}8\ ET - \hat{E}T\ /\ \sqrt{\alpha}$$

where

Y_i = CMI for week i
ET = Evapotranspiration for week i
$\hat{E}T$ = Normal evapotranspiration for week i
$\hat{P}E$ = Normal potential evapotranspiration for week i
α = RT / $\hat{P}E$

References

Buffington, L. C. & Herbel, C. H. (1965). Vegetational Changes on a Semidesert Grassland Range from 1858 to 1963, *Ecological Monographs*, 35: 139–164.

Curran, P. (1980). Multispectral Remote Sensing of Vegetation Amount, *Progress in Physical Geography*, 2: 55–79.

Denny, L. M. & Heddinghaus, T. R. (1987). The Crop Moisture Index, *Weekly Weather and Crop Bulletin*. U.S. Departments of Commerce and Agriculture, May 5, 1987.

Gay, C. W., Dwyer, D. D., Allison, C., Hatch, S. & Schickedanz, J. (1984). *New Mexico Range Plants*. New Mexico State University, Cooperative Extension Service, Circular #374. NMSU, Las Cruces, New Mexico. 84 pp.

Graetz, R. D. (1990). Remote Sensing of Terrestrial Ecosystem Structure: An Ecologist's Pragmatic View. In Hobbs, R. J. & Mooney, H. A. (Eds) *Ecological Studies Vol. 79: Remote sensing of biosphere functioning*, 5–30. New York: Springer-Verlag.

Hawley, J. W. (1986). Physiographic Provinces I. pp. 23–25. In: Williams, J. L. (Ed.) *New Mexico in Maps*. Albuquerque, New Mexico: University of New Mexico Press.

Holben, B. N. (1986). Characteristics of maximum-value composite images from temporal AVHRR data. *International Journal of Remote Sensing*, 7: 1417–1434.

Holechek, J. L., Piper, R. D. & Herbel, C. H. (1989). *Range Management Principles and Practices*. Englewood Cliff, New Jersey: Prentice Hall.

Huete, A. R. (1988). A soil adjusted vegetation index (SAVI), *Remote Sensing of Environment*, 25: 295–309.

Huete, A. A., Jackson, R. D. (1987). The suitability of spectral indices for evaluating vegetation characteristics on arid rangelands, *Remote Sensing of Environment*, 23: 213–232.

Justice, C. O. & Hiernaux, P. H. Y. (1986). Monitoring the grasslands of the Sahel using NOAA AVHRR data: Niger, 1983, *International Journal of Remote Sensing*, 7: 1475–1497.

Justice, C. O., Townshend, J. R. G., Holben, B. N. & Tucker, C. J. (1985). Analysis of the phenology of global vegetation using meteorological satellite data, *International Journal of Remote Sensing*, 6: 1271–1318.

Loveland, T. R., Merchant, J. W., Ohlen, D. O. & Brown, J. F. (1991). Development of a Land Cover Characteristics Database for the Conterminous U.S. *Photogrammetric Engineering and Remote Sensing*, 57: 1453–1463.

NOAA (1988). *Climatological Data – New Mexico*. 92.

NOAA (1989). *Climatological Data – New Mexico*. 93.

NOAA (1991). *NOAA Polar Orbiter Data User's Guide*. U.S. Department of Commerce, NOAA, NESDI, NCDC, and the Satellite Data Services Division, Washington, D.C.

Palmer, W. C. (1965). Meteorologic Drought. *U.S. Weather Bureau, Research Paper* No. 45. 58 pp.

Palmer, W. C. (1968). Keeping track of crop moisture conditions, nationwide: The new Crop Moisture Index, *Weatherwise*, 21: 156–161.

Perry, C. R. Jr. & Lautenschlager, L. F. (1984). Functional equivalence of spectral vegetation indices, *Remote Sensing of Environment*, 14: 168–182.

Peters, A. J. (1989). Coarse spatial resolution satellite remote sensing of drought conditions in Nebraska: 1987–1988. Ph.D. Dissertation, Department of Geography, University of Nebraska-Lincoln.

Society for Range Management (1989). *A Glossary of Terms Used in Range Management* (3rd Edn). Society for Range Management, Denver, Colorado.

Tucker, C. J., Vanpraet, C., Boerwinkel, E. & Gaston, A. (1983). Satellite Remote Sensing of total Dry Matter Production in the Senegalese Sahel, *Remote Sensing of Environment*, 13: 461–474.

Tucker, C. J., Townshend, J. R. G. & Goff, T. E. (1985). African Land-Cover Classification Using Satellite Data, *Science*, 227: 369–375.

Tucker, C. J. & Goward, S. N. (1987). Satellite remote sensing of drought conditions. pp. 145–151. In Whilhite, D. A. & Easterling, W. E. (Eds) *Planning for Drought: Toward a Reduction of Societal Vulnerability*. Boulder, Colorado: Westview Press.

U.S. Department of Commerce and Agriculture (1988). *Weekly Weather and Crop Bulletin*. Published weekly through the growing season jointly by the U.S. Departments of Commerce and Agriculture.

U.S. Departments of Commerce and Agriculture (1989). *Weekly Weather and Crop Bulletin*. Published weekly through the growing season jointly by the U.S. Departments of Commerce and Agriculture.

Walsh, S. J. (1987). Comparison of NOAA AVHRR Data to Meteorologic Drought Indices. *Photogrammetric Engineering and Remote Sensing*, 53 (8): 1069–1074.

Warnock, B. H. (1974). Impressions of the Chihuahuan Desert Plant Life, In Wauer, R. H. & Riskind, D. H. (Eds) *Transactions of the Symposium on the Biological Resources of the Chihuahuan Desert Region, United States and Mexico*. U.S. Dept. of the Interior, National Park Service Transactions and Proceedings Series No. 3: pp. xv–xvii.

Wilhite, D. A. & Glantz, M. H. (1987). Understanding the drought phenomenon: The role of definitions. pp. 11–27. In Wilhite, D. A. & Easterling, W. E. (Eds) *Planning For Drought: Toward a Reduction of Societal Vulnerability*. Boulder, Colorado: Westview Press.