Injury and Death or Recovery of Trees in Prairie Climate

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INTRODUCTION

Several years of decreasing precipitation initiated the 7 years of drought. By midsummer of 1934 it was clear that the prairie region of the Middle West was undergoing the greatest drought since the beginning of its recorded weather history. The 12 months following June, 1933, was the driest weather period ever recorded not only for the Dakotas, Minnesota, Nebraska, Iowa, Illinois, and Missouri, but also drought in Kansas, Oklahoma, and Colorado was very severe (Kincer 1934). This intensely dry period, as well as those in several of the following years, was accompanied by record-breaking temperatures, extremely low humidities, and exceptionally high rates of evaporation. These were the years also of high winds, swarms of grasshoppers, and great dust storms.

Great losses were suffered by native trees both along the western margin of woodland and within the area of climax deciduous forest. Where postclimax forest extends far westward along rivers and streams into the semihumid and dry grassland climates, losses were extremely heavy (Fig. 1). These losses occurred during the past decade of drought despite the fact that in the prairie area and especially west of the Missouri River the more mesic species of trees are not found and only the more drought resistant kinds occur. Compensations for low water content of soil, high wind, and low humidity supplied by rivers and streams were often inadequate.

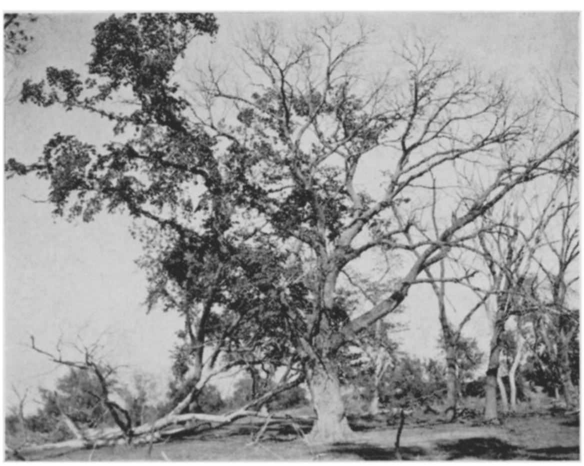

Fig. 1. Loss of elms by drought along the Weeping Water River in eastern Nebraska. They were growing on the flood plain and were protected from drying south winds by a steep bluff. Photo in May, 1944, showing some recovery. (Unless otherwise indicated all photographs are by the authors.)

FORESTS AND TREES IN PRAIRIE CLIMATE

It has been estimated that 15 percent of Iowa, owing to its many large rivers and network of streams, was forested. Perhaps nearly the same conditions occurred in the similar climate which prevailed over the prairies of Missouri. But only 2.5 to 3 percent of the area of Kansas and Nebraska was native forest. Along the Missouri River a strip of forest extends westward and northward from the main forested area to northeastern Kansas. It narrows rapidly where it extends farther northwestward in Iowa and Nebraska.

Effects of Drier Climate Northward and Westward

Decrease in area occupied by woody vegetation, decrease in number of species, dwarfing in size of individuals, and their confinement to the most favorable sites, are all well illustrated along the Missouri River in eastern Nebraska. The data are from Aikman's study of these forests (1929). In the south-

Fig. 2. (Upper) Wooded north-facing bluff on the Missouri River and trees along a ravine, 25 miles west of Yankton, South Dakota. (Lower) The south-facing slope of a similar bluff with patches of rough-leaved dogwood *(Cornus asperifolia)*, coralberry and snowberry (species of Symphoricarpos), and smooth sumac *(Rhus glabra)*. Bur oak *(Quercus macrocarpa)* occurs in the ravines.

east under an annual precipitation of 33 inches, the average width, in Nebraska, of the general potential forest area, which is dominated only in the more protected parts by red oak *(Quercus borealis maxima)*[1] and linden *(Tilia americana),* is about 25 miles. But in northeastern Nebraska under 28 inches of precipitation it is only 2.5 miles. The height of the trees in the best situations southeastward is 80 to 90 feet, but this decreases to an average height of 25 feet in the northwestern part of the area. Still farther northwestward, where red oak does not extend and the precipitation is only 22 to 23 inches, linden was found only on the side of the bluff, the north-facing slope, next to the river (Figs. 2 and 3).

FIG. 3. Forest of red oak *(Quercus borealis maxima)* and linden *(Tilia americana)* in southeastern Nebraska extending over hills and valleys several miles back from the Missouri River.

In the bur oak *(Quercus macrocarpa)* community, which occupied the tension zone between prairie or shrubs and the more mesophytic trees, the average height of the trees was reduced from 70 feet in southeastern Nebraska to 20 feet under a precipitation of 23 inches. The total number of upland, woody species of ecological importance was 62 in the southeast but only 31 in the northwest. The number of flood plain species was likewise reduced from 16 to 12 (Fig. 4).

Studies by Weaver, Hanson, and Aikman (1925) along certain streams flowing eastward into the Missouri River have added information regarding distribution of trees and communities of trees according to sites afforded by the stream and the ability of various species to tolerate adverse climatic conditions. For along these streams in prairie the balance between forest and grassland is so delicate that a little higher water content of soil, a slightly greater humidity, or protection from drying winds throws this balance in favor of tree growth, while the reverse conditions exclude it. Pioneer trees at the stream sources are those with light, windblown seeds, such as willows, cottonwood, elms, boxelder, and ash. Farther down stream, where a flood plain with portecting banks occurs, trees appear which spring from large rodent-carried fruits, such as black walnut *(Juglans nigra),* bur oak, and honey locust *(Gleditsia triacanthos).* At first the trees may occur in mixture—willows (*Salix amygdaloides, S. nigra,* and others), boxelder *(Acer negundo),* elms *(Ulmus americana* and *U. fulva),* walnut, oak, and hickory *(Carya cordiformis)*—all in the one undiversified habitat, the irregular flood plain. Still farther down stream, however, where the creek has deepened its channel and there is a lower flood plain subject to overflow, a higher flood plain or terrace, and sloping banks and bluffs, the trees are promptly grouped into definite communities. The intolerant willows largely disappear, boxelders clothe the lower flood plain; green and white ash (*Fraxinus pennsylvanica lanceolata* and *F. americana*), elms, and walnut cover the upper one; and oaks and hickories are found on the higher ground. Thus, a stream course cutting deep canyons has both the most diversified habitats and the largest number of communities of trees.

The more favorable climate for tree growth in southeastern Nebraska and eastern Kansas is indicated not only by the larger number of species present, but also by their greater development both in diameter and height (Fig. 5). Here they are found on hilltops as well as on hillsides and in the valleys. But as one travels westward, very soon the natural occurrence of trees is confined largely to flood plains, bluffs, and ravines. The decreasing precipitation

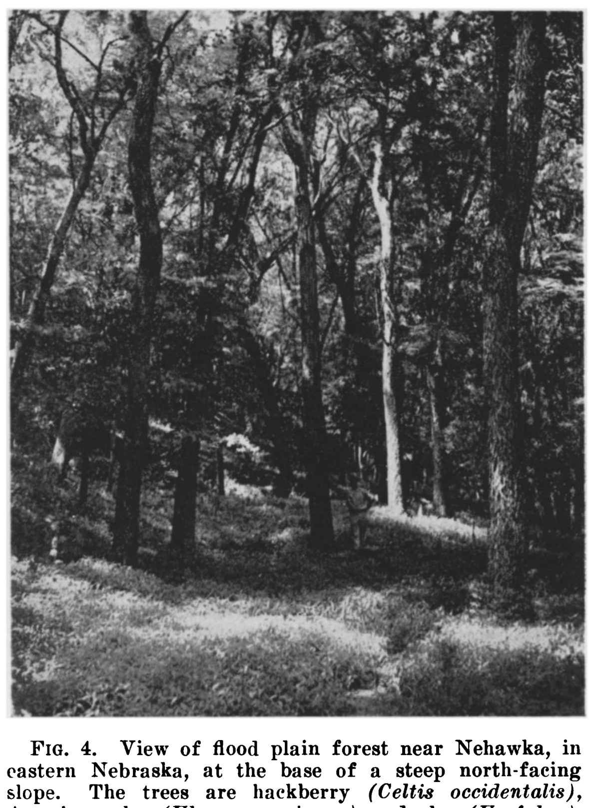

FIG. 4. View of flood plain forest near Nehawka, in eastern Nebraska, at the base of a steep north-facing slope. The trees are hackberry *(Celtis occidentalis),* American elm *(Ulmus americana),* red elm *(U. fulva),* green ash *(Fraxinus pennsylvanica lanceolata),* and Kentucky coffeetree *(Gymnocladus dioicus).* One very old hackberry, not shown here, was over 4.1 feet in diameter and 95 feet tall.

[1] Scientific names of trees and shrubs are according to Kelsey and Dayton, Standardized Plant Names; those of other plants Britton and Brown's Illustrated Flora.

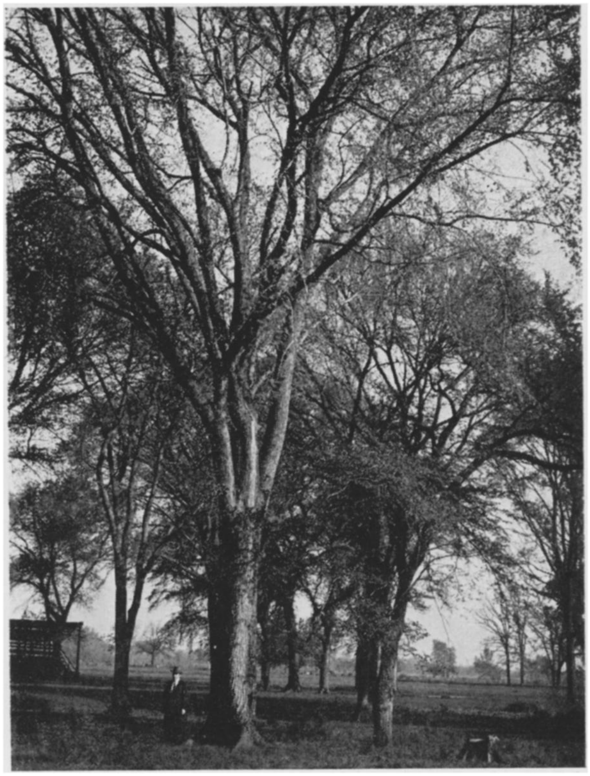

FIG. 5. American elm and other trees of a well developed flood plain community on the Big Nemaha River near Falls City, Nebraska. The tree in the foreground is 3.5 feet in diameter and 95 feet high.

westward, approximately an inch for each 25 miles along the eastern part of the Kansas-Nebraska border, and increasing evaporation are clearly recorded in rate of growth. The average rate of diameter growth of green ash on the flood plain of the Missouri River was found to be an inch in 3.1 years. On the upland the time interval increased to 5.2 years 40 miles westward, then to 6.8 years 55 miles farther west, and finally to 7.4 years 143 miles west of the first station. This decrease to one-half in rate of growth of ash was exceeded by that of the cottonwood *(Populus sargenti)*, which required only 1.1 years per inch diameter increment near the river but 3.4 years 143 miles westward (Aikman 1929).

FOREST COMMUNITIES AND TREES IN TRUE AND MIXED PRAIRIE

Only a few species of woody plants occur along the streams of central Nebraska and Kansas, and these are noticeably smaller in every way than those in the eastern portion of these states (Fig. 6). A height of 20 to 35 feet is common, and the deciduous trees are often confined to the lower banks of the streams. The lower branches usually occur only 5 to 10 feet above the soil, depending largely upon the degree of protection from winds. The drought-enduring deciduous species that grow in western Nebraska and Kansas are even fewer and smaller. They are restricted to some of the most protected sites and often occur as individuals rather than in groups (Fig. 7).

FIG. 6. Trees along the Saline River northwest of Hays, Kansas. The chief species are hackberry, American elm, green ash, and cottonwood *(Populus sargenti)*.

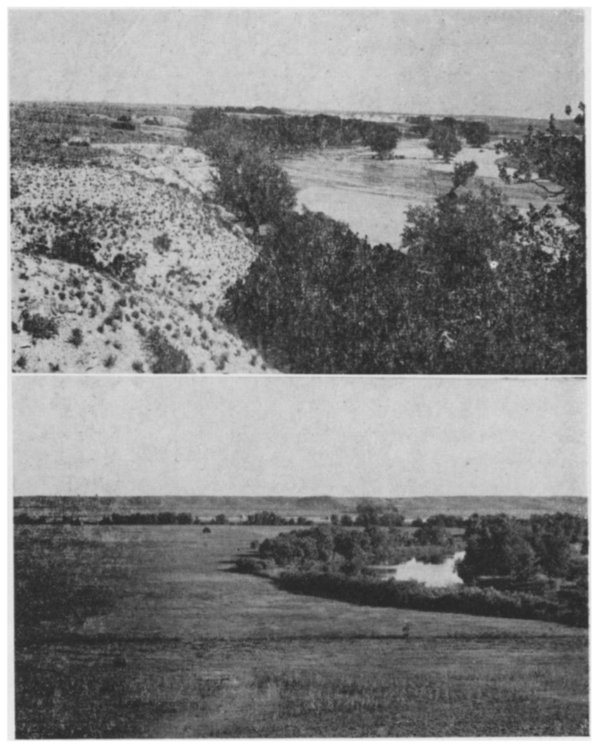

FIG. 7. (UPPER) Trees growing in the protection of a north-facing slope along the Saline River 16 miles northwest of Hays, August, 1941. (LOWER) View along the James River in eastern South Dakota showing the absence of trees except on the river banks.

A comparison of the forest communities and their structure in the eastern portion of the prairie climax with that of distribution of trees farther westward reveals striking differences. Distinct communities along the Missouri River in southeastern Nebraska, for example, extend westward for short distances over the uplands, but farther along the major streams.

An associes dominated by ash, elm, and cottonwood is typical of the flood plains. In fact, communities representing different stages in its development may be seen. Various willows, cottonwood, and boxelder represent an early stage, with sycamore *(Platanus occidentalis)* in local areas. Species of elm and ash, hackberry *(Celtis occidentalis),* and black walnut form a later one. Other common trees on well-developed flood plains are Kentucky coffeetree *(Gymnocladus dioicus),* black cherry *(Prunus serotina),* and much less frequently buckeye *(Aesculus glabra).*

Red oak and linden constitute the most mesic community; a rather constant component is the understory of ironwood *(Ostrya virginiana).* Here also are found black oak *(Quercus velutina),* yellow oak *(Q. muhlenbergi),* bur oak, shagbark hickory *(Carya ovata),* bitternut hickory, red and white elm, redbud *(Cercis canadensis),* and occasionally trees of several other species. Black oak and shagbark hickory form distinct though small communities in less mesic sites, often on upper slopes of hillsides above the community of red oak and linden.

The most xerophytic associes and consequently that of greatest extent is bur oak-bitternut hickory. The bur oak, which is by far the most important species, extends westward along the streams more than half way across Kansas and Nebraska, but to the Black Hills in the northwest. A score of other species of trees are found in these forests near the Missouri River, including some of all of the upland species previously mentioned but also red mulberry *(Morus rubra),* prairie crabapple *(Malus ioensis),* red cedar *(Juniperus virginiana),* hawthorn *(Crataegus mollis),* and honey locust. These, of course, may sometimes occur in the other communities as well.

Shrubs form a layer in these forests, the density of which varies with the amount of light reaching them through the canopy of trees. Where this is closed and dense many intolerant species fail to survive. Thus, in the deep shade of the red oak and linden forest there is no distinct layer of shrubs but only an occasional plant of prickly ash *(Zanthoxylum americanum),* wild black raspberry *(Rubus occidentalis),* or the twining honeysuckle *(Lonicera dioica),* and the climbing Virginia creeper *(Parthenocissus quinquefolia).* Mesic species of infrequent occurrence in these forest outposts are pawpaw *(Asimina triloba)* and redbud.

In the bur oak forest, especially, shrubs are abundant (Fig. 8). Here are found hazelnut *(Corylus americana),* prickly ash, buckthorn *(Rhamnus lanceolata),* raspberries (*Rubus strigosus* and *R. occidentalis*), dogwoods (*Cornus asperifolia* and *C. amomum*), and burning bush *(Euonymus atropurpureus).* Virginia creeper, wild grape *(Vitis vulpina),* bittersweet *(Celastrus scandens),* and poison ivy *(Toxicodendron radicans)* are the chief climbing vines. Gooseberry *(Ribes missouriense),* coralberry *(Symphoricarpos orbiculatus),* and the western snowberry *(S. occidentalis),* wild plum *(Prunus americana),* and smooth sumac *(Rhus glabra)* are very common.

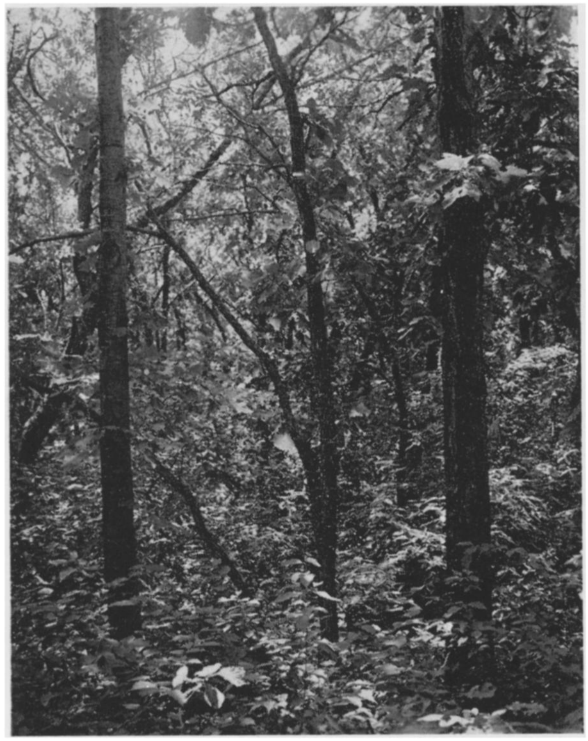

FIG. 8. Young oak-hickory forest on a hilltop in eastern Nebraska. Note the abundance of shrubs.

These shrubs extend outward to a considerable distance from the forest margins and the more xeric ones are found commonly even along small streams or in pockets in ravines. The wild plum forms thickets far from the woodland, smooth sumac behaves in a similar manner, and the species of Symphoricarpos are to be found where trees fail to grow.

The transition from these forests, with their layers of shrubs and woodland herbs and ground layer of mosses, lichens, and fungi, to the remnant of trees which occur farther westward is rather rapid. Most species soon reach their limits of tolerance to aridity, forest structure and community groupings gradually disappear, and size, rate of growth, and longevity of individuals all decrease as the environment becomes more and more unfavorable for trees. Finally they are found, if at all, only in small groups or as scattered individuals. Since the effects of drought on growth were studied most intensively in the western half of Kansas, distribution of the trees there will be described. Conditions there, however, are typically representative of the distribution of trees over vast areas of the dry mixed prairie, as those just described are in general representative of conditions of forests in the less arid true prairie eastward.

Native trees in western Kansas are mostly limited to banks of the larger streams and to broad, shallow ravines that are tributary to them (Fig. 9). They are mostly cottonwood and are widely spaced in the beds of moist intermittent streams. Scarcely any shrubs occur. Instead the soil beneath the trees is often occupied by grasses, mostly sand dropseed *(Sporobolus cryptandrus)*, blue grama *(Bouteloua gracilis)*, or buffalo grass *(Buchloe dactyloides)*. Where grasses were few or absent, sunflowers *(Helianthus annuus)*, lamb's quarters (*Chenopodium* spp.), Russian thistle *(Salsola pestifer)*, and other weeds often formed the lower story of vegetation. Usually no ponds from runoff water occurred, hence little storage of water resulted from dashing rains. Thus, sites favorable to the growth of trees were few.

FIG. 9. (UPPER) American elm and cottonwood in a broad, shallow ravine in a range 5 miles west of Phillipsburg, Kansas. (LOWER) Cottonwoods sparsely spaced in a shallow ravine north of Syracuse, Kansas, near the Kansas-Colorado state line. August, 1943.

Along sandy streams and rivers, as the Smoky Hill and Arkansas, woody plants are usually limited to a few species of trees and shrubs which grow in open stands. The trees, mostly cottonwood and willow, are usually restricted to small sandbars in the river bed, or to large bends where the stream flow is considerably retarded in times of high water (Fig. 10). Small clumps of shrubs, especially indigobush *(Amorpha fruticosa)* and sandbar willow *(Salix interior)*, are common but never abundant.

Streams that flowed continuously through areas of loam soil ("hard lands") maintained a supply of water for plant life; here the stands of trees and shrubs were not so sparse (Fig. 11). Even where the trees were located 8 to 12 feet above the water surface of the stream, their roots penetrated to the water table and were thereby able to secure enough moisture to survive even the most severe drought. Along such streams, trees and shrubs were found bordering both banks. Where a steep bank formed a north-facing slope the environment was even more mesic, as was indicated by the close cover of trees and shrubs. On the south-facing slopes the trees were fewer. Woody vegetation on the gentle slopes of the flood plains was usually limited to an open stand of trees and occasional clumps of the more xeric shrubs. The trees were frequently about equally divided in number among hackberry, American elm, and green ash. Also scattered sparsely among these were boxelder and cottonwood.

An understory of woody vegetation, composed mostly of coralberry, occurred on the gentle slopes. Wild grape, poison ivy, indigobush, and smooth sumac were common on steep north exposures. In fact, the shrubs often formed a fringe above the zone of trees near the upper part of the slopes. Farther upstream, which was also usually farther westward, the flow of water was intermittent and the stand of trees was distinctly more sparse. Here the cottonwoods formed a narrow, broken belt on each side of the stream. Occasional clumps of indigobush and wild plum also grew near the trees. Often no

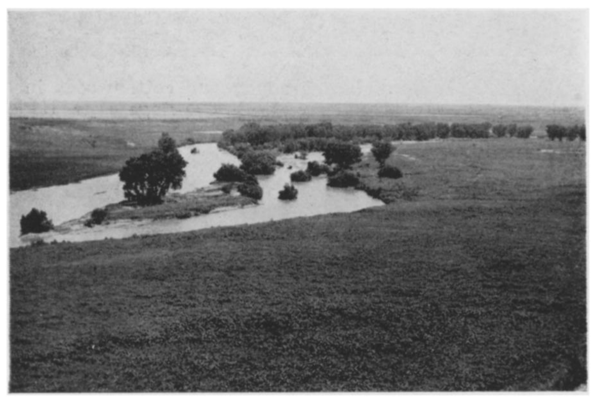

FIG. 10. Cottonwoods and willows along the sandy Smoky Hill River near Hays, Kansas. They are most abundant in the bends of the river where small flood plains have been built up. August, 1941.

FIG. 11. Trees confined to lower banks along Big Creek near Hays. Photo in late autumn.

trees occurred for long distances; the soil was clothed with tall grasses and weeds.

Springs that continued to flow throughout the drought supplied enough water in some places to form permanent ponds. Around these grew a luxuriant cover of woody vegetation (Fig. 12). The most abundant trees were cottonwood and willow. Shrubs were numerous. Those most common were the sandbar willow, indigobush, and snowberry.

Fig. 12. Willows (foreground) and cottonwoods in a marsh fed by continuously flowing springs near Hays. All the trees are alive. October, 1939.

Many of the streams of western Kansas had only an intermitten surface flow during the drought. Some of these ran through a sandy loam soil usually underlaid with strata of shales. The population of trees and shrubs along them became quite sparse since many of the roots were above the lowered water table. Their distribution was limited to occasional clumps in the most favored locations. Sometimes, however, moderately dense stands of trees extended for considerable distances, especially along north-facing slopes.

Trees and shrubs occurred at some distance from the stream bed where there were steep protecting slopes. On steep north-facing slopes with a mantle

Fig. 13. Native red cedars *(Juniperus virginiana)* growing on a limestone escarpment along Big Creek, 20 miles southeast of Hays. The deciduous trees along the stream have only sparse foliage, so severe was the drought. October, 1939.

of soil at their bases, trees frequently grew in abundance. In such sites red cedar often formed an important component of the woody vegetation (Fig. 13). The deciduous trees were usually American elm, hackberry, green ash, and boxelder.

In the heads of ravines often several miles from the streams conditions were quite xeric. But clumps of dwarfed hackberry and American elm were frequently found on the north-facing slopes (Fig. 14).

Fig. 14. Thin stand of dwarfed hackberry and American elm in a dry ravine near Hays. The sparse foliage is a result of the drought. October, 1939.

On the barren south-facing ones there was seldom more than an occasional small tree or clump of shrubs such as ill-scented sumac *(Rhus trilobata)*, New Jersey tea *(Ceanothus ovatus)*, or smooth sumac (Fig. 15).

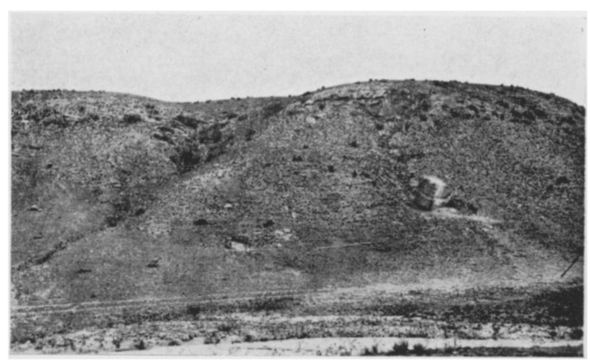

Fig. 15. Scattered plants of ill-scented sumac *(Rhus trilobata)* on a steep south-facing slope. Runoff was sufficient to remove nearly all the soil, leaving the underlying limestone exposed. October, 1939.

Where wide, shallow ravines extended to considerable distances from the main stream, water seldom flowed except for a brief period while carrying away the runoff from rains that fell on the adjacent watersheds. Here trees grew in clumps or were scattered thinly along the center of the ravines where their roots penetrated far into the black alluvial soil (Fig. 16). Hackberry, American elm, and ash were most commonly found with occasional occurrence of coralberry and snowberry on the gentle slopes. The steep north-facing slopes were often populated with a thin stand of ill-scented sumac, smooth sumac, and wild grape.

FIG. 16. Green ash, hackberry, and American elm in a broad, shallow ravine north of Stockton, Kansas. June, 1944.

VALUES OF TREES IN PRAIRIE

The greatest value of trees in prairie does not lie in financial returns from the utilization of the timber. Protection against the cold winds and drifting snow of winter and the hot drying winds during summer are of great importance to the welfare of the dwellers in the prairie. As stated by Shelford (1944): "After the eastern part of our continent had been occupied, there was a gradual shifting westward into the parkland areas which were characterized by groves of trees and trees along streams. There were rather large stretches of prairie between them in Illinois, and still larger stretches in Iowa and eastern Nebraska. The early settler avoided the prairies; at first in part for the reason that he thought they were not fertile because they were treeless. As his experience increased, there were added to this reason the menace of the prairie fires and the terror of winter storms."

Wood for the construction of buildings, for fences and for fuel, indispensable to the early settler, was to be found only along the streams. This scarcity of fuel was attested by the use of "cow chips," and the sturdy Kansas pioneer frequently obtained posts for fences by quarrying the rock from distant hillsides (Fig. 17). Also timber meant the proximity of water, and although permanent streams and continuously flowing springs were much more abundant than they are today, yet the problem of an adeqaute supply of water was an ever present one, at least farther westward. As settlements extended into the prairies, the pioneers soon planned to surround their homes with trees. This was encouraged by the Timber Culture Act of 1873. It resulted in the planting of many thousands of acres of trees in prairie, since a timber claim provided free title to an additional quarter section of land. Despite the fact that, for many reasons, most of this planting was futile, frequently such plantings did survive. Also thousands of groves were planted and nurtured by settlers bound by no legal obligations. They were planted solely because these homemakers appreciated the value of trees. Some of these planted groves still remain as living witnesses of the initiative and foresight of the prairie pioneers.

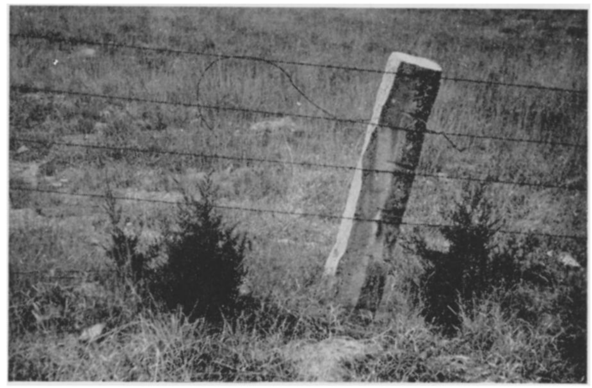

FIG. 17. Natural reproduction of red cedar along a fence in prairie where the seeds have been carried by birds. The post was hewn from the native rock.

The value of belts of trees in protecting crops from damage by desiccating winds is well known; such protection may result in increase in yields and at times avert crop failure. Protection of dwellings, farm buildings, and stock from wind and sun by suitably located trees adds immeasurably to the comfort of both man and his domestic animals. Protection to vegetable gardens, flower gardens, and orchards was afforded by trees, and in groups they were also very effective in preventing soil erosion. Many species of birds seek the shelter of trees and groves; they may forage widely for food and destroy many harmful insects, but return to trees for shelter, to build their nests and rear their young. Such shelter from the elements and their natural enemies is sometimes pitifully scarce. In remnants of a timber claim near Burlington, Colorado, flocks of mourning doves had nests at the rate of 6 to 8 per tree, some only a few feet above the ground (Fig. 18). Quail are usually found only where trees or shrubs are present in sufficient numbers to provide them protection and a home. Even such grassland birds as grouse and pheasants prefer the protection afforded by trees and shrubs to that of the herbaceous growth of the drier prairies. Other animals generally abundant eastward are in prairie found only where there is timber, particularly along the streams.

To the dweller of forests, the prairie pioneer, the landscape of the treeless grassland seemed extremely monotonous. There was an innate longing for the companionship of trees. His immediate ancestors were from the eastern deciduous forest, and theirs were from the forested continent of Europe. Man has always looked with awe and reverence upon a tree. It represents permanence—long periods of life, often the growth of centuries. Forest groves were man's first temples and were early used for religious rites

FIG. 18. Remains of a timber claim near Burlington, Colorado, in 1924. These ash trees are 37 years old, but only 3 to 4 inches in diameter and about 18 feet high. Note invasion of grasses, chiefly sand dropseed *(Sporobolus cryptandrus)*, in the foreground.

and ceremonies of various primitive peoples. Trees have always been a part of man's aesthetic and social life. The prairie pioneers used groves along the streams for places of recreation. Here the cool damp shade was indeed a welcome contrast to the sun and heat of the grassland. Picnics, religious gatherings, and political conventions were held under the protection of a dense growth of cottonwoods or the spreading canopy of the American elm. The recreational, aesthetic, and social values associated with groves and shade trees, though intangible, are nonetheless of high importance in the life of the individual. Trees lend a homelike and sheltered aspect. They beautify the environment and add to the happiness of man. A tree in a prairie landscape is a landmark in the distance, its growth is a measure of time, it is a part of the life of the community which everyone shares.

EARLY EFFECTS OF DROUGHT

The early effects of drought were so impressive and so widespread that numerous reports and statements are to be had. A summary of these early losses constitute therefore a more or less comprehensive review of the literature.

OBSERVATIONS IN 1934

Behavior of trees and shrubs during the severe drought in 1934 was studied along the valleys near Weeping Water in eastern Nebraska, where the prairie meets postclimax forest. Observations late in July showed that the leaves of smooth sumac had been wilting for many days. Rough-leaved dogwood *(Cornus asperifolia)* was also very much wilted, often beyond recovery. Many bushes of Missouri gooseberry were clothed with dead, yellow leaves, and the wild grape had grown into the sunlight only to have its foliage burned in the withering heat. Often the entire tops of black raspberry were dead. Beneath the shrubs were found groups of white avens *(Geum canadense)*, Solomon's seal *(Polygonatum biflorum)*, and other woodland herbs withered and often bleached white. The common chokecherry *(Prunus virginiana)* and sandbar willow *(Salix interior)* were frequently nearly defoliated and the tops of peach-leaved willow were often dry. The larger and better rooted older trees of these marginal forests were least affected.

The marginal postclimax forest at Weeping Water likewise bore the marks of severe drought. The water in the stream was very low and Cascade Creek, its main tributary, was dry. Even at a distance considerable damage could be detected among the crowns of the trees and closer examination showed that many individuals of most species had been injured.

On the flood plain the leaves of boxelder were wilted and dried, sometimes on the upper half or the unshaded portions of the trees only but often throughout their entirety. Various tree willows had suffered a similar fate (Fig. 19). Where soft maple occurred, nearly all the leaves were dried and discolored as by frost; similar injury was found in whole groves planted on uplands. The crowns of green ash were half dried and brown as a result of the scorching heat. Many trees of both American elm and red elm had wilted crowns. The scorched leaves did not turn brown or bleach white as did those of other species, but took on a bluish-gray color and soon fell to the ground. Black walnut was scarcely affected, perhaps as a result of its excellent root system, nor were trees of this species injured in even drier sites. Hackberry appeared to be in fair condition. Missouri gooseberry, elder *(Sambucus canadensis)*, and species of Symphoricarpos, all of the flood plains, were badly scorched, especially where they were exposed to direct insolation by clearing. Wild grape, poison ivy, and greenbrier *(Smilax hispida)* showed many dead or half-browned leaves. Under the trees many herbs, especially the wood nettle *(Urticastrum divaricatum)* and pale touch-me-not *(Impatiens pallida)*, appeared as if seared by a surface fire; sometimes a few uppermost green leaves persisted.

In the bordering belts of linden and red oak on steep north-facing slopes, one-third to one-half of the leaves of the shallowly rooted linden were brownish yellow and functionless; many had fallen to the ground (Fig. 20). The more deeply rooted red oak had shown as yet no permanent injury although the portions of the crown most exposed to the sun were wilted even in early morning. The severity of the drought was attested by the behavior of poison ivy. Long established vines, two inches in diameter, bore wilted leaves even in the shade in early morning, from the crown to the base of the tree. Virginia creeper had many leaves destroyed by drought. Where these lianas formed a ground layer, more dead than living foliage occurred. Wild grape often bore abundant ripening fruit, but the leaves were dead. Smooth-leaved honeysuckle and bittersweet were wilted. The mesic bladdernut *(Staphylea trifolia)* had both wilted and dead foliage. The black raspberry was killed back from the tips. The usual, rich ground layer of herbs was sadly depleted by the drought.

FIG. 19. (UPPER) Peach-leaved willows *(Salix amygdaloides)* on low ground with high water table near Lincoln, Nebraska. Note bluegrass *(Poa pratensis)* pasture in foreground. June, 1933. (LOWER) Same view showing death of willows and bluegrass by drought and replacement of bluegrass by rough pigweed *(Amaranthus retroflexus)* and other weeds. June, 1935.

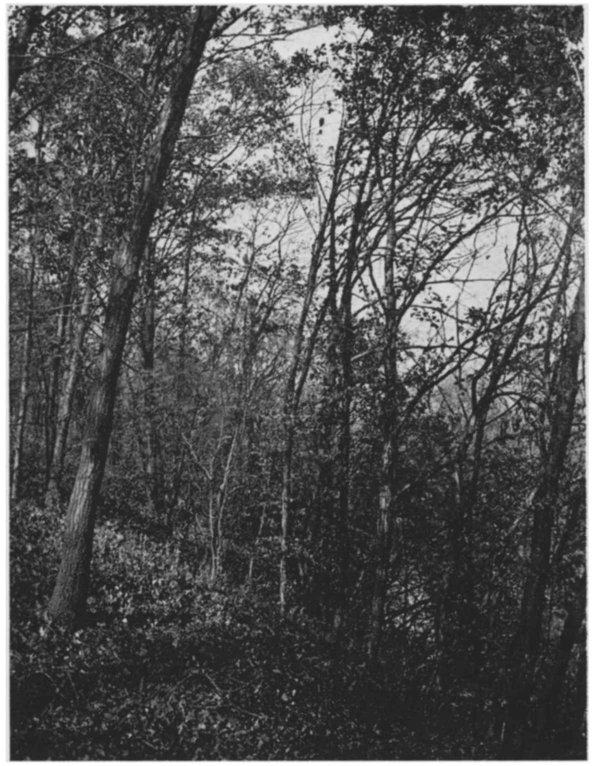

FIG. 20. Forest of red oak and linden on rocky north-facing slope on Cascade Creek near Weeping Water, Nebraska. Photo in spring before the drought.

Missouri gooseberry was half dead in the deep shade of this mesic forest type; rough-leaved dogwood was often wilted or the leaves dried; coralberry showed occasional injury. On the scattered growth of hazelnut the leaves were completely killed. The foliage of the rather dense layer of ironwood showed great drought injury both to seedlings and to well established trees. Sometimes the seedlings of the red oak and more often those of the linden were parched and burned.

In the bur oak forest that covered the upper slopes of the hills, often alternating with shrubs or grassland on the wind-swept tops, even greater drought prevailed. From a vantage point on a ridge, one could clearly see that many of the tops of the bur oaks had been badly scorched and that the leaves were dried. Often isolated trees or small groups withstood the drought best, partly because of their better developed root systems and especially because of the better circulation of the air about them, which reduced the high temperatures caused by the intense insolation. Where small openings occurred in the forest but general wind movement was retarded, scald injury to the bur oak often extended to the lowest branches. Scattered trees of wild black cherry with nearly all of the leaves burned were common. Elms were wilted or half defoliated in the oak forest. Intermixed trees of green ash, linden, ironwood, hawthorn, and other species were badly burned. The damage to red oak was less marked. In general it was in the tops of the crowns, which were under full insolation, that injury was most severe. Oak seedlings less than two feet tall were often damaged by the drought, but those more firmly rooted grew unharmed. Where seedlings two or more years old had invaded the adjoining grassland and made contacts with the soil below the roots of the grasses, they stood out prominently above the drying or dead bluestems and remained green until late fall.

The effect of heat was also often noted on the individual leaves. Where the cupped, drooping leaflets of sumac hung from the great horizontal midrib, for example, it was not the shaded tips that burned, despite their less advantageous relation to the water supply, but the arched bases which received the full impact of the sun. Thus, the basal half of the leaf was dead and the distal half still green.

The scattered undergrowth of Missouri gooseberry, prickly ash, and hazelnut on higher ground was as dry and brown as if subjected to heavy frost. In less xeric situations a few green leaves remained on the hazelnut, but everywhere they were at least half dried. In their contact with the dried bluestems of the native prairie, the new growth was only one-fourth or less of that indicated by the dead, fire-killed stems of the preceding year, and even this scanty foliage was as dry and crisp as that of the prairie grasses. Smooth sumac and coralberry had suffered much, but less than their more mesic chaparral co-dominants. Drought clearly revealed the relative mesic or xeric tendencies of the several species of shrubs. Frequently the green tops of sumac extended above the burned leaves in a hazelnut thicket, or the green foliage of coralberry contrasted with the withered leaves of rough-leaved dogwood or the dead ones of prickly ash. Of the main dominants the sequence as revealed by drought confirmed that of distribution, namely, sumac in the driest places as well as farthest from the forest borders, coralberry ranking second, followed by the rough-leaved dogwood. The more mesic hazelnut, which outshades them all, withstands less drought and pioneers closer to the forest border. Prickly ash succumbed to drought first of all.

By the end of August the effects of drought were even more severe in the Weeping Water forest. Many half-grown trees of boxelder were dead and all the leaves on older trees had dried. Drying of the crowns of green ash had progressed, and many trees of red elm and white elm were half defoliated. Neither black walnut nor hackberry showed much injury. Missouri gooseberry, coralberry, and snowberry were practically defoliated; many stems of the coralberry were dead. Both leaves and stems of elder had died. Wilted poison ivy still persisted. Herbaceous vegetation had practically disappeared and the ground was partially covered with leaves as after an early frost.

Although linden showed no increased injury, the fruits had dried without maturing. In the crowns of red oak growing on midslopes most of the leaves were half dried and on many trees they were entirely dry. Accompanying bur oak showed little or no drought injury nor did the red oak on lower slopes. Ironwood showed much more drying than formerly; it was not confined to the high crowns but occurred on all of the branches including those of saplings. This species looked as though it had been seared by the heat of a ground fire. On higher slopes especially, the dead stems were abundant. The ground was strewn with the dried leaves of this understory species and those of the two dominants. The undershrubs all showed severe wilting and many had succumbed. The dead, dried stems of hazelnut were easily broken. Losses of tree seedlings had increased.

Many trees of red oak on the hilltops and upper slopes were defoliated; some had died. On lower southwest slopes the foliage of the upper half of the trees was so badly burned that nearly all of the leaves were withered. Everywhere the foliage of the undergrowth of Missouri gooseberry and ironwood was completely dried and many plants were dead. Other shrubs, such as coralberry, snowberry, and smooth sumac, and most lianas had suffered a similar fate. Practically all herbaceous undergrowth had dried. But in pastures where competition was with bluegrass rather than bur oak, the coralberry, sumac, and hazelnut were still in fairly good condition.

Examination of the increment of wood laid down in the annual ring of 1934 showed that it was very narrow even in trees on the flood plain. It seldom exceeded one-third the width of that of 1933 and was sometimes only one-sixth as great.

Conditions similar to those at Weeping Water prevailed over much of eastern Nebraska and extended into the marginal forests of Iowa. Injury to shagbark hickory and various other trees was considerable. Westward the severity of drought increased. Woodlands bordering streams and planted groves in the western portion of the true prairie suffered the loss of many trees. Sometimes whole groves appeared dead, but the extent of the losses could not be accurately estimated until the end of another growing season (Fig. 21). Records of this terrible year of drought, the whole drought period, and the good years which followed, are to be found in the living survivors (Fig. 22).

FIG. 21. Drought-damaged trees of northern catalpa *(Catalpa speciosa)* bordering the west side of a large old grove of silver maple *(Acer saccharinum)*. The maples were all killed by the drought and removed for firewood. The few surviving trees are about 50 years old and 33 feet high. Photo near Elmwood in eastern Nebraska, September, 1943.

STUDIES IN THE NORTHERN PRAIRIES

As a result of the severe drought and hot winds which occurred during 1934 in western Minnesota, following a number of dry years, heavy damage occurred to shelter belts (Deters and Schmitz 1936). Losses had been heavy since 1932, but in 1934, in certain parts of the prairie region, it seemed that only a comparatively small number of plantations would survive. Five species, boxelder, willow, green ash, silver maple, and cottonwood (in order of their abundance), composed 90 percent of all the 28 species occurring in the shelterbelts. These also occurred commonly in or adjacent to the prairie region. A

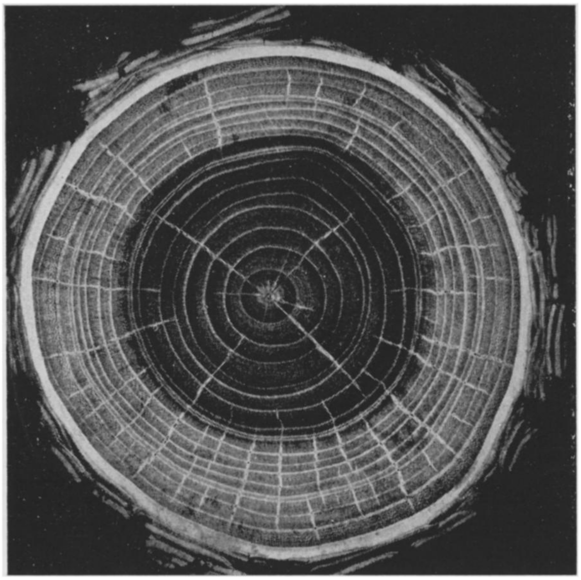

FIG. 22. Section of red elm growing on the south-facing slope of a rocky hillside near Weeping Water. The very narrow ring near the edge of the dark wood was put down during the extremely dry year, 1934. The next year was one of good rainfall as were also the years 1941 to 1943.

very extensive survey in 11 counties revealed that 25.5 percent of all the 28 species of trees examined were dead and that 14.5 percent had dead tops. Thus, 40 percent of all the trees were considered dead or dying at the end of the summer of 1934. Of the five chief species cottonwood suffered most (48 percent) and green ash least (8 percent).

Effects of the drought in North Dakota have been summarized for the writers by the Extension Forester, Mr. J. J. Zaylskie and Dr. C. B. Waldron from their field observations since 1936. "Practically all cottonwoods 30 years of age or older were killed during the drought, except in those places where there was a high water table. This is true also of boxelder; only in this case the trees died back to the ground and put forth sprouts, forming a rather dense hedge or undergrowth. Because of this new growth of the boxelder many persons have a decided liking for it. Willow has probably suffered greater losses even than the cottonwood, and can now be found only in those areas adjacent to streams, or where the water tables have been 3 to 5 feet underground. Many of the old windbreaks of cottonwood, willow, and some of boxelder have been almost entirely killed and now appear as white ghosts against the sky line. Much of these windbreaks was salvaged for fuel, posts, or rough timber. Still many millions of feet of rough lumber remains standing; but in most cases where the trees were not killed outright they have stagnated, the tops dying while the lower portions have straggly growths. Windbreaks and tree plantings in the Red River Valley did not suffer so severely during the drought years; but most plantings west of the valley were greatly damaged. In some counties at least 50 percent of the trees were killed during the period 1934-1936."

Ellison and Woolfolk (1937) state that the widespread drought of 1934 was the most severe in the recorded history of southeastern Montana. "In the summer of 1935 [near Miles City], yellowing foliage and dead individuals in many stands of pine and juniper attested the severity of the drought on upland trees, and 1934 diameter increments were, in the main, less than those of other years. In many stream bottoms tracts of cottonwoods had been injured and even killed. The heaviest losses of trees were on high ground where the original stand of trees and undershrubs was only half as dense as near the river. Previous dry years, especially 1931, have probably contributed to the damage." Much injury to woody plants was observed in stands of pine, juniper, cottonwood, sagebrush, and other species.

STUDIES IN THE CENTRAL PRAIRIES

Ramsey (1936) in discussing drought susceptibility of evergreens in Iowa, states that the history of windbreaks in that state began with the planting of quick-growing species of trees—cottonwoods, willows, boxelders, and silver maples—when the open prairie began to be dotted with farmsteads (Fig. 23). Since these short-lived deciduous trees failed to give adequate protection against winter winds, the farmers turned their attention to evergreen windbreaks. These were desired about farmsteads because of their ability to effectively check winter winds, and because they do not require so large an area as deciduous trees. Cooperative, experimental plantings of windbreaks were made in 1922. "Early in the spring of 1934 many observations of winter injury to evergreens were made, and reports came from all parts of the state of severe losses of both small and large trees." It was considered that evergreens are most subject to drought injury in winter. Losses by death were between 5 and 9 percent for ponderosa pine, white cedar, and Norway spruce, 10 percent for white pine,

FIG. 23. Cottonwood trees 2 to 2.5 feet in diameter in a pasture near Anita, Iowa. They died early in the drought. May, 1939.

20 for Scotch pine, and 39 percent for red pine. Red pine, Scotch pine, white pine, and white cedar showed percentage of drought damage of 6, 10, 15, and 29, respectively.

That the series of hot, dry seasons since 1930 has taken a heavy toll of both planted and natural timber in Kansas has been pointed out by Ware and Smith (1939). While in eastern Kansas only 5 percent of planted forest trees on farms were dead or had dead tops in 1936, in the central part 18 percent death and 23 percent injury was recorded. Trees in the western third of the state had suffered even more. Thirty-five percent had died and 20 percent had dead branches in their tops early in the drought. Examination of large numbers of planted trees on farms and rural school grounds throughout the state gave the following losses in percentages based on trees standing in 1936, not on the total number planted: red cedar and bur oak 1, Osage orange 8, American elm 10, black walnut 18, cottonwood 21, catalpa 25, hackberry 35, boxelder and black locust 36, mulberry 38, silver maple 46, green ash 53, and honey locust 54.

A survey of all the trees on 253 acres in Manhattan, Kansas, during the summer of 1934, showed that 20 percent were dead or dying, and an additional 30 percent were definitely injured as a result of the drought and heat. In the parts of the city containing natural or wild areas, 24 percent of the trees were dead or nearly dead, and only 47.5 percent were apparently still sound (Stiles and Melchers 1935).

In northwestern Nebraska, trees, shrubs, and a relict herbaceous flora meet in postclimax communities in the river valleys. Tolstead (1942) pointed out that "the deciduous trees [principally American elm, green ash, red ash, boxelder, hackberry, and cottonwood] grow in well aerated soils where moisture is available from a stable water table throughout the year (Fig. 24). Woodlands are common in the deep canyons and immediately along the streams, but the broad river valleys are usually occupied by scattered groves of trees alternating with chaparral and tallgrass meadow. The ecotone between the deciduous woods and the mixed prairie on the hillsides is narrow because of marked changes in depths to the water table. . . . Ponderosa pines grow . . . on rough stony land where run-in water is received from rock surfaces and where snow lodges during the winter. They are located well above the water table and must withstand varying periods of drought. Seedlings do not become established on broad, gentle slopes because the grasses are better equipped to obtain the available moisture. . . . Because deciduous trees are able to grow only where their roots have access to a permanent water table, there was little loss from drought. Ponderosa pine is especially resistant to drought, and only rarely were trees killed. But in a few dry canyons, which did not have a favorable water supply, mortality of the chaparral was as great as 85 to 95 percent."

FIG. 24. View from Chadron State Park in northwestern Nebraska, showing ponderosa pine *(Pinus ponderosa)* growing on the stony uplands and deciduous trees in the valley where there is a stable water table throughout the year. Photo by W. L. Tolstead in 1940.

STUDIES IN OKLAHOMA

Working in central Oklahoma, Harper (1940) states that severe drought during the years 1932-40 destroyed 20 to 50 percent of the trees in some areas of shallow upland soils where a xerophytic type of forest was growing or on bottomland soils containing a high percentage of clay where a mesophytic type of trees had developed.

Survival of trees that were alive at the beginning of drought in old shelterbelts in territory surrounding Goodwell, Oklahoma, was reported in 1938 by Bunger and Thomson. In order to obtain data in all habitats in which trees must live in that area, studies were made of shelterbelts on both shallow and deep soils, in cultivated and uncultivated areas, and in both moist and dry sites. By 1937 losses of red cedar were only 13 percent and those of Osage orange 35 percent. Honey locust lost 55 percent, ash 75, and black walnut 79 percent even this early in the drought. Only older, well established trees were studied, but trees in this region are very short-lived and at the age of 30 years appear to be mature.

LOSSES IN GENERAL

A rapid reconnaissance of tree plantations in a wide territory within which the shelterbelt zone was to be marked out, was conducted by Kaylor, Starring, and Ditman (1935) in the autumn of 1934. The percentage survival of trees, where survival is the proportion of living trees to the total number of trees found in the groves when examined and not the number originally planted, is shown in Table 1. These surveys were made in a strip 2 miles wide and extended from east to west almost across Kansas and Nebraska except for the width of two or three of the most easterly counties. In the Dakotas they began at the eastern boundary but did not extend so far westward; the southern strip extended westward from central Oklahoma into the panhandle of Texas. Results are shown in Table 1.

TABLE 1. Average survival of principal species examined in plantings.

Species	Groves in which occurring	Average Survival: In groves under 30 years old	In groves over 30 years old	In all groves
	Number	*Percent*	*Percent*	*Percent*
Green ash	635	48.5	20.4	29.5
Cottonwood	459	34.0	24.5	27.1
Boxelder	456	36.1	20.2	25.2
Mulberry	403	25.6	12.9	17.4
American elm	223	38.0	20.1	30.2
Black locust	208	20.8	23.3	21.9
Catalpa	127	26.6	9.7	20.1
Eastern red cedar	93	94.9	92.4	93.2

Survival by states was: North Dakota 43.1 percent, South Dakota 31.8, Nebraska 17.8, Oklahoma-Texas 28.4. Data for Kansas were not given. They found:

"The average heights of trees over 30 years in age of certain key species—those which usually give character to the groves—are as follows: cottonwood, 50 feet; American elm, 27 feet; green ash, 26 feet; black locust, 26 feet; and eastern red cedar, 17 feet. These values represent a general average for the region.

"Drought is undoubtedly of primary importance as a factor of damage and also as a test of the ability of individual species planted in shelterbelts to survive. During and after 1931, moisture conditions for plant life in the prairie-plains region became increasingly acute, and the summer of 1934 provided a devastating climax to the dry period.

"Although considerable losses had been reported before 1931, the majority of the shelterbelts seemed to have held their own fairly well despite moisture shortage, sleet, rodents, grazing, and insects. But the parching winds and searing temperatures of the last three years proved to be more than many of the trees could withstand" (Fig. 25).

THE CHANGING ENVIRONMENT

The prairie environment varies from semihumid near the deciduous forest to semiarid in the west. The region under consideration (from central Iowa westward) is, in general, characterized by relatively low annual precipitation occurring mostly during summer, frequent droughts (especially westward from the Iowa-Nebraska state line), and great range in extremes of temperature. Humidity is relatively low, and much wind, sometimes hot and desiccating and often of comparatively high velocities, occurs. Winds blow with considerable regularity over the level or undulating prairie landscape, and rate of evaporation is high in comparison with the amount of precipitation.

PRECIPITATION

Low precipitation in the Midwest is serious for trees not only because of the relatively small amounts but especially because of its erratic distribution. This applies not only to dry cycles but also to periods of drought during years of normal precipitation. Moreover, rainfall, especially in mixed prairie, is usually followed by clear, hot days and high wind movement, both of which promote rapid drying of the soil and high rates of transpiration.

A comparison of the distribution of the mean annual precipitation in true and mixed prairie before the great drought is pertinent to an understanding of the decreased natural distribution of trees west-

FIG. 25. (UPPER) Tree claim 8 miles northwest of Hays. Many of the green ash and a few honey locust *(Gleditsia triacanthos)* are still alive, but the Osage orange *(Maclura pomifera)* and American elm are nearly all dead. September 19, 1939. (LOWER) Tree claim of Osage orange 4 miles southwest of Hays, October, 1939. All of the trees died early in the drought.

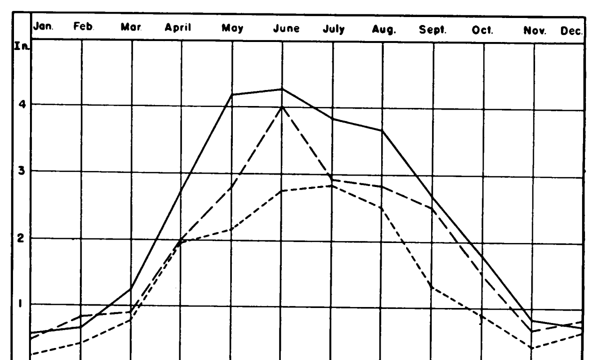

FIG. 26. Graphs showing the distribution of the mean annual precipitation in inches at Lincoln, Neb. (unbroken line), Phillipsburg, Kan. (long broken lines), and Burlington, Colo. (short broken lines).

ward. The data are from Lincoln in true prairie in eastern Nebraska, and from Phillipsburg (60 miles north of Hays) in mixed prairie in north central Kansas, and Burlington in eastern Colorado (Weaver 1924) (Fig. 26).

Casual examination of Figure 26 shows that most of the moisture falls during the growing season and only about one-tenth during the three winter months. Mean annual precipitation at the three stations from east to west is 28, 23, and 17 inches, respectively. The normal decrease of 5 inches at Phillipsburg from that at Lincoln, as well as the further decrease of 6 inches at Burlington, is quite evenly distributed throughout the year. The type of rainfall is quite similar throughout, consisting usually of heavy showers, often of short duration. This, however, is more marked in mixed prairie than in true prairie where the rains are more general. Westward, relatively more of the precipitation falls in light showers of 0.20 inch or less, which are of little or no value in increasing water content of soil.

Normal precipitation for the states of Kansas and Nebraska and the annual precipitation for the several years before, during, and after the drought are shown in Figure 27. The normal precipitation is that calculated for 1930; it is somewhat lower now because of the drought years. That the annual precipitation for Kansas was higher every year than that for Nebraska is due to two causes. Kansas extends somewhat farther east and not nearly so far westward as Nebraska, and precipitation here increases somewhat southward along a meridian. It may be noted that a period of dry years preceded the severe drought. Precipitation was lowest in 1934 and 1936, but because of previous desiccation of soil and vegetation 1939 was also one of the worst of the drought years. Any recovery of vegetation, herbaceous or arboreal, during 1935 and 1938—and there was considerable—was usually of little significance because of the following extremely dry years.

After the second year of extreme drought, the cover of grassland was greatly reduced and windblown dust effectively prevented rapid infiltration of water into the bared soil. Consequently, following showers much of the water rushed down the slopes into the streams where it was carried away rapidly (Fig. 28). Erratic distribution of precipitation, always a hindrance in this region to a continuous supply of available water, was very pronounced during the dry cycle. For example, in 1935 at Hays, Kansas, a rainy period of seven weeks duration in spring was followed by one of equal length during which there was scarcely any rainfall.

SOIL MOISTURE

Low available water content of soil occurs even during good years in true prairie. In mixed prairie water becomes nonavailable for plant growth at various depths during summer drought. The following conditions which prevailed in soils of silt loam texture during three years of almost normal precipitation are representative. Throughout the growing season of 1920 at Lincoln sufficient water was available at all depths to promote good growth. In the mixed prairie at Phillipsburg, July and early August were periods of soil drought and, at times, of actual deficiency of available water. At Burlington water content was favorable until June, but thereafter marked deficiencies were of frequent occurrence.

In 1921 an available supply of 5 percent moisture and usually 8 to 10 existed at all times and at all depths to 4 feet. At Phillipsburg water available for growth was almost exhausted once in July and twice in August; no water was available to a depth of 4 feet late in August. Conditions at Burlington were, as usual, much worse. At no time was water available in the third or fourth foot, while after June 30

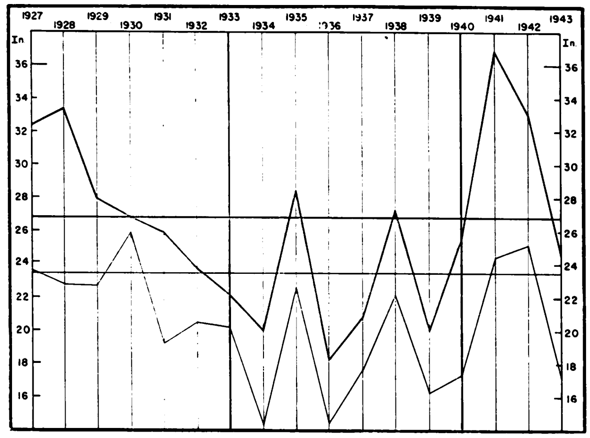

FIG. 27. Annual precipitation for Kansas (upper graph) from 1927 to 1943 inclusive, and normal precipitation (26.87 in.), heavy horizontal line. Annual precipitation for Nebraska (lower graph), and normal precipitation (23.50 in.), light horizontal line. The years of most severe drought lie between the heavy vertical lines.

FIG. 28. A stream near Hill City, Kansas, which formerly flowed continuously as a clear brook with many stretches where the water was held in deep pools. Since the occurrence of overgrazing, cultivation, and drought, torrents of water first washed the channel deep and then partially filled it with alluvial soil. The water table was lowered several feet and even during good years this stream is now only intermittent.

it was depleted repeatedly in the first and second foot.

In 1922 at Lincoln, notwithstanding a late summer drought, a margin of at least 5 percent of available water was found at all depths of sampling. A period when little or no water was available in the prairie soil occurred at Phillipsburg in June, and this condition was nearly constant from the middle of July until autumn. Rather continuous soil drought prevailed at Burlington after the middle of June, broken only occasionally by available moisture in the surface soil.

A continuous weekly record of available water content of soil in upland prairie has been obtained since 1918 at Lincoln and since 1933 at Hays. Complete data during the growing season for the years just before, during, and following the drought have only recently been published (Albertson & Weaver 1942, Weaver & Albertson 1944). Hence, only a general summary of conditions need be given here. At Lincoln there was water available for growth at all depths to 4 feet in 1932 and nearly always 5 to 10 percent was available. Similar conditions prevailed in 1933, except that percentages of available moisture were less. Although there was a good supply of soil moisture in the spring of 1934 it was gradually depleted, and by July 30 no water to a depth of 4 feet was available for growth, and less than 2 percent to 6 feet depth. Very similar conditions prevailed through August, and only the surface foot of soil was moist until April of the next year. Available water in 1935 was moderate in amount, and low after midsummer, but no serious deficiency occurred. But in 1936 available water below 2 feet rarely exceeded 2 percent. Water in the first 2 feet became exhausted in June and remained unreplenished until fall. In early fall no water was available at any depth to 5 feet. While there was 5 to 10 percent of water continuously available at 4 to 6 feet in 1937, the amount in the 2 to 4 foot depth was small, and at 1 to 2 feet usually less than 2 percent. No available water occurred in the surface foot late in August or early in September. The next year was one of abundant soil moisture at all depths to 6 feet, with only one dry period, in August. Dry periods, when the surface 6 inches of soil had no available water and the second 6 inches and the second foot had but little, occurred in May and August of 1939. During a very severe drought late in June and July of 1940, all available water was exhausted in the first and second foot and the amount in the deeper soil to 5 feet was reduced to less than 2 percent. But in 1941 to 1943, inclusive, water for plant growth was available at all times and at all depths to at least 6 feet, and it often occurred in large amounts.

At Hays there was about 2 percent residual water available to plants at certain depths below 2 feet in 1933, but none thereafter until 1941.[2] In the second foot of soil, water was nonavailable after the first week in June, 1933, and remained continuously unavailable except for two weeks in June, 1934, and during the entire month in 1935. From 1936 to 1940, inclusive, except for the last two weeks in July, 1940, the second foot of soil had no water available for plant growth. Even water in the surface foot was depleted to an amount nonavailable for growth during three two-week periods in 1933, one period of four weeks in 1934, and one seven-week interval in 1935. Three separate weeks without available water in 1937, two periods (one of five weeks and two of two weeks) in 1938, two periods each of two weeks duration and one in midsummer of four weeks, completed the record of the first foot until 1940. But even in that year of more than normal precipitation four separate weeks without available water in the surface soil occurred. Since nearly all these periods of deficient water in the surface foot occurred when water was also nonavailable at any depth to 5 feet, the prairie plants succumbed or became dormant. But the heavy precipitation in 1941 and especially in 1942 again wet the soil to a depth of at least 5 feet. In 1943 precipitation was low and the soil again became dry.

While these data are from upland soil covered, at least before drought, with prairie vegetation, they are probably fairly representative of conditions in old tree claims and windbreaks planted on similar upland soil. The supply of soil water on the hillsides underlaid with limestone varied greatly. For example, repeated measurements of soil moisture in the first 24 inches above the limestone at Hays indicated that the supply became deficient late in June, 1933, and continued thus in the summer months during the worst years of drought. Samples of soil were also obtained from clay pockets and crevices running vertically through the limestone strata from 3 to 8 feet beneath the soil surface. The clay in these pockets had a high water content and the presence of myriads of roots indicated that during intense drought it was from here that much of the moisture was obtained.

Lowering of the Water Table

The low precipitation during drought did not recharge the ground water normally, and the adjustment of underflow together with discharge by transpiration, evaporation, and seepage to streams lowered the water table considerably in places (Condra 1944). The water table in many ravines and lowland terraces (first and second bottoms) fell 3 to 4 feet during the long period of drought (1933-1941) not only in Nebraska but also over much of the Midwest. In some instances it was even greater. With the lowering of the water table many streams stopped flowing. Lateral seepage often became less and the drying up of springs was common under the low rainfall. The movement of the water table beneath uplands, of course, is much slower and was measured only in tenths of inches. Where it is many feet below the soil surface it has no effect upon the growth of trees, since their roots extend downward only a relatively short distance.

[2] Cracks and fissures, often concealed at the surface, frequently occurred in the thoroughly dried soils and permitted runoff water to enter and moisten the soil deeply in some places, but not generally.

Temperature

The high temperatures accompanying drought may be seen by an examination of Figure 29, where data from both Lincoln and Hays are shown. The year 1930 was selected as one with approximately normal predrought temperatures. Its temperatures are compared with those of the extremely dry year 1934. At Lincoln, increases above 1930 of 6° to 16.5° F. in mean temperatures were common until the middle of June, after which increases of 2° to 12° often occurred. During only three weeks were the mean temperatures lower than in 1930. Here also mean maximum temperatures were regularly 7° to 20.5° higher in early summer, and mean maximum temperatures of 101° to 107° occurred during three weeks in midsummer.

At Hays increases of 10° to 14° in mean weekly temperatures above those of 1930 were common until the middle of June, and 2° to 10.5° thereafter, except during three weeks when the mean temperatures were slightly lower than in 1930. The second week in July had a mean temperature of 92°. Except during four weeks, increases of 11° to 18° in mean maximum temperatures were common until late in July and August. The highest weekly maximum was 109.8°, and during five other weeks the mean maximum temperatures ranged between 101° and 107°.

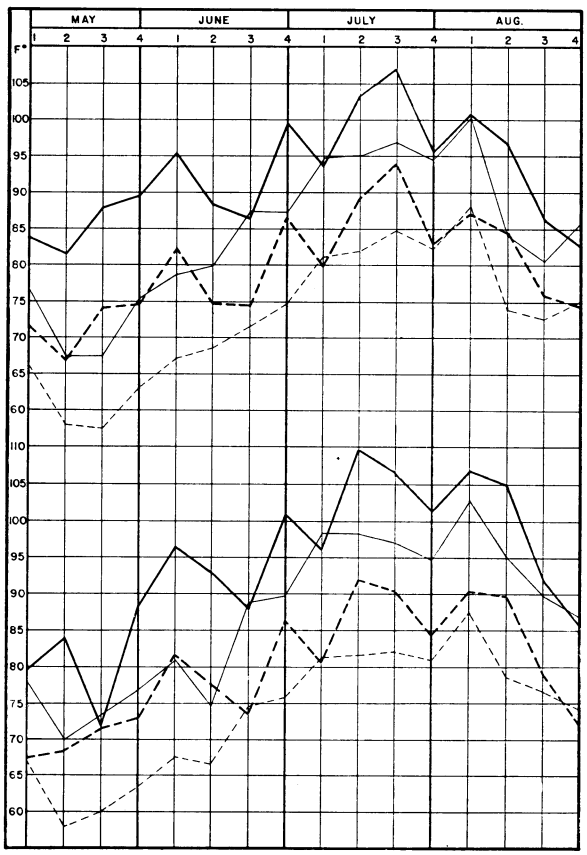

Fig. 29. Average temperatures by weeks at Lincoln, Neb. (upper) and Hays, Kan. (lower) during a predrought year (1930), and one of severe drought (1934). Mean daily temperatures in 1930 are shown by light broken lines and in 1934 by heavy broken lines. Mean maximum temperatures in 1930 are shown by light unbroken lines and in 1934 by heavy unbroken lines.

Evaporation

Losses of water from Livingston's non-absorbing, cylindrical, porous cup atmometers are shown for the season 1920 in Figure 30. The data are representative for 1921 and 1922 also, since similar constant differences in the rates of water loss were ascertained. Evaporation was greatest throughout the season at Burlington (23 to 57 cc. average daily losses), intermediate at Phillipsburg (12 to 32 cc.), and least at Lincoln (9 to 25 cc.).

Amounts of evaporation in inches from a free water surface during the growing seasons of 1930 and 1934 are shown for Lincoln and Hays in Figure 31. Even casual examination reveals the very much higher monthly evaporation rates during the dry year. Sometimes they were one-third or more greater than during the predrought year. Extremely high losses occurred during June, July, and August. Unfortunately, evaporation at the two stations cannot be

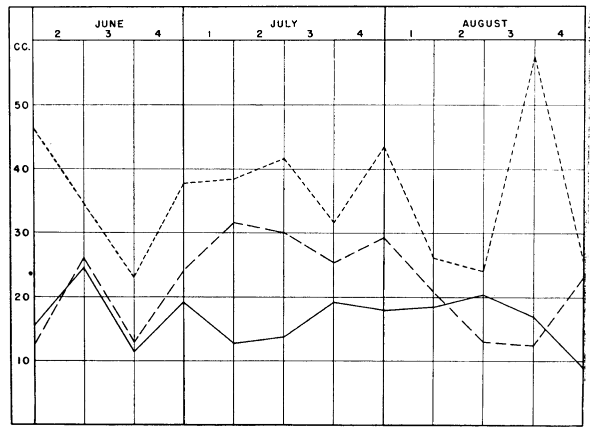

Fig. 30. Average daily evaporation by weeks at Burlington, Colo. (short broken lines), Phillipsburg, Kan. (long broken lines), and Lincoln, Neb. (unbroken line), in 1920.

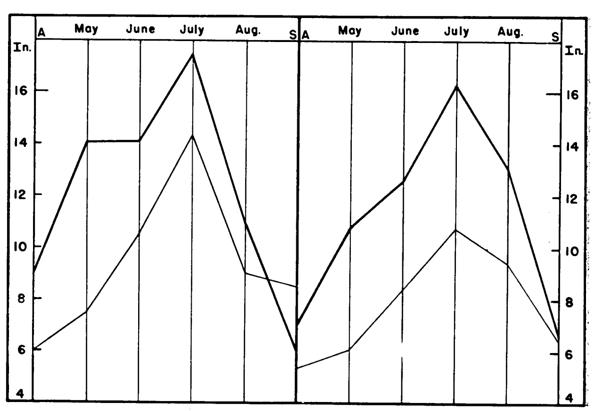

Fig. 31. Evaporation in inches from a free water surface at Lincoln, Neb. (left) and Hays, Kan. (right) in 1930 before the drought (light line) and during the severe drought of 1934 (heavy line).

compared, since data for both years at Lincoln were obtained from the regular Weather Bureau tank exposed 14 inches above the soil surface, and that from Hays from a much larger tank with exposed water surface 2 inches above that of the soil. Data comparable with those at Lincoln (or the reverse) were not obtainable for both years.

In addition to recurrent adverse environmental conditions, trees in prairie are subjected to injury by many kinds of insects, rodents, and other harmful organisms. These were formerly considered as environmental factors, but such activities are best understood as coactions (Fig. 32).

FIG. 32. Coaction between jackrabbits and young honey locusts at Hays. Russian thistles lodged about the trees in this windbreak and caused the snow to drift. When other food was scarce, jackrabbits ate the bark (note white patches of sapwood) and thus caused the death of the trees.

CAUSES AND NATURE OF INJURY

A report has been made by Hursh and Haasis (1931) on the effect of a drought of extraordinary severity in the southern Appalachian region during the summer of 1925. The deficiency of the precipitation was expressed by early browning and premature leaf fall. Most of the trees on good sites apparently recovered completely the following year. On upper slopes and on shallow or rocky soils some trees were severely injured or killed either directly or subsequently through secondary agencies. Partially killed crowns, resulting in stagheaded trees, were of common occurrence on shallow soils. Four years after the drought all trees that had maintained normal foliage during this dry period showed no evidence of injury. About half of the trees showing definite drought injury completely recovered. The remainder sustained injury in the form of dead branches in the crown or were killed by drought or by secondary causes.

Although young trees, even on prairie uplands, may not be retarded in their growth by moisture deficiency during years of good precipitation, trees reach maturity rapidly when the quantity of available moisture in the soil is restricted. After a period of only 20 to 30 years the vigor of most trees in open mixed-prairie sites begins to decline. Such a condition, even without drought, provides a favorable environment for the invasion of insects and disease-producing organisms. Within 50 years the average planted grove in the mixed prairie will disappear, since here reproduction from stumps or seedlings only rarely occurs.

Unrestricted grazing was found by Kaylor et al. (1935) to be one of the commonest causes of excessive mortality in old timber claims and windbreaks. In nearly all of them there had been grazing at some time or other during the life of the trees. Some were kept free of livestock until the beginning of the drought, when scarcity of regular feed and the necessity for shelter from the terrible heat forced the farmer to open his groves to the stock. This resulted in much trampling and the resultant unfavorable conditions for water absorption. The roots of trees were often exposed, and any seedlings, saplings, or sprouts were eaten, as well as the lower branches of the trees. It has been pointed out by McComb and Loomis (1944) that in western Iowa bur oak in the original prairie on loess soil showed no injury even on severely exposed sites during drought, but heavily pastured bur oak was killed or severely injured. American elm was killed and bur oak injured on a moderately pastured north slope, but no signs of injury were evident in unpastured reproduction on the south slope of the same hill.

The evil effects of grazing wooded areas has only recently begun to be at all fully understood (Day & Den Uyl 1932, Den Uyl, Diller, & Day 1938, and Dambach 1944). Any damage to trees by livestock, jackrabbits, insects, fungi, or other causes makes them more susceptible to injury by severe drought.

Relatively little is known concerning the drought resistance of different species of trees, or of the same species at different ages, except such information as has been obtained empirically by observing whether or not certain trees will survive in a given climate. Shirley (1934) and Shirley and Meuli (1939) have experimented with a desiccating chamber which maintained nearly a constant saturation deficit. Potted seedlings of trees of several species were subjected to desiccation, and relative drought resistance judged by the length of time the trees survived and the water content of soil at death. In nature several factors are involved. A chief one of these in the Midwest is the competition of the tree seedlings with grass. Such competition affects the growth of both roots and tops and results in high mortality of the trees. Root competition for available soil moisture and soil nutrients as well exerts a profound effect upon establishment, survival, and growth of trees, as has been shown by experiments in the prairie near Lincoln, Nebraska.

EFFECTS OF COMPETITION OF GRASSES

For sustained growth, trees require relatively large amounts of water. In a dry prairie climate they grow naturally on alluvial and terrace lands along streams and on stream banks, and in portected places in rough uplands. These are all places which from time to time are laid bare or have been bared by running water or at least where the prairie grasses cannot invade or where their hold has been broken by natural causes. The establishment of seedlings in upland prairie is extremely difficult because of competition with the grasses for water. On lowland they are shaded by the tall grasses so completely that death usually ensues. These are conclusions not only from observations but from several years of experimentation (Clements, Weaver, & Hanson 1929).

The success of the tree plantations in the prairie has led to the assumption that even the true prairie owes its persistence to fire and that the climatic relations are not controlling. The fact is overlooked that such groves have been artificially aided in a number of ways, such as the destruction of the grass cover, the use of clean tillage or mulches, or actual watering, and the employment of young trees tall enough to escape overshading. In short, the most critical time in the whole process, that of germination and establishment, is avoided by the use of transplants, while the physical factors and competitive relations are profoundly modified to the advantage of the trees.

In extensive experimental work on competition of seedling trees with grasses, seedlings of soft maple *(Acer saccharinum),* honey locust, American elm, boxelder, and green ash were grown under four degrees of competition. Four long parallel trenches 4 inches wide and 4 inches deep were made in prairie on low, level land by removing the native sod. They were filled with loose prairie soil free from roots and the seed sown, water being added from time to time to insure germination and establishment. Four degrees of competition were obtained as follows:

1. In the first trench, the sod was overturned to a depth of 4 inches to a distance of 6 inches on either side, and was then thoroughly pulverized to constitute a mulch. Frequent shallow hoeing kept this area free from all vegetation during the following seasons. The overhanging grasses along the edges were kept clipped to insure good lighting and thus confine the competition to the soil.
2. The grass along the second trench was kept clipped to the ground to a distance of 6 inches on both sides. There was practically no competition for light, the demands of the clipped cover for water and nutrients were moderate, and the corresponding competition was not severe.
3. Along the third trench the grasses were watered rather freely from time to time during the first year, and especially in periods of drought. They were not trampled and since sufficient water was present at all times, the competition in this row was chiefly for light and to some extent for nutrients.
4. Trees in the fourth trench were flanked by the grasses of the prairie and were entirely unaided in competition with them.

As a whole, the mortality among the trees increased with the degree of competition. Figure 33 is representative of the relative development; watering caused the grasses to grow more vigorously, with the consequence that the trees received even less light than in the unaided row. Some deaths occurred each year. At the end of the third year the average loss of all trees in the mulched row was 31 percent, in the clipped 62, while it was 79 and 92 percent, respectively, in the watered and unaided rows.

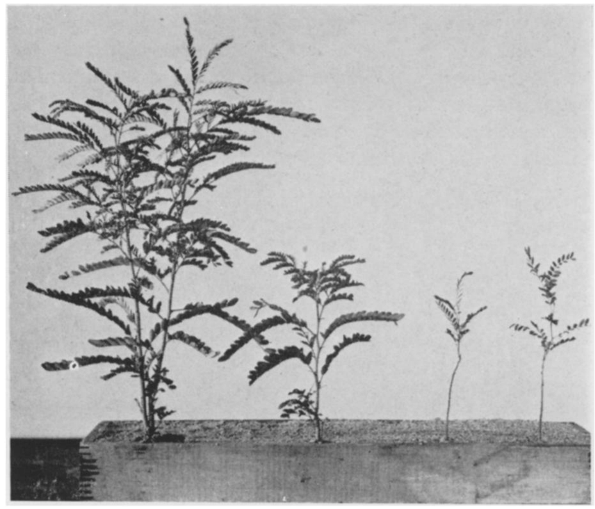

FIG. 33. Representative year-old seedlings of honey locust grown in mulched (left), clipped, watered, and unaided (right) rows. Explanation in text.

Development of the root systems in the third year was directly in proportion to the tops. Depth of the taproot of honey locust after three years was 6.5 feet in the mulched row, 5 feet in the clipped, 1.7 feet in the unaided and watered rows. Branching was profuse in the surface 2 feet, 1 foot, and 0.5 foot of soil in the above sequence. Average lateral spread from the taproot of a great mass of fine roots (nearly all up and down the row) was 4.5, 2.5, and 0.5 feet, respectively.

Results of these studies are in accord with later studies on windbreaks which showed that cultivation of the soil in the arid prairie climate until a complete crown cover was established had a decidedly beneficial effect by reducing the competition from grasses and weeds (George 1943).

Further evidence that competition with grasses is very effective in retarding the development of trees has been obtained by Pearson (1934, 1936, 1942). These studies show conclusively that dominance of grasses retards and may prevent regeneration of forest trees. The fine network of absorbing roots of trees may be quite as dense as that of grasses (Fig. 34).

ROOT DISTRIBUTION IN RELATION TO DROUGHT RESISTANCE

The nature and adaptability of the root system of trees in a manner to obtain the greatest possible amount of soil moisture is a fundamental concept in a study of drought. In an investigation of the invasion of prairie by forest, Weaver and Kramer (1932) pointed out that the invasion of trees into

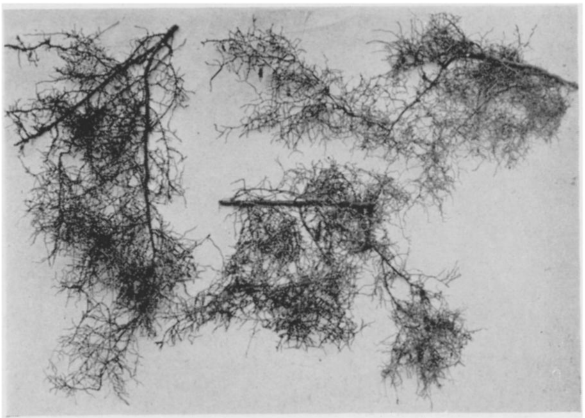

FIG. 34. Fragments of roots of green ash grown in upland, showing the fine network of branches developed in dry soil.

grasslands was primarily a phenomenon of plant competition and that water in dry climates was the chief factor concerned.

Examination was made of the root system of bur oak, a most xeric forest tree, in silt loam soil in eastern Nebraska. A mature tree 37.5 feet tall, 14 inches in basal diameter, and 65 years old, was excavated. The taproot tapered rapidly and extended downward to a depth of 14 feet. It gave rise to 30 or more large main branches, most of which arose in the first 2 feet of soil. Most of the main branches, which varied from 1 to 7 inches in diameter, extended outward 20 to 60 feet before turning downward. Some grew more deeply than the taproot. All branched repeatedly, and together they occupied a very large volume of soil. Many branches of the main lateral roots grew vertically downward 8 to 15 feet, each resembling more or less the taproot system of a young oak tree. Others extended obliquely or vertically upward and filled the surface soil with mats of absorbing rootlets. The weight of the roots equaled that of the top; the volume of the roots was about one-tenth less than that of the parts above ground.

These writers concluded that the scarcity of the water supply, at least during recurrent periods of drought, was the chief external factor promoting extensive root development. They state: "That the adaptation of a species to its habitat is largely a matter of root development is a viewpoint that is being strongly supported by rapidly accumulating evidence." They also state that "although the root habits of a tree are governed, first of all, by hereditary growth characters of the species, they are often quite as much the product of environment."

Holch (1931) examined in eastern Nebraska the development of the root systems of seedlings and saplings of five deciduous forest trees growing in various habitats, including plowed prairie. In former prairie land the taproot of bur oak reached a depth of 4.5 feet the first year and 7 feet the third, when the wonderfully branched root system occupied a circular area 4 feet in diameter to a depth of 6 feet. Shagbark hickory and red oak, both less xeric species, had somewhat shorter taproots which were less extensively branched. Walnut had a deep and remarkably well-branched root system. That of linden, which is rarely planted westward, reached only 1.2 feet the first year but later its roots spread widely in the surface two feet of soil and a few penetrated to about 5 feet.

Biswell (1935), working in the prairie region of central Missouri, found many important variations in the root habits of trees due to differences in environment. Seedlings of boxelder penetrated into the loess soil twice as far as in clay and almost three times as far as in alluvial soil where growth was greatly retarded by deficient aeration during early summer. The root system of boxelder was found to be very plastic. On upland both taproot and major branches of 5-year-old trees penetrated to a depth of 12 feet. But in alluvial soil of a flood plain the taproot of a 15-year-old tree was only 9 feet deep. Many strong laterals spread outward near the surface of the soil to a distance of 5 to 12 feet. The root system of honey locust was readily modified by environment. In upland soil taproots of 6-year-old saplings penetrated to 5 feet, but on the flood plain to a depth of only 2 feet, and laterals extended outward 10 to 17 feet. The shallowly rooted cottonwood of the flood plains sent its strong taproot deeply in upland soil; a 3-year-old tree reached a depth of 9 feet, but lateral spread was small. Conversely, mature trees growing in sandy soil along rivers where the water table is permanently high, are sometimes blown over by the wind. Then they exhibit a "flat-bottomed" root system, the laterals extending widely but the depth of penetration being shallow.

Such knowledge helps one to understand the behavior of trees in different habitats under the impact of drought. For example, the parents of the first author planted rows of cottonwood trees over a hill-top near Hill City in central Kansas about 1900. Nearly all of these trees, undoubtedly deeply rooted, survived the early years of the drought and did not completely succumb to it until 1939. This was in sharp contrast to the early death of similar trees, which were probably shallowly rooted, growing along a nearby intermittent stream.

Hayes and Stoeckeler (1935), in a study of the relationships between trees and soil in the shelterbelt zone, examined the root systems of 126 trees and shrubs on fine textured and sandy soils. Particular emphasis was given to the depth of root penetration. In general, the vigor and the percentage of survival of trees throughout the well-drained uplands and terraces increased with the sand content of the soils and decreased with the clay content, a phenomenon related to the available moisture supply in both sandy and clayey soils at all times, and especially during droughts. Fine textured soils were not wet deeply; in fact, below 2 to 3 feet these soils never attain their field-carrying capacity, except possibly in years of highest precipitation. Larger, older, and more drought resistant trees were nearly always found to be more deeply rooted than trees of the opposite description. Except in areas where the ground water lies high the shallow-rooted trees were more subject to serious injury or death during periods of deficient precipitation.

They classified hackberry, honey locust, bur oak, mulberry, and Osage orange as more deeply rooting (10 to 20 feet where soil was moist to these depths). Green ash, American elm, red cedar, and boxelder were of intermediate root depth (5 to 10 feet). Willow, cottonwood, and catalpa were much more shallowly rooted (1 to 5 feet). Their observations indicated that the slower-growing trees have a greater life span in the shelterbelt zone.

A 50-year-old American elm, 45 feet high, was found to be rooted mostly in the first 3 feet of clay loam, but partly in the second 3 feet of silty clay loam. Nearly the entire root system of a green ash 46 years old in silt loam over a claypan had grown in the surface 3 feet of soil. None of the trees best adapted to planting in the Great Plains seemed to be seriously affected by the zone of lime accumulation in the soils, the so-called lime layer. A 50-year-old bur oak was rooted only 8 feet deep in clay loam soil. It had penetrated quite beyond the zone of lime enrichment, which occurred at 2.5 to 3.5 feet. The roots of most trees were more numerous above the zone of lime enrichment, that is, the upper 2 to 3 feet, where such factors as water, aeration, nutrients, and soil organisms are more favorable for growth.

George (1939) states that: "Trees on the northern Great Plains are often comparatively shallow rooted, which is caused by absence of sufficient moisture at greater soil depths. The trees, therefore, must rely largely on current moisture." Yeager (1935), working at Fargo, North Dakota, where the average annual precipitation is 22.3 inches, found that of 31 species of trees and shrubs excavated more than 97 percent of the roots by actual count occurred in the first 4 feet of soil.

Direct Causes of Injury and Death

Death of trees and shrubs on flood plains and terraces sometimes occurred within a few months if the water table lowered rapidly and shallow root systems occurred only in the upper layer of soil. Paradoxical as it may seem, trees in ravines continuously moist before the great drought in general succumbed first while those deeply rooted in the drier upland soil died later, if indeed they did not survive the drought. Where a permanent supply of water was available few or no trees died; in fact, as will be shown, some benefited by a moderate lowering of the water table and concomitant better soil aeration. Injury and death of woody plants due to the effects of drought were often the result of continuous adverse climatic conditions over an extended period of time. The process resulting in drought injury was usually gradual and began long before death actually occurred. Drought injury among trees is doubtless a recurrent condition at least throughout the drier portions of the prairie. It was present in a mild form during droughts of short duration, but became very general and severe during the continued and intense drought of the 'thirties. It was then that destruction became very great.

Injury to Foliage

The early signs of drought on the uplands were given by the vegetation beneath the trees, especially those which occurred in open stands. Here there was rolling, folding, or curling of leaves, few or only partially developed flower stalks, and withering and falling of the foliage. As drought continued the density of the herbaceous cover was reduced somewhat in proportion to the decrease in water content of soil, an adjustment to the changed environment which woody plants could not make.

Aside from the wilting, discoloring, or shedding of the foliage already described for early drought, an early outward sign of prolonged drought among deciduous trees was reduction in size and number of leaves. Often, only a half crop of small leaves was produced (Fig. 35). Likewise, defoliation of the

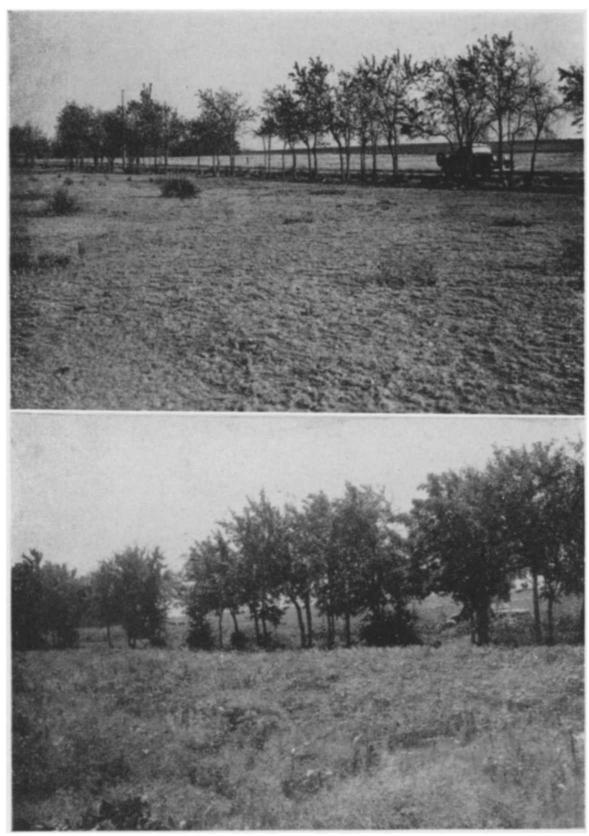

FIG. 35. (UPPER) Osage orange in central Kansas with scant foliage during drought, 1933. (LOWER) The same hedgerow in 1944, showing dense foliage, and sprouts from the bases of some of the old trees.

FIG. 36. Cottonwoods along an intermittent stream in central Kansas which have suffered much damage from drought. September, 1939.

outer portions of the crown was of common occurrence (Fig. 36).

Foliage of trees was often reduced and in many instances almost totally destroyed by grasshoppers, web worms, and leaf-eating larvae of other insects. Such attacks usually occurred during years of great drought when the amount of other green vegetation was limited or had dried completely. The dry weather was favorable for canker worms or web worms which are ordinarily washed from the trees by rains, but during drought trees along the Missouri River and elsewhere were sometimes defoliated two or three times during a single season. When green herbage became scarce or absent on uplands, and not abundant even in ravines, swarms of grasshoppers migrated to the low ground and fed upon the leaves of trees and shrubs. On the hillsides and elsewhere, smooth sumac, for example, was not only defoliated but the bark also was removed from the stems. Such injury was common eastward at least to the Missouri River. Only a few species, such as red cedar, were immune, at least from severe injury. Most trees, shrubs, and woody vines were considerably damaged and some were completely defoliated. On certain introduced species, especially Colorado blue spruce *(Picea pungens)* and tamarisk (*Tamarix* spp.), grasshoppers were at times so numerous, at least locally, that the foliage was scarcely visible. Not only the leaves but also the bark of the twigs and small branches were eaten; this resulted in the death of the spruce but not of tamarisk, which sprouted from the base. Trees in timber claims and windbreaks also suffered heavily early in the drought; later they presented less foliage, but injury by grasshoppers continued heavy on moist lowland. On numerous occasions some deciduous trees were entirely defoliated by grasshoppers, leaf beetles, blister beetles, or other leaf-eating insects.

INJURY TO BRANCHES

When the foliage was reduced in amount by whatever cause, the branches were exposed to high insolation during periods of great heat and low humidity. This was probably a cause of much direct injury (Fig. 37). Desiccation resulted in death of the tips of branches, sometimes rather generally but most usually in the tops of the crowns. This permitted the entrance of wood borers of various genera and species, or other insect larvae, as well as fungi, into the dead or partially dead wood. Death of the tree often proceeded rapidly from the tips of the branches toward their base through the combined influence of desiccation and wood borers. If soil moisture was restored before death was complete, deterioration was slowed or stopped and often growth was resumed from the living branches.

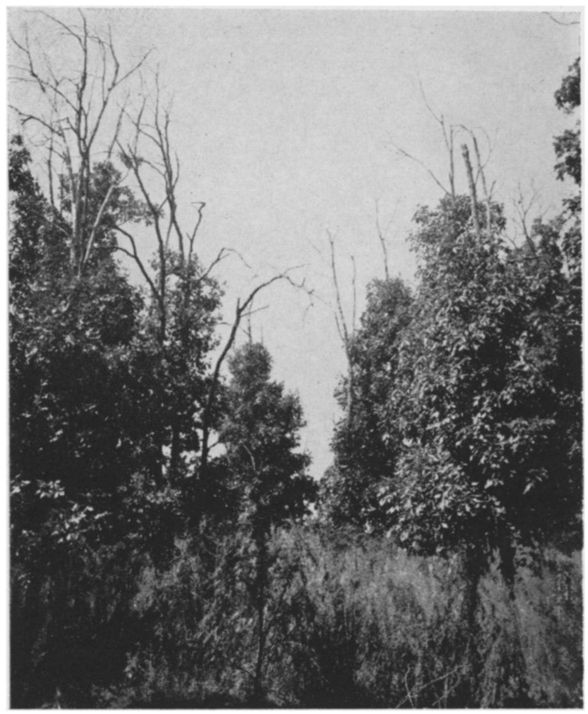

FIG. 37. Interior of a woodland of shagbark hickory *(Carya ovata)* near Nehawka in eastern Nebraska. Before the drought this forest of 35- to 45-year-old trees was in good condition, but in 1943 scarcely an uninjured tree was found.

Infestation by wood borers undoubtedly aided drought in injuring or in causing the loss of many trees by death. Examination of the wood of honey locusts at Hays by cutting sections of the trunk and large branches at different heights revealed that the number of wood borers increased downward from the parts that had recently died. They were present at a distance of several feet from the partially dead wood.

RECORD OF LOSSES

Throughout the years of drought while the writers were studying the destruction of grassland (Weaver

& Albertson 1936, 1940, Albertson & Weaver 1942, 1944), and finally its recovery (Weaver & Albertson 1943, 1944), considerable attention was given to the losses of both native and planted trees and shrubs. Because of the arduous and extensive work on grassland, time for a record of losses of trees was limited. It was confined largely to the western half of Kansas, although many observations and counts of dead trees were made elsewhere. The method consisted in an actual count of all standing trees living and dead that were found in dry ravines, in the protection of bluffs, along intermittent streams, and more abundantly along continuously flowing streams or about springs. Much study was also given to trees planted as groves or timber claims, windbreaks, and hedgerows. In nearly all, the counts were made early in the drought years and again several years later. Thus, a large amount of factual data has been obtained.

Destruction of Native Trees and Shrubs

The native trees in the area are typically representative not only of the farthest westward extension of deciduous forest into the dry prairies but also they illustrate in general similar conditions southward in western Oklahoma and northwestern Texas. Westward on the plains of Colorado woody growth, if present, is even more sparse. To the northward in the hardlands of Nebraska and the Dakotas conditions similar to or even more adverse than those in Kansas prevail, except here ponderosa pine is found in addition to the far western outposts of deciduous forest (Kellogg 1905).

LOSSES IN DRY RAVINES AND ON STEEP BLUFFS

Extensive areas of the Great Plains are characterized by rolling hills with dry ravines, which receive runoff water, extending far back from the streams into the uplands. Except for the level uplands where trees do not occur naturally, the dry ravines are the most xeric sites in which woody vegetation is found. Sometimes trees occur only as individuals. They are always found most abundantly near the bases of the north-facing slopes. But where the slopes are steeper and some seepage through underlying rock occurs, both lower slopes may support them. Trees in many such ravines have been studied; typical results are shown in Table 2.

An examination of Table 2 reveals that early losses of hackberry (4 to 7 percent) were much lower than those of American elm (16 to 27 percent).[3] Although losses of both species increased greatly with the continuation of drought those of hackberry (48 percent) were still far less than those of elm (76 percent). On the south-facing slope all of the elms and three-fourths of the hackberry had died by 1939. It was more sparsely populated and the trees survived for a longer time probably because they were more deeply rooted. In all sites death of hackberry was consistently less than that of elm. Of a total of 20 elms and 32 hackberry trees growing in a ravine

[3] *Ulmus americana* is the only species of elm growing naturally in the region. Hereafter it will be designated simply as elm. Likewise, green ash *(Fraxinus pennsylvanica lanceolata)* will be called ash.

TABLE 2. Loss of native trees in ravines near the Saline River at Hays, Kansas.

Species	Year	Habitat	Number of Trees		Percent Loss
			Living	Dead	
American elm.....	1935	South-facing slope...	26	5	16
	1935	North-facing slope...	237	90	27
	1939	" " " ...	78	249	76
Hackberry.......	1935	South-facing slope...	22	1	4
	1935	North-facing slope...	153	11	7
	1939	" " " ...	86	78	48

4 miles west of Hays, three-fourths of the elms had died by 1938 but only one-fourth of the hackberry trees (Fig. 38).

FIG. 38. Typical dry ravine on rocky soil in natural grassland near Hays, showing condition of elm and hackberry in the spring of 1939.

A few miles east of Woodward, Oklahoma, observations were made in May 1938, of trees growing on north-facing slopes. Many of the tops of elms were badly damaged by drought and wood borers. Farther up the protecting slopes, many of the trees had died and the remainder were seriously damaged.

In ravines formed by cutting through loessial or glacial deposits, limestone formations are absent, hence the trees in these locations are firmly rooted in deep rich soil. Lateral seepage, however, is as common here as in the limestone outcrops. It has been estimated by Bennett (1939) that the water table was lowered as much as 20 feet in some places in the Great Plains by gullies cut through the substrata. Under these conditions much of the vegetation, including scattered trees and shrubs was unable to survive on the limited rainfall.

Studies made north of Osborne, Kansas, in ravines on the highland indicated that elm and hackberry had been reduced to less than one-third the original number. In the fall of 1939, ravines along the Smoky Hill River 60 miles southeast of Hays were studied to determine the nature of growth and drought injury. The trees were mostly elm, hackberry, ash, and cottonwood, but occasionally bur oak. Even in this more mesic habitat nearly 50 percent of the elm and bur oak were dead; the others suffered somewhat less.

In a ravine in a buffalo grass pasture about 9 miles south of Superior, Nebraska, much destruction had occurred to bur oak. The trees grew in a loam soil underlaid with limestone. Where the soil was deepest they were 28 feet tall and 8 to 12 inches in diameter. But on the rocky slopes a height of only 20 feet and a diameter of 5 to 7 inches were attained. All were dead or badly injured (Fig. 39).

FIG. 39. Bur oak in the upper portion of a dry ravine near Superior in south-central Nebraska, showing great destruction by drought.

On steep north hillsides at Weeping Water, in eastern Nebraska, where the soil was also underlaid with limestone, a mortality of 80 percent was suffered by red oak, as well as by the linden near the base of the slope. Many other trees and shrubs also succumbed (Fig. 40).

In a large prairie near Alma in south-central Nebraska, the mortality rate of elm was extremely high; in some places all had died (Fig. 41). Near Lincoln in eastern Nebraska trees of elm and ash in a ravine running through a large prairie had lost half their number by 1939. The remainder had suffered considerably as was indicated by the numerous dead branches in their tops. Young trees and shrubs showed less injury from drought than did the older ones. Similar losses in shallow ravines and on slopes in southwestern Iowa have been observed. Indeed, such losses were widespread through much of the true and mixed prairie.

The shrubs near Hays, limited generally to ill-scented sumac, snowberry, and smooth sumac, experienced a high mortality, especially when growing together in dense clumps. It was not uncommon to find large communities of these shrubs on exposed slopes which, except for a few small plants, had succumbed to drought. Shrubs on north hillsides suffered much smaller losses (Fig. 42).

In ravines along which runoff water finds its way into the streams there occurred depressions or pockets which thus receive a supplementary water supply. Here sometimes were found thickets of wild plum, some of which had suffered greatly from drought. Many were entirely buried under the drifts of dust. Elsewhere the dust had accumulated to a depth of a few inches to several feet. This contributed greatly to their death, for so poorly did the rain water penetrate the dust that the soil in which the plums were rooted often remained dry. This phenomenon was not local but occurred eastward at least as far as the Missouri River.

FIG. 40. Injury to red oak and to linden (center) growing near Weeping Water at the foot of a steep north-facing slope where the other trees were all destroyed by drought. May, 1944.

FIG. 41. Shallow ravine near Alma in south-central Nebraska in which American elms were all dead in August, 1939.

Trees were usually more abundant near the base

FIG. 42. Steep, rocky, north-facing slope with ill-scented sumac. Note the dead bushes at the left near the top of the hill.

of steep bluffs than on the higher slopes or below the base of the bluffs on more level land away from the "seeps" between the rock strata. The mortality rate in these locations depended greatly upon the exposure to the sun and desiccating winds (Table 3).

TABLE 3. Death of trees on steep slopes 16 miles north of Hays in June, 1935.

Species	Habitat	Number of Trees		Percent Loss
		Living	Dead	
Red cedar.	West exposure.....	28	2	7
" " .	North exposure....	39	0	0
" " .	Northwest exposure	28	0	0
Elm......	Northwest exposure	48	22	31
Ash.......	Northwest exposure	19	11	37

Even in the best protected sites there were definite signs of drought. Many of the leaves of red cedar had fallen and formed a brownish litter beneath the trees. Dead branches were common.

A much larger area in this locality was examined three years later. Losses of red cedar had increased to 35 percent; death of hackberry and ash were 31 and 43 percent, respectively, but loss of elm was 93 percent.

TABLE 4. Losses of trees on a steep bluff 16 miles north of Hays in August, 1938.

Species	Number of Trees		Percent Loss
	Living	Dead	
Red cedar...........	328	175	35
Ash................	363	276	43
Hackberry..........	91	40	31
Elm................	8	101	93

The shrubs found in this locality in 1935 were definitely affected by drought. At least 90 percent of ill-scented sumac and snowberry had succumbed. In fact scarcely any remained except those that were growing in small depressions. The sparse population of smooth sumac, however, had sustained only slight loss.

Red cedars on a north-facing bluff on the Smoky Hill River 30 miles southwest of Hays suffered more from drought than in any other site. In 1937, 60 percent were dead, and two years later the death toll had increased to 80 percent (Fig. 43). Sixty miles east on a less xeric north-facing bluff, the average loss of red cedars did not exceed 10 percent. But locally, especially where the trees extended above the brow of the bluff, large numbers had died (Fig. 44). Here the deciduous trees (elm, hackberry, ash, and cottonwood) showed the same low mortality. But on higher land beyond the rocky outcrop, where the roots were unable to obtain moisture from the "seeps" between the layers of rock, the loss was considerably greater. Studies on a similar site near a small stream north of Russell revealed 1 percent loss of red cedar and 10 percent each of ash and hackberry, but all of the elms had died.

Summarizing, the average percentages of losses in

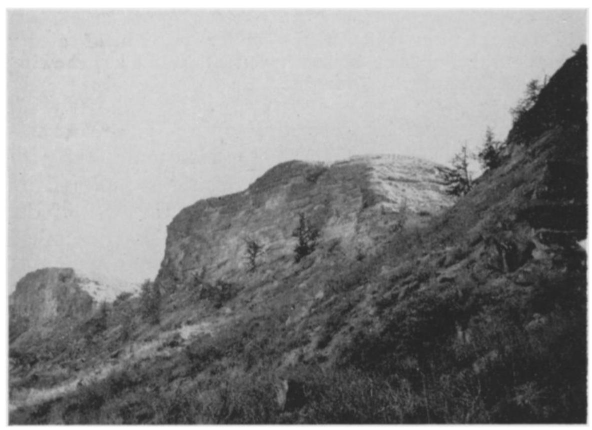

FIG. 43. Native red cedars growing in the shelter of limestone cliffs in central Kansas. July, 1939.

FIG. 44. Old, gnarled red cedars near the brow of a steep north-facing bluff 20 miles northeast of Hays. October, 1939.

ravines late in the period of drought were, approximately, elm 70 and hackberry 36. On bluffs, percentages of losses were red cedar 37, elm 56, ash 33, and hackberry 28. The loss of red cedar was high in comparison with that of deciduous trees due to its great loss (80 percent) on a dry bluff where no other species were found.

LOSSES ALONG INTERMITTENT STREAMS

Many streams in western Kansas had only an intermittent flow of water even during years of normal precipitation. The source of this water was runoff from the surrounding higher land or seepage from hillsides following heavy rain. During the drought years the streams were usually dry in summer. The general lowering of the water table left the roots of the trees quite above a continuous water supply. Mortality along such streams was high (Table 5).

TABLE 5. Losses of trees along a small stream near Hill City, Kansas.

Species	Year	Number of Trees		Percent Loss
		Living	Dead	
Cottonwood.....	1935	80	78	49
	1939	28	130	82
Peach-leaved willow........	1935	17	98	85
	1939	5	110	96

The water in this stream had cut through sandy soil and flowed over a layer of shale. There were approximately 300 trees, mostly cottonwood and peach-leaved willow, along a half mile of this stream. Hackberry and elm were found on the steep bluffs some distance from the creek. The first study was made in 1935 after three years of continuous drought. The water table had been lowered sufficiently to leave most of the roots of the trees in dry soil. Of 158 cottonwoods 49 percent had died. Death toll of willows was 85 percent. Even among the living trees numerous dead branches occurred in their tops. As the drought continued the losses became greater. By the autumn of 1939 the mortality of cottonwoods had reached 82 percent, and that of willows was 96. In similar sites along other streams losses were fully as great; in some places, however, where the trees were protected from desiccating winds, a much larger percentage survived the drought. The loss of cottonwoods varied greatly with the distance above the bed of the stream, as is shown in Table 6.

Of a total of 307 trees 211 died. The greatest loss (98 percent) occurred where the trees were growing well above the stream. On the flood plain where the trees were shallowly rooted a loss of 62 percent was found. This was probably a result of the rapid lowering of the water table. Smallest losses (9 percent) occurred in the intermediate site. Destruction of shrubs along dry and intermittent streams was usually high. Rough-leaved dogwood and wild plum especially were injured, also wild currant and indigobush were harmed to a smaller degree.

TABLE 6. Mortality of cottonwoods near a small stream west of Hill City in October, 1935, after three years of drought.

Habitat	Height above bed of stream	Number of Trees		Percent Loss
		Living	Dead	
On knoll........	20 feet	4	168	98
In valley........	12 feet	70	7	9
On flood plain....	6 feet	22	36	62

Observations made along the Solomon River near Woodston in 1938 revealed that approximately 45 percent of the cottonwoods and willows growing near the river were dead. Elm and hackberry, which usually grew farther back from the stream, lost about 75 percent.

Similar observations were also made along streams near Grand Island, Nebraska, in 1938. Approximately 50 percent of the trees were dead (Fig. 45). Large numbers of dead elms were also found on the river terraces near Missouri Valley, Iowa. Cottonwoods and willows growing on the flood plains and thus nearer the water table had suffered relatively small losses.

FIG. 45. Destruction of trees by drought along the banks of Salt Creek 12 miles south of Lincoln. The trees are mostly ash and elm 40 to 50 feet high, with native bluestem prairie in the foreground.

On sandy streams such as the Smoky Hill River near Hays, losses were comparatively light (Fig. 10). Here most of the trees were cottonwood and willow and they soldom attained large size before they were washed away by floods, hence their age was considerably less than that of the trees growing along streams flowing through a heavy soil. The percentage of loss due to drought was negligible on the flood plain but often great farther from the river.

LOSSES ALONG CONTINUOUSLY FLOWING STREAMS AND ABOUT SPRINGS

Streams in which there was a continuous surface flow of water during drought were few in this western area. Studies of mortality of trees along Walnut Creek near Rush Center were made in August, 1938, and in September of the following year. Occasionally a dead tree was found near the water's edge in the midst of many thriving ones; but the most common sign of drought was the dead branches in the tree tops. Here elm, hackberry, and ash occurred rather abundantly, and cottonwood and boxelder more sparingly. Death of trees was limited to about 2 percent.

On Big Creek 10 miles southeast of Hays, losses were much higher. The stumps in the foreground of Figure 46, where dead trees had been removed, supplied mute evidence of the desiccation that occurred along this stream, where the flow of water although continuous during the drought was greatly reduced in volume. Death of trees varied greatly but the average was about 10 percent.

Fig. 46. Hackberry, American elm, and green ash along Big Creek southeast of Hays where loss by drought was only 10 percent. Most of the dead trees had been removed.

Along Pawnee Creek 12 miles west of Larned, Kansas, and 30 miles farther south on the Medicine Lodge River near Wilmore, a count of trees in 1938 revealed a loss of approximately 5 percent. They were elm, hackberry, and black locust. But many of the tops of the living ones had numerous dead branches.

Farther southwest, on the Canadian River in the panhandle of Texas, cottonwood, hackberry, and elm formed an irregular belt on both sides of the stream. Here relatively small losses were found even as late in the drought as the spring of 1938. Doubtless some dead trees had been removed, but the damage was generally limited to scattered dead branches in the crowns.

Summarizing, average losses in percentage of trees along continuously flowing and intermittent streams were as follows: elms 5 and 62, hackberry 5 and 75, and cottonwood 6 and 59. Along intermittent streams loss of willow was 70 percent. Along continuously flowing streams black locust lost only 5 percent.

Death of trees growing near running springs was rare. Usually the only apparent damage was revealed in their tops, particularly near springs with a sufficient flow to continuously maintain a high water table. Other springs that became mere seeps were unable to supply sufficient water to support trees during the most intense drought (Table 7). In 1942, after two years of above-normal precipitation following seven years of drought, the loss of willows was 89 percent and that of cottonwoods 55.

Table 7. Number of living and dead trees and percentage of loss of each species near a spring at Hill City.

Species	Year	Number of Trees		Percent Loss
		Living	Dead	
Willow..........	1935	37	0	0
	1942	4	33	89
Cottonwood.....	1935	137	3	2
	1942	63	77	55

Destruction of Trees in Timber Claims, Hedgerows, and Windbreaks

During the latter part of the nineteenth century, many of the pioneers obtained a tract of 160 acres of land from the Federal Government by complying with the provisions of the Timber Culture Act of 1873. Usually 10 acres of land were broken and planted to trees 6 to 9 feet or more apart in rows 6 to 9 feet distant. The soil in these claims usually was cultivated 8 to 10 years until the trees were well established, after which often they received no further care. Severe losses occurred during the dry periods previous to 1933. It remained, however, for the recent drought to almost annihilate the survivors (Figs. 47 and 48). As many as 24 timber claims were examined in a single day, and practically without exception all trees were dead. Occasionally, however, a few half-dead trees remained in the lower places where they were kept alive by run-in water from the higher land (Fig. 49). Although Osage orange

Fig. 47. Destruction of trees in a grove about 50 miles west of Lincoln. July, 1935.

(Maclura pomifera) was the tree most commonly found in timber claims, it was not unusual to find the remains of black walnut, black locust, honey locust, ash, and catalpa.

When cultivation of timber claims was discontinued, the ground was readily occupied by an understory of vegetation. The first plants to invade were weedy annuals such as sunflower, lamb's quarters, and pigweeds. These annuals were gradually replaced by perennial plants such as sand dropseed, western wheat grass *(Agropyron smithii)*, and goldénrod *(Solidago mollis)*. The competition for water by a rather dense cover of grasses and forbs was sufficient to cause considerable loss among the trees. Frequently posts for fence construction were obta'ned by cutting some or all of the trees of Osage orange a short distance above the ground. Usually a large number of sprouts developed from the remaining stumps and formed a shrub-like growth.

Although great variations in losses were found, due to differences in soil, topography, and kind of trees, data given in Table 8 are representative. Death of the ash (86 percent) was much greater than that of Osage orange, where only 45 percent succumbed. But later in drought all trees of both kinds died.

FIG. 49. Timber claim 6 miles north of Hays showing death of trees except in low ground. Undoubtedly death was due in part to injury from grazing and trampling. September, 1940.

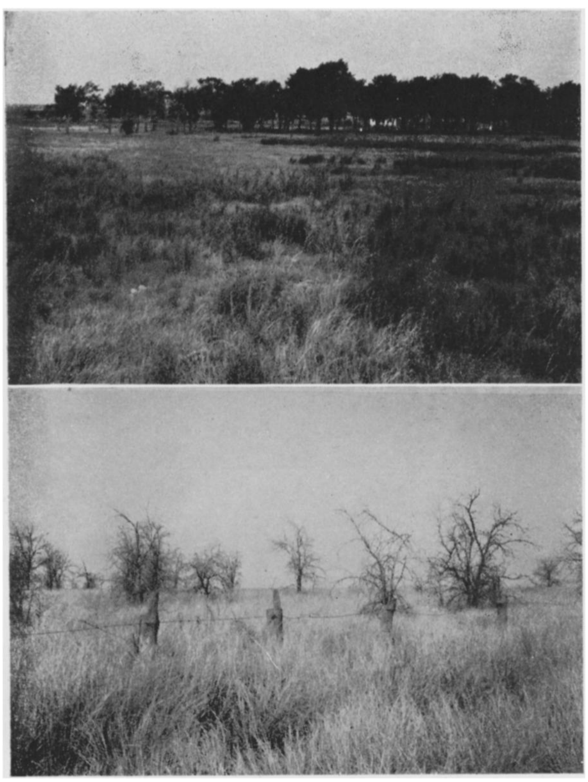

FIG. 48. (UPPER) A timber claim of black locust *(Robinia pseudoacacia)* near Ogallah, Kansas, August, 1942. The trees were given good care for a number of years and have survived the drought much better than those in most similar timber claims. (LOWER) Timber claim near Hays, October, 1939. The ground had not been cultivated for many years, hence the Osage orange died early in drought. Stumps in foreground that hold the wire are what remain of honey locust that died before the drought.

In general, the greatest losses occurred on the higher land. Often timber claims originally contained several hundred trees of Osage orange. Some were cut for fence posts, but sprouts grew from the base before the onslaught of the drought. After seven years of extreme desiccation, however, few or no trees remained alive except those favored by run-in water.

Opinion of early settlers who witnessed both the planting and deterioration of timber claims in this region was that Osage orange was the most drought resistant of all the trees planted. Catalpa, which is now rarely seen, was the first to succumb; it was followed by black locust and ash.

Where timber claims were located on lowland, the trees survived the drought much better. This is illustrated by a tree claim near Hill City (Table 9). There was no loss of honey locust in 1935, although a few trees did die later in the drought. But black locust lost three-fourths of its numbers early in drought; death among the cottonwoods was only 14 percent.

A hedgerow is simply a row of trees along the roadside or between fields. The use of this name in the prairie, where it is locally termed hedge fence, was probably derived from the very extensive plantings of "hedge" or Osage orange for this purpose. Frequently they are found on both sides of the roadway. The trees were always planted closely; usually this

TABLE 8. Loss of trees on timber claim near Wakeeney, Kansas.

Species	Year	Number of Trees		Percent Loss
		Living	Dead	
Ash	1935	25	158	86
	1939	0	183	100
Osage orange	1935	88	73	45
	1939	0	161	100

TABLE 9. Percent loss in a lowland tree claim near Hill City.

Species	Year	Number of Trees		Percent Loss
		Living	Dead	
Black locust...	1935	37	113	75
Cottonwood...	1935	87	14	14
Honey locust..	1935	12	0	0

spiny hedge made a fence unnecessary. Since honey locust and black locust were likewise planted closely, competition for water usually retarded their growth and in the western half of Kansas a height of only 15 feet was common (Fig. 50). Eastward, however, they attained at least twice this stature.

FIG. 50. (UPPER) Ash hedgerow near Bird City in northwestern Kansas. Recovery was limited to a few trees in a depression (right) where they had survived the drought. (LOWER) Hedgerow of Osage orange near Belleville, Kansas, where all of the trees have died. Total loss was common in the central and western parts of both Kansas and Nebraska.

Trees in hedgerows suffered about the same fate as did those in timber claims. Dead trees were usually scattered throughout before the drought began, and by 1935 as many as 75 percent had died in the most exposed sites. The loss increased, however, and during the autumn of 1939 scarcely a living tree was found. Life remained in the lower branches of only a few; these survivors usually were on low ground.

A hedge of approximately 400 trees near Carneiro, 80 miles east of Hays, suffered a mortality of 38 percent in 1939, but there was no further loss (Table 10). A few miles distant, near Ellsworth, the loss among 3,200 trees was 99 percent. Mortality in a hedge near Ogallah, 25 miles west of Hays, was 88 percent, and 91 percent loss was found in one north of Stockton.

TABLE 10. Losses in hedgerows of Osage orange, September, 1942.

Location	Number of Trees		Percent Loss
	Living	Dead	
Near Ellsworth......	15	3,185	99
Near Carneiro.......	249	152	38

About 120 miles northeastward near Mankato, Kansas, the death toll was fully as heavy in many places as farther westward. Most of the hedgerows on upland suffered heavily in early drought and by 1939 many were completely dead. Osage orange also suffered considerable damage in central and eastern Kansas and Nebraska.

The loss of trees in windbreaks was extremely heavy unless the soil was cultivated or irrigated. The dust storms of 1935 contributed greatly to this loss through partial burial of the lower parts of trees in great drifts of loose soil. Sometimes these drifts were 4 to 8 feet deep and consequently covered many branches (Fig. 51). Not only did the compacted soil damage parts of the trees by interfering with aeration, but water could not penetrate through the dust to the soil about the roots.

FIG. 51. Windbreak of honey locust in central Kansas which died soon after the dust storms of 1935. Drifts of dust 4 to 6 feet high covered the lower portions of many of the trees.

In a windbreak near Dighton trees had been planted in 1893 and had been given little care until after the drought was well advanced. All but a few of the deciduous trees (ash, elm, and others) had died, but red cedars were still growing in the fall of 1939 (Fig. 52).

On high ground south of Medicine Lodge, Kansas, 90 percent of the honey locust were dead in May, 1938. Three-fourths of the elm had died, and the remainder had much damaged tops.

At Alva, Oklahoma, all the elm and hackberry in some windbreaks were dead; in others mortality was at least 50 percent. Farther west at Perryton in the panhandle of Texas, the windbreaks were few and small, but the loss was not so great as farther north

FIG. 52. Farm in western Kansas where nearly all the deciduous trees in a timber claim have died, and only a few red cedars, planted in 1893, are still alive. September, 1939.

near Liberal, Kansas, where 80 percent or more of ash, honey locust, and black locust were dead.

Windbreaks near Kearney, Nebraska, suffered a similar fate to those south of Hays. A few half-dead trees were found in some. Piles of dead trunks cut for firewood were all that remained of many windbreaks that formerly furnished much portection from the cold, north, winter winds.

Observations in western Iowa in 1938 showed that many windbreaks located on high land had suffered much damage, and "hundreds of thousands of adapted trees on suitable or even protected sites were killed or very severely damaged" (McComb & Loomis 1944). In eastern South Dakota a loss by drought of half of the trees in windbreaks was usual.

In summarizing losses it may be pointed out that those which occurred early and mostly after the first extremely dry year (1934) have already been recorded. With ensuing dry years and an accumulating moisture deficit (which was 25 to 34 inches of rainfall at many stations) both injury and mortality increased. It seems probable that in Nebraska and Kansas an average of at least 50 to 60 percent of the trees (aside from young shelter belts) died, and half of the remainder sustained great to moderate injury. Even near the Missouri River entire plantations were destroyed, forests on protecting slopes (nearly all of which were grazed) suffered losses as high as 90 percent, and flood plain trees died in enormous numbers with the lowering of the water table. Red cedar, hackberry, bur oak, and honey locust rank high among trees that endured drought. Silver maple, black locust, boxelder, and cottonwood were less successful in enduring the long periods of desiccation.

RECOVERY FROM DROUGHT

Although there was a return to normal precipitation over much of the prairie area in 1940, drought as measured by recovery of both herbaceous and arboreal vegetation continued still another year. This interval was necessary, as has been shown by Weaver and Albertson (1944), to moisten the parched soil. Over much of the mixed prairie water penetration was confined to a depth of 3 feet even in 1941. Trees and shrubs that retained some life at the close of the drought usually remained alive for a time unless infestation by wood borers was so complete or the trees so nearly dead that they were unable to resume growth even under favorable climatic conditions.

RENEWED GROWTH WITHIN THE CROWN

Recovery was shown principally and most commonly by renewed growth within the crown. This was usually local but sometimes general. Most of the trees in the driest sites, as in dry ravines, were either killed outright during drought or their living tissue was reduced to a small amount. In many places only an occasional branch had any leaves, especially during the later years of this great period of desiccation. When moisture was again available growth was initiated in those branches and twigs where some living tissue still remained. Even after three or four years af favorable environment leafy branches were often so few and the foliage so sparse that the trees produced very little shade (Fig. 53).

FIG. 53. Drought-stricken American elm growing in a dry ravine near Hays, showing the sparse foliage produced even after the drought. September, 1944.

This greatly retarded the return of the mesic grasses and forbs which formerly grew in the shade beneath scattered trees. In fact, there was little vegetation of any kind. Hence, even where the slope was moderate, there was much runoff and considerable erosion. In less xeric places where injury was not so great a new and complete cover of foliage was soon developed. This phenomenon was especially pronounced in hackberry (Fig. 54).

Trees growing in dry drainageways which received considerable runoff water often resumed vigorous growth. For here much of the lower portion of the trees retained some life. Foliage of the renewed part of the crown was unusually dense. This probably resulted from an abundant supply of water, nutrients,

Fig. 54. (Upper) Group of trees, mostly hackberry, in a ravine at the foot of a north-facing slope near Hays in 1939, showing very sparse foliage. (Lower) Same view in 1942 after three years of good precipitation.

Fig. 55. Ash, boxelder, and elm in a shallow ravine near Lincoln in 1942. More than 50 percent of the trees were dead. Others renewed growth from the live wood and unusually dense foliage may be seen.

and perhaps accumulated food for these parts, since the roots were apparently not reduced in proportion to the crown (Fig. 55). Similar renewal of growth was found over a wide territory.

In sites less exposed to drought, as on protected, steep, north-facing slopes, recovery began early and progressed rapidly. Where only the upper part of the crown had died, rapid growth soon hid from view many of the dead branches and only the uppermost remained as witnesses to a great catastrophe. The crowding of the very leafy new shoots presented an unusual appearance; the trees had lost their former symmetry of branching and graceful spreading of the crowns (Fig. 56). Many depressions along highways were occupied by a moderately dense growth of trees, especially cottonwood. Those on the lower ground that survived the drought made rapid recovery by renewed growth within the crown. The conditions of growth when drought was most severe in the fall of 1939 and that after five years of recovery are shown in Figure 57. The foliage was so dense in 1944 that no effects of drought could be seen in the trees in the lowest places.

Trees on Sweet Water Creek, an intermittent stream 14 miles northeast of Hays, responded to a better environment in much the same manner. The trees in the most xeric sites had died whereas at least parts of those in the wetter places had survived. Elm suffered less deterioration than did the cottonwood, hence renewed growth was generally distributed throughout its branches. Conversely, the cottonwood had foliage only in the lower part of its crown (Fig. 58).

Even along the better watered streams recovery by growth of tops was common as late as 1944. While the water in such streams probably never failed completely, yet because of the lowering of the water table some trees died and many of the remainder suffered some damage.

Recovery in tree claims was almost entirely limited to renewed growth of tops or to sprouts from the base of the trees (Fig. 59). Recovery in a timber claim of ash in eastern Colorado is shown in Figure 60. Most of the trees were dead but in some life

Fig. 56. Renewed growth in tops of green ash (left) and American elm (center) on a steep north-facing slope near Stockton, Kansas, in June, 1944.

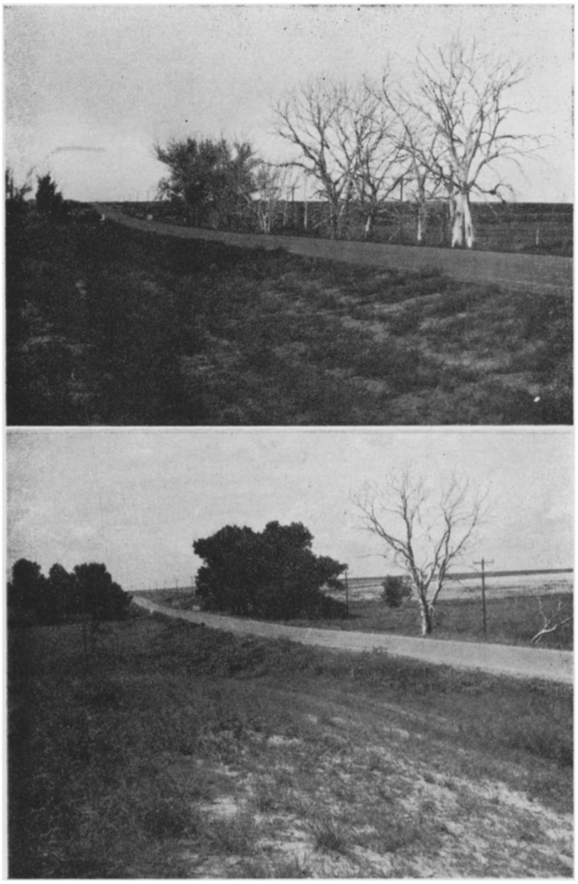

FIG. 57. (UPPER) Large cottonwoods on low ground near Wakeeney in west-central Kansas. Only trees on the lowest ground survived. September, 1939. (LOWER) Same view in 1944. Most of the dead trees had been removed, but those that survived, some of which were 65 years old, produced a dense foliage which hid from view many of the remaining dead branches.

FIG. 58. Trees along an intermittent stream near Hays. Note the dense foliage of the elm (left) and on portions of the cottonwoods that remained alive.

FIG. 59. Remnants of a timber claim on level lowland near Broken Bow in central Nebraska. Abundance of buffalo bur *(Solanum rostratum)* and other weeds indicate much grazing and trampling. The green ash which were not dead showed life only in the lower portions of their crowns.

FIG. 60. Remnants of an extensive timber claim on hard land east of Cope, Colorado. Nearly all of the trees remaining in 1943 were dead; a few had dense foliage, mostly in the lower branches.

still persisted in portions of the crown. In many trees the foliage was so dense that the general appearance was that of witches' brooms.

Many of the trees with only a few living branches will probably survive but a very few seasons even with the best environmental conditions. Few could endure another period of drought. How long those with moderate injury to the crown can survive cannot be foretold.

In hedgerows on high land in the western half of Kansas trees that had suffered little injury were rarely found; a few had only an occasional green branch; nearly all were dead. In trees that did survive, revival of growth was slow, especially in the Osage orange, and even after three years of recovery no great change had occurred.

On the lowland, where drought was less severe, renewal of growth was rapid when a favorable environment again prevailed. During drought the foliage was sparse but well distributed throughout the crown. Later it not only became thicker but actually denser (in 1944) than normal foliage before the drought.

Recovery by Basal Sprouts or Replacement by Seedlings

A second but minor method of recovery was the production of sprouts from the base of the trunk if it remained alive, or from the stumps of such trees that had been removed for firewood. Many such sprouts grew rapidly and in 2 to 3 years had attained, even in the more arid regions, a height of 5 to 10 feet. Sometimes root sprouts developed, especially from trees growing on steep banks and slopes, where many roots had become exposed by soil erosion. Initiation of root sprouts was often due to injury resulting from trampling by cattle. In any instance these new shoots seemed to be well supplied with water and their early growth was very rapid.

Fig. 61. Reproduction by seed of hackberry and elm about large trees that died as a result of drought and were removed. Fifty annual rings were counted in the stump in the foreground. The site is a north-facing slope near Stockton, Kansas.

A third method of recovery of woody vegetation was the replacement of dead trees by seedlings. Seedlings of any species of tree were found only where the trees were growing naturally, and never in great abundance. They were not found in timber claims, windbreaks, or hedgerows in mixed prairie and in only a few of the best old timber claims eastward nearly to the Missouri River. Almost all of the old timber claims were being grazed or had been pastured. Grazing and trampling is always inimical to growth of trees. Seedlings have played an important role in restoring woody vegetation, especially among the native trees in ravines, on steep slopes, and along intermittent streams. In many of these locations, after the drought great numbers of small trees 6 inches to several feet in height were scattered about in the open spaces left by the death of the parent trees (Fig. 61). Many young trees of hackberry and elm were becoming established on north-facing slopes. The older ones had probably begun growth before the death of the parent trees. Red cedars continued to replace their losses throughout the drought. In fact, there is considerable evidence that this species is not only replacing its losses but actually extending its area of occupation. Seedlings were often most numerous on steep slopes and in fence rows where livestock were excluded.

EFFECT OF CHANGING ENVIRONMENT ON GROWTH

In order to ascertain the effect of drought upon the rate of growth, a study was made of the annual radial increment of the uninjured or least injured trees. A comparison of total increase in radius during the 8 wet years (5 preceding and 3 following the drought) with that of the 8 dry ones has also been made. That the years 1928 to 1932, and 1941 and 1942, had relatively high precipitation may be seen even by casual examination of Figure 62. The intervening years were all either extremely or moderately dry.

An increment borer was used to obtain cores of wood, 3 feet above the soil, from the different species of trees found growing in various sites. At each sampling station cores were taken from each of 3 to 8 trees (except in rare cases where only 2 trees were found) in dry, intermediate, and wet habitats. All the stations were in the western half of Kansas. The habitats classed as dry were the driest that could be found in each location, such as dry ravines and drainage channels. Almost without exception the soil was underlaid at some depth within the zone of root distribution by bedded limestone. Those classed as wet were the most moist, such as stream banks and places near living springs. The intermediate habitats were intermittent streams where the water table had been lowered during the dry years.

Hackberry, elm, and ash were the trees most commonly sampled. Southwestward, however, cottonwood was frequently the only species found. Osage orange was sampled only in hedgerows, most of which had been planted on dry upland. Some hedgerows, however, extended across ravines. Here it was possible also to obtain cores from trees growing in intermediate habitats.

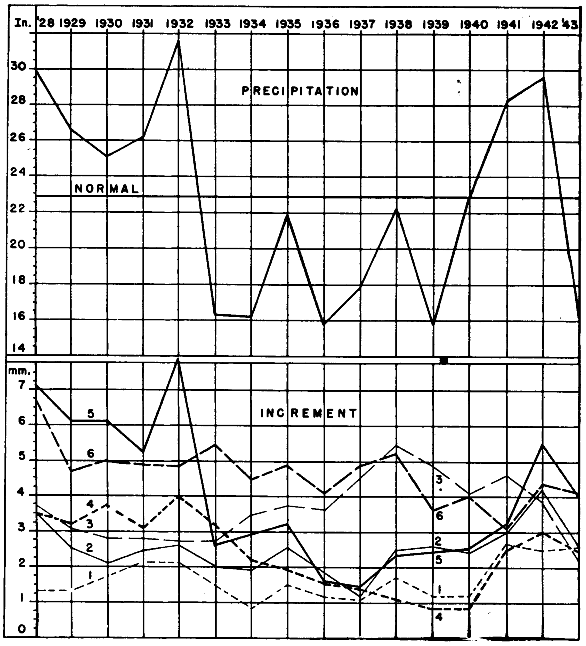

FIG. 62. (UPPER) Graphs showing the annual precipitation with departure from the normal at Hays, Kansas, before, during, and following the great drought. (LOWER) Graphs showing average annual increments of growth of hackberry and American elm in dry habitats (1 and 4), intermediate ones (2 and 5), and in wet sites (3 and 6).

STUDIES ON HACKBERRY

Studies on hackberry were made in dry ravines at three widely separated stations. These were in a pasture at Hays, at Hill City 50 miles northwest of Hays, and near Plainville 16 miles north of Hays. The trees were 30 to 45 years old, 6 to 17 inches in diameter (measured as were all the trees, at 3 feet in height), and 16 to 20 feet tall. The millimeters of increase in growth during the wet and dry years were 14.7 and 11.5, 25.5 and 14.5, and 11.4 and 10.4, respectively.[4] The last ravine was an extremely dry one, which accounts for the slow growth. Great differences were found here in the growth of different trees. The average increment of growth during the wet years was 17.2 mm. It was 29 percent less during the dry years (12.2 mm.).

The first station with an intermediate habitat was 12 miles southeast of Hays at Munjor on Big Creek. The second was at Hill City near Jack Creek, and the third 16 miles north of Hays at Stockton. The trees were 43 to 64 years old, 9 to 17 inches in diameter, and 20 to 30 feet high. Millimeters of increase in radius during wet and dry periods were 23.0 and 17.1, 27.7 and 27.1, and 27.9 and 20.2, respectively. The average increment of growth during the wet years was 26.2 mm. It was 18 percent less during the dry ones (21.5 mm.).

Since trees were far more abundant in wet habitats along continuously flowing streams where the water table was high, larger numbers of samples were taken. Cores were obtained on Big Creek near Hays, on Walnut Creek near Rush Center 30 miles southward, and on Sawlog Creek 80 miles southwest of Hays. These trees were 26 to 100 years old, 8 to 23 inches in diameter, and from 25 to 60 feet tall. The millimeters of radial growth during the wet period and the dry one were 27.5 and 30.5, 17.0 and 18.5, and 15.2 and 13.3, respectively. The average growth increments for the two periods were 19.9 and 20.8 millimeters, respectively. Thus, growth was slightly greater here during the dry years.

During the wet years rate of growth was 66 percent as great in the dry habitats and 76 percent as much in the wet ones as that in the intermediate sites. Similar values during the dry years were 57 and 97 percent.

STUDIES ON AMERICAN ELM

Cores were obtained from elms growing in three different sites as described for hackberry, except a dry ravine 40 miles north of Hays at Stockton was substituted for the one at Hill City, since no elms grew there. These trees were 27 to 48 years old, 5 to 18 inches in diameter, but only 16 to 30 feet tall. The increments of growth in millimeters during the dry and wet years were, in the same order as for hackberry, 23.8 and 14.7, 22.5 and 12.5, and 16.8 and 13.2. Great variation occurred at the second station. One tree, apparently much more favorably and deeply rooted in the rock crevices than the others, made growth increments of 35 and 23 mm., while for another, some rods distant, they were 7.5 and 6.9. In one tree growth during drought even slightly exceeded that during the wet years. The average increments of growth of all trees during the wet years was 21.0 mm. It was 35 percent less (13.5 mm.) during drought.

Trees in two intermediate habitats were sampled. One was the first such habitat where hackberry also grew; the other was 40 miles northeast of Hays near Natoma. The trees were 54 to 70 years old, 9 to 25 inches in diameter, and 30 to 40 feet tall. Growth increments in millimeters in the usual sequence were 43.4 and 20.2, and 16.1 and 16.5, respectively. Averages were 29.8 and 18.4.

Cores were obtained from elms at five stations in wet habitats. The first three were those named as wet habitats for hackberry. Another was near a marsh on the Smoky Hill River near Hays, and the fifth was on the Saline River near Plainville, 16 miles north of Hays. The trees were 20 to 66 years old, 9 to 22 inches in diameter, and 25 to 50 feet high. Growth increments in millimeters at the several stations were, in order, 37.5 and 36.6, 37.1 and 37.3, 24.8 and 29.9, 37.0 and 46.0, and 46.3 and 38.9. The average increments of growth for all trees during the wet years was 36.5 millimeters and for the dry ones 37.7. During both wet and dry years growth of elm was most rapid in the wet habitats. During wet years it was 18 percent less in intermediate habitats and 42 percent less in dry ones. Similar decreases for

[4] Foresters ordinarily give similar growth data in inches of increase in diameter at breast height (4.5 feet above ground)—the commonly accepted height for such measurements.—C. F. K.

Table 11. Average increment of growth of hackberry and American elm at each of several sites in dry, intermediate, and wet habitats during a period of eight wet years (W) and a similar period of drought (D). Average age and size of the trees are also given.

Habitat	Growth	Age	Diam.	Height
	HACKBERRY			
	mm.	*years*	*inches*	*feet*
Hays, Ravine	W 14.7 D 11.5	36	8	19
Hill City, Ravine	W 25.5 D 14.5	38	13	19
Plainville, Ravine	W 11.4 D 10.4	38	7	16
Mean average	W 17.2 D 12.2	37	9	18
Munjor, Big Creek	W 23.0 D 17.1	53	13	23
Hill City, Jack Creek	W 27.7 D 27.1	48	13	22
Stockton, Dry wash	W 27.9 D 20.2	53	12	30
Mean average	W 26.2 D 21.5	51	13	25
Hays, Big Creek	W 27.5 D 30.5	49	9	42
Rush Center, Walnut Creek	W 17.0 D 18.5	57	15	36
Jetmore, Sawlog Creek	W 15.2 D 13.3	55	14	28
Mean average	W 19.9 D 20.8	54	13	35
	AMERICAN ELM			
Hays, Ravine	W 23.8 D 14.7	40	11	21
Stockton, Dry wash	W 22.5 D 12.5	36	7	17
Plainville, Ravine	W 16.8 D 13.2	48	18	29
Mean average	W 21.0 D 13.5	41	12	22
Munjor, Big Creek	W 43.4 D 20.2	58	25	30
Natoma, Dry wash	W 16.1 D 16.5	60	12	37
Mean average	W 29.8 D 18.4	59	18	33
Hays, Big Creek	W 37.5 D 36.6	45	19	43
Rush Center, Walnut Creek	W 37.1 D 37.3	40	16	32
Jetmore, Sawlog Creek	W 24.8 D 29.9	53	18	33
Hays, Smoky Hill River	W 37.0 D 46.0	20	15	22
Plainville, Saline River	W 46.3 D 38.9	27	12	39
Mean average	W 36.5 D 37.7	37	16	34

the dry years were 51 and 64 percent. These data are summarized in Table 11.

Effects of Drought on Annual Increment

The effect of drought upon radial growth may be more plainly seen where the yearly growth increments (1928 to 1943) are shown by graphs. Both hackberry and elm were sampled in dry, intermediate, and wet habitats at Hays and the data are shown in Figure 62. It is significant that in the dry habitat from 1928 to 1934 the increment in the elm (Graph 4) was about twice that of the hackberry (Graph 1). Then the growth rate of elm decreased, until in 1938 it was less than that of hackberry, and except for one year (1942) it remained less.

Growth of both species in intermediate habitats (Graphs 2 and 5) corresponded well with the graph of precipitation. Fluctuations in the growth of elm were very much greater than those of hackberry. Also the rate of growth was much higher until the beginning of drought in 1933. But during the drought, rate of growth was much the same in both species. With the return of abundant soil moisture the elm again grew more rapidly.

In wet habitats the growth increment in the elm (Graph 6) was again nearly twice that of the hackberry (Graph 3) during the wet period previous to the drought. Furthermore, no great decrease occurred during drought in either species. In fact, the trend generally was upward in the hackberry until near the end of the drought. From 1938 until 1941 the increment was even slightly greater in the hackberry than in the elm. The general trend in both species, however, was downward after 1938, except that growth in elm increased when soil moisture became plentiful.

These graphs indicate that elm was more adversely affected by drought than hackberry, and also that it grew more rapidly in intermediate habitats except during drought than in either dry or wet ones. Moreover, rate of growth of hackberry in wet habitats was greater during drought than during the wetter years. Elm also grew quite as well in wet places during the dry years as before or following them.

In the study of these and the following species of trees only general correlations with growth in dry, intermediate, and wet sites during periods of high and low precipitation have been pointed out. Irregularities in growth may have been due in part to reduced or increased vigor following drought, to excentric growth which would result in errors in the samples, or to damage to the foliage by insects or fungi or by wind and high temperatures. Twigs and branches may have been damaged directly by high insolation when foliage became sparse or by effects produced by scorched leaves which remained attached to them (Reed & Bartholomew 1930). Degree of lowering of the water table and poor aeration of soil during rainy periods are, of course, factors of the environment. While these were not measured, nor variation due to other possible causes studied, yet it seems clear that the chief cause of periodic variation in growth was due overwhelmingly to the changing environment and much less to any other cause or combination of causes.

STUDIES ON ASH

Samples were taken from trees in a timber claim on level upland near Goodland in northwestern Kansas. The planted area was originally about 20 acres. A cultivated field on the west had been the source of much dust which had blown into the grove and buried the trunks of some trees to a depth of 2 to 4 feet. The north end of the long rectangular grove was bounded by a deep ditch along the highway. This supplied extra water for growth and was actually a moderately moist site. Except here, drought had taken so heavy a toll that only a few living trees remained. These were along the north end of the west border and between this border, and the trees along the road. All the trees had been injured by drought, especially in the tops of the crowns, but dead branches also occurred near the base. Replacement of branches from dormant buds on living trees gave grotesque shapes to these relicts. Cores were taken only from those individuals least damaged; some from those on the western edge and others from the interior. These trees, which average 28 years in age and 5 inches in diameter, were only 17 feet tall. That the increment of growth was very small is shown in Table 12.

The trees near the ditch which were older and much larger were used as an example of an intermediate habitat. Here growth was more than twice as great as in the dry sites during the dry years and also much greater during the wet ones. Cores of ash in intermediate sites were taken at three other stations where hackberry or elm or both had been sampled. The average increment of growth during the wet years was 26.8 mm. or 77 percent greater than that in the dry sites (15.1 mm.). During the dry years the increment was only 16.7 mm., but even this was more than 2.5 times greater than that in the dry sites (6.0 mm.).

Cores from trees in wet habitats were taken along creeks or rivers at Hays, Rush Center, Jetmore, Plainville, and Hill City, where previous work had been done. In addition samples were also taken on Sappa Creek about 5 miles north of Edson, which is east of Goodland. The results are shown in Table 12, where it may be seen that the average rates of growth during the wet and dry years were only slightly different (28.0 mm. and 26.3 mm., respectively). Nor did this much exceed average growth in the intermediate habitats during wet years. But during drought it was 57 percent greater. The slowest growth occurred at Jetmore, the most southwesterly station and consequently the most arid one.

RELATIVE GROWTH OF HACKBERRY, ELM, AND ASH

Growth of the three species of forest trees in each of the three habitats may be understood better by examination of Table 13. Data on ash from the dry habitat are not included since only at Goodland had the trees been transplanted. Increment in elm growing in dry habitats was greater than it was in hackberry.

TABLE 12. Average increment of growth of green ash and cottonwood at each of the several sites in dry, intermediate, and wet habitats during a period of eight wet years (W) and a similar period of drought (D). Average age and size of trees are also given.

Habitat	Growth	Age	Diam.	Height
	GREEN ASH			
	mm.	*years*	*inches*	*feet*
Goodland, Edge of grove	W 11.8 D 7.1	28	5	16
Goodland, Interior of grove	W 18.4 D 4.9	28	5	17
Mean average	W 15.1 D 6.0	28	5	17
Goodland, Grove near ditch	W 23.1 D 14.8	43	10	24
Hill City, Jack Creek	W 29.9 D 16.4	20	6	20
Munjor, Big Creek	W 32.0 D 25.1	44	16	30
Natoma, Dry wash	W 22.3 D 10.6	52	10	33
Mean average	W 26.8 D 16.7	40	11	27
Hays, Big Creek	W 32.8 D 40.3	28	11	41
Rush Center, Walnut Creek	W 32.6 D 32.0	45	15	38
Jetmore, Sawlog Creek	W 14.7 D 13.0	53	9	28
Plainville, Saline River	W 23.9 D 25.1	37	11	38
Hill City, Jack Creek	W 36.8 D 27.7	20	8	22
Edson, Sappa Creek	W 27.4 D 19.6	23	8	27
Mean average	W 28.0 D 26.3	34	10	32
	COTTONWOOD			
Syracuse, Dry wash	W 8.5 D 9.5	65	24	40
Brownell, Grove	W 39.5 D 29.0	22	12	30
Wakeeney, Dry wash	W 29.0 D 16.9	65	36	60
Hill City, Hedgerow	W 22.9 D 14.1	51	16	36
Mean average	W 25.0 D 17.4	51	22	42
Hays, Smoky Hill River	W 37.0 D 30.0	35	24	40
Hays, Dry wash	W 64.5 D 36.5	30	23	38
Hill City, Jack Creek	W 52.1 D 27.9	26	19	39
Hill City, Springs, Jack Creek	W 82.8 D 55.0	35	27	45
Mean average	W 59.1 D 37.4	32	23	41
Hays, A marsh	W 61.5 D 87.0	20	14	30
Rush Center, Walnut Creek	W 39.8 D 53.8	65	22	40
Mean average	W 50.7 D 70.4	43	18	35

TABLE 13. Average total growth in mm. of hackberry, elm, and ash during eight wet years (W) and eight dry ones (D), in dry, intermediate, and wet habitats.

Habitat	HACKBERRY		ELM		Ash	
	W	D	W	D	W	D
Dry	17.2	12.2	21.0	13.5	....	....
Intermediate	26.2	21.5	29.8	18.4	26.8	16.7
Wet	19.9	20.8	36.5	37.7	28.0	26.3

In the intermediate habitats elm again grew more rapidly than the other species during the wet years, but was exceeded in rate of growth by hackberry during the dry ones. Ash grew at the same rate as hackberry during the wet period, but was exceeded by both hackberry and elm during the dry period.

Elm made its best growth during both wet and dry periods in the wet habitats. Ash grew much more rapidly here than in the intermediate site during the dry period, and slightly better during the wet one. But hackberry made its most rapid growth in the intermediate habitats. In the wet habitat the growth of elm was most rapid, and that of hackberry the slowest.

STUDIES ON COTTONWOOD

Rate of growth of cottonwood was studied at Syracuse near the Kansas-Colorado state line in the drier southwestern part of Kansas, at Brownell 45 miles southwest of Hays, as well as at Wakeeney northwest of Hays, and at Hill City. Growth was very slow at Syracuse, and averaged slightly better during the dry years than the wet ones. Mean average growth in the dry sites was 25.0 mm. during the period of wet years, and 17.4, or 30 percent less, during the dry ones (Table 12).

At the four stations representing intermediate habitats, growth was 59.1 mm. during the 8 wet years and 37.4 during drought.

The growth increment was higher in the wet habitat at Rush Center during the dry years and very much higher at Hays than during the wet ones. Mean average increment was 50.7 mm. in wet years but 70.4 in drought. Thus, growth during dry years was 53 percent less in dry habitats than in intermediate ones, and in wet habitats 88 percent greater. But during wet years growth was 58 percent less in dry habitats and 14 percent less in wet ones than in intermediate sites. Cottonwood grew much faster in all habitats than hackberry, elm, or ash

STUDIES ON BUR OAK AND OSAGE ORANGE

Rate of growth of bur oak was ascertained in an intermediate site at Natoma and a wet one on Salt Creek near Paradise, 40 miles northeast of Hays. During wet and dry periods, respectively, growth in the moderately moist site was 17.1 and 10.8 mm. At both stations the trees averaged 54 years in age; they were 12 to 15 inches in diameter but only 36 to 38 feet tall. Increase in radius during the wet years in the wet habitat (18.6 mm.) was scarcely greater than that in the drier ones. But during the dry period the trees grew more rapidly (14.4 mm.) than those in the intermediate site.

Effects of wet and dry periods on the growth of Osage orange were ascertained for a number of trees in a timber claim on upland (dry site) and where they extended across a ravine (intermediate site) near Rush Center. In the dry site trees 5 inches in diameter, 10 feet high, but 38 years old grew 15.2 mm. and 10.2 mm. during wet and dry periods, respectively. Trees in the ravine were 9 inches in diameter, 15 feet high, but only 30 years old. Their growth rate during wet years (22.6 mm.) and dry ones (20.1 mm.) was 33 and 49 percent greater, respectively, than that in the same timber claim on the upland.

SUMMARY

This study describes the effects of the greatest drought since the beginning of recorded weather history on forests and trees growing in a prairie climate. The area considered extends from central Iowa westward into Colorado and includes the territory from southern Oklahoma to Canada.

Data are from a wide range of sources; they include predrought surveys of trees and conditions for their growth in grassland which give a necessary background for an understanding of their injury and death or recovery in different sites. The most intensive studies were made in the western half of Kansas.

A major area of postclimax forest occurs along the Missouri River. Here the forests are composed of several communities; red oak-linden *(Quercus borealis maxima-Tilia americana)* is the most mesic, black oak-shagbark hickory *(Quercus velutina-Carya ovata)* is intermediate, and bur oak-bitternut hickory *(Quercus macrocarpa-Carya cordiformis)* the most xeric. Communities of shrubs often occur as a transition from forest to prairie. In Nebraska all of these forests suffered heavily from drought as they did elsewhere, at least when pastured.

Decrease in size of individuals, decrease in number of species, and confinement to the most protected sites are marked northward, and especially westward where the climate becomes more arid. A height of trees of 70 to 90 feet diminishes rapidly to 25 to 45 feet; rate of growth in diameter decreases one-half or more 150 miles westward from the Missouri River.

Along prairie streams westward from the Missouri River forest communities rapidly disappear, and the typical condition is an intermingling of forest trees along the flood plain. Farther westward trees are mostly confined to the banks of the larger streams and to broad, shallow ravines tributary to them, or to the vicinity of springs. Some are found in the shelter of steep protecting bluffs. In the driest prairies trees occur naturally, if at all, only as small groups or as individuals in the most protected places along streams. Planted trees occur in timber claims, windbreaks, and hedgerows, but sparsely in the more arid western prairies.

Early effects of the drought were very impressive and widely reported; the literature revealed that in Minnesota 40 percent of all the trees in shelterbelts, mostly boxelder, willow, green ash, silver maple, and cottonwood, were considered dead or dying in 1934. In North Dakota practically all maturing cottonwoods, willows, and boxelders were killed, except where the water table was continuously high; the boxelders often recovered by root sprouts. Great damage to trees occurred in Montana. Losses by death of coniferous trees in Iowa in the spring of 1934 ranged from 5 to 39 percent. Trees in central Kansas showed 41 percent death or injury and those westward 55 percent in 1936. In central Oklahoma 20 to 50 percent death of trees occurred and much higher losses of 35 to 79 percent were reported in western Oklahoma by 1937. Reconnaissance of tree plantations late in 1934 showed 43 percent survival of standing trees in North Dakota, 32 in South Dakota, 18 in Nebraska, and 28 in the Oklahoma-(northern) Texas area. As the drought progressed earlier losses were greatly increased.

Predrought data on mean annual precipitation, average weekly evaporation, and water content of soil from eastern Nebraska, north-central Kansas, and eastern Colorado are presented. They show clearly the semiarid environment west of the Missouri River and why it becomes even more inimical to growth of trees westward. A period of dry years preceded the severe drought. Precipitation was lowest in 1934 and 1936, but because of previous desiccation of soil and vegetation 1939 was also one of the worst drought years. The extremely low precipitation during these years and the weekly amounts of available soil moisture (which were very frequently nil to 6 feet in depth during the drought) were ascertained. The water table in many ravines and lowland terraces fell 3 to 4 or more feet over much of the Midwest. Trees on upland root far above the normal water table. Evaporation was extremely high and sometimes one-third or more greater than during a predrought year. Increases of 6° to 15° F. in average weekly temperatures were common, and average weekly maximum temperatures of 101° to 109° sometimes occurred.

The chief cause of injury was a lack of sufficient available water. This was due to low precipitation but was accentuated by one or more of several causes, as competition for water by grasses, decreased rate of water infiltration and rapid runoff, drying up of streams and springs, and a rapid fall of the water table in ravines and lowland terraces. Lack of an adequate water supply also resulted from low humidity, high evaporation, desiccating winds, and the inability of trees to accommodate their root systems to the rapidly changing environment. Unrestricted grazing was a common cause of excessive mortality in timber claims and windbreaks.

Experimental data on the harmful effects of competition with grass on both roots and shoots of trees have been presented. Root distribution of the same tree species in different types of soil including alluvial soil with a high water table has been noted, and the general relation between root extent and distribution in different sites to drought resistance is pointed out.

Injury and death of woody plants due to the effects of drought were often the results of continuous adverse conditions over an extended period of time. But death of trees and shrubs on flood plains and terraces sometimes occurred in a relatively short time if the water table lowered rapidly. Effects of early drought were wilting, discoloring, withering, or shedding of the foliage. An early outward sign of repeated yearly drought among deciduous trees was great reduction in size and number of leaves and defoliation of the outer portions of the crown. Great injury was also often caused by partial or total and sometimes repeated defoliation by grasshoppers, web worms, and leaf-eating larvae of other insects; such attacks usually occurred during the years of great drought.

Exposure of branches with reduced foliage to high insolation, great heat, and low humidity was a common cause of injury. Desiccation resulted in the death of the smaller branches, and permitted the entrance of wood borers, other insect larvae, and fungi. Desiccation and wood borers caused the death of the branches to proceed rapidly downward; often the entire tree succumbed.

In western Kansas, which is representative of other prairie states in this latitude, counts on hundreds of trees were made in 1935 and again late in the drought or after its close. Losses in the most xeric places where trees grew naturally were high, in dry ravines (American elm *(Ulmus americana)* 70 percent, and hackberry *(Celtis occidentalis)* 36) and on bluffs (American elm 56, hackberry 28, and green ash *(Fraxinus pennsylvanica lanceolata)* 33 percent). Losses of red cedar *(Juniperus virginiana)* were usually less than any of the preceding. Average losses in percentage of trees along continuously flowing streams and intermittent streams were American elm 5 and 62, hackberry 5 and 75, and cottonwood *(Populus sargenti)* 6 and 59. Loss of willows (*Salix* spp.) along intermittent streams was 70 percent. Death of trees growing near running springs was rare. But about springs that almost failed to flow in drought, a mortality of 55 percent of cottonwoods and 89 percent of willows was recorded.

Destruction in long-established timber claims was high. Severe losses occurred during dry periods previous to 1933; the great drought almost annihilated the survivors. Where 45 percent of Osage orange and 86 percent of green ash were dead in 1935, all had succumbed by 1939. Even in tree claims on lowland early in drought black locust *(Robinia pseudoacacia)* had lost 75 percent and cottonwood 14 percent.

Losses of trees in windbreaks were nearly always heavy. Dust storms contributed greatly to this loss through partial burial of the trees in great drifts of soil, sometimes 4 to 8 feet deep. Losses of green ash, American elm, hackberry, and other deciduous trees were frequently 80 to 90 percent and sometimes more. In some places trees of red cedar alone survived.

Of 3,200 trees in a hedgerow of Osage orange (*Maclura pomifera*) all but 15 succumbed. Such high losses were typical.

Average losses of trees in Nebraska and Kansas were probably 50 to 60 percent by death and an additional 20 to 25 percent suffered severe to moderate injury. Red cedar, hackberry, and bur oak endured drought especially well; silver maple, boxelder, and cottonwood seemed less well adapted to endure long-continued drought.

Effect of drought upon the radial growth of uninjured or least injured trees in western Kansas was ascertained. Cores were taken with an increment borer from 3 to 8 trees of hackberry and American elm in each of three sites (dry, intermediate and wet) at each of 3 to 5 widely separated stations in western Kansas. Growth during 8 good years was compared with that during 8 dry ones. During the good years rate of growth of hackberry was 66 percent as great in the dry habitats and 76 percent as much in the wet ones, as that in the intermediate sites. Similar values during the dry years were 57 and 97 percent. During both good and dry years growth of elm was most rapid in the wet habitats. During good years it was 18 percent less in intermediate habitats and 42 percent less in the dry ones. Similar decreases for the dry years were 51 and 64 percent.

In dry habitats from 1928 to 1934, the increment of growth in American elm each year was about twice that of hackberry. Then its growth rate decreased until in 1938 it was less than that of hackberry, and remained less even after the drought. In intermediate habitats fluctuations of growth in elm were much greater than those in hackberry. In wet habitats the general trend of hackberry was upward until near the end of the drought, but growth rate of elm decreased slightly.

Average rate of growth of green ash was about the same in both wet and intermediate habitats on good years, but in dry habitats it was only slightly more than half as great. But on dry years the average rate of growth decreased 36 percent in intermediate habitats from that in wet ones and 77 percent in the dry habitats. Ash in intermediate habitats during the wet period grew at the same rate as hackberry, but less rapidly than elm; but in wet habitats during the dry period it grew more rapidly than hackberry but less rapidly than elm. Rate of growth of cottonwood, bur oak, and Osage orange were also determined.

Trees that retained some life at the close of the drought usually remained alive temporarily unless infestation by wood borers was so complete or the trees so nearly dead that they were unable to resume growth. Recovery was shown principally and commonly by renewed growth locally within the crown. In dry sites even after 3 or 4 years of good precipitation leafy branches were sometimes few and foliage was sparse. But where drought had been less severe foliage of the renewed portions of the crown was unusually dense. Often the dead branches in the tops of the crown were soon obscured by new ones where moisture was plentiful. Sprouts developed from the bases of certain trees grew rapidly. Dead trees were partly replaced by seedlings but only where the trees grew naturally. In this manner red cedars continued to replace their losses throughout the drought. Seedlings were not found in timber claims, windbreaks, or hedgerows in mixed prairie, and only rarely in unpastured places eastward to the Missouri River.

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