Spatial relationships among lightning, precipitation and vegetative cover in watersheds of the Rio Puerco Basin: An introduction

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Abstract.-This paper explores the question "is there a relationship between seasonal precipitation amounts and vegetative cover at a specific site near Grants, New Mexico?" Several hypotheses will be investigated. One is that the organizing factor for vegetation response to precipitation is the amount of summer precipitation from convective thunderstorms. The variable winter precipitation (high in El Niño years and low in La Niña years) does not provide a dependable amount of moisture, and plant cover or basal areas are not well correlated with it. Alternatively, winter or annual precipitation amount may be the organizing factor for vegetation response. Otherwise, factors such as land use activities, soil type, geological features, temperature, etc., could be the primary organizers of vegetation pattern within the study site. A Geographic Information System (GIS ARC/INFO) vector data structure will be used to organize, analyze and display the data. Final products will include GIS thematic maps of the study area that display precipitation and vegetation data. The results of statistical and spatial operations such as linear regressions, interpolations and kriging will be presented and discussed in a subsequent publication.

INTRODUCTION

It is often assumed that the earth's atmosphere and climate regimes are major controlling factors in the distribution and amount of vegetation in the biosphere (Neilson 1986). Thus, plant distribution patterns can be correlated with the spatial and temporal patterns of available water (Barbour et al. 1980). The response to specific meteorological events (e.g., individual storms, successive days of extreme heat or drought), however, is species specific due to differences in physiology and life history (Neilson 1986). For example, the shallow roots of blue grama are responsive to light rainfall events in semi-arid regions (Sala and Lauenroth 1982).

Water availability is important to ecosystem function, and can be a limiting factor for vegetation in the semi-arid southwest. It affects rates of photosynthesis, regeneration and mortality (Yeakley et al. 1994) as well as resistance to herbivory (Cates et al. 1983, Louda 1992). Variations in precipitation affect plant communities because primary production, precipitation quantity and soil texture are inter-related. For example high precipitation (> 370 mm) on clayey soils is associated with high primary production rates while low precipitation amounts favor good production rates on coarse and rocky soils due to greater infiltration (Risser 1991). Such differences in moisture and temperature regimes are evident in the major vegetation types of NM.

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Cloud-to-ground lightning strikes have been correlated with measured precipitation (Battan 1965, Vorpahl et al. 1970, Pipegrass et al. 1982, Gosz et al. 1993, 1995). In NM, most lightning occurs during the summer monsoon season (Gosz et al. 1993, 1995). This regional-scale convective pattern usually begins in early July and continues until the end of September (Stensrud et al. 1995). Precipitation that occurs during the winter in NM is due to frontal storms and is generally not accompanied by lightning strikes.

This paper introduces a project that explores the question "is there a relationship between seasonal precipitation amounts and vegetative cover in watersheds of the Rio Puerco Basin?" A schematic of potential organizing factors for vegetation patterns at a specific site is presented in Table 1. These include seasonal precipitation amounts, long-term annual precipitation amounts, and factors other than precipitation.

Seasonal moisture can affect plant community composition. In a study of two fir species, Pavlik and Barbour (1991) determined that red fir was a superior competitor to white fir following high winter precipitation. Also, low summer precipitation favored white fir while high summer precipitation favored red fir. Neilson (1986) distinguished between establishment of warm season (often C_4) species promoted by dry winters and establishment of cool season species (often C_3) that is promoted by wet winters. Also, C_4 grasses that are already established depend on summer moisture. *Thus, seasonal precipitation* amount may be the organizing factor.

Vegetation response to precipitation may be organized by the amount of *summer precipitation* from convective thunderstorms. If variable winter precipitation (high in El Niño years and low in La Niña years) does not provide a dependable amount of moisture, plant cover or basal areas may not be well correlated with it. A prediction that follows is that areas receiving equivalent amounts of precipitation inferred from lightning strike data during the monsoon season of late June through September have a similar vegetation response (measured as basal area or percent cover within the study site). This response may vary by plant species. For example, warm season grasses and forbs may be more responsive to summer moisture than deep-rooted trees which are dependent on winter precipitation for survival.

Alternatively, *winter precipitation* amount may be organizing vegetation response. A prediction that follows is that there will not be a significant relationship between summer precipitation inferred from lightning strike data and vegetative cover. The correlation between precipitation and vegetation might be detectable using winter precipitation amounts, but that relationship would not hold when based solely on the lightning data. Then portions of the study site that consist of vegetation species that are most dependent on winter moisture could be excluded from the lightning-inferred precipitation analyses. For example, data from the Niwot Ridge Long-Term Ecological Research (LTER) site show that alpine vegetation patterns are largely controlled by snow distribution. The study indicated that some species such as *Poa*

Table 1. Potential organizing-factors for vegetation at a specific site.

Precipitation	Not precipitation
Seasonal	land use [Naveh and Lieberman 1984]
[Pavlik and Barbour 1991, Neilson 1986]	geological features
Summer	soil type [Risser 1991]
grasses, forbs [Neilson 1986]	solar activity [Scuderi 1993]
Winter	temperature [Briffa et al. 1990]
trees [Walker et al. 1993]	fire history [Swetnam and Baisan 1995]
Long-term Annual	biotic interactions—
(including oscillations and anomalies)	competition, herbivory, etc. [Silvertown et al. 1994]
[Yeakley et al. 1994]	

artica, a bluegrass, are restricted to areas of deep snow. Patterns controlled by snow distribution included plant species, community composition, and green-biomass indicated by normalized difference vegetation index (NDVI) data (Walker et al. 1993).

Another alternative is that *long-term annual precipitation* determines vegetation pattern on the landscape. In this case, precipitation amounts and vegetation patterns should be similar by ecosystem type (e.g., grassland, pinion-juniper woodland, mixed conifer and fir forests). Different ecosystem types may have annual precipitation amounts that are statistically different, but such a relationship would not be assessed using the lightning data because of its temporally-restricted nature. Yeakley et al. (1994) simulated the response of three forests and one grassland ecosystem to oscillations in long-term annual precipitation regimes. There was a substantial above-ground biomass response by forests while shortgrass prairie exhibited a broad tolerance to annual precipitation oscillations. Biomass of the boreal forest was less responsive than either deciduous hardwood forest or a transitional zone of mixed boreal/hardwood forest.

Finally, *factors other than precipitation* (i.e., land use activities, geological features, soil type, solar activity, temperature, fire history, biotic interactions, etc.) may be the primary organizers of vegetation pattern within the study site. For example, Silvertown et al. (1994) noted that while grassland communities were affected by annual changes in weather, indirect effects of competition were more important. Effects of temperature (Briffa et al. 1990) and solar activity (Scuderi 1993) on tree growth have been analyzed using tree-ring records. If such factors are more important, then precipitation amounts inferred from lightning data will not be closely related to vegetative cover.

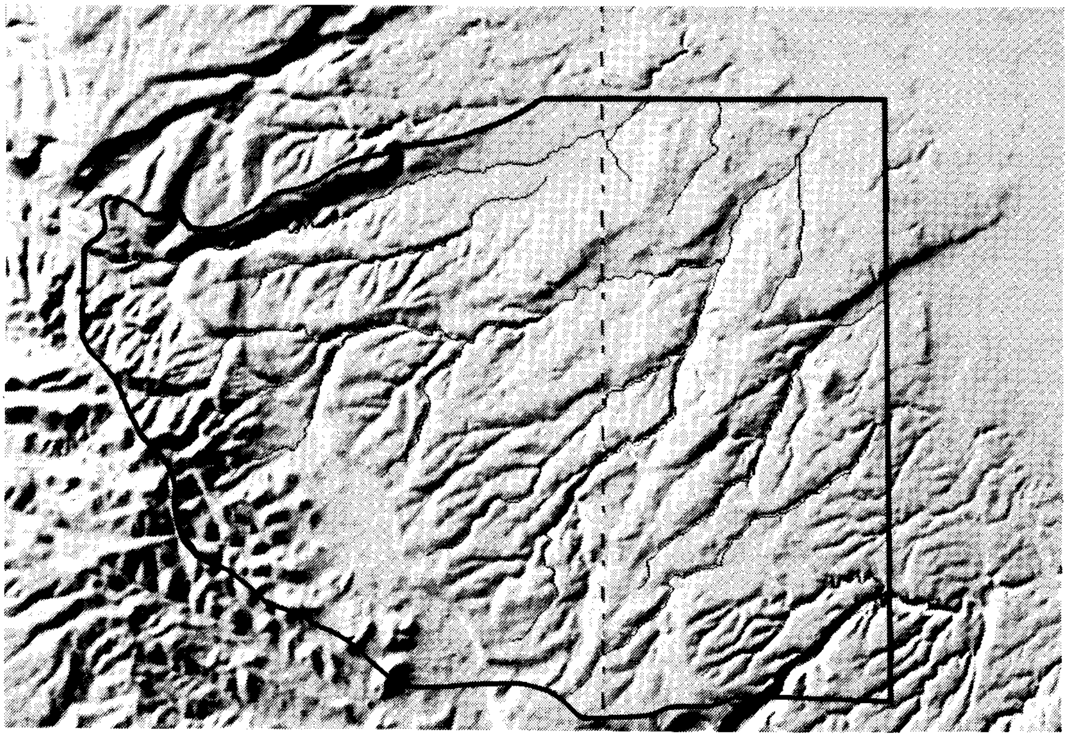
Study site description

The study site is Pole Canyon within the Rio Puerco Basin, in the west Rio San Jose watershed near Grants, NM (fig. 1). It is within the Mt. Taylor Ranger District, Cibola National Forest. The site was selected for pragmatic reasons, i.e., extensive resource inventory data are available. It is based on a 140 km^2 area that was established by the Forest Service as a prototype for ecosystem management. Their analysis area was defined by administrative boundaries rather than watershed area. If drawn along watershed boundaries, it includes the combined area of Pole Canyon, Limekiln Canyon and Prop Canyon, but excludes the Zuni Canyon iragment.

Pole Canyon is located on the east side of the Continental Divide (Oso Ridge) in the Zuni Mountains. Elevations range from 1,999 m (6,560 ft) to 2,821 m (9,256 ft) at Mt. Sedgwick. The land ownership is primarily National Forest (134 km*), but the analysis area contains blocks of state land and small parcels of private land. It is traversed by many roads, including state roads 180, 425, 448 and 49, but some forest roads are scheduled for obliteration. Land use activities within the study site include timber harvest, mining, recreation, hunting, and livestock grazing. It is an important area for wildlife habitat, including Mexican spotted owls. The grassland areas have a dense road system, including unregulated 'two-track' roads. The District expresses concern for erosion rates throughout the analysis area. Mineral rights are held throughout extensive areas within the study site, excluding the far north and western portions.

The study site lies within the Navajo Section of the Colorado Plateau Geomorphic Province (USDA Forest Service 1994a). The main geological feature is San Andres Limestone, while the western edge of the site is Pi-e-Cambrian rock (granite). Dispersed, larger patches of alluvium and sandstone occur, and there are narrow areas of basalt flow to the southwest corner. Small patches of Lower Chinle Formation occur throughout the area.

A Terrestrial Ecosystem Survey (TES) was completed for this area in 1993, but final results are not published. These data include taxonomic name, mean canopy coverage, canopy height, and percent basal area of current vegetation (USDA Forest Service 1986). Vegetation types range from grassland and shrubs at lower elevation to piñon-juniper woodlands at intermediate elevations, through mixed conifer areas at high elevation. Preliminary results are summarized in an unpublished manuscript (USDA Forest Service 1994a). Some representative soil and potential natural vegetation types for some of the 28 soil map units within the study area are shown in Table 2.



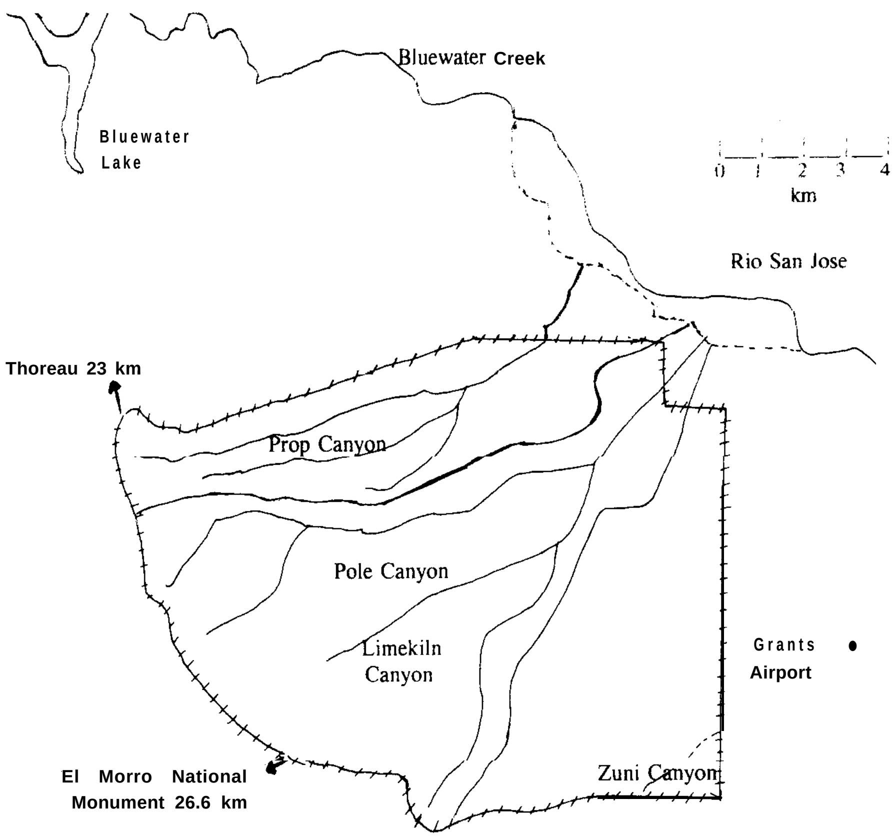


Figure 1. Pole Canyon ecosystem management analysis area (140 km^2, hatched boundary) located about 3 km west of Grants Municipal Airport, NM. (GIS map prepared by USDA Forest Service, Southwestern Region, Geometronics Group.)

Table 2. Pole Canyon Terrestrial Ecosystem Survey site description of soil and vegetation type by map unit. BA and CC are existing basal area and canopy cover totals for graminoid, forb, tree and shrub classes. Vegetation codes: *Bogr2*, blue grama; *Chna2*, rabbitbrush; Jude, alligator juniper; *Jumo*, one-seed juniper; *Pipos*, ponderosa pine; Pied, piñon pine; Psmeg, Douglas fir; and *Quga*, Gambel oak. Note that map unit numbers were subsequently changed from 30 to 31 and from 510 to 508.

Mao unit no.	Tvoe	%BA	%CC
30	Pachic Haplustolls, coarse-loamy, mixed		
	Bogr2 (graminoid); *Chna2* (shrub)	18	46
153	Typic Eutroboralfs, fine, mixed		
	Pipos, Pied, Jude, Jumo (trees): *Quga* (shrub)	18	87
166	Typic Ustochrepts, loamy-skeletal, mixed		
	Pied, Jumo (trees)	11	41
250	Typic Caiciustolls, loamy-skeletal, mixed, mesic [Pedon #8]		
	Pied, Jumo (trees)	9	41.2
256	Typic Ustochrepts, loamy-skeletal mixed, calcareous		
	Jumo (trees)	20	49
256	Typic Haplustalfs, fine-loamy, mixed, mesic, calcareous [Pedon #2]		
	Jumo (trees)	17	29
256	Typic Ustrochrepts, loamy-skeletal, mixed, calcareous [Pedon #3]		
	Jumo (trees)	18	31.5
256	Lithic Ustrochrepts, loamy, mixed, calcareous		
	Jumo (trees)	20	45.5
302	Typic Dystrochrepts, loamy-skeletal, mixed		
	Psmeg, Pipos (trees)	12.1	67.6
303	Typic Dystrochrepts, loamy-skeletal, mixed		
	Psmeg, Pipos (trees)	15	73.7
504	Typic Argiborolls, clayey-skeletal, montmorillonitic		
	Pipos, Pied, Jumo (trees)	12	42
504	Typic Eutroboralfs, fine, montmorillonitic		
	Pipos, Pied, Jumo (trees)	20	49.4
510	Typic Argiborolls, clayey-skeletal, montmorillonitic		
	Pipos (trees)	14.2	57
605	Andic Eutrochrepts, loamy-skeletal, mixed		
	Psmeg, Pipos (trees): *Quga* (shrub)	14	58

Grassland areas are primarily located in the northeastern section, and include blue grama, NM needle and thread grass, and western wheatgrass (USDA Forest Service 1994a). A shrubland area of Apache plume occurs in the lower reaches of Pole Canyon. Treeland areas include woodland, conifers, and extremely localized deciduous forest. Conifers are primarily ponderosa pine, some Douglas fir and southwestern white pine. Other dominant species include Gambel oak, mountain mahogany and cliffrose. An aspen stand is found on the northeast aspect of Mt. Sedgwick.

Narrowleaf cottonwoods are primarily within the Pole Canyon drainage (Paul Tidwell, unpublished report). Fire suppression may have affected the vegetation within the area, and conifers are characterized as "unnaturally dense" by the Mt. Taylor District. For example, canopy cover is 100% near Mt. Sedgwick (USDA Forest Service 1994a). A fire history of the area is available from 1975 to present, and it indicates that small lightning fires occur in most years. Fires that originated from human activities were also recorded (Paul Tidwell, unpublished report).

LIGHTNING, PRECIPITATION AND VEGETATIVE COVER

Each of the variables (lightning, precipitation and vegetation) are discussed separately below, followed by a description of the inter-relationships among variables.

Lightning detection

Lightning detection networks locate lightning strokes that are in progress by sensing electromagnetic fields (NOAA 1982, Moran and Morgan 1995). The detection equipment for this study is the Model 141 Advanced Lightning Direction Finder, a product of Lightning Location and Protection, Inc. (LLP) in Tucson (fig. 2). Since 1976 the BLM has operated the lightning detection network for the western United States (Krider et al. 1980). The national network was initiated in 1984 at the State University of New York at Albany, and is currently operated by GeoMet Data Services, Inc., a "sister company" to LLP (GeoMet Data Services, Inc. 1994).

The equipment detects more than 90% of all cloud-to-ground lightning within 370 km, tapering to 70% at the maximum range of 1,110 km (LLP 1987). The accuracy of the detection equipment is

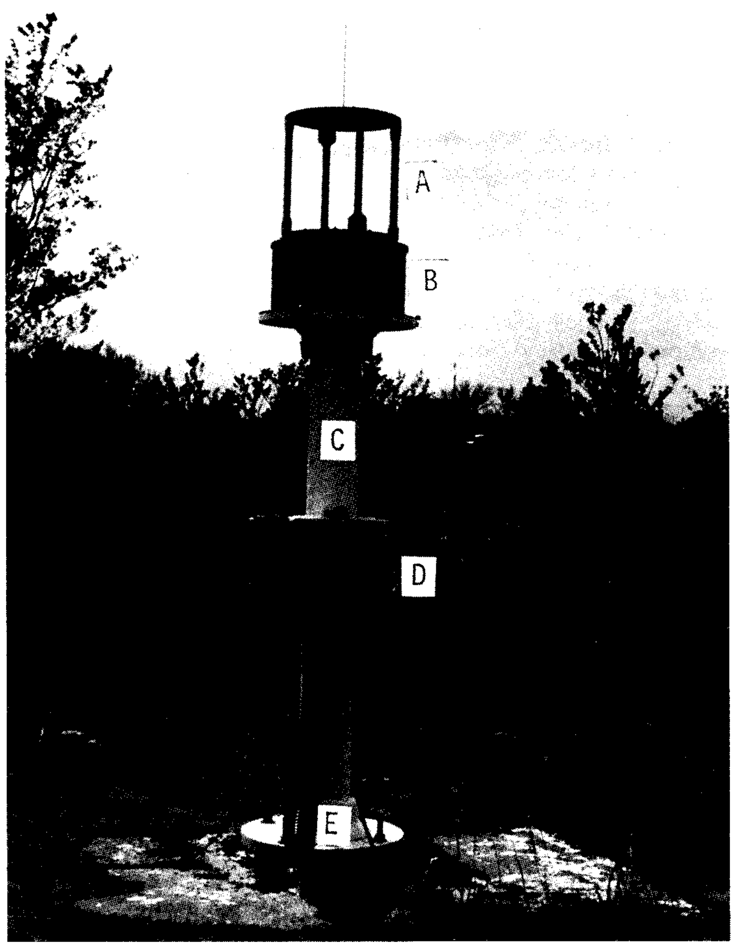


Figure 2. Lightning Location and Protection, Inc. Model 141 Advanced Lightning Direction Finder located at Socorro, NM. Components include antenna assembly (a); electronic module with three circuit boards (b); mast (c); AC power supply (d); and communication and power cables (e). It is part of the national network of wideband magnetic direction finders, an accurate system for lightning detection.

about 2 km (Maier et al. 1984). Accuracy is greatest near the center of the network and less near the periphery. Performance factors include antenna alignment, small random errors due to background noise, site errors due to complex terrain or conducting objects (e.g., power lines) nearby, distance to the detector, and maintenance. The closest instruments to the Pole Canyon site are in Albuquerque and Socorro, NM, and are serviced by the National Interagency Fire Center, USDI Bureau of Land Management, Boise, ID, at least twice per year. These stations are part of a network of gated wideband magnetic direction finders located throughout North America. Five other sites are in NM (Krider 1992).

The detection system consists of the Advanced Lightning Direction Finder, a position analyzer and a system data terminal (Lightning Location and Protection, Inc. 1986). The direction finder determines direction to the lightning strike point using two loop antennas and an electric-field antenna containing top and bottom circuit boards. Thus, it detects an impulse (radio frequency) of the return stroke. The direction finder also contains an electronics module that includes a Central Processor Unit Board, a Pulse Discrimination Logic Board and an Analog Front End Circuit Board. It collects data for strike time, angle, signal strength and number of strokes. The direction finder then transmits the data through the communication cable in binary or ASCII form (by serial link) to a position analyzer. The position analyzer contains a microcomputer system to compute, map and record the location and time of the strike. It combines data from at least two detectors to calculate the location of the lightning flash. Data from the position analyzer is transmitted to a system terminal (remote display processor) that produces color geographic maps.

Data collected from the network operated by the National Interagency Fire Center is transferred by satellite to the Irving Langmuir Laboratory for Atmospheric Research at NM Institute of Mining and Technology in Socorro. From there, data are sent by the INTERNET system to UNM. The raw data are edited using the LLPEDT program and archived in the Sevilleta Long-Term Ecological Research (LTER) data base at UNM. Data were pre-processed prior to being archived. Data processing includes conversions (Greenwich Mean Time to local time; additional fields for Julian day and year), removal of unnecessary diagnostic information, removal of station name for strike detection, and screening for invalid entries. Archived data include eight factors: year of observation, Julian day, time of strike (Mountain Standard Time), latitude, longitude, strength of each strike, number of return strokes per strike, and a reliability code (Gosz et al., 1993, 1995).

Precipitation

NM receives most of its moisture from the Gulf of Mexico, and July and August are the rainiest months (Tuan 1969). According to the Terrestrial Ecosystem Survey, precipitation in the Pole Canyon ecosystem management analysis area ranges from 360 mm yr^{-1} at lowest elevations to 740 mm yr^{-1} in the fir areas near Mt. Sedgwick. Average annual precipitation is 640 mm for mixed conifer areas, 560 mm for ponderosa pine forest, 500 mm for ponderosa pine forests mixed with piñon pine, and 400 mm for piñon-juniper woodlands (USDA Forest Service 1994a). Both summer monsoons and El Niño/Southern Oscillation (ENSO) events affect the precipitation patterns, and are described below.

In NM a significant percent of the total annual precipitation can occur during thunderstorms of the monsoon season. Monsoons are large regional movements of air masses that bring a change in the precipitation pattern. Wet monsoons occur in the summer when there is a seasonal reversal of the winds and a large influx of moisture onto continents. The monsoons that affect NM are the result of a "summer high pressure jump" of 5-10 degrees north latitude off the Pacific coast, and the southward shift of the high pressure system (i.e., the Bermuda High) off of the Atlantic Ocean. The pressure change begins in late June to early July, as east winds bring moisture from the Gulf of Mexico into the southwest.

The large-scale "Mexican monsoon" was described by Douglas et al. (1993). It is centralized over northwestern Mexico, and observed over NM and southern Arizona. Precipitation patterns of the monsoon can be detected by monthly mean rainfall, satellite imagery and rawinsonde data. One index for onset of the monsoon is when dew point temperature at Sky Harbor airport in Phoenix equals or exceeds 10° C (50° F) for three consecutive days (Gourley, pers. comm.) Douglas et al. (1993) discussed the relative importance of horizontal advection of moist air onto the continent from the east or southeast. Their results emphasize the impact of vertical transport by convection, the lower troposphere as the moisture source, and the contribution of moisture from the eastern tropical Pacific Ocean. Stensrud et al. (1995) suggest that the moisture source for convection is the Gulf of California.

El Niño/Southern Oscillation (ENSO) events are characterized by changes in sea-surface temperatures and atmospheric pressures over the tropical Pacific Ocean. Planetary-scale circulation is affected, and local weather responds in other parts of the world, i.e., at mid-latitudes. This climate link between geographically separate areas is known as a teleconnection. The Southern Oscillation is the changing air pressure gradient between the eastern and western tropical Pacific Ocean. The Southern Oscillation Index detects whether climate conditions are "normal", El Niño or La Nina based on the normalized monthly average air pressure difference between Tahiti and Darwin, Australia. During a high index period pressure is high over the eastern Pacific near Tahiti and low over the Western Pacific near Darwin. Conversely, during a low index period pressure rises over the west and falls over the east Pacific Ocean, reducing the pressure difference between Darwin and Tahiti (UCAR 1994).

An El Niño event begins when the air pressure gradient starts to weaken and the southeast trade winds are diminished (Moran and Morgan 1995). During an El Niño event the surface waters of the eastern tropical Pacific Ocean are anomalously warm, upwelling is suppressed off the coast of Ecuador and northern Peru, and the Southern Oscillation Index is low (Dahm and Moore 1994). During a La Niña event, opposite conditions occur, i.e., abnormally low sea-surface temperatures of the eastern tropical Pacific Ocean, exceptionally strong southeast trade winds, and a high Southern Oscillation Index.

Precipitation and runoff regimes in most of NM (i.e., areas other than the eastern plains) have a teleconnection to the El Niño-Southern Oscillation (ENSO) during the fall, winter and spring. High rainfall and spring runoff occurs as a local response to El Niño. As a result precipitation amount during the winter/spring is almost the same as precipitation amount during the summer. The increase in runoff is amplified compared to the precipitation response. Conversely, drought conditions and low spring runoff occur in response to La Nina events (Dahm and Molles 1992, Molles and Dahm 1992). Data for the Gila and Rio Salado watersheds in NM showed that average precipitation was 2.1 to 2.8 times greater in El Niño vs. La Nina years. Also, average spring runoff was 6.0 to 7.4 times greater in El Niño years vs. La Niña years (Dahm and Molles 1992). Increased fire frequency is also associated with La Niña events (Swetnam and Baisan 1995). Although the years 1991-1994 corresponded to an extended El Niño event, precipitation increases are detectable in October through May, rather than during the monsoon season (Dahm and Moore 1994).

Monitoring methods and stations

The most comprehensive precipitation data near Pole Canyon are collected by the National Weather Service. Three sites triangulate the area: Grants airport to the east, Thoreau to the north, and El

Table 3. National Weather Service precipitation monitoring sites near Pole Canyon.

Site Name, ID	Location		Elevation, m
Grants airport, 368204	Cibola Co.	35" 09' 59" x 107" 53' 57"	1987
Thoreau, 883004	McKinley Co.	35" 24' 35" X 108" 13' 50	2177
19 km SE, 883404	McKinley Co.	35" 18' 00" X 108" 08' 50"	2263
El Morro National Monument, 278501	Cibola Co.	35" 02' 17" X 108" 20' 57"	2203

Morro National Monument to the southwest (Table 3). Data for atmospheric moisture are only available at Grants. The Thoreau site was moved during this study period: data collection was terminated at the first location on December 1992, and moved 19 km (12 mi) SE. Data collection at the second Thoreau site began in July 1994. Discrepancies that might occur due to this change can be corrected using the Double Mass Balance Technique (Kohler 1949).

The National Weather Service uses a standard gauge to measure rainfall that accumulates in a cylinder attached to a cone-shaped funnel. A measuring stick calibrated in increments of 0.01 inch is used to record precipitation that accumulates over 24 hours. Methods for surface observations are published by the U.S. Department of Commerce, NOAA (1988). NOAA precipitation and humidity data were purchased from the Western Regional Climate Center, Atmospheric Sciences Center, Desert Research Institute, in Reno, Nevada. Data were obtained on computer disk in American Standard Code for Information Interchange (ASCII) format. Published precipitation data (NOAA 1992-1994) are summarized in Table 4, and indicate that about 40% of the annual precipitation occurs during the months of June through September. At Grants, long-term average precipitation is 253 mm yr^{-1} (Morris et al. 1985). At high elevations near Mt. Sedgwick precipitation amounts would be considerably higher, i.e., 740 mm (USDA Forest Service 1994a). Long-term data for El Morro National Monument show an average precipitation of 307 mm yr^{-1}, compared to 274 mm yr^{-1} at Thoreau (Gabin and Lesperance 1977). These data alone are inadequate to characterize the Pole Canyon study site. Gauges only account for precipitation at a specific site and can not accurately quantify regional precipitation amounts due to the localized nature of summer thunderstorms.

Table 4. Precipitation totals (mm) at selected monitoring sites near Pole Canyon (NOAA 1992-1994).

	1992	1993	1994
Grants			
JUN	11.7	0.0	4.6
JUL	42.7	10.9	21.3
AUG	47.2	107.4	38.1
SEP	31.2	8.9	36.1
Year	344.4	319.3	296.9
El Morro			
JUN	11.2	4.6	17.5
JUL	45.2	2.0	39.6
AUG	76.5	195.1	35.6
SEP	15.0	8.9	46.7
Year	407.7	460.5	397.8
Thoreau			
JUN	5.1	—	—
JUL	56.9	—	29.2
AUG	73.7		34.8
SEP	20.6		76.5
Year	—		—

Vegetative cover

The study site has a wide range in vegetation types along the elevational gradient, and examples are shown in Figure 3. Percent vegetative cover or basal areas could be considered as a coarse measure of primary production or terrestrial ecosystem structure. Factors that can modify vegetative cover include available soil moisture, land use activities (grazing, mining, recreation, etc.), extended drought or flooding, and herbivory. Accelerated soil erosion can cause areas to be less suitable for vegetation growth and reduce productivity. Erosion rates have been a concern throughout the Rio Puerco Basin (USDI Bureau of Reclamation 1994, Watts et al. 1994). The Mt. Taylor District has also expressed concern for existing high densities of dwarf mistletoe, and the potential for increased levels of bark beetles, spruce budworms, and root disease.

The Southwestern Region of the Forest Service has a standardized protocol for the inventory of terrestrial ecosystems (USDA Forest Service 1986; Miller et al. 1993). A completed Terrestrial Ecosystem Survey (TES) was required for each ecosystem management study site, including the Pole Canyon analysis area. Vegetation inventories were completed in 1993 but have not yet been published, and these data will be included in the study. Data for both potential vegetation and observed vegetation are contained in the TES. Potential natural vegetation is "the vegetation that would exist today if humans were removed from the scene and if the plant succession after his removal were telescoped into a single moment. The time

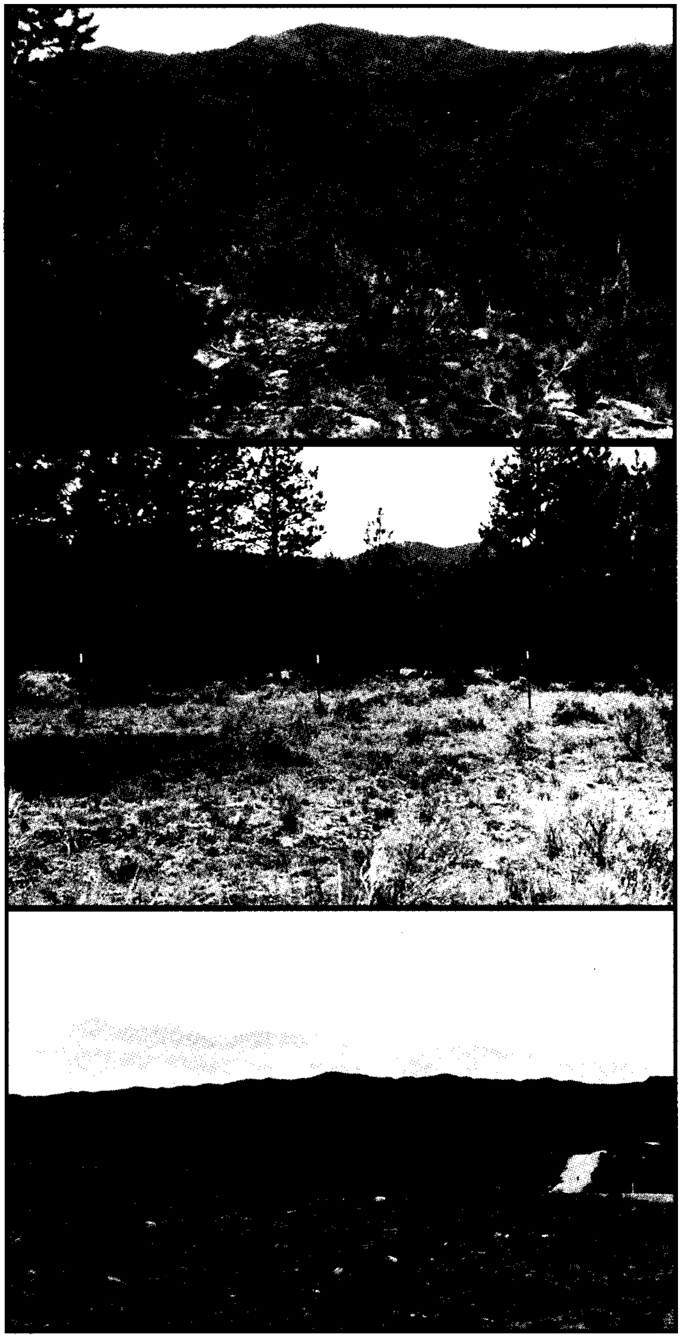


Figure 3. Vegetation gradient within the Pole Canyon study site. Note foreground of piñon-juniper at SR 180 near junction of SR 425 (- 2,377 m) and background of Mt. Sedgwick fir at 2,821 m (top); ponderosa pine from SR 425 at SE boundary of private land, ~ 2408 m (middle); and foreground of grasses and shrubs near piñon juniper ecotone at -2,045 m from from above Limekiln Canyon on SR 180 (bottom).

compression eliminates the effects of future climatic fluctuations, while the effects of human's earlier activities are permitted to stand. (National Atlas of the United States, Rev. 1985)" (USDA Forest Service 1993). Potential vegetation is estimated by soil and climate class.

TES reports are based on aerial photographs (1:24,000 scale) and field verification. Map units are initially drawn based on topography, geology and vegetation within stereoscopic views of aerial photographs, and then verified by field surveys. Data for each unit include classifications of climate, soils (taxonomy, depth, rock fragment, soil texture and other), slope, land types, vegetation (taxonomy and canopy coverage) and climax class (climatic, edaphic, topographic, fire or zootic). Vegetation data are recorded both according to species and grouped as trees, shrubs, forbs and grasses. During TES field verification, percent canopy cover and basal area are recorded for at least three site descriptions within each map unit. Sampling sites include 375 m2 circular plots and 25 by 15 m calibration plots for canopy cover measurements. Percent canopy cover is recorded for trees, shrubs, forbs and graminoids. Percent basal area is recorded for combined tree/shrub, graminoid and forb categories and by other classifications such as bare soil. Plant names are abbreviated using standard protocol of the Soil Conservation Service, i.e., the *Plant List of Accepted Nomenclature,* Taxonomy and Symbols (PLANTS) data base.

A separate vegetation survey for existing timber resources was conducted at a finer resolution by the Mt. Taylor Ranger District. Vegetation classes include grassland, shrubland and treeland. Each stand within the treeland areas is rated for effective ground cover as low (< 25%), moderate (26-75%), or high (> 75%). Vertical structure, horizontal structure, dominant species, and habitat type are also recorded for treeland areas. These data are stored in Oracle format in the Rocky Mountain Resource Information System (RMRIS) and could also be used in the analyses.

INTER-RELATIONSHIPS AMONG VARIABLES

The data sets that will be used to determine the organizing factor include the variables precipitation, humidity, lightning strikes and vegetative cover. The first step is to determine the mathematical relationship between precipitation and lightning strikes. This will be accomplished by calculating the best-fitting regression equation relating precipitation amount (y^1) to lightning strikes (x_1) and humidity (x_2),

$$\text{i.e., } y^1 = a + b_1x_1 + b_2x_2.$$

Next, precipitation contours for the study site will be drawn based on the multiple regression equation. Finally, the relationship between predicted precipitation amounts (y^1) and vegetative cover within the Pole Canyon study site will be determined by spatial and statistical analyses.

Lightning-precipitation relationship

Some measure of atmospheric moisture is needed to predict precipitation volume from lightning strikes (Gosz et al. 1993, 1995). This adjustment is necessary because if the moisture content of air at the surface is too low then virga (precipitation from the base of a cloud that evaporates completely prior to reaching the ground) will result. Variables that might be used include relative humidity, absolute humidity, specific humidity, and dew point temperature or wet bulb depression.

Humidity is commonly measured indirectly using a psychrometer to obtain a wet bulb and a dry bulb thermometer reading. Actual air temperatures are obtained from the dry-bulb thermometer. The wet bulb provides the temperature due to evaporative cooling. Humidity is determined from the difference between the two readings, called the *wet bulb* depression. A psychrometric table is used to determine the percent relative humidity and dew point temperature using the dry-bulb temperature and the wet-bulb depression. At 100% relative humidity the dew-point, wet-bulb and ambient air temperatures are equal.

Calculations of precipitation that occurs from June through September will underestimate the annual precipitation. For example, on the Sevilleta some lightning strikes occur during the months of May and October, which is outside of the monsoon season (Gosz et al. 1995). This underestimate is due to precipitation from frontal storms. Frontal thunderstorms are typically associated with vigorously-rising air along a cold front's surface that is uplifted to the condensation level. These storms can persist for days (Moran and Morgan 1995). In contrast, convective thunderstorms are associated with rising air due to intense solar heating of the ground and are short-lived. Annual precipitation includes all sources, e.g., both convective and frontal thunderstorms.

Prior studies

This research is based on methods developed by Gosz et al. (1993, 1995). Study sites were the Sevilleta National Wildlife Refuge north of Socorro, NM, and the Pecos River Watershed. They found a significant correlation between precipitation data (collected using a network of tipping-bucket gauges) and lightning strikes within a three km radius of the collection site. One strike resulted in approximately 36,190 m^3 of precipitation within the radius, at an average depth of 1.3 mm. The greatest correlations were produced by multiple regressions between number of lightning strikes, precipitation depth in mm and relative humidity. Analysis of the relationship between lightning and precipitation by month was more accurate than by daily records.

Convective precipitation is often highly random over the landscape. Some analytical problems may arise due to such spatial variability in atmospheric moisture and other variables. The three km radius used by Gosz et al. (1993, 1995) provided the best spatial scale for estimating precipitation according to R^2, the square of the correlation coefficient. Other scales ranging from one to ten km from the gauging site provided less accurate estimates of precipitation. Presumably the three km radius most accurately reflected the scale of thunderstorm cells and the limitations of the lightning detection network.

Precipitation-vegetation relationship

Plant growth as primary production is highly related to both temperature and moisture (Aber and Melillo 1991). Soils provide the major water storage mechanism for terrestrial ecosystems. Thus, both the amount of precipitation and the soil volume and texture determine water availability (Aber and Melillo 1991). Summer precipitation largely affects plant productivity, and can result in rapid growth for grass and forb species (Gosz et al.

1995), but it has high spatial variability. For some vegetation such as warm season grasses, the monsoon season has the greatest effect on vegetation growth since concurrently warm temperatures stimulate growth. In addition, lightning makes nitrogen in the atmosphere available to biota as nitrogen oxides by electrification (Keller 1988). Precipitation that falls outside of the selected months will also affect vegetation growth, and some species depend more heavily on soil moisture from winter precipitation. For example, trees with deep roots may not be able to utilize summer precipitation that does not penetrate deeply into the soil. Thus, winter moisture can be critical for conifer survival.

Extended El Niño events like the 1991-1994 anomaly can greatly increase grass cover in the southwest (Swetnam and Baisan 1995). Drought conditions, including response to La Nina events, produce an increase in fire frequency that is detectable in histories reconstructed from fire-scar data. If fire exclusion has significantly promoted conifer growth in Pole Canyon, then it could affect the direct relationship between precipitation amount (inferred from lightning) and ground cover. Conversely, fire suppression can also promote catastrophic crown fires, which would reduce vegetative cover (Swetnam and Baisan 1995).

Precipitation quantity is one factor that determines the productivity of terrestrial ecosystems, and it is particularly important for semi-arid areas. Other limiting factors include heat (temperature), available sunlight and inorganic nutrients such as nitrogen, phosphorus and trace metals. Too much of a factor, e.g., environmental contaminants, can also be limiting. Thus, any factor near or beyond the limits of tolerance for vegetation growth can be a limiting factor (Odum 1993).

Analysis and products

A Geographic Information System (GIS ARC/INFO) vector data structure will be used to organize, analyze and display the data. It may be necessary to transform all data (i.e,. from ASCII files) to a standard dBASE format for importing into ArcView, etc. Spatial analyses, queries, and data summaries could then be performed in ArcView (ESRI 1994). At least three years of climatological data (e.g., June to September for 1992 - 1994) will be included in the spatial analyses. The statistical and spatial analyses will help determine whether areas receiving equivalent amounts of precipitation during the monsoon season have a similar vegetation response as indicated by vegetation cover. Multiple linear regression (Zar 1974, Kachigan 1991) will be used to develop the correlation between precipitation, humidity and lightning variables at the meteorological sites, and to calculate precipitation depth at other sites based on the lightning data and regression equation. Precipitation isopleths will be generated by spline interpolation. Kriging can be used to select appropriate weights for the interpolation (Venkatram 1988, Star and Estes 1990, Kassim and Kottegoda 1991).

A GIS cross tabulation, i.e., a two-dimensional table of inferred precipitation amount vs. vegetation variables, can be generated to summarize the data. Plots of precipitation amount and number of lightning strikes over time will also be included. The data may be transferred to an external statistical analysis package such as SPSS (SPSS, Inc. 1990) or SAS (SAS Institute, Inc. 1988) for analysis. Precipitation contour maps based on the relationships between lightning and moisture content of the atmosphere will be displayed. The results of statistical and spatial operations such as linear and multiple regressions, interpolations and kriging will be presented and discussed in a subsequent publication. Table 5 contains a list of tasks associated with this project.

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Table 5—Lightning research tasks.

Acquire Data for Study Site

- *Lightning Sevilleta LTER archives (ASCII format)*
- *Precipitation/humidity — Western Regional Climate Center*
- *Vegetation Forest Service TES data in GIS, rBASE, and hard copy format*

Display Initial Data for Pole Canyon Study Site

- *Potential natural or existing vegetation (trees, shrubs, grass)*
- *GIS maps such as three dimensional elevation map, ownership boundaries, streams*

Check Data Base Structure: Pre-process Data (convert from ASCII to dBASE format)

Lightning Data

- *Clip area containing Pole Canyon site and 5 km square around precipitation sites*
- *Reclip data to new boundaries by watershed, if necessary*
- *Output clipped data to dBASE form*

Lightning-Precipitation Relationship

- *Count number of strikes in (3 km) radius from each precipitation station*
- *Develop linear regression using humidity, precipitation and lightning strikes*
- *Using a (2 km) grid over the study site, count number of strikes in (3 km) radius from each grid point, use regression equation and interpolation to map precipitation amount*

Lightning-Precipitation-Vegetation Relationships

- *Produce cross tabulation of precipitation class vs. percent cover class*
- *Display theme maps if look-up tables can be generated*

Statistics

- *Develop multiple regression to predict precipitation*
- *Interpolate/krig precipitation data*
- *Use external packages like SPSS or SAS for spatial analysis*

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