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Throughfall, stemflow, and infiltration rates for *Juniperus Ashei* on the Edwards Plateau, Texas

by

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Thesis

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

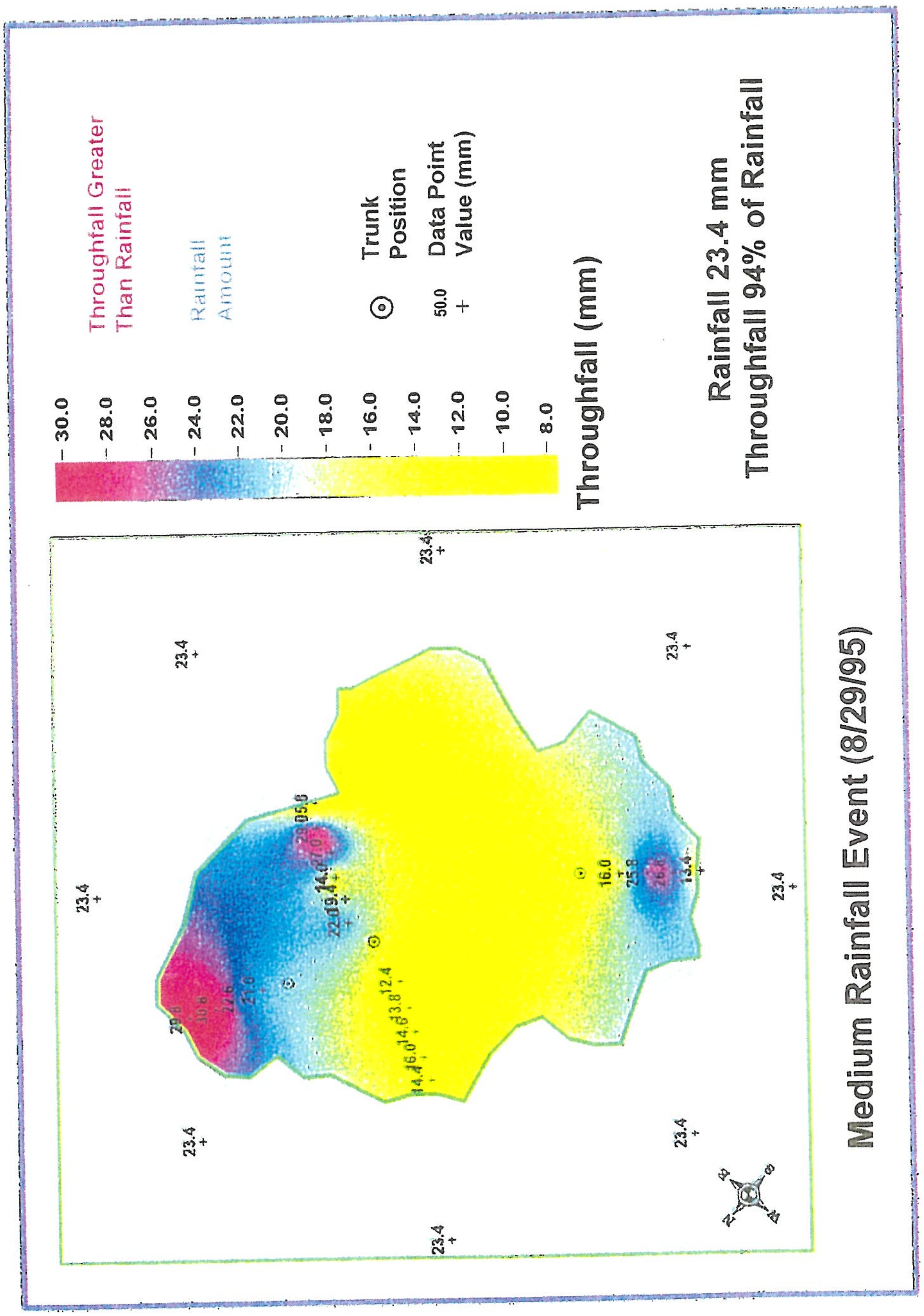
for the Degree of

Master of Arts

The University of Texas at Austin

May 1997

Illustration 5 Throughfall Map, Moderate Rain



Vita

Jack D. Slaughter Jr. was born in Englewood, California in 1948. He was raised and educated in Ohio, West Virginia, and Texas where he attended the University of Texas at Austin. He was awarded a B.A. in 1970 in Plan II, a major he has never been able to describe succinctly but always valued. He mentally pruned the Edwards Plateau from horseback for years but never doubted the rightness of juniper in the landscape. He worked in native landscaping and irrigation. He visited Fjordland in New Zealand where he realized how different surface hydrology can be in a relatively undisturbed landscape and vegetation. He hopes to find purposeful work in restoration ecology.

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Throughfall, stemflow, and infiltration rates of *Juniperus ashei* on the Edwards Plateau, Texas

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Abstract

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the Edwards Plateau,

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The University of Texas at Austin, 1997

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Throughfall, stemflow, and infiltration rates for Ashe juniper were studied on the Edwards Plateau, Texas. Throughfall was measured in a mature stand and a bush form stand of *Juniperus ashei* (Buch.) and found to be 83.9% of rainfall for the bush stand and 92.9% for the mature stand. Stemflow was found to be significant. An accumulation equal to 5 times the measured rainfall for the year of the study was captured in a stemflow collector. Infiltration beneath the juniper canopy was reguarly measured to exceed 180 mm/hr. Infiltration rates on grass dominated plots adjacent to the juniper test plots were found to be much lower. Soil properties of the juniper and grass plots were analysed and compared.

Acknowledgements

I would certainly like to acknowledge the time and effort given to me by my supervising committee: Dr. Francisco L. Pérez, Dr. Steven Hall, and to Brother Daniel Lynch who granted me access to his site and years of observations. I would also like to thank Dr. Jack Sharpe of the University of Texas Geology Department for the use of the rainfall simulator and his interest in my project. John Crutchfield of the Brackenridge Field Laboratory was helpful in providing space for my experiments and background on the changes to this site over the last fifty years. Dr. Chuck Sexton of the United States Fish and Wildlife Service Balcones Canyonlands Refuge helped me find test sites and provided me valuable insight on the flora and fauna of the Refuge. Tor Neilands of the University of Texas Computation Center Help Program has been more than helpful in explaining the statistics I generated. Gary Terrell has certainly gone beyond his duties in working out computational problems. Most of all I would like to thank my fellow graduate student Peter Dana for taking time from his important work to help me with myriad tasks from casting the demons out of my computer to helping to produce the charts and maps in this thesis.

January 10, 1997

Table of Contents

List of Figures

List of Illustrations

Introduction

On much of the Edwards Plateau of Texas *Juniperus ashei* Buchholz now constitutes 50% of the arborescent cover (Buechner, 1944 and Van Auken, 1993). It is found on rocky scarps, on more moderate slopes with oaks and elms, on the level pastures with grasses and mesquite, and growing down to the stream's edge with pecans and cotton woods (Van Auken, 1988). Ashe juniper is but one of the 13 species of juniper in North America today (Correll and Johnson, 1970). It is somewhat surprising that being so omnipresent there is not more known about the baseline ecology of Ashe juniper. Until quite recently the usual mention of juniper in the scientific literature concerned its pattern of increase and methods of removal. Now researchers have begun to ask what is the role of juniper in the landscape and if there really is a juniper problem (Blomquist, 1990).

Ashe juniper is judged to be a fierce competitor with grasses especially in terms of water usage. Ranchers frequently quote the maxim that it takes 100 pounds of water to produce 1 pound of wood. No mention is made of the conversion ratio for grasses. Most other trees except mesquite are not vilified for their water usage characteristics as are juniper. Few have attempted to quantify any of Ashe juniper's water budget processes. This study will investigate several important components of Ashe juniper's water budget such as: a) the pattern of throughfall b.) stemflow and c.) the relative rate of infiltration of rainfall beneath the juniper canopy as compared to that on native grass communities.

This study will not attempt to derive a rate of soilwater uptake and evapotranspiration but will rely upon other studies for this important information

(Owens and Schreiber, 1992). In general the emphasis will be on surficial soil characteristics such as compaction, bulk density, percentage of organic matter, and particle size analysis of the upper 10 cm. of the soil. Of course the infiltration of rainwater is not purely a surface phenomenon but the soil surface is the crucial first test as to whether rainfall runs-off or infiltrates further into the soil and bedrock. It is also perhaps the fraction of the soil profile most strongly affected by humans and vegetation. Because the Edwards Plateau is a mosaic of juniper/oak woodlands and grasslands it is important that both constituents of the savannah biome be investigated and compared. In this study, an infiltration test plot for juniper is always matched with a plot having similar conditions of slope, aspect, and soil series but dominated by a grassland community. The soil conditions and groups vary greatly between sites but not between matched plots to highlight any pattern deriving from the effects of vegetation whether juniper or grasses. The field techniques used are similar to those used by others on live oak *Quercus virginiana* Mill. and two common grass species, sideoats gramma *Bouteloua curtipendula* (Michx.) Torr. and curly mesquite grass *Hilaria belangeri* (Steud.) Nash. (Thurow *et al,* 1987). Whenever possible a historical component will be employed, as the linkage between vegetation and soil cannot be expected to create instantaneous changes.

A Review of the Literature on Ashe Juniper

THE NATURAL HISTORY OF ASHE JUNIPER

There are nearly forty species of *Juniperus* worldwide occurring mainly in the Northern hemisphere. At least thirteen species are native to the United States and Canada. These shrubs or small trees are mostly dioecious evergreens having a scale-like foliage and a fleshy female cone that resembles a berry (Correll and Johnson, 1979). These trees are wind pollinated and the male trees produce copious amounts of pollen in the early spring. Although regarded as a tree of the xeric, stony uplands in the western United States, juniper species inhabit nearly every major soil group and botanical province of North America (Preston, 1989).

Ashe juniper (*Juniperus ashei* Buch.) is named for the forester William Willard Ashe (1872-1932) and is also known as Mountain Cedar, Rock Cedar, Cedar Brake, Texas Cedar, Sabino, Enebro, Tascate, and Cedro (Vines, 1960). Ashe juniper was first published as a separate species by the botanist John T. Buchholz (Buchholz, 1930), who was dealing with a population near Eureka Springs, Arkansas. He also noted the common name Ozark White cedar because of the thick white sapwood when compared to that of eastern Red Cedar (*Juniperus virginiana* L.) with which Ashe juniper is associated in Arkansas and Missouri. Buchholz spent a good deal of time distinguishing between populations of one-seed juniper (*Juniperus monosperma [Engelm.] Sarg.)* occurring in Arizona and Colorado and the Ozark specimens of Ashe juniper. He easily distinguished Ashe juniper from eastern Red Cedar in the field by the former's: a.) forked, bush-like trunk b,) one-seededness c.) serrate-dentate leaf margin d.) stiffer branchlets and e.)

ore pleasant odor of crushed twigs. In *The Flora of Texas* C. L. Lundell lists the ıur previous synonyms of Ashe juniper as being: 1) Cupressus sabinoides H.B.K. 817 2.) Juniperus mexicana Spreng. 1830 3.) Juniperus sabinoides H.B.K. 1845 nd 4.) Sabina sabinoides H.B.K. 1903 (Lundell, 1966).

Buchholz accurately described the range of Ashe juniper in the Ozarks but apparently was not aware of the separate populations in the Ouachita and Arbuckle mountains of Oklahoma nor of the main population on the Edwards Plateau of Texas. The range of the Ashe juniper is centered on the Edwards Plateau of Texas and extends northeastwards through Oklahoma into Arkansas and southern Missouri and southwestward into northern Mexico (Correll and Johnson, 1979). Vines reports that the range extends into Guatemala (Vines, 1960). (wrong)

The Edwards Plateau covers some 93,240 square kilometers and is composed of mainly Cretaceous Period limestones and dolomites that were raised along the Balcones Fault some 10 million years ago (Riskind and Diamond, 1988). This curving fault defines the eastern and southern border of the Edwards Plateau and is often called the Balcones Fault. The subregion of the Edwards Plateau that borders the Balcones Fault is now refered to as the Balcones Canyonlands to distinguish the biotic province from the geological structure and to emphasize that the province extends some distance into the plateau itself, not just along the scarp. It is characterized by a highly dissected terrain in which the valley floors are often 100 meters lower than the ridges. The early Spanish reports of the region commented on the characteristic layers of resistant rock protruding along the scarps which they called *balcones* or balconies. The flora of the Balcones Canyonlands is perhaps the most varied of the Edwards Plateau because of the niches afforded by the many mesic valleys. All of the fieldwork for this thesis was done in this subregion. The subregion on the northeastern margin of the Plateau has broader valleys with less relief and is termed the Lampassas Cut Plains. To the west of the Balcones Canyonlands the terrain is less dissected even though the altitude rises steadily. The aridity and openness of the landscape increases as one moves west. Short grasses replace the mid-grasses of the Balcones Canyonlands and mesquite (*Prosopis glandulosa* Torr.) replaces Ashe juniper. This subregion is usually termed the Central or Western Plateau. There is no well accepted western border for the Plateau but in general both the Pecos river and the escarpment of the Llano Estacado are regarded to be beyond the Edwards Plateau. The last subregion is the Llano Uplift or Central Mineral Region. This topographic basin lies to the north of the Balcones Canyonlands. The Llano uplift is composed of pre-Cambrian granites, and metamorphism along the margins is common. Because this area is geologically and edaphically so distinctive some do not include it within the Edwards Plateau at all but make it a separate region (Tharp, 1939; Godfrey *et al*, 1973). Ashe juniper is infrequent on the granitic Llano Uplift. The line of demarcation between thick stands of Ashe juniper on calcareous soils and perhaps an occasional juniper on the granitic soils can be quite sharp, as on the road which approaches Enchanted Rock from the south (Whitehouse, 1933). However Ashe juniper's eastern neighbor *J. virginiana* covers similar granite domes in Georgia but stops abruptly where the Blackland Prairie meets the Edwards Plateau along the Balcones Canyonlands Escarpment. Both of these borders seem to be too abrupt to be attributed to changes in climate but rather are more likely edaphic borders due to changes in parent material. On the Llano Uplift mesquite appears to take the place of Ashe juniper in the landscape. On the Edwards Plateau mesquite shares its habitat with juniper, although mesquite seems to prefer the deeper soils and full sunlight of the valleys. Mesquite becomes more common to the west as the Edwards Plateau loses relief and becomes more open (Riskind and Diamond, 1988).

Junipers hybridize easily and at various times Ashe juniper has been claimed to be a hybrid or descendant of each of its nearest neighbors *J. virginiana* to the east, one-seed juniper (*Juniperus monosperma* [Englem.] Sarg). to the west, and Mexican juniper (*Juniperus mexicana* Spreng.) to the south (Vines, 1960). Part of this problem in nomenclature is probably due to the plasticity of the genus *Juniperus* and partly due to the rapid advances in plant systematics. Roughly speaking, different species of juniper are found as one moves east to west across North America. The greatest concentration of species in the U.S. occurs in the Intermountain West where at least 8 of the 13 U.S. species occur. Certainly the ranges of many of these junipers extend into Mexico which some believe to be the focus of speciation for junipers as well as many oaks and pines. The Balcones Canyonlands and the Cross-Timbers regions of north Texas and Oklahoma may well have functioned as a link for woodland species between the mountains of northern Mexico and the eastern hardwood forest in Arkansas.

Although as a genus juniper is well documented in the Pleistocene, Ashe juniper inhabits a zone in which there have been relatively few opportunities for the preservation of pollen or macro-fossils. Few lakes or bogs have been found on the Edwards Plateau with a pollen record undisturbed by periodic droughts that expose and oxidize the spores. Few packrat middens have been preserved except on the western edges of the plateau because the climate is too mesic. Some recent success has been made in the examination of cave deposits along the eastern edge of the Plateau where pollen, macrofossils of both plants and animals, and soil deposits have been analyzed (Toomey *et al*, 1992; Hall and Valastro, 1994). In general, Ashe juniper can be said to most likely have been present on the Edwards Plateau since Full-Glacial times but less common than at present with grasses then being more dominant.

A brief reconstruction of climate on the Edwards Plateau for the last 20,000 years as presented by Toomey *et al* (1992) would show: a) cooler and moister conditions than at present for the period 20-14,000 yr. B.P. b) in late glacial times (14-10,500 yr. B.P.) increasing summer temperatures causing less effective moisture c) in the early to middle Holocene (10,500-5,000 yr B.P.) increasingly drier conditions particularly after 8,000 yr B.P., a period known as the Altithermal d) in the late Holocene (5,000-2,500 yr B.P.) conditions on th Edwards Plateau were drier than at any other time in the last 20,000 years e) also in the Late Holocene (2,500-1,000 yr B.P.) more mesic conditions returned to the Plateau with possibly greater effective moisture than at present and f) in the Modern period (1,000 yr B.P. to Present) a drying and establishment of drought cycles occurred (Toomey *et al*, 1992). Because the Plateau was far from the ice front and the assumed shift in temperatures downwards in Full-Glacial times is thought to be in the range of 6° C, there is no reason to assume that Ashe juniper was excluded from its range by climate. Present climatic variation between the northern and southern extremes of Ashe juniper's range is greater than 6°C. (but it would have been outcompeted by East. decid. spp.)

Juniper may not have been favored in more mesic conditions than at present but an examination of the frequency of Ashe juniper shows that it is a generalist and not a specialist in regards to habitat. Van Auken described the woody vegetation of the Southeastern Escarpment and Plateau as two major community-types: the deciduous forests and the evergreen forests (Van Auken, 1986). Each forest type was further divided into sub-types that are distributed along a moisture gradient. For the deciduous forest the sub-types are in order of decreasing moisture: riparian, creek, and north-slope. For the evergreen forest the sub-types are based on bedrock geology but again in order of decreasing moisture they are: Hilltop Edwards, Edwards, Glen Rose, and Buda. The only two woody plants that appear in each of the seven sub-types in significant numbers are Ashe juniper and Texas persimmon (*Diospyros texana* Scheele.). Because Ashe juniper is at present adapted to a reasonably wide range of moisture and temperature variability, there seems to be no reason for Ashe juniper to be excluded from the Plateau by climatic changes as they are presently understood for the past 20,000 yr B.P.

The pollen evidence at Friesenhahn Cave in Bexar County, Texas suggests that during late glacial times both juniper and oak pollens were in the lower range for modern short grass prairies, where pollen deposition from these taxa results from isolated pockets of trees or long distance transport (Hall and Valastro, 1995). The pollen evidence also shows that while *Juniperus* constituted only 7% of the sample and *Quercus 3%*, grassland pollens consisting of *Poaceae*, *Asteraceae* (excluding *Artemisia)*, and *Chenopodiaceae* averaged 64% of the sample in the > in Canyon Pleistocene lacustrine deposits in the cave. The pollen evidence would suggest something analogous to a modern short grass prairie in terms of its percentages of *Poaceae* and *Ambrosia*, or a tall grass prairie in terms of its percentage of *Chenopodiaceae*. Small amounts of deciduous tree pollen were found including

Carya, *Fraxinus*, *Ulmus*, *Juglans*, *Liquidamber*, and *Alnus* which constituted 6% of the glacial age assemblage (Hall and Valastro, 1995). *Pinus*, most likely Texas papershell pinyon (*Pinus remota)*, was found in Friesenhahn Cave to constitute between 7 to 34% of the pollen assemblage. Pine pollen is preferentially preserved by high concentrations of sporopolenin in their exines whereas many deciduous tree pollens are preferentially destroyed resulting in unreasonably high percentages for these coniferous species (Rowley and Prijanto, 1977). The pollen evidence suggests that the Edwards Plateau was predominantly a grassland with pockets of trees possibly found in the canyons and on steep scarps. It is to be noted that pollen analysis is often resolvable only to genus and therefore pollen does not constitute proof that Ashe juniper and not another species was present at this time.

The vertebrate remains of the prairie dog *Cynomys* have been found in a similar cavern near the center of the Plateau, Hall's Cave. The presence of this fossorial rodent suggests that a soil sufficiently deep for burrowing and a grassland biome were present (Toomey *et al*, 1992). Stratified cave deposits at both Friesenhahn and Hall's Caves point to increasingly xeric conditions in the early Holocene followed by a period of rapid erosion of the soil mantle which coincides with the disappearance of prairie dog remains at about 8,000 yr B.P. (Toomey *et al*, 1992). The pollen assemblage at Friesenhahn Cave also shows a rapid increase in the percentages of *Juniperus* and *Quercus* and a decline in the grasses *Poaceae* at this time (Hall and Valastro, 1995). Clasts of limestone begin to show up in the clay deposits in the caves at the beginning of this period of rapid erosion suggesting that bedrock was being exposed. Ashe juniper has a reputation as an early pioneer species on rocky scarps as can be seen on nearly any recent roadcut in Central

Texas. Juniper could have exploited these recently exposed sites resulting in the rapid increases in pollen percentages observed.

Vertebrate evidence of a different sort would suggest the long association of juniper and oak in the Balcones Canyonlands if not the entire Edwards Plateau. The golden-cheeked warbler (*Dendroica chrysoparia)* is endemic in regards to its breeding location to the juniper/oak woodlands of Central Texas (Neck, 1986). These birds have an obligate relationship with Ashe juniper to provide their nesting materials. The birds depend greatly on the oaks, particularly the red oak (*Quercus texana)*, to provide insects for their brood (Sexton, pers. com., 1995). The inch worms which feed on the new leaves of the oaks in late spring are an important prey species for the golden-cheeked warblers. The oaks and the associated inch worms have a much broader range than that favored by the warblers for a breeding site. The addition of Ashe juniper with its loose strands of bark as it reaches maturity is essential to define prime warbler habitat. Apparently other juniper species that occur on the Edwards Plateau or throughout the broad range of oaks do not have the loose, fibrous bark favored by the warblers. Even where Ashe juniper/red oak woodlands occur outside the Edwards Plateau such as the Arbuckle Mtns. of Oklahoma or the Ouachita Mtns. of Arkansas and Missouri there are no breeding populations of golden-cheeked warblers reported. These more northern sites may be too distant from the warbler's winter range of Guatemala but neither have breeding pairs been reported in the mountains of northern Mexico where Ashe juniper/red oak woodlands also occur. An inference might be that acceptable juniper/oak woodlands must have existed in Central Texas or nearby for a very long time to have become so essential to the golden-cheeked warbler.

A chemosystematic and taxonomic study of specimens throughout the range of Ashe juniper has shown the taxon to be remarkably similar and free of hybridization from either *J. virginiana* or red-berry juniper (*Juniperus pinchotti* Sudw.), its immediate neighbors (Adams and Turner, 1970). Some differences in terpenoids, peridoxases, and morphological characters point to possible relict populations in the center of the Plateau and on the southern border extending into northern Mexico (Adams, 1977). Adams infers from the homogeneity of the main population of Ashe juniper that it is a product of a recent expansion of range, most likely since the Pleistocene. He suspects that the center for expansion of the more recent type populations characterized by high percentages of camphor in their leaves is to be found near Brady or Burnet in Texas. Relict populations that are likely ancestral in chemical characteristics extend from New Braunfels to the Sierra del Carmen and the Serranías del Burro of the Big Bend region. This chemosystematic evidence is in agreement with the pollen and macrofossil evidence that Ashe juniper existed on the Edwards Plateau during full glacial times but most likely underwent a rapid expansion of range sometime after 8,000 yr B.P. (Hall and Valastro, 1995; Toomey *et al*, 1993).

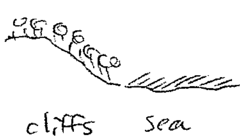
THE HISTORICAL PERIOD

Written historical accounts of the vegetation of the Edwards Plateau begin in the 18th century with reports of explorers and missionaries. The accounts become more numerous as Anglo settlers push into the area in the 19th century (Weniger, 1984). These accounts are often vague as to geographic location, confusing as to taxonomic classification, and totally lacking the precise ordination of plant communities that is the basis of contemporary ecological studies. Nonetheless, important information about the landscape and the vegetation can be derived from a compilation of the reports. It is clear from the descriptions that the Plateau had a much greater proportion of grasslands to woodlands than is presently seen. Instead of completely wooded hillsides and coalescing clumps of trees on the valleys, the appearance was more open and similar to a savannah. This appearance has been corroborated by data derived from surveyor's measurements (Weniger, 1988). The distance between "witness trees" was recorded by surveyors following a metes and bounds description of property. Methods have been developed to convert the surveyors point to point measurements into tree densities (Oosting, 1942; Jones and Patton, 1966). A mean distance of 21 meters between trees was taken to indicate a savannah, 7 meters or less was deemed a woodland, intermediate distances were regarded as woodland grading into savannah. Data from pre-1860 witness tree accounts in 13 Edwards Plateau counties, shows the counties in the Llano Uplift to have been primarily wooded; the counties along the Balcones Canyonlands to have been intermediate; and the three interior counties investigated [Burnet, Kerr, and Menard] to have been primarily grassy or savannah (Weniger, 1988).

In his book *The Explorers' Texas* Del Weniger goes to some trouble to distinguish between two types of landscape described by settlers with the terms "plains" and "prairies" which seem to be synonymous in current usage (Weniger, 1984). To the early Anglo settlers "plains" meant a level, treeless landscape and was applied to places like the Llano Estacado. "Prairies", however, had degrees of rolling relief and could contain significant numbers of trees within the grasses either as singles, mottes, or fringing forests on adjacent hillsides. In this sense Dr. Ferdinand Roemer, a visiting geologist and naturalist to the Edwards Plateau in

1846, could speak of "the forests of the prairies" (Roemer, 1935). Some prairies are reported to have been dotted with single trees, often either oaks or mesquite, in a random pattern. On other prairies particularly near the Gulf Coast the trees would be found in dense, monospecific thickets called "mottes" by the French for their mound-like appearance.

Forests were frequently noted along rivers and streams in a pattern now termed gallery forests by biogeographers. Forests also existed on steep hillsides and ridges flanking the predominantly grassed valleys. The reoccurring metaphor for this mixed landscape of forested hills and grassed valleys is that of a coastal seascape. In numerous accounts by men of different backgrounds, forests are likened to mainlands, islands, and promontories while the grasses are described as resembling the rolling sea (Weniger, 1984). When trees appeared singly and dotted over the landscape the scene was described as resembling an orchard or a great European park. Such a pattern would now be termed a savannah, dominated by grasses but containing up to 30% trees (Barbour *et al*, 1987).



There are many reports that attest to the presence of juniper or cedar as it was called by the settlers. Rarely is juniper said to dot the prairie singly as are oaks and mesquite. Thick stands of juniper called "brakes" were noted along the Balcones Escarpment. Dr. Ferdinand Roemer visited the German settlements at New Braunfels and Fredericksburgh in 1846. He met Ferdinand Lindheimer in New Braunfels who had collected botanical specimens on the Edwards Plateau to be preserved and sent for study in Europe (Roemer, 1935, pp. 111-112).

> On another occasion I made an excursion with Lindheimer to Mission Hill, which rises on the plain of the plateau lying north of the city. Our path lead us again past the springs of the Comal, but suddenly ascended the steep,

> wooded slope of the hill. The firm layers of a yellowish, white, celicious limestone were visible everywhere. The cedar trees, (*Juniperus Virginiana* L.) which covered the slopes exclusively, formed an impenetrable thicket through which a path had to be cut. The cedars here are not the stunted shrub-like plants found in the Northern States of the Union, but are stately trees with straight trunks, seldom more than twenty to twenty-five feet in height and one and one-half feet thick. They have a uniformingly spreading crown. This cedar forest was a treasure to the colonists of New Braunfels, since the wood was preferred above all others on account of its durability when used in building houses and fences. A section of this cedar forest was destroyed by a forest fire during my stay in New Braunfels. The fire spread rapidly due to the resinous nature of the wood and the close stand of the trees.

Because this site was on a steep hillside with exposed limestone, one would expect the juniper to be Ashei or *Juniperus sabinoides* H.B.K. as was the correct botanical synonym at this time. *J. virginiana* would be expected to be found on the nearby Blackland Prairie and not on exposed hillsides. It is unclear whether Roemer or Lindheimer made the identification but extant specimens collected by Lindheimer in New Braunfels and examined by C. L. Lundell are clearly *J. ashei* (Lundell, 1966). *J. virginiana* is predominately a single trunked tree whereas Ashe juniper tends to be multiple trunked or shrub-like, particularly where it has germinated in full sun. An Ashe juniper that has germinated and grown in the shade of a closed canopy is likely to be single trunked as it stretches for sunlight. Perhaps Roemer or Lindenheimer, depending too heavily on this one morphological characteristic, bungled the identification. Nevertheless, there seems to be clear evidence in descriptions, pollen, and botanical specimens still preserved in herbaria that Ashe juniper was present and recognized as a useful tree by Anglo settlers in Central Texas of the 1840's.

There is no extant account that would provide a detailed ordination in terms of the frequency or coverage of Ashe juniper at the time of Anglo settlement. The accounts would seem to imply that juniper was common but less frequent and less dominant than it is at present. The most common habitat for juniper according to settlers' accounts would be on steep, rocky hillsides where juniper appeared in monospecific groves or "brakes" as they were called. Oaks and mesquites are described as dotting the prairies singly but not junipers. At present it is quite common to find junipers as singles or small coalescing clumps within a predominantly grassland community

THE ROLE OF FIRE

Juniper was perhaps restricted to rocky, upland sites in the past by fire. Wells speculated that fire could not reach juniper brakes from below because of a lack of fine fuel such as grasses which colonized the thinnest soils only poorly (Wells, 1966). Many hills and ridges were reported by settlers to have been covered thickly in grasses along their broad summits. Junipers along scarps may have been protected from fire descending upon them because fire does not move so easily downslope as upslope due to predominant local winds. Gehlbach agreed with this pattern of juniper distribution in the past but adds a further protected habitat as that beneath live oak (*Quercus virginiana*) mottes (Gehlbach. 1988). When these oaks are mature their branches reach the ground some distance from the trunk and impart a measure of protection from fires.

Studies have shown that Ashe juniper has a high mortality from fires until it has attained a bole diameter greater than 4 centimeters (Fonteyn *et al,* 1988). Due possibly to higher moisture levels under the canopy, juniper mortality is less beneath those trees which were leafed out at the time of the burn. Live oak and Plateau live oak therefore give some measure of year-round protection. Deciduous canopies, whether oak, elm, or hackberry give less protection. Because juniper canopies are also evergreen and hang quite low, even to the ground in most instances, they offer protection for their own seedlings. Fine fuel load is often quite low under junipers even compared to other low, evergreen canopies.

do fire test - old vs. new foliage

Historic fire frequency on the Edwards Plateau is difficult to evaluate. Thunderstorms and lightning are common there and can occur at any season. Thunderstorms are most likely to occur late in the spring and early in the fall but day time heating and the movement of a persistent dry-line in west Texas spark many summer storms in the late afternoon and early evening (Bomar, 1983). Most likely significant fires developed in the past during late summer after wet seasons when significant loads of standing dead matter in the bunch grasses acted as a fine fuel load. If the vegetation patterns described by early visitors to the Edwards Plateau are accurate, then fire frequency on the level plains may have been more frequent than that on the small prairies fringed by wooded hillsides. A fire on the level plains could become quite extensive because natural firebreaks were few and the wind could spread the fire widely. Fire on the small prairies bordered by woods may have burned less frequently because the trees were somewhat resistant to burning and narrow grass strips between these prairies might prove a bottleneck to the spread of fire. The wind in the dissected terrain may have proved more changeable and less forcefull in spreading the fire than the wind on the open plains.

Whether deliberately or not, humans have certainly affected fire frequency. Much speculation has been given to the use of grass fires by the Indian population in order to: a) attract grazers to new growth b) reduce undergrowth c) prevent pursuers or rout defenders in raiding and d) to signal distant bands. Little recognition is given to the role of accidental fires caused by humans. The number of fires created for cooking once or twice a day multiplied by the number of individuals or small bands constructing them must have been far greater than the number of cloud to ground lightning strikes on any one day. There is no seasonality to cooking fires nor is there a subsequent rainfall likely if the fire should break out. The more nomadic and fragmented human bands become, the more likely it is that the cooking fires are not confined to previously used and presumably safer sites. The drowning of embers with water may have been less common due to distance from water and the lack of large storage vessels. Many fires extinguished only with soil can persist and break out hours later. The charcoal remains that are used to determine fire frequency give no evidence as to whether the fire was natural or autogenic and what were its purposes, if any. It is plausible that fire frequency dramatically increased when human occupation reached the Plateau some 10,000 years ago.

Starting with Spanish missionaries in the 18th century and continuing with the Anglo settlement at least until the end of the 19th century, fire frequency may have increased beyond the levels of the period of Indian occupance if for no other reason than that an increase in population would equal an increase in the number of daily cooking fires. Spanish missionaries brought sheep and goats, over 17,000 in the five missions of San Antonio in the 1760s (Weniger, 1984). Sheep, unlike cattle, are not able to utilize tall herbage so the grasses which were reported to be as high as the back of a cow were seasonally burned in order for the sheep to use the emergent new growth. As Anglo settlers scattered throughout the Plateau, they employed fire to clear woodlands and to break up the dense prairie sod in preparation for plowing and agriculture. Weniger speculates that there was a steady crescendo in the number and extent of fires caused by humans on the Plateau for at least 200 years prior to the twentieth century. The closing of the open range and the shift to agriculture encouraged people to practice fire suppression after the 1890s.

Given the susceptibility of juniper to fire, this does not sound like an effective scenario for the expansion of the habitat of juniper without the added pressure of overgrazing. The invention of barbed wire concentrated herbivores on the Plateau to levels which were unsustainable for many of the native bunch grasses. Stocking rates were often ten times that which is customary today (Buecher, 1944). Cattle also preferentially graze mid-grasses such as little bluestem and over a period of time can shift the composition of a grassland to short grasses, annuals and forbs (Smeins *et al*, 1974). High frequency of fire and overgrazing exposes bare ground to the establishment of species such as the junipers. The juvenile foliage is quite prickly and is rarely used as forage by domestic or native herbivores. The adult foliage is sometimes used by deer and goats but is seemingly not preferred. Fire suppression by humans and the reduction of the fine fuel load as the prairies were converted from mid-grasses to short grasses under grazing pressure might have allowed the junipers to attain a size in which they were less susceptible to mortality by fire. Juniper brakes that had been confined by fire to rocky scarps were most likely little affected by an increase in fire frequency. Fire did not conduct well over the sparsely vegetated ground; the trees were little employed for grazing; and the steep sites were not coveted by humans for agriculture. These cedar brakes were sufficient to provide a seed source capable of colonizing the grasslands once effective danger from fires was removed.

JUNIPER GERMINATION AND ESTABLISHMENT

Ashe juniper seems to possess ample capacity to rapidly increase in numbers if its main control, fire, is removed. Female junipers first begin setting fruit with viable seed between the ages of ten to twenty years (Johnson and Alexander, 1974). Age is difficult to determine accurately in junipers but in relative terms this is the same age at which junipers become much less susceptible to ground fire. The amount of fruit varies from year to year with a season of relatively low production following one of high production. The seed bank beneath a female juniper can be quite large and was estimated at 16,588 seeds per square meter in one recent study (Blomquist, 1990). These seeds can be found in both the litter and the mineral soil. The seedbank has seeds with and without the covering of fruit. Seed viability, however, is low. Blomquist reports viability at 0.3% based on a tetrazolium test. This low viability rate contrasts with a laboratory study of germination of fresh seed from 4 Ashe juniper trees in which germination averaged 37.5% (Blomquist, 1990). In the field, predation by microarthropods may account for the low rate of viability. Increased populations of such microarthropods have been shown to occur beneath the canopies of alligator and one-seed junipers when compared to those found in the adjoining grassland communities (Whitford, 1987). However, even with such a low rate of viability the large numbers of seeds in the seed bank is more than adequate for replacement and population expansion.

The two factors that appear to be most significant in aiding germination of the fresh seed crop are cold stratification and the removal of the fruit covering. Various temperatures between 0.5 to 5°C and various durations from 30 to 180 days have been employed by researchers on other species of juniper as a cold stratification treatment (Fisher *et al*, 1987; Johnson and Alexander, 1974). These temperatures are below the winter average for much of the Edwards Plateau so the minimum requirements may well be significantly higher. In her germination tests Blomquist showed that cold stratification at 2-5°C had a significant positive impact over germination at ambient temperatures no matter which other treatments were involved (Blomquist, 1990).

The removal of the fruit covering from the seed had the greatest positive effect on germination. Only 0.2% of the control seed with intact fruit germinated, but with the fruit removed, 32% of the seed germinated. Fruit can be removed by desiccation or by passage through the intestinal tract of many animals. Birds and mammals would be the most likely vectors for the dispersal of Ashe juniper seeds, particularly if the possibility of the rapid expansion of habitat was to be considered. American robins *(Turdus migratorius)*, scrub jays *(Aphelocoma coerulescons)*, cedar waxwings *(Bombycilla cedrorum)*, raccoons *(Procylon lotor)*, and ringtails *(Bassiriscus astutus)* as well as domestic sheep and goats are known to readily consume Ashe juniper berries (Blomquist, 1990). Many other mammals, rodents, and birds could be added to this list as occasional consumers of juniper fruit.

Seed dispersal is mainly local with the greatest concentrations being found beneath the female trees where germination is common if not favored. The seeds may remain in the digestive tracts of birds for only a short time such as the 11.7 minutes that a *J. virginiana* seed has been calculated to be retained by a cedar waxwing (Holthuijzen, 1984). Favored perches and roosts may be important nodes of expansion of habitat of juniper by avian vectors. Seedling junipers are quite common beneath oaks and other trees where they may be accorded some measure of protection from fire as has already been noted.

Fowler has noted that a nurse tree effect would enhance germination and establishment of Ashe juniper by moderated temperature and moisture regimes (Fowler, 1988). The juniper that establishes in full sunlight may be more important to the present dominance of juniper than one that germinates and competes with other trees for nutrients. Wire fences make effective perches for many birds but have no means of modifying the environment beneath them. The common occurrence of many young junipers beneath such fences would seem to indicate that the dispersal of juniper seed without the fruit covering is the essential step in germination and establishment and not the provision of a specialized environment. The percentage of seedlings that are successful in establishment may well be greater beneath nurse trees but the important pattern of juniper encroachment on grasslands is one of coalescing clumps and not an advancing woodland front (Blomquist, 1990). Juniper can establish on fully illuminated, rocky, unprotected locations. It is these outliers or solitary trees that quickly fragment grasslands while outcompeting the grasses beneath the canopies for resources, whether light, moisture, or nutrients.

The general pattern of herbaceous plants beneath a juniper canopy is such that the density of these plants, mostly grasses, decreases rapidly as one moves from the drip line towards the trunk (Fuhlendorf, 1992). The decrease can be more gradual where browsers such as goats have raised the juniper canopy and allowed more light to penetrate further towards the trunk. Yager (1993) examined the possible mechanisms for the apparent reduction in germination of grasses beneath Ashe juniper. Three possible mechanisms were investigated in both the laboratory and the field in regards to the germination and establishment of two native grasses, *Boutelaua curtipendula* (Michx.) Torr. and *Leptochloa dubia* (Kunth in H.B.K.) Nees. These mechanisms were: a) physical shading caused by the juniper canopy b) allelopathic substances, either volatile or water-soluble, derived from the fresh juniper foliage and c) physical or allelopathic effects derived from the juniper litter. Some inhibitory substances derived from fresh foliage were detected in the laboratory but considered to be ecologically insignificant in the field. No such allelopathic substances were found in the litter or soil beneath Ashe juniper canopies. The physical effect of the accumulation of litter proved to be significant in reducing grass germination. Finely ground litter did not reduce germination but intact litter apparently provided a quick drying and inhospitable moisture regime for germination. The physical effects of shading by the evergreen juniper canopy were significant in lowering the growth rate of established grass seedlings (Yager, 1993)

THE HISTORIC SHIFT IN DOMINANCE ON SAVANNAS

In 1917 the State Forester of Texas presented a paper discussing the spread of timbered areas on the Edwards Plateau (Foster, 1917). What he and others described was a shift in dominance away from perennial grasses and towards shrubby trees such as Ashe juniper and shin-oak (*Quercus sinuata* Torr.) (Bray, 1904). Foster recognized that these trees had not been absent from the Plateau but instead confined to canyons, bluffs, and riparian zones. He found the shift towards woody plants particularly surprising since rainfall averaged 25 inches per year on the Plateau, a condition which in the ecological thinking of the time was thought to heavily favor perennial grasses. He believed that over-grazing and the suppression of fire brought about the changes made visible in the 25 to 30 years preceding his paper. What Foster and Bray described could be termed the origin of the "brush problem" on the Edwards Plateau. This situation was deemed a problem in that the increase in tree/shrub percentages was believed to result in a decrease in grass biomass available to grazers. Less kindly the "brush problem" has been termed a "shrub invasion" with the woody plant either juniper or mesquite being termed a noxious exotic introduced from other regions, generally Mexico. Perhaps more accurately the process has been termed a conversion of savannas to woodlands which implies only a shift in relative importance of the woody and herbaceous cover (Archer, 1989).

Smeins (1983) takes a decidedly long range perspective on the brush problem in terms of climatic change and the development of the savanna, desert, and grassland biomes during the last 25 million years. He does not believe that the vegetation of the Southwest was static in more pristine and less human dominated times, but rather has been in flux since the Pleistocene in response to a trend of increasing aridity. He, along with others, believes that humans could have exerted a triggering effect on environmental conditions by means of influencing fire frequency, conversion of the most productive sites to agriculture, and overgrazing, which lead to erosion and a change in regional hydrology (Hastings and Turner, 1965; Van Devender and Spaulding, 1979). The global increase in carbon dioxide levels since the 1850s has perhaps given woody plants a slight advantage over warm season grasses (Emmanuel *et al*, 1985). Hastings and Turner (1965) believe that a change in climate towards warmer, drier conditions in the North American Southwest has led to the increase in woody plants. They think that this climatic change was synchronous with the movement of Europeans into the Southwest but the truly human induced effects of overgrazing and reduced fire frequency had less impact than this climatic change.

This same "brush problem" has been reported in many rangeland communities in North America. Mesquite, both honey mesquite (*Prosopis glandulosa* Torr.) and velvet mesquite (*Prosopis juliflora* (Swartz) DC), have dramatically increased on rangelands from South Texas to New Mexico (Archer, 1989; Smith and Schmutz, 1975). Creosote bush (*Larrea tridentata* (DC) Coville) and sagebrush (*Artemisia spp).* are not palatable to most livestock and are on the increase on western ranges even under conditions of reduced grazing pressure (Beck and Tober, 1985; Young *et al,* 1979). The pinyon/juniper woodlands of the southwest are commonly believed to be expanding to the detriment of perennial grass communities (Jameson, 1987). Studies of the Jornada and the Santa Rita Experimental Ranges in New Mexico and Arizona showed a rapid conversion from desert grassland to desert scrub that continued even after grazing was curtailed (Buffington and Herbel, 1965; Humphrey and Mehrhoff, 1958).

Working on honey mesquite and perennial grass competition in south Texas, Archer (1989) has constructed a model of succession that explains the conversion of savannahs to woodlands. He believes that a grassland community under pressure from either climate change or grazing pressure might undergo a shift in seral stages such as tall-grass to mid-grass to short-grass. If the disturbance is relieved, there would be a slow re-establishment of equilibrium at a higher or climax stage. If, however, the intensity or duration of the disturbance is too great a "transition threshold" is crossed and a regime of shrub-driven succession replaces the graminoid-driven succession as the steady state. The important distinction is that the time and energy required to recross this threshold is dramatically greater than that required, for example, to re-establish from a short-grass to a mid-grass community. Others have described this inertial stage as a "ball in cup" or "Russian hills" (Laycock,1991; Forman and Godron, 1978). The general idea is that there are several steady state plant communities possible for an area and not a single "climatic climax" as described by Clements (1916). The type, severity, and duration of the disturbance regime is what determines which of several steady states a region will support. Between these different steady states there is a much greater distance than between seral stages in any single succession. Once a disturbance to the edaphic or hydrologic characteristics of an area is begun, the removal of the agent of disturbance may be insufficient to halt the decline or to begin recovery to prior conditions.

If fire is the prime mechanism by which grasslands are maintained, then in contrast shrublands may outcompete grasslands where subsoil moisture is more abundant or reliable than topsoil moisture. Walter (1985) postulated that in semi-arid savannahs there is a two-tiered environment of soil moisture. Perennial grasses with an intensive root system can only utilize the moisture present in the upper 2 meters of the soil whereas woody plants with an extensive root system can utilize the deep soil moisture and exploit cracks in the regolith. If growing season rains are adequate, perennial grasses can prevent "brush encroachment" by limiting the amount of water that reaches the subsoil and by fire in the dry season. When such savannas are overgrazed not only the living grass tissue is removed but also the standing dead matter. The litter may be consumed or pulverized, exposing the mineral soil to raindrop impact. The raindrop force is often sufficient to disintegrate the soil peds and cause surface sealing as soil fines create a relatively impervious layer on the surface. Compaction of the soil surface is also common when the hooves of grazing animals and the wheels of agricultural machinery close pore spaces and vacuoles in the soil. A compacted and sealed soil crust dramatically reduces infiltration of rainwater. Walter (1985) contends that the upper soil is more affected by the sealing and compaction than is the subsoil. The loss of grass biomass eliminates the portion in the water budget once alloted to grass transpiration. Significant rainfall events can still overcome sealing and compaction to replenish subsoil moisture. Overgrazing removes the fine fuel necessary to the movement of grassfires and allows woody plants to reach a stage where they are more fire resistant. When woody plants become well established on grasslands, a mosaic of resistant and flammable plants is formed, limiting the spread of fires even if pockets of grass have an adequate fuel load for burning. The shrub-driven succession is now in place and an alternate steady state can be said to exist (Archer, 1989; Laycock, 1991).

Walker *et al* (1981) expanded on Walter's two tier moisture explanation with a series of equations involving infiltration and perennial grass recruitment. These equations also highlighted a threshold effect where grasslands became unstable and were rapidly converted to shrublands. Again they named drought and overgrazing as possible triggering effects that could push a savannah community from a grass driven to a shrub driven succession. A shift in the timing of precipitation towards the dormant season for perennial grasses could also favor evergreen sclerophyllous vegetation that could produce growth at any season when there was adequate moisture (Walter, 1973). Some studies also claim that this successional threshold between grasses and woody plants can also be exceeded when the cover provided to rodents by the rapid spread of even juvenile woody plants results in heavy predation of grass seeds and shoots by rabbits, voles, and other rodents (Hobbs and Mooney, 1986).

A further clue to the importance of balance between topsoil and subsoil moisture is that fire frequency alone may be insufficient to maintain savannahs. Plant community composition and fire frequency were investigated on two similar mesas in Utah (Madany and West, 1983). Both mesas had comparable vegetation and topography at the beginning of European settlement in this area at the end of the nineteenth century. One mesa was heavily grazed until it became part of Zion National Park in the 1930s. The other mesa was never grazed due to inaccessibility but did maintain an average population of browsers and their predators. The mean fire frequency interval for the grazed mesa was 4 to 7 years whereas that for the ungrazed mesa was 69 years. The grazed mesa showed much higher densities and cover of pine, oak, and juniper saplings than the ungrazed mesa. A histogram of establishment for ponderosa pine on the grazed mesa showed a dramatic peak during the period of the most intensive grazing in the 1920s.

The broad generalization that the brush problem is primarily driven by hydrology may or may not apply to Ashe juniper. The western regions of the Edwards Plateau approach a semi-arid climate but the Balcones Escarpment and the Oklahoma and Arkansas portions of the range of Ashe juniper are considerably more humid. Much of the soil on the more dissected portions of the Escarpment is less than 2 meters in depth. However, the Edwards Plateau has been visited by extensive cycles of drought and has been grazed intensively for more than a century. The higher rainfall averages of the Escarpment may not represent as much effective moisture as it seems. Much of the yearly rainfall may arrive in intense storms that quickly overcome the infiltration capacity of the thin soils and extensive run-off and erosion are the main results. Indeed, the Edwards Plateau holds several records for rainfall amounts over brief periods of time that are at or near world records (Bomar, 1983).

Ashe juniper certainly would seem to have the ability to reach down to moisture supplies in the regolith. Examination of the root system of young junipers shows a strongly developed taproot of a foot or so and a spreading, fibrous mat of support and feeding roots developing nearer the soil surface. The common appearance of juniper as a pioneer species along road cuts and rocky scarps highlights the ability of Ashe juniper to establish and thrive on weakly developed soils. The fractured limestones of the Plateau hold and transport water even where soil cover is minimal and it is likely that juniper posseses the ability to reach and exploit these sources of moisture.

It is worthwhile to investigate the water budget of Ashe juniper not only as a possible explanation of the rapid conversion of savannahs to woodlands but also to determine what the effects might be on regional hydrology at a time of increasing demands on the water supply by residential and manufacturing concerns. The water budget of a plant has basically two parts: a) by what means and in what amounts is moisture delivered to the root zone of a plant and b) in what manner and amounts is this moisture utilized by the plant. The first part of the water budget can be further divided into the processes of canopy interception, throughfall, stemflow, litter interception, and infiltration into the mineral soil. These processes are both primary and surficial in that rainwater can only enter the plant or soil after it has passed these barriers. The second part of the water budget, evapo-transpiration, will be discussed but is not part of the field work of this study.

INTERCEPTION, THROUGHFALL AND STEMFLOW

During a rainfall event the canopy of a tree, shrub, or herbaceous plant will first intercept a certain amount of rain before the leaves, twigs, branches, and bark become saturated and begin to drip or convey the rainwater to the ground. The shape of the canopy, the leaf area index, the roughness of the surface of leaves and bark, the seasonal stage of the canopy, the initial moisture content of the canopy surface, and whether the precipitation is in the form of rain, sleet, or snow; all of these factors have a significant impact on the percentage of precipitation that reaches the ground (Branson *et al*, 1981). Windy conditions during or following a precipitation event may cause leaves to drop moisture that otherwise might have remained caught. Similarly, dry winds or intense sunlight following precipitation might evaporate moisture that otherwise might have been conveyed to the soil surface as throughfall or stemflow (Branson *et al*, 1981).

Throughfall is precipitation that passes through the canopy without striking a plant surface or is briefly detained then dripped. The force of raindrop impact is greatly lessened by this brief detainment. There is a certain period before the canopy is saturated and begins to drip and there is often a longer period after precipitation has ceased when the canopy continues to deliver water to the soil surface. This lag time could be important in delaying soil saturation where rainfall exceeds infiltration capacity and the excess is lost to run-off. Different canopies have different patterns and percentages of throughfall. On many trees a dripline is formed at the edge of the canopy where water is delivered in quantities exceeding that of the rainfall itself. These concentrations are most often at the expense of areas located nearer the center of the tree.

Stemflow is the water that flows down the branches and trunks to be delivered in high concentrations around the base of the plant. The bark absorbs some stemflow but this is generally lumped with the canopy interception of leaves and stems. Smooth surfaced plants with a high leaf area index and an acutely angled branching pattern such as corn (*Zea maize)* can deliver significant concentrations of stemflow to a small area at the base of the plant (Van Elewijck, 1989). Stemflow also delivers concentrations of nutrients that have been dry deposited on leaves then leached and conveyed to the base of the plant by the flowing water. Throughfall will also show concentrations where dry deposits of nutrients are important. Concentrations vary with the time spent in contact for leaching and the effective area that contributes to the throughfall or stemflow. In general, stemflow is more concentrated than throughfall (Branson *et al,* 1981).

Henderson *et al* (1977) found that canopy interception averages 10 to 20 percent of precipitation across a wide range of forest types. Helvey (1971) found interception to be greatest in a spruce/fir/ hemlock forest, intermediate in pine, and least in deciduous forest but the differences were slight. The water intercepted is not necessarily a total loss in the water budget. While the intake of moisture from leaves may not be significant, wet leaves have a lower transpiration loss than dry ones as the ambient humidity is increased (Goodell, 1963). It is certainly agreed that the canopy is an area of dry deposition of nutrients such as potassium, sodium, sulfur, calcium, and nitrates (Lindberg *et al,* 1986). Free air precipitation will contain some of these elements but the concentrations on the leaves and bark will be higher. These elements are then leached and deposited on the soil surface as throughfall or stemflow. Any moisture that remains on the canopy can be lost to evaporation but the nutrients remain reconcentrated in temporary storage. In nutrient poor environments with high degrees of run-off some highly soluble nutrients would be lost without temporary storage on leaves and bark.

Junipers have a short, scale-like leaf that remains year round somewhat like that of the spruce/fir/ hemlock forest, reported by Helvey (1971) to be on the high end of canopy interception. Losses may be highest where snow is a significant part of the precipitation total. Not only can snow accumulate in greater amounts than does rain before becoming throughfall or stemflow but also it can sublimate directly back into the atmosphere without ever becoming liquid. Many western juniper species live in a climate where snow is significant but Ashe juniper does not, except perhaps in the northeasterly portions of its range. Skau (1964) investigated two juniper species: a) Utah juniper (*J. osteosperma* (Torr.) Little) and b) alligator juniper (*J. deppeana* Steud.) for interception, throughfall, and stemflow. His findings have been used by Thurow (1994) and others as an approximate value for Ashe juniper because the canopies were considered to be similar. Skau claimed 17% of the precipitation was intercepted and lost by the canopy. Eddleman (1983) reported that a large *Juniperus occidentalis* in Oregon intercepted 74% of the total annual precipitation of which snow was a significant part.

Most early studies determined canopy interception by measuring throughfall accumulations in four randomly placed canisters, averaging that amount, and then subtracting the average from the accumulation collected in a nearby clearing. Wilm (1943) is often cited as a methodological source. Four random spaced data points would be unable to detect a complex pattern and would almost surely miss very localized points where branches drip throughfall at "elbows" in amounts comparable to that of stemflow. Such branch elbows frequently yielded accumulations 2 or 3 times that of the free air rainfall in this present study. The other method sometimes employed is to determine a threshold at which the canopy reaches saturation and begins to have significant throughfall. Collings (1966) used this method to arrive at the estimation that the first .5 inch of rainfall in a summer storm is lost to canopy interception in a juniper/pinyon forest. A very light rain will have a much higher proportion of interception than will one of greater intensity or duration. Some studies try to express throughfall or interception as a function of storm size, and weight that number by the frequency or importance of such storms to a region (Thurow *et al*, 1987).

Certainly other species of trees, shrubs, and grasses have their own percentages of canopy interception, throughfall, and stemflow. Live oaks (*Quercus virginiana* Mill.) on the Edwards Plateau are reported to intercept 25.4% of rainfall when they are found in mottes (Thurow *et al*, 1987). This study used over 40 random data points per motte to determine throughfall. Some chaparral shrubs have been shown to have interception rates of 4 to 31% depending on size, density, and type of precipitation (Branson *et al*, 1981).

Grasses require a different methodology and their rates of stemflow and canopy interception are frequently measured in the laboratory using rainfall simulators. These measurements may not be directly comparable to those obtained in the field with tree species. The tall bunchgrass big bluestem (*Andropogon gerardi* Vitman) had canopy interception losses of 57 to 84% and the sod forming buffalograss (*Buchloe dactyloides* (Nutt.) Engelm.) of 17 to 74% depending on rainfall intensity (Clark, 1940). Using different methods and accounting for the importance of storm size, Thurow *et al* (1987) determined that the mid-grass sideoats gramma (*Bouteloua curtipendula* (Michx.) Torr.) had canopy interception losses of 18% while the shortgrass curly mesquite (*Hilaria belangeri* (Steud.) Nash.) had losses of 10.8% of the annual rainfall for the Edwards Plateau.

Grasses tend to retain as standing dead matter materials that trees and shrubs would most likely shed to accumulate as litter above the soil. Rainwater that has moved through the canopy as either throughfall or stemflow undergoes additional interception losses in the litter before it can reach the mineral soil. Thurow *et al* (1987) assign an average of 20.7% of the rainfall to litter interception beneath live oak mottes. After totaling losses, only 53.9% of the average rainfall reaches the mineral soil beneath live oak.

As was the case with canopy interception, litter interception is not necessarily a "loss". A thick layer of litter resistant to decay beneath oaks or junipers would : a) reduce evaporative losses from the mineral soil; b) serve as a secondary storage area for nutrients delivered by throughfall or stemflow; c) be the source of organic matter to the soil surface improving nutrient balance and water retention capacity and; d) resist compaction of soil pores that enhance infiltration. Ashe juniper can build a litter layer 3 to 7 centimeters deep because the scale-like leaves decay so slowly. Yager (1993) determined that Ashe juniper litter retards germination not so much by allelopathic substances as by being a poor media for germination. Finely ground litter had no problems in allowing germination, but apparently the intact litter was slow to wet and quick to dry. Other species of juniper have been observed to exhibit hydrophobic characteristics. Scholl (1971) thought that the top layer of litter and soil of *J. osteosperma* was hydrophobic. Gifford (1970) thought that the juniper litter contributed to overland flow in a juniper/ pinyon community. Yager (1993) was aware of these findings and of the fact that Bonnet (1960) had reported from field observations that the soil beneath Ashe juniper litter often remained dry after a rainfall event but found no hydrophobic characteristics in a thorough study. She did observe, however, that the drainage tended to follow preferential pathways so that wetting might not be initially uniform.

Stemflow is by far the most difficult input to quantify for junipers due to their shaggy bark and irregular trunks that branch so close to the ground in some species. Usually a thin metal collar is placed about the trunk, sealed and formed into a spout that leads to a collecting vessel. Skau (1964) reported stemflow in junipers to be negligible. Young *et al* (1984) reported .53 liters of stemflow per centimeter of rainfall. Thurow *et al* (1987) measured 3.3% of the annual rainfall delivered to the soil as stemflow. They added stemflow to throughfall to determine the amount of precipitation that reached the litter layer. Other researchers treat stemflow separately or ignore interception by the litter layer and thus reach different percentages of rainfall to reach the mineral soil.

Stemflow concentrates water and nutrients from the entire canopy and delivers them to a small substrate area. The soil at the base of the trunks of live oaks, an area with a radius of 100mm based on infiltration capacity, received 212% of the yearly rainfall as stemflow (Thurow *et al*, 1987). Young *et al* (1984) tested the stemflow of Western juniper (*J. occidentalis*) for nitrate-nitrogen levels and found them to be greatly increased over the levels in free air precipitation for only the first rain to break the summer drought. Similarly, they found increased nitrate-nitrogen levels in the soil at the base of the tree. Almost certainly, substances left on the canopies by dry deposition would be leached and found in increased concentrations by stemflow. Grasses also have stemflow but this is more difficult to measure or to separate from throughfall. Concentrations of 150 to 200% of open air rainfall have been determined to occur at the base of some forms of grasses (De Pluvey, 1982). Much of the research on stemflow in grasses has been done on corn and other agricultural plants but not on range grasses (Van Elewijck,1989).

INFILTRATION

Infiltration is the process by which water moves downwards from the soil surface through the soil profile. It is not a static process but rather one in which rates are normally high at the onset of precipitation, when many of the soil pores may still be full of air. In time the soil becomes saturated and the infiltration rate drops rapidly until it reaches a steady state, usually termed terminal infiltration rate or *infiltration capacity* (Thurow and Carlson, 1994). What seems at first a simple process quickly becomes a nightmare of physics when one considers the infinite variability of soils both horizontally and vertically. Darcy's Law states that water tends to move from a location where potential energy is high to one where potential energy is low (Miyazaki, 1993). The three components of potential energy are matric potential, gravitational potential, and osmotic potential. Only in clayey soils is osmotic potential an important constituent but then most developed soils contain a clay fraction. Matric potential and gravitational potential are the driving forces of infiltration in most cases. Gravitational potential is predictable and well understood. Matric potential describes the interaction of soil particles and water in soil pores. Matric potential is a friction, a loss of total potential of water due to the microscopic roughness and tortuosity of the micropores through which water travels in the soil. The terms saturated and unsaturated hydraulic conductivity are also used to describe conditions of matric potential. When the volume of water in a soil decreases, the cross-sectional flow area decreases, while resistance and tortuosity increase (Miyazaki, 1993). The measurement and prediction of saturated or unsaturated conductivity is difficult enough in the lab with an inert aggregate but a living soil presents several orders of magnitude more difficult.

Soils are clearly an amalgam of organic and inorganic constituents and processes. In a single handful of soil, the pore size may be controlled by the physical properties of the parent rock but the pore connectivity might derive from the pathways of now decayed rootlets of a grass that once occupied the site. This study will focus on those aspects which might be ascribed to differences of plant communities on the same soil. Field measurements of infiltration might lack much of the precision and isolation of inputs that is available in the laboratory but they are inclusive of the multitudinous factors and states that describe a biological condition.

Much of the fieldwork on infiltration has been done on soils used for agriculture or grazing. For both the Edwards Plateau and the range of Ashe juniper, grazing would most likely be the dominant land use. Grazing adds humans to the mix of physical, chemical, and biological forces that influence soil processes such as infiltration. In grazing, as opposed to herbivory, cattle, sheep , or goats may be confined to a site in densities and for durations that are beyond the carrying capacity of the grasses or soil. Additional feed from other fields or regions is brought in to sustain animals on a range that is declining in production of forage or where the condition is simply ignored. Much of the differences in infiltration rates, bulk density, or percentage of organic matter in the soils of this study may have less to do with the different inputs of grass and juniper communities than with the low palatability of Ashe juniper to browsers. Only the Saint Edward's site in this study could be said to have incurred minimal disturbance by grazing or agriculture. Gifford and Hawkins (1978) published a review showing that no known grazing system improved the infiltration rates of rangelands in North America. Higher grazing intensities usually resulted in lower infiltration rates. Cessation of grazing improved hydrological conditions but often slowly.

The most important factor correlated with high infiltration rates is high plant biomass or percentage of cover (Thurow *et al*,1986). The amount of plant cover may well be more important than whether that plant cover is tree, shrub, or grass. Other studies indicate that infiltration is higher in descending order by life form from trees, to shrubs, bunchgrasses, and sodgrasses (Box, 1961; Wood and Blackburn, 1981). Above ground biomass would closely follow this lifeform progression also. However, when grazed, the grasses lose biomass and litter. Bare ground exposed in the grass interstices frequently increases. Junipers attain high degrees of cover and biomass because they are less palatable to goats, deer and other browsers than are many other plants. The positive correlation between percent of cover and high infiltration rates may indicate that lessening raindrop impact is important. The force of rainfall on bare ground can disaggregate the peds causing soil sealing and a lack of pore space at the soil surface (Wilcox and Wood, 1989). Canopy interception not only decreases the force of rainfall but slows the input of water, which can be significant in a time sensitive process such as infiltration.

The size and connectivity of pores in a soil determines how much water or air can be stored as well as the rate of flux between the two phases. Pore size is strongly influenced by the particle size distribution of the soil. Larger particles tend to produce larger and more connected pores. The effective unit in most soils, however, is not the particle but the ped or aggregate of organic and inorganic particles that function as a crumb structure. In a ped clay-sized particles bind aggregates of sand, silt, and organic matter to form a larger unit and larger pores than would be possible without the connective capacity of clays. If peds are disaggregated by the force of raindrop impact, the pore spaces may be greatly reduced forming a thin layer of low permeability which drastically reduces infiltration.

A high biomass and percentage of plant cover may also influence the amount of litter present, which has been shown to correlate with higher rates of infiltration (Wilcox *et al*, 1988). A litter layer would add further physical protection from raindrop impact as well as being a source of organic material in the soil. Infiltration may be aided by the presence of significant amounts of organic matter in the soil because the particles are: a) large with large intervening pore spaces b) absorptive, with a high water retention capacity c) effective in promoting connected micropores by encouraging soil microfauna and root development and d) the source of chemicals and gases that when combined with water develop the soil (Facelli and Pickett, 1991).

Bulk density or weight per unit of volume is a good measure of porosity in soils of similar composition (Buol *et al*, 1989). A compacted soil will have less pore space and less connectivity between the pores as well as a higher bulk density. Bulk density is frequently measured by taking a core of the upper 10 or 15 centimeters of the soil, air drying it, weighing it, and calculating the weight per unit of volume. Used in this manner, bulk density is an estimation of surficial conditions and soil structure. Thurow *et al* (1986) investigated hydrologic characteristics in three plant communities, oak mottes, bunchgrasses, and sodgrasses, and found that bulk density was significantly lower beneath oaks than on grasses no matter what the lifeform or grazing regime. The lower bulk density also correlated with higher aggregate stability, higher percentages of organic matter, and higher infiltration rates. The oak mottes acted as sinks for the sediment production that was most active in the grass interstices. Runoff reached the oaks and entered the soil due to the higher infiltration rates leaving soil fines that had been carried by the runoff to gradually mound the area beneath the trees. McCalla *et al* (1984) also found that bulk density had the greatest predictive value in determining infiltration rates.

In regions that have a more pronounced freeze/thaw cycle for the soil than does the Edwards Plateau, the bulk density is lowest in the spring and then increases throughout the summer (Wilcox, 1994). The agents for lowering of bulk density in areas without significant freezing may well be soil macro and microfauna. Anything which leaves tunnels in the upper soil, including plant roots, could be responsible for improving porosity, bulk density, and infiltration. Plants could contribute to these processes not only directly but also by providing food and a moderated environment for the soil fauna. A thick layer of litter might be most important in temperature regulation and addition of organic matter to the soil.

The practice of grazing increases bulk density by removing biomass and litter while also compacting the ground with the action of the grazer's hooves. Wood and Blackburn (1981) believe that the effects of trampling are greatest in the upper 3 to 5 centimeters of soil. There has been a good deal of speculation by Alan Savory (1978) that the hoof action of excited cattle breaks up the soil crust, removes dead matter from bunchgrasses, and in general stimulates the establishment and growth of grasses. Published, experimental evidence has yet to confirm these unorthodox views. Wood and Blackburn (1981) concluded that all grazing systems have a negative impact on infiltration, and that grazing in greater intensities and durations has the greatest effects.

Infiltration rate is of course strongly related to the depth of soil. Greater soil depth equals greater storage capacity in most cases. A greater storage capacity will also extend the time interval before saturation is reached. For shallow soils, small changes in soil depth will have much greater impacts on infiltration rates than may at first be imagined (Wilcox *et al,* 1988). Shallow soils are common on slopes of the Edwards Plateau. When measured by a rainfall simulator, the infiltration rate of a soil on a pronounced slope may be much higher than that of a similar soil with less slope because of the action of throughflow. Throughflow or interflow is the term used to describe water that has infiltrated into the soil but moves laterally due to a combination of slope and impervious layers until it exits the soil as a shallow seep to either re-infiltrate or become part of the run-off. The combination of shallow soils, steep slopes, and the stair-step topography of weak and resistant bedrock makes throughflow an important process on the Edwards Plateau and in particular on the Balcones Canyonlands portion.

If the entire slope is involved in a normal precipitation event, each higher slope zone is contributing soil water moving laterally to each lower slope zone. The infiltration rate may not be much different from that of a similarly shallow soil in a horizontal position.. A rainfall simulator on a steep slope, however, loses soil water laterally beneath the sampling area but does not gain any from above. Most rainfall simulators have been limited to sites of relatively little slope perhaps due to the bulkiness of their pumps, tanks, and trailers. One hand held simulator has been developed for measuring infiltration on very steep slopes but the small sampling area (1 square meter) makes it probable that rates measured will be significantly higher than in a natural precipitation event (Wilcox *et al,* 1986).

Rocks on the soil surface and within the soil itself are negatively correlated with infiltration (Wilcox *et al,* 1988). Buried rocks obviously lower total porosity and storage capacity. Surface rocks may provide some protection from raindrops impacting areas of sparse vegetation. A rocky carapace on the soil may well be the result of poor infiltration and subsequent erosion rather than its primary cause.

Large continuous openings on the soil surface or macropores often form preferential channels of infiltration through which water moves into the soil at greater volumes and velocities than through the surrounding soil (Bevin and Germann, 1987). These macropores derive from many sources, such as fossorial rodents, other soil fauna notably ants and earthworms, the living and dead roots of plants in particular of trees, and cracks in the soil caused by drying or freezing. These macropores can form in a year or so but may persist for perhaps a century. Even a small amount of macroporosity can increase the flux density of soil more than one order of magnitude in soils of low to moderate matrix conductivity (Bevin and Germann, 1981). The flow through these macropores is turbulent and not laminar as in the surrounding soil matrix. Water can bypass areas of low permeability to deliver water to the subsoil much more rapidly and in greater quantities through macropores. In general, Bevin and Germann (1982) believe that macroporosity is most developed in undisturbed, usually forested areas. Macropore channels can be studied by the use of dyes or tracer elements. Although the wood of Ashe juniper is slow to decompose, soil water often flows preferentially along the surface of roots. The moister and less extreme temperatures beneath the canopy of juniper as well as the presence of litter and high percentages of organic matter in the soil may well be a favorable environment for soil fauna as compared to that on the grasslands. A higher degree of macroporosity may form beneath juniper than grasses and it may persist better there, where it is protected from the trampling of grazers and the soil sealing of raindrop impact.

The importance of infiltration rates to regional hydrology is that most precipitation that does not infiltrate becomes run-off which has the capacity to cause interrill erosion (Thurow and Carlson, 1994). The potential for significant erosion is high when the presence of steep slopes, thin soils, and regular episodes of drought which are common on the Edwards Plateau are considered. The Edwards Aquifer, which dominates the Balcones Canyonlands portion of the Edwards Plateau, is unusual in that up to 80% of its recharge comes from crack systems in the bedrock of streams and not from the slow, deep drainage into the bedrock of the total catchment area (pers. comm. Sharpe, 1996). Schemes have been proposed to increase run-off and thus to increase capture of groundwater. There are at least two problems with equating increased run-off with increased groundwater supplies. The first is that factors which increase run-off may well increase the amount of water in streams at peak periods but can also decrease the time period that these streams carry water. Water infiltrated into the soil and regolith could be a slower delivery system to the streams which could allow water to be captured by the bedrock crack system for longer periods of time. A stream that carries water the breadth of its channel may capture more water than one that is underfit but it is not certain that increases in depth of flow equate with more efficient capture. The second problem is that high run-off can bring transported silt and clay that can seal the cracks and fissures in the streambed defeating the purpose of increasing groundwater capture. For the many other aquifers of the Edwards Plateau which do not have the special characteristics of the Edwards aquifer, increased run off is usually a loss of potential water for deep drainage into the aquifer.

GAS EXCHANGE CHARACTERISTICS

The last important component of the water budget of any plant is evapotranspiration. The quantities and efficiencies with which a plant uses moisture affects how much soilwater passes through the vadose zone to become groundwater that can be tapped for human purposes (Branson *et al*, 1981). Most western juniper species have been decried as water wasters. Owens and Schreiber (1992) compared the gas exchange characteristics of live oak and Ashe juniper on the Edwards Plateau. They found live oak to be more efficient than juniper in capturing soil moisture when it was abundant. Live oak leaves increased net photosynthesis, transpiration, and conductance linearly in response to precipitation. These same processes showed little response to increased soil moisture in juniper. Both live oak and Ashe juniper have observed drought tolerance. Live oak, however, can respond more quickly when moisture is present than can Ashe juniper. The inference is that live oak can utilize more soilwater than can Ashe juniper when rains are infrequent. Perennial grasses have much different gas exchange characteristics than do trees and may well use less soilwater acre for acre than do trees. Many grasses may all but cease photosynthesis during drought or winter. When moisture is finally available, grasses respond more slowly than do evergreen trees because they must acquire new foliage (Owens and Scheiber, 1992).

Field Methods

The objective of this study is to determine what differences in soil processes (such as infiltration) and which differences in soil properties (such as bulk density, water repellency, percentage of organic matter, and particle size distribution) might be attributable to the effect of existing vegetation. The two plant communities chosen are Ashe juniper and grasslands. Both of these communities are widespread, variable in composition, and interlocked in the vegetational mosaic of the Edwards Plateau. In order to highlight the effect of vegetation, a wide range of soils and site histories were selected.

SITE SELECTION

The juniper sites were chosen with regards to: a] the purity of the stand and b] the relative age of the stand. Junipers are by no means monospecific even in the densest cedar breaks. Junipers are frequently intermingled with oaks, elms, and hackberries. Other trees, shrubs, forbs, and grasses were found in all sites but the intention in site selection for the placement of the infiltrometer was to minimize the effect of other trees which might be adding significant amounts of organic matter to the soil.. The infiltrometer sites were placed least twenty-five feet from the canopy of a mature tree of a different species. The litter was examined to determine that it was mostly of juniper origin and that wind or water movement had not incorporated the litter of other tree species with it. Somewhat less vigilance was given to excluding the effect of understory shrub litter. Many grasses exist in varying densities beneath juniper canopies but no effort was made to choose infiltrometer sites free of grasses other than to insure that the site was well within the tree canopy and not beneath an opening of branches or trees. Frequently lower branches had to be pruned away to set up the infiltrometer.

Some consideration in site selection was given to the relative age of the juniper stand in terms of young, adult, or mature. This classification seeks to detect a pattern of slight changes in soil properties and processes in a young stand and more pronounced changes in a mature stand. No attempt was made to derive an absolute age for a juniper stand except at St. Edwards where accurate records were available. Coring an Ashe juniper would be problematic due to its branching habit, which produces multiple trunks which frequently begin within six inches of the soil line. Growth rings of the branches could easily be mistaken for growth rings of the trunk, if Ashe juniper can be said to have a single trunk. Such a mistake could lead to a significantly greater age being assigned to a specimen. Ashe juniper is also a good candidate for a tree that is able to put on more than one set of annular rings a year. This species is evergreen and inhabits a mild climate with rainfall peaks in both the spring and fall. Year round photosynthesis with several growth spurts is a distinct possibility.

Basal circumference was measured on selected trees but because of the deep fluting of the multiple trunked specimens it might seem more impressive in print than in the field. Basal circumference has been used to age date Ashe juniper within a limited area but such estimates could be misleading when applied across the range of soils and microenvironments that this study entails; therefore, relative age terms derived from growth form and appearance are used in this study. Seedling means a specimen possessing the bluish-green, prickly juvenile foliage. Such specimens are generally less than a foot in height and perhaps less than two years in sites were then sought to match them. The actual placement of the infiltrometer was also chosen as a best example for grasses being free of shrubs or trees and with little bare ground.

FIELD DESCRIPTION AND SAMPLING

In order to quantify the vegetational composition of the juniper and grassland sites, fifty-foot crossing transects were laid out with the infiltrometer plot as the center. One axis ran parallel to the slope and the other ran perpendicular to the slope. At one foot intervals the intercepted vegetation was described by genus and species if possible and by lifeform (i.e. graminoid) if identification was doubtful. Many young and non-reproductive specimens of forbs and grasses were encountered and had to be described by lifeform. Many bare spots, particularly beneath juniper, were encountered and listed as such. An effort was made to describe the edges of the shrub and tree canopies while still noting any understory vegetation. The crossing transects were chosen because they describe more adequately the patchy vegetation mosaic than the more traditional one hundred-foot transects. Frequently, one arm of a juniper transect might extend into the adjoining grassland and viceversa.

Four soil samples were taken at each infiltrometer plot whether in juniper or grassland plots. Each sample site was located several feet upslope, downslope, left, or right of the infiltrometer plot. Care in placement was taken to avoid surface rocks and plant crowns. First the litter was tested for water repellency using a dropper, and rated as absent, slight, or strong. Next the litter was removed and the mineral soil also tested for water repellency. Three or more readings of compressibility were taken on the soil surface with a pocket penetrometer held perpendicular to the ground surface (Pérez, 1991). Some of the juniper soils were very near the lower threshold for an accurate measurement by the penetrometer while some of the grassland soils seemed too resistant. The actual soil sample was taken with a pair of steel cylinders 5 centimeters in interior diameter that were driven to a depth of 7.5 cm. This depth was chosen because previous studies had suggested that most of the effects of trampling and compaction lie just above this depth (Wood and Blackburn, 1981). After both cylinders were driven to depth, they were excavated, capped, and emptied into one specimen bag. If an unseen obstruction such as a rock or root prevented the cylinder from being driven to depth, the cylinder sampling site was moved and penetrometer readings were taken again.

INFILTROMETERS

Mechanisms used to simulate and measure infiltration are called infiltrometers. Many professionals such as hydrogeologists, range scientists, pedologists, agriculturalists, engineers, and geomorphologists are concerned with infiltration and fashion various infiltrometers suited to the parameters of their research. There are both lab and field techniques of measurement. Laboratory approaches offer greater precision and control of variables but that control is achieved by strongly simplifying soil/water processes. The most common lab infiltrometer would be a Darcy tube which contains a soil, aggregate, or rock sample through which water flows from higher to lower hydraulic head while its rate and volume is measured. If it were possible to sample an undisturbed core that fit tightly in the tube, the Darcy tube would be the most accurate, fine scale measurement of infiltration available. When the sample is not lithified but consists of an aggregate or a soil, it becomes increasingly difficult to maintain the integrity of factors important to infiltration such as: macropores, vacuoles, compaction, surface phenomena, horizons, and vegetation. At best the Darcy tube measures the inherent porosity due to particle size of a sample, but has problems replicating hydraulic conductivity. Darcy tubes are most commonly used by hydrogeologists on lithified materials in the phreatic zone.

Field infiltrometers focus on surficial processes and operate on a scale of 3 to 60 square feet. A major division is between flood infiltrometers and rainfall simulators. Flood infiltrometers are frequently used by engineers and agriculturalists. Water is ponded in a furrow or a series of cylinders. Infiltration is calculated as both a function of time and the amount of water added to keep the reservoir at a constant level. Ponding may simulate flood irrigation or a reservoir's ground water loss but it does a poor job of mimicking rainfall. Cylinder infiltrometers are less useful as slope and stoniness increase. This study was originally attempted using a cylinder but the combination of hydraulic head and subsurface disturbance caused by driving the apparatus into the stony ground gave widely varying and unrealistically high rates of infiltration. Hydrogeologists also employ a flood infiltration technique requiring the placement of lysimeters at various depths that register differences in vacuum pressure. This method gives a good picture of infiltration at moderate depths (1 to 6 feet) but has problems with slope and with the placement of lysimeters without affecting soil structure.

Rainfall simulators employ pump-driven nozzles or gravity flow devices to mimic rainfall. Range scientists in particular are concerned with raindrop size and velocity in their erosional studies. Modern nozzles can reliably create a consistent droplet size and pattern. Some simulators point the nozzles upward to gain greater impact velocity; some point downwards to minimize the effect of wind; some are mounted on a mechanical boom 7 feet above the soil surface and are believed to obtain 70% of the terminal velocity of a natural raindrop; and some consist of a single nozzle mounted on a tripod sampling a 3 foot diameter circle (Branson *et al*, 1981, and Wilcox *et al*, 1989). Most methods employ a wetted buffer zone to slow the loss of infiltrated water moving outwards from the sampling area. The smallest tripod mounted simulator uses a 1,000 liter water storage tank and gasoline powered pump to produce pressure (Wilcox *et al*, 1989). The larger mobile infiltrometers use 300 gallon tanks mounted on two wheeled trailers. Rainfall rates are calculated either by a standard gauge placed in the sampling area or by calculating rate of application per surface area. These simulators can mimic rainfall over a fairly large sampling area (20 to 60 square feet) without disturbing the soil, but they lack true portability and have problems with vegetation taller than grasses. The most portable tripod version is mobile within garden hose range of a truck and can handle sloping ground but sacrifices scale of sample.

Gravity rainfall simulators can be as large as the pump driven versions but tend to be smaller. The droplets are formed in a grid by either holes along a pipe, hypodermic needles, or lengths of yarn. Compared to the pump driven models these gravity versions tend to lack in impact velocity and randomness of location. The apparatus I used was built by Karen Jarocki of the University of Texas Geology department for her Master's thesis, based on a design by Jorgensen and Gardner (1987). The two reservoirs hold 20 liters of water each. The sampling area is 2 feet by 3 feet and the droplets fall to the soil surface from a height of two and a half feet. The droplets are formed by pinholes in 9 copper pipes arranged in rectangular grid 4 inches apart with a hole every inch, or approximately 180 orifices. A drop spreading device built of screen wire was placed 4 inches below the distribution grid to spread the droplets in a random pattern but this did not occur. Droplets impacted in much the same spot throughout the test and showed a linear pattern, unlike rainfall. Because the apparatus is gravity fed the rate of application is high at the start and diminishes throughout the test. This pattern is not abnormal for rainfall but makes it difficult to calculate the true rate of infiltration. Since only one of the juniper soils produced any appreciable run-off, the rate of infiltration of most of the juniper soils can only be said to be above that of the capacity of the apparatus. What was measured was the response to a simulated rainfall event on a pair of grass or juniper dominated soils. This apparatus did deliver fair portability, a good response to slope, and the ability to operate under a low juniper canopy

INFILTROMETER PLACEMENT

The infiltrometer was positioned with its long axis parallel to the slope. The legs were adjusted to make the tubing grid horizontal instead of following the slope and pitch of the soil surface. Each plot was chosen to have some slope so that any water not infiltrated could run onto a collection plate and into a collection bucket. Metal strips were driven to a depth of one inch on the remaining three sides to contain and channel any overland flow towards the collection plate. On the grassland plots, the grasses were clipped and discarded with as little disturbance to the soil surface as possible. The intent of this procedure was to nullify any interception component by the grass canopy, since measurements on juniper were also done with canopy effects being absent. Admittedly, the loss of the grass canopy could lead to soil sealing because peds were disaggregated by raindrop impact, but the situation was the same for juniper and the size and velocity of the raindrops was well within the regional average. In general it is believed that infiltrometers overestimate the rates of infiltration because of "edge effects" so any slight decrease in infiltration caused by clipping the grasses is a corrective if an advantage is not afforded the juniper plots. No effort was made to remove the litter from either the grass or juniper plots but bunch grasses hold a good deal of their litter as standing dead matter which was removed in the clipping.

Many researchers prefer to soak the plot with water at this point, then to cover it with plastic and allow the soil to attain field capacity overnight. It is certainly true that the initial conditions are the most important factors in determining the rate of infiltration, but the pairwise comparison of vegetation is the main focus of this study rather than any absolute rate. It was decided to run a full infiltration test under initial conditions which differed greatly from one location to another but only slightly between the grass and juniper plots. The full test was run again the next day on the same plots after they had reached field capacity. In this way much useful data was gained about the infiltration response to rainfall under both dry and saturated conditions. Real comparisons of rates between different locations exist only in the saturated test performed the second day. The initial conditions between different locations varied too much for location/location comparisons. Initial tests could not be compared between locations but it was possible to see that dry conditions did not change much the pattern of response when a juniper plot was compared to a grassland plot.

The procedure for measurement was to open the mixing valve and to start the timer when water began to emerge from the tubing grid. Often the valve had to be closed further during the first minute to achieve a reasonable approximation to rain. One of the main limitations of this apparatus was that water could not be administered at the same rate on different days nor at the same rate for the duration of any one test. The reasons for the variance are several. The mixing valve had to be mostly closed in order that water would drip and not gush from the orifices. Being a gate valve, there is no point of calibration that assures that the degree of openness today is not different from that of yesterday after transportation and storage. Even with careful treatment during a single day flow rates can change when the apparatus is moved between plots and a large air bubble develops in the supply line. When the mixing valve is opened sufficiently to eliminate the bubble, it is difficult to return the valve quickly to the setting under which the previous test was conducted. An effort was made to monitor and adjust the rate of flow for the first few minutes of the test but different flow rates resulted. This would sometimes drain the reservoirs in but twenty-five minutes while at other times it took more than thirty-five minutes to reach the same point. The main emphasis was made to keep the rates consistent on juniper and grass on the same day. Variance between days or locations was less successfully dealt with. The second pattern of variation resulted from the fact that the water was gravity fed and not pressurized. As the hydraulic head decreased, the rate of flow slowed down. During the initial five minutes, ten to twelve liters of water might flow. During the final five minutes, only four to six might be applied. This pattern is not dissimilar from that of many convectional storms on the Edwards Plateau, but it does confound the pattern of increasing time and decreasing rates of infiltration seen in many textbooks.

At the end of each five minute interval, two things were measured. First the amount of water applied was noted and often there were small differences between the left and right reservoir. Next, the collection bucket was exchanged for a dry one and the accumulated run-off was measured in a thousand milliliter graduated cylinder. Any reading of less than thirty milliliters was called a trace because that was the minimum reading on the cylinder. Often it was necessary to empty the collection bucket several times during a five minute test period lest it overflow.

THROUGHFALL TEST PLOTS

At the Balcones Field Laboratory throughfall measurement plots were established in the two juniper stands that were previously tested for soil properties and infiltration. The stand in the Experimental Garden was termed the bush grove in reference to its characteristics and perceived age. The stand in the site named Upper BFL for soil and infiltration tests was designated as the mature grove. In each grove a grid of canisters were placed at 60 cm intervals to measure throughfall accumulations after each rainfall event. The grid crossed at the trunk of the largest and most accessible tree in the mature grove. The bush grove was composed of at least four Ashe junipers of roughly equivalent age. Here one axis of the grid passed through the largest trunk of the largest juniper in the center of the grove. The other axis in the bush grove lay between the canopy edge and the trunk of the nearest juniper, both of which were approximately 240 cm from the canopy edge. This axis did not then cross the other at the dominant trunk so measurements of some interior points were not recorded.

After each rainfall event, the rainfall accumulation was measured from a standard collector mounted 150 cm above the ground and more than 10 meters away from any surrounding obstruction. This collection device was in the Experimental Garden. The throughfall canisters were made to approximate that of the rainfall canister which was 10 cm in width and 30 cm in depth. The accumulation of throughfall was measured in millimeters with the same instrument used to measure rainfall. The throughfall canister was then emptied and repositioned at the same point for the next event. The procedure was the same for the mature grove.

Initially, stemflow was measured in both the bush and the mature grove. A thin, metal collar was placed about the trunk to lead the stemflow into a spout and then a large collection canister which was sealed so that no water other than stemflow could enter it. Leakage that allowed stemflow to bypass the collar proved to be a problem despite several attempts to seal the gaps. These leaks were so severe on the mature trunk that measurements of stemflow on this trunk were eventually abandoned as being too inaccurate. The bush grove trunk yielded better data so all stemflow amounts noted in this study are from this single trunk. The later measurements are perhaps more accurate than the earlier ones because leaks were plugged and a larger collection canister provided after problems developed. In an effort to ascertain the direction and magnitude of error in the stemflow measurement, a known amount of water was applied above the collar and compared to that amount which was collected. The stemflow collector caught only half of the amount of water applied. No effort was made to account for this under-reporting other than to mention it here. All stemflow measurements reflect actual volumetric accumulations.

LABORATORY METHODS

The soil cores were air dried for several weeks and then weighed to ascertain bulk density. No effort was made to remove large organic matter, stones, or particles greater than 2 mm in size for the bulk density measurement. A 30 to 40 g subsample was taken from each of the 16 grass and 16 juniper dominated soils to measure percentage of organic matter and particle size distribution. The subsamples were first ground with mortar and pestle to break the aggregates and then sieved to remove all material greater than 2 mm in size called gravel. The subsamples were weighed before and after treatment in a muffle furnace for 4 to 6 hours at slightly less than 400 °C to ascertain the percentage of organic matter present in each subsample by the loss-on-ignition method. This temperature was chosen because fine soil grains are not affected by it (Ball, 1964).

The percentage of fines was then determined for each subsample using the hydrometer method. A threshold value of 50 microns was used to describe the sand/silt boundary. All soil particles equal to or less than 50μ were regarded as fines and their percentage of the entire sample was then computed.

ANALYSIS PROCEDURES

Throughfall and stemflow measurements for each rainfall event were entered in an EXCEL spreadsheet. A number was assigned for each measurement at every event to express the level of confidence in that measurement. The throughfall canisters were occasionally partially knocked over by the action of wind or animals. If these canisters had any accumulation of throughfall at all, they were given a level of 2 *i.e.*, moderate confidence. If a canister were completely knocked over and had no throughfall accumulation, it was given a confidence number of 3, low. No disturbance of the canister earned a confidence number of 1, high. Stemflow measurements were never given a confidence number of 1 to reflect the doubt that even under undisturbed conditions only a percentage of the true stemflow was measured.

The soil and infiltration data were also entered in EXCEL spreadsheets and the charts and statistics were produced in this software package except for the throughfall maps. The throughfall maps each describe a single event of low, medium, or heavy rainfall intensity. The production of these maps involved SURFER and MAP INFO software packages. In order to interpolate a throughfall accumulation for those points between data canisters, the Kriging method was used with a value equal to the rainfall being assigned to points outside the juniper canopy. Kriging is a technique for interpolating values at fixed grid points from a set of known points. The technique is one that modifies the interpolation weighting scheme using the statistical trends measured in the set of original known points. Given a model of the variance of the original points in two dimensional space, a variogram model, the technique finds interpolation weights that result in regularly spaced grid values that express trends suggested by the original data. These maps of throughfall were produced using Golden Software's Surfer package using a linear variogram model (Golden Software, Inc., 1995).

Site Histories and Descriptions

SAINT EDWARD'S UNIVERSITY

It is quite rare that one would have access to a closely observed plot that has been maintained and documented for more than forty years now. In 1954 during an extended drought a 0.11 hectare enclosure was fenced on the campus of Saint Edward's University in Austin, Texas by Brother Daniel Lynch to be included in a study of grassland succession. This plot enclosed a portion of a relic grassland of some 8 acres on the Western edge of the Blackland Prairie and near the Balcones Escarpment that marks the Eastern edge of the Edwards Plateau. The wire circumscribed a mosaic of two grassland communities composed of little bluestem (*Schizachyrium scoparium* var. *frequens* (C.E. Hubb.) Gould) which was dominant in the portion with the deeper soil and red three awn (*Aristida longiseta* Steud.) sharing dominance in the shallow segment with several forbs. At the time the study began on October 20, 1956, some 123 species were represented: 4 trees, 5 shrubs, 1 woody vine, 93 forbs, 16 grasses, 2 sedges, and 2 rushes. At this point none of the trees were over 6 feet tall (illustration 1). The entire grassland had been lightly grazed by horses for some time before the enclosure was fenced in 1954. Fire disturbed the plot during 1957. Slowly the unfenced portions of the grassland were brought into the maintenance pattern of the campus and mowed periodically.

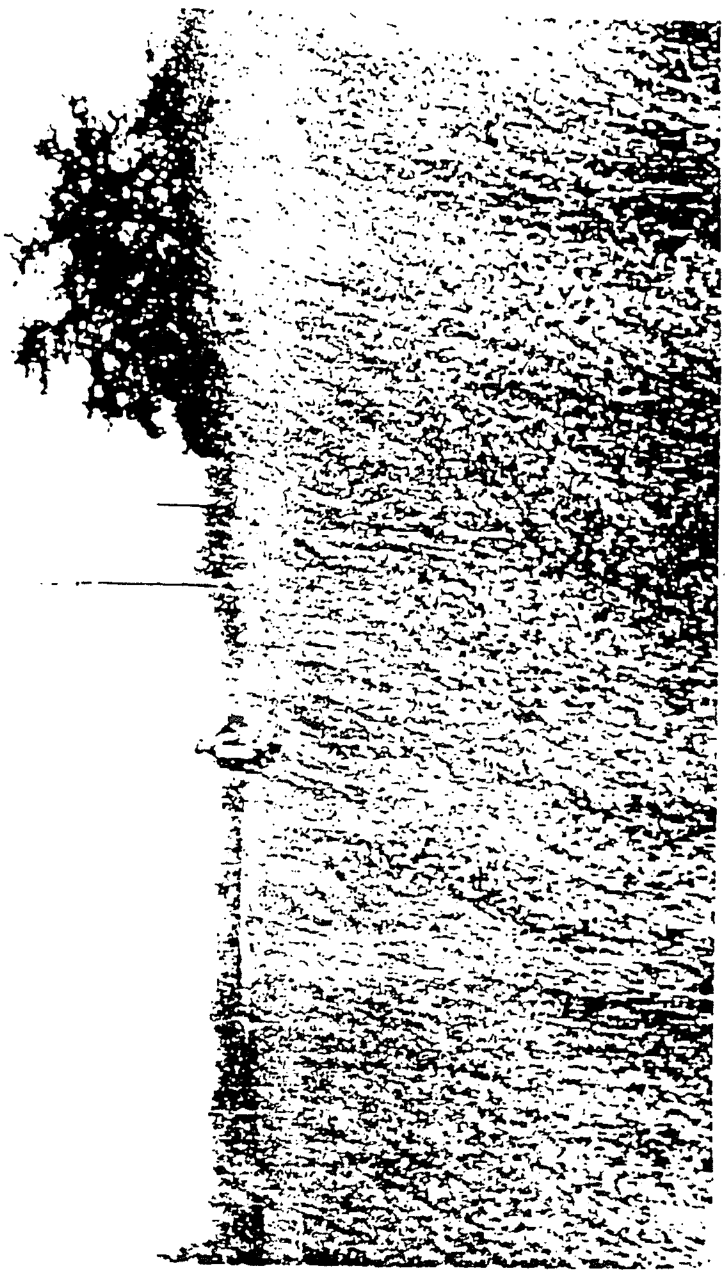
As a normal rainfall pattern began to reassert itself, and in the absence of fires species composition began to change on the plot. New species of woody plants and grasses were present in 1960-61 when a set of phenological observations were made. Two annual grasses (*Trisettum interruptum* Buckl. and

Sporobolus vaginiflorus (Torr.) Wood) had become dominant in the three-awn community. The addition of two species of trees (*Ulmus americana* L. and Ashe juniper) plus one shrub (*Baccharis salicina* T.& G.) had greatly changed the appearance of the plot, initiating a rapid change from a grassland to a woodland (illustration 2). When the infiltration tests were run in the spring of 1995 only a narrow strip of little bluestem remained unwooded. This strip had been somewhat disturbed by heavy equipment when a telephone pole was installed nearby but otherwise it had remained unchanged since 1954.

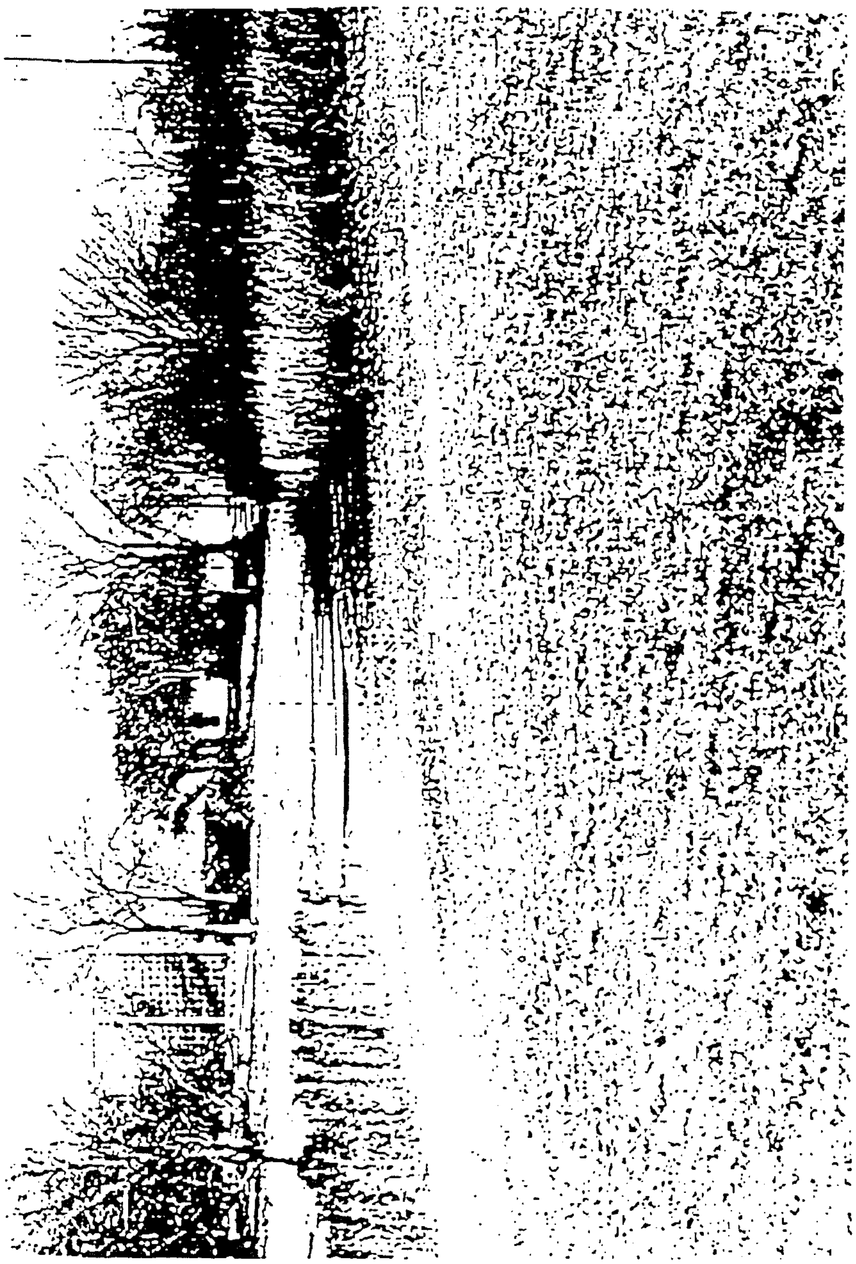
The Soil Survey of Travis County lists this plot as part of the Eddy series overlaying Austin chalk (Werchan *et al,* 1974). The plot has a slope of about 3% and is described as having a surface horizon of 3 inches thickness that is a grayish-brown clay loam or gravely loam. The underlying material is a weakly cemented chalk. The proximity of an intermittent stream to the plot has perhaps increased the percentage of silts and clays in comparison to a typical Eddy soil. The controlling difference that provided the sharp boundary between the two grass communities during the drought was one of soil depth, which markedly affected soil moisture potential during stress conditions.

In the absence of fire, the plot was rapidly converted into a juniper woodland. Each additional shrub or tree increased the shade and the number of perches where birds could deposit additional seeds of woody vegetation. By 1986 the canopy formed by Ashe juniper could be said to be closed. In 1965 Michael L'Annunziata, a student of Brother Lynch, ran some soil tests to determine the percentage of organic matter underneath the two different grass communities. The deeper soils underneath the little bluestem had a higher percentage of organic matter in each of three depth intervals than did those of the shallower soils dominated by red three awn during the drought. The 1995 soil samples were taken to a depth of 7.5 centimeters whereas L'Annunziata's were taken to a depth of 10 cm but the resulting percentages were quite similar. The other intervals analyzed in 1965 were 10-20 cm and 20-30 cm. No such interval was tested in 1995. The original analysis determined that approximately 30% more organic matter was present at each interval under little bluestem than under red three awn.

Illustration 1 St. Edward's Plot 1957



stration 2 St. Edward's Plot 1976



BRACKENRIDGE FIELD LABORATORY

Located on the North bank of the Colorado River, the 88 acre Brackenridge Field Laboratory (BFL) is part of a larger tract of 503 acres on both sides of the river which were presented to the University of Texas by Colonel George W. Brackenridge in 1910. The research lab, located at 2907 Lake Austin Blvd., Austin, Texas, was begun in 1962 and dedicated on April 21, 1967. The complex consists of lab buildings, greenhouses, population enclosures, aquatic tanks, an experimental garden, and various plant communities such as grasslands and juniper/oak woodlands. A portion of this site was operated as a rock quarry and several residences existed before the area was dedicated as a research facility.

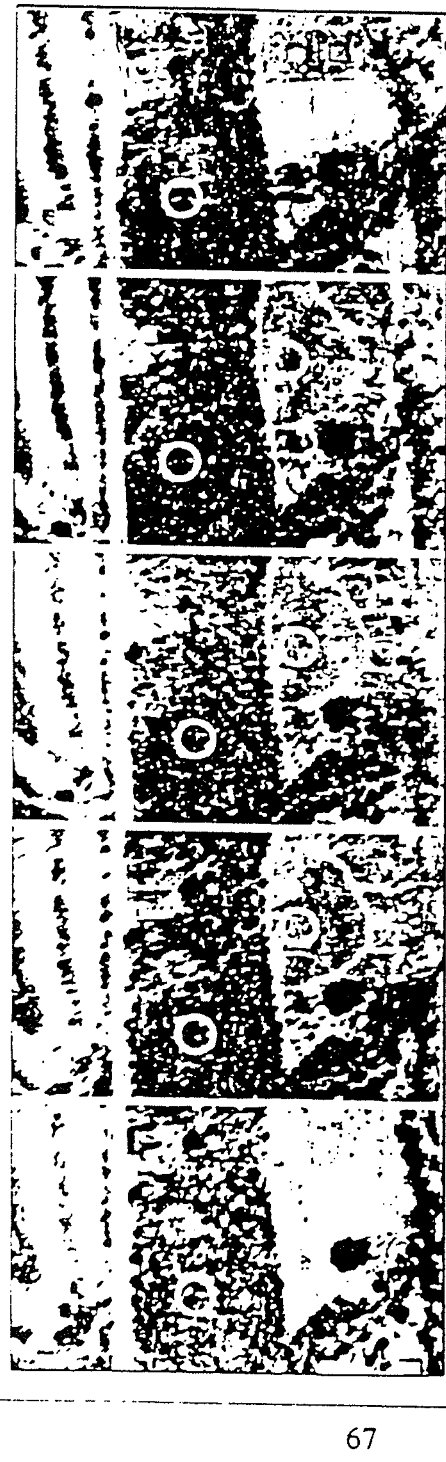
Two sites were observed at the BFL for the duration of this project. Infiltration and throughfall experiments were run on both the Upland and the Experimental Garden sites. The Upland site is located 75 feet northwest of the aquatic population tanks. It is a juniper/oak woodland with small openings of grasslands. Examination of a sequence of aerial photographs dating back to the 1920s shows that this site had been a woodland with few openings, until an acre was cleared to accommodate the aquatic population tanks in the late 1960s (illustration 3). A buffer strip was created between the fenced tankyard and the woodland. This 30 by 100 foot strip is now dominated by little bluestem and several herbaceous perennials. It was here that the upland grassland infiltration plot was established. The juniper plot is adjacent to the grassland and consists of a closed canopy of Ashe juniper and red oak (*Quercus texanum*). First an infiltration series was run, and then a throughfall grid was established beneath the canopy of one of the largest junipers. This stand of junipers was designated as the mature form to differentiate it from the younger, bush form grove of junipers in the Experimental Gardens. Most of the mature juniper canopy is above head height and more open, less dense than the bush form. This particular juniper cannot be identified with confidence from the aerial photographs but its basal diameter of 61 inches and its peeling bark puts it in the mature classification with an arbitrary assigned age of 40+ years. A number of exotic understory shrubs (*Ligustrum spp*) .had been removed from beneath this juniper's canopy prior to this study and may have contributed to the open understory condition of this site.

The Soil Survey of Travis County, Texas describes this location as part of the Travis soils and Urban land series (Werchan *et al,* 1974). Positioned on the higher river terraces, these soils have an 18 inch thick surface layer of gravely fine sandy loam changing from brown in the upper sections to light reddish-brown in the lower ones. Below this and to a depth of some 50 inches is a red gravely sandy clay..

The lower river terrace site is contained within the Experimental Garden unit of the BFL. The bush form throughfall site is on the second terrace above the floodplain of the Colorado River. The bush form grove is approximately 150 feet west of the Rare Plants greenhouse. The Experimental Garden has been enclosed by an 8 foot high chain-link fence to exclude deer since 1967. The aerial photographs show the garden to have been dominated by grasses throughout the 70 year sequence (illustration 3). A scattering of trees was present between the two terraces until the facility was opened, at which point the trees were bladed down and the field plowed by tractor twice a year. According to John Crutchfield, the facility manager, the plowing on the upper portion was discontinued in the mid-1970s and the junipers and mesquite began to return. The photo of 1973 shows no visible trees on the location of the bush form site. This grove has been designated as adult stage due to its structure and has been assigned the arbitrary age of twenty years. The grove consists of four juniper trees and some seedlings of different species. After the infiltration tests were performed, this grove was equipped as a throughfall test site. The canopy conditions of this grove are quite different in density and height from that of the mature stand. These rapidly expanding stands of juniper are quite common on the Edwards Plateau. The greater part of the garden is dominated by grasses and herbaceous perennials notably little bluestem (*Schizachyrium scoparium*) and gayfeather (*Liatris mucronata).*

The Soil Survey designates this area as part of the Hardeman and Urban lands soil series (Werchan *et al,* 1974). Undisturbed Hardeman soils have a surface layer of fine brown sandy loam approximately 56 inches in depth. Below this is a reddish-yellow silt loam. These soils occupy flood plains and terraces. They are built-up over old alluvium. Permeability is deemed moderately rapid and available water capacity high when the soil is in an undisturbed condition. Given the history of plowing, the nearness of residences until the late 1960s, and the operation of a stone quarry some 150 yards upslope, these soils can hardly be considered undisturbed. The juniper infiltration plot on this site was the only one to register significant amounts of run-off. This may reflect the lingering effects of disturbance and compaction.

Illustration 3 BFL Site Composite Photograph



Composite Aerial Photograph of Brackenridge Field Laboratories
Upper Left Circle is Mature Growth
Lower-Right Circle is Bush Growth

Rodgers Ranch

The Rodgers Ranch is located in Northwestern Travis county of Texas near the confluence of Cow Creek and Bee Creek. This 3,703 acre ranch on the Edwards Plateau was owned and operated by Regina Rodgers as a cattle ranch until it was acquired by the United States Fish and Wildlife Service in 1992 as the first large acquisition for the Balcones Canyonlands Refuge. This property is only one portion of a much larger Rodgers Ranch reputedly won in a poker game at the turn of the century. There is no detailed fire or grazing history available for this property other than to say that only cattle were present at the time of sale although goats could have been present when mohair was profitable from the 1930s to the 1950s. The many downed juniper limbs were in part due to an arrangement to cut cedar posts in the late 1980s.

The Balcones Canyonlands Refuge was the first refuge dedicated to the preservation of neotropical migrant birds specifically; the golden-cheeked warbler and the black-capped vireo which nest only in this province. The Rodgers Ranch is prime golden-cheeked warbler habitat. The warblers require mature Ashe juniper bark as nesting material and feed primarily on insect larvae found in stands of Texas red oak (*Quercus* texanum). Black-capped vireo prefer dense stands of immature *Quercus sinuata* called shinneries. The USFWS hopes to encourage the formation of shinneries on the broad ridge plateaus by the use of fire and mechanical means. The mission of the Balcones Canyonland Refuge is in part to return the landscape and vegetation to conditions that existed prior to Anglo occupance. The eventual refuge has an approved boundary of some 40,000 contiguous acres of which approximately 14,000 have been acquired at this time.

The first infiltration test plot is located on one of the broad, rocky benches descending to Bee Creek. The site is some 500 lfeet from the major ranch road and 1,000 feet from the northwest fence line. The vegetation is a grass/juniper mosaic, common on the Edwards Plateau, with equally small and irregular stands of either juniper or bunchgrasses and forbs. The patches average 50 to 75 feet in length along the long axis and seem to be about evenly divided as to either grass or juniper dominance.

The soils are classified by the Soil Survey for Travis County, Texas as part of the Brackett series with steep rock outcrops (Werchan *et al,* 1974). These shallow, rocky, well-drained soils are underlain by limestone and marls. About 75% of the soil surface is covered by limestone fragments from 2 to 4 inches in size. This is underlain by a brownish-gray gravelly clay loam or gravelly loam 4 inches thick. Below this horizon there is a pale brown clay loam that extends some 15 inches to regolith.

The aspect is north facing with a moderate slope of less than 10 degrees. Several animal and vehicle trails cross and link the grass patches while avoiding the juniper stands. The juniper stand tested seemed to have been used by cattle or deer as a bed ground since depressions and droppings were observed.

Illustration 4 Throughfall Map, Light Rain

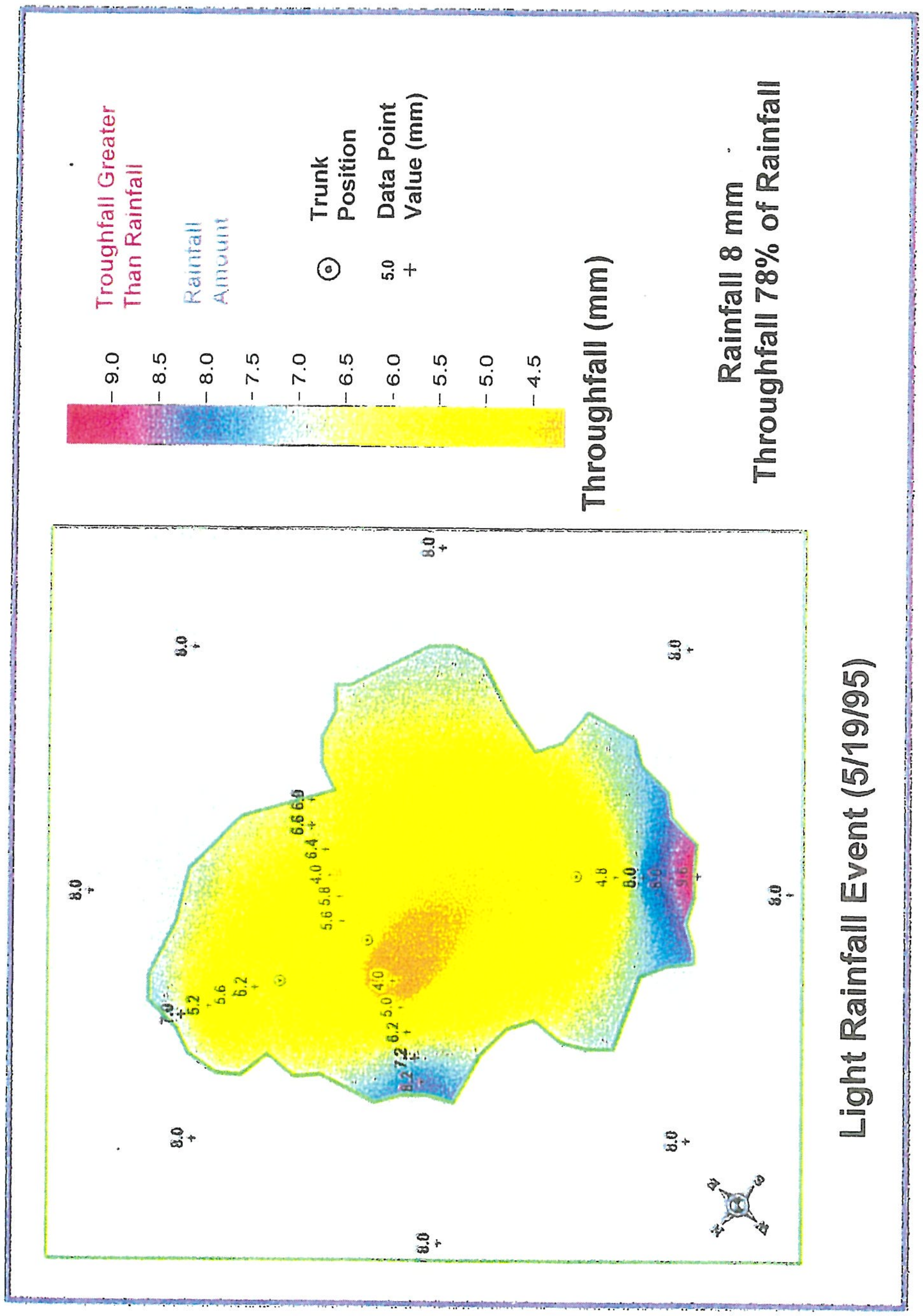
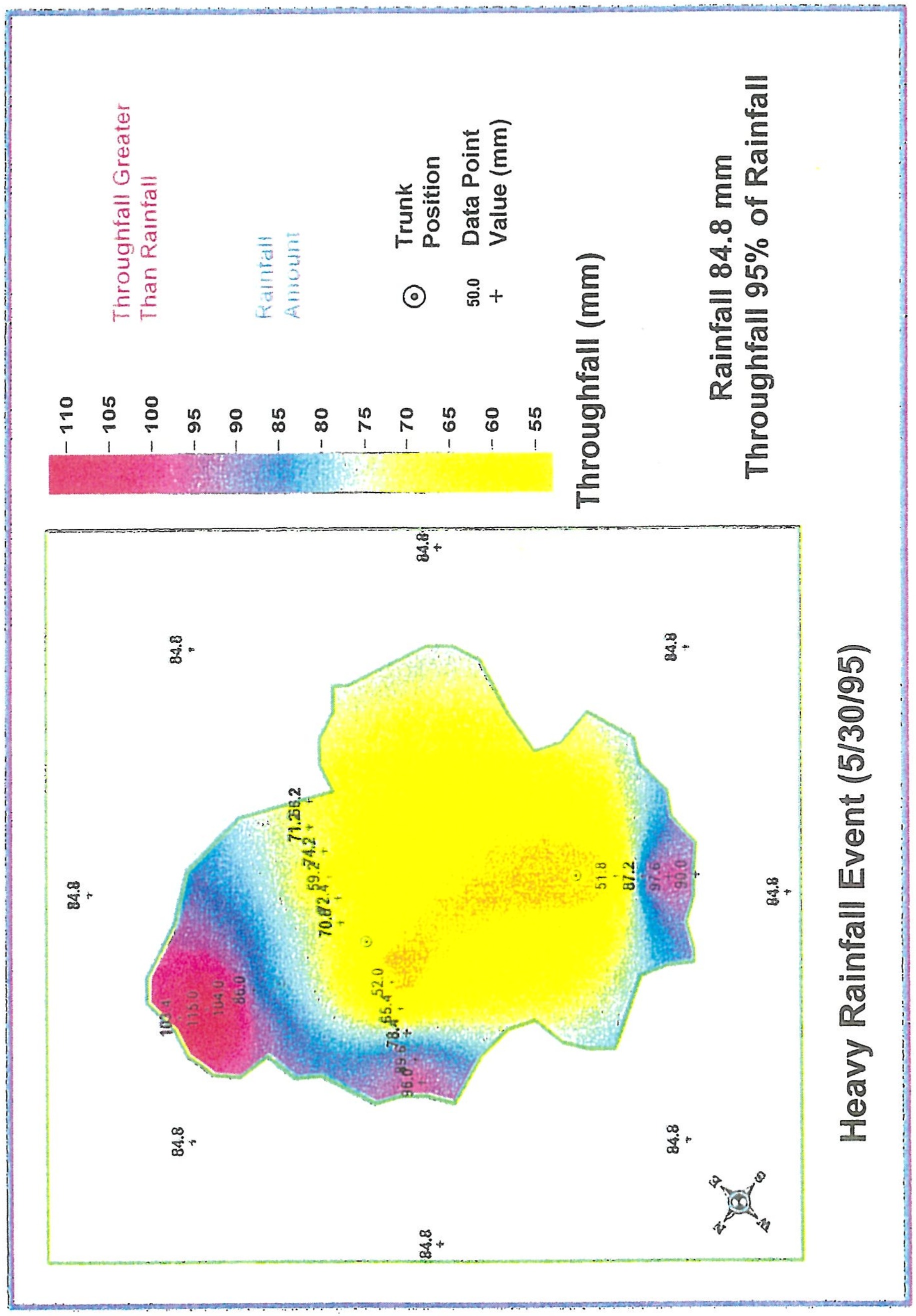


Illustration 6 Throughfall Map, Heavy Rain



Results of the Field and Laboratory Investigations

CANOPY INTERCEPTION AND THROUGHFALL

The percentage of throughfall beneath the canopy of either the bush or mature stands of Ashe juniper measured in this study was in range of that measured by Skau (1964) for either Utah or alligator juniper and that determined by Thurow *et al* (1987) to be representative of live oak mottes. The unweighed data gathered over a year for 28 rainfall events would place throughfall for the bush grove at 70.5% with one standard deviation of 26.8. The mature grove of Ashe juniper showed a slightly higher mean for throughfall at 73.9% ± 30.4. These figures represent a cumulative mean of all throughfall percentages so that the mature and bush groves could be compared even though they had different numbers of collection canisters. An F-test was performed to reveal if the series of 28 percentages of throughfall for the bush grove was significantly different than that for the mature grove. The test showed no significant differences with an F of 1.29 and a $p<0.26$.

The total measured rainfall accumulation encompassing 28 events over a year was 638.1 mm. The total throughfall for the bush grove was 535.6 mm or 83.9% of rainfall. Total throughfall for the mature grove was 588.9 mm or 92.3% of the total rainfall. Canopy interception, being the inverse of throughfall, would be 16.1% for the bush grove and 7.7% for the mature grove . These figures do not include the contribution of the stem which will be discussed separately. Most likely these figures underestimate the percentage of throughfall for Ashe juniper because no attempt has been made to weigh the figures when a collection cylinder was partially or completely knocked over by wind or animals, presumably resulting in lower accumulations.

Light rainfall events resulted in low throughfall percentages and high rainfall events resulted in high percentages of throughfall for both the bush (figure 1) and the mature (figure 2) groves. Within these charts there appears to be a threshold for throughfall at a rainfall accumulation of 3.4 mm. Even at this very low amount of rainfall, the throughfall was 46.4% for the bush and 39.2% for the mature. Some researchers prefer to state canopy interception as a threshold for each event at which point throughfall begins. Collings (1966) put this threshold at 0.5 inches or 12 mm for a pinyon/juniper woodland. He states that 74% of all rainfall less than 0.5 inches is lost to canopy interception. In regions where total precipitation is low or dominated by low intensity rainfalls, this threshold concept becomes more important. The lowest measured rainfall event in this study was 0.6 mm and yielded no throughfall accumulation. The other two low-end events of 0.8 and 1.5 mm measured only traces of throughfall in both the bush and the mature groves. Several rainfall events of low accumulations were not recorded because the rainfall was so localized that I did not realize that the event had occurred until too much time had elapsed for accurate measurements. The greatest accumulation measured in this study was 84.8 mm (figure 3).

At a rainfall accumulation of 8 mm, throughfall percentage was already 78.5% for the bush and 73.1% for the mature grove. During the heaviest rainfall events, throughfall percentage for the bush exceeded 95% while the mature grove registered 108% of the rainfall expected to be collected with no canopy present. The curve of throughfall as a function of rainfall intensity might be even smoother except that these events are generally convective or frontal thunderstorms with high winds and partially or completely knocked over canisters were common.

The data was examined to see if throughfall percentages dramatically increased when one rain day closely followed another. It would seem likely that if the canopy and bark were already wet the percent of canopy interception would be less and throughfall would be greater. Such cases were too few and still within the variance for that intensity of a rainfall to be statistically significant. A light mist might only wet the ground beneath a canopy only when several rain days are conjoined but a pre-wetted canopy may well be insignificant for rainfall events greater than 12 mm.

The overall pattern of throughfall for both the bush and the mature stand was one of decreasing accumulations as one moved from the canopy edge towards the trunk. Throughfall along the canopy edge frequently exceeded that of rainfall in the clearing during individual events. This was usually true of the quadrant that faced the advancing storm. Three rainfall events were selected and mapped to illustrate this pattern. The values for areas between the data points were interpolated by krieging. A color scale was chosen to represent the values of throughfall as a percentage of rainfall. A break in the color scale at the amount of rainfall for an individual event was intended to highlight accumulations in excess of rainfall amounts. The light intensity event (illustration 4) measured 8 mm of rainfall with a throughfall percentage of 78.5%. The medium intensity event (illustration 5) measured 26 mm of rainfall with a throughfall of 96.4%. The heavy intensity event (illustration 6) measured 84.8 mm of rainfall with a throughfall of 95%.

Each map shows an area of throughfall in excess of rainfall. This area shifts from event to event presumably in response to the direction of the on-coming storm. The method selected for interpolating values between data points is quite conservative and it is likely that the area receiving throughfall in excess of rainfall is a much broader arc than as depicted in the maps. As a cumulative percentage, the southwestern quadrant of the bush grove received the highest percentage of throughfall at 82%. This quadrant would be facing the on-coming summer storms in the usual pattern for this area. The northeastern quadrant received the next highest throughfall percentage at 75%; the northwest received 67% and the southeastern received the least throughfall at 63%. Ordinarily, winter storms would approach from the northwest but the year of the study was one characterized by a severe winter drought. It is also possible that the prevailing wind patterns in this part of the valley are somewhat different. Another map of the bush grove (figure 4) shows these cumulative throughfall percentages by quadrant and by individual data point.

The orientation and situation of the mature grove was somewhat different than that of the bush stand. All lines of the collection canisters reached from the edge of the canopy to the single trunk but only on the B and the L series was that edge bounded by a narrow open meadow. The other two series, A and R, started at the division of two juniper canopies and then progressed towards the trunk. When a cumulative percentage of throughfall for all rainfall events at each data point was made, all four series showed a similar progression from greater to lesser throughfall as one moved from canopy edge towards the trunk (figure 5). This suggests that each tree in a stand is acting separately in terms of throughfall. If the entire stand acted as a unit, throughfall percentages would decline with distance from the open field. Total throughfall for a mesoscale area would be significantly less as stands or cedar brakes can be quite extensive. This study indicates that a great part of the total throughfall comes from the contribution of points near the edge of the canopy. Although it is slim statistical evidence, the pattern implies that there are peaks and valleys of throughfall percentages within a mature juniper stand that relate to the canopy edges of the individual trees. It is assumed that wind sufficiently strong to agitate the branch tips is the mechanism that sheds rain off of the canopy creating the peaks of throughfall seen in both the bush and mature grove. Although the Brackenridge Field Laboratory has an anemometer, it proved to be inoperative so neither wind speed nor direction during the rainfall events could be monitored other than by inference based on observations at the time of a rainfall event but from a different location.

The other important pattern of throughfall best illustrated in the mature grove is the significance of some interior points that produce throughfall in amounts that regularly exceed rainfall in the clearing. These points do not appear to be beneath an opening in the canopy but rather where concentrated amounts of throughfall drip after traveling down the branches until they reach an obstruction which causes them to drip rather than flowing farther. The inference that connects these points with stemflow is that they both share a distinctive reddish brown tint to the substrate, most likely derived from the bark and dry deposition. The true stemflow is the deepest tint, these interior points are lighter of tint, and the concentrations near the canopy edge are without tint. Indeed, most points more than 1.25 meters away from the canopy edge showed some degree of tinting but the points of highest accumulation showed the deeper tint.

One of the points in the mature grove, (B7), was highly regular in producing throughfall in excess of rainfall. The cumulative percentage of throughfall for this point was 121% ± 85 of rainfall. Throughfall at this point in excess of rainfall could exceed rainfall at intensities as low as 15 mm, but in general the greatest impact was seen in events greater than 24 mm. B7 seemed to correspond with a slightly sharper than normal bend in the branch above it. Several such "elbows" might occur in any bush or mature form juniper canopy. Presumably, a mature canopy might have a greater contributing zone for stemflow corresponding with such an "elbow". Points of throughfall in excess of rainfall were found in the bush form but not in the same magnitude or regularity as B7 in the mature form. The points on either side, B6 and B8, also had high percentages of throughfall that was at times in excess of rainfall, sometimes B6 or B8 had greater accumulations than did B7, it is likely that at times the throughfall drips in between collection canisters. One inference that might be derived is that the pattern of lower throughfall percentages as one moves from the edge of the canopy towards the stem does not reflect the increasing density of the canopy as proposed by Skau (1964), but rather reflects increasing importance of stemflow on branches that may drip at very regular points or be added to the main stemflow. The importance of these points may lie in their similarity to true stemflow both in terms of amounts of water and concentrations of nutrients derived from dry deposition. Such concentrations may be important not only to the juniper but also to any understory plant

STEMFLOW

Skau (1964) determined that stemflow on Utah (*J. utahensis)* and alligator (*J. deppeanna)* juniper was insignificant, perhaps totaling 1 to 2% of the average annual precipitation. Young *et al* (1984) measured stemflow on Western juniper (*J. occidentalis*) and determined that 0.53 liters of rainwater flowed down the stem for each cm of rainfall. In this study stemflow for Ashe juniper, although difficult to measure accurately, was found to be a significant component of the water delivered to the litter or the mineral soil beneath the canopy. The total rainfall measured during 28 events over the period of more than a year measured 638 mm. The total measured stemflow on the bush trunk was 3256 mm. Difficulties already discussed made measurement of stemflow on the mature juniper highly under-reported but there is reason to believe that it exceeded stemflow reported on the bush form. The trunk from which the measurements were taken on the bush is but the largest and most accessible of four juniper trunks that make up the grove. When the collection device on the trunk was benchmarked, it measured only half of the water applied to the stem above the collar. Even without weighing these error sources, stemflow equaled more than 5 times the amount of precipitation received. The procedure in

bush stand – would have been more for mature stand

Young *et al* (1984) would predict a stemflow of 33.8 liters if Ashe juniper were comparable to *J.occidentalis*. Such a measurement is appropriate to Ashe juniper although it may be too low.

Stemflow was calculated as a percentage of rainfall for each event in this study. The mean of the total series was 502% ± 438. When stemflow percentages were charted by rank of rainfall event, the resulting curve was much more irregular than when percentage of throughfall was similarly compared (figure 1). Efforts to smooth the curve by removing events with the greatest known error did not appreciably affect the results (figure). Stemflow appears to commence at rainfall totals of 7 mm and tends to increase as rainfall levels increase. Like some of the throughfall canisters, the stemflow collector always showed a dark reddish brown tint. When stemflow is added to throughfall, the cumulative mean becomes 92% ±41 for the bush grove. The total loss of rainwater to the canopy and bark of Ashe juniper would be only 8% as opposed to 25.4% canopy loss for live oak mottes as calculated by Thurow *et al* (1987).

Since there were only 19 throughfall collection canisters and 1 stemflow collector, it is reasonable to inquire if the trunk constitutes 1/20 of the total area or if the stemflow measurement has been given too much weight. The total area under the bush canopy was 858.4 square meters and the total area of the 19 collection canisters was 1.5 square meters or 0.17% of the total. If the stem is assigned an effective radius of 0.5 meters then the stem constitutes 0.9% of the total area. Since there were 4 juniper stems in the grove and only 1 was measured for stemflow, the inclusion of the single stem canister with an equal weight as 1 of the 19 other canisters does not seem excessive.

This study shows stemflow on Ashe juniper to be a significant part of the water budget for the plant. Such amounts clearly increase the percentage of precipitation that reaches the litter and mineral soil. Stemflow may be an important mechanism in the establishment of Ashe juniper on thin, rocky soils with little moisture retention capacity. Stemflow may also play a part in the spread of juniper into grasslands in time of drought. The large amounts of stemflow are created at the expense of increased throughfall within the canopy which might have benefited understory growth. In the western portions of the range of Ashe juniper where precipitation is much less, stemflow may not be as significant as rainfall intensity declines. It was not possible in this study to identify a threshold at which stemflow begins nor was it possible to correlate rainfall intensity to percentage of stemflow. The researcher is convinced that the stemflow amounts in this study under-report accumulations, and that a more accurate and broad based study will find stemflow to be even more significant in the water budget of Ashe juniper.

LITTER INTERCEPTION

Water that has passed through the canopy or down the stem must then move through an often thick and extensive litter layer before reaching the mineral soil. Ashe juniper measured 2 to 5 cm in depth beneath both the bush and mature stands. Litter was not continuous but patchy in both stands. The thickest accumulations tended to be near the trunk and the thinnest towards the canopy edge. The litter appeared to have been reworked by overland flow in the bush stand. Here, the litter would pile thickly against any barrier such as a trunk, downed limb, or bunchgrass crown. The arc shape of these litter barriers had the end points aligned upslope suggesting not only movement by overland flow but also a temporary surface ponding of run-off. Such impedance of overland flow may have allowed the ponded water time to then infiltrate into the soil. Thurow *et al* (1987) surmised that live oak mottes were acting as sediment sinks because their high rates of infiltration allowed run-off from pastures the time and capacity to become soil water. This may well be the case with the Ashe juniper litter which, because it is composed of small scales with serrate edges, has the ability to interlock and form a small structure capable of ponding small amounts of water. Any discussion of losses of rainwater to litter interception must be balanced with the yet unmeasured ability of this litter to hold run-off temporarily and allow increased amounts of infiltration. The litter was of a more uniform depth in the mature grove and showed less sign of ponding. Raindrop splash was evident on the sides of the collection canisters after the heaviest events.

Yager (1993) measured the wetting and drying characteristics of juniper litter. She found no hydrophobic response in the litter. During germination tests, she wetted the litter by a rainfall simulator and found it to gain 50 to 60% of its initial dry weight in absorbed moisture. The litter quickly dried to a level below 20% in 2 days. Under field conditions, Ashe juniper would rarely receive throughfall in such amounts and frequencies. It is probable that in these thick litter accumulations water flow does not occur as a uniform wetting front but through preferential flow channels as suggested by Walsh and Voight (1977). Such pathways might leave large areas of litter unwetted and lead observers such as Scholl (1971) or Bonnett (1960) to assume that either the litter was hydrophobic or that interception losses were very high.

No actual litter interception loss measurement was done for Ashe juniper in this study but a value of 20% loss may be assigned using the measurements of

Thurow *et al* (1987) for live oak mottes. Juniper litter may be more persistent than live oak litter but its small scales offer less area for water to be trapped than does the cupped underside of a live oak leaf. Infiltration tests were run with the juniper litter present and removed at the Saint Edward's site. There was no apparent decrease in the infiltration rate of juniper soils with the litter removed.

Juniper litter may have an important place in the water budget of Ashe juniper. Based on observation, it seems unlikely that the importance is one of a net loss of soil water due to litter interception loss. The effect of juniper litter as a mulch reducing evaporation loss, as a source of organic matter to the soil, as protection against raindrop impact, and as an environment favorable to soil micro-fauna that promote infiltration should at least balance out interception losses.

INFILTRATION

Once the remaining rain water has reached the mineral soil, it must either infiltrate, become temporarily ponded, or run off. The clear pattern that emerged from the infiltration tests is that each one of the juniper-dominated soils had a higher infiltration rate than that of its paired grass-dominated soil. In only one of four sites did the juniper soil produce significant amounts of run-off. The rainfall simulator could produce precipitation equivalent to 180 mm/hr for brief periods. The infiltration capacity of the juniper soils exceeded this rate on 3 out of 4 sites. On the grass-dominated soils, however, significant run-off was produced at every site during both the initial conditions and the wetted to field capacity infiltration tests. Run-off began during the first 5 minutes in each infiltration test of grass soils.

The wetted to field capacity test gives the best approximation of infiltration capacity of a soil. The initial conditions tests were run both to wet the soils for the second more relevant test and to see if any interesting pattern appeared. The beginning of run-off in the first 5 minutes during the initial conditions test may be indicative that the entire soil profile was not involved in infiltration. Either a compacted surface or a shallow, buried zone of compaction caused infiltration capacity to be exceeded quite rapidly even during the period when capacity is usually the highest. Because the rainfall simulator was gravity fed, the first 5 minutes produced the highest rate of precipitation. However, infiltration in the juniper-dominated soils exceed this high rate of precipitation during most tests.

At the Saint Edward's site, the wet test on grass produced an infiltration rate of 140 mm/hr. The test on juniper produced only a trace of run-off which may well have been raindrop splash rather than true overland flow. The infiltration rate for the juniper soils at this site can only be said to exceed 180 mm/hr. Thurow *et al* (1986) used a larger rainfall simulator that produced precipitation at a steady rate of 203 mm/hr for 50 minutes. They placed infiltration rates in live oak mottes at nearly 200 mm/hr for the duration of the test. This may be a reasonable approximation for juniper but since no ponding or intermittent flow was observed, the infiltration rate of juniper dominated soils may greatly exceed that of live oak soils.

At the Experimental Gardens site at the BFL, significant run-off was produced during the initial conditions and wetted to field capacity for both juniper and grass dominated soils. The infiltration rate during the wet test for grass was 66 mm/hr. The rate for juniper was 90 mm/hr. Both tests lasted 25 minutes during which time 40 liters of water was applied. The effective area of the rainfall simulator was 6.6 square meters. The grass plot produced 21.86 liters of run-off or more than 54% of the rainfall. The juniper plot produced 15.2 liters of run-off of 38% of the rainfall. These infiltration rates may have continued to fall if the rainfall simulator had a larger capacity. In none of the tests can there be confidence that the terminal infiltration capacity was reached.

This site had an important difference from the others in that it was plowed yearly as part of the management program for the Experimental Gardens. Most likely the exact position of the juniper plot had not been plowed in 20 years. This figure is derived from aerial photographic evidence and the approximate age of the grove. The soil in both the juniper and adjoining grass plots showed little evidence of horizons when the core was taken for bulk density measurements. It is possible that a buried, compacted layer or plow pan had developed. Such a condition could dramatically limit infiltration by reducing the effective soil depth to a fraction of its actual measurement. This site is also unusual in its proximity to the Colorado River. This section of the river is controlled by a constant level dam and it is unlikely that it has been an active flood plain in more than 50 years.

On the Upper BFL site, the infiltration rate for grass was 94.3 mm/hr. Run-off measured 14.1 liters of an application of 40 liters, or 35%. The juniper plot produced only 30 ml of run-off that may well have been rainsplash. The infiltration rate for the juniper soil at this site can be said to exceed 181 mm/hr. This site had similar soil characteristics in terms of bulk density, percentage of organic matter, percentage of fines, and surface compaction to that of the Experimental Garden. This similarity may indicate that a history of plowing or heavy machinery use could reduce infiltration rates for long periods of time after disturbance ceased.

The tests at the Rodgers Ranch placed the infiltration rate for grass at 122 mm/hr. Run-off was recorded at 35% of the application rate, or 14 liters out of 40 applied. No run-off was produced on the juniper plot. Because of the valve setting, the infiltration rate can only be said to exceed 122 mm/hr at this location. These tests were performed during a very dry August and showed how significant run-off can occur during brief, high intensity storms.

The infiltration tests run by Thurow *et al* (1986) also compared the response of vegetation types. The live oak mottes produced rates that declined only slightly to just under 200 mm/hr for the duration of the 50 minute test. The soils of the bunchgrass community began at 190 mm/hr but steadily declined to 170 mm/hr by the end of the test. The soils of the sod grass community began the test at 175 mm/hr and sharply declined to 110 mm/hr. In this study, bunch grasses dominated the grass plots on each site. Little blue stem (*Schizachyrium scoparium)* and Texas wintergrass (*Stipa leucotricha*) were the two most common bunchgrasses on the study sites. Low sod forming grasses were present but not dominant on the grass test plots. The infiltration readings for grass in this study were closer to those of sod grasses in the Thurow study. It is not that the plants carry with them an absolute infiltration rate, but that they have relative capacities and abilities to interact with the soil. The inference is that the infiltration rate beneath trees and large shrubs is greater than that of grasses because some feature or features of their growth form interacts with the soil to promote infiltration capacity. Several tests were run to try and identify the soil property most strongly correlated with the difference in infiltration rates between the juniper dominated soils and those dominated by grasses.

BULK DENSITY

Bulk density has previously been discussed in this study as a good indicator of the degree of porosity present in a soil sample. A high degree of porosity often results in a high infiltration capacity. There were significant differences in bulk density between the juniper and grass soil samples. The mean bulk density for the 16 juniper soil samples was 2.1 g/cc. The mean for grass was 2.93 g/cc. An F-test of the two series of measurements indicated that the two data series were statistically different with $f=3.88$ and $p< 0.063$.

A comparison between the bulk densities of juniper and grass dominated soils (figure 7) shows even more meaningful differences when arranged by site. The lowest infiltration rates occurred at the Experimental Garden site where the mean bulk density is highest for both juniper and grass soils. Since only a lower limit for infiltration was measured for juniper soils on the other three sites, it is difficult to correlate bulk density with infiltration with the greatest confidence. The variability in bulk density readings for juniper soils is highlighted by the consistency with which the grass soils are grouped about the 3 g/cc level. If macropores or other preferential flow channels are important to infiltration in soils, then it may be expected that certain soil properties vary widely across the surface of the soil. For grass, the St. Edward's site produced the highest infiltration rate but its range of bulk density measurements is quite similar to that of the Upper BFL site, which had the second lowest infiltration rate. Bulk density could be increased wherever 1) gravel is abundant 2) lighter soil constituents such as organic matter predominate 3) the percentage of soil fines is so high that porosity decreases, and 4) a surface or buried horizon of compaction has reduced porosity.

Bulk density may well be the simplest and quickest indicator of infiltration capacity. With many more measurements, the differences in bulk density in juniper or grass dominated soils might become more distinct. Because so many other factors can come into play, the best comparisons are within the same soil series. However, the more a pattern carries across different soils the more that pattern can be attributed to changes in vegetation and not to the inherent similarities and differences in soils.

ORGANIC MATTER

The mean percentage of organic matter in a juniper-dominated soil was determined to be 6.4% ±2.3 and that of a grass-dominated soil to be 3.4% ±1.6. However, an F-test of the two series of percentages found the differences not to be statistically significant with an F of 2.2 and $p<0.069$. The effort to separate the litter layer from the soil may have resulted in too low a reading for the juniper soils. The grass soils rarely displayed a litter layer.

Again, the best comparison between grass and juniper soils lies within a single site and not across all sites (figure 8). As in the case of bulk density, the lowest means of percentage of organic matter lie within the site of the lowest infiltration rate. Similarly, there can be little confidence in the linkage of high percentages of organic matter to high rates of infiltration because only the lower limit of infiltration for juniper is identified on 3 sites. If the percentage of organic matter is plotted against bulk density (figure 9), then it can be seen that an increase in organic matter decreases the bulk density (cf. Pérez, 1992). A greater number of samples would be needed to see if the variability in readings diminishes. A rainfall simulator with a greater capacity might better illuminate the linkage of high infiltration rates with high percentages of organic matter.

PERCENTAGE OF FINES

For the purposes of this study, fines are defined as soil particles smaller than 50 microns. This category would include most definitions of silt and clay sized particles. The relative percentage of fines in a sample could affect bulk density in at least two opposite ways. First, fines are of course the smallest soil particles and a very high percentage of fines could result in low porosity and a high bulk density because with compaction the pore spaces would be the smallest possible. Secondly, however, fines bind together particles of sand, gravel, and organic matter to form aggregates that are much larger in size and porosity than the individual constituent parts.

The mean percentage of fines over the 4 sites for juniper was 34.4% ±9.6 and 31.8% ±9.8 for grass-dominated soils. An F-test of the two series indicated that there was no signicant difference with $F=1.05$ and $p<0.46$. A graph of the percentage of fines for grass and juniper grouped by site (figure 10) would look similar in shape to that of percentage of organic matter (figure 8). A relatively higher percentage of fines occurred in the St. Edward's and Rodgers Ranch samples, where infiltration was highest for grass. The distinction for this graph is that there is very little variation between the values of the grass and juniper derived soils.

When the percentage of fines is charted against bulk density (figure 11), it becomes evident that the percentage of fines is not related to bulk density. If there is an interaction between fines and bulk density, it is most likely in the production of aggregates. A test for aggregate stability would better define the relationship between bulk density, fines, and infiltration rate than would a simple calculation of percentage of fines. The higher bulk density measurements found in the grass dominated-soils do not derive from having more silt and clay sized particles than do the juniper soils, but result from differences in percentage of organic matter (Pérez, 1992). Thurow *et al* (1986) found that aggregate stability was significantly greater in the live oak mottes than either the bunchgrass or sodgrass communities. Aggregate stability also involves high percentages of organic matter and the oak mottes also had higher percentages of this material than did either the bunchgrass or sodgrass community.

PENETROMETER READINGS

The penetrometer measures the resistance of the soil surface and gives an indication of surface compaction. Bulk density is certainly increased when the soil is compacted and the primary pore spaces are collapsed. A compacted soil layer, even a thin or surficial one, adversely affects infiltration. The mean penetrometer reading for the grass-dominated soils was 2.2 ± 1.5 kg/cm^2. For juniper soils the mean was much lower at 0.57 ± 0.35 kg/cm^2. An F test of the two data sets indicated they were significantly different witn an $F=18$ and $p<3.85$ times 10 to the minus 20.

The juniper soils may have had less surface compaction because the low canopy restricted access by large animals and machinery. The higher amounts of litter on the soil surface and organic matter within the juniper soils could have acted as a protective and resilient layer. The role of the canopy in mitigating raindrop impact has already been discussed. These same factors coupled with the increased moisture and moderated temperatures beneath the juniper canopy may have promoted soil fauna such as worms, beetles, and springtails. An active soil fauna would continually rework the soil fabric leaving behind tunnels, burrows and other vacuoles that could become preferential pathways for infiltration. Except for the barrier effect of the juniper canopy, all of these factors that reduce surface compaction could occur on an undisturbed grassland soil. A grassland with extensive interspaces between plants and disturbance by grazing or other human activities would likely be less resistant to the forces of compaction. Also, the agents that lessen compaction and promote infiltration such as soil fauna would not be favored in an open and depauperate environment.

Since 3 or 4 penetrometer readings were taken in the vicinity of each soil core collected to measure bulk density, the penetrometer readings were averaged then charted against the bulk density of the appropriate sample. The resulting graph (figure 12) shows the juniper soils to cluster about the left hand third of the graph indicating a wider range of bulk density than penetrometer readings. The grass soils are grouped in the upper third of the chart revealing a broader range of penetrometer readings than bulk density measurements. The penetrometer readings were more sensitive to initial conditions than were bulk density samples which were air dried before measurement. Also, the soil core extended 7.5 cm beneath the soil surface. A compacted surface layer might strongly affect penetrometer readings but impact bulk density only partially.

The highest mean penetrometer readings of 3.6 kg/cm^2 occurred on grass soils taken at the Rodgers Ranch in August, 1996 but did not result in the highest bulk density measurement or the lowest infiltration rate. The St. Edward's tests were done in the spring of 1995 several days after a rain. Here, the penetrometer registered the lowest mean for grass of 0.74 kg/cm^2 and for juniper of 0.41 kg/cm^2.

The St. Edward's site also showed the least difference in penetrometer readings between grass and juniper soils. The Rodgers Ranch had the second highest difference between penetrometer readings for grass at 3.6 kg/cm^2 and juniper at 0.7 kg/cm^2. The infiltration rate for grass on both sites was high with St. Edward's at 140 mm/hr and Rodgers Ranch at 122 mm/hr.

Given equivalent initial conditions, the penetrometer may be a good indicator of potential infiltration rate. It is , however, a very surficial measurement as performed in this study and would have little ability to indicate infiltration problems with a buried, compacted layer such as the suspected plow pan at the Experimental Gardens. The main significance of these penetrometer readings is the disparity between those on grass soils and those on juniper soils under the same initial conditions and locale. A surface compaction may be overcome during an extensive rainfall event but a good deal of run-off might be generated even under dry conditions before that happens. The penetrometer readings, however, may give a clue to understanding why the grass soils always produced significant run-off during the first 5 minutes of the initial conditions test even when the soil was very dry.

Figure 2 Mature Throughfall Percentage and Rank

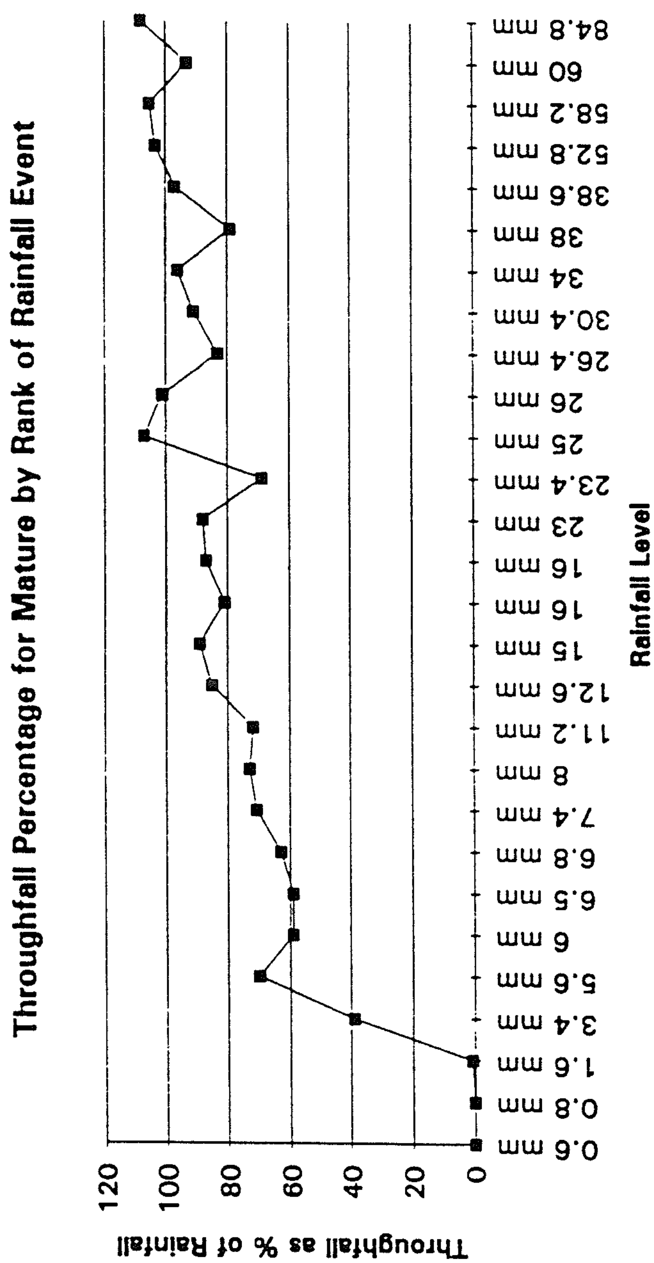


Figure 1 Bush Throughfall Percentage and Rank

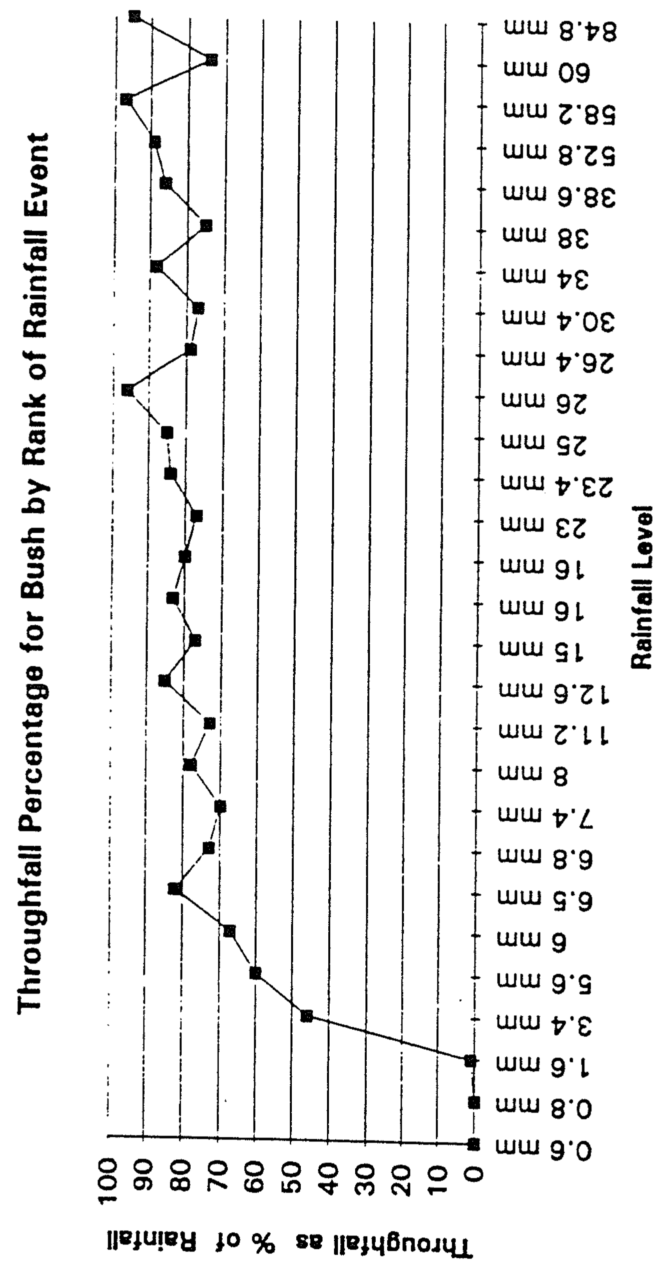


Figure 3 Rainfall by Rank

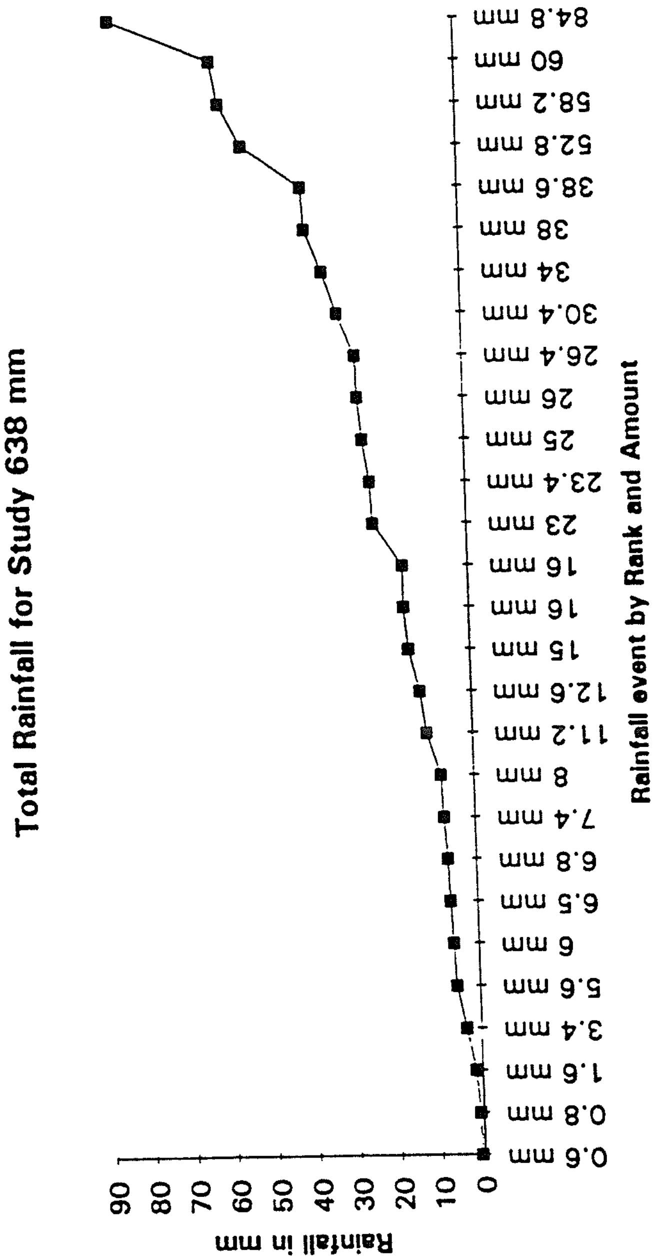


Figure 4 Bush Cumulative Throughfall Percentage

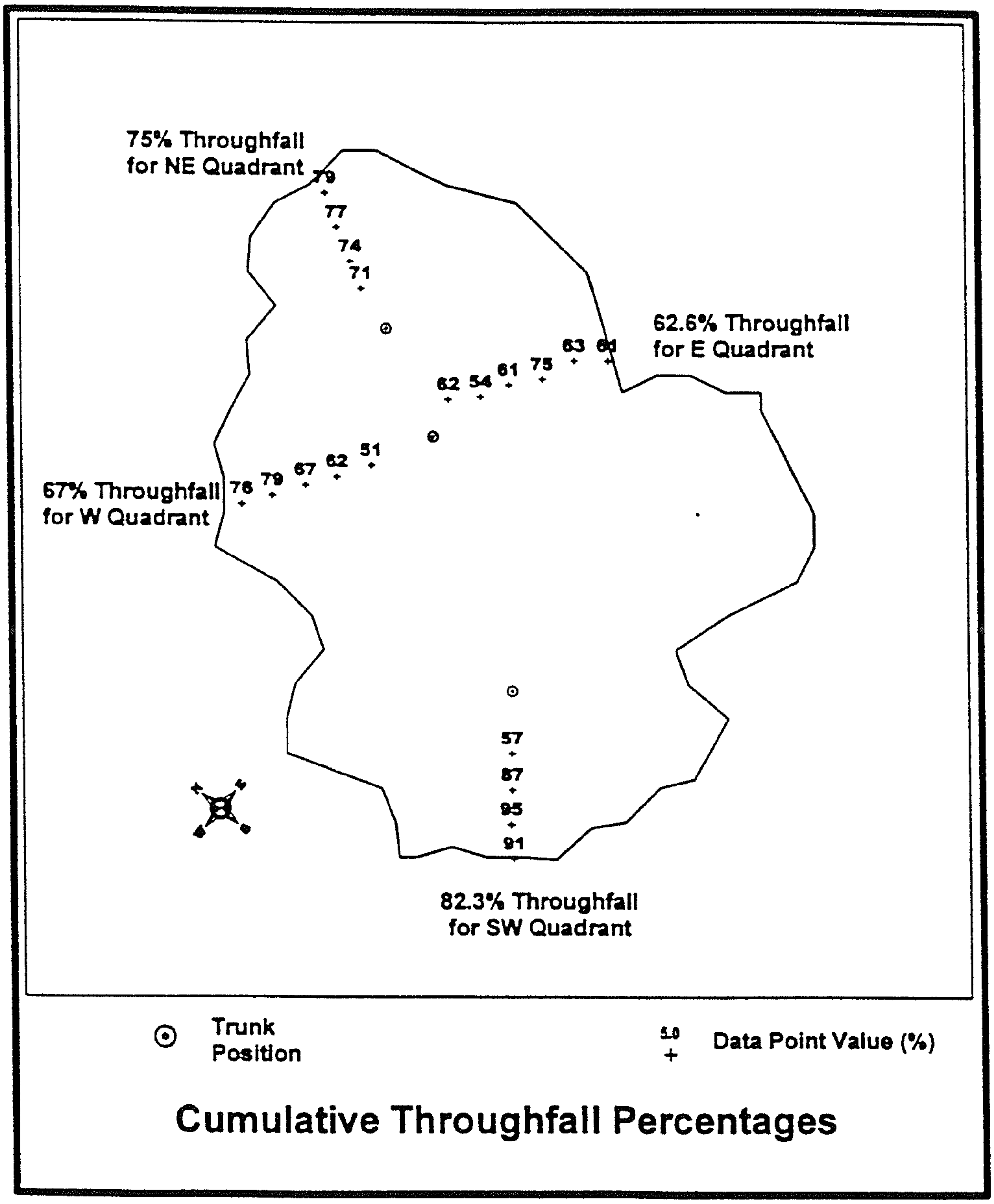


Figure 5 Mature Cumulative Throughfall Percentage

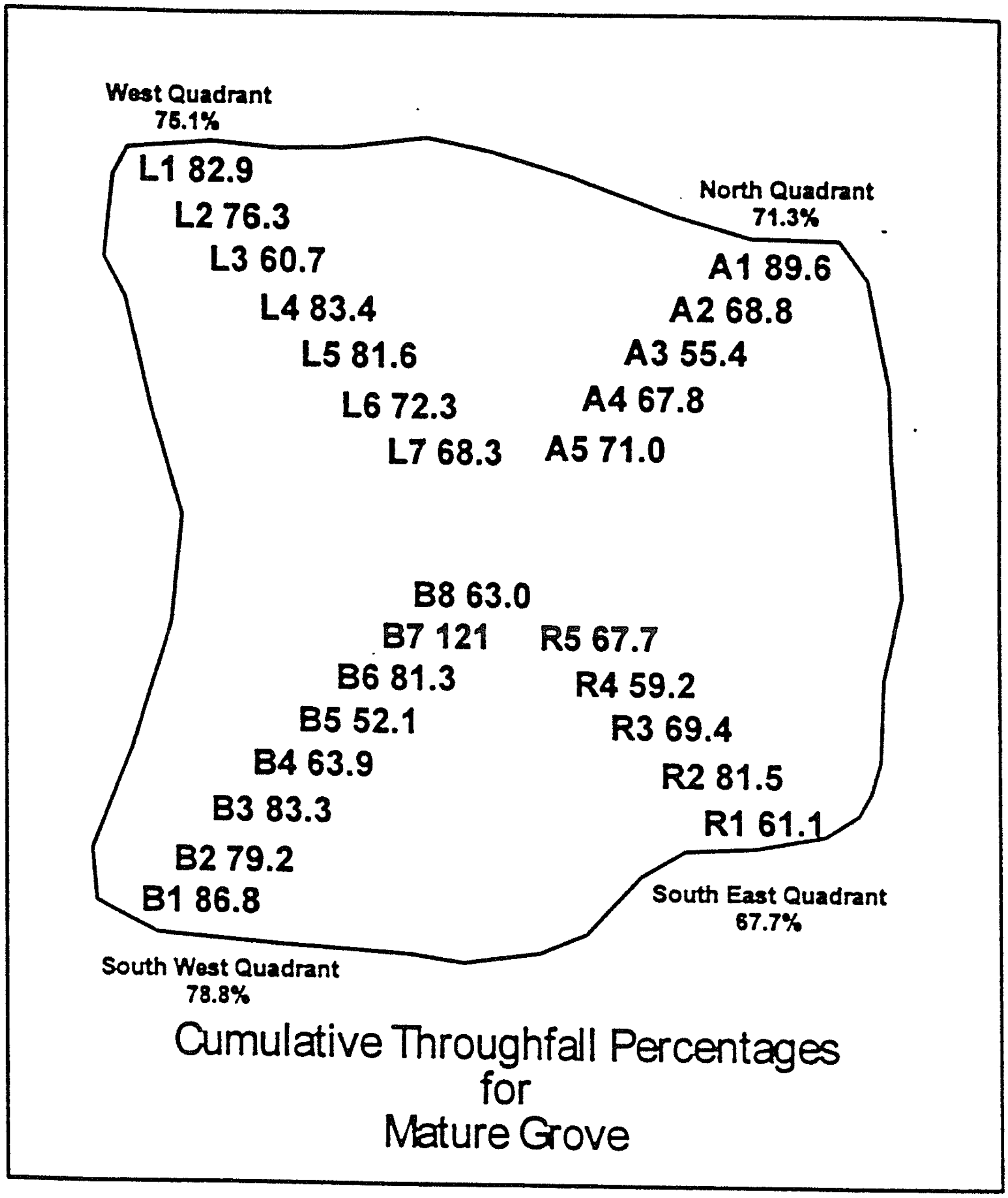


Figure 6 Stemflow Curve

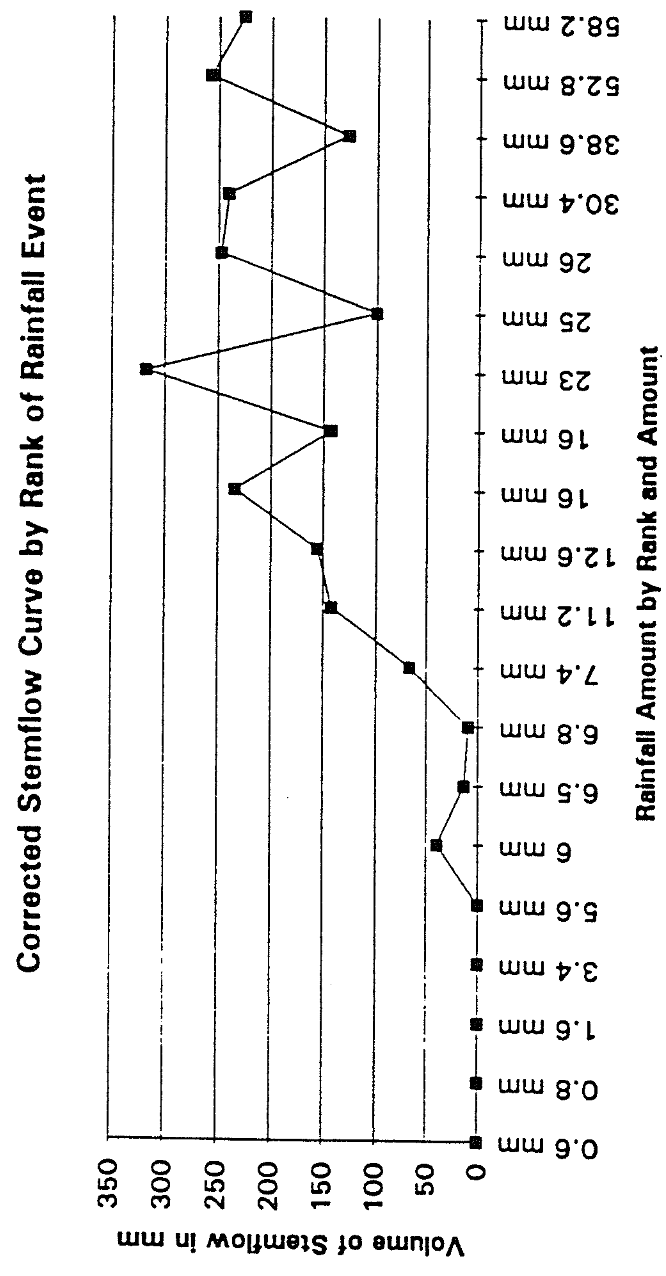


Figure 7 Bulk Density for Grass and Juniper

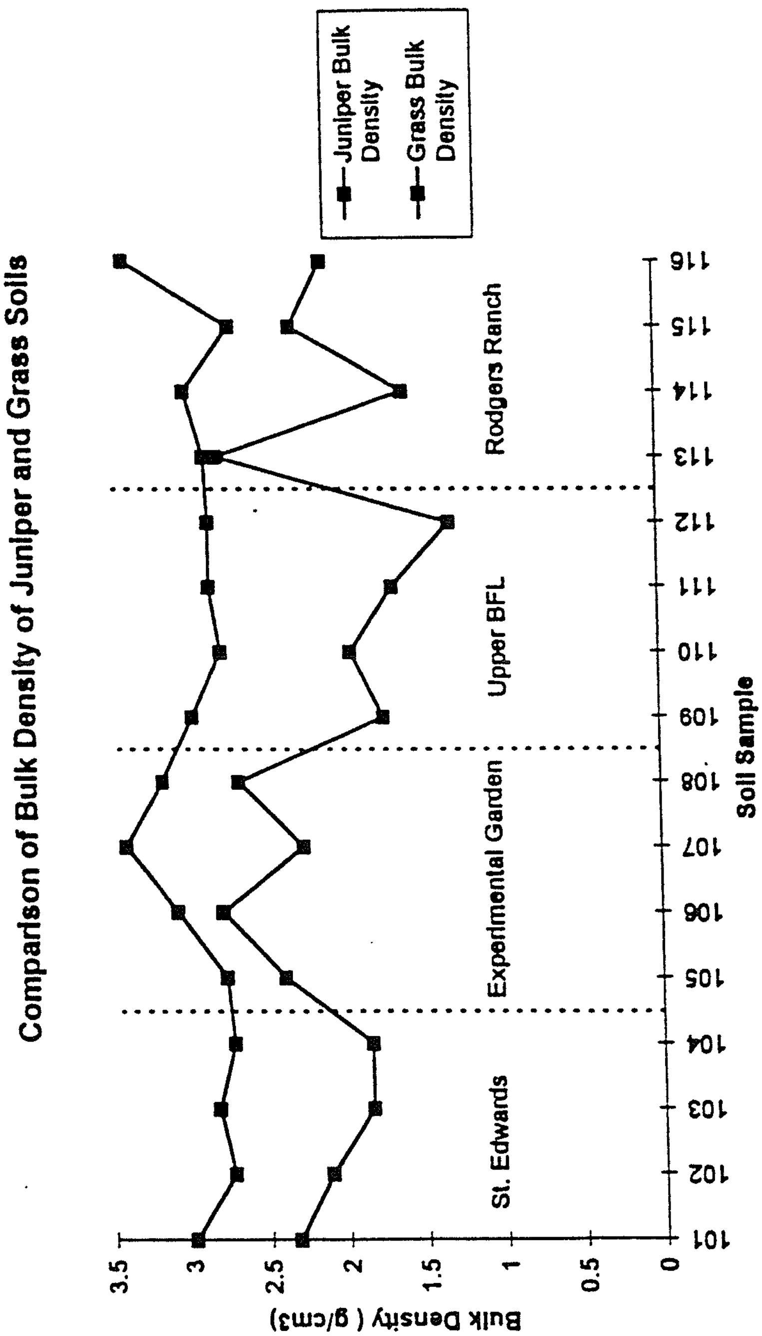


Figure 8 Percentage of Organic Matter for Grass and Juniper

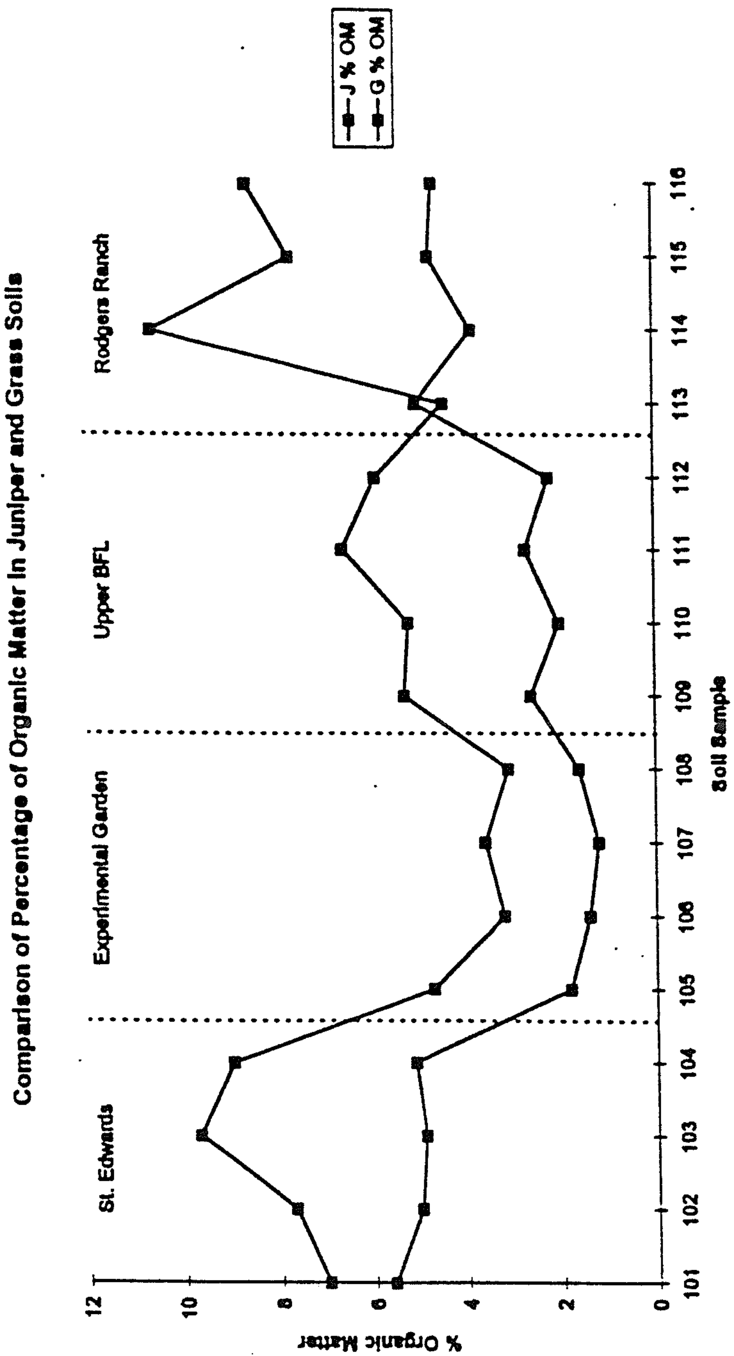


Figure 9 Bulk Density versus Organic Matter

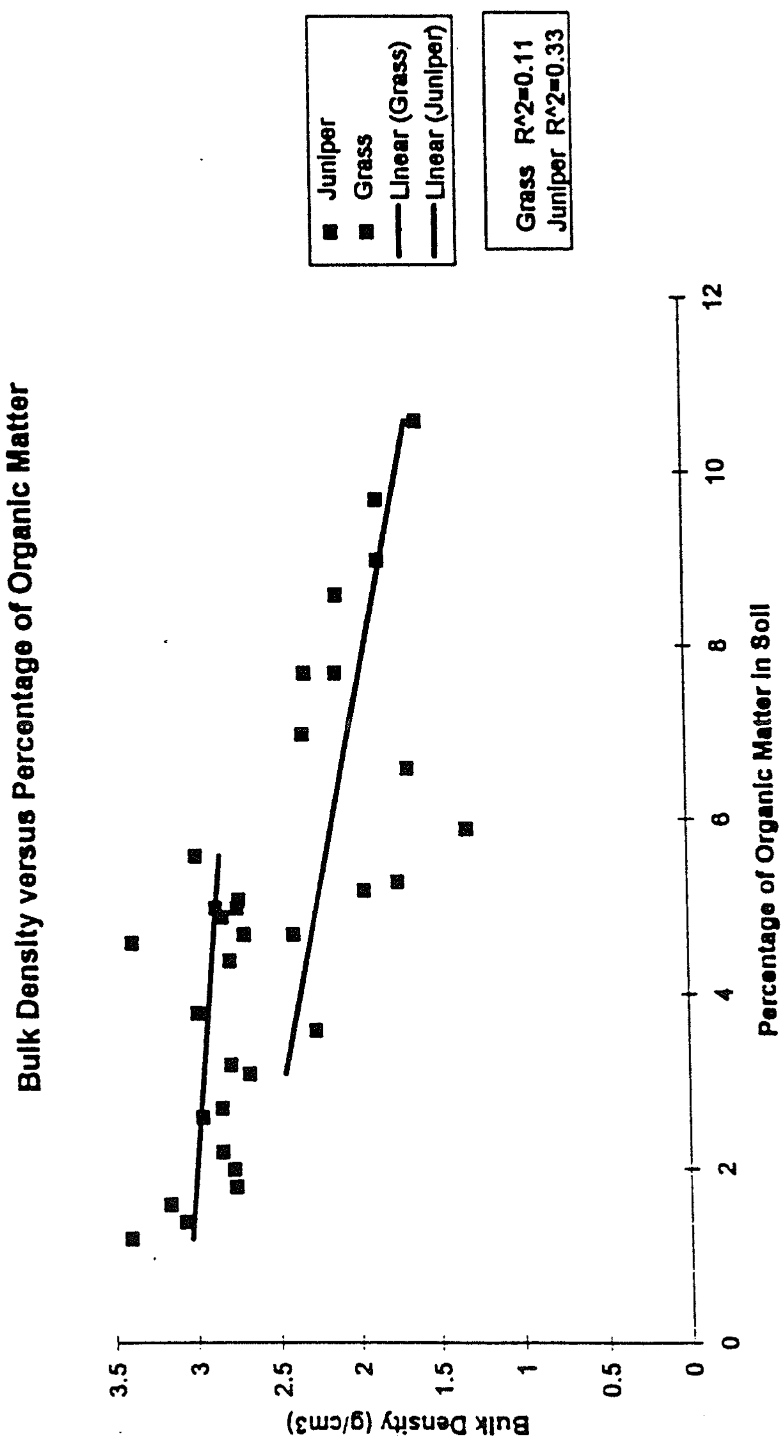


Figure 10 Percentage of Fines

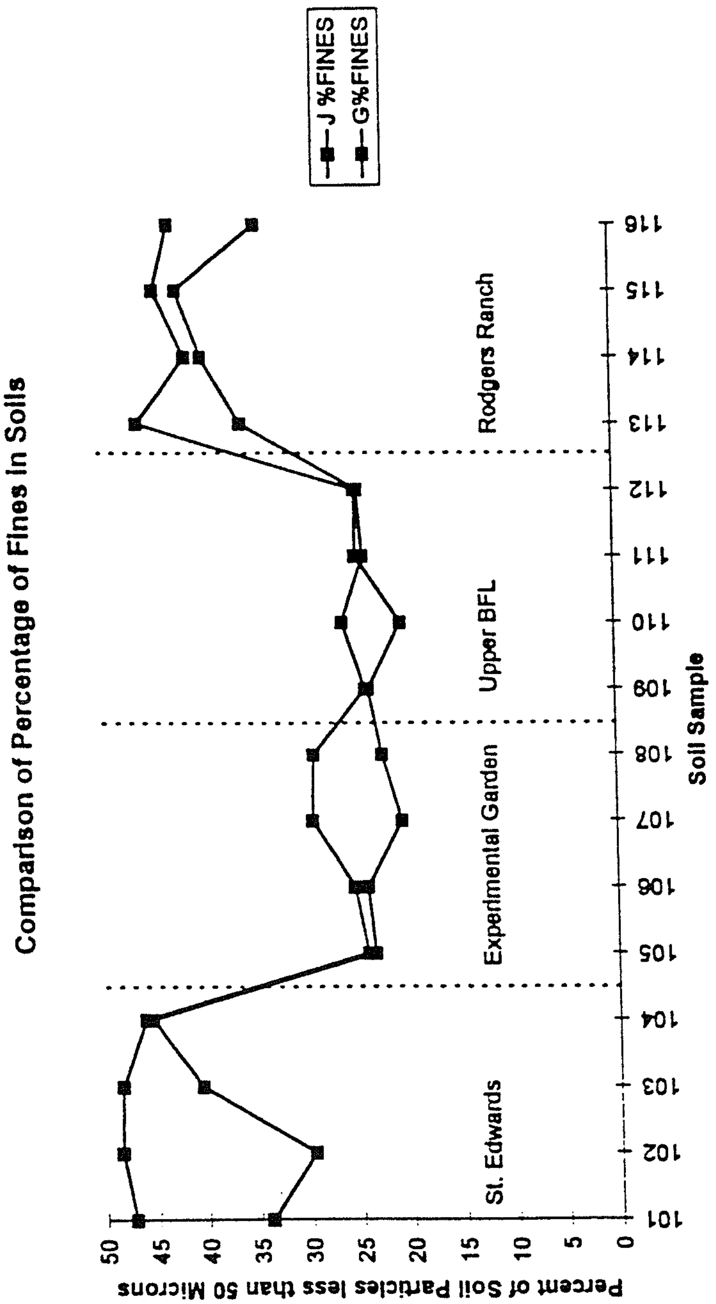


Figure 11 Bulk Density versus Fines

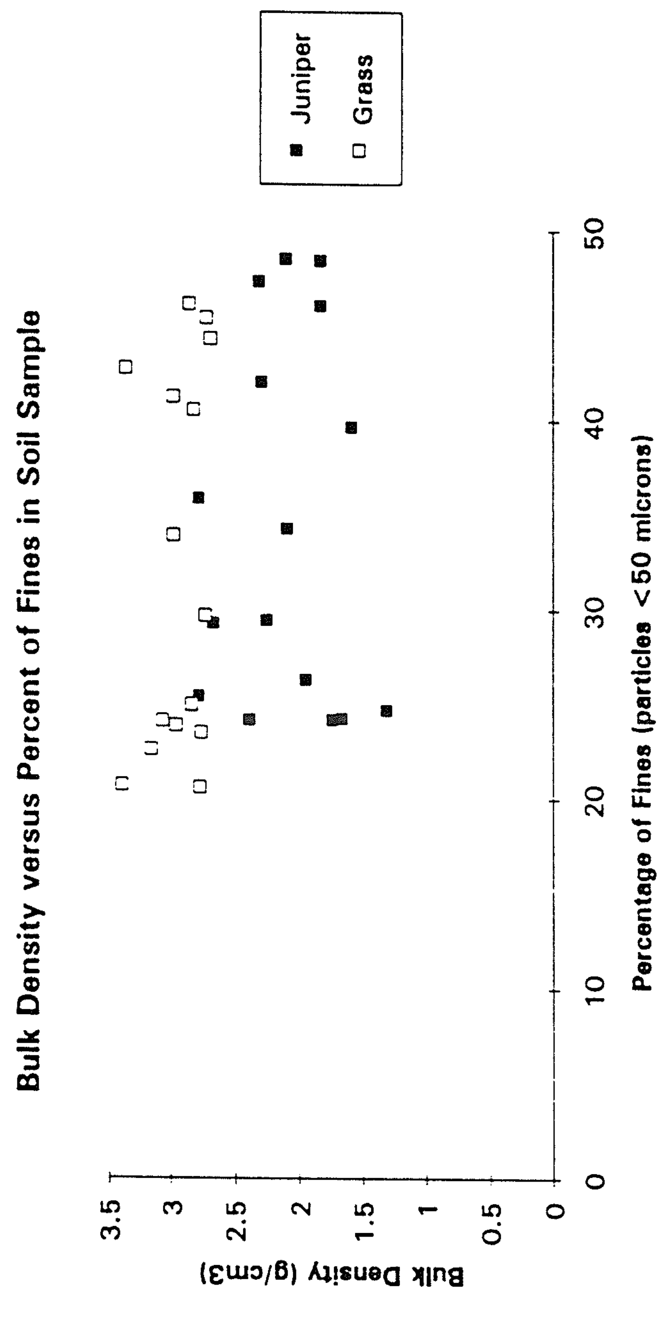
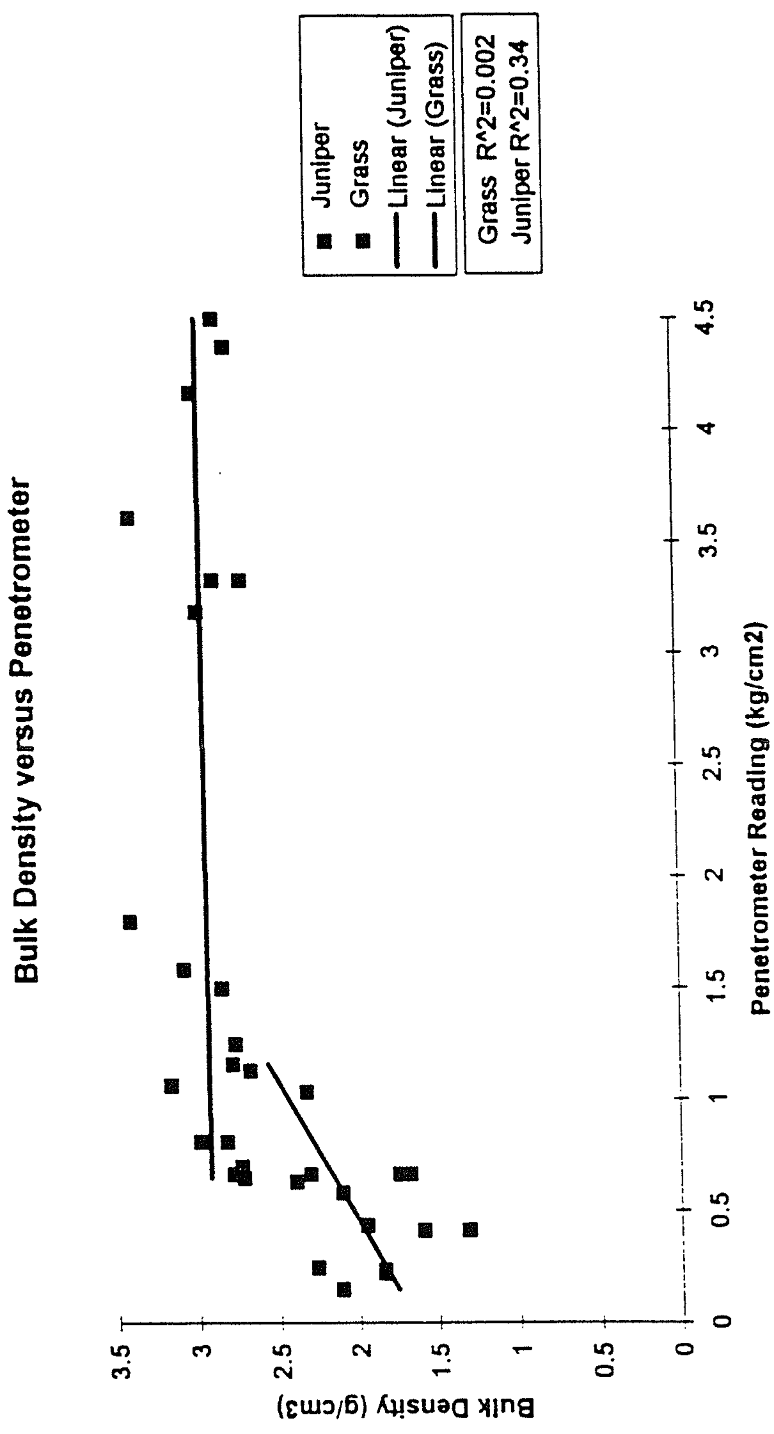


Figure 12 Bulk Density versus Penetrometer Reading



Conclusions

Ashe juniper is not an exotic tree newly arrived to the Edwards Plateau. Macro-fossils and pollen assemblages from Friesenhahn and Hall's Cave show juniper to have been present for at least the last 10,000 years on the Edwards Plateau (Toomey *et al*, 1992). The obligate association for nesting materials between the endemic golden cheeked warbler (*Dendroica crysoparia*) and mature Ashe juniper is unlikely to be a recent development (Neck, 1986). European settlers accounts dating back more than 150 years clearly identify juniper as being a common and valuable tree of the Edwards Plateau (Weniger, 1984). Specimens still exist in arboreta that were collected on the Plateau in the 1840's that are certainly Ashe juniper (Lundell, 1966).

These same settlers accounts suggest that the pattern of juniper distribution has changed (Weniger, 1984). Once, juniper was confined to rocky scarps and live oak mottes (Gehlbach, 1988). Fire was the most likely confining force since Ashe juniper shows a high mortality to fire until its bole diameter is greater than 4 cm (Fonteyn *et al*, 1988). At the beginning of the twentieth century it was noticed that Ashe juniper was increasing rapidly and spreading into grasslands from which it was historically absent (Foster, 1917).

It may be that fire suppression practiced by Anglo settlers allowed juniper to become established on the grasslands. The suppression of fire may have been accomplished by the depletion of native perennial grasses due to grazing pressure more than by any overt human actions (Buechner, 1944). The grasses had traditionally constituted the fine fuel load that ignited and spread the prairie fires

(Wells, 1965). It has also been suggested that an increased fire frequency which began with the arrival of paleo-indians on the Edwards Plateau and built to a rapid crescendo with the spread of European settlers in the last 200 years weakened the native grassland community to the point at which it was unable to sustain the continued disturbance of grazing and agriculture (Weniger, 1984).

By the turn of the century, Ashe juniper was no longer confined but became established on a wide variety of habitats and moisture regimes (Gehlbach, 1988). Ashe juniper possesses the ability to spread over a long distance quickly and into a variety of habitats. The synchronous ripening of the berries and observations suggest that early spring migratory birds may be responsible for rapid, long distance dispersal (Chavez-Ramirez, 1992). The wide variety of mammals that are occasional consumers of the juniper berries assures a dispersal into number of different habitats. The Ashe juniper seedlings become established in either sun or shade (Blomquist, 1990). The juvenile foliage is prickly and rarely browsed. The adult juniper foliage is more palatable but is not favored by native or domestic animals (Fuhlendorf, 1992). Once Ashe juniper populations had expanded into so many habitats, it was able to quickly recolonize any locale from which it had been removed by either fire or human actions.

The historical conversion of savannas to woodlands is one that has been investigated in many parts of the world (Archer, 1989). Ashe juniper increased at the expense of grasses on the Edwards Plateau. In other regions, other trees and woody shrubs were the increasers. It has been hypothesized that woody shrubs are able to reach sub-surface moisture unavailable to grasses and take advantage of a disturbed hydrologic system where surface sealing of the soil prevents most rainfall events from evenly wetting the upper meter of soil (Walker *et al*, 1981). Some combination of drought, grazing, surface compaction, and suppression of fire can cause a savanna community to cross a threshold from a grass-driven to a shrub-driven succession (Laycock, 1991).

Once established, woody shrubs or trees such as Ashe juniper can compete with grasses by making a favorable moisture regime for themselves and an unfavorable regime for any understory plant. Stemflow can gather water and nutrients far in excess of rainfall accumulations and deliver them to a very limited area at the base of the tree where only the tree can benefit (Barbour *et al*, 1987). This moisture in excess of rainfall is possible because water that would have become an even distribution of throughfall from the canopy edge to the trunk has been channeled by stemflow to highly localized drip points and the base of the main stem. It can quickly become difficult for other trees, shrubs, or grasses to establish underneath the canopy of Ashe juniper because of the increasing area of reduced moisture, shading, and the physical effects of the juniper litter layer (Yager, 1993).

Canopy interception, throughfall, stemflow, litter interception, infiltration and evapo-transpiration are the main components of all plants to some degree or another. The intent of this study has been to establish a quantifiable percentage or rate for canopy interception, throughfall, stemflow, and infiltration for Ashe juniper. An effort has been made to present this information in the same form as previous work on other major components of the Edwards Plateau vegetation such as live oak, bunchgrasses, and sodgrasses so that comparisons are possible.

Throughfall for Ashe juniper in this study ranged between 84% for the bush grove to 92% for the mature grove. The rate of throughfall for Ashe juniper is therefore higher than that determined for live oak at 71% (Thurow *et al*, 1987). Throughfall is dependent on storm intensity and the live oak study was performed on the western more arid edge of the Edwards Plateau and the percentage of throughfall for live oak on the wetter eastern edge of the Plateau where this study took place could be expected to rise. The pattern of throughfall for Ashe juniper appears to be not even but in increasingly smaller percentages as one moves from the canopy towards the trunk. The high percentage of throughfall is achieved by amounts in excess of rainfall that occur near the edge of the canopy on the quadrant facing the on-coming storm. Throughfall in excess of rainfall can also occur at interior points where stemflow down branches is interrupted by drip points. Throughfall can approach 50% in rainfall events as light as 3.4 mm, in heavier rainfall events the throughfall can approach 100% particularly in storms with significant winds.

Although difficult to measure and to quantify with the other components of the water budget, stemflow occurs in significant amounts in Ashe juniper. An accumulation greater than 5 times the total rainfall for the duration of the study was measured at the base of one juniper in the bush grove. In contrast, stemflow on live oak was measured at only 3.3% of rainfall (Thurow *et al*, 1987). This high rate of stemflow significantly lowers the losses termed canopy interception for Ashe juniper.

Litter interception was not measured in this study. It may be significant since litter accumulations under juniper can be thick and extensive. The mechanism of preferential flow channels may keep litter losses low (Facelli and Pickett, 1991). The same value for litter interception that has been established for live oak, 20.7%, can be accepted provisionally for Ashe juniper (Thurow *et al,* 1987). Since throughfall and stemflow are significantly higher for Ashe juniper than for live oak, then the total interception losses for Ashe juniper are less than those for live oak if comparisons across different moisture regimes are valid.

Once the remaining rainwater reaches the ground, it is easily infiltrated beneath Ashe juniper. Significant run-off was produced on only 1 of 4 sites tested during both initial conditions and after having been wetted to field capacity. On the adjoining plots dominated by grasses, significant run-off occurred early and continuously during both tests on all sites. The infiltration rate on the majority of juniper sites can be said to exceed 180 mm/hr. Tests for infiltration under live oak mottes have been recorded at 200 mm/hr. (Thurow *et al,* 1987). Various soil properties such as bulk density, percentage of fines and organic matter, and surface compaction were investigated to illuminate the difference in infiltration rates between those on grass dominated soils and those on juniper soils. Low bulk density, a higher percentage of organic matter and a lesser amount of surface compaction seemed to be the most significant properties associated with higher infiltration rates.

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