AIIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

301/587-8202

Centimeter

Inches

MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 1

Conf-9408157--1

LA-UR- 94-2782

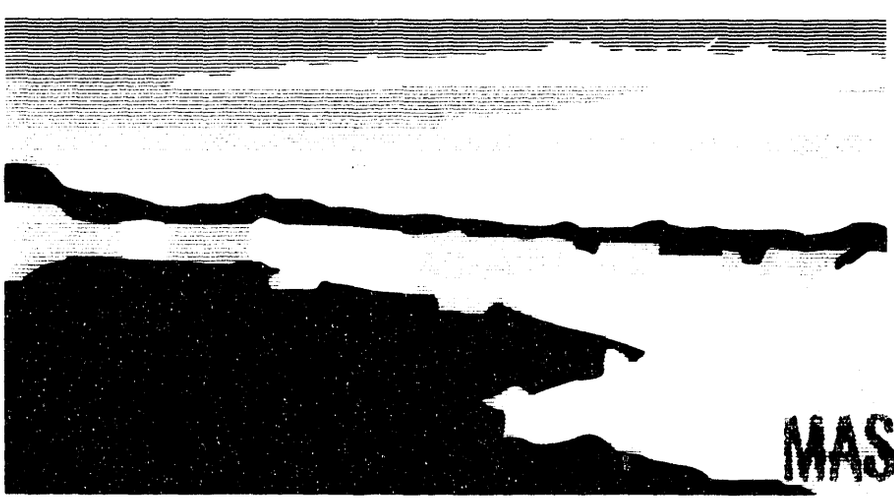
Title: HYDROLOGY AND ECOLOGY OF PINYON-JUNIPER WOODLANDS: CONCEPTUAL FRAMEWORK AND FIELD STUDIES

Author(s): Bradford P. Wilcox
David D. Breshears

Submitted to: Forest Service Conference on Pinyon-Juniper
August 9, 1994
Flagstaff, AZ

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.



Los Alamos
NATIONAL LABORATORY

MASTER

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Form No. 836 R5
ST 2629 10/91

HYDROLOGY AND ECOLOGY OF PINYON-JUNIPER WOODLANDS: CONCEPTUAL FRAMEWORK AND FIELD STUDIES[1]

Bradford P. Wilcox and David D. Breshears[2]

Abstract: Pinyon-juniper woodlands represent an important ecosystem in the semiarid western United States. Concern over the sustainability of, and management approaches for, these woodlands is increasing. As in other semiarid environments, water dynamics and vegetation patterns in pinyon-juniper woodlands are highly interrelated. An understanding of these relationships can aid in evaluating various management strategies. In this paper we describe a conceptual framework designed to increase our understanding of water and vegetation in pinyon-juniper woodlands. The framework comprises five different scales, at each of which the landscape is divided into "functional units" on the basis of hydrologic characteristics. The hydrologic behavior of each unit and the connections between units are being evaluated using an extensive network of hydrological and ecological field studies on the Pajarito Plateau in northern New Mexico. Data from these studies, couped with application of the conceptual model, have led to the development of a number of hypotheses concerning the interrelationships of water and vegetation in pinyon-juniper woodlands.

INTRODUCTION

Semiarid landscapes, although generally sparsely populated, are of tremendous global importance. They occupy a huge landmass and provide many valuable resources. By definition, these are water-limiting environments; even small changes in the water budget, whether caused by changes in climate or by disturbance, can greatly affect vegetation patterns. The global phenomenon of "desertification," produced by the combined effects of overgrazing and drought (Grover and Musick 1990, Schlesinger et al. 1990), provides troubling evidence of the sensitivity of semiarid landscapes to such changes. Concern over the sustainability of these areas continues to mount.

The ability to control change and to prevent degradation of semiarid environments depends on understanding–and, eventually, predicting–the close interactions between water dynamics and vegetation patterns. Characterizing these complex interactions, however, presents a particularly formidable challenge given the great heterogeneity of these landscapes. Hydrologic phenomena, such as precipitation and runoff, are highly variable in semiarid environments, in both space and time; and many of these landscapes exhibit considerable–and often abrupt–variations in elevation, topography, and soils. As a result, one finds a wide range of vegetation patterns and an

---

[1] Paper presented at Pinyon-Juniper Symposium (Flagstaff, AZ, August 8-12, 1994).

[2] Wilcox is a hydrologist and Breshears is an ecologist in the Environmental Science Group, MS J495, Los Alamos National Laboratory, Los Alamos, NM 87545. The authors gratefully acknowledge the many technicians and staff members in the Environmental Science Group who have contributed to the studies described here. Technical editing was provided by Vivi Hriscu and illustrations were done by Andi Kron. This work was funded by the Environmental Restoration Program, Los Alamos National Laboratory.

accompanying large number of transitional zones between vegetation patterns. These zones (known as tension zones, or ecotones) are thought to be particularly sensitive to disturbance and to climatic fluctuations, including those resulting from an elevation in greenhouse gases (Gosz and Sharpe 1989, Gosz 1992, Yeakley et al. 1994).

At Los Alamos National Laboratory, we are developing a conceptual framework that simplifies spatial heterogeneity through the delineation of "functional units" based on hydrologic characteristics. (This framework is drawn from hypotheses already in the literature as well as hypotheses from our own research). We are particularly interested in the application of this framework to the pinyon-juniper woodlands that dominate the Laboratory environment and which are among the semiarid systems showing strong signs of disturbance-induced change (Everett 1986). Movement of contaminants, currently a key area of investigation at Los Alamos, is occurring mainly within these woodlands. Because contaminant movement can take place at many different scales–from as small as a waste disposal pit to as large as the entire 116-km^2 Laboratory complex–and because it is so closely linked with hydrological patterns, the framework offers an effective approach to understanding, and thereby mitigating the effects of, contaminant migration.

To test the hypotheses on which our framework is based, and to continually refine and improve it, we are establishing a network of field studies that will provide the needed data. These field studies are described below.

SITE DESCRIPTION

The area in which our field studies are being conducted includes most of the Pajarito Plateau of north-central New Mexico (fig. 1). Formed by a series of violent volcanic eruptions beginning some 1.4 million years ago (Crowe et al. 1978), the plateau measures about 12 x 36 km and ranges in elevation from 1910 to 2730 m. To the west, it butts up against the Jemez Mountains. To the east, a parallel drainage network has created a series of finger-like mesas separated by canyons, through which intermittent and ephemeral streams flow toward the Rio Grande. The resulting topography is complex, characterized by four major features: mesa tops, canyon bottoms, north-facing slopes, and south-facing slopes (fig. 2).

The Pajarito Plateau has a semiarid, temperate mountain climate. Average annual precipitation varies with elevation, from about 330 to 460 mm (fig. 1), of which about 45% occurs in July, August, and September (Bowen 1990, fig. 3a). Most summer precipitation occurs as intense afternoon and evening thunderstorms, with an average year seeing 58 thunderstorm days (Bowen 1990). Differences in precipitation with elevation are most dramatic during July and August. In winter, precipitation occurs mostly as snow, with the greatest accumulation at the higher elevations. Temperatures are moderate: in the summer, daytime temperatures are generally below 90° and nighttime temperatures are around 50° F; in winter, daytime temperatures range from about 30° F to 50° F and nighttime temperatures from 15° to 25° F (fig. 3b).

A complex mosaic of soils have developed on the plateau, as a result of interactions between parent material, topographic position, and climate (Nyhan et al. 1974). The parent material for most soils is the Bandelier Tuff, an enormous ash flow constituting the uppermost geologic unit on the plateau. Soils may develop from residual tuff or from tuff that has been reworked by surface processes and is redeposited as slope wash, alluvium, or colluvium. The El

Cajete pumice (from the latest volcanic eruption, some 50,000 years ago) and wind-blown sands also provide material for soil development.

Topographic position is a second important factor in soil development. Mesa-top soils are generally the oldest and best developed; they range in depth from a few centimeters at the mesa edge to over a meter near the center of the mesa. The surface-soil horizons are characterized by a loam to sandy-loam texture, whereas deeper horizons are typically argillic (clay to clay loam). Canyon-bottom soils, developed mainly on alluvium, are young and poorly developed. South-facing canyon walls, which are often steep, have little soil material; north-facing slopes have shallow soils that are dark and high in organic matter.

The major vegetation zones of the Pajarito Plateau include juniper grassland (1600 - 1900 m), pinyon-juniper woodland (1900 - 2100 m), ponderosa pine forest (2100 - 2300 m), and mixed conifer forest (2300 - 2900 m) (Allen 1989). By far the most extensive are the ponderosa pine forest and the pinyon-juniper woodland. As can be seen from fig. 4, the vegetation patterns are largely dependent on elevation and topography.

CONCEPTUAL FRAMEWORK

The dissimilarity of the elements that make up a highly heterogeneous system does not necessarily make the system difficult to understand; rather, the dissimilar elements can be arranged such that the relationships between and among them are more predictable. The heterogeneity that is visually apparent in vegetation patterns across semiarid landscapes is related to differences in hydrological characteristics, that is, the amount and availability of water. Small differences in plant-available water can influence the type and density of vegetation cover. Conversely, changes in vegetation cover can significantly influence the distribution of water.

Although our conceptual framework is based on, and serves as a guide for, our field studies in a specific area, it also applies to other semiarid environments–especially ones having a range of elevations and/or topographic features. The framework simplifies investigation of the movement of water and sediment (and, thereby, contaminants), as well as the interrelationships between water availability and vegetation cover, by dividing the semiarid landscape into a series of "functional units" on the basis of hydrologic behavior. Because differences in elevation and topography are the major determinants of hydrologic behavior at the larger scales, these differences form the basis for distinguishing between functional units at those scales; at smaller scales, the units are delineated on the basis of differences in vegetation and soils. Differences between units may be gradual in some cases and abrupt in others, but for the purposes of the framework the units are depicted as distinct entities.

The sources of most of the environmental contamination at Los Alamos are located on mesa tops in pinyon-juniper woodlands. Therefore, our conceptual framework for the Pajarito Plateau delineates five scales that are relevant to contaminant movement within and from pinyon-juniper woodlands on mesa tops (fig. 4). At each of these scales, we identify functional units as units that are hydrologically distinct: the hydrologic behavior of a given functional unit in one area will be similar to that of its counterpart in another area; the differences in hydrologic behavior between functional units in one area will be consistent with those in another area. Table 1 shows the functional units identified at each scale and the hypotheses formulated with respect to hydrologic differences between units and hydrologic connections between units.

The largest scale, to which we refer as the ***regional scale***, includes the entire plateau and parts of the adjacent Jemez Mountains (fig. 5). At this scale, the major hydrologic dichotomy is between streamflow that is perennial (or intermittent, i.e., continual for at least part of the year) and streamflow that is ephemeral. Very generally, perennial flow is generated from melting of snow packs that accumulate at the higher elevations. In the functional unit characterized by perennial flow, water is available in excess of the evaporative demand (at least during part of the year), and the most likely pathway of flow is subsurface.

Ephemeral flow, on the other hand, is generated mainly by intense summer thunderstorms; in this hydrologic unit, the pathway of flow is surface, which carries much higher amounts of sediment. Whereas the high-elevation "perennial stream" functional unit contributes more water, the lower-elevation "ephemeral stream" functional unit contributes more sediment. From the standpoint of water movement (and associated transport of sediment, contaminants, and nutrients), the dichotomy is important. For example, to predict how much runoff is produced from the Jemez Mountains and Pajarito Plateau, the major considerations are the amount of snow accumulation in the higher elevations and the amount of water lost in transmission through the alluvial channels in the lower elevation zones. (In this area, the boundary between the "perennial stream" and the "ephemeral stream" functional units corresponds roughly to that between the ponderosa pine and the mixed conifer forest.)

The next smaller scale of the framework, which we call the ***plateau scale*** (because in our area it is represented by the Pajarito Plateau itself), is the same as the "ephemeral stream" functional unit. At this scale, the two most important determinants of hydrologic behavior are *elevation* and *topography*. For this reason, functional units are delineated according to differences in both elevation and topography (fig. 5).

Three functional units are delineated along the *elevational* gradient, each characterized by one of the major vegetation types: ponderosa pine forest, pinyon-juniper woodland, and juniper grassland. As elevation increases, precipitation is higher and potential evapotranspiration is lower, resulting in more plant-available water and deeper percolation of water into the soil profile. The different vegetation patterns are related to these different moisture patterns (Lauenroth et al. 1993, Breshears 1993). These functional units are not hydrologically connected except by stream flow through the canyons. In other words, only canyon-bottom areas will receive additional inputs of water from upstream functional units.

Four functional units are delineated along the *topographic* gradient (fig. 5). These units are mesa tops, canyon bottoms, north-facing slopes, and south-facing slopes. Differences in plant-available water (and thereby in vegetation) among these functional units are related mainly to differences in solar radiation and soil characteristics. Inputs of solar radiation are greatly affected by slope position. Soils also differ with topography (canyon-bottom soils, for example, are deep, sandy soils that readily absorb water; in contrast, south-facing slopes may be mostly exposed bedrock or have very shallow soils with limited water-holding capacity).

Inputs of water by precipitation, although similar for all four topographic functional units, are substantially augmented for the canyon-bottom areas as runoff is received from the other areas, especially the mesa top and south-facing slopes. In other words, water and sediment are redistributed among these functional units, with the mesa tops and south slopes acting as source areas and the canyon bottoms as the major sinks. The north-facing slopes may be sources or sinks, depending on whether they are providing water and sediments to the canyon bottoms or gaining water from the mesa tops (as is the case especially during winter snowmelt-Wilcox, 1994).

The next scale is that of the pinyon-juniper woodland. At this ***woodland scale***, we delineate two functional units: canopy and intercanopy. Hydrologic differences between these two zones have been observed in pinyon-juniper woodlands (Roundy et al. 1978, Breshears 1993) as well as in other shrubland types (Blackburn 1975, Seyfried 1991). Infiltration rates are typically much higher in the canopy zones as a result of soil and cover differences. We believe that there is little if any exchange of surface water or sediment between the two units. More runoff and sediment movement are generated from the intercanopy zones, but very little of the water or sediment is carried into the canopy zones because these form mounds, slightly higher in elevation than the intercanopy zones. (This hypothesis is consistent with Seyfried's [1991] observation that in sagebrush rangelands, the intercanopy areas are interconnected.) On the other hand, a subsurface hydrologic connection between the two units has been demonstrated by Breshears (1993), who has documented that both pinyon and juniper-juniper in particular-extract water from neighboring intercanopy soils.

We have selected the intercanopy functional unit as the next scale in our framework. At the ***intercanopy*** scale, we define two further functional units: herbaceous patches and bare patches. During runoff-producing rainstorms, most of the runoff is generated from the bare patches, whereas the herbaceous patches act as sinks for this water and associated sediment. Given a large enough runoff event, the herbaceous patches will generate some runoff as well.

Finally, the smallest scale of the conceptual framework is that of the ***herbaceous patch***. Within a herbaceous patch, distinct functional units are individual herbaceous plants, areas of cryptogamic cover, and bare ground. We believe that the infiltration capacity of each of these units is different, bare ground having the lowest, cryptogamic cover somewhat higher, and individual plants the highest.

FIELD STUDIES

While the conceptual framework outlined above facilitates thinking about water and sediment movement through semiarid landscapes, and how such movement affects-and is affected by-vegetation patterns, it also gives rise to further questions: exactly how do these functional units differ hydrologically? What are the hydrological connections between/among them? We have formulated hypotheses to respond to a number of these (see Table 1), and are now collecting data that will allow us to test many of them (some have already been tested by others).

Most of the hydrologic and ecologic investigations that are providing us with data for our conceptual framework are concentrated at four locations along the elevational gradient of the plateau: one in a ponderosa pine forest and three in pinyon-juniper woodlands (fig. 2). In addition to these, a network of USGS stream-gauging stations has been established across the plateau; and at several other sites, periodic measurements are being made of plant physiological variables. Most of these studies have been initiated within the last 3 years, but build on previous hydrological and ecological investigations (Allen 1989, Lajtha and Barnes 1991, Lajtha and Getz 1993, LANL 1994).

Regional Scale

At this scale, the functional units are the mountains and the plateau. Information about the hydrologic behavior of these units is being gathered through the USGS stream-gauging network on the plateau (fig. 2). Stations have been installed in ten of the major canyons; some of these,

such as Los Alamos, Pajarito, and Canada del Buey, have more than one gauge. These data will contribute to our understanding of the hydrologic connections between the functional units.

Plateau Scale

The functional units at this scale correspond to the major vegetation types on the plateau: ponderosa pine forest, pinyon-juniper woodland, and juniper grassland. Currently, runoff and erosion data are being collected from one ponderosa pine hillslope (Ponderosa site) and two pinyon-juniper hillslopes (TA-51 and Bandelier). The catchment areas range in size from 0.5 to 1.0 ha. At the Ponderosa and TA-51 sites, subsurface flow from the hillslope is also being measured. These data have already proved useful in understanding water movement within areas characterized by each of the three vegetation types. In addition, soil moisture data are being collected along the elevational gradient of the plateau, at the Ponderosa, TA-51, and White Rock sites. Although these are point measurements, they can be averaged to enable comparison of soil moisture values between the different functional units.

At this time, data are being collected only from the mesa-top functional unit (the small catchment studies described above could also be considered as within this unit).

Woodland Scale

The two functional units at this scale are canopy zones and intercanopy zones. These functional units are being studied at the TA-51 and White Rock sites. At TA-51, runoff and erosion are being measured from 30-m^2 plots in intercanopy zones (Wilcox 1994). Although the initial runoff measurements were only total volume, the plots have subsequently been modified so that runoff can be monitored continuously. Differences in soil moisture between canopy and intercanopy zones are measured both by neutron attenuation and time-domain-reflectometry (TDR). The two methodologies are complementary: neutron attenuation allows soil moisture to be determined incrementally with depth (in our case up to 3 m); TDR provides continuous soil moisture monitoring, but only an integrated average of soil moisture along the length of the probe. Measurement of deep soil moisture by TDR requires horizontal insertion of probes into an excavated profile; such measurements are being taken in a few locations. Finally, we are also collecting data on plant physiological variables that will allow us to relate soil moisture changes with plant water dynamics.

Intercanopy Scale

At TA-51, runoff and erosion are being monitored from small plots (1 - 2 m^2) representing the two functional units identified at this scale: herbaceous patches and bare patches. These plots are paired with larger plots (4 m^2) that encompass both bare and herbaceous zones. The data thus obtained provide information about the hydrologic connections between these two functional units. Soil moisture is also being measured as a basis for examining relationships between soil moisture and vegetation cover (or the lack of it) within each unit.

Herbaceous Patch Scale

Hydraulic conductivies are being determined in the field for the hydrologic units at this scale: individual herbaceous plant, cryptogamic cover, and bare patch.

Major Findings to Date

Although these studies have been under way for only a short time, they have already yielded data that significantly advance our understanding of water movement and its interrelationships with vegetation on the Pajarito Plateau (and in other semiarid environments as well). At the TA-51 study site, a 2-year pilot study has provided valuable insights concerning runoff and erosion in intercanopy zones of pinyon-juniper woodlands (Wilcox 1994); and preliminary data from the Ponderosa site is demonstrating that subsurface flow can be an important contributor to winter runoff. (No subsurface flow has yet been observed in pinyon-juniper woodlands.)

Observation of the relationship between hydrological behavior and ecological response at our various study areas has stimulated much thought about ecosystem processes. For example, we are perplexed about the much higher rates of erosion (orders of magnitude higher) at our Bandelier study site than at the other sites. We find these differences throughout the plateau: some pinyon-juniper woodlands are eroding at alarming rates, while others appear to be quite stable.

Using soil-moisture and plant-water response data collected from many locations across the plateau and ecological theory developed at other areas, Breshears (1993) developed a simple, yet powerful model for predicting vegetation cover in semiarid landscapes. Ongoing ecological studies are unraveling the complex relationships between juniper, pinyon, and blue grama, as they compete for soil water in intercanopy zones (Breshears et al., unpublished manuscript). These studies are complemented by work relating tree canopy geometry to inputs of solar radiation (Lin et al. 1992, Rich et al. 1993).

IMPLICATIONS

The approach outlined in this paper, of dealing with landscape heterogeneity by dividing the landscape according to hydrologic response, holds promise for effectively addressing many scientific and management concerns in pinyon-juniper woodlands. It can complement the sophisticated mathematical models used by scientists to predict movement of water, sediment and contaminants (Seyfried and Wilcox 1995); and can help managers evaluate the potential impacts of management actions. The approach is greatly strengthened by the network of field studies, which is furnishing one of the most comprehensive ecological and hydrological data bases for pinyon-juniper woodlands.

At Los Alamos National Laboratory, we need to predict long-term contaminant migration from two different types of sources: (1) low-level contamination covering large areas (many km^2) and (2) localized, high-level contamination, such as in a landfill or contaminant spill area. In some areas of the first type, contaminant concentrations may be sufficiently low as to not warrant remedial action-the environmental effects of remediation could be much greater than those associated with contamination (Breshears et al. 1993). At the same time, erosional processes can

cause preferential deposition of contaminated soils in specific locations, such as canyon bottoms. The need to improve our ability to predict the movement of contaminants from mesa-top woodlands to canyon bottoms led to the development of our conceptual framework. On the basis of our observation that runoff and erosion are greatest from patches of bare soil and will move through the interconnected intercanopy areas to the canyons below, we defined the woodland scale of the framework in terms of canopy and intercanopy areas (the latter comprising bare and herbaceous zones). The addition of percolation theory (Gardner et al. 1992) to predict the movement of contaminants may further increase the predictive capability of the framework for this application.

At Los Alamos, landfills exemplify the second type of potential source of contamination. Because erosion is the major mechanism by which contaminants could be released, the ability to predict rates of landfill erosion over the long term is critical to devising effective remedies. Covers for these landfills (a combination of various soil layers and vegetation types) are being designed to reduce the potential for movement of contaminants beyond the landfill boundaries. Erosion rates are most effectively reduced by herbaceous cover, but given the long periods over which these landfills must remain stable (> 100 years), the potential for changes in vegetation cover must be factored into the design. By clarifying the linkages between hydrological and ecological processes, our framework can contribute to the development of a model for predicting these changes in pinyon-juniper woodlands.

In addition, the framework and the data being collected could prove useful in addressing the overall problem of erosion in pinyon-juniper woodlands. Management strategies for reversing this trend focus on increasing the amount of herbaceous cover. Our studies of the relationships between vegetation cover and soil moisture could lead to improved methods for doing that.

In summary, we believe that the extreme heterogeneity of semiarid landscapes can be described in terms of variations in the hydrologic properties of the components of these landscapes. The resultant variations in vegetation, both in space and over time, have created the need for a model, or framework, that will allow us to predict the relationships between water, sediment, and vegetation dynamics. Several testable hypotheses have already resulted from the framework we are developing. As we test these hypotheses using the data from our network of field studies, we hope to improve our predictive capabilities, and thereby our ability to solve environmental problems in semiarid landscapes.

LITERATURE CITED

Allen, C.D. 1989. Changes in the landscape of the Jemez Mountains, New Mexico. University of California, Berkeley, 346 p.

Blackburn, W.H. 1975. Factors influencing infiltration and sediment production of semiarid rangelands in Nevada. Water Resources Research. 11(6):929-937.

Bowen, B.M. 1990. Los Alamos Climatology. Los Alamos National Laboratory Report LA-11735-MS.

Breshears, D.D.; Johnson, S.R.; Myers, O.B.; Meyer, C.W.; and Martens, S.N.(in progress) Differential use of shallow intercanopy water by *Juniperus monosperma* and *Pinus edulis*: coupling of canopy and intercanopy patches in semiarid woodlands.

Breshears, D.D. 1993. Spatial partitioning of water use by herbaceous and woody lifeforms in semiarid woodlands. Ph.D. dissertation, Colorado State University, Fort Collins, CO. 78 p.

Breshears, D.D.; Whicker, F.W.; Hakonson, T.E. 1993. Orchestrating environmental research and assessment for remediation. Ecological Applications. 3(4):590-594.

Crowe, B.M.; Linn, G. W.; Heiken, G; and Bevier, M.L. 1978. Stratigrapy of the Bandelier Tuff in the Pajarito Plateau. Los Alamos Scientific Laboratory Report LA-7225-MS.

Dawson, T.E. 1993. Woodland water balance. Trends in Ecology and Evolution. 8:120-121.

Everett, R. L. (ed.) 1986. Proceedings: Pinyon-Juniper Conference. USDA Forest Service, Intermountain Research Station, Ogden, Utah, INT-215:581

Gardner, R. H.; Turner, M. G.; Dale, V. H.; O'Neill, R. V. 1992. A percolation model of ecological flows. In Hansen, A. J.; di Castri, Francesco (eds.), Landscape Boundaries: Concequences for Biotic Diversity and Ecological Flows. Ecological Studies 92, Springer Verlag, New York.

Gosz, J.R. 1992. Gradient analysis of ecological change in time and space: implications for forest management. Ecological Applications. 2(3):248-261.

Gosz, J.R.; Sharp, P.J.H. 1989. Broad-scale concepts of climate, topography, and biota at biome transitions. Landscape Ecology. 3(3/4):229-243.

Grover, H.D.; Musick, B.H. 1990. Shrubland encroachment in southern New Mexico, USA: an analysis of desertification processes in the American Southwest. Climate Change. 17:305-330.

Hook, P.B. 1992. Individual-plant scale patterns of roots and soil resources in shortgrass steppe. Colorado State University, Fort Collins, CO.

Lajtha, K., Getz, J. 1993. Photosynthesis and water-use efficiency in pinyon-juniper communities along an elevation gradient in northern New Mexico. Oecologia. 94:95-101.

Lajtha, K.; Barnes, F.J. 1991. Carbon gain and water use in pinyon pine-juniper woodlands of northern New Mexico: field versus phytotron chamber measurements. Tree Physiology. 9:59-67.

Lin, T.C.; Rich, P.M.; Heisler, D.A.; and Barnes, F.J. 1992. Influences of canopy geometry on near-ground solar radiation and water balances on pinyon-juniper and ponderosa pine woodlands. American Society for Photogrammetry and Remote Sensing, 1992 Annual Meeting. 285-294.

Los Alamos National Laboratory. 1993. Installation Work Plan for Environmental Restoration. LA-UR-93-3987.

Nyhan, J.W.; Hacker, L.W.; Calhoun ,T.E.; and Young, D.L. 1978. Los Alamos National Laboratory, Los Alamos, New Mexico, 102

Rich, P.M.; Hughes, G.S.; Barnes, F.J. 1993. Using GIS to reconstruct canopy architecture and model ecological processes in pinyon-juniper woodlands. Proceedings of the Thirteenth Annual ESRI User Conference. Volume 2:435-445.

Richie, J.T. 1972. A model for predicting evaporation from a row crop with incomplete cover. Water Resources Research. 8(5):1204-1213.

Roundy, B.A.; Blackburn, W.H.; and Eckert, R.E. Jr. 1978. Influence of prescribed burning on infiltration and sediment production in pinyon-juniper woodland, Nevada. Journal of Range Management. 31(4):250-253.

Schlesinger, W.H.; Reynolds, J.F.; Cunningham, G.L.; Huenneke, L.F.; Jarrell, W.M.; Virginia, R.A.; and Whitford, W.G. 1990. Biological feedbacks in global desertification. Science. 247: 1043-1048.

Seyfried, M.S.; Wilcox, B.P. 1995. Scale and the nature of spatial variability: field examples having implications for hydrologic modeling. Water Resources Research. (in press).

Seyfried, M.S. 1991. Infiltration patterns from simulated rainfall on a semiarid rangeland soil. Soil Science Society of America Journal. 55:1726-1734.

Walter, H. 1971. Ecology of tropical and subtropical vegetation. Oliver and Boyd, Edinburgh.

Whittaker, R. H. 1975. Communities and Ecosystems. Macmillan, New York.

Wilcox, B.P. 1994. Runoff and erosion in intercanopy zones of pinyon-juniper woodlands. Journal of Range Management. 47:285-295.

Wilcox, B.P.; Seyfried, M.S.; Cooley, K.R.; and Hanson, C.L. 1991. Runoff characteristics of sagebrush rangelands: modeling implications. Journal of Soil and Water Conservation. 46(2):153-158.

Wilcox, B.P.; Wood, M.K.; Tromble, J.M. 1988. Factors influencing infiltrability of semiarid mountain slopes. Journal of Range Management. 41(3):197-206.

Wilcox, B.P.; Wood, M.K. 1989. Factors influencing interrill erosion from semiarid slopes in New Mexico. Journal of Range Management. 42(1):66-70.

Yeakley, J.A.; Moen, R.A.; Breshears, D.D.; and Nungesser, M.K. 1994. Response of North American ecosystem models to multi-annual periodicities in temperature and precipitation. Landscape Ecology. (in press).

Table 1. Conceptual framework scales and functional units: hypotheses.

Scale	Size (km)	Functional units	Hypotheses concerning hydrologic differences	Hypotheses concerning hydrologic connections
Regional	25-50	• mountains • plateau	Sustained flow is generated from mountain environments because of accumulation of snow. Flow from the plateau is mostly ephemeral and results from intense summer thunderstorms (Wilcox et al. 1991).	Flow of water and sediment is from the mountains to the plateau and occurs primarily through the canyons. Most runoff generated from mountain snowmelt infiltrates into the canyon bottoms of the plateau.
Plateau (elevational gradient)	10-25	• ponderosa • pinyon-juniper • juniper	Precipitation increases with elevation resulting in deeper soil moisture, which is related to the proportion of woody cover (Walter 1971, Breshears 1993)	Boundaries between these units may fluctuate because of climatic variability or disturbance. Hydrologic connections occur mainly through the canyons.
Plateau (topographic gradient)	1-5	• mesa top • north slope • canyon bottom • south slope	Solar radiation input is affected by topography and modifies plant-available water (Whittaker 1975)	Runoff and sediment is generated from the mesa tops and south-facing slopes and flows mostly to the canyon bottoms.
Woodland	0.01-1	• canopy • intercanopy	Water and energy fluxes are modified by the presence of woody plants (Blackburn 1975, Dawson 1993, Breshears 1993, Seyfried, 1991)	There is little exchange of water and sediment between the canopy and intercanopy areas, with the exception of extraction of intercanopy soil water by woody plants. Intercanopy areas are interconnected.
Intercanopy	0.005-0.01	• bare • grassy	Water and energy fluxes are modified by herbaceous cover (Richie 1973, Wilcox et al. 1988, Wilcox et al. 1989)	Most runoff and erosion is generated from bare areas. Grassy areas often serve as sinks for water and sediment, preventing larger scale runoff.
Herbaceous patch	0.001-0.005	• bare • cryptogam • grass	Water and energy fluxes are modified by individual herbaceous plants (Hook 1992)	At this scale much of the runoff and most erosion is generated from bare ground.

Table 2. Pajarito Plateau field investigations: ongoing collection of hydrological and ecological data at mesa-top sites.

Data category	Mesa-top sites			
	Ponderosa Site (ponderosa; elev. 2315 m)	TA-51 (pinyon-juniper; elev. 2140 m)	White Rock (pinyon-juniper; elev. 1985 m)	Bandelier (pinyon-juniper; elev. 1950 m)
Runoff - Catchment				X
Runoff / erosion - Hillslope	X	X		
Runoff / erosion - Plot	X	X		
Runoff / erosion - microplots		X		X
Interflow	X	X		
Soil moisture - neutron attenuation	X	X	X	
Soil moisture - TDR	X	X	X	
Soil temperature	X	X		
Weather station	X	X	X	X
Snow depth and density	X	X.		
Stem dendrometers	X	X	X	
Conductance	X	X	X	
Plant water Potential	X	X	X	

FOOTNOTES

[1] Paper presented at Pinyon-Juniper Symposium (Flagstaff, AZ, August 8-12, 1994).

[1] Wilcox is a hydrologist and Breshears is an ecologist in the Environmental Science Group, MS J495, Los Alamos National Laboratory, Los Alamos, NM 87545. The authors gratefully acknowledge the many technicians and staff members in the Environmental Science Group who have contributed to the studies described here. Technical editing was provided by Vivi Hriscu and illustrations were done by Andi Kron. This work was funded by the Environmental Restoration Program, Los Alamos National Laboratory.

Figure Caption List

Figure 1. Pajarito Plateau study area, including annual precipitation isoclines (from Bowen, 1990)
Figure 2. Topographic features of the Pajarito Plateau and locations of field studies
Figure 3. (a) Monthly mean precipitation and (b) monthly mean maximum and minimum temperatures at Los Alamos and White Rock, New Mexico (from Bowen, 1990)
Figure 4. Major vegetation types on the Pajarito Plateau (Los Alamos Environmental Research Park documentation, 1976).
Figure 5. Conceptual model for the Pajarito Plateau, showing functional units at each scale.

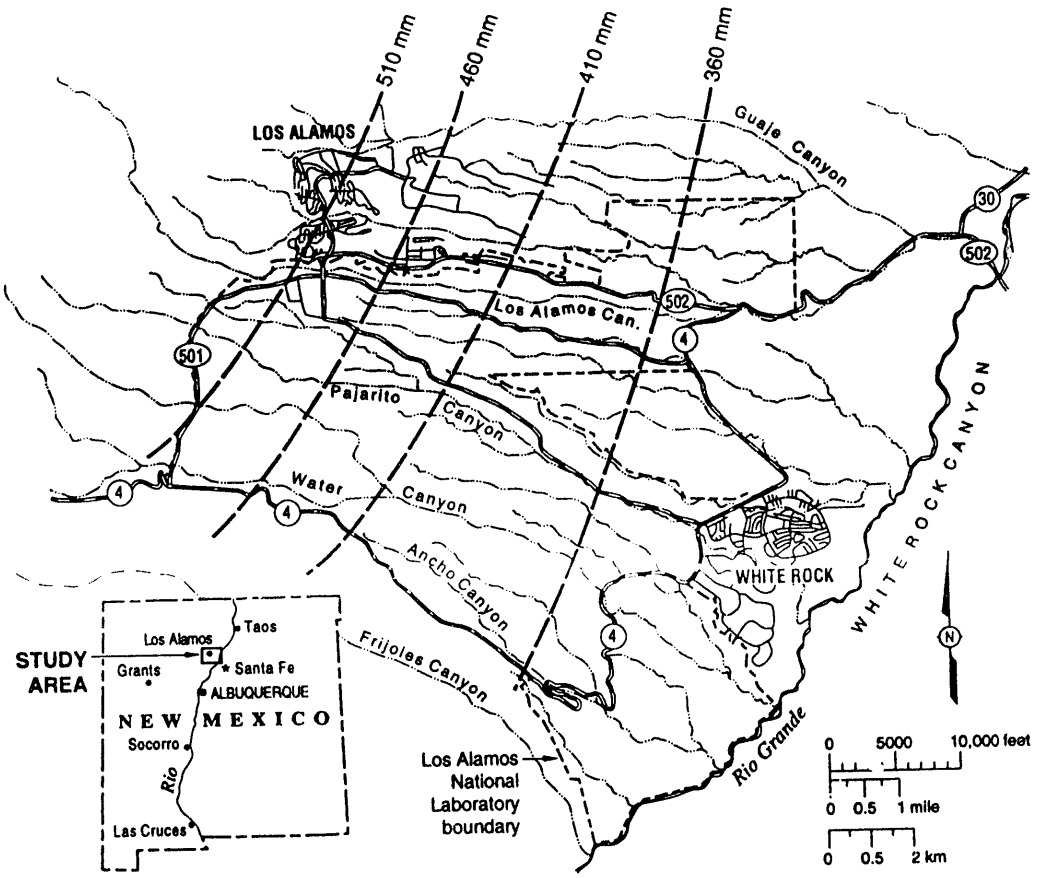


Figure 1. Pajarito Plateau study area, including annual precipitation isoclines (from Bowen, 1990).

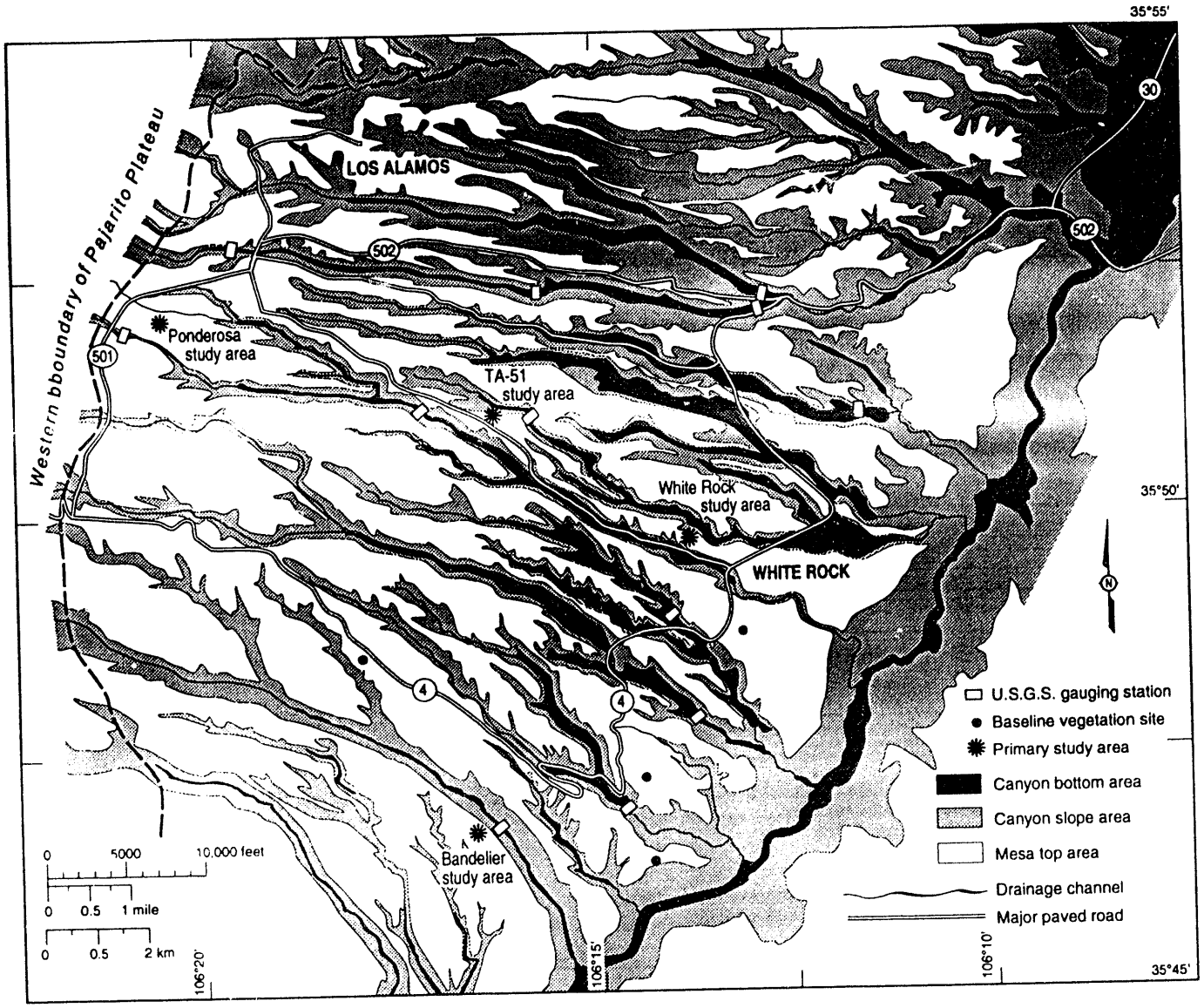


Figure 2. Topographic features of the Pajarito Plateau and locations of field studies.

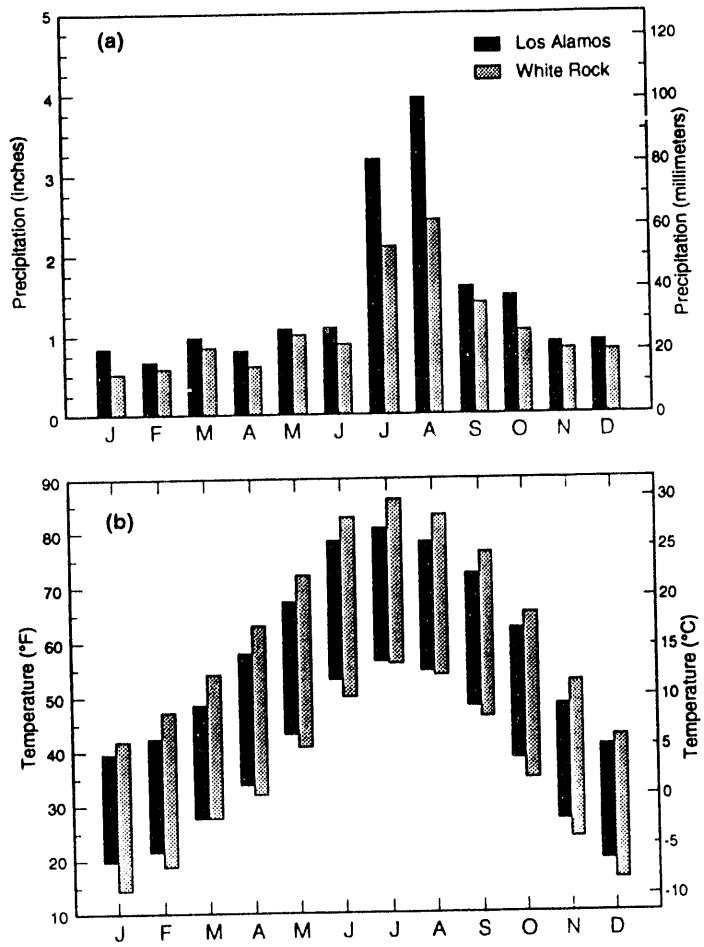


Figure 3. (a) Monthly mean precipitation and (b) monthly mean maximum and minimum temperatures at Los Alamos and White Rock, New Mexico (from Bowen, 1990).

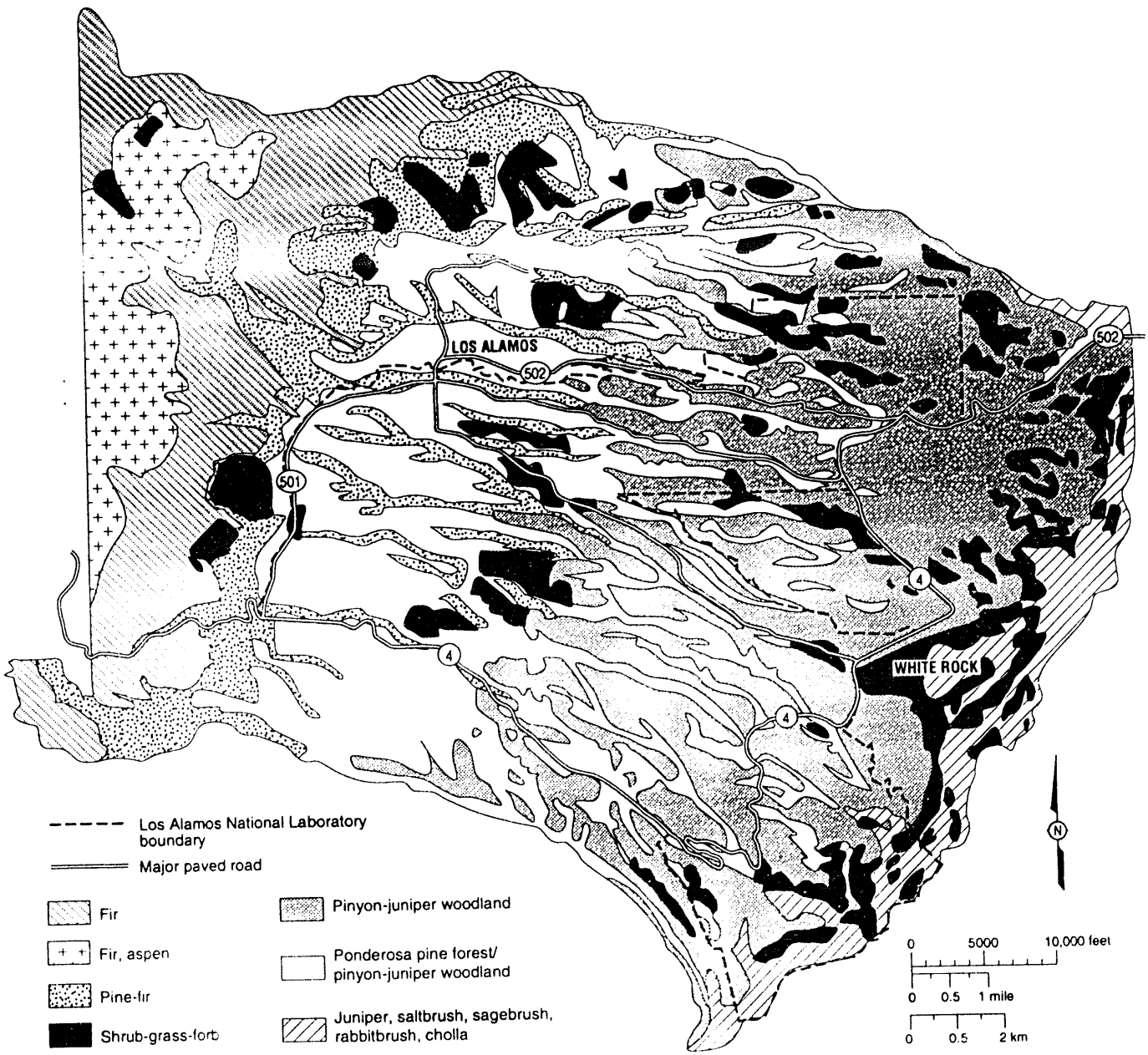


Figure 4. Major vegetation types on the Pajarito Plateau (Los Alamos Environmental Research Park documentation, 1976).

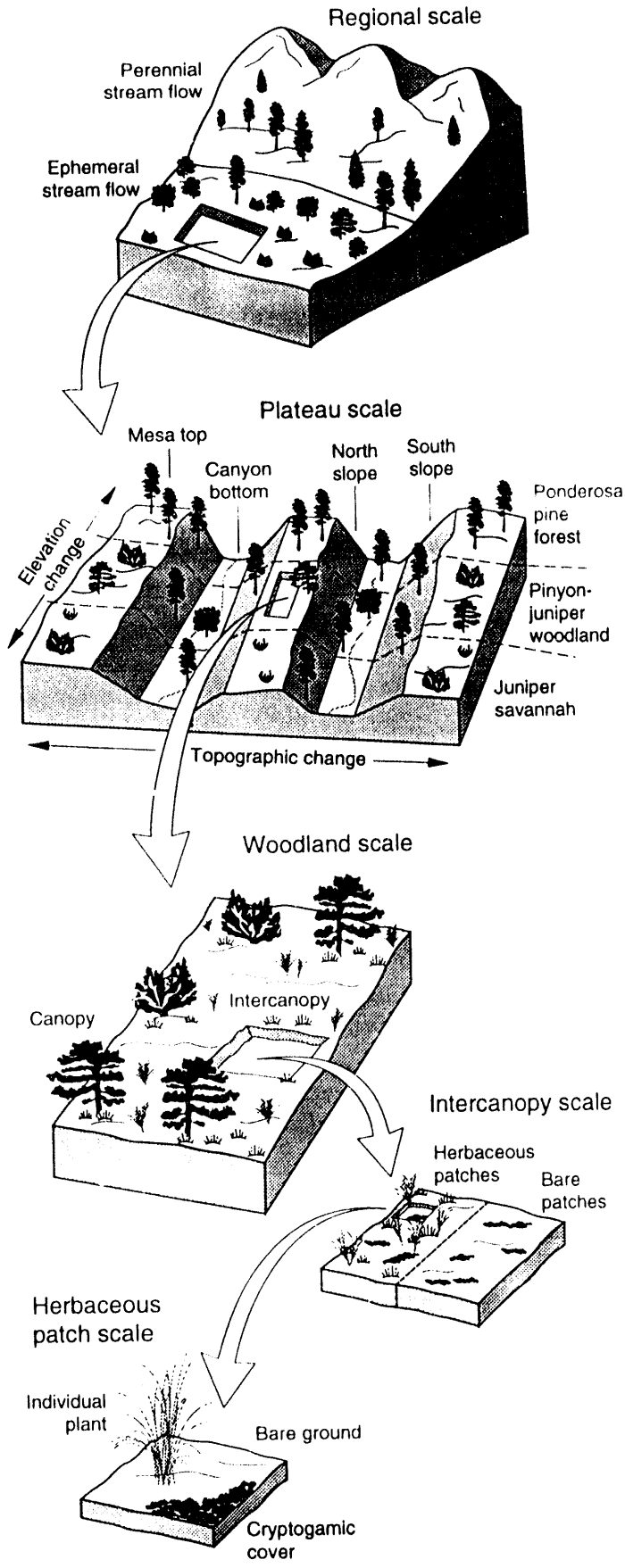


Figure 5. Conceptual model for the Pajarito Plateau, showing functional units at each scale.

DATE
FILMED
10/13/94

END