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A Study of the Vegetation of Northeastern Arizona

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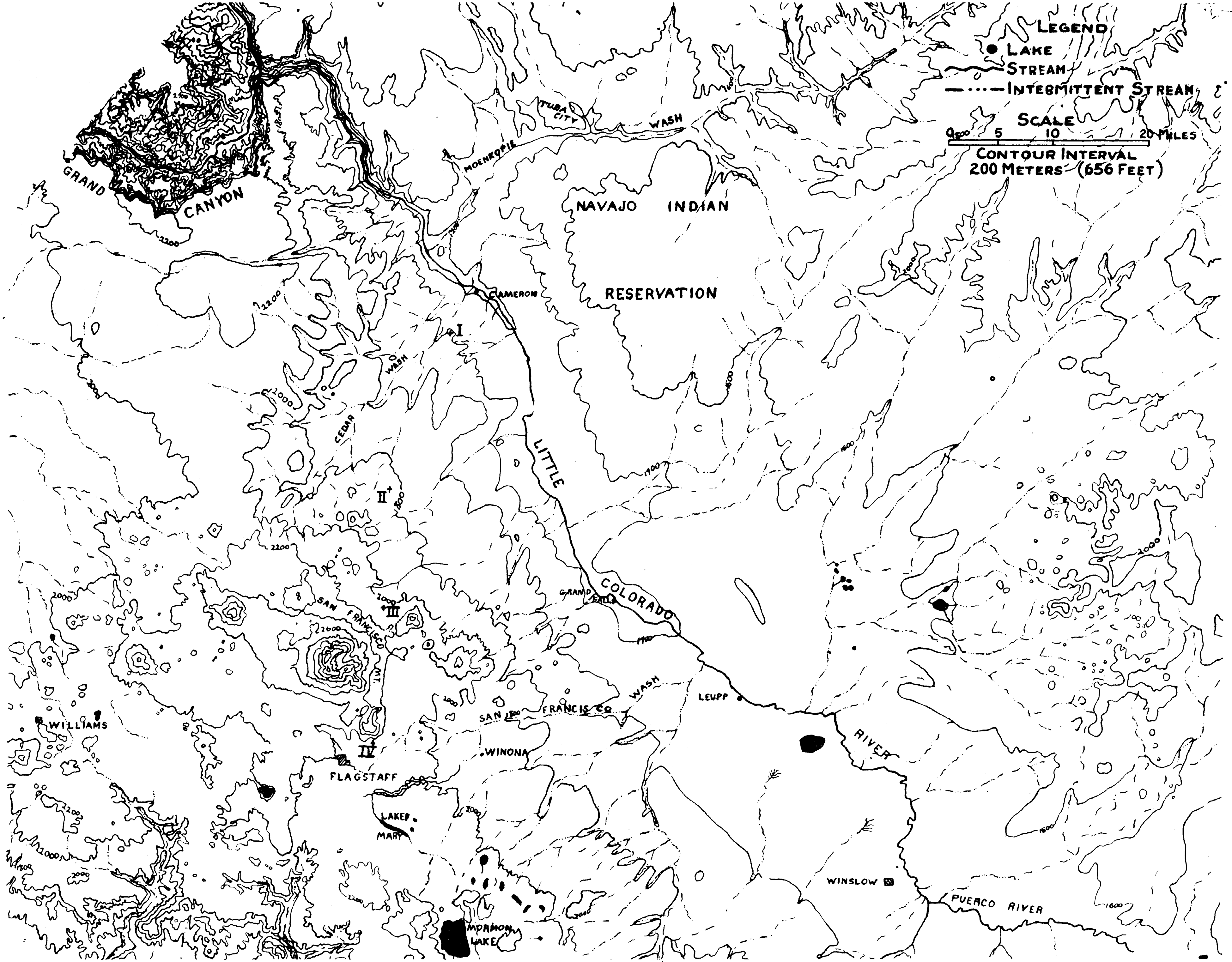

FIG. 1. Map showing a portion of northeastern Arizona. I = *Artemisia-Atriplex* station, II = *Aristida-Bouteloua* station, III = *Pinus-Juniperus* station, IV = *Pinus scopulorum* station.
Prepared from map of Arizona, Arizona Bur. of Mines and U. S. Geol. Surv.

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A STUDY OF THE VEGETATION OF NORTHEASTERN ARIZONA

BY HERBERT C. HANSON, Ph.D.

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INTRODUCTION

The State of Arizona is marked by a great series of cliffs that extend from the mouth of the Grand Canyon of the Colorado River in the northwestern part of the state southeastward into New Mexico. This line of cliffs, rising 1000 to 4000 feet above the desert plains forms the southwestern and southern boundary of the great physiographic province called the Colorado Plateaus. It is roughly circular and includes northeastern Arizona, northwestern New Mexico, western Colorado, and a large part of Utah. This province is subdivided by a number of deep canyons and high cliffs into numerous plateaus. The southwestern part, south of the Colorado River and west of the Little Colorado River, dominated by San Francisco Mountain (12,611 feet in elevation), is known as the San Francisco Plateau. East of this plateau, between the San Juan and the Little Colorado-Puerco rivers, lies the Navajo Country.

The purpose of this paper is to describe the vegetation of portions of the Navajo Country and the San Francisco Plateau and to attempt to correlate the widely varying vegetational types with environmental factors. The most intensive work was carried on near Flagstaff in the *Pinus-Pseudotsuga* Formation, in the *Pinus-Juniperus* Formation, in the *Stipa-Bouteloua* Formation, and in the *Atriplex-Artemisia* Formation; the last three lying east and northeast of Flagstaff. The field studies were conducted during the summers of 1922 and 1923. While considerable work had already been done by Pearson (1913, 1920, 1923) and others on the western yellow pine forest, nothing beyond brief reconnaissance work has been done on the vegetation as a whole.

On account of the lack of a taxonomic work or an adequate herbarium collection covering this region, and hence the difficulty in making exact determinations, the author has become greatly indebted to Dr. Aven Nelson and Dr. Paul C. Standley for the identification of many plants. Much time and considerable work were required to learn the flora of the region. Very little collecting had been done before this study was started. Several new species and varieties have been described by Dr. Aven Nelson from the writer's collections. The suggestions and criticisms received from Drs. J. E. Weaver and R. J. Pool and the careful reading of the proof by Professor T. J. Fitzpatrick have been greatly appreciated. The facilities provided by the universities of Arizona and Nebraska are gratefully acknowledged.

GEOGRAPHY OF THE NAVAJO COUNTRY

PHYSIOGRAPHY

The Navajo Country viewed as a whole is a plateau, the general surface of which is 5500 feet in elevation. Above this level the mountains rise and the canyons are depressed. This plateau has been so greatly dissected that it presents "a ruggedness probably surpassed by few other parts of the world" (Gregory, 1917:117). The original surface of the plateau has been dissected into mesas, buttes, ridges, spires, towers, canyons with vertical walls, and washes. These, with dunes and volcanic necks are repeated over and over to form a confusing but fascinating landscape. The influence of aridity is seen in most of the topographic features; such as, numerous sand dunes, wind-abraded surfaces, walls of bare rock instead of talus slopes, streams carrying water only after showers, etc. The variously colored rocks; grays, reds, browns, greens, and blues, have

caused the name, "Painted Desert," to be applied to various sections as around Cameron (see map, Fig. 1) and the region north of Adamana and Carrizo. Deposits of petrified wood are common. The dome-shaped Navajo Mountain, just across the line in Utah, rises to an elevation of 10,416 feet, like "an island in the midst of a sea of waterworn and windworn, brilliantly colored sandstone." Carrizo Mountains, near the northeastern corner of the state, ascend to 9,000 feet and the flat-topped Chuska Mountains extend along much of the boundary line between Arizona and New Mexico.

GEOLOGY

The predominant rock of the whole Navajo Country is sandstone of medium grain, perhaps 80% of the exposed layers are sandstones. Limestone and conglomerate are much less frequent. The numerous and varied topographic features owe their form to the kind of rock of which they are composed. The vertical cliffs of towers, pinnacles, needles, mesas, canyons, and mountains are formed of easily eroded shales and sandstones protected by a more resistant cap. The igneous rocks form dark-colored spires, pinnacles, cones, dikes, and necks, used for centuries as landmarks on long Indian trails that contrast strongly with the bright and variegated sandstone walls. The badland topography, irregular buttes, bobbins, dolls, etc., is usually formed of easily eroded shales and sandstones not capped by more resistant rock. Rounded domes, overhanging cliffs, natural bridges, pockets, etc., are formed in the easily eroded Navajo sandstone (Jurassic) when not protected by a resistant cap. Slab-talused mesa and canyon slopes are formed from Moenkopie sandstone (Permian), due to its breaking up into lenticular and flat, ripple-marked blocks, up to 10 feet and more in

diameter. Most of the rocks belong to Jurassic, Triassic, Cretaceous, and Pennsylvania strata (Gregory, 1917).

The structure of the Navajo Country differs from the plateaus of the Grand Canyon region in that it is characterized by numerous broad and narrow synclines and anticlines. As many as 18 folds have been counted from the San Juan River to the Little Colorado and Puerco rivers. Faults of any significance are absent. The plateau region to the west has more faults and fewer folds.

Soils

Most of the surface soil is sandy. Rock surfaces, left bare by wind and water action, are very common. The soil in numerous places is extremely shallow or confined to the crevices between the rocks. Sand dunes, often of large size, are common. Adobe soils occur occasionally in the valley of the Puerco and Little Colorado rivers and sandy clay-loam occurs on the broad mesas north of Holbrook and Adamana and in other restricted areas.

Drainage

The major stream of the region is the Colorado River, which forms the northwestern boundary (Fig. 1). The two chief tributaries of the Colorado are the San Juan River, forming the northern boundary, and the Little Colorado River, which with its branch, the Puerco River, forms the western and southern boundaries. The Colorado flows through canyons whose vertical walls often exceed 1500 feet. The San Juan, from its mouth to Chinle Creek (about 150 miles), flows through a canyon 1000 feet deep. Above the Chinle the cliffs rapidly diminish to less than 100 feet in height. The gorge of the Little Colorado where it joins the Colorado is 3000 feet deep. The stream bed rises with a rapid gradient so that above Grand Falls,

which is 130 feet high and 400 feet wide, the canyon has disappeared and the valley is flat and broad with a flood-plain over a mile wide.

There are innumerable drainage channels throughout the Navajo Country. These, often, become half filled with sand, blown in during the dry season. After a single, violent summer shower the water may rise 5 to 10 feet, deeply trenching the sand in a few hours and carrying great loads of silt to the muddy, major streams. The prevailing type of stream is intermittent, flowing only after rains. Most of the streams are in sharply cut canyons, only a few are in broad washes. The run-off is very great owing to the violence of the showers and the steepness of the slopes. The gradients range from 45 to 60 feet per mile in the longer streams, as the Chinle, to 160 feet in the short ones.

GEOGRAPHY OF THE SAN FRANCISCO PLATEAU

PHYSIOGRAPHY

The dominating feature of the San Francisco Plateau is San Francisco Mountain, which rises to 12,611 feet and has a diameter at about 8000 feet of 9 to 12 miles. The crest of this great crater has six major peaks and several minor ones over 11,000 feet high. The steep slopes descend quickly to 7000-6500 feet, which forms the general elevation of the plateau as a whole. On the east and north-east sides the elevation decreases gradually and fairly uniformly to about 4000 feet along the Little Colorado River. On the north the plateau extends to the Grand Canyon of the Colorado and on the west and south it extends to the faults which mark the edge of the desert-plains. On the southeast the plateau is continuous with Mogollon Mesa and other elevated regions which extend into New Mexico.

Most of the plateau has a gently rolling, youthful topography, with occasional mountains of small area rising to 10,000 feet. In the vicinity of San Francisco Mountain, especially on the east and northeast sides, are about 300 volcanic cones rising from only a hundred to a thousand feet above the general surface. In the southern part of the region occasional precipitously walled canyons occur, of which the largest are 1000 to 1500 feet deep and about 8 miles long.

The outer slopes of San Francisco Mountain and other large cones are marked by alluvial fans, composed of coarse lava fragments. These fans, deposited when the climate was colder and more moist, are today being dissected.

Geology

The chief geologic feature of the plateau is the evidence of terrific volcanic activity. This occurred at three different periods, with quiet intervals, extending from the late Pliocene to the Quaternary. During the first period widespread eruptions of basalt were poured from about 100 small cones upon Kaibab limestone (Pennsylvanian). Today this lava covers about 2200 square miles. During the second period six large cones, including San Francisco Mountain, were formed. The lava exposed on these mountains varies from andesites to rhyolites. During the third period basalt was poured from 200 new cones over 1200 square miles. Just before the third flow the whole region was raised 4000-6000 feet by faulting, leaving sharp faults on the west and south sides and a great monocline on the east to the Navajo Country (Robinson, 1913).

The surface rock of the regions north, northwest, and southeast of the lava field is the white to grayish Kaibab limestone. Rarely in the volcanic field, as near Flagstaff, is the red sandstone of the Moenkopie Formation (Per-

mian) exposed. Between the Little Colorado and the eastern edge of the lava field a broad strip extending from below Cameron to Winslow exposes this infertile, ripple-marked, rapidly eroding sandstone.

Soils

Most of the soil of the plateau is clay-loam or adobe with rocks and bowlders intermixed. The soils of basaltic origin are heavier than the limestone soils. Sandy soils are not common. Mountain slopes, especially those of San Francisco Mountain, have a large proportion of coarse materials with a sandy or gravelly subsoil. East and northeast of San Francisco Mountain are extensive areas of cinder soils, composed of coarse, black, volcanic cinders. On the slopes of volcanoes, especially, scoriaceous soils, mixtures of slag and pumice-like materials, occur. The "parks" usually have fine, stiff, alluvial soil, with few or no rocks or bowlders.

Drainage

There are 12 principal watercourses or washes in this area. Only one, Oak Creek, is perennial. The watercourses are not always well defined in the igneous rock but in the limestones and sandstones they form shallow valleys or vertically walled canyons. The eastern half of the region drains into the Little Colorado, the northwestern part into the Colorado River through Cataract Creek, and the southwestern part into the Verde River.

The precipitation sinks or runs rapidly away over most of the region, due to the porous rock. There is a large amount of underground drainage as is indicated by "bottomless pits" in various places. The winter snow disappears quickly, with much run-off, usually by April 1.

A number of lakes occur on the plateau south and southeast of Flagstaff. The largest of these are Mormon, Stoneman, and Mary. The first two were dry from about 1894 to 1905 so that the areas were used for agriculture. Before and after this period the water was 10-15 feet deep in Mormon Lake.

THE VEGETATION

Looking northeast from the summit of San Francisco Mountain one can see within 35 miles six formations occurring in zones, ranging from alpine summits to sage-

TABLE 1. *A comparison of classifications of the vegetation of northern Arizona*

Merriam (1890)	Pearson (1920)	Shreve (1917)	Clements (1920)	Shantz (1923)
Alpine zone above 11,500 ft.	Alpine zone above 11,500 ft.	Alpine summits	Alpine meadow climax	
Subalpine or timberline zone 10,500-11,500 ft.	Engelmann spruce 9500-11,500 ft.	Northern mesophytic evergreen forest	Sub-alpine forest climax	
Hudsonian or spruce zone 9200-10,500 ft.				
Canadian or balsam fir zone 8200-9200 ft.	Douglas fir 8300-9500 ft.		Montane forest climax	Western pine forest
Neutral or pine zone 7000-8200 ft.	Yellow pine 6700-8300 ft.			
Piñon zone 6000-7000 ft.	Piñon-juniper 5000-6700 ft.	Western xerophytic evergreen forest	Woodland climax	Southwestern coniferous woodland
Desert area 4000-6000 ft.	Desert grassland 3000-5000 ft.	Desert-grassland transition	Grassland climax	Plains grassland
		Great Basin microphyll desert	Sagebrush climax	Northern desert shrub

brush desert. These formations have been variously named by different ecologists, as shown in the preceding table.

These authors agree essentially in classifying the higher zones, but there are rather pronounced differences in the treatment of the desert and grassland bordering the Little Colorado River. These differences will be discussed as each zone is treated in detail. On account of its completeness and ease of application to field conditions the classification of Clements (1920:114) will be used in this paper.

THE SAGEBRUSH CLIMAX (*Atriplex-Artemisia* FORMATION)

The Basin Sagebrush (*Atriplex-Artemisia* Association)

While Merriam (1890) and Pearson (1920) do not differentiate between the desert and the grassland below 5000-6000 feet, Shreve (1917) shows a large portion of northeastern Arizona as sagebrush and another large portion as Desert-grassland Transition. Shantz's map (1923) shows a strip of sagebrush extending up the Little Colorado-Puerco rivers as far as Adamana, bordered on each side by short-grass plains. Clements (1920:155) considers the sagebrush along the Little Colorado as an extra-regional tongue of the main sagebrush region to the north, "persisting because of peculiar local conditions or because the proper climax has not yet occupied all of its climatic region." Later, Clements (1923:105-106) apparently considers the sagebrush with the grassland as part of the mixed prairie association; the sagebrush communities giving way to the grasses in succession. Thornber (1910: 276) says that "seven or eight inches of timely summer rainfall will insure, ordinarily, a good growth of the bunch grasses, a heavier precipitation inducing a correspondingly greater yield, while five inches or less of summer rainfall, especially, when poorly distributed, results in

very unsatisfactory growth." The rainfall from May to October inclusive in the lower Little Colorado Valley averages 2.86 inches at Leupp (7-year record), 2.73 at Tuba City (24-years), and 3.87 at Winslow (17-years). The grasses in all these places are sparse and shrubs dominate.

Before discussing the classification further it is well to describe the vegetation. As one descends on a gentle slope toward the Little Colorado the grassland is gradually replaced by scrub. It is impossible to draw a sharp line between them, especially since the grassland extends down into the valleys as long tongues into the sagebrush desert. The desert is well developed in the valley of the Little Colorado extending northward from Leupp. At Cameron it occupies a strip 10 miles wide on the west side of the river. On the east side much of the northern half of the Navajo Country is desert. While there is considerable variation in the aspect of the desert the predominating one is the sparse, gray scrub, 1 to 3 feet high, alternating with bare areas over most of the slopes, hilltops, and cliffs (Plates I, II, III). Along the sandy washes there is a fringe of taller, greener shrubs (Plate III, A), and in the pockets of canyons there may be a dense growth of still taller shrubs and small trees. A similar type of low sagebrush desert in southeastern Washington has been described by Weaver (1917). The following list shows the more important ecological species.

DOMINANT SPECIES *(consociations)*

Atriplex confertifolia	Isocoma heterophylla
A. canescens	Chrysothamnus graveolens
Gutierrezia glomerella	Artemisia tridentata
Artemisia bigelovii	Eurotia lanata

SECONDARY SPECIES

Shrubs	*Grasses*
Ephedra torreyana	Hilaria jamesii
Yucca glauca	Sporobolus airoides
Fallugia paradoxa	S. strictus

Schmaltzia trilobata
Encelia frutescens resinosa
Coleosanthus wrightii
Amsonia brevifolia
A. arenaria
Parryella filifolia
Coleosanthus scaber
C. linifolius
Forestiera neomexicana
Lycium parviflorum
L. pallidum
Eriogonum divergens
E. simpsonii
Dondia fruticosa
Sarcobatus vermiculatus

Bouteloua eriopoda
B. curtipendula
B. gracilis
B. barbata
Tridens pulchellus
Erioneuron pilosum
Muhlenbergia porteri
Oryzopsis hymenioides
Pappophorum wrightii
Sitanion rigidum
Polypogon lutosus
P. monspeliensis
Agrostis stolonifera

Herbs (exclusive of grasses)

Crassina grandiflora
Psilostrophe tagetinae
Senecio filifolius
Leucelene ericoides
Wislizenia refracta
Stanleya arcuata
Galpinsia lavendulaefolia
Chylisma scapoidea
Chamaesaracha coronopus
Physalis hederaefolia
Nuttallia multiflora
Eriogonum tenellum
Arenaria aculeata

Gilia inconspicua
Wedeliella incarnata
Quamoclidion multiflorum
Euphorbia flagelliformis
E. revoluta
E. fendleri
Croton texensis
Phacelia corrugata
Tetraclea coulteri
Coldenia nuttallii
Houstonia rubra
Malvastrum leptophyllum
Sphaeralcea arizonica

The best developed vegetation was found along the broader washes (Plate III, A), in the rather broad valleys where the soil was deep, and on the limestone areas (Plate II). The poorest vegetation occurred on the red sandstone areas where the soil was only a foot deep, or less, for miles in extent, on gravel, sand (Plate III, B), or cinder areas, and on places where wind and water erosion was particularly effective (Plate III, B). In the broad valleys, where the soil was four or more feet deep, there were often found dense growths of *Hilaria jamesii* and *Sporobolus airoides,* with a scattered growth of *Atriplex conferti-*

folia and *A. canescens.* A few species, *Sporobolus strictus, Sphaeralcea arizonica, Chamaesaracha coronopus, Crassina grandiflora, Opuntia* sp., occurred less frequently. *Sporobolus airoides* formed large, coarse bunches, 3 to 4 feet high, the stiff, dry culms of the preceding year protecting the young shoots from overgrazing. *Hilaria* has spread its hard and sharply pointed shoots along the surface of the ground, rooting at the nodes. Although greatly relished by stock it is very resistant to overgrazing. Rapid erosion has cut narrow channels, 3 to 5 feet deep and 2 to 5 feet wide, in many of these valleys. This has reduced the water-content of the soil, which, in turn, produced a poor growth of grasses near the channel.

Along the sides of the larger washes occurred a narrow fringe of green shrubs, taller and much denser than the usual scrub (Plates I and III). This fringe consisted chiefly of *Fallugia paradoxa,* sprinkled with its conspicuous white flowers or clumps of long hairy fruits, giving it its common name, Apache plume, large plants of *Atriplex canescens, A. confertifolia, Amsonia brevifolia, A. arenaria, Lycium parviflorum,* and *L. pallidum,* the latter two belonging to the characteristic flora of the southern Arizona desert plains. A greater abundance and variety of herbs occurred between and under the shrubs. Especially characteristic species were *Senecio filifolius, Chamaesaracha coronopus, Tetraclea coulteri,* and *Malvastrum coccineum.* Another plant, common in southern Arizona, *Muhlenbergia porteri,* was frequently found climbing among the shrubs, where it was well protected from grazing. The plants found in the broad valleys were common between the shrubs. Along the small washes most of the above-named herbs were present but less abundant. The shrubs, however, were limited to *Atriplex canescens, A. confertifolia,* and *Gutierrezia,* larger in size than on the desert slopes and plains. In pockets of can-

yons denser and taller scrub was found, thickets of *Forestiera neomexicana* occurred frequently. In the larger canyons and river valleys cottonwoods, *Populus wislizeni*, and willows, *Salix*, were found in small groves and scattered singly at infrequent intervals.

Near the station where factor readings were obtained was an area of rocky limestone several square miles in extent. The surface was strewn with fragmented gray limestone varying in size from pebbles to large slabs. The soil was shallow, a foot or less in depth and often the solid rock lay exposed over many square yards. But the vertical and horizontal cracks between the slabs and blocks were filled with dark brown soil, rich in humus and high in moisture when compared with the rest of the desert. Soil moisture samples taken throughout the 1923 season showed that there was water available for plant growth to a depth of 20 cm. (the usual soil-depth) during the whole season in the limestone soil but only after July 22 in red sandstone soil. Practically no difference was found in the alkalinity of the two soils, both being only slightly alkaline, according to the Wherry test (Wherry, 1920). Great differences were noted in the vegetation due to the richer and moister soil. There was a much greater abundance of individuals, a greater number of species, of which several were found here only. Plate II, A, shows the much greater abundance of plants on the limestone soil in the foreground as compared with the red sandstone in the background. Plate II, A, and the quadrat in Fig. 2, show the abundance on the limestone of the grasses *Bouteloua gracilis, B. eriopoda,* and *Hilaria jamesii;* of the shrubs *Atriplex confertifolia* (usually small plants), *Yucca, Gutierrezia, Artemisia bigelovii;* and of the herbs *Galpinsia lavandulaefolia, Malvastrum leptophyllum, Crassina grandiflora, Sphaeralcea, arizonica, Pentstemon desertopictus, Houstonia rubra,* and *Arenaria aculeata.* The

last three were found only in the cracks of the limestone. *Pentstemon desertopictus,* a new species discovered by the author and reported only from this locality, was especially interesting in that the shoot was only 1 to 3 inches high

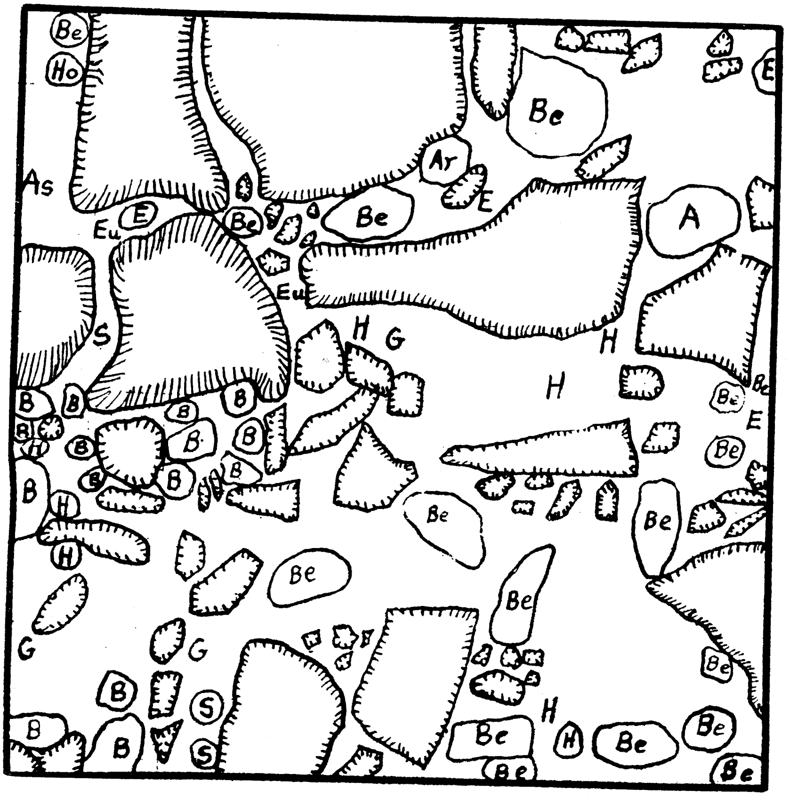

FIGURE 2. Meter quadrat on limestone soil in *Artemisia-Atriplex* Association. August 17, 1923. Shaded areas are rocks.

A	= Artemisia bigelovii	G	= Gutierrezia glomerella
B	= Bouteloua gracilis	Ar	= Arenaria aculeata
Be	= B. eriopoda	As	= Aristida fendleriana
S	= Sporobolus strictus	H	= Hilaria jamesii
E	= Eriogonum simpsonii	Ho	= Houstonia rubra
Eu	= Euphorbia glyptosperma		

but the long fibrous roots extended mostly horizontally for several feet in the moist soil between the slabs of rock. The dwarfness of *Atriplex confertifolia,* compared to its size on the red sandstone, was also striking (Plate II, B). Other species occurring chiefly on the limestone were *Bouteloua barbata, B. curtipendula, Erioneuron pilosum, Eriogonum simpsonii, Echinocereus* sp., and a low platyopuntia. *Aristida fendleriana, Ephedra torreyana,* and *Sporobolus strictus* were scattered. Although the area had been heavily grazed for many years it is noteworthy that more characteristic grassland species, especially grasses, occurred in greater abundance on the limestone than elsewhere on the desert. This shows clearly that the lack of sufficient moisture, and not overgrazing, prevents the grasses from dominating this region.

Over extensive areas, where the soil was only 5 to 20 cm. deep and the underlying rock was not fissured, the vegetation was very sparse (Plate I). Small, gnarled bushes of *Atriplex confertifolia, A. canescens, Ephedra torreyana,* with clumps of *Hilaria* and an occasional *Sporobolus airoides,* occurred at intervals of one to several meters where the soil-depth on the red sandstone was about 20 cm. deep. Individuals of *Yucca glauca, Ephedra torreyana, Leucelene ericoides, Tridens pulchellus,* and *Euphorbia glyptosperma* were scattered. As the soil became thinner the plants become smaller and more scattered and *Hilaria* and *Sporobolus* disappeared quickly. Low, densely tufted individuals of *Tridens* occurred on the thinnest soils, which recalled its similar distribution and habit on the southern Arizona deserts. On rocky sandstone outcrops, where the soil was very thin or lacking on the surface but where the narrow crevices furnished soil several feet deep, the most common plants were dense, low shrubs of *Artemisia bigelovii, Gutierrezia glomerella, Artiplex canescens,* and *Eriogonum divergens.* The common occurrence of plants

growing in lines or rows was usually explained by an underlying crevice. Other plants occurring here were *Encelia, Atriplex confertifolia, Coleosanthus scaber, C. linifolius, Tridens, Bouteloua eriopoda,* and *Sporobolus strictus.* In the larger cracks *Fallugia paradoxa* and *Schmaltzia trilobata* flourished. The flattening of the roots in narrow, vertical, and horizontal fissures, and the large number and tortuous course of the branches in small amounts of soil, explain partly how these plants can grow on the seemingly most barren soil in this arid climate.

In the vicinity of Tuba City and eastward sand is very common, forming dunes and filling the stream-beds. An important invader of the sand, as well as of the cindery soil near Leupp, was the low, greatly branched, leguminous shrub, *Parryella filifolia.* This glandular, evil-smelling plant, with its small, pinnately-arranged leaflets, was a good soil-binder and dune-builder (Plate III, B). Other important pioneers were *Euphorbia revoluta, E. flagelliformis, Hilaria jamesii, Heliotropium convolvulaceum, Wedeliella incarnata, Tragia ramosa, Nuttallia multiflora, Quamoclidion multiflorum, Croton texensis,* and *Coldenia nuttallii.* This stage is succeeded by a mixture of *Atriplex, Chrysothamnus graveolens,* and other shrubs, with *Sporobolus* and *Hilaria* and other herbs interspersed. North and northeast of Tuba City *Artemisia tridentata,* more or less mixed with other shrubs already named, formed the climax.

On account of the dominance of *Artemisia, Atriplex, Gutierrezia, Eurotia, Chrysothamnus,* and other shrubs characteristic of the sagebrush climax to the north; the scarcity of the grasses; and the severely arid conditions of soil and climate this region has been classified under the sagebrush formation rather than under desert-grassland. It shows a relationship to the desert-plains of southern Arizona by the presence of a few characteris-

tically southern species, such as *Encelia, Tridens, Muhlenbergia porteri,* etc., but in no way is it a continuation of it through the Grand Canyon as stated by Merriam (1898:22). Instead the desert scrub of western and southern Arizona gradually gives way to sagebrush desert in the Grand Canyon and the transition line is probably about where Shantz has shown it near the mouth of Cataract Creek (1923), far below the junction of the Little Colorado River with the Colorado River.

THE GRASSLAND CLIMAX *(Stipa-Bouteloua* FORMATION)

The Desert Plains *(Aristida-Bouteloua* Association)

Leaving the Little Colorado River the ascent toward San Francisco Mountain is on a very gentle gradient, except in a few places where the lava flows ended abruptly, leaving steep but not very high slopes. The vegetation changes gradually from the dominance of scattered shrubs to that of grasses. At first the grasses are dominant only in the narrow valleys, with shrubs elsewhere. Then the grasses dominate wider valleys, next the slopes, and finally the summits, with only occasional shrubs, usually in disturbed areas such as prairie-dog towns. The shrubs give way first to *Hilaria jamesii,* which dominates a large transition zone. *Hilaria* is replaced by *Bouteloua eriopoda,* which, in turn, gives way to *B. gracilis* as the lower border of the woodland is reached. The following list gives the more important and characteristic species.

DOMINANT SPECIES *(consociations)*

Bouteloua eriopoda   Bouteloua gracilis   Hilaria jamesii

SECONDARY SPECIES

Shrubs	*Grasses*
Atriplex canescens	Sporobolus airoides
Gutierrezia glomerella	S. strictus
Chrysothamnus bigelovii	Bouteloua curtipendula
Tetradymia inermis	Stipa neomexicana

Coleosanthus linifolius	Aristida longiseta
Schmaltzia trilobata	Sitanion rigidum
Fallugia paradoxa	Oryzopsis hymenioides
Eurotia lanata	Muhlenbergia porteri

Herbs (exclusive of grasses)

Crassina grandiflora	Chenopodium pratericola
Psilostrophe tagetinae	Oreocarya multicaulis
Leucelene ericoides	Asclepias arenaria
Hoffmanseggia jamesii	Ximenisia exauriculata
H. drepanocarpa	Gaillardia pinnatifida
Senecio filifolius	Erigeron nanus
Sphaeralcea arizonica	Phaseolus dilatatus
Eriogonum cernuum	Hedeoma oblongifolia
Euphorbia glyptosperma	Opuntia hystricina

The central part of this zone was occupied by an almost pure stand of *Bouteloua eriopoda* (Plate IV, A). At first sight it seemed to form a sod but closer examination showed bunches or small mats. These were 4 to 6 inches in diameter and a foot or more high at maturity, covering only about 25% of the soil, 75% being bare ground (Fig. 3). In spite of this large amount of open soil the consociation was closed to invaders except during unusually moist seasons because of the low supply of available soil moisture and the great extent to which the first foot was occupied by roots. Excavations showed that the great majority of the roots were in the upper foot and that they decreased very rapidly below this level. In some places no roots were found below one foot. This root distribution, as well as the rapid growth of the shoots, is correlated with the shallow and gradual penetration of the summer rains. At the end of the summer, 1922, the rain had penetrated only to a depth of 14 inches, and in 1923 there was no available moisture in the second foot until August 9 (Fig. 15), but in the first 4 inches it was available on July 9 (Fig. 13). On account of the lack of drinking water for stock this fine grass, extending over many square miles, was ungrazed.

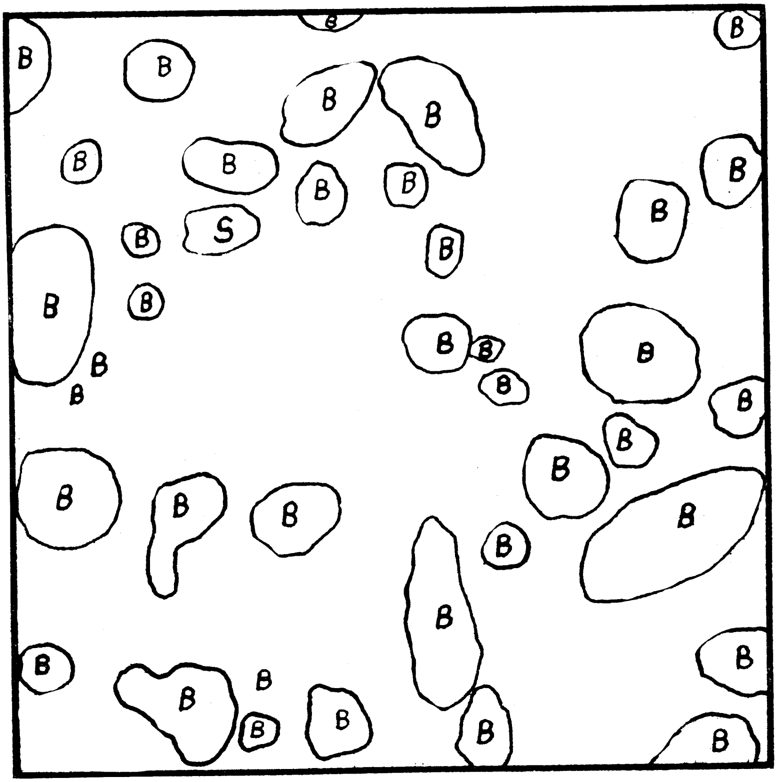

FIGURE 3. Meter quadrat in *Bouteloua eriopoda* Consociation of the *Aristida-Bouteloua* Association. September 2, 1923.
B = Bouteloua eriopoda S = Sporobolus strictus

Below this consociation, first *Hilaria jamesii* (Plate IV, B), and then *Sporobolus airoides* and the desert shrubs, especially *Atriplex canescens,* increased in number, while *Bouteloua eriopoda* decreased. This was due to increased xerophytism, especially in soil moisture. Higher up, due to increased soil moisture, *Bouteloua gracilis,* replaced *B. eriopoda* rather rapidly, so that in the openings between the cedars and piñons very little of the latter was to be found. Over much of the *B. eriopoda* grassland, but espe-

cially near the upper tension line, were scattered bushes of *Chrysothamnus graveolens,* 1 to 3 feet high. On rocky hills and ridges the shrubs *Schmaltzia trilobata, Fallugia paradoxa, Tetradymia inermis,* and *Coleosanthus linifolius* formed the dominant vegetation. *Muhlenbergia porteri* was found infrequently in the scrub and *Stipa neomexicana* and *Sitanion rigidum* occurred frequently in the sunny places.

The disturbance of the uniform grass vegetation by prairie-dogs was conspicuous for miles (Plate V, A). The most important first invaders on the fresh mounds and denuded areas were the weedy plants *Sphaeralcea arizonica, Euphorbia glyptosperma, Leucelene ericoides, Chenopodium pratericola, Oreocarya multicaulis, Eriogonum cernuum, Senecio filifolius,* and *Hoffmanseggia drepanocarpa. Aristida longiseta* was frequently found as a relict from the former vegetation, as it is not eaten by the prairie-dogs. A few plants of *Bouteloua eriopoda* and *Hilaria jamesii* were also found at times but as these were preferred next to *Stipa* by the rodents they were in decidedly poor condition. Often *Atriplex canescens* came in with these first invaders or shortly after them. Other shrubs, *Chrysothamnus bigelovii, Eurotia lanata,* and *Tetradymia inermis,* sometimes followed or accompanied *Atriplex* but usually *Hilaria* and *B. eriopoda* succeeded the weedy stage if undisturbed by the rodents. Common species on cindery areas were *Leucelene ericoides, Euphorbia glyptosperma,* and *Erigeron nanus. Crassina grandiflora,* spreading by rhizomes, was especially conspicuous on account of the circular mat-like patches, often several feet in diameter, in disturbed areas or between grass clumps. Plants characteristic of roadsides and other disturbed places were *Senecio filifolius, Psilostrophe tagetinae, Helianthus annuus, Gutierrezia glomerella, Salsola tragus, Eriogonum cernuum,* and *Amaranthus powellii.*

On account of the complete dominance of *Bouteloua eriopoda* (Plate IV, A) over so extensive an area, the absence of disturbing agencies, such as grazing, and also because of the intermediate environmental factors, this zone has been classified as the *Aristida-Bouteloua* Association, with three consociations, viz. *Bouteloua eriopoda, B. gracilis,* and *Hilaria jamesii.*

THE WOODLAND CLIMAX *(Pinus-Juniperus* FORMATION)

The Piñon-Cedar Woodland *(Pinus-Juniperus* Association)

The piñon-cedar woodland occupies a zone 5 to 10 miles wide between the grassland and the yellow pine forest. On the whole the trees are low, 20 to 30 feet high, and widely spaced as shown in Plate VI, A. The spaces between the trees were covered with short tufts of *Bouteloua gracilis.* This type of woodland has been termed savannah by Clements (1920:199). Only on the slopes of washes and draws in this area did the trees grow closely enough together to cast practically continuous shade but even here openings frequently occurred (Plate VI, B). The following list gives the more characteristic species of this open woodland.

DOMINANT SPECIES *(consociations)*

Juniperus monosperma	Pinus edulis

SECONDARY SPECIES

Shrubs

Chrysothamnus bigelovii	Fallugia paradoxa
Tetradymia inermis	Schmaltzia trilobata

Grasses and sedges

Bouteloua gracilis	Stipa neomexicana
B. curtipendula	S. comata
B. eriopoda	Sitanion hystrix
Hilaria jamesii	S. elymoides
Aristida arizonica	Sporobolus ramulosus
A. longiseta	Cyperus fendlerianus

Herbs (exclusive of grasses)

Capnoides aureum	Chenopodium incisum
Astragalus allochrous	Mollugo cerviana
A. wootoni	Drymaria sperguloides
A. thompsonae	Bahia dissecta
Opuntia rhodantha	Lygodesmia fendlerianus
O. whipplei	Euphorbia serpyllifolia
Lathyrus decaphyllus	E. revoluta
Oreocarya suffruticosa	Pentstemon lananthus (new species)
Gilia longiflora	Hymenopappus nudatus
Petalostemon exilis	Verbena ciliata
Drymaria fendleri	Cheirinia asperrima
Sanvitalia aberti	

For the most part the herbs and shrubs that occurred in this association had invaded downward from the yellow pines or upward from the grassland. Even *Bouteloua gracilis* was much better developed in the yellow pines. In the larger openings between the trees ("parks"), as Deadman's Flat (Plate V, B), *Chrysothamnus bigelovii* was the dominant shrub and in a few localities farther north near the Grand Canyon *Artemisia tridentata* dominated. But the piñons and cedars were invading these areas and would ultimately form the climax. On rocky ridges and slopes *Tetradymia inermis, Fallugia paradoxa,* and *Schmaltzia trilobata* were often abundant. The only abundant grass was *Bouteloua gracilis,* the others listed never occurred abundantly except locally.

Characteristic plants of cindery areas were *Sanvitalia aberti, Chenopodium incisum, Mollugo cerviana, Euphorbia serpyllifolia, E. revoluta, Sporobolus ramulosus, Drymaria fendleri,* and *Polanisia trachysperma.* Along roadsides and on abandoned roads or other disturbed areas the first invaders were *Salsola tragus, Verbena ciliata, Psilostrophe tagetinae,* and other weeds.

The dominance of the two conifers and of *Bouteloua gracilis* between the trees at this altitude (average 6000 feet), instead of a dominance of *B. eriopoda,* was due pri-

marily to the greater and more uniform supply of soil moisture and to lower temperatures than in the grassland. Figure 13 shows that in 1923 in the upper 10 cm. of soil there was an abundance of available moisture after July 14, except on August 9. In the 10-30 cm. layer (Fig. 14) moisture was available the entire season except for the period, June 22 to July 6. In the 30-60 cm. layer water was available the entire season (Fig. 15). Similar results were obtained in 1922. The clay soil was very retentive of moisture and the abundance of rocks and bowlders decreased evaporation. Below the first 10 cm. the soil in the crevices was always moist. On account of the greater depth of moist soil here as compared with the grassland the roots penetrated much more deeply. *Bouteloua gracilis* requires more moisture than *B. eriopoda,* while the latter requires a higher temperature, for optimum growth. *B. gracilis* was near its limit of xerophytism in the lower part of this association. The tufts were very small in area, extending over only a few square inches, the leaves very short, and the fruiting stalks infrequent. The grass was so dwarfed that it looked like another species.

THE MONTANE FOREST CLIMAX *(Pinus-Pseudotsuga* FORMATION)

The Petran Montane Forest *(Pinus-Pseudotsuga* Association)

In the region studied *Pinus scopulorum* became dominant at about 6800 feet, the exact elevation varying with topography. On moister areas, as along stream courses, the yellow pines, and even Douglas firs, occurred below this altitude. On ridges and other xerophytic sites, as cinder slopes, piñons and cedars extended much higher. The yellow pine formed practically a pure forest up to about 8300 feet but above this to about 9400 feet the

Douglas fir was more abundant, mixed with yellow pine, limber pine *(Pinus flexilis)*, *Abies concolor*, and *Populus tremuloides*. The following list gives the more important species ecologically.

DOMINANT SPECIES *(consociations)*

Pinus scopulorum
P. flexilis
Pseudotsuga mucronata
Abies concolor

SECONDARY SPECIES

Trees

Juniperus monosperma
J. pachyphloea
Pinus edulis
Populus tremuloides
P. angustifolia
P. wislizeni
Quercus gunnisonii
Q. arizonica
Q. gambellii
Juglans major
Acer glabrum
Negundo interius
Salix nigra

Shrubs

Cowania stansburiana
Gutierrezia longifolia
Ceanothus fendleri
Rhus cismontana
Rosa fendleri
Cercocarpus montanus
Ribes inebrians
Amelanchier bakeri
Odostemon repens
Mahonia fremontii
Schmaltzia trilobata
Chamaebatiara millefolium
Fallugia paradoxa
Chrysothamnus graveolens
Yucca baccata
Sorbus scopulina
Prunus virens Goodingii
Lonicera arizonica
Robinia neomexicana
Vitis arizonica
Symphoricarpos pauciflorus
Sericotheca dumosa

Grasses and sedges

Muhlenbergia trifida
(= gracilis)
Festuca arizonica
Blepharoneuron tricholepis
Muhlenbergia wrightii
Bouteloua gracilis
Aristida arizonica
A. fendleriana
Agropyron smithii
A. tenerum
Koeleria cristata
Sitanion elymoides
Andropogon scoparius
A. hallii
A. nutans
Stipa comata
Bouteloua curtipendula
B. procumbens
Stipa pringlei
Sporobolus confusus
Agrostis palustris
A. hiemalis
Eleocharis palustris
Carex subfusca
Juncus brunnescens
Scirpus americanus
Bromus richardsonii
Eragrostis neomexicanus

Ptelea tomentosa
Sambucus neomexicana
Cornus instolonea
Poa annua
Poa fendleriana
Panicum sciaphyllum

Herbs (exclusive of grasses)

Monarda pectinata
Sophia incisa
Oenothera hookeri
Lotus wrightii
Astragalus humistratus
Oxytropis lambertii
Lithospermum multiflorum
Pteridium aquilinum
Vagnera stellata
Apocynum angustifolium
Valeriana arizonica
Clematis ligusticifolia
Zygadenus elegans
Geranium atropurpureum
G. richardsonii
Castilleja integra
Lupinus palmeri
L. kingii
Psoralea obtusiloba
P. micrantha
Senecio uintahensis
S. spartioides
Solidago trinervata
Oreocarya multicaulis
Pentstemon virgatus
P. teucrioides
P. bridgesii
Eriogonum alatum
E. racemosum
E. bakeri
Persicaria persicaria
Thalictrum wrightii
Ranunculus hydrocharoides
Aquilegia chrysantha
A. elegantula
Linum lewisii
Calochortus nuttallii
Hypericum formosum
Kelloggia galioides
Artemisia wrightii
A. dracunculoides
Machaeranthera canescens
Aster commutatus
Achillea lanulosa
Coreopsis cardaminefolia
Erigeron divergens
E. flagellaris
E. speciosus
Prunella vulgaris
Peritoma serrulata
Potentilla monspeliensis
P. atrorubens
Gilia aggregata
G. inconspicua
Mertensia pratensis
Galium fendleri
Calliandra humilis
Pyrola sp.
Antennaria glandulosa (new sp.)
A. rosulata
Hedeoma diffusa

The yellow pine forest, which today commands the admiration of travelers as it did of the early explorers, is one of the finest forests of this species in America. In northern Arizona it covers a strip 10 to 40 miles wide, extending southeastward into New Mexico and northward toward the Grand Canyon. North of the Grand Canyon,

on the Kaibab Plateau, it is again developed in full grandeur. The yellow pine forest is decidedly open. The trees, ranging to over 120 feet high and over 3 feet in diameter, are scattered irregularly, leaving enough space between them to permit a good growth of grasses and other herbs (Plate VIII, A). Or they may occur in groups covering areas 25 to 100 feet in diameter, separated by openings, 25 to 150 feet in diameter. Larger openings, a few acres to several square miles in area, called "parks," are frequent. Pearson (1913) has studied one of these parks in relation to the surrounding forest, concluding from his study that the unfavorable climatic conditions and perhaps the soil conditions, too, prevent the invasion of pines. On account of the importance of the yellow pine as a lumber-producing tree its distribution, reproduction, growth, etc., have been studied by several investigators (Haasis 1921, 1923; Jaenicke *et al.* 1915; Leiberg *et al.* 1904; Shreve 1917), especially Pearson (1920, 1923).

The climax vegetation of the lower consociation consists of the yellow pine, shading less than one-third of the ground, with a bunch type of grass dominating the openings (Plate VIII, A). On the fine, clayey soils *Festuca arizonica* was the most common and abundant, while on more sandy and stony ground *Muhlenbergia trifida, Blepharoneuron tricholepis,* and *Andropogon scoparius* were more abundant. In the spaces between the bunch grasses, especially on more or less disturbed soil, other grasses and a great variety of dicotyledons were found. Especially common were *Sitanion elymoides, Bouteloua gracilis, Koeleria cristata, Artemisia wrightii, Castilleja integra, Pentstemon virgatus, Geranium atropurpureum, Erigeron divergens, Lotus wrightii, Oxytropis lambertii, Oreocarya multicaulis,* and *Gilia aggregata.* The quadrat shown in Fig. 10 is fairly typical of much of the climax vegetation on the less clayey soil but the weeds indicate

slight disturbance. Pearson (1923) has shown that where *Festuca* is distinctly dominant pine reproduction is usually deficient but that other herbaceous vegetation favors reproduction by affording protection from excessive insolation, winter-killing, and frost-heaving.

Three primary successions, the hydrosere and two xeroseres, one starting on rocks, the other on cinders; and two secondary successions, one due to over-grazing and one due to cultivation and other disturbance, were studied. These are represented graphically in Fig. 4.

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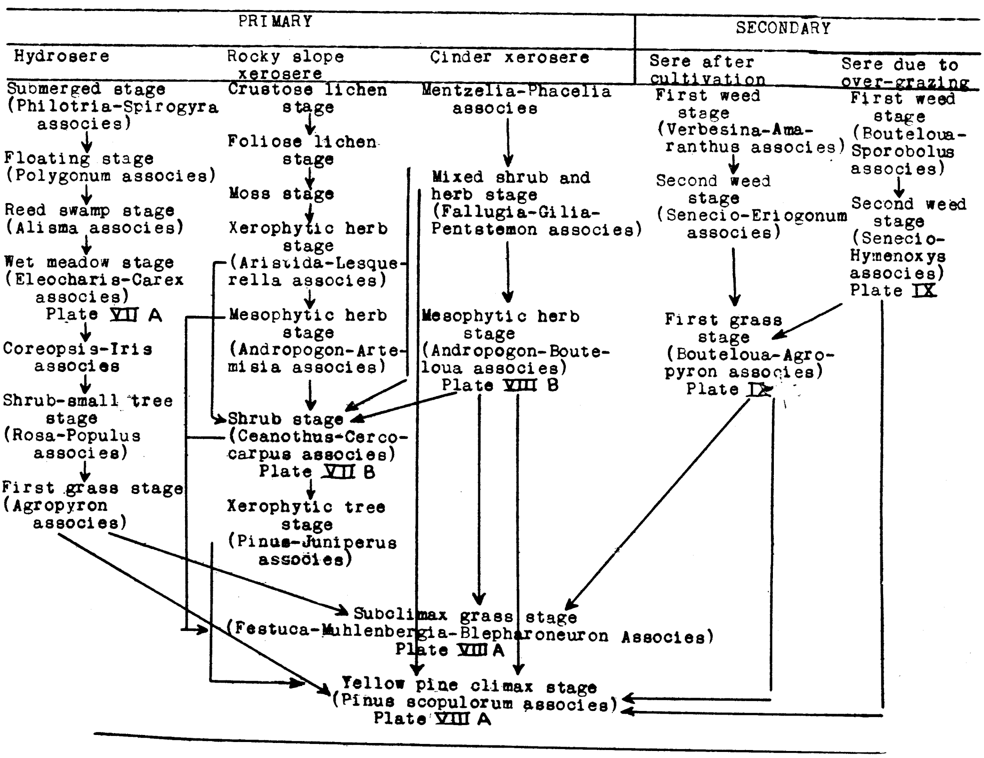

FIGURE 4. Diagram of primary and secondary successions in the *Pinus scopulorum* consociation. Flagstaff.

The hydrosere in this region is poorly represented and the early part is considerably abbreviated or telescoped due to rapid drainage and to the xerophytic conditions that obtain much of the year. The submerged stage is found in a few scattered lakes and ponds. A number of algae, *Spirogyra* spp., *Zygnema,* etc., and *Philotria canadensis* characterized this stage in the few localities studied. The floating stage was represented by *Polygonum muhlenbergii,* adapted for floating by means of the swollen petioles. On account of the lack of sufficiently extensive areas of wet soil the reed swamp stage, represented by *Alisma plantago-aquatica,* was usually telescoped into the following stage or it was entirely missing. The wet meadow stage (Plate VII, A) was found in a number of localities, as around springs and on the shores of creeks, lakes, and ponds. Although never occupying a large area, a large number of species were found. The more characteristic were *Eleocharis palustris, E. acicularis, Carex subfusca, C. occidentalis, Juncus brunnescens, J. dudleyi, J. longistylis, Halerpestes cymbalaria, Ranunculus hydrocharoides, R. subsagittatus, Agrostis palustris, Alopecurus aequalis, Polygonum persicaria, Cyperus fendlerianus, Mimulus langsdorfii, Equisetum arvense, E. laevigatum,* and *Radicula sphaerocarpa.* In a number of places where the soil was drier, never wet on the surface except after rains, a community of herbs, chiefly, occurred. On the borders of ponds this was represented usually by *Coreopsis cardaminefolia,* while on the borders of streams and on other low areas, *Iris missouriensis* formed extensive beds. The following plants were scattered in similar habitats: *Sidalcea neomexicana, Sisyrinchium campestre, S. demissum, Delphinium scopulorum, Orthocarpus luteus, Valeriana trachycarpa,* and *Gentiana bigelovii.* Often this stage did not occur, as on the borders of lakes and streams, where the shrub and small tree stage followed the wet

meadow. The chief plants in this woody stage were low, 2 to 8 feet high, young trees of *Populus wislizeni, P. angustifolia,* and *Salix nigra* (Plate VII, A). *Vicia americana* and *Muhlenbergia racemosa* climbed among dense growths of these young trees. In canyons dense tangles of *Cornus instolonea* were associated with these trees. The last grew to a fairly large size here, and *Negundo interius* and *Juglans major* also occurred, forming the characteristic deciduous canyon forest. On the drier slopes, above the *Coreopsis-Iris* zone, *Rosa fendleri* sometimes formed a narrow zone. In still drier sites *Rhus cismontana* was occasionally found in fairly small clumps. Often the rose as well as the other shrubs were entirely lacking and the wet meadow, or the *Coreopsis-Iris* associes, was followed directly by the grass stage. The chief species in this stage was *Agropyron smithii.* This community was poorly represented as the subclimax grasses and dicotyledons invaded quickly. The yellow pine accompanied or followed the grasses very quickly as a rule, forming the climax association.

The xerosere beginning with rocky slopes (Plate VII, B) showed the usual invasion by crustose and foliose lichens, followed by mosses and then by the xerophytic herb stage. The first grasses and herbs to appear in the thin, dry soil in small crevices were *Aristida arizonica, A. fendleriana, Antennaria* spp., *Artemisia wrightii, Gilia inconspicua, Lesquerella intermedia, Thelypodium micranthum,* and *Calliandra humilis.* This stage was followed by a more mesophytic herbaceous stage or by a shrub stage. Some of the common plants in the herbaceous stage were *Andropogon hallii, A. nutans, A. scoparius, Artemisia wrightii, A. dracunculoides, Potentilla hippiana, Lithospermum multiflorum,* and *Hedeoma nana.* The mesophytic herb stage was followed by the subclimax grass stage. The shrub stage, which often followed the xerophytic herb

stage, was found frequently on rocky south slopes. The more common species were *Cercocarpus montanus, Ceanothus wrightii, Mahonia fremontii, Yucca baccata, Coleosanthus wrightii, Garrya wrightii, Chrysothamnus graveolens, Agave* sp., *Cowania stansburiana, Schmaltzia trilobata, Chamaebatiaria millefolium, Ptelea tomentosa, Sericotheca dumosa,* and *Fallugia paradoxa.* Mixed more or less with these shrubs, often in a dense tangle, on some of the south slopes were found *Pinus edulis, Juniperus monosperma,* an occasional *J. pachyphloea, Quercus gambellii, Q. arizonica,* and *Q. gunnisonii.* The shrubs were replaced as the slopes became more mesophytic by the climax forest of yellow pine.

The xerosere on the cinders is splendidly shown on the large cinder areas 10 to 15 miles northeast of Flagstaff. Here the cinders have been deposited to depths of several feet in many places. Conditions for plant life are so extreme that no invasion has yet occurred over large areas. The first invaders were the herbs *Aristida longiseta, Euphorbia fendleri, Mentzelia multiflora, M. densa, Phacelia corrugata, Sporobolus ramulosus, Physaria newberryi,* and the shrubs, *Chrysothamnus graveolens, Fallugia paradoxa,* and *Eriogonum fendlerianum.* These plants, as well as most of those in the second stage, were characterized by very xerophytic leaves and stems and shallow but extremely widely spreading root-systems. The second stage showed a greater abundance and variety of plants among which characteristic species were *Pentstemon palmeri, P. barbatus, Gilia aggregata, Phacelia glandulosa, Thelypodium linearifolium, Bahia dissecta, Eriogonum aureum, Coleosanthus grandiflorus, Artemisia wrightii, Sitanion hystrix, Chrysothamnus graveolens,* and *Fallugia paradoxa.* The third stage, the mesophytic herb stage, consisted of more deeply rooted species. This stage was found where the humus content was greater although

the cinders were still abundant (Plate VIII, B). Characteristic species were *Andropogon hallii, Bouteloua gracilis, Andropogon scoparius, Commelina dianthifolia, Allionia comata, Geranium atropurpureum,* and *Kuhnia rosmarinifolia.* The third stage was usually followed by the sub-climax grass stage, *Festuca,* however, not occurring. The pines invaded any of the stages except the first. Plate VIII, B, shows the pines growing in almost pure cinders. The shrub and xerophytic tree stages were often telescoped out in this succession. Where they did occur the more common species were *Pinus edulis, Chrysothamnus graveolens, Fallugia paradoxa, Coleosanthus wrightii,* and *Cercocarpus montanus.*

Numerous sites afforded opportunity for studying the secondary successions on disturbed areas occasioned by cultivation, road-building, prairie-dog activity, etc. In fields that had been recently abandoned (Fig. 5) and in cultivated fields the most common and abundant weeds were *Verbesina encelioides, Amaranthus powellii, A. graezicans, A. blitoides, Salsola tragus, Chenopodium album, C. leptophyllum,* and *Portulaca oleracea.* Along roads and on abandoned roads the common first invaders were *Verbena bracteosa, Peritoma serrulata, Sisymbrium altissimum, Polygonum aviculare, Salsola tragus,* and *Senecio spartioides.* On new prairie-dog mounds *Marrubium vulgare, Senecio spartioides,* and *Peritoma* were very common. Weeds characteristic of low, moist areas were *Veronica xalapensis, Helianthus annuus, Rumex crispus, Echinochloa crus-galli, Melilotus alba,* and *Persicaria persicaria.* Numerous other weeds were found along streets, in waste places, and on areas adjacent to barns and other buildings.

A field that had been broken in 1919 and planted with oats the same year, with potatoes in 1920, and with rye in 1921, but abandoned in 1922 and 1923, showed in 1923

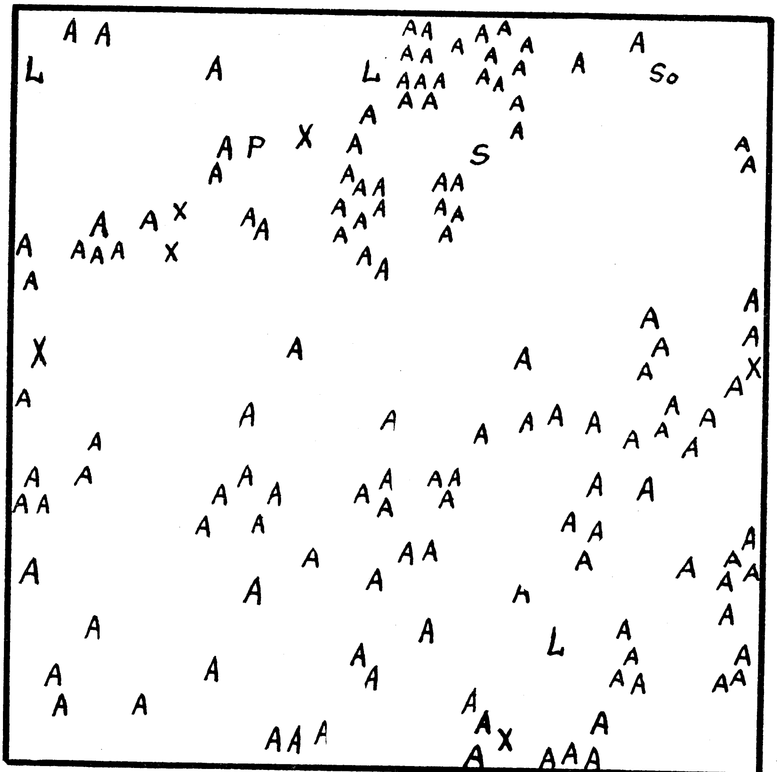

FIGURE 5. Meter quadrat in a field that had been abandoned one year, in potatoes the preceding year, near Flagstaff. July 31, 1923.

A = Amaranthus powellii	S = Salsola pestifer
L = Lactuca integrata	So = Solanum triflorum
P = Peritoma serrulata	X = Ximenisia exauriculata

a great variety of plants (Fig. 6). The most abundant species were *Salsola pestifer, Cryptanthe fendleri, Sophia obtusa, Sisymbrium altissimum, Anogra coronopifolia,* and rye. Other plants occurring frequently were species characteristic of the second weed stage. Plants typical of the first grass stage, as *Bouteloua gracilis* and *Lotus wrightii,* were rare but it is significant that they had already

entered. The field was rapidly changing from the first to the second weed stage.

The second weed stage was marked by a larger number of species and by the kind of species that typically accompanied grasses in later stages. The more common and

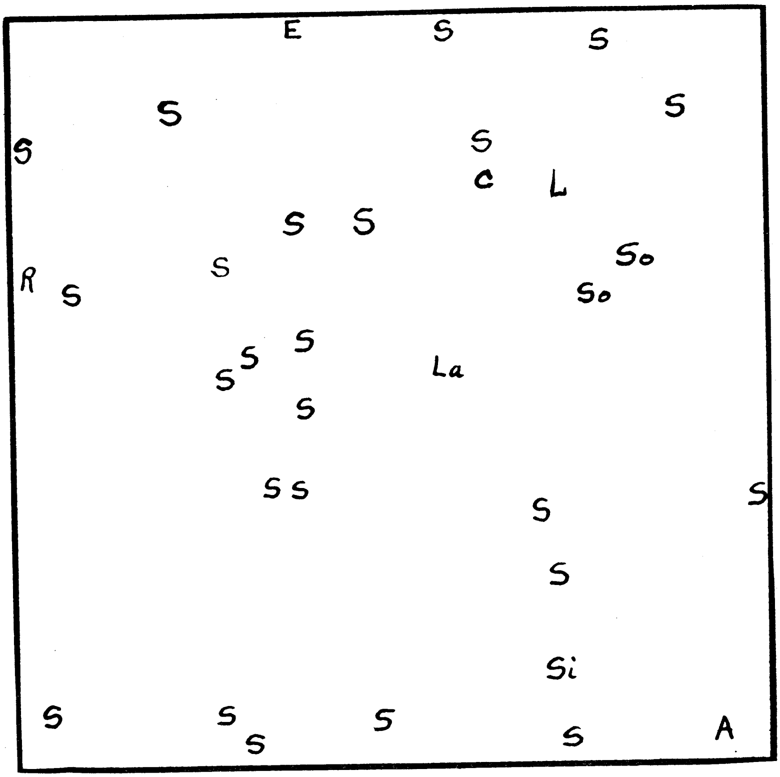

FIGURE 6. Meter quadrat in a field that had been idle in 1923 and 1922, in rye in 1921, in potatoes in 1920, and broken and planted to oats in 1919, near Flagstaff. July 31, 1923.

A = Amaranthus powellii	R = Rye
C = Cryptanthe fendleri	S = Salsola pestifer
E = Eriogonum sp. (seedling)	Si = Sisymbrium altissimum
L = Lactuca integrata	So = Sophia obtusa
La = Lappula occidentalis	

abundant species were *Eriogonum polycladon, E. racemosum, Senecio spartioides, Sophia obtusa, Eriocarpum gracile, Plantago argyrea, Lappula occidentalis, Physalis fendleri, Astragalus humistratus, Castilleja integra, Artemisia wrightii, Machaeranthera canescens, Lupinus hillii, Cryptanthe fendleri,* and *Cheirinia asperrima.* In the third stage, the first grass stage, *Bouteloua gracilis* sometimes dominated almost to the exclusion of other plants (Plate IX, A). Other characteristic plants were *Agropyron smithii, A. tenerum, Poa annua, Sitanion elymoides, Koeleria cristata, Artemisia wrightii, Cryptanthe fendleri, Lotus wrightii, Eriogonum cernuum, Solidago trinervata, Erigeron divergens, Eriocarpum gracile, Achillea lanulosa, Pentstemon virgatus, Castilleja integra,* and *Geranium atropurpureum.* This stage was followed by the subclimax grass stage or by the climax directly.

The secondary succession due to overgrazing was also abundantly represented. The first weed stage occurred on areas that had been used for bedding grounds constantly or had been severely trampled. Characteristic plants were the short-lived weeds *Sporobolus ramulosus* and *Bouteloua gracilis* (six-weeks grasses), *Verbena bracteosa, Veronica xalapensis, Polygonum aviculare, Erigeron divergens,* and *Euphorbia glyptosperma.* The second weed stage (Fig. 7, Plate IX, B), found on areas that had been less severely treated, consisted of taller weeds chiefly. The more important of these were: *Hymenoxys floribunda, Senecio spartioides, Lupinus hillii, L. palmeri, Solidago trinervata, Asclepias galioides, Eriogonum alatum, E. racemosum, Pentstemon virgatus, Geranium atropurpureum, Chrysothamnus graveolens, Schmaltzia trilobata,* and stunted plants of *Bouteloua gracilis* and *Agropyron smithii.* This stage was succeeded by the first grass stage, which was very similar to the first grass stage in the sere

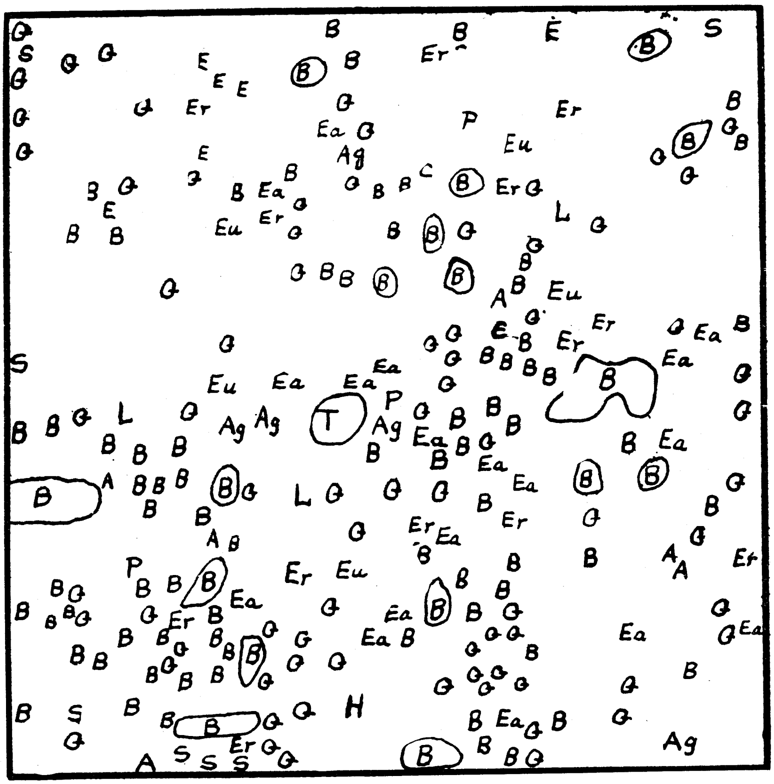

FIGURE 7. Meter quadrat in a badly overgrazed range near Flagstaff, see Plate IX, B. July 30, 1923.

A = Anogra coronopifolia
Ag = Agropyron smithii
B = Bouteloua gracilis
C = Ceanothus fendleri
E = Eriogonum racemosum
Ea = E. alatum
Er = Erigeron divergens
Eu = Euphorbia glyptosperma
S = Solidago trinervata
G = Hymenoxys floribunda
H = Hymenopappus mexicanus
L = Lithospermum multiflorum
P = Pentstemon virgatus
T = Tithymalus luridus

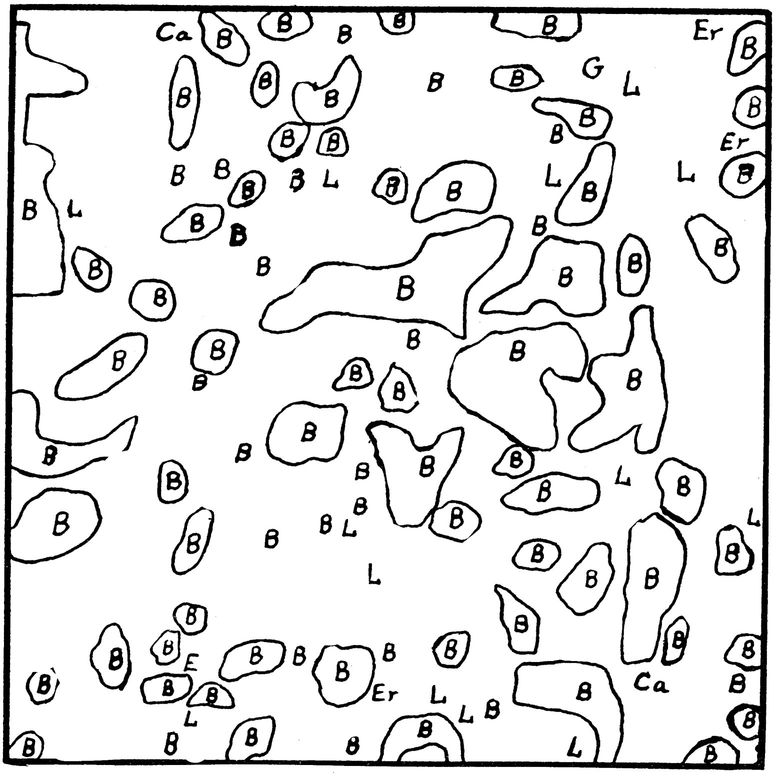

FIGURE 8. Meter quadrat in a slightly overgrazed range near Flagstaff. July 30, 1923. Symbols as in Figure 7 and
Ca = Castilleja integra Er = Eriocarpum gracile

following cultivation, but often showed a greater variety of species. *Agropyron smithii* often formed almost pure stands. The quadrats (Figs. 7, 8, 9, 10) show a series beginning with a badly overgrazed field in the second weed stage shown in figure 7 (Plate IX, B). The large number of individuals, the abundance of *Hymenoxys,* and the stunted condition of *Bouteloua gracilis* are especially characteristic. The quadrat in Fig. 8 shows that *Bouteloua*

was having an opportunity to spread into small mats, and the quadrat in Fig. 9 shows that the other bunch grasses, *Andropogon scoparius* and *Muhlenbergia trifida,* were beginning to shade out the *Bouteloua.* The quadrat

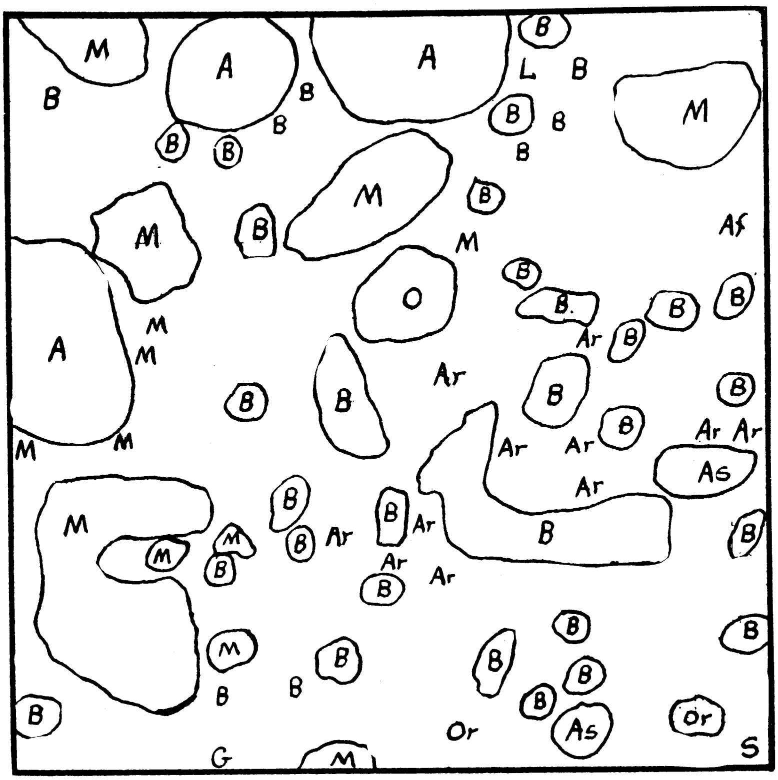

FIGURE 9. Meter quadrat in a slightly grazed range near Flagstaff. August 30, 1923.

A = Andropogon scoparius
Af = Artemisia forwoodii
Ar = A. gnaphalodes
As = Aristida arizonica
B = Bouteloua gracilis
G = Gilia aggregata
L = Lotus wrightii
M = Muhlenbergia trifida
O = Oxytropis lambertii
Or = Oreocarya multicaulis
S = Sitanion elymoides

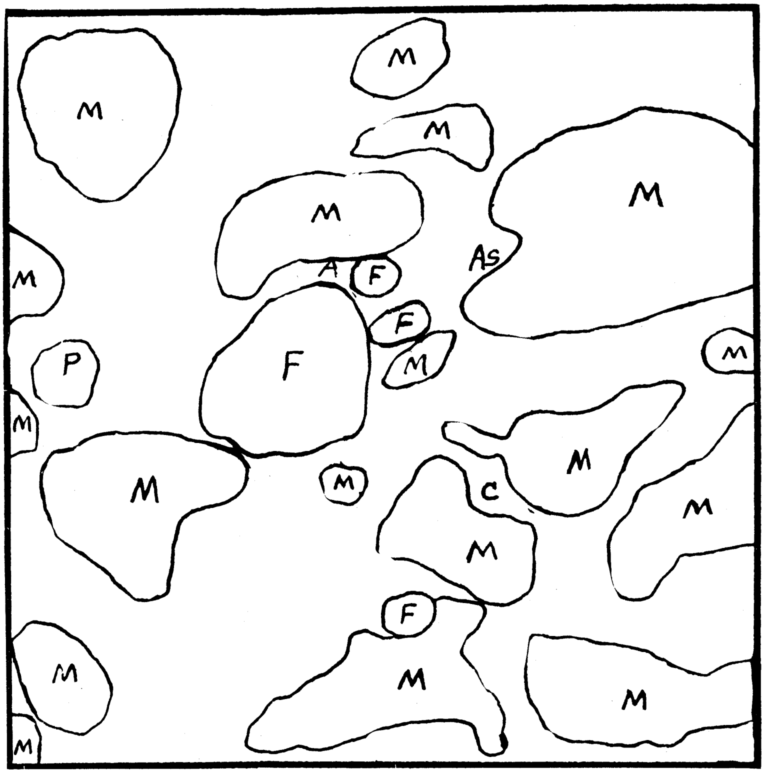

FIGURE 10. Meter quadrat in an ungrazed area near Flagstaff. August 1, 1923.

A = Achillea lanulosa	F = Festuca arizonica
As = Astragalus humistratus	M = Muhlenbergia trifida
C = Cirsium perennans	P = Potentilla lemmoni

shown in Fig. 10, mapped in an ungrazed area, shows strikingly the absence of *Bouteloua* and the dominance of the large bunches of *Festuca arizonica* and *Muhlenbergia trifida.*

THE ENVIRONMENTAL FACTORS

Location of Stations

Particular care was exercised in choosing the stations so that the readings would be typical of each association. The sagebrush station was located on a fairly level area of thin, sandy soil, underlaid by red sandstone of the Moenkopie Formation (Plate I, B). This was on the west side of the Little Colorado River, a short distance southwest of Cameron. Within an eighth of a mile of the instruments was a large plateau-like area of Kaibab limestone (Plate II, B). A very open stand of the desert shrubs, especially *Atriplex canescens, A. confertifolia,* and *Ephedra torreyana,* grew on this red sandstone soil but on the limestone soil plants were growing in a greater abundance and variety. Rocky cliffs ("rims"), narrow valleys, and stream-beds were frequent. The grassland station was located during the season of 1922 on a gentle south slope covered with a fairly dense stand of *Bouteloua eriopoda* and *Hilaria jamesii* (Plate IV, B). The clayey soil had been derived from basalt of the first lava flow and contained a large number of coarse rock fragments. During the summer of 1923 the station was maintained on a fairly level plateau covered with a closed community of *Bouteloua eriopoda* (Plate IV, A). The soil was similar to that of the 1922 site. The woodland station was located in 1922 on a rather level plateau-like area covered with an open growth of *Juniperus monosperma* and *Pinus edulis.* A carpet of low *Bouteloua gracilis* occupied the large openings between the trees (Plate VI, A). In 1923 this station was operated on a north-facing, gentle slope of a ravine. Over most of the slope the trees were closely enough together to form a true forest (Plate VI, B), but nowhere in this region was the woodland so well developed as near the south rim of the Grand Canyon. The soil in both sites was an extremely rocky, stiff clay,

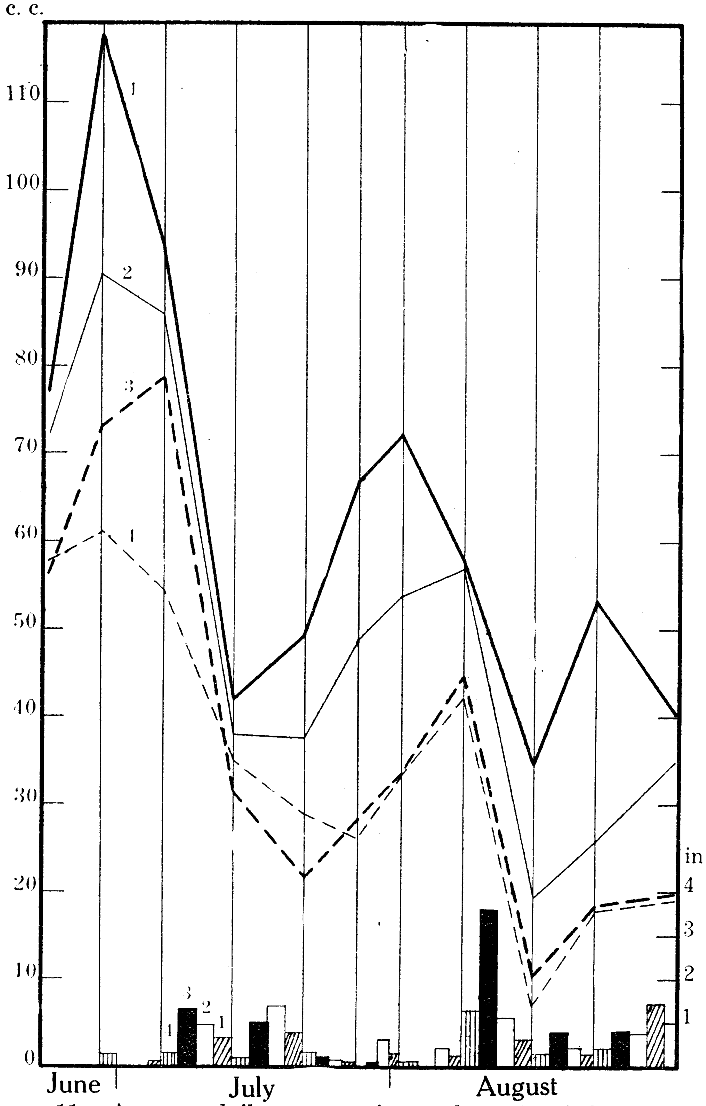

FIGURE 11. Average daily evaporation and total rainfall for each period between readings, 1923. 1 = *Artemisia-Atriplex* Association, 2 = *Aristida-Bouteloua* Association, 3 = *Pinus-Juniperus* Association, 4 = *Pinus scopulorum* Consociation.

derived from the underlying basalt. Both stations were about 20 miles northeast of Flagstaff. The yellow pine station was located in the open pines on a gentle south slope a short distance east of Flagstaff (Plate VIII, A). The surface soil was sandy loam, changing gradually to almost pure sand at three feet. The surface was strewn with bowlders. The area had been cut over years ago but there were enough large trees and new growth now to form a typical yellow pine forest.

PRECIPITATION

The precipitation was measured in the four stations during 1923 by means of standard rain gauges. Readings were taken every week. The amounts for each station are shown in Fig. 11. It will be noted that the rainy season began in two of the stations with slight rains during the week June 29-July 6 but that it was not until the following week that any appreciable rain fell in all the stations. The total precipitation from June 13 to September 3 was 4.29 inches in the sagebrush station, 5.65 in the grassland, 7.72 in the woodland, and 3.00 in the yellow pines. Comparing these figures with the mean precipitation shown in Fig. 12 it will be seen that in 1923 the rainfall was about 2.5 inches above the average in the woodland, 2 inches above in the sagebrush, and about 3 inches below in the yellow pine forest. Fig. 12 shows that throughout the entire region there are two periods of heavier precipitation separated by drier intervals. The moister periods are July-August and December-March. The months of May and June are very dry, forming the arid fore-summer. The period, September-November, is not so dry in comparison with the rest of the year in the sagebrush and grassland as in the tree associations. The precipitation varies greatly from year to year. At Flagstaff in the yellow pines it varies from about 15.5 inches

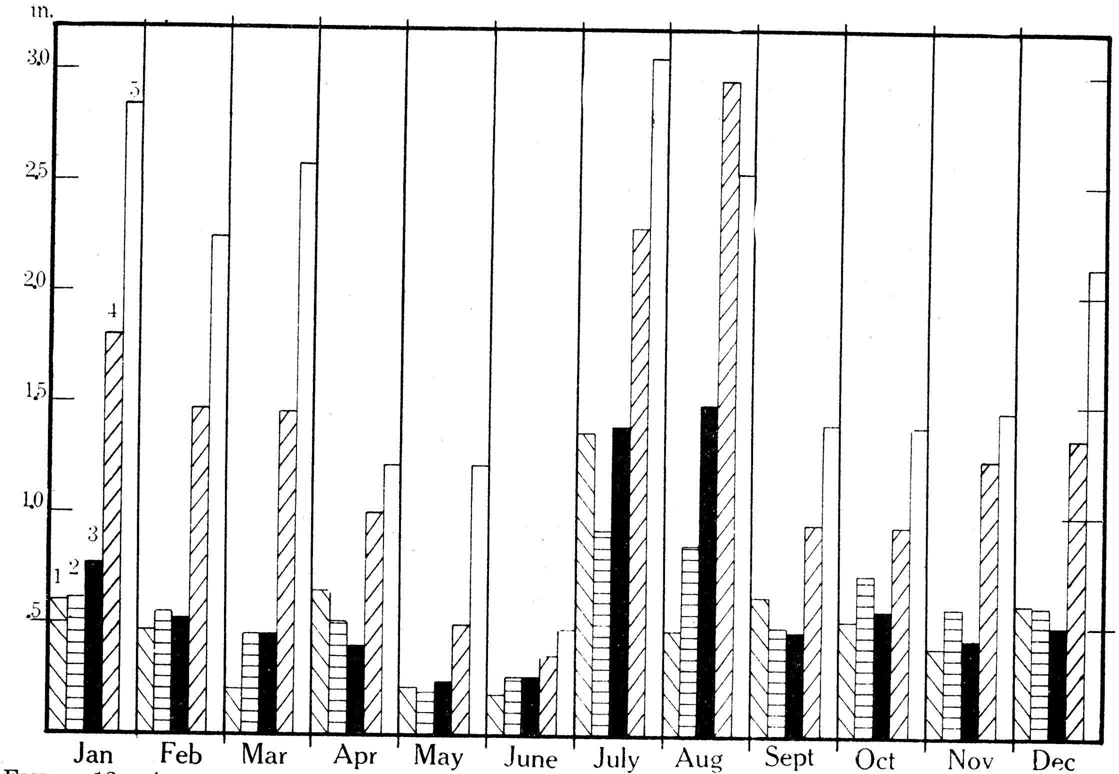

FIGURE 12. Average monthly rainfall. 1 = *Artemisia-Atriplex* Association (Leupp), 2 = *Artemisia-Atriplex* Association (Tuba City), 3 = *Aristida-Bouteloua* Association (Winslow), 4 = *Pinus-Juniperus* Association (Cosnino), 5 = *Pinus scopulorum* Consociation (Flagstaff).

to 28 inches per year (mean of 34 years being 22.62) and in the sagebrush from less than 5 to about 11 inches (mean of 24 years at Tuba City being 6.75 inches).

The snowfall varies even more. At Flagstaff it varies from about 32 to 162 inches annually (mean of 25 years being 79.2 inches). At Tuba City it varies from 2.5 to 25 inches (mean of 21 years, 15.5 inches). The snow disappears rapidly in the desert and grassland, while in the yellow pines it usually accumulates to depths of 3 or 4 feet. By April most of the snow has disappeared in the yellow pines and the soil is moist enough to permit the growth of many plants, but in the grassland and sagebrush most of the vegetation is dormant until the summer rains begin.

The most significant aspects of the precipitation in relation to the vegetation are the irregularity in distribution and amount, the dry May-June period, and the moist July-August period.

Soil Moisture

Soil samples for the determination of water-content were secured on an average of once a week in all stations during the summers of 1922 and 1923. Because of the abundance of rocks and bowlders making it impossible to use a soil auger it was necessary to dig the samples with pick and spade. Care was exercised so that the samples would represent the entire depth for which they were taken. The average depth of the red sandstone soil in the sagebrush was only 20 cm. and on the limestone area it was only after trying in many places that a sample could be secured to 20 or 30 cm. between the rocks. In the grassland and cedars the bowlders were larger and fewer so that samples could be secured to 60 cm. In the yellow pines readings were taken regularly to 60 and occasionally to 90 cm.

The march of soil moisture during the summer of 1923 is represented in figures 13, 14, 15. The graphs for 1922 were very similar so they are not given. In general the most important features are the low moisture content in the surface 10 cm. until the summer rains begin, the upward trend from the first week in July into September, the large and rapid fluctuations caused by evaporation and rainfall, and the narrow margin of available water, even during the rainy season, in the grassland and sagebrush.

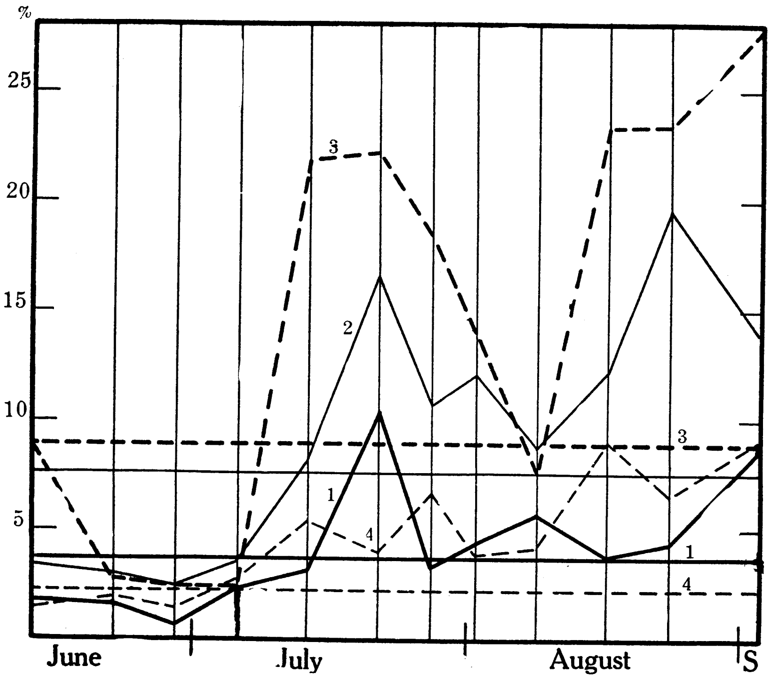

FIGURE 13. Soil moisture at 0 — 10 cm. during the summer of 1923. The horizontal lines represent the hygroscopic coefficients. 1 = *Artemisia-Atriplex* Association, 2 = *Aristida-Bouteloua* Association, 3 = *Pinus-Juniperus* Association, 4 = *Pinus scopulorum* Consociation.

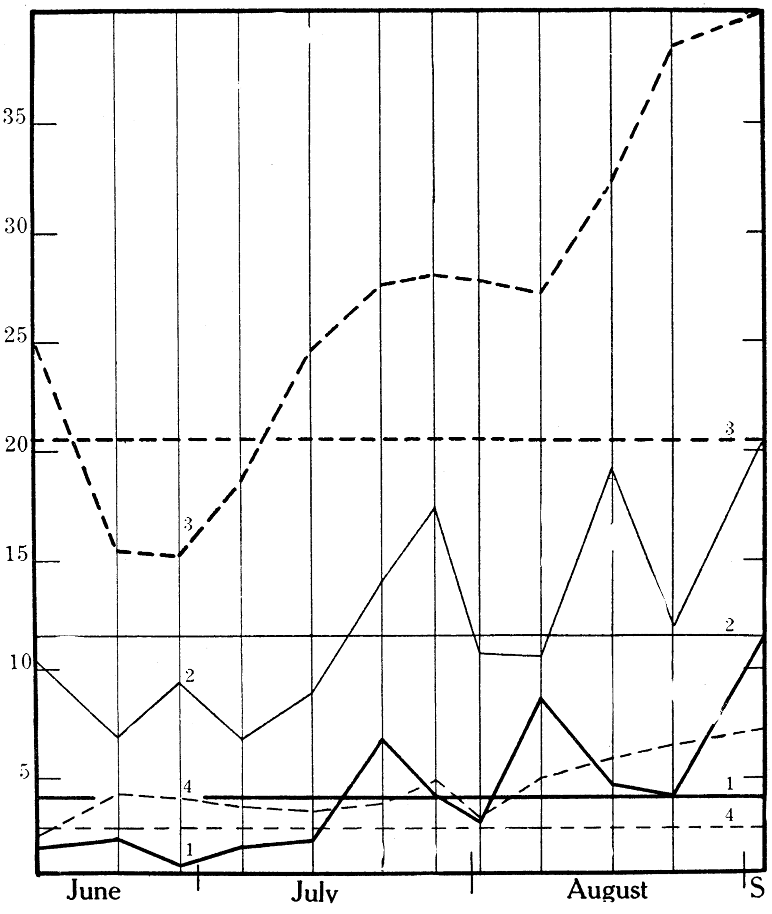

FIGURE 14. Soil moisture at 10 — 30 cm. during the summer of 1923. Legend as in Figure 13.

In the red sandstone soil in the sagebrush, moisture did not become available in the surface 10 cm. layer until the July 29 reading in 1922, and July 22 in 1923. Moisture had been available, however, for plant growth for short periods for about a week preceding these dates be-

cause the vegetation was green by July 22 in 1922 and by July 14 in 1923. This shows how quickly the plants respond to the smallest amounts of available moisture. The determinations were not made often enough to catch these small amounts, which lasted probably for short periods only. On the limestone area in 1923 the moisture

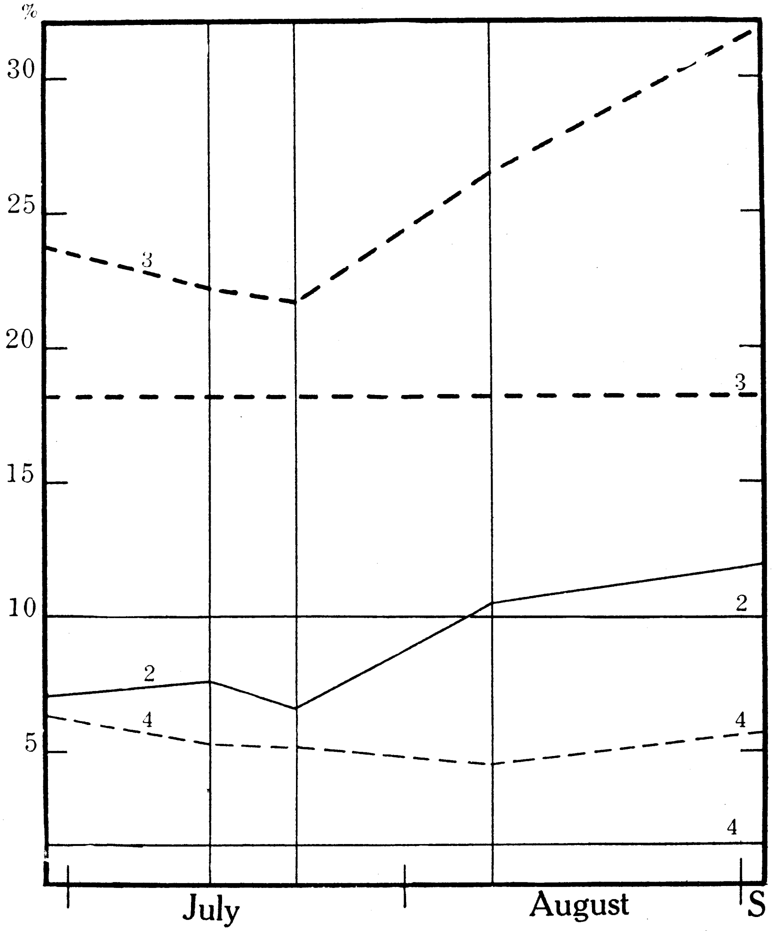

FIGURE 15. Soil moisture at 30 — 60 cm. during the summer of 1923. Legend as in Figure 13.

was available a week before it was available in the sandstone soil. Only on 3 dates in 1923 was there much available water in the surface 10 cm. in the sandstone soil. In the 10-20 cm. layer the moisture did not become available until July 9, 1922, and July 22, 1923, and once or twice later each summer it fell below the hygroscopic coefficient. Of the total of 12 determinations 6 or 7 showed that no moisture was available. On the limestone soil, however, at this same depth, moisture was available the entire summer. The most significant features of these determinations are the short season during which water is available for growth, the sudden fluctuations, the narrow margin of available water, and the rapid response of the vegetation to the first summer rains. The rapidity with which the desert is "painted green" has been noted by many travelers.

In the grassland the moisture in the 0-10 cm. layer first exceeded the hygroscopic coefficient on July 29 in 1922 and July 14 in 1923. In the 10-30 cm. layer this occurred on August 5 in 1922 and July 22 in 1923, and in the 30-60 cm. layer on August 9 in 1923. The direct relation to rainfall is again noted, especially in the first 30 cm. By the end of the season the rains had penetrated to a depth of only 40 cm. Most of the roots were located in the first 30 cm. A period of low rainfall, 1.1 inches in the 3 weeks preceding August 9, reduced the soil moisture below the hygroscopic coefficient in both the 0-10 and 10-30 cm. layers for about two weeks. The vegetation did not turn green as rapidly as in the desert, probably because these grasses required more water and because the dry, ungrazed tufts of the previous year obscured the new growth. By July 29 in 1922 the new grass leaves were 2-5 inches long. The most important features of these findings are practically the same as for the desert and that more moisture was available in the grassland than in the desert.

In the woodland the moisture in the 0-10 cm. layer became available on July 9 in 1922 and July 14 in 1923. In the 10-30 cm. layer it was available at all readings in 1922 except on June 25, July 22, August 18, and August 30; and in 1923 except June 22, 29, and July 6. In the 30-60 cm. depth the moisture was available during the entire season. The soil was very clayey, having a hygroscopic coefficient of 20.5% in the 10-30 cm. layer. *Bouteloua gracilis,* which formed the bulk of the herbaceous vegetation, did not grow so rapidly as the grasses at the lower stations. By July 15, 1922, the leaves had grown only 1 to 2 inches. The most important features of these findings are the much higher water content in the woodland as compared with the two lower associations and the greater continuity of available moisture though still subject to wide fluctuations, especially in the surface layer.

In the yellow pine forest the soil moisture in the surface layer remained below the hygroscopic coefficient until July 6 in 1923 and in 1922 it never went below. This difference was caused by the abnormally low rainfall during the early part of the 1923 summer. In the 10-30 cm. level it was available both years at all readings except June 13, 1923. The 30-60 cm. and 60-90 cm. layers had plenty of available moisture both seasons. In spite of the low rainfall during the summer of 1923 sufficient moisture was available to allow growth to continue the entire summer. An important difference between the tree stations on the one hand and the desert and grassland stations on the other is that the former have plenty of available moisture in the second foot and below during the entire summer but the other two must wait for the summer rains to soak down. The data show, too, that in the latter stations very little water reaches the second foot. This is an important factor in explaining the pres-

ence of mostly shallow-rooted species in the two lower associations and deeply rooted species, as the bunch grasses and trees, in the two higher stations.

The data indicate that in all the stations a very critical, if not the most critical, time for plant life is the arid fore-summer. The droughts later in the summer are also critical in the grassland and desert stations. Pearson (1920:158) has concluded that in the Douglas fir and Engelmann spruce zones the most critical drought period for reproduction is in the fall instead of in the fore-summer. This is due to the snow accumulated during the winter keeping the soil moist until the summer rains begin.

Not all of the summer rain replenishes the soil moisture because the run-off and percolation are very high in many sites. This loss of water is aided by the violence of many of the summer showers. Streams are filled to overflowing very quickly and then in a few hours after the storm the streamways are dry again. The rapidity with which the soil dries out after a shower was noted many times especially in the desert.

HUMIDITY

Friez and Sons' hygrothermographs, protected in well ventilated shelter houses, were used to secure continuous records of humidity. The instruments were checked every week with a psychrometer. During the summer of 1922 one instrument was installed in the sagebrush desert and another in the grassland. The following summer the grassland instrument was operated in the yellow pine station. From the records the mean day humidity was secured by averaging the 6 readings at two-hour intervals beginning with 8 A. M. The night humidity was secured in the same way beginning with 8 P. M. The mean day as well as the mean night humidities were then averaged for approximately weekly periods.

TABLE 1. *Average day and night relative humidities in the sagebrush and grassland during 1922*

		June 25-July 2	July 9-14	July 15-21	July 22-28	July 29 Aug. 4
		%	%	%	%	%
Day	Sage	22.8	21.9	......	28.5	38.8
	Grass	30.0	25.1	28.0	27.1	37.8
Night	Sage	26.5	26.4	......	41.5	55.3
	Grass	40.4	34.4	42.7	40.3	56.6

		Aug. 5-9	Aug. 12-17	Aug. 18-24	Aug. 25-29	Av. for season
		%	%	%	%	%
Day	Sage	33.3	36.5	55.4	32.0	33.6
	Grass	34.1	35.9	45.0	29.6	33.1
Night	Sage	39.6	51.4	64.2	44.5	43.7
	Grass	45.1	45.7	64.3	43.5	46.3

Table 1 shows that there was very little difference in the relative humidities of the *Atriplex-Artemisia* and *Aristida-Bouteloua* associations. The average day humidity for the season was 33.6% in the former and 33.1% in the latter. In some periods it was higher in the grassland, in other periods in the sagebrush. The mean night humidity for the season was 43.7% in the desert and 46.3% in the grassland, a difference of only 2.6%. Both the day and night humidities were much lower during the arid fore-summer than during the rainy period. In both associations large and sudden fluctuations occurred due to

showers or to the rapid lowering of temperature by cool winds or by great radiation at night. Differences in the vegetation of these two associations certainly can not be explained on the basis of humidity.

TABLE 2. *Average day and night relative humidities in the sagebrush and yellow pine forest during 1923*

		June 6-12	June 13-21	June 24-30	July 1-7	July 8-12	July 13-20	July 21-22
		%	%	%	%	%	%	%
Day	Sage	14.9	19.0	12.8	26.6	33.1	35.8	35.5
	Y. P.	28.8	28.6	24.2	34.3	40.5	45.4	56.2
Night	Sage	19.2	20.4	15.3	39.6	46.1	54.6	53.9
	Y. P.	36.8	34.8	32.4	40.6	57.7	59.5	69.6

		J. 27 A. 1	Aug. 2-8	Aug. 9-14	Aug. 15-21	Aug. 22-27	A. 28 S. 2	Av. for season
		%	%	%	%	%	%	%
Day	Sage	29.0	22.8	46.1	36.1	36.1	49.2	30.5
	Y. P.	45.6	39.7	61.8	53.6	48.6	50.7	42.9
Night	Sage	41.3	32.5	64.9	53.0	45.3	65.9	42.5
	Y. P.	55.2	47.9	66.1	64.5	61.1	64.9	53.2

As was to be expected the humidity during the summer of 1923 was much lower in the sagebrush than in the yellow pine forest (Table 2). The average day humidity for the season in the former was 30.5%, in the latter 42.9%, a difference of 12.4%. The night humidity was 42.5% in the desert and 53.2% in the pines, a difference

of 10.7%. The rainfall was about half of the normal in the pines and somewhat above normal in the desert, so in most seasons the differences in humidity would be even greater. The table shows that the humidity was low in both stations until the first week in July when the summer rains began (Fig. 11). During the rest of the season the dependence of humidity upon rainfall is very pronounced as a comparison of table 2 and figure 11 shows. The rains during July 1-22 produced fairly high humidity while the scant rainfall during July 27-August 8 reduced the humidity 10-22%. The heavier rainfall in the week following August 8 caused the humidity to rise rapidly again, falling again later as the rains decreased. Humidity is certainly one of the important factors to be considered in explaining the differences in the vegetation of these two associations.

Temperature

The temperature data were secured by means of Friez and Sons' hygrothermographs. These were installed as described under "Humidity" and checked every week. During the summer of 1922 the instruments were operated in the sagebrush and grassland and during the following season in the sagebrush and yellow pine forest.

A comparison of the continuous records shows that the maximum temperatures were about the same in the sagebrush and in the grassland but that the minimum were on the average 8° F. lower in the grassland. Mean day and night temperatures were secured in the same way as the mean day and night humidities and these are shown in table 3.

TABLE 3. *Average day and night temperatures in the sagebrush and grassland during 1922*

		June 26 July 2	July 9-14	July 15-21	July 22-28	July 29 Aug. 4
		° F.	° F.	° F.	° F.	° F.
Day	Sage	83.8	88.9	87.0	84.1	80.2
	Grass	82.7	88.6	85.4	83.8	77.8
Night	Sage	71.8	78.6	75.4	72.3	69.6
	Grass	66.1	70.8	69.0	67.1	62.9

		Aug. 5-11	Aug. 12-17	Aug. 18-24	Aug. 25-29	Av. for season
		° F.	° F.	° F.	° F.	° F.
Day	Sage	83.6	83.9	72.3	85.9	83.3
	Grass	82.5	80.1	72.7	83.9	81.9
Night	Sage	75.9	72.2	67.0	74.5	73.0
	Grass	67.7	64.2	59.1	67.3	66.0

The mean day temperature was only slightly higher in the sagebrush than in the grassland, rarely more than 2.5° F., but the night temperature averaged 7° F. higher in the former. The table also shows that there was less difference between day and night temperatures in the sagebrush than in the grassland. The average difference in the former station was 10.3° F., in the latter 15.9° F. Although the temperatures are similar in these two associations the slight differences render the sagebrush more xerophytic than the grassland. Plants with high heat requirements might find their limits in the desert but

the grassland would be too cool. It is a rather striking fact that the differences in temperature were greater than those in humidity between these two associations.

The data obtained during 1923 in the desert and in the yellow pine forest are summarized in Table 4. The

TABLE 4. *Average day and night temperatures in the sagebrush and yellow pine forest during 1923*

		June 6-12	June 13-21	June 23-30	July 1-7	July 8-12	July 13-20	July 21-26
		° F.	° F.	° F.	° F.	° F.	° F.	° F.
Day	Sage	82.0	71.2	84.1	83.6	77.3	77.9	78.1
	Y. P.	72.0	64.0	80.3	75.0	69.5	70.1	67.5
Night	Sage	65.3	59.2	69.8	71.6	69.0	68.0	69.8
	Y. P.	49.0	45.2	57.7	58.9	55.0	58.3	55.3

		J. 27 A. 1	Aug. 2-8	Aug. 9-14	Aug. 15-21	Aug. 22-27	A. 28 S. 2	Av. for season
		° F.	° F.	° F.	° F.	° F.	° F.	° F.
Day	Sage	85.2	85.4	75.5	77.8	82.4	74.6	79.6
	Y. P.	71.1	74.4	64.0	64.4	66.4	65.4	69.5
Night	Sage	76.0	77.1	66.9	68.1	71.5	64.0	68.9
	Y. P.	58.1	61.3	55.6	51.9	55.8	51.9	54.9

differences in temperature between these two stations were considerable. The average day temperature for the season was 10.1° F. higher in the desert and the night temperature 14° higher. Until about July 20 the day temperature in the yellow pines was a trifle higher than

the night temperature in the sagebrush but during the remainder of the season the situation was reversed. The difference between day and night temperatures in the yellow pines averaged 14.6° F., in the sagebrush 10.7°.

Since the hygrothermograph records were obtained for only two seasons the more extensive data of the U. S. Weather Bureau were utilized so far as possible. The mean monthly temperatures of three stations in the sagebrush desert (Leupp, Winslow, and Tuba City), and one in the yellow pine forest (Flagstaff), were averaged and are shown in Figure 16. The temperature at Flagstaff averages about 10° F. lower than in the desert, slightly more in summer and slightly less in winter.

The length of the growing season is an important aspect of temperature in that it is often a decisive factor in determining the composition of native vegetation as well

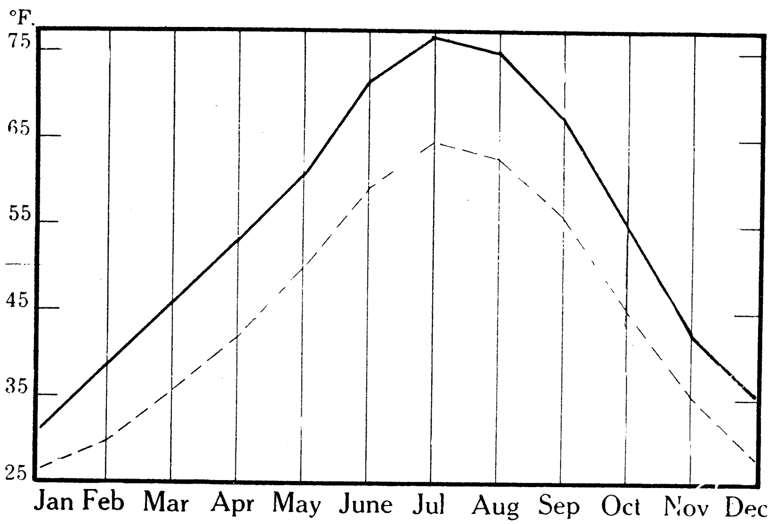

FIGURE 16. Average monthly temperatures for the year in the *Artemisia-Atriplex* Association (upper curve) and in the *Pinus scopulorum* Consociation (lower curve).

as the growing of crops. The average length of the growing season in the sagebrush (average of Leupp, Winslow, and Tuba City) is 166 days, varying from 128 to 235. In the yellow pines (Flagstaff) it is 114 days, varying from 79 to 143. The difference in the average length of the growing season in the two associations is 52 days. This explains why peaches, melons, and other fruit can be successfully grown under irrigation in the vicinity of Tuba City but only such crops as the small grains, potatoes, and vegetables are grown around Flagstaff.

Haasis (1923) has shown the importance of winter temperatures in relation to yellow pine seedlings in the vicinity of Flagstaff. Of 3,139 seedlings, mostly in their first winter, 16% were killed by frost heaving. Pearson (1913) showed the mean air temperature was 2.7° F. higher in the forest than in one of the larger parks, and that the soil temperature at 2 feet was 5° F. higher in the park.

WIND

In the vicinity of Flagstaff in the yellow pines the winds are prevailingly from the west, in the sagebrush from the southwest. The winds in all the associations are especially strong and drying during the period April-June. Clouds of dust and sand are blown across the desert, especially east of the Little Colorado River, but in the yellow pines sandstorms do not occur. During the rainy season the winds, though not so strong as during the arid fore-summer, increase the evaporation in all the stations but the greatest effect at this time is seen in the desert. On many days it was observed that in the yellow pines there was only a moderate breeze but in the grassland and desert there was a strong wind.

The scouring and eroding action of the wind is widely spread in the desert, making difficult in many places the establishment of even first invaders. Frequently the rock

had been swept bare of all surface soil. Sand dunes are common east of the Little Colorado River and in many places stream-courses are filled with sand during the arid fore-summer and scoured out during the rainy season. The abrasive action of the dust- and sand-laden wind is especially severe during the fore-summer. The herbaceous plants suffer most. Shrubs, with dense crowns and small xerophytic leaves, which abound in the desert, are best able to resist this wind action.

EVAPORATING POWER OF THE AIR

The evaporating power of the air was measured by means of Livingston's standardized cylindrical atmometers set up in duplicate in each station in the usual method.

TABLE 5. *Average daily evaporation in all stations for 1922 and 1923*

1922

	Sage-brush	Grass-land	Wood-land	Montane forest
	cc.	cc.	cc.	cc.
June 14-18	87.9	77.9	60.7	33.3
June 18-25	58.8	67.6	51.2	28.2
June 25-July 9	52.1	38.8	38.1	31.9
July 9-15	37.7	32.4	35.8	......
July 15-22	30.7	28.4	28.1	18.2
July 22-29	74.0	70.1	47.3	20.5
July 29-August 5	46.9	40.7	29.1	18.5
August 5-12	50.1	49.6	34.7	14.9
August 12-18	33.7	38.4	26.2	9.5
August 18-25	22.0	20.7	26.9	14.5
August 25-30	35.5	35.6	46.4	29.8
August 30-September 4	22.8	22.6	26.2	10.2
Average for season	46.0	43.6	37.6	29.0

1923

	Sage-brush	Grass-land	Wood-land	Montane forest
	cc.	cc.	cc.	cc.
June 13-23	76.8	72.1	56.1	58.0
June 23-29	117.8	90.9	73.2	61.1
June 29-July 6	93.5	85.9	78.7	54.5
July 6-14	42.0	37.9	31.4	34.9
July 14-22	49.2	38.0	21.8	28.9
July 22-28	66.7	48.6	28.2	26.2
July 28-August 2	72.3	53.7	33.7	33.4
August 2-9	57.9	56.7	44.6	42.0
August 9-17	34.5	19.5	10.3	6.9
August 17-24	53.0	26.1	18.4	18.1
August 24-September 3	40.3	34.9	19.8	18.8
Average for season	62.0	50.1	37.0	35.3

The old cylinders were replaced with new ones every 6 weeks in 1922 and every 4 or 5 weeks in 1923. Rain correctors were not used.

The average daily evaporation for the season from June 14 to September 4, 1922, was 46 cc. in the sagebrush, 43.6 in the grassland, 37.6 in the woodland, and 29.0 in the yellow pine forest; a ratio of 100:94:82:63. The readings were rather similar in the desert and grassland stations during this summer because the grassland station was located toward the lower end of the association. The following summer the station was located nearer the center.

The evaporation was greater in all the stations in 1923 (Fig. 11) than during the preceding season because of the lower rainfall. The average daily loss from June 13 to September 3 was 62 cc. in the sagebrush, 50.1 in the grassland, 37.0 in the woodland, and 35.3 in the pines; a ratio

of 100:81:60:57. There was much less difference between the yellow pine and woodland stations than in the preceding year because a denser woodland station was used and because the rainfall was abnormally low in the yellow pine station but it was in excess in the woodland. Fig. 11, where the rainfall in the stations is plotted for the periods corresponding to the evaporation readings, shows clearly how the evaporation losses are related to rainfall. During the arid fore-summer when there is practically no rainfall the daily evaporation was extremely high. From June 13 to July 6 it averaged 96 cc. in the sagebrush, 83 cc. in the grassland, 69 cc. in the woodland, and 58 cc. in the yellow pines. With the beginning of the summer rains the evaporation fell rapidly but as soon as the rainfall decreased (July 22-Aug. 9) the evaporation rose again at once. This same close relation to rainfall was noted in 1922.

The most important features of these evaporation data are the extremely high rates especially in the desert and grassland, the sharp decline at the beginning of the summer rains so that the curve goes downward as the summer advances instead of upward which characterizes the evaporation curves of most parts of the United States, the close relation to rainfall, and the variation from year to year (35% greater in 1923 than in 1922 in the sagebrush). There can be no doubt of the importance of the effect of the evaporating power of the air upon the plant life in all the associations.

Light

The entire region is noted for its bright, clear days, so the sunshine percentage is very high. On account of the open vegetation light is generally a minor factor. The shade under the piñons and cedars excludes the grama grass and favors a taller and more varied flora. The shade

of shrubs and trees in the montane forest often prevents the growth of the bunch grasses that are usually found in the openings between the trees. Pearson states (1923:41) that yellow pine seedlings will not thrive in places that are shaded by trees half of the day or more. The abundance of light-colored rock in the desert causes strong reflections from below. The black cinders, frequent in the other stations, common in the yellow pines, absorb heat very quickly in the sunlight. Cover, in the form of dead grass, needles, etc., protect the soil in many places, especially in the higher associations, in this way tending to preserve soil moisture and to lower soil temperatures.

CORRELATION OF VEGETATION AND ENVIRONMENTAL FACTORS

The most important factors influencing plant growth in this region are soil moisture, evaporating power of the air, and temperature.

The soil moisture data (Figs. 13, 14, 15) show that the periods when water is not available for growth during the growing season become more frequent and of longer duration as one descends from the yellow pine forest to the piñon-cedar woodland, grassland, and sagebrush desert. Droughts every two to four weeks, when the soil moisture is reduced below the non-available point, coupled with high evaporation, as is the case in the two latter associations, prevent the growth of all plants except the most xerophytic. When water is more constantly available as in rock crevices, heads of canyons, etc., some of the more mesophytic plants that usually occur in the higher associations are found even on the desert. The soil moisture is, of course, directly dependent upon precipitation and this varies from an annual mean of 23 inches at Flagstaff in the yellow pines to 7 inches at Tuba City in the sagebrush. The form in which the

precipitation occurs is important, as snow accumulates to a depth of 4 feet during the winter in the yellow pines while on the desert it melts quickly after falling. The snow not only serves as a source from which the soil can be replenished with water but also forms a cover that lessens dessication of the soil as well as the wilting of young or small plants, such as yellow pine seedlings. In May and June the soils are usually dry as dust in the desert and grassland while in the pines there is still plenty of available moisture (Figs. 13, 14, 15). A great loss of precipitation occurs in many places due to the great amount of run-off and rapid percolation. In the desert, where the precipitation is already very low, the run-off is unusually high because of the numerous steep gradients and rocky surfaces. The percolation is very rapid, also, because of the porous soil. It is remarkable how quickly the effects, except erosional, of a shower will disappear in many parts of the desert. In the other stations the losses from these causes are less. The lower limits of the associations must be delimited largely, it appears, on the basis of the amount and duration of soil moisture, because when this is adequate characteristic species of the higher associations occur far down in the lower ones. Even young cedars were found occasionally on the limestone area on the desert. The data recorded under soil moisture show that there was plenty of available moisture in the soil of the rock crevices.

There was not much difference in the temperature of the grassland and sagebrush but between these associtions and the two higher ones the differences were considerable and probably exert a controlling influence. Many plants of the lower associations must be prevented from becoming established in the higher ones because of the shortening of the growing season, averaging 166 days in the desert and 114 at Flagstaff in the yellow pines,

and also because of the increased duration of temperatures below freezing. Shreve (1915:96) has shown that a duration of more than 18 hours of freezing temperature is fatal to *Carnegiea gigantea* and concludes from this and additional data that the upper limits of many of the desert plants of southern Arizona are probably due to this aspect of temperature. The downward distribution of some species may be prevented by the increased duration of high temperature in the lower associations. Maximum temperatures above 90° F. are rare in the yellow pine forest but in the grassland and desert they frequently exceed 100° F. The intensity and duration effects of temperature have been discussed in a number of publications (Bates 1923, Livingston & Shreve 1921, Shreve 1916), the fullest treatment being by Livingston and Shreve (1921).

The evaporating power of the air is strong in all the associations, ranging from an average daily loss for the summers of 1922 and 1923 of 54 cc. in the sagebrush, to 47 in the grassland, to 37 in the woodland, and 32 in the yellow pines. The effects of these high rates are noted in the commonness of xerophytic habits, as dense and spiny scrub, thick grass mats, scurfy, succulent or highly cutinized leaves, etc., the scarcity of mesophytic plants, and the telescoping of the hydrosere. The desert shrubs and herbs are especially well adapted to endure the desiccating power of the air. The capacity of these shrubs to remain dormant during most of the year and to endure droughts even during the summer rainy season is one of the most important features of this desert vegetation. In this respect *Atriplex confertifolia* and *A. canescens* are more xerophytic than *Artemisia tridentata* (Kearney *et al,* 1914:399). The high evaporation rates are due to the low rainfall, low humidity, strong drying winds, and strong solar radiation. The lower limits of many plants characteristic of the higher associations must be due, in part

at least, to their inability to maintain the high transpiration occasioned by the dry air in the lower associations. The replacement of *Artemisia tridentata* by the low, scrubby *A. bigelovii* on most of the desert along the Little Colorado River is because the latter is much better fitted to cope with the extremely xerophytic conditions.

Light is only a minor factor in a comparison of these four associations as it is about equally strong in all although there is a somewhat higher percentage of sunny days in the lower associations than in the higher.

Wind, topography, and soil composition are the most important indirect factors. The wind is especially strong and drying during the arid fore-summer, May-June, when the plants are already severely taxed by the lack of rain and low humidity. Most of the plants in the lower associations remain dormant during this season but the plants in the higher associations are drawing upon the moisture that is left over from the melting of the winter snow. It appears that one of the most important factors in the survival of species on the desert and grassland is the long, desiccating fore-summer. This very likely accounts for the lack or scarcity in the desert along the Little Colorado River of such species as *Artemisia tridentata, Chrysothamnus* spp., *Erigeron* spp., *Balsamorrhiza* spp., *Delphinium,* and others common in the sagebrush association farther north. Topography and soil composition are important chiefly through their influence upon soil moisture. They play an important rôle in increasing run-off and percolation, especially in the desert, where steep slopes and sandy and gravelly soils are common. In the woodland and yellow pines the greater abundance of clay brings about higher and more constant moisture contents, favoring the more mesophytic plants.

The absence of species characteristic of the desert scrub in western and southern Arizona on the desert along the

Little Colorado River is probably because the frost period is too long, 202 days, average of Leupp and Tuba City; the average winter temperature (December-February) too low, 35° F., average of Leupp, Tuba City, and Winslow; and because of the excessive minima, -12 to -19° F. The limits for the desert scrub are about 175 days for the frost period, 39° F. mean winter temperature, and absolute minima of -1 to -5° F. These figures are based on U. S. Weather Bureau records from places at the limits of the Desert Scrub, as St. George in Utah; Las Vegas and Caliente, in Nevada; Long Pine and Independence, in California; and Supai and Kingman in Arizona.

The sagebrush association is not better developed along the Little Colorado because of the long drought period in the spring, only about one inch of precipitation occurring on the average, from April to June inclusive. Probably, also, the summers are too hot, the mean maximum being slightly above 91° F., which rarely occurs in the larger sagebrush farther north.

GROWTH EXPERIMENTS

In order to make a further comparison of the vegetation and the environments in the different associations small plats of Pinto beans and Canada field peas were planted and fenced on July 14 in each station. On account of the thin dry soil in the sagebrush the plants failed to grow. The peas also failed to grow in the yellow pines. In the yellow pine and woodland stations the gardens were made in openings between the trees and in all the stations the native vegetation was cleared away and the soil well-spaded.

On July 21, one week after planting, there was a germination for the beans of 77% in the woodland, 13% in the grassland, and none in the yellow pines. The better germination in the first station was due chiefly to the

TABLE 6. *Growth of Pinto beans and Canada field peas in different associations. Planted July 14, data collected September 3, 1923*

Station	Ave. leaf area per plant (one side only)		Ave. dry weight of leaf blades per plant		Ave. dry weight of stems and petioles per plant		Ave. thickness of mature leaves
	sq. cm.	%	g.	%	g.	%	%
				Beans			
Yellow pines	173.9	100.0	0.696	100.0	0.255	100.0	100.0
Woodland	156.8	90.2	0.412	59.2	0.177	69.6	85.3
Grassland	108.4	62.3	0.317	45.6	0.139	54.5	73.5
				Peas			
Woodland	58.7	100.0	0.106	100.0	0.206	100.0	86.2
Grassland	26.8	45.6	0.055	52.5	0.132	63.9	100.0

moister soil. On July 27 the percentages were 98, 73, and 93 while the average heights were 4.5, 3.5, and 3.0 cm. in the respective stations. Since uniform seed had been selected the much lower germination in the grassland was due to the dry soil. On September 3 the average heights were 10 cm. in the woodland with the flower buds turning white, 6 cm. in the grassland and flower buds also turning white, and 6 cm. with very small, green flower buds in the yellow pines. Practically all the plants had survived in each station.

The peas on July 21 showed a germination of 63% in the woodland and 14% in the grassland. Six days later 74%, averaging 4.5 cm. high, were growing in the former station and 46%, averaging 1.5 cm. high, in the latter. The effect of the drier soil in the grassland is again noted. On September 3, most of the plants having survived, the peas

in the woodland averaged 15 cm. with green, 2- or 3-seeded pods, but those in the grassland were 10 cm. with smaller, green, 1-seeded pods.

All the data, summarized in table 6, show that the best development of all the characters, except height, in the beans occurred in the yellow pine station. Leaf area, dry weight, and leaf thickness were all greatest in the yellow pines, less in the piñon-cedars, and least in the grassland. The greatest differences were found in the dry weights of the leaf blades, the ratio being 100:59:46; the least differences in leaf thickness, 100:85:73. The smaller amount of growth in the piñon-cedars as compared with the yellow pines could scarcely have been due to soil moisture because there was plenty of available water in both (Figs. 13-15). It appears that the drier air in the former station must have been an important factor as the ratio for the evaporating power of the air during the growth period (July 14-September 3) was inversely proportional to the ratios found for leaf area and thickness. The evaporation ratio during this period was 100 in the grassland, 63.8 in the woodland, and 55.6 in the yellow pines. The smaller amount of growth in the grassland as compared with that in the woodland was due to the lower soil moisture as well as to the more xerophytic aerial conditions in the former station. From July 14 to September 3 the evaporation was 57% greater in the grassland and the available soil moisture was much more plentiful and uniform in the woodland. All the characters measured for the beans; leaf area, dry weight of blades, dry weight of stems and petioles, and leaf thickness, were better developed in the woodland than in the grassland.

But in the peas the leaf thickness was somewhat greater in the grassland than in the woodland (ratio of 100:86), and the other characters were better developed in the woodland. The peas showed greater differences than the

beans. The ratio between the woodland and grassland for leaf area was 100:69 for the beans and 100:45 for the peas; for dry weight of blades 100:77 for the beans and 100:52 for the peas; and for the dry weight of the stems and petioles 100:78 for the beans and 100:64 for the peas. Both plants agree in showing that leaf area was affected more than the other characters by increased xerophytism.

The average ratio of leaf area, dry weight of blades, and dry weight of stems and petioles, between the woodland and grassland for the beans was 100:74.8, for the peas 100:53.9. This great difference shows that Pinto beans and Canada field peas vary greatly in sensitivity to environmental factors or in the capacity to respond to the environmental stimuli. The average of these two ratios, 100:64.3, certainly gives a more exact summation of climatic factors in their relation to plant growth than instrumental temperature, humidity, evaporation, etc., data can possibly afford. It is interesting to note that the evaporation ratio (100 in the grassland to 63.8 in the woodland) between these two stations was almost exactly inversely proportional to this average ratio and that the ratio for the amount of available soil moisture in the 10-30 cm. layer was 100 in the woodland to 25 in the grassland.

CONCLUSION

The region studied in this paper is located in northern Arizona, extending from San Francisco Mountain, near Flagstaff, to the Navajo Country, east of the Little Colorado River, covering an area of approximately 2000 square miles. It includes 6 climax formations: the Alpine Meadow above 11,500 feet, the Subalpine Forest above 9500 feet, the Montane Forest above 6800 feet, the Woodland above 5600 feet, the Grassland above about 5200 feet, and the Sagebrush below this. The vegetation and environmental factors have been studied in the last four.

The sagebrush area is near the southern limit of the *Artemisia-Atriplex* Association, so well developed in Utah. The scattered gray scrub, only 1 to 3 feet high, alternating with bare rocky or gravelly soil is the predominating aspect. The dominant genera are *Atriplex, Artemisia, Gutierrezia, Isocoma, Chrysothamnus,* and *Eurotia.* The summer rains, beginning in the first week of July and marking the close of the very arid fore-summer, bring into activity a large number of secondary species, all xerophytic. The low precipitation, about 7 inches annually, coupled with the shortness of the rainy season, July-August, following the dry months of April, May, and June when less than an inch falls, is the ruling factor. The large amount of run-off caused by the general steepness of the slopes and the great degree of percolation through the predominatingly porous soil, render much of this precipitation useless so far as the plants are concerned. Soil moisture is rarely much above the hygroscopic coefficient and periods of drought, with no water available for plants, recur commonly throughout the summer. The evaporating power of the air is very great. The average daily losses for the summers of 1922 and 1923 were 46 cc. and 62 cc. The average day and night temperatures for the summer of 1922 were 83° F. and 73° F.; for 1923, 80° F. and 69° F. The frostless season has an average length of about 166 days. Maximum temperatures over 100° F. are common during the summer. The mean winter temperature (December-February) is about 35° F. and absolute minima from -12° F. to -19° F. have been recorded. The average day and night humidities for the summer of 1922 were 34% and 44%; for 1923, 30% and 42%. The wind is usually strong and drying. Wind erosion and deposition are common. The sunlight is usually bright and the number of sunny days in the year is very high.

The grassland forms a zone only about 10 miles wide between the sagebrush desert and the woodland. It forms gradual transition zones with both of these adjacent associations. On account of the abundance of the chief dominant, *Bouteloua eriopoda,* it belongs to the Desert plains or *Aristida-Bouteloua* Association. *Hilaria jamesii* joins *B. eriopoda* in dominating the transition zone to the desert and *B. gracilis* becomes more abundant than *B. eriopoda* as the woodland is entered. The grassland is composed of bunches or small mats, 4 to 6 inches in diameter, a foot or more high at maturity, and covering only about 25% of the ground. Shrubs, especially *Atriplex* and *Chrysothamnus,* are scattered here and there, especially in disturbed soil. The vegetation does not begin to grow until the summer rains begin. The precipitation is greater than in the desert. During the summer of 1923 about 6 inches fell in the grassland and 4 in the desert. Soil moisture was more constantly available but still subject to non-available periods throughout the rainy season. The soil moisture is located in the surface soil, penetrating but a short distance into the second foot (30-60 cm.) by September 1, thus accounting for the abundance of roots in the first foot and the scarcity in the second. The daily evaporation for the summer averaged 44 cc. in 1922 and 50 cc. in 1923. Its close relation to rainfall, as in the other stations, was striking. The average day and night temperatures for the summer of 1922 were 82° F. and 66° F., only slightly lower than in the desert. Summer maxima were also similar. The average day and night humidities for the summer of 1922 were 33% and 46%, only a trifle higher at night than in the sagebrush while the day humidities were practically the same. The wind was hardly as strong as in the desert and erosional effects were rare. The soil was clayey, intermixed with rocks, hence moisture was retained better. The topography and slopes

were gentle as a rule and there was not so much run-off as in the desert.

The woodland formed a zone about 5 to 10 miles wide above the grassland. The dominant trees were *Juniperus monosperma* and *Pinus edulis,* hence the zone belongs to the *Pinus-Juniperus* Association. The trees were low, 20 to 30 feet high, and widely spaced. The large openings between the trees were covered with short tufts of *Bouteloua gracilis,* with the shrubs *Chrysothamnus bigelovii* and *Artemisia tridentata* occasionally dominating some of the larger openings. True forest conditions rarely obtained and most of the herbaceous plants were not shade-enduring species. As the average annual precipitation is about 16 inches the rainfall of 8 inches during the summer of 1923 was probably about 2.5 inches in excess. The rainfall in the grassland and in the desert was also above normal during this summer. Soil moisture was available in the second foot (30-60 cm.) throughout the season but in the first foot short periods of non-available water contents intervened. On the whole, moisture was much more plentiful and constant than in the grassland and desert. The average daily evaporation for the summer of 1922 was 38 cc., the following summer 37 cc. The soil was very clayey so the rainfall was not lost easily because of percolation and evaporation. There was considerable run-off on some of the slopes but on the whole the rains penetrated fairly well.

The yellow pine forest *(Pinus-Pseudotsuga* Association) covers a strip 10 to 40 miles wide in northern Arizona. The dominant tree between 6800 and 8300 feet is *Pinus scopulorum,* while from 8300 to 9400 feet *Pseudotsuga mucronata, Abies concolor,* and *Pinus flexilis* are mixed with *P. scopulorum.* Below 8300 feet *P. scopulorum* forms an extensive, open forest with bunch grasses and other sun-requiring herbs in the openings. The dominating

plants in these openings are the bunch grasses *Muhlenbergia trifida, Festuca arizonica,* and *Blepharoneuron tricholepis.* A much larger variety of shrubs and herbs occurred in this association than in any of the others. Three primary and two secondary successions have been worked out and are shown graphically on page 29. The telescoping of the early part of the hydrosere is especially noteworthy. The average annual precipitation is 23 inches. The winter snows accumulate to depths of 3 or 4 feet. The melting of the snow increases the soil moisture, so growth of most species begins before the summer rains. The arid fore-summer is not so severe as in the other three associations. There is usually available soil moisture to a depth of about 3 feet and beyond throughout the summer although it runs pretty low in the surface soil during May and June. The average daily evaporation for the summer was 29 cc. for 1922 and 35 cc. for 1923. During the latter season the rainfall was about half normal. The average day and night temperatures for the summer of 1923 were 69° F. and 55° F. The length of the growing season averages 114 days at Flagstaff, 52 days less than in the sagebrush. Maximum temperatures seldom exceed 90° F. The mean winter temperature (December-February) is 28° F., 7° F. colder than in the sagebrush. The average day and night humidities for the summer of 1923, probably somewhat drier than normal, were 43% and 53%. Wind action is not severe because of the protection afforded by the trees and other windbreaks but during the arid fore-summer it is very drying. The soil is adobe clay over much of the area, in other places sandy, rocky, or cindery. Percolation is very rapid in the more porous soils and runoff is great on the numerous steep slopes but on the more level areas there is considerable run-in.

A comparison of the factors in the four associations shows that the annual precipitation averages about 23

inches in the yellow pine forest, 16 in the piñon-cedar woodland, and 7 in the sagebrush; the grassland being between the last two. The snowfall averages 79 inches at Flagstaff and only 15 at Tuba City in the sagebrush. The soils in the yellow pines and in the woodland act as reservoirs for water which is always available for plant growth below 1 foot (30 cm.), but in the grassland and sagebrush the deeper soils are usually dry and the plants must await the penetration of the summer rains. The day humidity for the summer in the yellow pines averaged about 43%, in the grassland and sagebrush about 32%. The average day temperature for the summer averaged about 69° F. in the yellow pines and about 81° F. in the grassland and sagebrush. The growing season has an average length of 114 days in the yellow pines (Flagstaff) and 166 in the desert. The mean winter temperature (December-February) was 28° F. in the yellow pines and 35° F. in the desert. The average daily evaporation for the summer of 1923 was 62 cc. in the sagebrush, 50 cc. in the grassland, 37 cc. in the woodland, and 35 cc. in the yellow pines; a ratio of 100:81:60:57.

Growth measurements on Pinto beans and Canada field peas during the summer of 1923 integrated the climatic factors in three of the associations. The ratio between the yellow pine forest, the piñon-cedar woodland, and the grassland for the dry weight of the leaf blades of beans was 100:59:46; and for leaf thickness 100:85:73. The average ratio of leaf area and dry weight of shoots for the woodland and grassland was 100:75 for the beans and 100:54 for the peas and the evaporation ratio was 100:64.

The most important factors in the segregation and maintenance of the formations in this region are soil moisture, temperature, and the evaporating power of the air.

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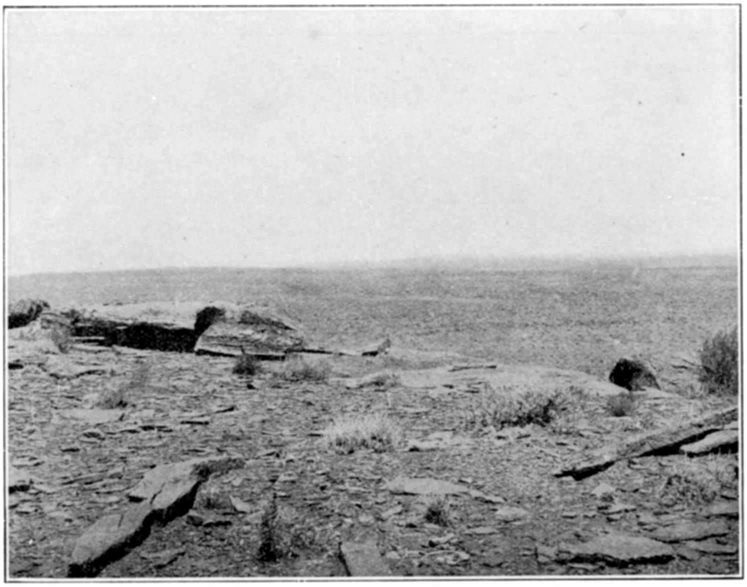

PLATE I, A. *Artemisia-Atriplex* Association on red sandstone soil. The chief plants on the rocky ledge in the foreground are *Artemisia bigelovii* (in center), *Eriogonum divergens, Atriplex canescens,* and *Encelia frutescens resinosa.* On lower area in background are *Atriplex confertifolia* and *A. canescens,* chiefly. July 29, 1922.

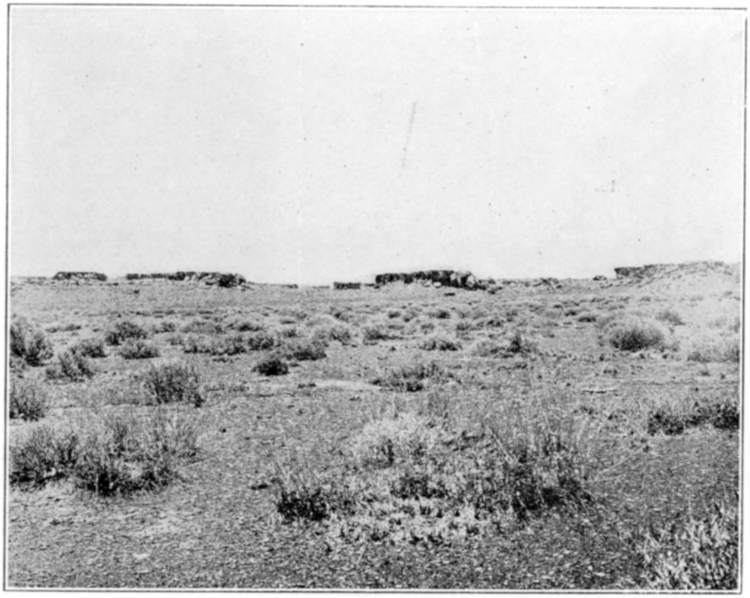

PLATE I, B. *Artemisia-Atriplex* Association on red sandstone soil. The chief plants are *Atriplex canescens* and *A. confertifolia*, with clumps of *Hilaria jamesii* and *Sporobolus airoides*. July 29, 1922.

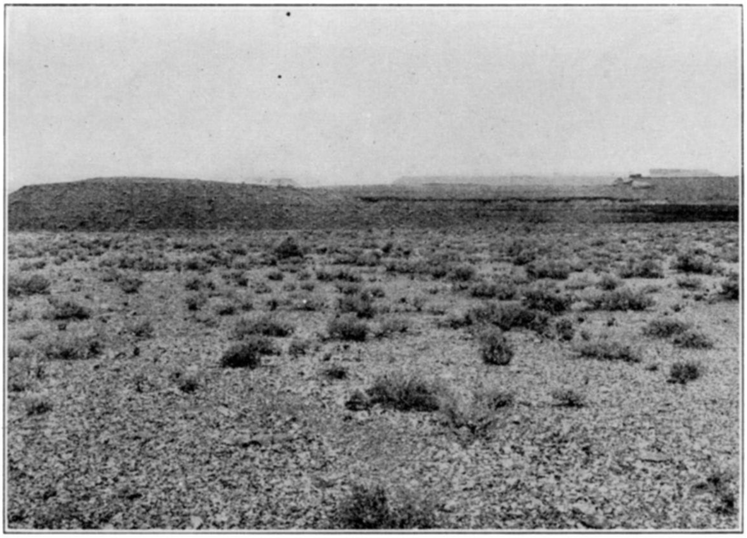

PLATE II, A. *Artemisia-Atriplex* Association on limestone soil in the foreground and red sandstone soil in the background. August 25, 1923.

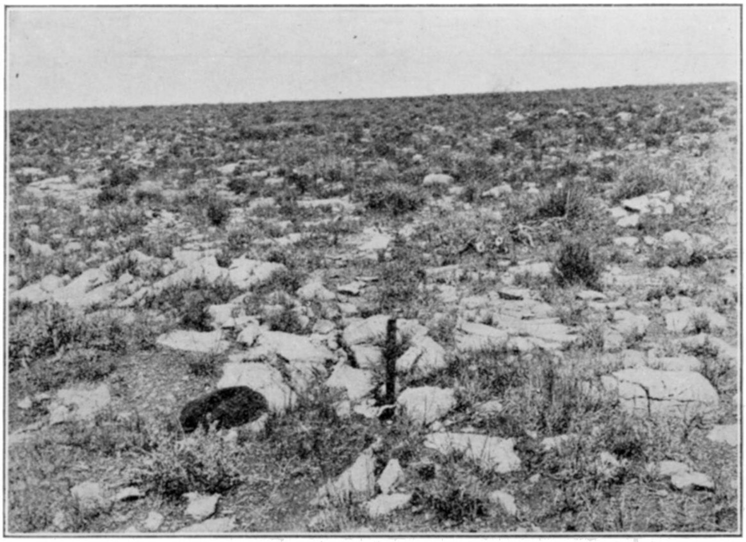

PLATE II, B. Detail of the *Artemisia-Atriplex* Association on the limestone soil. Common plants are *Atriplex confertifolia* in front of cap, clumps of *Bouteloua gracilis* on both sides of cap, *B. eriopoda* and *Hilaria jamesii* at right of ruler, *Gutierrezia glomerella* (dark clumps), *Atriplex confertifolia* (light clumps), and *Yucca glauca* (at right) in background. August 17, 1923.

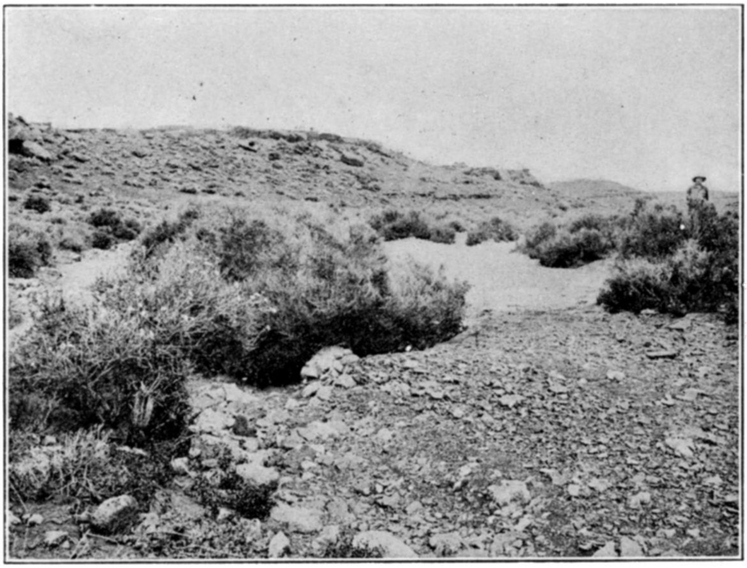

PLATE III, A. Stream-bed (wash) in the *Artemisia-Atriplex* Association near Cameron. The common plants bordering the wash are *Fallugia paradoxa* with white flowers, *Coleosanthus wrightii*, *Atriplex canescens*, *Physalis hederaefolia*, *Muhlenbergia porteri*, and *Amsonia* spp. August 25, 1923.

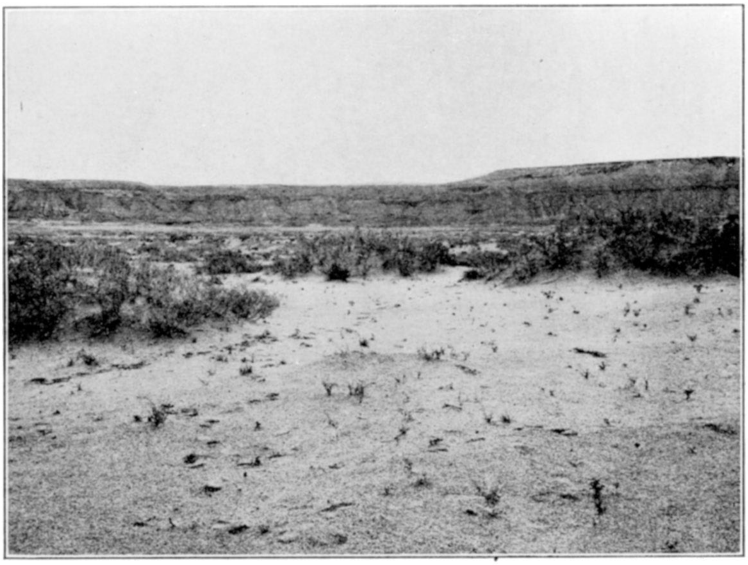

PLATE III, B. Sand dune area near Tuba City in the *Artemisia-Atriplex* Association. On the mounds the vegetation is chiefly *Parryella filifolia*; *Hilaria jamesii*, chiefly, in the foreground with scattered *Yucca glauca, Sphaeralcea arizonica, Parryella,* and *Sporobolus airoides.* August 25, 1923.

Plate IV, A. A pure stand of *Bouteloua eriopoda* covering many square miles in the *Aristida-Bouteloua* Association. San Francisco Mountain in the background. August 25, 1922.

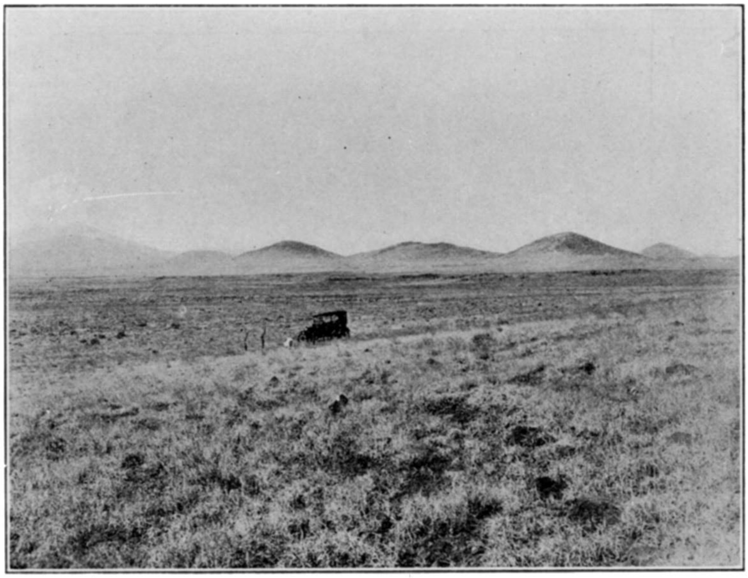

PLATE IV, B. *Bouteloua eriopoda-Hilaria jamesii* grassland in the lower part of the *Aristida-Bouteloua* Association. Piñon-cedar woodland on north slopes and grassland on south slopes of cinder cones in background. San Francisco Mountain in background at left. July 29, 1922.

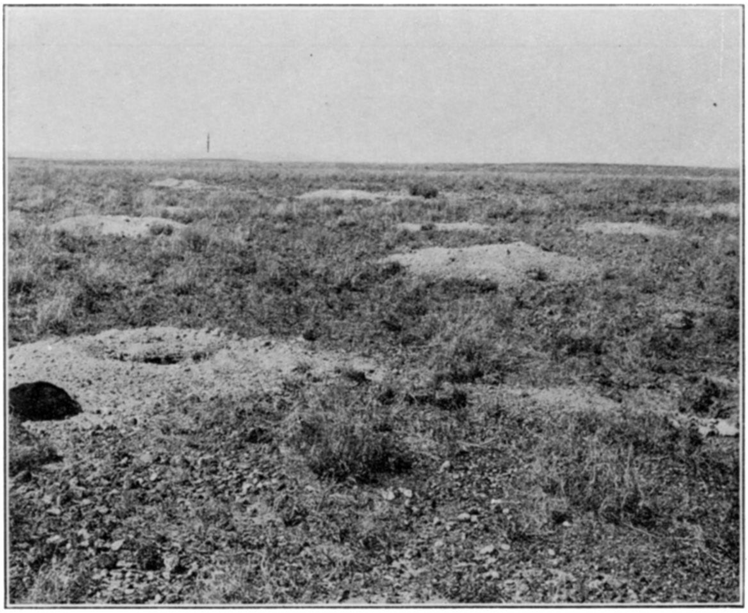

PLATE V, A. A prairie-dog town in the *Aristida-Bouteloua* Association. The grasses are destroyed in the following order: *Stipa neomexicana, Hilaria jamesii, Bouteloua eriopoda.* Chief plants here are *Hilaria* and *Bouteloua.* August 25, 1922.

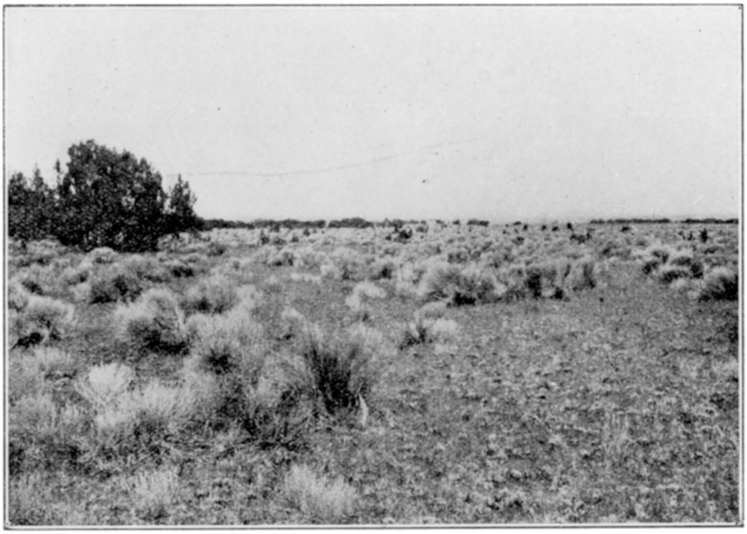

PLATE V, B. A large opening in the *Pinus-Juniperus* Association, covered chiefly with *Chrysothamnus bigelovii* and *Bouteloua gracilis*, being invaded by *Pinus edulis* and *Juniperus monosperma*. Deadman's Flat. September 2, 1923.

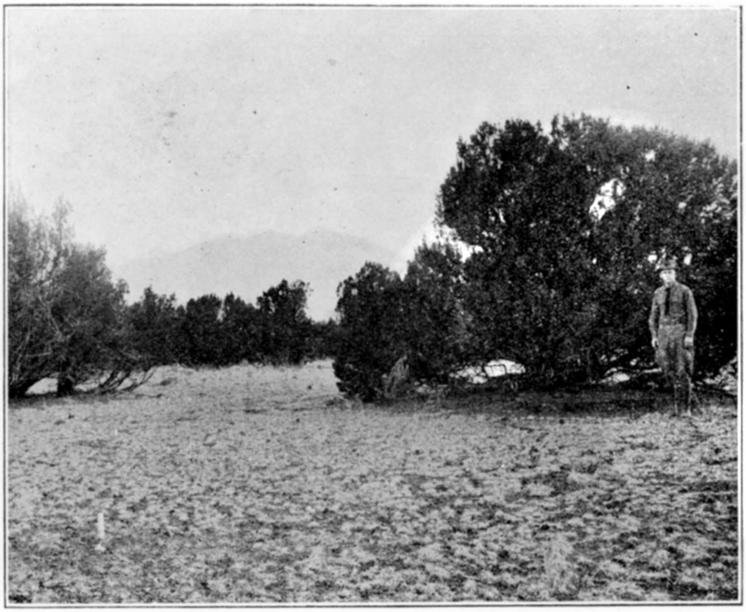

PLATE VI, A. *Pinus-Juniperus* Association. *Bouteloua gracilis* in the openings between the trees, *Pinus edulis* and *Juniperus monosperma*. San Francisco Mountain in the background. July 29, 1922.

PLATE VI, B. *Pinus-Juniperus* Association on a north-facing slope. The trees are *Pinus edulis* and *Juniperus monosperma*; the herbs in the small openings in the foreground are *Bahia dissecta, Bouteloua gracilis,* and *Aristida arizonica.* September 2, 1923.

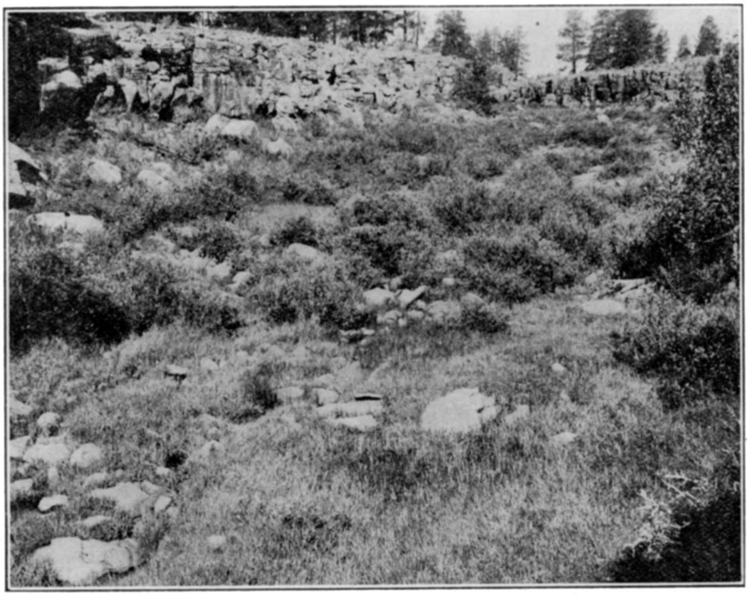

PLATE VII, A. *Eleocharis-Carex* Associes in the foreground, the chief plants are *Eleocharis palustris, Juncus brunnescens, Agrostis palustris,* and *Mimulus langsdorfii. Rosa-Populus* Associes in the background, *Populus angustifolia* and *Rosa fendleri,* chiefly. In the *Pinus scopulorum* Consociation near Flagstaff. August 21, 1923.

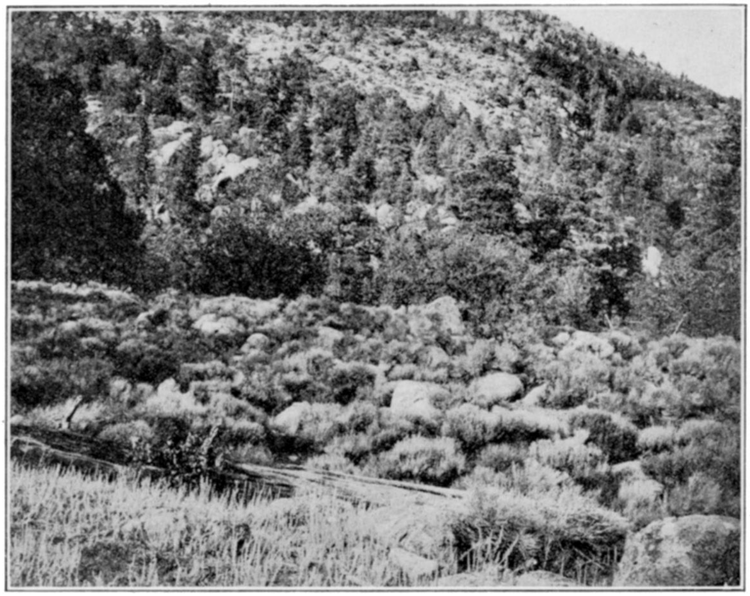

PLATE VII, B. In the *Pinus scopulorum* Consociation near Flagstaff. *Artemisia wrightii* in the extreme foreground, *Chrysothamnus graveolens* beyond log, *Quercus gambellii* beyond this, on the dry slopes xerophytic shrubs, in the draws *Pinus scopulorum, Abies concolor,* and *Pseudotsuga mucronata.* August 21, 1923.

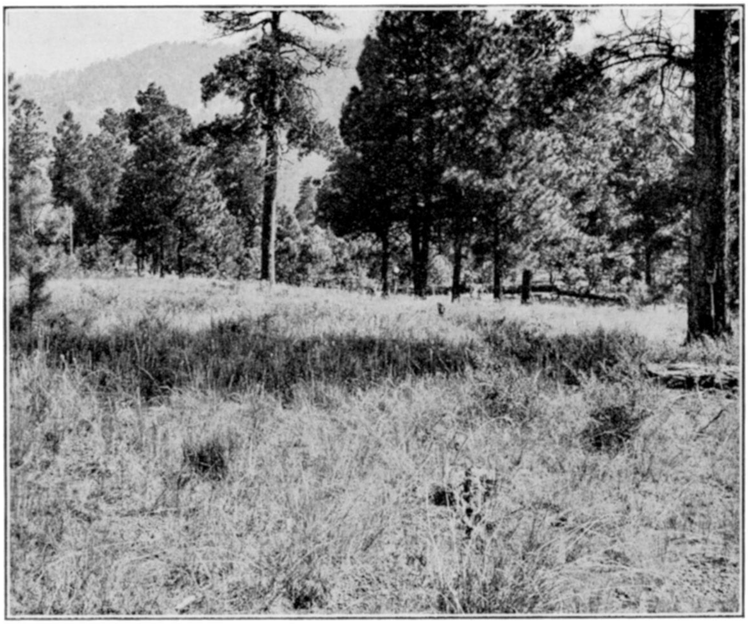

PLATE VIII, A. Vegetation typical of rather sandy soil in the *Pinus scopulorum* Consociation near Flagstaff. The most common plants are *Muhlenbergia trifida, Blepharoneuron tricholepis, Andropogon scoparius, Artemisia wrightii, Sitanion elymoides,* and *Ceanothus fendleri* (at right). 7,000 feet. August 6, 1922.

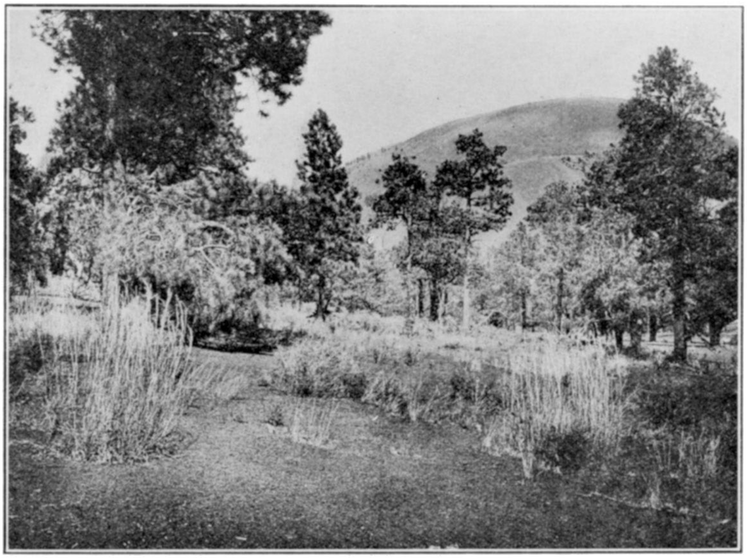

PLATE VIII, B. Third stage in the invasion of cinders near Flagstaff. Tall grass is *Andropogon hallii,* clumps of *Bouteloua gracilis* are common, with *A. scoparius, Fallugia paradoxa,* and *Chrysothamnus graveolens* scattered. Trees are *Pinus scopulorum.* Sunset Mountain in background. August 31, 1923.

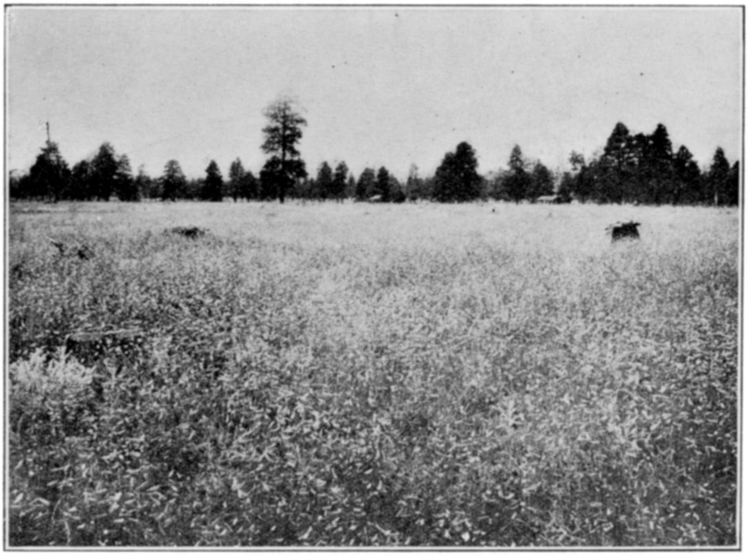

PLATE IX, A. An almost pure stand of *Bouteloua gracilis* in an abandoned field in the *Pinus scopulorum* Consociation near Flagstaff. August 31, 1923.

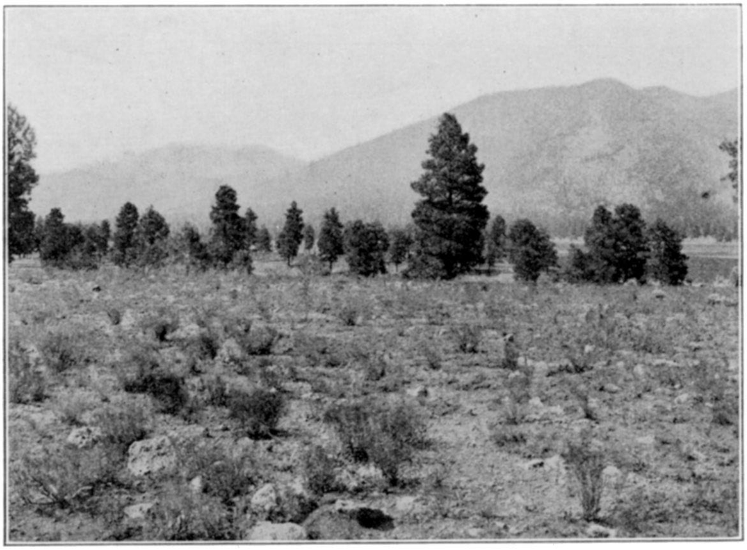

PLATE IX, B. A badly overgrazed range in the *Pinus scopulorum* Consociation near Flagstaff. *Hymenoxys floribunda* is especially abundant while the clumps of *Bouteloua gracilis* are badly dwarfed. Xerophytic south slope of Mt. Elden in background at right, San Francisco Mountain in background at left. August 21, 1923.