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Seasonal and inter-annual relationships between vegetation and climate in central New Mexico, USA

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Abstract

Linear correlations between seasonal and inter-annual measures of meteorological variables and normalized difference vegetation index (NDVI) are calculated at six nearby yet distinct vegetation communities in semi-arid New Mexico, USA Monsoon season (June–September) precipitation shows considerable positive correlation with NDVI values from the contemporaneous summer, following spring, and following summer. Non-monsoon precipitation (October–May), temperature, and wind display both positive and negative correlations with NDVI values. These meteorological variables influence NDVI variability at different seasons and time lags. Thus vegetation responds to short-term climate variability in complex ways and serves as a source of memory for the climate system.

Keywords: AVHRR; NDVI; Remote sensing; Climate–vegetation interactions; North American monsoon; Southwestern North America

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1. Introduction

Interactions between the atmosphere and land surface strongly influence variability in climate and land surface processes. These interactions work both ways. Climate is an important determinant of land surface characteristics such as biome distributions, vegetation phenology, and energy balances (Neilson, 1986; Lu et al., 2001). The land surface can feed back to the climate through modifications in albedo, evapo-transpiration, soil moisture, radiation flux partitioning, and aerodynamic roughness, interacting with atmospheric processes such as mesoscale circulation, cloud formation, and subsequent precipitation (Lu et al., 2001). Modeling studies on a global scale show that the vegetation portion of the land surface interacts with the atmosphere to produce significant effects on regional climate (Betts et al., 1997; Bounoua et al., 2000). In a modeling study over the semi-arid central United States, variability in vegetation phenology influences the regional climate through changes in surface moisture and energy balances (Lu et al., 2001). Despite this progress in understanding global- and regional-scale variability in climate and land surface processes, accurate descriptions of local climate–vegetation interactions are still relatively few.

The objective of this data analysis is to identify seasonal and inter-annual relationships over an 11-year period between local climate and remotely sensed "greenness" at six different vegetation communities in a diverse semi-arid environment characterized by sharp gradients of vegetation. The analysis is based on an earlier study (Weiss et al., 2003), which demonstrated that behavior of a greenness index at these nearby communities relates to existing differences in vegetation features. Moreover, temporal fluctuations in greenness exhibit significant variability consistent with seasonal and inter-annual changes in precipitation.

Greenness is measured using the normalized difference vegetation index (NDVI) based on remotely sensed advanced very high resolution radiometer (AVHRR) images with 1 km^2 spatial and twice daily temporal resolution (Weiss et al., 2003). NDVI is the ratio of the amounts of reflectance in the near infrared (NIR) and red (RED) portions of the electromagnetic spectrum (ranges 0.72–1.10 and 0.58–0.68 μm, respectively), calculated using the formula

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{RED})/(\mathrm{NIR} + \mathrm{RED}).$$

NDVI has been related to biophysical variables such as leaf area, canopy coverage, productivity, and chlorophyll density as well as to vegetation phenology. (Goward et al., 1985; Justice et al., 1985; Tucker et al., 1985; Townshend and Justice, 1986; Spanner et al., 1990; Yoder and Waring, 1994; Peters and Eve, 1995; Prince et al., 1995).

Using NDVI as a proxy for these biophysical variables has allowed relationships between vegetation and meteorological variables over various spatial and temporal scales to be identified in arid and semi-arid environments. Malo and Nicholson (1990) examined six vegetation formations across Mali and Niger in the Sahel of western Africa over a 4-year period, finding strong linear relationships between the annual integrated (i.e. 12-month sum) NDVI and annual precipitation, and between monthly NDVI and precipitation from the concurrent plus two preceding months. With 3 years of NDVI data, Peters and Eve (1995) observed the phenology of Chihuahuan Desert grassland and scrub vegetation over a region in southern New Mexico responding throughout the growing season to recent precipitation. Over a 4-year period, correlations between monthly NDVI values for 130 km^2 of mixed grass prairie in western Nebraska and monthly precipitation amounts were greatest with the previous month's rainfall (Szilagyi et al., 1998). Temperature in the form of growing degree days and growing season precipitation displayed significant correlation with a growing season NDVI value for nine grassland cover classes in a northern and central Great Plains region with a 4-year data record (Yang et al., 1998). Correlations between monthly measures of these variables were also observed with grass and shrub vegetation types in China over a 10-year period (Li et al., 2002).

In arid and semi-arid environments, precipitation is generally the most important factor influencing primary productivity (Hadley and Szarek, 1981; Lin et al., 1996) and ecosystem structure and dynamics (Lange et al., 1976; Sala et al., 1982). Other meteorological variables such as solar radiation, temperature, and wind can have both positive and negative effects on vegetation in this region (Chew and Chew, 1965; West and Gasto, 1978; Moorhead and Reynolds, 1989; Jongejans and Schippers, 1999; Okin et al., 2001). It is thus hypothesized that significant positive relationships appear between precipitation and NDVI seasonal values across the Sevilleta. Significant positive and negative relationships may also appear between other meteorological variables and NDVI.

To examine these hypotheses, correlations are calculated between meteorological variables and spring (pre-monsoon) and summer (monsoon) NDVI averages of six vegetation communities during the period from 1990 through 2000. Lag correlation relationships are examined to explore the role of vegetation as a source of memory in the climate system. The statistical relationships between climate and NDVI are interpreted in terms of known characteristics of dominant and common plant species, thus describing how individual or combinations of meteorological variables can modulate variability in seasonal NDVI values.

2. Data and analysis techniques

2.1. Biological setting

The Sevilleta National Wildlife Refuge and Long-term Ecological Research (LTER) site (hereafter Sevilleta) is located approximately 100 km south of Albuquerque, New Mexico, USA (Fig. 1). Following Weiss et al. (2003), the vegetation communities examined in this study are Great Plains/desert grassland (GPGrslnd), Chihuahuan Desert (ChiDes), piñon-juniper woodland (PJWdlnd), juniper savanna (JunSav), Colorado Plateau shrub-steppe (CPShbStp), and Colorado Plateau grassland (CPGrslnd) (Moore, 2001; Table 1).

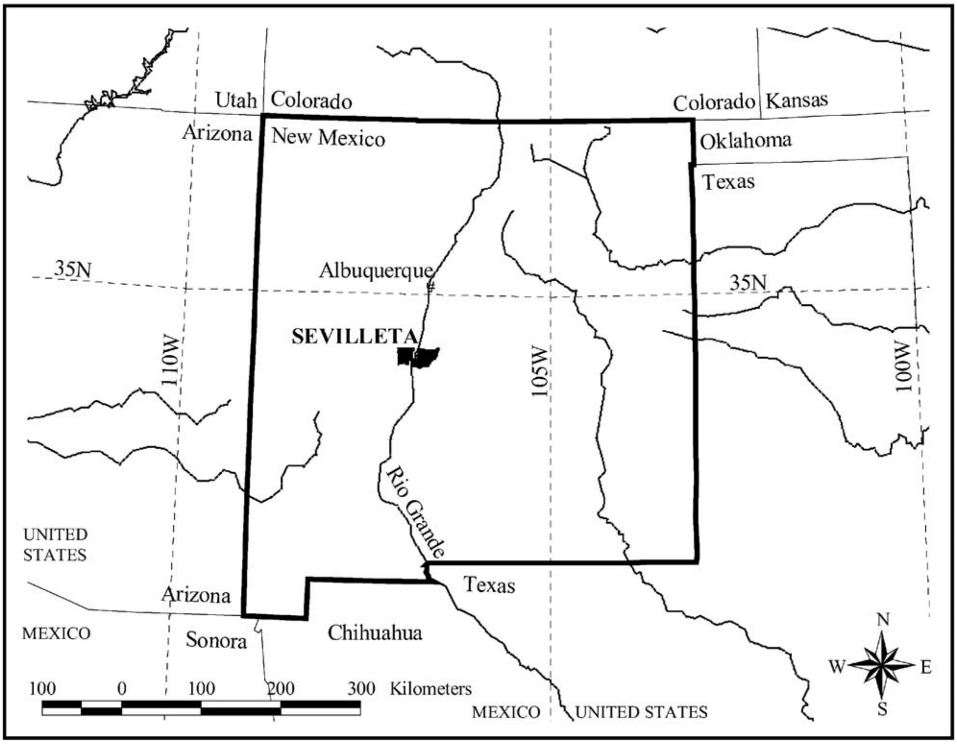

Fig. 1. Location of the Sevilleta LTER site, approximately 100 km south of Albuquerque, New Mexico, USA.

These vegetation communities cover extensive areas in southwestern North America. Great Plains grasslands enter the southwest through southern Colorado and northwestern Texas, extending to areas in southwestern New Mexico, northwestern Chihuahua, northeastern Sonora, and southeastern and west-central Arizona (Brown, 1994). The Chihuahuan Desert, largest of the three warm North American deserts (Mohave, Sonoran, and Chihuahuan), covers areas in eastern Chihuahua, western Coahuila, San Luis Potosí, southern Nuevo Leon, northeast Zacatecas, eastern Durango, southwest Texas, and southern New Mexico, as well as small areas in southeastern Arizona and northeastern Sonora. Piñon-juniper woodlands with piñon pine (*Pinus edulis*) and one-seeded juniper (*Juniperus monosperma*) and juniper savannas with one-seeded juniper are found in western Texas, central and southern New Mexico, and areas of Arizona south of the Mogollon Rim. Colorado Plateau shrub-steppe, typically located north of the 36th parallel, occupies approximately 59,570 km^2. Extensions reach into northern Arizona and New Mexico. Colorado Plateau grasslands cover areas in southern Utah, northern Arizona, north-central New Mexico, and southwestern and south-central Colorado.

Table 1
Meteorological station properties (Moore, 2001) and principal vegetation classes (Muldavin and Milne, 1993; Shore, 2001a) of the six vegetation communities. Principal vegetation classes comprise at least 80% of the analysis area of each vegetation community

Vegetation community	Meteorological station elevation and location	Principal vegetation classes
Great Plains/desert grassland	1596 m 34.36N, 106.69W	Transition Chihuahuan and Great Basin grasslands Transition Chihuahuan and Plains grasslands
Chihuahuan Desert	1538 m 34.22N, 106.80W	Chihuahuan Desert grasslands Great Basin grasslands Chihuahuan or Great Basin lowland/swale grasslands Chihuahuan Desert shrublands transition Chihuahuan and Great Basin grasslands
Piñon-juniper woodland	1971 m 34.37N, 106.54W	Rocky Mountain conifer woodlands Rocky Mountain conifer savanna
Juniper savanna	1766 m 34.40N, 107.04W	Rocky Mountain conifer savanna Great Basin grasslands Chihuahuan Desert grasslands Rocky Mountain conifer woodlands
Colorado Plateau shrub-steppe	1503 m 34.30N, 106.93W	Great Basin shrublands Great Basin grasslands
Colorado Plateau grassland	1547 m 34.41N, 106.93W	Great Basin grasslands transition Chihuahuan and Great Basin grasslands

2.2. Climatic setting

As is the case throughout southwestern North America, abundant sunshine, lack of moisture, and highly variable precipitation characterize the climate of the Sevilleta. Atmospheric dynamics are largely dominated by westerly large-scale systems from October through May, whereas influence from the North American monsoon is prominent from late June through September (Douglas et al., 1993; Sheppard et al., 2002). El Niño-Southern Oscillation (ENSO) cycles affect inter-annual precipitation variability during the winter and spring (Andrade and Sellers, 1988; Sheppard et al., 2002). El Niño events typically result in above average precipitation during these seasons while La Niña events typically provide below average precipitation. Inter-annual variability during the summer is less coherent and more difficult to associate with large-scale climate variability. A network of meteorological stations at the Sevilleta monitors large spatial and temporal

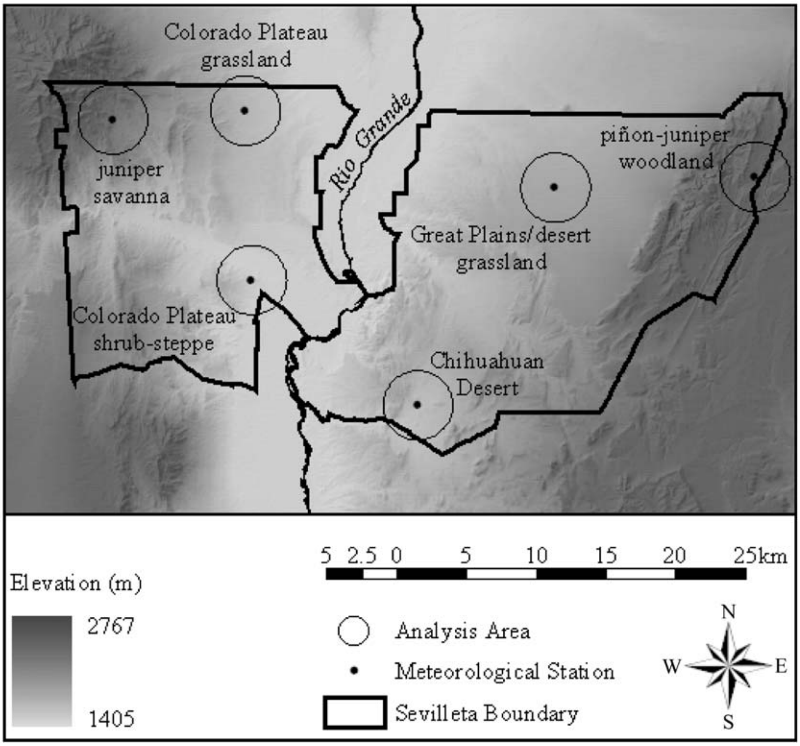

Fig. 2. Locations of the six analysis areas are outlined by 5 km diameter circles that surround a meteorological station. Actual spatial extent of the areas is further limited by the Sevilleta boundary for all areas except the Great Plains/desert grassland. Elevation data are from Shore (2001a).

variations in weather, facilitating studies of joint climate and vegetation variability. Individual meteorological stations are associated with each of the six vegetation communities in this study.

Monthly averages from January 1990 through December 2000 of 12 meteorological variables (Moore, 2001) measured at stations 40 through 45 of the Sevilleta were obtained (Fig. 2). Although there currently exist 10 stations at the Sevilleta, these six were chosen for having the lengthiest matching data records. Stations 40 through 45 range in elevation from 1503 to 1971 m (Table 1). Meteorological variables include various measures of temperature and wind, solar radiation, relative humidity, vapor pressure, and precipitation (Table 2).

It is certain that no one variable is representative of most of the monthly meteorological variability found at the Sevilleta, nor is it likely that all 12 variables are genuinely independent. Factor analysis, a class of multivariate statistical methods suitable for analyzing multidimensional data sets, is utilized in the next section to examine the underlying patterns and relationships of the 12 variables. This analysis condenses the 12 meteorological variables into a smaller set of factors. By isolating factors that account for the greatest variability, redundancy is minimized

Table 2
The 12 meteorological variables used in the factor analysis

Variable	Abbreviation	Units
Mean maximum temperature	MMaxT	°C
Absolute maximum temperature	AMaxT	°C
Absolute minimum temperature	AMinT	°C
Mean daily temperature	MDT	°C
Mean % relative humidity	M%RH	—
Mean vapor pressure	MVP	mb
Mean wind speed	MWS	m/s
Average maximum wind speed	AMaxWS	m/s
Maximum wind speed	MaxWS	m/s
Average daily solar radiation	ADSR	kW/m^2
Precipitation	Prc	mm

Sensor height for temperature, solar radiation, and relative humidity is at 2.5 m, wind is at 3 m, and precipitation is at 0.5 m (Moore, 2001).
Raw data are reported as hourly averages.

and the fundamental variables may be better understood (Kachigan, 1986; Clausen and Biggs, 2000).

2.3. NDVI

NDVI values for the six vegetation communities were derived from AVHRR biweekly composite images available from the Sevilleta (Shore, 2001b), and rescaled to a range from 0 to 200 (United States Geological Survey, 2001). Following Weiss et al. (2003), 1 km by 1 km NDVI values were extracted in grid format from each AVHRR image using ArcView and ArcInfo geographic information system (GIS) software (ESRI, 1999). NDVI values for a given vegetation community were derived and averaged within an analysis area of a five kilometer-diameter circle centered on a meteorological station (Fig. 2). The size of each area was limited to account for the localized rainfall from convective thunderstorms during the summer (Weiss et al., 2003).

The "spring" season is defined for this study as March through June, before the climatological onset of monsoon rainfall. The "summer" season follows from July through October (Weiss et al., 2003). Division of the growing season allows the analysis to distinguish potentially different sensitivities of vegetation to climate anomalies before and during the rainy season. Average NDVI values for spring ($NDVI_{SP}$) and summer ($NDVI_{SU}$) for each of the six vegetation communities, for each year of the analysis period, were calculated from nine ($NDVI_{SP}$) or eight ($NDVI_{SU}$) biweekly composite periods. $NDVI_{SU}$ values for the 1994 growing season were not included in this analysis due to the failure of the NOAA-11 satellite in mid-September (Minor et al., 1999).

$NDVI_{SP}$ values display ordinal consistency and uniform behavior (Fig. 3). The piñon-juniper woodland exhibits the highest $NDVI_{SP}$ value every year. The juniper savanna shows the second highest values except in 1991 and 1995 when $NDVI_{SP}$ values of the Great Plains/desert grassland are similar. Excepting these 2 years,

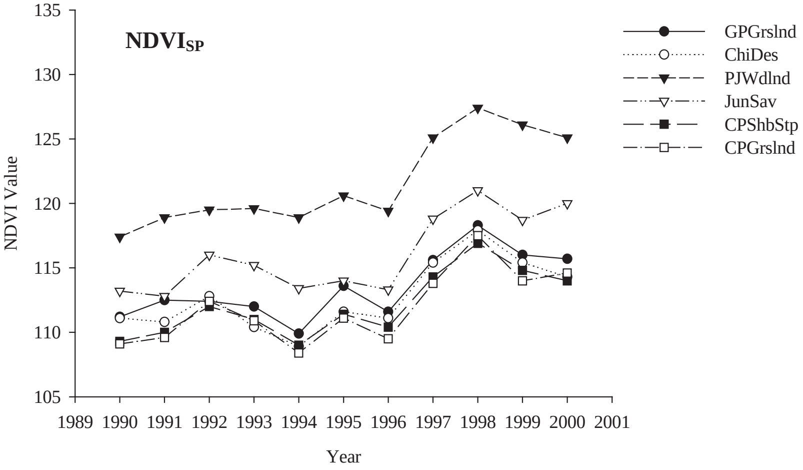

Fig. 3. NDVI$_{SP}$ time series (1990–2000) of each of the vegetation communities.

values at the Great Plains/desert grassland are lower and similar to values computed for the Chihuahuan Desert, Colorado Plateau shrub-steppe, and Colorado Plateau grassland. General increases in NDVI$_{SP}$ for all communities occur from 1990 to 1992, 1994 to 1995, and 1996 to 1998, while general decreases occur from 1992 to 1994, 1995 to 1996, and 1998 to 2000.

NDVI$_{SU}$ values display less ordinal consistency and uniform behavior than those observed for NDVI$_{SP}$ (Fig. 4). The piñon-juniper woodland again exhibits the highest NDVI$_{SU}$ value each year while the juniper savanna usually displays the second highest; in 1991 the Great Plains/desert grassland and Chihuahuan Desert record a higher NDVI$_{SU}$ value whereas in 1996, only the Great Plains/desert grassland is higher. In 1995, the NDVI$_{SU}$ value for the juniper savanna is similar to that of the Great Plains/desert grassland. Compared to NDVI$_{SP}$ values, NDVI$_{SU}$ values showed greater separation between the Great Plains/desert grassland, Chihuahuan Desert, Colorado Plateau shrub-steppe, and Colorado Plateau grassland, as values were typically higher at the Great Plains/desert grassland and Chihuahuan Desert. General increases in NDVI$_{SU}$ mostly occur from 1990 to 1992 and 1995 to 1998, while general decreases occur from 1992 to 1995 and 1999 to 2000. Notable exceptions are the decrease from 1996 to 1997 at the Great Plains/desert grassland and the truncated increase/early decrease at the piñon-juniper woodland in 1998.

3. Results

3.1. Factor analysis

Factor analysis was performed on the correlation matrix of meteorological variables (Table 2) using MINITAB™ Release 13 statistical software (Minitab Inc.,

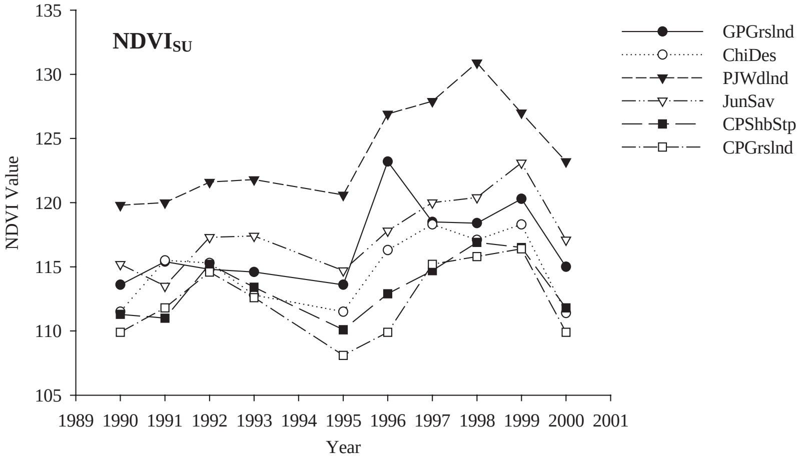

Fig. 4. NDVI$_{SU}$ time series (1990–2000) of each of the vegetation communities. NDVI$_{SU}$ for 1994 are omitted due to the shortened observation period of the growing season.

2002). The correlation matrix was chosen over the covariance matrix to standardize the weighting of each variable in the analysis. For instance, the correlation matrix allows relatively drier stations to be directly compared to relatively wetter stations (Comrie and Glenn, 1998). As a preliminary step, principal components analysis (PCA) was carried out to determine the number of factors to derive, based on the distribution of eigenvalues and explained variance. Varimax rotation (Richman, 1986) was applied to determine loadings of the meteorological variables on the retained factors.

The initial PCA of the meteorological variables yielded three underlying dimensions that cumulatively explained 90.9% of the total variance, indicating that three factors should be retained. After rotation, the variables mean daily temperature, mean maximum temperature, mean minimum temperature, absolute maximum temperature, absolute minimum temperature, and average daily solar radiation had relatively high loadings on Factor One, denoted the "air temperature" factor (Fig. 5). Maximum wind speed, average maximum wind speed, and mean wind speed had relatively high loadings on Factor Two, "air movement". Precipitation and mean percent relative humidity had relatively high loadings on Factor Three, "air moisture". Mean vapor pressure was the only variable not loaded strongly on a single factor, but instead had relatively high loadings on both Factor One and Factor Three. These three rotated factors accounted for 91.0% of the total normalized variability among the meteorological variables measured at the six stations, with Factor One explaining 53.3%, Factor Two 21.1%, and Factor Three 16.6%.

Surrogate variables, or unique meteorological variables chosen to represent each of the factors, were then identified. It was desirable for the surrogate variables to be nearly uncorrelated (i.e. statistically independent). High loading values of the rotated

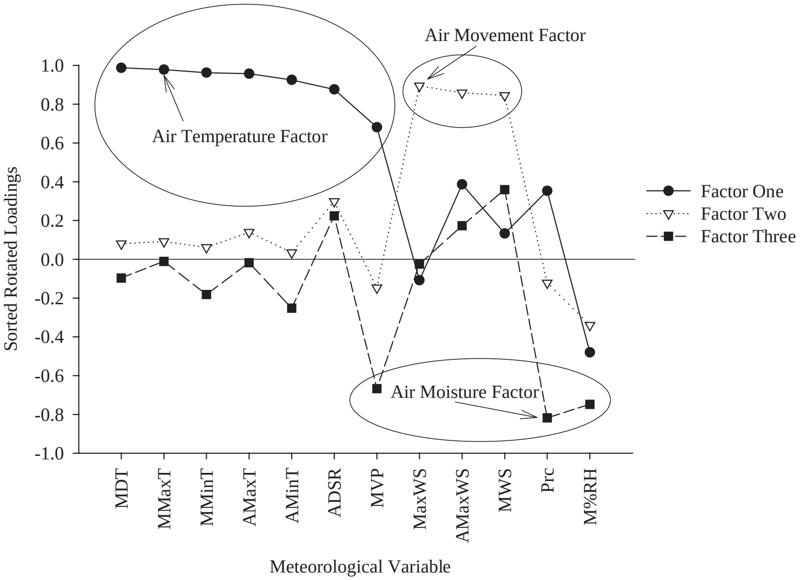

Fig. 5. Sorted rotated loadings of meteorological variables on three retained factors. See text for details of the factor analysis. Arrows point to the individual surrogate variables (mean maximum temperature, T, maximum wind speed, W, and precipitation, P) that are selected to represent each factor.

principal components in combination with low Spearman's rank order correlation coefficients were sought. Spearman's rank order correlation coefficient (values from -1 to $+1$) measures the monotonic association between two variables, a measurement of one variable increasing or decreasing with the other, even when the relationship between the two variables is not necessarily linear (Ott, 1993).

In choosing a surrogate variable to represent each of the three factors that explain the meteorological regime at the Sevilleta, high loading values in combination with low Spearman's rank order correlation coefficients (Table 3) were sought, maximizing explained variance and minimizing correlation between the variables. All temperature variables and the average daily solar radiation variable were highly correlated, expressing relationships observed in the previous factor analysis. A similar pattern emerged in the wind variables. Mean percent relative humidity had its highest positive correlation with precipitation, whereas precipitation had its highest correlation with mean vapor pressure. Mean vapor pressure showed high correlations with the temperature variables and with precipitation. Mean maximum temperature (henceforth T to represent mean maximum temperature as the surrogate variable for the air temperature factor), maximum wind speed (henceforth W to represent maximum wind speed as the surrogate variable for the air movement factor), and precipitation (henceforth P to represent precipitation as the surrogate variable for the air moisture factor) variables were chosen as surrogates to represent the air temperature, air movement, and air moisture factors, respectively (Fig. 5).

Table 3
Spearman's rank order correlation coefficients among the meteorological variables

	MmaxT*	MMinT	AMaxT	AMinT	MDT	M%RH	MVP	MWS	AMaxWS	MaxWS*	ADSR
MMinT	**0.93**										
AMaxT	**0.98**	**0.91**									
AMinT	**0.89**	**0.97**	**0.86**								
MDT	**0.98**	**0.98**	**0.96**	**0.94**							
M%RH	**−0.46**	**−0.33**	**−0.44**	**−0.27**	**−0.41**						
MVP	**0.70**	**0.78**	**0.69**	**0.78**	**0.75**	**0.24**					
MWS	**0.21**	**0.13**	**0.25**	**0.10**	**0.19**	**−0.55**	**−0.17**				
AMaxWS	**0.45**	**0.42**	**0.48**	**0.38**	**0.45**	**−0.57**	0.06	**0.86**			
MaxWS*	0.03	0.00	0.07	−0.04	0.02	**−0.29**	**−0.20**	**0.61**	**0.63**		
ADSR	**0.85**	**0.79**	**0.85**	**0.75**	**0.84**	**−0.67**	**0.41**	**0.44**	**0.66**	**0.17**	
Prc*	**0.29**	**0.45**	**0.31**	**0.47**	**0.37**	**0.47**	**0.73**	**−0.29**	−0.07	**−0.19**	**0.10**

Correlations with absolute value greater than 0.*xx* are significant at the $\alpha = 0.05$ level and shown in bold print.

Surrogate variables for the three principal meteorological factors (MmaxT, MaxWS, Prc) are denoted with an asterisk.

Time series for the entire analysis period representing the monthly averages for T, W, and P among the six meteorological stations can be seen in Fig. 6. The 11-year T time series displays a strong annual cycle, with a range from 6.3°C to 35.6°C. The warmest years occurred in 1995, 1996, and 1999 and coldest in 1990, 1991, and 1992. Highest wind speeds (W) are typically recorded in spring, although the W time series exhibits large inter-annual variability. W ranges from 12.3 to 22.5 $\mathrm{m\,s^{-1}}$ with the windiest years in 1995, 1996, and 2000 and calmest in 1992, 1993, and 1994. The P time series also shows much inter-annual variability in addition to the seasonal maximum associated with the monsoon. Monthly values of P range from 0.0 to 106.7 mm with the greatest annual amounts in 1991, 1994, and 1997 and least in 1993, 1995, and 1999.

Average seasonal cycles of temperature at the six communities show constant order associated with elevation (Fig. 7). Higher elevation communities (juniper savanna and piñon-juniper woodland) are significantly cooler than the others. Among the four lower elevation communities, the Chihuahuan Desert and Colorado Plateau shrub-steppe are slightly warmer than the Great Plains/desert grassland and Colorado Plateau grassland. Highest values consistently occur in June and July and the lowest values in December and January. Inter-annual temperature variability is greatest in November, December, January, and February (Weiss, 2002). May and September also display notable variability.

The 11-year average annual W cycle (Fig. 8) shows more variability across the stations than does T. The highest yearly values occur in a range of spring months from March through May while the lowest yearly values occur in a range of summer and autumn months from August through October. Order is mostly constant as the piñon-juniper woodland community consistently records the lowest W values, followed by the remaining communities from April through

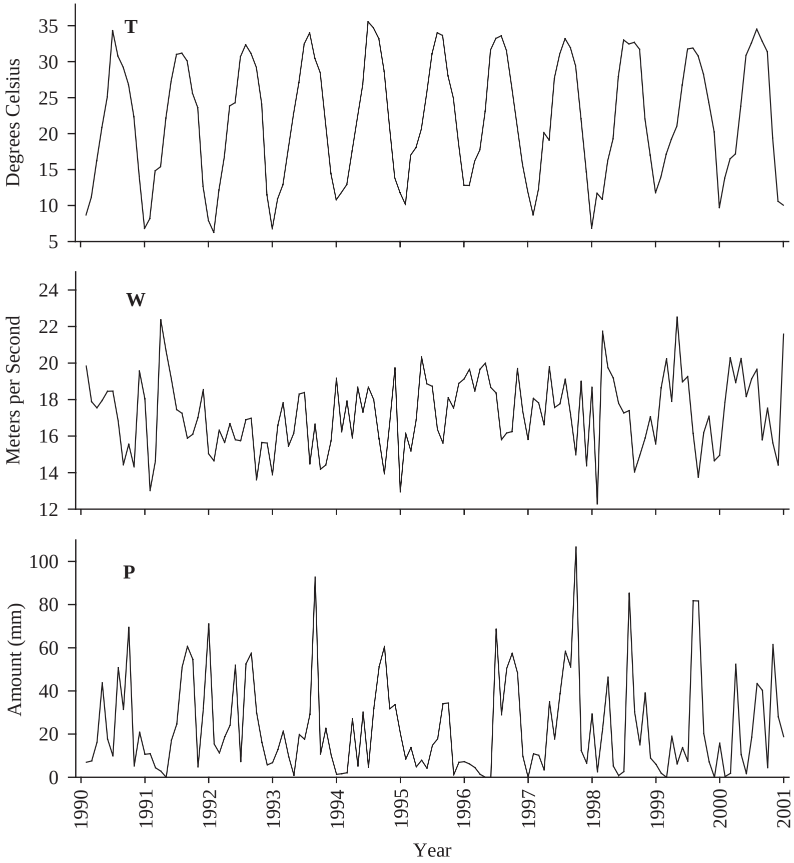

Fig. 6. Monthly six-station average T, W, and P for the analysis period (1990–2000).

October. From November through March, the juniper savanna community records notably higher W.

The 11-year average annual P cycle shows little variability across the communities, as the highest monthly amounts consistently occur in July, August, and September (these 3 months accounting for about half the annual total) with lower amounts in the other months (Fig. 9). With the exception of April, order is nearly constant as the piñon-juniper woodland records the highest P amounts, followed by the remaining vegetation communities. The juniper savanna and Chihuahuan Desert receive the next greatest amounts, followed by the Colorado Plateau shrub-steppe, Great Plains/desert grassland, and Colorado Plateau grassland. Average monthly precipitation amounts during the analysis period ranged from 5.1 to 68.3 mm considering all six vegetation communities (Moore, 2001).

As listed in Table 4, seasonal measures of T, W, and P for correlating with $NDVI_{SP}$ values are the concurrent spring (SP), the non-monsoon season from

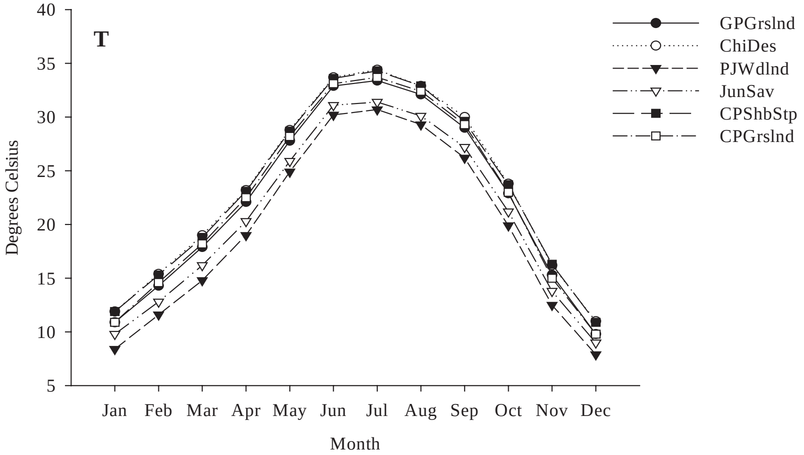

Fig. 7. Monthly average (1990–2000) T (°C) at the meteorological stations at each of the vegetation communities.

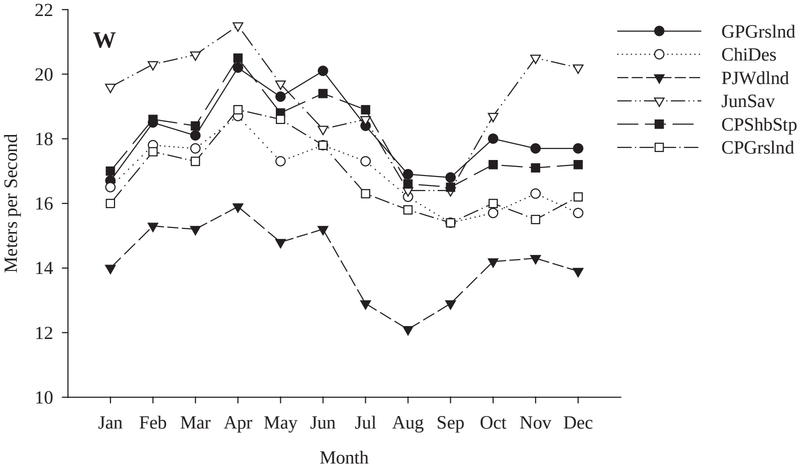

Fig. 8. Like Fig. 7, but for monthly average W (m/s).

October through May (OM), the previous summer (PSU), and the previous spring (PSP). For $\mathrm{NDVI}_{\mathrm{SU}}$ values, these measures are the concurrent summer (SU), the current water year from October through September (WY), the previous spring (PSP), the previous non-monsoon season (POM), and the previous summer (PSU). Lag times greater than 1 year are not considered due to limitations in data record length. Concurrent surrogate meteorological variables were shifted 28 days ahead of the computation periods for the respective NDVI values. For example, spring surrogate meteorological variables are computed from 28 days before the start of the $\mathrm{NDVI}_{\mathrm{SP}}$ period to 28 days before the end of the $\mathrm{NDVI}_{\mathrm{SP}}$ period.

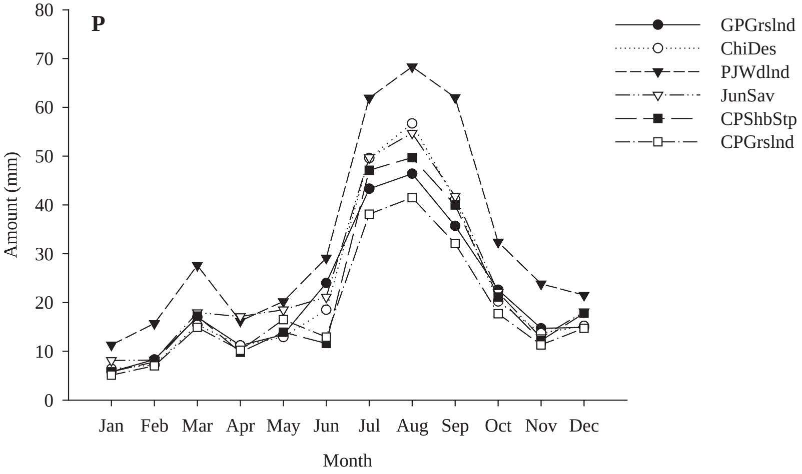

Fig. 9. Like Fig. 7, but for monthly average *P* (mm).

Table 4
Seasonal NDVI and surrogate meteorological variables used in linear correlation calculations

NDVI Season	Current and antecedent seasons	Surrogate meteorological variables identified from factor analysis	Current and antecedent season variables
$NDVI_{SP}$	Concurrent spring ($_{SP}$)	Mean maximum temperature (T)	T_{SP}, T_{OM}, T_{PSU}, T_{PSP}
	Non-monsoon ($_{OM}$)		
	Previous summer ($_{PSU}$)	Maximum wind speed (W)	W_{SP}, W_{OM}, W_{PSU}, W_{PSP}
	Previous spring ($_{PSP}$)	Precipitation (P)	P_{SP}, P_{OM}, P_{PSU}, P_{PSP}
$NDVI_{SU}$	Concurrent summer ($_{SU}$)	Mean maximum temperature (T)	T_{SU}, T_{WY}, T_{PSP}, T_{POM}, T_{PSU}
	Water year ($_{WY}$)		
	Previous spring ($_{PSP}$)	Maximum wind speed (W)	W_{SU}, W_{WY}, W_{PSP}, W_{POM}, W_{PSU}
	Previous non-monsoon ($_{POM}$)	Precipitation (P)	P_{SU}, P_{WY}, P_{PSP}, P_{POM}, P_{PSU}
	Previous summer ($_{PSU}$)		

3.2. Linear correlations

Each of the three surrogate meteorological variables was correlated with $NDVI_{SP}$ and $NDVI_{SU}$ values at the six vegetation communities. The results are summarized in the bar charts in Fig. 10 (for $NDVI_{SP}$) and Fig. 11 (for $NDVI_{SU}$). Statistically

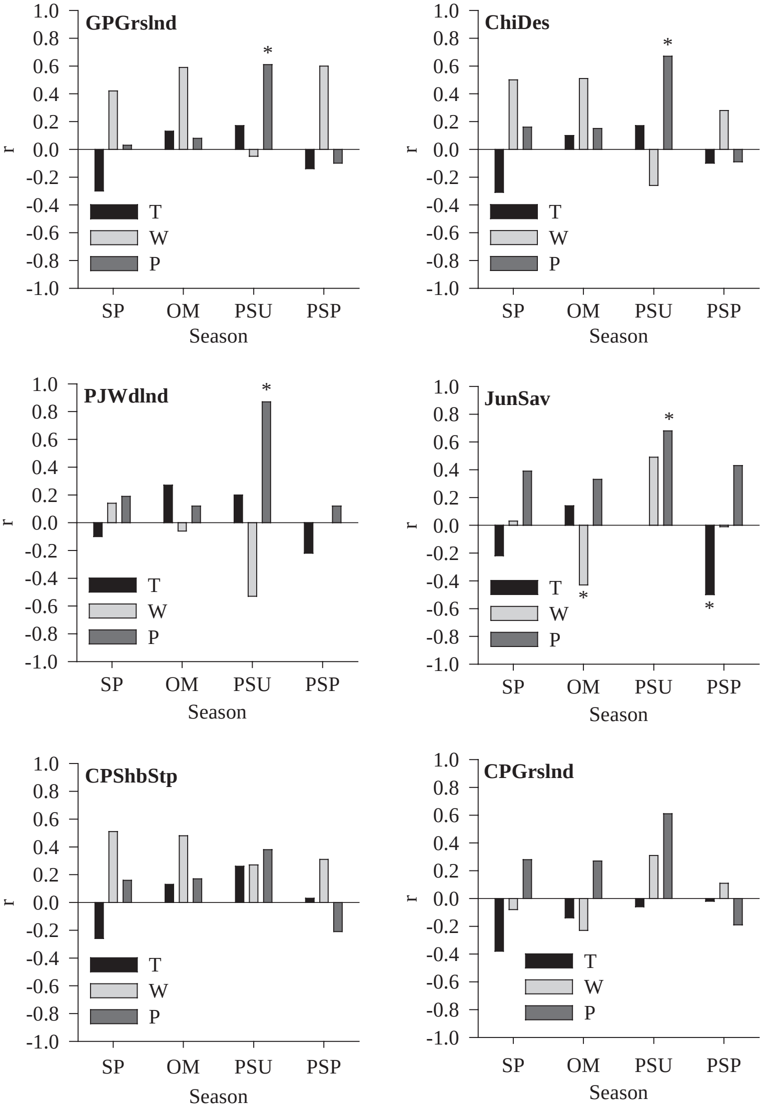

Fig. 10. Linear correlations between $\mathrm{NDVI_{SP}}$ and seasonal meteorological variables T, W, and P. Correlations with p-values <0.05 are marked with an asterisk. Each cluster of three bars depicts correlations for a different time lead relative to $\mathrm{NDVI_{SP}}$ values, as listed in Table 4: SP denotes meteorological variables during the same spring season (with a 28-day lead); OM is the previous October–May non-monsoon season; PSU is the previous summer; PSP is the previous spring, one full year prior to $\mathrm{NDVI_{SP}}$.

significant correlations (p-values<0.05) are denoted with an asterisk. The largest correlations are summarized briefly here, then interpreted in terms of vegetation characteristics in the following section.

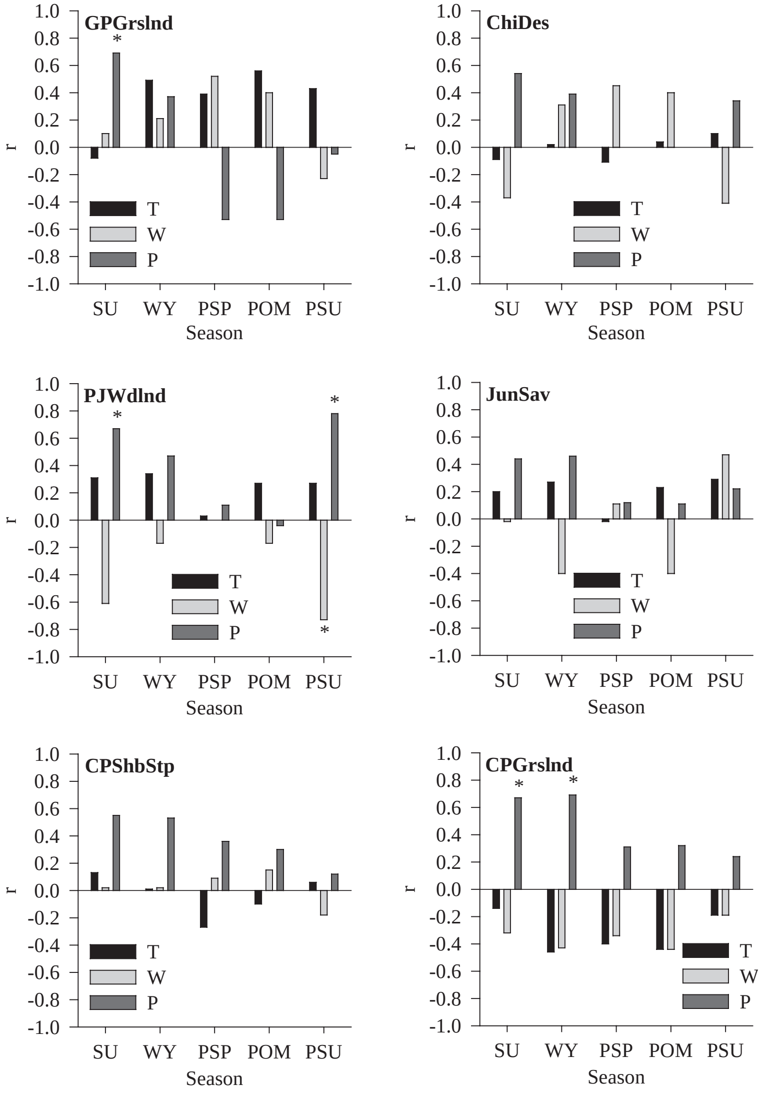

Fig. 11. Like Fig. 10, but for correlations between $\mathrm{NDVI}_{\mathrm{SU}}$ and seasonal meteorological variables at various lead times (see Table 4): SU is current summer; WY is antecedent water year; PSP is the antecedent spring (from the same year); POM is the previous non-monsoon season; PSU is the previous summer, one full year prior to $\mathrm{NDVI}_{\mathrm{SU}}$.

The principal concurrent meteorological correlations with $\mathrm{NDVI}_{\mathrm{SP}}$ are local wind speed, not local precipitation. The largest such correlations occur at the Great Plains/desert grassland, Chihuahuan Desert, and Colorado Plateau shrub-steppe. Positive precipitation correlations exceed wind speed correlations at the other analysis areas, but these correlations are smaller. Temperature correlations are less significant but negative for concurrent spring values at all analysis areas. Precipitation shows up significantly in Fig. 10 when $\mathrm{NDVI}_{\mathrm{SP}}$ is correlated with rainfall from the previous summer. Such lag correlations are present at every analysis area and are statistically significant at four of six analysis areas.

A very different set of correlation relationships is present for $\mathrm{NDVI}_{\mathrm{SU}}$ fluctuations. At all six analysis areas the concurrent precipitation is most highly correlated with $\mathrm{NDVI}_{\mathrm{SU}}$, as might have been anticipated from previous studies. Precipitation during the prior water year and the previous seasons is also important at most analysis areas. These correlations are all positive except for the Great Plains/desert grassland, where antecedent precipitation is negatively correlated with $\mathrm{NDVI}_{\mathrm{SU}}$. Other notable summer results include the negative correlation between $\mathrm{NDVI}_{\mathrm{SU}}$ and concurrent and previous summer wind speed at the piñon-juniper woodland, and the negative correlations between $\mathrm{NDVI}_{\mathrm{SU}}$ and both W and T for all lag times at the Colorado Plateau grassland analysis area.

4. Interpretation of linear correlations

Possible causal and meaningful relationships between T, W, P, and local vegetation (Table 1) are based on physiological processes as well as on observations from field studies reported in existing literature. In understanding physical meanings of these linear correlations, it is important to consider location (i.e. vegetation community), sign of the correlation, and season of the meteorological variable (Fritts, 1974). In addition, plant responses to sequences of meteorological conditions are species specific (Neilson, 1986). The following physical mechanisms for the linear correlations cannot be regarded as definitive, but may serve as useful discussion points for development of climate–vegetation models.

4.1. T seasonal values

A negative correlation between T_{PSP} and $\mathrm{NDVI}_{\mathrm{SP}}$ appears at the juniper savanna analysis area (Fig. 10) and may relate to the length of growing seasons and subsequent length of non-growing seasons. Warmer spring temperatures translate into a shortened spring growing season as evaporative demand rises and conditions become unfavorable for cool season vegetation. Warmer (cooler) temperatures during the previous spring inhibit (promote) growth of Indian ricegrass (*Oryzopsis hymenoides*), which attains greater size when soils are relatively cool during late spring (Pearson, 1979).

Positive correlations between T_{WY}, T_{POM}, and $\mathrm{NDVI}_{\mathrm{SU}}$ at the Great Plains/desert grassland analysis area (Fig. 11) may also relate to the lengths of growing and non-growing seasons. Warmer (colder) temperatures during the end of the designated summer season and during the beginning of the designated spring season are conducive (detrimental) to the growth of some local vegetation species such as soapweed yucca (*Yucca glauca*), an evergreen species observed to have a bimodal growth pattern with peaks in the spring and fall (Maragni et al., 2000), mesa dropseed (*Sporobolus flexuosus*), a grass species that also has growth peaks during the spring and fall while being limited by freezing night-time temperatures (Gibbens, 1991), and winterfat (*Krascheninnikovia lanata*), which increases growth during warmer spring temperatures while delaying growth under cooler spring temperatures (West and Gasto, 1978). Local perennial grasses such as black grama (*Bouteloua eriopoda*) and blue grama (*B. gracilis*) require "…relatively high night temperatures to produce new growth" (Peters and Eve, 1995).

4.2. *W seasonal values*

Several positive correlations between various seasonal W and both $\mathrm{NDVI}_{\mathrm{SP}}$ and $\mathrm{NDVI}_{\mathrm{SU}}$ values occur at the Great Plains/desert grassland, Chihuahuan Desert, juniper savanna, and Colorado Plateau shrub-steppe analysis areas (Figs. 10 and 11). These positive correlations are consistent with effects of wind on seed dispersion and atmospheric dust deposition. In arid environments, plant seeds that are dependent upon wind as a means of dispersion are common in both number and proportion (Howe and Smallwood, 1982). According to Jongejans and Schippers (1999), "wind can be regarded as the most important vector for seed dispersal in open grassland vegetation." Grassland vegetation constitutes significant portions of the Great Plains/desert grassland, Chihuahuan Desert, juniper savanna, and Colorado Plateau shrub-steppe analysis areas (Table 1).

Despite being poorly understood, nutrient input via the atmosphere is commonly accepted as a significant contributor to nutrient budgets of arid ecosystems (Littmann, 1997). An increase in nutrients can positively affect local growing conditions; after precipitation, nutrients are commonly considered to be the most important abiotic factor limiting plant growth in arid environments (Gutierrez and Whitford, 1987).

Negative correlations between W_{PSU} and $\mathrm{NDVI}_{\mathrm{SP}}$ (Fig. 10) and W_{PSU}, W_{SU}, and $\mathrm{NDVI}_{\mathrm{SU}}$ occur at the piñon-juniper woodland analysis area. A negative correlation also occurs at the juniper savanna analysis area between W_{OM} and $\mathrm{NDVI}_{\mathrm{SP}}$ (Fig. 10). These correlations may relate to evapo-transpiration and atmospheric dust deposition. Windier conditions generally cause increases in evapo-transpiration rates (Jones, 1992). This results in a decreased amount of available moisture at the surface as well as a decrease in photosynthesis due to less gas exchange between the vegetation and atmosphere from the closure of stomata.

Atmospheric transport of dust can also be a mechanism of degradation resulting in the death of plants by burial and abrasion, the interruption of nutrient accumulation processes, and the loss of soil resources (Okin et al., 2001). Dust deposition on resinous leaves of plants such as creosotebush (*Larrea tridentata*) can occur, decreasing water-use efficiency and tolerance of water stress and potentially reducing carbon gain (Sharifi et al., 1999). Creosotebush is present at the juniper savanna analysis area (Muldavin and Milne, 1987) and exhibits growth during spring and fall (Chew and Chew, 1965; Sharifi et al., 1988; Peters et al., 1997).

4.3. P seasonal values

Several positive correlations between various seasonal P and both $\mathrm{NDVI}_{\mathrm{SP}}$ and $\mathrm{NDVI}_{\mathrm{SU}}$ values occur among all vegetation communities (Figs. 10 and 11). These positive correlations may relate to higher precipitation amounts elevating soil moisture levels and lowering surface soil temperatures. $\mathrm{NDVI}_{\mathrm{SP}}$ of the Great Plains/desert grassland, Chihuahuan Desert, piñon-juniper woodland, juniper savanna, and Colorado Plateau grassland all displayed positive correlations with P_{PSU}. Due to the autoregressive nature of the NDVI, relatively high (low) NDVI values from the previous summer tend to precede relatively high (low) NDVI values of the current spring. That is, growth of plants during the previous summer translates to higher NDVI values during that season, an effect that is carried over into the following spring. This explanation most fits the relationship between NDVI and biophysical variables such as leaf area and canopy coverage.

Positive correlations occur between P_{SU} and $\mathrm{NDVI}_{\mathrm{SU}}$ at all communities and between P_{WY} and $\mathrm{NDVI}_{\mathrm{SU}}$ at the piñon-juniper woodland, juniper savanna, Colorado Plateau shrub-steppe, and Colorado Plateau grassland (Fig. 11). In connection with the Great Plains/desert grassland, black grama, blue grama, galleta (*Hilaria mutica*), and snakeweed (*Gutierrezia sarothrae*) have been observed to respond to summer precipitation (Everett et al., 1980; Ehleringer et al., 1991; Stephens and Whitford, 1993; Dodd et al., 1998). Precipitation during late summer promotes a second period of growth for winterfat (West and Gasto, 1978).

The amount and timing of high summer physiological activity of creosotebush in the Chihuahuan Desert is dependent on large rainfall amounts (Reynolds et al., 1999). Growth of black grama, galleta, snakeweed, and shadscale (*Atriplex confertifolia*) is a function of water availability (West and Gasto, 1978; Everett et al., 1980; Ehleringer et al., 1991; Stephens and Whitford, 1993; Peters et al., 1997). Herbaceous annuals of the Chihuahuan Desert are also responsive to precipitation, growing rapidly with available soil moisture (Gutierrez and Whitford, 1987; Guo and Brown, 1997).

For the piñon-juniper woodland, piñon pine exhibits high use of summer precipitation in geographical areas such as the Sevilleta where influence of the North American monsoon provides precipitation to lessen high soil temperatures, allowing root activity at the surface (Flanagan et al., 1992; Pendall, 2000; Williams and Ehleringer, 2000). Galleta and snakeweed are also responsive to summer precipitation (Everett et al., 1980; Ehleringer et al., 1991).

At the juniper savanna, one-seeded juniper has demonstrated the ability to utilize summer soil moisture near the surface (Breshears et al., 1997). Studies examining amounts of monsoon precipitation that lessen high soil temperatures and thus allow piñon pine root activity at the surface reported similar results for Utah juniper (*J. osteosperma*) (Flanagan et al., 1992; Williams and Ehleringer, 2000). Utah juniper is more common than one-seeded juniper in the Great Basin piñon-juniper woodland areas of northwestern New Mexico, western Colorado, Utah, northern Arizona, Nevada, and eastern California (Brown, 1994). One-seeded juniper is more prevalent in central and southern New Mexico, sub-Mogollon Arizona, and western Texas. The two are genetically similar, as evidence of possible hybridization between the two has been observed in northwestern New Mexico (Adams, 1994). It is therefore arguable that the Utah and one-seeded junipers display some functionally analogous behavior and that the aforementioned conclusions of studies of Utah juniper may also hold for one-seeded juniper. Activity of black grama, galleta, snakeweed, and shadscale is a function of water availability (West and Gasto, 1978; Everett et al., 1980; Ehleringer et al., 1991; Stephens and Whitford, 1993; Peters et al., 1997). The amount and timing of high summer physiological activity of creosotebush is dependent on large rainfall amounts (Reynolds et al., 1999).

Regarding the Colorado Plateau shrub-steppe, higher amounts of summer precipitation allow increased growth of black grama and galleta (Everett et al., 1980; Stephens and Whitford, 1993; Peters et al., 1997). Fourwing saltbush (*A. canescens*) and shadscale respond to precipitation during cooler months of the summer (West and Gasto, 1978; Lin et al., 1996). For the Colorado Plateau grassland, summer precipitation encourages activity of galleta, snakeweed, black grama, creosotebush, fourwing saltbush, and shadscale (West and Gasto, 1978; Everett et al., 1980; Ehleringer et al., 1991; Stephens and Whitford, 1993; Peters et al., 1997; Dodd et al., 1998).

The rooting activity of piñon pine may contribute to the positive correlation between P_{PSU} and $\mathrm{NDVI}_{\mathrm{SU}}$ at the piñon-juniper woodland. With previous summer precipitation adequate for reducing high soil temperatures and thus allowing root activity at the surface, surface roots remain present and capable for water uptake during the following summer once moisture becomes available. Piñon pine has the capacity to respond to small precipitation events that result in moisture penetrating only to the upper soil layers (Williams and Ehleringer, 2000).

Negative correlations between P_{POM} and $\mathrm{NDVI}_{\mathrm{SU}}$ and between P_{PSP} and $\mathrm{NDVI}_{\mathrm{SU}}$ occur at the Great Plains/desert grassland analysis area (Fig. 11) and may relate to negative interactions between cool and warm season species. In an 18-year data record, Guo and Brown (1997) did not observe desert annuals to be abundant in successive growing seasons. Possible mechanistic reasons for these interactions include the presence of biseasonal species, the increase of granivore, herbivore, parasite, or pathogen populations, the emission of CO_2 by decomposing biomass, which may inhibit germination, and the depletion and immobilization of resources such as nitrogen.

5. Discussion

The expectation of positive correlation between P and NDVI seasonal values is clearly confirmed for summer greenness, but concurrent precipitation anomalies seem less important for greenness fluctuations in spring. Antecedent precipitation is negatively correlated with $\mathrm{NDVI}_{\mathrm{SU}}$ at the Great Plains/desert grassland analysis area. In addition, T and W seasonal values are correlated with NDVI seasonal values in some cases. The existence of significant correlation at multiple time lags between NDVI and each of the three surrogate meteorological variables demonstrates the complexity of climate–vegetation interactions.

Malo and Nicholson (1990) observed differential responses to moisture by six different vegetation types in a study of NDVI in the Sahel, Africa. Correlations between T, W, and P and NDVI seasonal values differ among the six vegetation communities analyzed in this study, indicating that these communities respond differently to multiple factors of local climate variability. For instance, the piñon-juniper woodland, the vegetation community in this study with the highest number of trees, was the only community displaying strong correlation to summer precipitation in the contemporaneous summer, following spring, and following summer. As previously mentioned, rooting activity near the soil surface, soil volume access, and root storage of water by piñon pine and juniper help explain this relationship. Differential responses between meteorological variables and vegetation are important, as they may have implications for ecosystem water balance, energy balance, vegetation response to climate anomalies and climate change, and local species coexistence (Kepner et al., 2000; Williams and Ehleringer, 2000). In the case of the piñon-juniper woodland, significant changes in summer precipitation variability may substantially affect the current ecological functioning of this community.

The absence of strong correlation between NDVI and cool season precipitation (i.e. spring, October–May, and the water year; all influenced by ENSO) may be surprising, as rain and snow melt infiltrate soils during this period of low temperatures and thus low evaporative demand and recharge soil moisture (Swetnam and Betancourt, 1998; Sheppard et al., 2002). This result suggests that precipitation during the cool season influences vegetative growth over longer time-scales or temporal windows not resolved in this study. It may also reflect that vegetation response to cool season rain and snow is affected by growth carried over from the previous summer, a consequence of the bimodal pattern of annual rainfall and subsequently the growing season across this region. Bimodal growing seasons alter nutrient dynamics of annual plant communities in southwestern North America, creating interactions across seasons (Gutierrez and Whitford, 1987; Guo and Brown, 1997). Such cross-seasonal interactions are less known with respect to perennial vegetation and study of these conditional dynamics is warranted.

Stronger relationships between NDVI and multiple meteorological factors might result through use of climatic indices that are designed to synthesize relative dryness or wetness conditions, such as the Crop Moisture Index or Palmer Drought Index (PDI), both obtainable from the NOAA Climate Prediction Center. The PDI shows high correlation with the Standardized Precipitation Index (SPI; obtainable from the Western Regional Climate Center), an index based solely on precipitation, at the 8 to 12 month time-scale (McKee et al., 1993). Furthermore, interpretation of the PDI is spatially inconsistent (i.e. not the same for all areas) and difficult in regions of variable topography such as southwestern North America (Alley, 1984; Guttman, 1991, 1998). Future work examining relationships between vegetation and indexes estimating relative wetness and dryness should consider such characteristics and incorporate several indexes into investigations.

The correlation of concurrent and seasonally lagged surrogate meteorological variables with seasonal NDVI values is consistent with Fritts' (1974) observation that climatic conditions prior to a given growing season generally display equal or higher amounts of correlation with tree ring growth than climatic conditions during that growing season. Meteorological variables defined over the concurrent spring correlated with $\mathrm{NDVI}_{\mathrm{SP}}$ at the Great Plains/desert grassland, Chihuahuan Desert, and Colorado Plateau shrub-steppe. Meteorological variables defined over the concurrent summer correlated with $\mathrm{NDVI}_{\mathrm{SU}}$ at all six analysis areas. $\mathrm{NDVI}_{\mathrm{SP}}$ and $\mathrm{NDVI}_{\mathrm{SU}}$ values of all analysis areas exhibited correlation with seasonal values of meteorological variables that expressed a seasonal time lag. This suggests that $\mathrm{NDVI}_{\mathrm{SP}}$ and $\mathrm{NDVI}_{\mathrm{SU}}$ variability responds to meteorological factors from timescales of months (e.g. current summer) to a year (e.g. previous summer). Vegetation is thus acting as a source of both short- and long-term memory in the climate system, a result that may have significant implications for climate anomalies determining the configuration and role of vegetation feedbacks to the atmosphere among different biomes. These relationships are difficult to verify using existing biosphere models because many mechanisms, especially non-local effects such as nutrient deposition, are not represented.

Fritts (1974) also observed that correlations between climatic conditions and tree ring growth changed in significance at different times of the year, demonstrating complex relationships between tree ring width and climate variables. The results of this study show changes in correlation significance between seasonal values of meteorological variables and NDVI. For instance, the Great Plains/desert grassland did not show correlations with seasonal T values during the spring. During the summer, however, correlations appeared between T_{OM} and $\mathrm{NDVI}_{\mathrm{SU}}$ and between T_{WY} and $\mathrm{NDVI}_{\mathrm{SU}}$. Similarly, T_{PSP} and $\mathrm{NDVI}_{\mathrm{SP}}$ at the juniper savanna analysis area displayed correlation; no correlations occurred at this area between $\mathrm{NDVI}_{\mathrm{SU}}$ and seasonal T values.

The importance of the North American monsoon for vegetation at the Sevilleta is clear. $\mathrm{NDVI}_{\mathrm{SU}}$ and P_{SU} show correlation at all analysis areas, demonstrating that summer growth is strongly controlled by precipitation. Memory of the previous monsoon season appears at the Great Plains/desert grassland, Chihuahuan Desert, piñon-juniper woodland, juniper savanna, and Colorado Plateau grassland, as $\mathrm{NDVI}_{\mathrm{SP}}$ and P_{PSU} are correlated. No significant correlation between $\mathrm{NDVI}_{\mathrm{SP}}$ and P_{PSU}, however, occurred for the Colorado Plateau shrub-steppe. Several vegetation species at this analysis area are noted for their affinities to the Great Basin (Muldavin and Milne, 1987), where precipitation follows a very different seasonal cycle with most falling in the winter and early spring (Williams and Ehleringer, 2000). Longest memory of the previous monsoon season is displayed at the piñon-juniper woodland, where correlation is exhibited between $\mathrm{NDVI}_{\mathrm{SU}}$ and P_{PSU}. Root systems of evergreen trees of this community have access to a larger volume of soil and thus soil moisture as well as greater water holding capacity than the grass and shrub species that are prevalent at the other communities, allowing tree growth to be less dependent on the frequency of precipitation events (Li et al., 2002).

General climate conditions are assumed to be static in this analysis, but studies similar to this one using longer time series should consider trends (non-stationarity) of both climate and vegetation. Substantial vegetation dieoffs across the Sevilleta occurred during the 1950s drought (Betancourt et al., 1993, pp. 42–62). Creosotebush and juniper establishment in grasslands has been documented for large areas of the southwest (Betancourt et al., 1993, pp. 42–62; Reynolds et al., 1999). Field studies to investigate the spatial and temporal dynamics of grassland and shrubland transition zones are underway at this time at the Sevilleta near the Great Plains/desert grassland analysis area (Milne and Gosz, 1989).

Climate change also occurs on long time-scales across southwest North America. Inter-annual El Niño-Southern Oscillation cycles in the Pacific Ocean are known to be modulated on decadal-century time-scales (Betancourt et al., 1993, pp. 42–62), as is the response of southwestern North America climate to El Niño (Gutzler et al., 2002). More severe drought periods than any resolved in this study have occurred in the recent past (e.g. 1898–1904, 1952–1956). Pluvial periods likewise have taken place, with the most recent during the 1980s and 1990s, including the initial years of the present record.

The local correlations derived in this study can be used to suggest hypotheses for climate–vegetation interactions across much larger scales. For example, precipitation from the previous summer might be expected to correlate with spring NDVI values of Great Plains/desert grassland, Chihuahuan Desert, piñon-juniper woodland, juniper savanna, and Colorado Plateau grassland vegetation communities in other areas of southwestern North America. Attempts to scale the results of individual vegetation communities up to regional scales, however, will require caution. Scaling up results pertaining to precipitation, for instance, may present difficulty due to different seasonal precipitation cycles found in the southwest and effects of these cycles on vegetation. Williams and Ehleringer (2000), for example, observed that summer precipitation use by dominant tree species of piñon-juniper woodlands varied systematically at six sites from southeastern Arizona to northern Utah. Summer rainfall use was greater at the southern sites, where summer precipitation amounts are higher on average. Use of summer rainfall declined abruptly at the northern sites, a peripheral region of the North American monsoon (Adams and Comrie, 1997; Higgins et al., 1997; Comrie and Glenn, 1998; Williams and Ehleringer, 2000). The first step in applying the local results of this study to larger areas is to determine spatial patterns of vegetation seasonality and variability in southwestern North America.

6. Summary

Using NDVI and meteorological data from 1990 through 2000, seasonal and inter-annual relationships are calculated for six distinct vegetation communities in semi-arid central New Mexico with air temperature, movement, and moisture factors. These correlations demonstrate both contemporaneous and time-lagged relationships between vegetation communities and local climate. Monsoon season precipitation appears as a central climatic influence on vegetation variability for the contemporaneous summer, the following spring, and the following summer. Possible causal and meaningful explanations of these relationships can be put forth with physiological processes and observations of vegetation from field studies reported in existing literature.

The results confirm the utility of NDVI as an index of integrated vegetation variability on small (5-km), short (seasonal) scales in a region of very sharp gradients of topography and precipitation, despite the known heterogeneity of lifeforms and surface coverage within each analysis area. Thus remotely sensed surface data with the resolution of NDVI seem promising for additional future studies of land surface-atmosphere interactions.

Results of this study also enhance knowledge of complex relationships between climate and vegetation. Variability of the meteorological regime needs to be fully understood in order to examine all of the various climatic factors that may influence vegetation. Presence and absence of time-lagged correlations indicate vegetation acting as both short- and long-term memory sources in the climate system. Differential responses between vegetation communities and meteorological variables, as evidenced in this study, may have implications for climate and vegetation of southwestern North America in regards to water balance, vegetation response to climate anomalies and climate change, local species coexistence, and vegetation feedbacks to the atmosphere.

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