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DEPARTMENT OF BOTANY
THE UNIVERSITY OF NEBRASKA

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CONSERVATION DEPARTMENT
OF THE
CONSERVATION AND SURVEY DIVISION
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As defined by law, the Conservation and Survey Division of the University includes the following state departments and surveys: Soil, Geological, Water, Biological, Industrial, Conservation, and Information Service. Its major purpose is to study and describe the state's resources and industries for use in development. Reports of the Division are published in three series, i.e., Nebraska Soil Survey, Nebraska Geological Survey, and the Conservation Department.

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Quantity of Living Plant Materials in Prairie Soils in Relation to Run-off and Soil Erosion

INTRODUCTION

The menace of soil erosion did not appear in the west until much of the prairie was broken for cropping or weakened by continuous overgrazing. The grassland sod is a great conserver of rainfall; the amount of run-off water is relatively small, and the soil is firmly held against the forces of erosion. This study is concerned with the rôle that the living underground plant parts play in promoting the absorption of water by the soil, and especially their importance in reducing run-off. Their holding of the soil against the forces of water erosion has been experimentally determined. A study of the quantity of living plant materials in native prairies and pastures near Lincoln, Nebraska, has just been completed. These materials—largely the underground parts of grasses—are composed of roots, rhizomes, and the bases of stems. In the case of non-grassy species or forbs, they sometimes include corms, bulbs, and certain other underground plant structures.

The relation of the vegetation to the effectiveness of the precipitation in supplying water to the soil is one of great importance. When the fate of the water falling as drops of rain is studied, it is found that a part is intercepted by the vegetation and never reaches the soil. Much water is lost as run-off when absorption is not sufficiently rapid. This frequently results in erosion. Large amounts are absorbed by the soil and again used by the plant, especially when the vegetation has produced good soil structure and abundant humus. Some water may percolate beyond the depths of the roots of even the most deeply rooted species.

The cover of vegetation and the amount of living and dead organic materials in the soil both play an extremely important rôle in all of these processes. Although this study is not concerned primarily with the effects of the cover of vegetation on soil water relations, yet plant cover is closely related to quantity of underground plant parts and to run-off. Hence, brief consideration will be given to the interception of rainfall, decrease in run-off, and promotion of absorption by the cover of vegetation.

Rainfall Interception.—When rain falls in either light or heavy showers a large amount of it never reaches the ground. It is intercepted by plants and is again lost to the air by direct evaporation. Extended experiments have shown that much water is held as thin films on the upper surfaces of leaves or as drops or blotches or retained in capillary depressions such as those adjacent to veins. In wooded areas large quantities also accumulate on the surfaces and in the crevices of the bark of trunks and branches of trees from which it evaporates. The amount thus retained is reduced by the wind, but the rate of evaporation is increased. Interception losses are so great that they are considered of much importance by certain engineers in calculating the run-off or yield of drainage basins. The most extensive work has been done by Horton (1919) who found that the mean interception loss under 11 different species of trees in New York was about 40 per cent of the total rainfall. The amount of water lost to the soil in this manner varied from 70 to 100 per cent in light showers and was about 25 per cent in heavy, long-continued rains. The water running down the trunks of the trees was caught and measured, and this was not included in the amount intercepted. The interception losses on the Seneca River drainage basin above Seneca Falls, N. Y., for the summer of 1915, for example, amounted to 11 per cent of the precipitation. It was determined experimentally that the interception losses from certain fully grown cereal and leguminous crops were only slightly less than those due to trees. Hence, a cover of growing crops or of prairie vegetation probably intercepts an appreciable part of the precipitation and in this way actually diminishes the water supply. Water thus intercepted is lost to the soil. It can cause neither run-off nor erosion. But the same cover that intercepts the precipitation likewise exerts a pronounced effect upon the force with which the raindrops strike the soil and their entrance into the soil by absorption.

Decrease in Run-off.—Where there is a cover of grass the force of the rain is broken by the foliage of the grass and other herbs and by the litter of fallen leaves and stems beneath. Hence, the rain does not beat directly upon the soil. The lodgement of the undecayed materials among the stems of the grasses forms an intricate series of minute dams and terraces which tend to hold the water until it can percolate into the soil. Abundant humus creates a spongelike condition in the top soil which increases its capacity to absorb and hold water. Hence, run-off in the prairie is usually slight unless the rains are heavy. Even during heavy rainfall the water that does run off is usually clear, since the soil is firmly held in place by the bases of the plants, by their widely spreading and much-branched rhizomes, and by their widely and deeply spreading root systems. This may be illustrated by a single example. During a rainfall of 5 inches over a period of two days, the run-off from a native prairie on a 5° slope was only 3 per cent, all clear water. On a similar slope only 35 feet distant in wheat stubble, the run-off was 28 per cent, and more than 1/100 inch of surface soil was washed away (Weaver and Noll, 1935).

Increase in Run-off and Erosion.—It is only when the vegetation is closely grazed, and the amount of roots and rhizomes diminished that serious erosion begins. Other factors being equal, the intensity of erosion is directly proportional to the decrease in the amount of vegetation, both above and below ground. Upon prairie areas from which the vegetation has been largely or completely removed by overgrazing, the rain drops beat upon the bare soil like millions of little hammers. The soil, already trampled by grazing animals, is further compacted and its absorbing capacity reduced. The cohesive force between the soil particles is lessened as the surface becomes muddy. They shift their position under the effect of the beating rainfall and fill up the soil pores. Thus the absorbing capacity is reduced. The excess water accumulates on the surface and on running off removes with it the surface soil particles, the humus, and the dissolved salts.

Interrelation of Tops and Roots.—A cover of vegetation protects the soil. The first line of defense against the elements is above ground; the more formidable one is the plant parts within the soil. These are interdependent. The roots supply the tops with water and nutrients. The rhizomes store

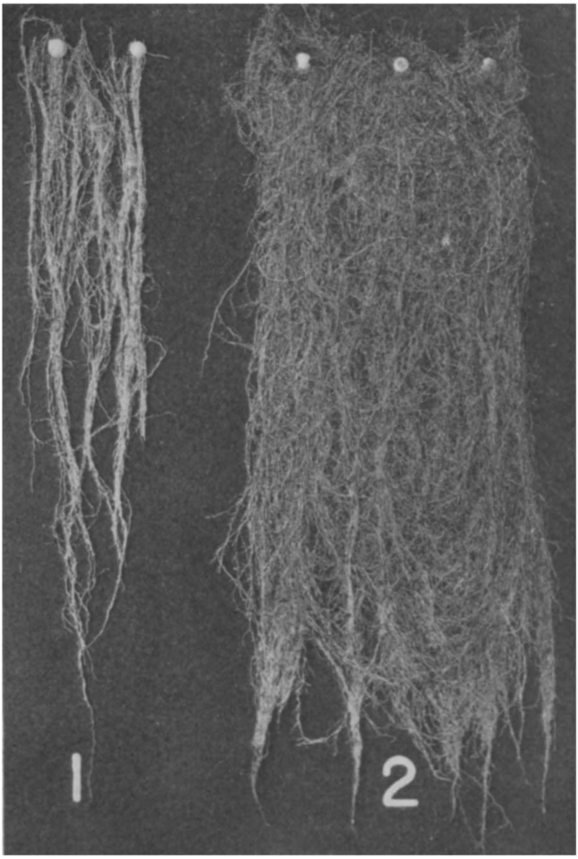

FIG. 1.—Roots of little bluestem (*Andropogon scoparius*) produced during a single growing season from blocks of sod about 5 inches square and 4 inches deep. These were grown under exactly the same conditions, except the top was clipped 6 times from No. 1. It yielded only 8 per cent as many roots by weight as the unclipped control, No. 2 (Biswell and Weaver, 1933).

the food and produce new tops. Roots and rhizomes are supplied with food from one source only, the green cover of vegetation. If this is too often destroyed by repeated close

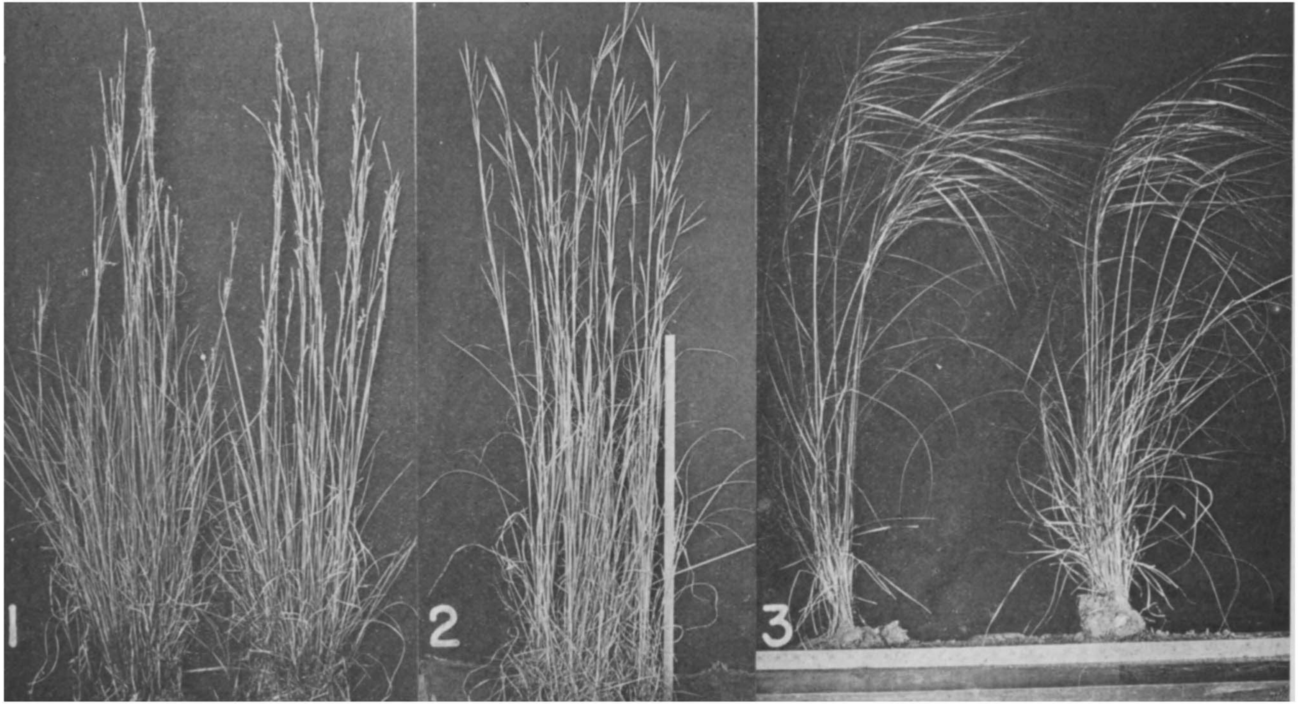

FIG. 2.—1, Little bluestem about 2.5 feet tall; 2, big bluestem about 6 feet tall; and 3, needle grass 3 feet tall. All have fully developed flower stalks.

grazing the underground parts weaken, die, and decay (Fig. 1). The prairie is replaced by another type of vegetation; this type by annual weeds; and the next stage is bare soil, easily eroded.

TYPES OF PRAIRIE

Recent extensive studies by Weaver and Fitzpatrick (1934) have shown that six types of grassland characterize the tall-grass prairies of eastern Nebraska. Two of these—the slough grass (*Spartina michauxiana*) type and the tall panic grass-wild rye (*Panicum virgatum-Elymus canadensis*) type—occur only in low soil that is too wet and poorly aerated for the development of big bluestem (*Andropogon furcatus*). A minor type found locally on the driest uplands is characterized by prairie drop seed (*Sporobolus heterolepis*). These were not considered in this study. Fully 85 per cent of the prairie and perhaps more is included in the three remaining and most extensive types of grassland, *viz.*: the big bluestem (*Andropogon furcatus*) type, the little bluestem (*Andropogon scoparius*) type, and the needle grass (*Stipa spartea*) type (Fig. 2).

TYPES OF PASTURE

When the native prairie is grazed certain changes occur. These changes take place very gradually under moderate grazing or slight overgrazing, but within a period of 2 to 5 years where overgrazing is pronounced. Although the changes in the plant populations are continuous until the soil is finally almost or entirely bare, for convenience of study they may be grouped into several more or less distinct stages.

Under moderate grazing the amount of forage usually exceeds the needs of the grazing animals. This often results in an irregular cover, some local areas being well grazed while others are scarcely grazed at all. The amount of bluegrass (*Poa pratensis*) is usually only 3 to 10 per cent. Certain native grasses and forbs increase in abundance while others decrease. But these changes occur within the prairie flora itself and are not influenced by invaders from without (Fig. 3).

A second stage in deterioration is indicated by a great increase in the abundance of bluegrass, or blue grama grass (*Bouteloua gracilis*), or buffalo grass (*Bulbilis dactyloides*), the latter especially on low ground. Not infrequently all three are found. These grasses, unlike needle grass and the bluestems, do not bear their leaves on elongated stems. Instead they grow close to the soil. Hence, they are much less injured by grazing and trampling. Many legumes have permanently disappeared, and slender grama (*Bouteloua curtipendula*) has usually greatly increased. Often closely grazed areas alternate with those that are undergrazed because of the presence

FIG. 3.—Lightly grazed upland prairie; the bunches are little bluestem.

of last year's forage, especially bunches of little bluestem, drop seed (*Sporobolus asper*), and other grasses.

A third stage is indicated when the area held by bluegrass and the short grasses overbalances that occupied by the native bluestems and other tall grasses. The latter are clearly declining but are still abundant. The grass cover is well intact everywhere; it is interspersed with a moderate number of prairie forbs which have become weeds and also a moderate

FIG. 4.—1, An old pasture near Lincoln where the original big bluestem has been entirely replaced by bluegrass (dark areas) and buffalo grass (light areas). 2, A square meter of pure buffalo-grass in full bloom.

number of long-lived weedy invaders not found in ungrazed prairie. The ravines and other much-grazed places are usually clothed with pure bluegrass or short grass.

Under long continued grazing and trampling the native bluestems and other prairie grasses disappear. This stage is characteristic of the bluegrass or short-grass pastures or of a mixture of these two (Fig. 4). Often the cover is broken in numerous small areas. Weeds are abundant, both perennials and those of lesser duration. The sand drop seed (*Sporobolus cryptandrus*) occurs in trampled areas, frequently in dense stands.

The final stage occurs where only fragments of bluegrass or short grasses are found. The sand drop seed may still occur in small patches but the dominant grasses are annual weeds such as wire grass (*Aristida oligantha*), small rush grass (*Sporobolus neglectus*), stink-grass (*Eragrostis major*), crab-grass (*Syntherisma sanguinale*), and numerous other grasses and forbs (Fig. 5). In many places the soil, although never turned by the breaking plow, is entirely bare.

FIG. 5.—Weed stage in the deterioration of bluestem prairie. The conspicuous weeds are woolly plantain (*Plantago purshii*) and a sage (*Artemisia gnaphalodes*), but numerous weedy grasses also occur. Note the bare soil.

Owing to the labor involved the quantity of underground plant materials was not determined in all of the stages but only in the more critical ones in the degeneration of the prairie.

METHOD OF SAMPLING AND WASHING

The method of determining the amount of living plant materials underground, while laborious, was simple and direct. In each type typical small areas were selected for excavation. It is believed that long and intimate association with the grassland permitted of the selection of very representative samples. These were taken in early spring before much new growth had occurred, all within a radius of 8 miles of Lincoln. Hence the climatic conditions were identical, including a mean annual precipitation of 27.8 inches (Weaver and Himmel, 1931). Only a few soil types were concerned and care was taken to note any significant differences in soil texture and structure.

An iron frame one meter (39 and 3/8 inches) long and one-half meter wide was placed upon the ground, after all the vegetation above ground had been cut flush with the soil surface and the debris cleared away. The soil within the frame was then removed as blocks of sod. These were inverted in a wooden frame and cut smoothly at a depth of exactly 4 inches. Then the remaining soil to a depth of 12 inches was removed, in vertical columns as far as possible, and added to the portion cut from the blocks of sod. Thus the soil of the entire one-half square meter to a depth of one foot was removed in two samples, one including the 0 to 4 inches depth, the other 4 to 12 inches. After transporting to the greenhouse, the soil was soaked in water about 48 hours. It was then washed away from the roots, rhizomes, and other plant parts.

Methods of washing varied somewhat depending upon the amount of clay. A screen 5 feet long and 3 feet wide, with 11 meshes per inch was laid upon a second screen of coarse mesh which was fastened to a wooden frame supported in a horizontal position. About 100 pounds of soil were placed on the screen at one time and sprayed with a gentle stream of water from a hose. By tilting the screen repeatedly the soil was rolled upon it in such a manner that the clay was washed from the soil mass without having to penetrate through it. By continued washing and later by kneading the soil with the hands there was finally left on the screen only the plant parts and a small amount of coarse soil particles. Care was always exercised not to direct the stream of water through a thin layer of soil against the screen, and practically no roots were lost. The few that went through the meshes were recovered from a second screen placed about a foot below the first. During the washing process the larger roots were removed from the soil as they became visible and placed in water in large buckets. To these were added the residue of soil and roots when washing was complete. The water in the buckets was stirred vigorously whereupon the roots floated on the surface and were recovered by pouring the water through a screen of 28 meshes per inch. This process was repeated several times in order to recover all of the roots. It was estimated that less than 1 per cent of the roots was lost, a negligible amount considering the variation in root distribution in the prairie. After the roots and other plant materials were partly dry but not yet brittle, each lot was carefully examined in detail, and any foreign matter, such as lime or iron concretions, fragments of leaves. etc., removed.

The plant materials thus obtained were not entirely living. Undoubtedly some rhizomes were dead and perhaps not a few roots. It was not expedient to separate the dead from the living plant parts, in fact as long as they were undecomposed and not lost by washing the part they played in holding the soil against erosion was similar to that of living materials.

Some doubt was at first experienced as to the treatment of the roots and other underground parts of forbs, which occurred at least in small amount in practically all of the samples. A single woody root of the lead plant (*Amorpha canescens*), for example, bulked large both in volume and dry weight as compared with that of the roots of the grasses. Since the underground parts of the forbs were so irregularly distributed and were so variable in quantity the error introduced by them into determinations of volume and dry weight was avoided by discarding them from every sample. For just as the grasses are the dominant vegetation in prairie above ground, often to the almost entire exclusion of forbs, so too their rhizomes and roots form the dominant bulwark in holding the soil. All samples were selected in representative stands of prairie cover where an abundance of forbs did not occur.

DETERMINATION OF VOLUME AND WEIGHT

The volumes of the plant materials were determined while they were thoroughly water soaked but dried outside until no liquid water clung to them. This was accomplished by spreading the wet material of each sample, freed so far as possible from excess water, in a thin layer on a large table and permitting it to dry, with frequent turning, until the water outside had evaporated. While the end point of drying was arbitrarily determined, all samples were treated as nearly alike as possible, and repeated tests showed that errors introduced by the method were relatively small.

A simple but accurate apparatus was devised for determining the volume. A glass jar, 18 inches high and 4.75 inches in diameter had attached to it a U-tube of 5 mm. diameter, which served as a siphon. The jar was filled with water which was then allowed to siphon out to the level of the short end of the tube outside the jar, about 3.5 inches from the top, the long arm inside extending to the bottom. When the rhizomes and attached roots were then submerged the overflow water was caught in a 500 c.c. graduate. The damp surfaces of the plant materials were immediately wetted and if the sample was put slowly into the jar no air bubbles were formed. It was necessary to divide large samples in determining volume. The volume of the plant parts was read directly as c.c. of water displaced.

The roots were then recovered, air dried, placed in small flour sacks and oven dried at 100°C. until they reached a constant weight.

NEED OF LARGE SAMPLES

A striking feature of any area of native grassland is the constant variation in the cover. This is true even when relatively small areas are examined. These changes in the quantity, distribution, and kinds of aboveground plant materials are no less striking than are those in the soil. The great variability in rhizomes, roots, etc., is marked where the soil is washed completely away from even the surface four inches (Fig. 6). Similar or even greater variations occur in the underground materials of bluegrass and other types of pastures even where the sod is selected for its uniformity, the amount depending in part upon the previous degree of grazing.

One-half square meter of a very uniform stand of *Stipa spartea* was excavated in two equal parts. The volumes of roots in the surface 0-4 inches were 402 and 405 c.c., respectively, and in the deeper layer 258 and 242 c.c. Dry weights of roots in the same order were 108 and 112 gm. and 60 and 56 gm. Thus in the first layer, volume of plant materials differed less than 1 per cent and the dry weight only 4 per cent. In the second layer of soil, volume of roots varied only 7 per cent, and a variation in dry weight of 7 per cent was also determined.

A typical square meter quadrat of *Andropogon furcatus* was selected on low level ground. It was divided into quarters and each one-fourth square meter excavated, washed, and volumes and weights determined separately (table 1).

TABLE 1.—*Volumes and weights of underground materials in big bluestem sod.*

Sample	Volume, c.c. 0–4″	Weight, gm. 0–4″	Volume, c.c. 4–12″	Weight, gm. 4–12″
1	765	288	295	102
2	770	255	240	88
3	799	265	250	96
4	836	292	270	94

Had the two half-meter quadrats been selected so that they included samples 1 and 2, and 3 and 4 respectively, differences of volumes in the first and second soil layers would have been 7 and 3 per cent. Had they included 1 and 4, and 2 and 3 respectively, differences would have been 2 and 15

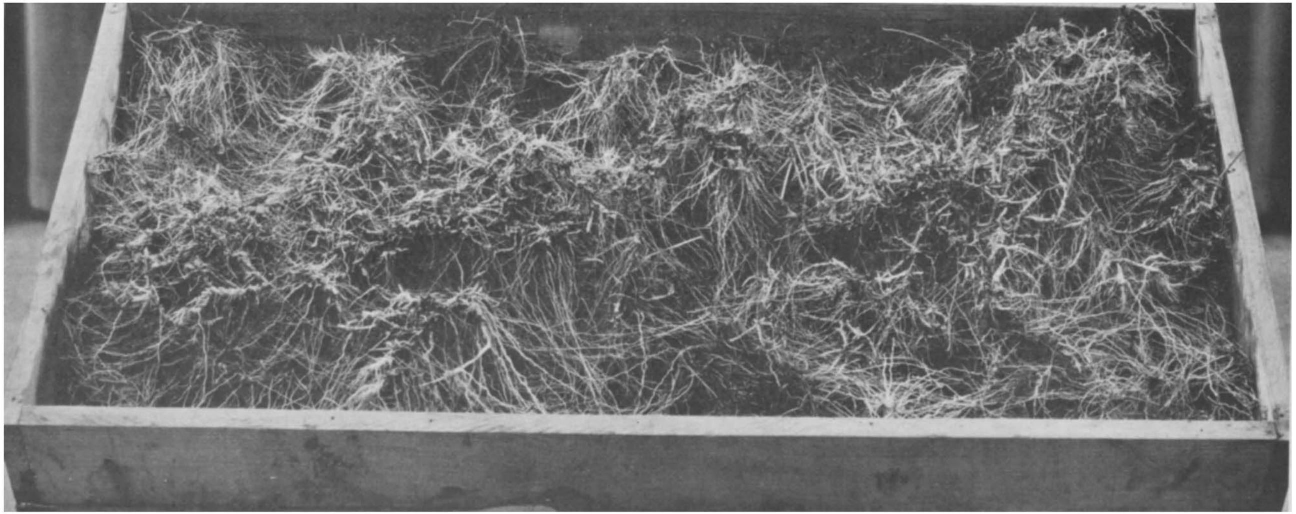

FIG. 6.—Underground parts from a block of sod of big bluestem 1 meter (39⅜ inches) long, 0.5 meter wide, and 10 cm. (4 inches) deep. The soil was washed away leaving the rhizomes and roots in place. Note that they are rigid enough to maintain approximately their original position. They are nature's chief bulwark against soil erosion.

per cent. Likewise differences in dry weights in the first case would have been 3 and 0 per cent in the two layers of soil; in the second arrangement 12 and 6 per cent.

Two half-square meter quadrats, adjoining end to end, were selected in an upland pasture where the native grasses over a considerable area had been entirely replaced by bluegrass. The quarter meters were numbered from 1 to 4, excavated, and the volumes and weights of underground parts determined separately (table 2).

TABLE 2.—*Volumes and Weights of Underground Materials in Bluegrass Sod.*

Sample	Volume, c.c. 0–4″	Weight, gm. 0–4″	Volume, c.c. 4–12″	Weight, gm. 4–12″
1	397	119	200	58
2	372	123	135	46
3	293	103	149	52
4	290	111	180	56

Differences in volume of roots between any two samples in the 0-4 inches of soil varied from 1 to 37 per cent, and in the 4-12 inches 10 to 48 per cent. Variations in dry weight ranged from 3 to 19 per cent in the surface layer and 3 to 26 per cent in the deeper one. The half-meter sample including samples 1 and 2 yielded 21 per cent greater total volume and 7 per cent greater total weight than the quadrat including samples 3 and 4, in this apparently uniform cover. Differences in yield may have been due to closer grazing of samples 3 and 4 than 1 and 2 during previous years.

From these data it may readily be seen that small samples would be quite unsatisfactory. The surface of one-half square meter when excavated to 12 inches depth involved the removal and washing of 5.38 cubic feet or more than 500 pounds of soil. The washing alone required 6 to 8 hours time of an experienced man. Such samples seem not only as large as were practicable but also covered enough area to yield representative data. They give the actual variations in the field. This study is based on a total of 106 separate samples.

AMOUNT OF UNDERGROUND PLANT MATERIALS IN PRAIRIE

BIG BLUESTEM TYPE

The two grassland types of greatest importance and widest extent are those characterized by *Andropogon furcatus* and *Andropogon scoparius,* respectively (Fig. 7). While little bluestem is found on uplands, big bluestem is best developed on lower moist slopes and well aerated lowlands. In fact, it was in practically complete possession of them. Sometimes it also occurs over limited areas on well watered, nearly level uplands (Weaver and Fitzpatrick, 1934). Big bluestem usually grows in such pure, dense stands that this species alone forms on an average about 78 per cent of the vegetation. It is frequently accompanied by small amounts of Indian grass (*Andropogon nutans*), a tall grass of similar habits. On lower and midslopes big bluestem not only shares dominance with little bluestem but also regularly forms 5 to 25 per cent of the grass cover in the little bluestem type of uplands except on the driest hilltops and ridges.

Big bluestem is a sod-forming grass. The individual stems in well established sod are usually spaced more than a centimeter apart. They are grouped into mats of open sod with so much space intervening that the total ground cover rarely exceeds 25 per cent and averages only about 13 per cent. The dense, widely spreading foliage varies in height from 1.5 to over 3 feet but mature flower stalks in late summer reach 5 to 10 feet.

The primary roots develop rapidly. Two months after germination these range from 14 to 40 inches in depth. Many of the roots of the secondary root system spread considerably, often 8-11 inches laterally at a depth of a foot. During the first growing season, even under competition, the roots reach a working level of 2 feet or more.

The very abundant roots of mature plants grow both vertically and obliquely downward. A few grow almost horizontally. They thoroughly occupy the soil and form a dense sod. Some roots extend obliquely more than a foot before turning downward. The mature roots are coarse (0.5-3 mm. in diameter) and tough, but poorly branched in comparison with upland grasses. Depths of 5 to 7 feet are usually attained.

FIG. 7.—1, Big bluestem in September on low ground in eastern Nebraska. The grass is 8 to 10 feet tall. Sage prominent in the foreground. 2, Little bluestem prairie in midsummer with a lower layer of prairie cat's foot and an upper one of white prairie clover, lead plant, and blazing star. The bunches of little bluestem are 18 inches tall.

The rhizomes of mature plants are very coarse, usually 3 to 6 mm. thick, much branched and frequently continuous for distances of 6 to 10 or more inches. The general level of the great majority is about 1 to 2 inches below the soil surface; they are common to a depth of 4 inches and a few extend even deeper. Thus the rhizomes alone form a rigid, coarse, open network, which is further anchored by the multitude of coarse, branched roots arising from them. These roots frequently arise at the rate of 20 to 25 per square inch. The rhizomes are studded above by the abundant coarse stem bases one to two inches of which are buried in the soil. The whole stem-rhizome-root system forms a magnificent network for holding the soil against erosion.

The volumes and weights of six samples are given in table 3. The volume in the surface 0-4 inches varied from 1,040 to 1,635 c.c. and the dry weight from 398 to 557 gm. This is directly in accord with the observed development of tops and also correlates directly with the type of soil. Samples 3 and 4 were taken from a heavy silt loam type of Wabash soil; the other four from a colluvial phase of the same soil type which contained a considerable amount of sand. The 4-12 inches of soil yielded a minimum of 399 and a maximum of 535 c.c. of roots.

TABLE 3.—*Volume and weight of underground plant parts in three types of native prairie. The numbers are for depths of 0 to 4 and 4 to 12 inches respectively, and those at the foot of the columns are the averages.*

Big bluestem Andropogon furcatus				Little bluestem Andropogon scoparius				Needle grass Stipa spartea			
Volume, c.c. 0-4″	4-12″	Weight, gm. 0-4″	4-12″	Volume, c.c. 0-4″	4-12″	Weight, gm. 0-4″	4-12″	Volume, c.c. 0-4″	4-12″	Weight, gm. 0-4″	4-12″
1371	399	445	109	1219	638	369	172	850	415	204	87
1040	432	398	130	1128	405	303	98	883	454	199	108
1535	535	544	190	1185	409	342	110	1130	560	262	118
1635	520	557	189	1270	570	457	143	752	438	178	91
1270	426	424	136	1252	393	435	112	715	328	197	81
1079	457	407	150	1215	460	352	117	807	500	220	116
1322	461	462	151	1211	479	376	125	856	449	210	100

The average volume in the surface layer (1,322 c.c.) and the average dry weight at both levels (462 and 151 gm. respectively) exceed that of any grasses studied. The volume of roots in the second level (461 c.c.) was slightly surpassed by that of the little bluestem.

The great decrease of plant materials in the second level is due largely to the position of the bulky, heavy rhizomes in the surface soil.

LITTLE BLUESTEM TYPE

Andropogon scoparius is the principal grass of this most important upland type. The little bluestem forms not only by far the most extensive type of uplands but also it occupies an area in the midwestern tall-grass prairies, as a whole, many times as great as that dominated by big bluestem. Little bluestem easily exceeds in importance all other upland species combined. It usually constitutes 55 per cent of the vegetation and sometimes 90 per cent. On lower hillsides it shares the land with big bluestem. Chief accompanying species are Kentucky bluegrass, needle grass, prairie drop seed, Indian grass, and slender grama grass, but there is nearly always a considerable number and variety of forbs. Little bluestem ordinarily forms an interrupted sod, the mats or tufts being so dense that most other species grow only in the spaces between them. Pronounced development of bunches occurs on steep slopes where run-off is greatest. These are usually 6-8 inches or less in extent (but sometimes 1.5 by 2 feet) and rather irregular in shape.

The leafy stems grow compactly in the bunches and sod mats. Even where poorly developed, 50-80 stems occur per sq. dm. and there are often 100-300 crowded in a similar area. The stems tiller freely and are leafy to the base. The foliage cover varies in height in late summer from 7 to 12 inches on dry uplands, but increases to 15 inches or more in favorable situations. Flower stalks range from 1.5 to 3 feet in height. The ground cover in this type seldom exceeds 25 per cent and an average cover of about 15 per cent has been determined.

The root system develops rapidly. Four or more tillers and 8 to 10 roots 12 to 22 inches long are produced the first summer. The young roots are fine and extremely well branched, some of the branches attaining lengths of 3 to 4 inches.

The short rhizomes of mature plants are usually 0.25 to 1 inch long and 3 to 7 mm. in diameter. They possess numerous short branches and give rise at depths of 0.5 to 1.5 inches to erect stems the bases of which are thickly sheathed with basal remnants of old leaves. Such tufts may occur singly, but more often many are found together composing the larger bunches or mats of sod.

The mature root system consists of a vast network of threadlike roots and masses of finely branched rootlets, some over 30 inches long. Thus the soil beneath the sod and several inches on all sides of it is filled with a dense mat of roots to a depth of two or more feet, the deeper roots extending to 4 or 5 feet. During heavy run-off on grazed land, the leafy bases of the densely grouped stems and the abundant, coarse, short rhizomes break the force of the water, while the network of minutely interlaced roots forms a felted mat which holds the surface soil. Serious erosion occurs only when the stand is so weakened that the holding power between the bunches gives way. But even this happens only after a considerable period of time.

The volumes and weights of six samples, all secured from Lancaster loam soil, are given in table 3. The volumes, especially in the surface layer of soil, are remarkably uniform, varying from only 1,128 to 1,270 c.c. In the deeper layer they range from 393 to 638 c.c. Plant materials in the surface soil vary in weight from 303 to 457 gm. and in the deeper layer from 98 to 172 gm. The samples that yielded highest had a slight mixture of the coarse Indian grass; also the vegetation was poorest on the sample with the lowest yield.

The average volume in the surface layer is somewhat lower than that of the big bluestem; that of the deeper layer is slightly higher. The dry weights, however, are 19 and 17 per cent less in the two soil layers respectively.

NEEDLE GRASS TYPE

Stipa spartea is the dominant of a second upland type of prairie. Steep, dry ridges and xeric slopes, especially where the soil is thin and perhaps sandy or gravelly, are frequently more or less dominated by this type. Moreover, it is often abundant on flat lands at the heads of draws and is readily distributed over broad washes on lower slopes that are subject to overflow and deposit during exceptionally heavy rains. In pure growth it is not very abundant in southern Nebraska but increases in importance in northern Nebraska and South Dakota.

Stipa is a bunch grass (Fig. 2). The bases of the widely spaced bunches are usually only 1 to 5 cm. (but sometimes 12 cm.) in diameter. The foliage varies in height from 14 to 36 inches and the flower stalks are 3 to 4.5 feet tall. The basal cover in this type of vegetation averages only 11 per cent; a minimum of 7 and a maximum of 14 per cent were found. The foliage spreads so widely, however, that the abundance of this grass is easily overestimated. The chief grasses associated with it, besides the two bluestems and bluegrass, are June grass (*Koeleria cristata*), prairie drop seed, Indian grass, slender grama, and two small panic grasses (*Panicum scribnerianum* and *P. wilcoxianum*).

Seedlings develop so rapidly that by midsummer the parent culms are often 8-12 inches tall and possess 5 leaves and 3 or 4 tillers. By this time the fine, well branched root system is usually 15-20 inches deep and in good contact with the moist soil.

The bases of the plants in the characteristic bunches extend 1 to 1.5 inches below the surface of the soil. These slightly enlarged bases of scores of closely aggregated stems play no small part in stabilizing an area. From the base of the bunch there arise numerous, tough, well branched roots, 1 to 2 mm. in diameter, usually at the rate of 75 to 100 per square inch. Many of these spread widely in the shallow soil and with other plants in this grass type firmly bind the soil.

The root system of mature plants usually reaches depths of 2.5 to over 3 feet and sometimes 4.5 feet. It is exceedingly well fitted for absorption in the upper soil levels. Numerous, profusely branched, smaller roots fill the surface foot and the larger ones give rise to many laterals which divide into fine branches in the deeper soil.

Data on volumes and weights of plant materials in the soil are given in table 3. Except for the third sample, which was taken in relatively low ground, the volumes in the surface layer are fairly uniform. With a single exception, volumes in the deeper soil layer vary from 415 to 560 gm. Considerable differences are shown in the dry weights. The smallest is 178 gm., the largest 262 gm. Compared with little bluestem, the plant materials average consistently less. The decreases in volumes in the two levels respectively are 29 and 6 per cent; and decreases in weight 44 and 20 per cent.

The amount of materials in each of the three types of grassland are shown in figure 10.

FIG. 8.—Bluegrass pasture on land formerly occupied by big bluestem. Only a few relics of the native grass occur (see foreground). Irregularity of grazing results from cattle avoiding dung-covered areas. Because of the increased supply of nitrogen in such areas, there is a rank growth of grass.

AMOUNT OF UNDERGROUND PLANT MATERIALS IN PASTURES

Certain grasses that occur somewhat sparingly in the tall-grass prairie spread rapidly when the prairie is grazed (Fig. 8). Chief among these are the two short grasses, blue grama (*Bouteloua gracilis*) and buffalo grass (*Bulbilis dactyloides*), and Kentucky bluegrass (*Poa pratensis*). The xeric short grasses occur normally only where the bluestems and other taller grasses are in thin stands and consequently produce little shade. In native prairies they are found in small amounts on the most xeric slopes and driest ridges or sometimes on lower ground where soil conditions are such that taller grasses do not thrive. Kentucky bluegrass is a rather constant component of the prairie. It has spread very widely since the coming of the white settlers and is now found practically everywhere. Several factors have contributed to the invasion of bluegrass along ravines and in lowlands and to its extension in smaller amounts to the uplands. Chief among these is the cessation of prairie fires and the practice of the annual removal of the grasses by mowing for hay. This removes the shade of the taller competitors and permits bluegrass to make a rapid, early growth in spring (cf. Weaver and Fitzpatrick, pp. 179 to 182, 1934).

BLUEGRASS PASTURES

Kentucky bluegrass is a smooth perennial with numerous, long, running rootstocks arising from its base. It grows in small bunches or tufts which are often spaced 1 to 4 or more cm. apart, even in a dense growth, but together they form a more or less continuous sod. The rhizomes are abundant to a depth of 2 to 3 inches; often they extend to 3 and occasionally to 4 inches, rarely deeper. Some are 5 to 10 or more inches long and many produce new sprouts even at depths of 3 to 3.5 inches. They vary in thickness from 1 to 2 mm. and are frequently branched. These long, tough, nearly horizontal stems aid the roots, which are fully as abundant and even finer than those of the short grasses, in holding the soil in place. Under severe erosion the stems and rhizomes, unlike those of all the preceding grasses, are not rigid enough to remain in place but sink away as the soil is removed. This dense tangle of exceedingly fine roots, etc., then affords a wonderfully efficient protection against further washing away of the soil (Fig. 9).

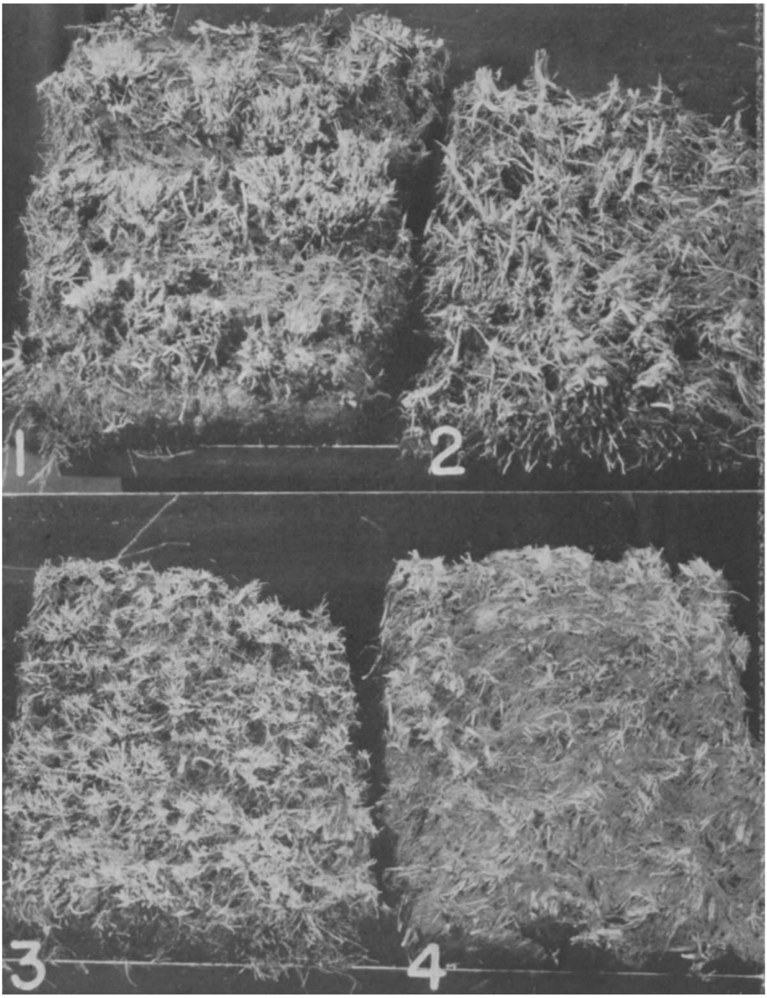

FIG. 9.—Blocks of sod with vegetation removed to the soil surface and the soil washed away to a depth of 1 inch. 1, Little bluestem; 2, big bluestem; 3, buffalo grass; and 4, bluegrass. Note the varying ground cover of stem bases.

The dark-colored, fine, fibrous roots occur in such abundance that with the creeping rootstocks they form a dense, tough sod. Some of the roots have a wide lateral spread, often running nearly parallel with the soil surface at depths of only 0.2 to 0.3 feet for distances of 1 to 1.5 feet from their origin. Usually they extend more obliquely or even vertically downward. In well established bluegrass pastures, depth of penetration of the bulk of the roots often does not exceed 32 inches, although some extend deeper. Intermixed with native grasses, the root extent is much greater.

Since *Poa pratensis* is the most frequent pasture type replacing the bluestem prairies, 5 samples were secured from typical lowland pastures (formerly occupied by big bluestem) and 5 from upland prairies that had degenerated into bluegrass pasture. In every case the stand was practically pure. The upland soil was Lancaster loam or Carrington silt loam; that of low ground was Wabash silt loam, or a transitional type.

The volume of the plant materials from upland to the 4-inch soil level varied from 583 to 940 c.c. depending largely upon the density of stand (Table 4). The root materials in the deeper layer were (with one exception) very uniform (329 to 360 c.c.). Materials from the lowlands varied widely, the first two samples being taken from a pasture that had been rather lightly grazed for a period of two years.

Dry weight on the upland in the surface layer varied from 180 to 263 gm.; on the lowland from 199 to 390 gm. A variation from 71 to 107 grams of roots occurred in the deeper layer of upland soil; in the lowland it ranged from 38 to 54 grams.

Comparing upland with lowland bluegrass, the average volume and average dry weight in the surface soil were 17 and 18 per cent less, respectively, in the drier soil. In the second soil layer, however, exactly the reverse occurred, the upland grass exceeding the lowland 85 per cent in volume and 94 per cent in weight. Without exception root materials were less both in volume and weight in the deeper layer on the low ground. This is explained by the deeper and better rooting habit of bluegrass in the drier upland soil.

TABLE 4.—*Volume and weight of underground plant materials in three types of native pasture. The numbers are for depths of 0 to 4 and 4 to 12 inches respectively, and those at the foot of the columns are the averages.*

Lowland bluegrass Poa pratensis				Upland bluegrass Pca pratensis			
Volume, c.c.		Weight, gm.		Volume, c.c.		Weight, gm.	
0-4″	4-12″	0-4″	4-12″	0-4″	4-12″	0-4″	4-12″
1305	129	335	38	769	335	242	104
1375	208	390	48	583	329	213	107
676	170	252	51	940	235	263	71
619	180	199	53	729	360	180	100
727	189	234	54	898	355	253	92
940	175	282	49	784	323	230	95
Blue grama Bouteloua gracilis				**Buffalo grass Bulbilis dactyloides**			
Volume, c.c.		Weight, gm.		Volume, c.c.		Weight, gm.	
0-4″	4-12″	0-4″	4-12″	0-4″	4-12″	0-4″	4-12″
1059	207	257	76	982	344	292	105
1108	566	240	140	721	360	232	100
1197	560	262	112	1030	470	280	124
1305	350	334	78				
1167	421	273	101	911	391	268	110

Underground plant materials in bluegrass pastures showed a marked decrease over those of the former vegetation. The volume in upland decreased 35 and 33 per cent; the dry weight 39 and 24 per cent. Decreases in volume in lowland were 29 and 62 per cent and the decreases in weight were 39 and 68 per cent respectively.

A striking difference between the bluegrass and all other types was the large amount of dead materials in the soil. In one 0 to 4-inch sample these were laboriously separated from living materials so far as it was possible to distinguish the two conditions. They constituted 25 per cent of the volume and 30 per cent of the weight. It seems that roots and rhizomes are both much longer lived among the prairie grasses. At least only a small amount of non-disintegrated dead material was found in the soil.

GRAMA GRASS PASTURES

Bouteloua gracilis is a tufted, perennial, sod-forming grass that is characteristic of the Great Plains and mixed prairies westward where it is a dominant covering vast areas. The leaves grow in tufts very close to the soil surface, and reach a general height of 3 to 5 inches. The flower stalks are 8 to 12 inches high. The rhizomes are relatively short and fine but the stems are often so closely grouped that in dense stands they furnish a ground cover of 60 to 80 per cent. The rhizomes are short, like those of little bluestem, but somewhat finer. From the branched rootstocks the leaf-sheathed stems arise in great numbers; hence the apparently continuous sod of grama grass resolves itself into closely aggregated tufts or bunches. They are all bound firmly together into a unit of sod, however, by the very abundant, tough, wiry roots, 25 to 50 of which may arise from a single inch of the tangle of underground stems. The roots, though rarely a mm. in diameter, occur in such numbers that when the soil is entirely washed from a block of sod 4 inches deep they alone form a mat nearly an inch in thickness. Roots of seedlings develop rapidly, a depth of 7 to 11 inches is attained in 44 days and 20 to 33 inches by the end of the first growing season. Large numbers of fine, threadlike, profusely branched roots arise from the base of each plant; they spread widely near the surface, sometimes to 18 inches laterally; other roots extend obliquely or directly downward. The surface 18 inches of soil is especially well ramified by them and depths of 3 to nearly 6 feet are attained.

Four representative samples of *Bouteloua gracilis* were secured from the upland Lancaster loam soil (Table 4). The first sample had been closely grazed for many years, the second and third had been protected for a single year, and the fourth, which occurred in a moderately grazed pasture, was well protected by the accumulated debris of former years. The average volume of plant materials in the 0 to 4 inches (1,167 c.c.) is 4 per cent less than that of the little bluestem, and the 421 c.c. in the 4 to 12 inches is 12 per cent less. Production of dry matter (273 gm.) is 27 per cent less than that of little bluestem in the first layer, and the 101 gm. from the deeper soil is 19 per cent less (cf. Table 3).

BUFFALO GRASS PASTURES

Bulbilis dactyloides is very similar in habit of growth to *Bouteloua gracilis* except that the dense masses of sod—often furnishing a basal cover of 65 to 85 per cent—result largely from propagation by stolons. This low perennial, also at home on the Great Plains, has short leaf blades, the foliage usually reaching a height of only 3-4 inches. The plants are unisexual. The clumps or patches bearing the pistillate spikes or heads are so short that the inflorescence is partly hidden among the leaves. The staminate spikes are usually only 4-6 inches high.

The root habit resembles that of blue grama grass both in fineness and degree of branching as well as in rapid development. It often penetrates even more deeply. When grown from seed, short stolons develop the first year of growth and they are 3 to 10 inches in extent in June of the second summer. Buffalo grass forms a denser sod than blue grama grass and requires more water than this grass for its best development. The rhizome habit is very similar to that of grama grass. An additional anchorage against erosion being furnished by the abundant wiry stolons which bind together the units of the sod mat above ground. Where wind or water has eroded the upper inch of soil the rigid rhizomes and stems of buffalo grass and grama grass, like those of the little bluestem and needle grass, remain standing at their former levels (Fig. 9).

The three samples for determination of volume and weight were all taken from old, heavily grazed pastures on relatively low ground. The sod was well developed in a heavy phase of Wabash silt loam. The volume of plant materials in the surface 4 inches (911 c.c.) was 22 per cent less than that yielded by the blue grama grass; the 391 c.c. of the 4-12 inches depth was 7 per cent less. Differences in weight, however, were less marked, that in the surface layer (268 gm.) was only 2 per cent less; while the 4-12 inches of soil yielded (110 gm.) 8 per cent more than the grama grass.

The amount of materials in the three types of pastures are shown in Figure 10. The replacement of big bluestem by buffalo grass resulted in a decrease of 31 and 15 per cent in volume of plant materials, and 42 and 27 per cent in their weight.

PASTURES IN VARIOUS STAGES OF DEGENERATION

Numerous samples were taken from various pastures that showed different stages of degeneration. These are arranged in three groups for both upland pastures, formerly vegetated with little bluestem, and lowlands which were originally covered with the big bluestem type (Table 5).

On the upland, data from seven samples of the early stage are given. They are representative of little bluestem prairie that has been heavily grazed for one year (and where invasion of bluegrass has been slight) as well as more moderately grazed areas in which bluegrass had increased until it formed about one-half of the cover. The early stage on the lowland is represented by fewer quadrats but of similar treatment.

The medial stage on the upland includes blue grama grass, western wheat grass (small areas of which are found in most pastures), and poor, moderate, and good stands of bluegrass, which vary with previous grazing treatment. On the lowland the medial stage includes buffalo grass and various stands of bluegrass.

The late stage is usually much alike on both high and low ground. The sand drop seed (*Sporobolus cryptandrus*), a more or less decumbent perennial, characterizes the much grazed and trampled areas, and, where abundant, it indicates the late stage in degeneration. The remainder of the soil sampled supported only weedy annual grasses and forbs. It may be noted that in these samples volume of materials as well as dry weight is small.

A summary of a total of 60 samples in various upland prairie and pasture soils, and 34 samples from lowland areas is given in table 6. The samples of needle grass are not included since other samples from the upland pastures were all from areas which probably formerly supported little bluestem, just as all the lowland areas were once covered with a growth of big bluestem.

TABLE 5.—*Volume and weight of underground plant materials at three stages of degeneration of prairie due to pasturing. Numbers as in preceding tables.*

Early Stage

Volume, c.c. 0-4″	Volume, c.c. 4-12″	Weight, gm. 0-4″	Weight, gm. 4-12″	Type, etc.
				UPLANDS
865	370	234	79	Several years light grazing
1012	292	255	86	One year heavy grazing
833	405	235	100	
827	419	233	120	
834	380	240	101	About ½ tall grasses, ½ bluegrass
806	316	270	93	
954	403	243	98	
876	369	244	97	Average
				LOWLANDS
1066	249	289	71	Big bluestem grazed heavily 1 yr.
1172	365	345	98	
1036	423	365	114	½ big bluestem, ½ bluegrass
1091	346	333	94	Average

Medial Stage

Volume, c.c. 0-4″	Volume, c.c. 4-12″	Weight, gm. 0-4″	Weight, gm. 4-12″	Type, etc.
UPLANDS				
729	360	180	100	Poor stand of bluegrass
1059	207	257	76	Blue grama grass
1108	566	240	140	
1197	560	262	112	
573	318	128	61	Western wheat grass
769	335	242	104	Moderate stand of bluegrass
583	329	213	107	
940	235	263	71	Excellent growth of bluegrass
898	355	253	92	
873	363	226	96	Average
LOWLANDS				
727	189	234	54	One-half stand of bluegrass
1305	129	335	38	Excellent growth of bluegrass
1375	208	390	48	
982	344	292	105	Pure thick stand of buffalo grass
721	360	232	100	
1030	470	280	124	
676	170	252	51	Poor stand of bluegrass
619	180	199	53	
929	256	277	72	Average

Late Stage

Volume, c.c. 0-4″	Volume, c.c. 4-12″	Weight, gm. 0-4″	Weight, gm. 4-12″	Type, etc.
320	127	99	41	Open stand of drop seed
701	221	198	91	Thick stand of drop seed
375	102	101	26	Annual grasses and forbs [1]
476	115	109	22	Annual wire grass [2]
393	98	112	25	Texas crab grass [3]
271	107	67	25	Wild barley, annual drop seed, wire grass
165	64	47	15	
450	232	121	64	Annual drop seed, fetid marigold
394	133	107	39	Average

[1] Annual drop seed (*Sporobolus neglectus*) and fetid marigold (*Boebera papposa*).
[2] *Aristida oligantha*; a little wild barley (*Hordeum pusillum*).
[3] *Schedonnardus paniculatus*; a little stink-grass (*Eragrostis major*).

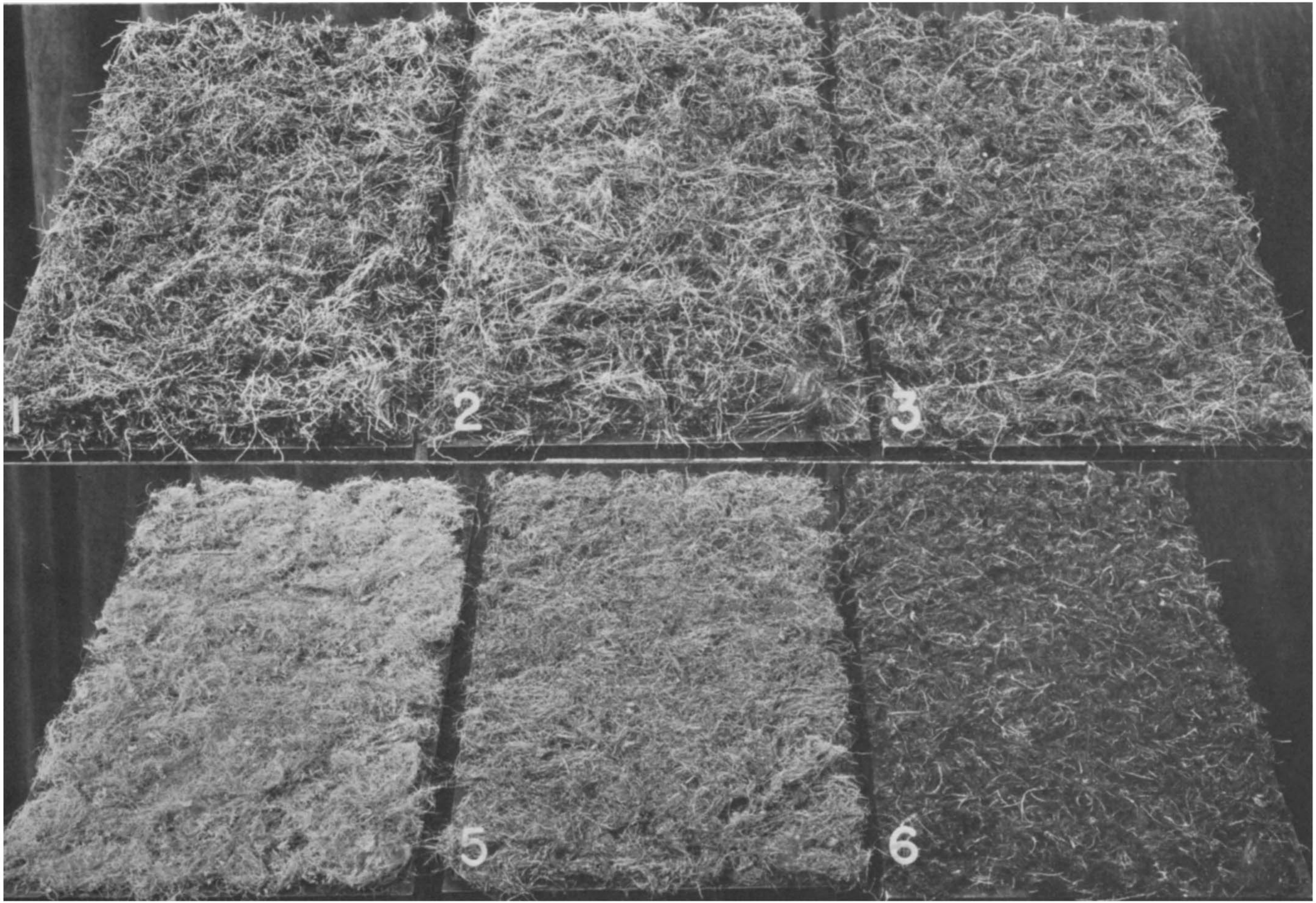

FIG. 10.—Legend on page 36.

TABLE 6.—*Percentage decrease in volume and weight of underground plant materials from the original type as a result of continuous overgrazing.*

State of Degeneration	Volume, c.c. 0-4″	Volume, c.c. 4-12″	Weight, gm. 0-4″	Weight, gm. 4-12″	Per cent Decrease Volume		Per cent Decrease Weight	
Upland Types								
Ungrazed Prairie (Little bluestem type)	1211	479	376	125	......	......	......	......
Early stage of degeneration	876	369	244	97	27.6	22.9	35.1	22.4
Medial stage of degeneration	873	363	226	96	27.9	24.2	39.9	23.2
Final stage of degeneration	394	133	107	39	67.4	72.2	71.5	68.8
Lowland Types								
Lowland Prairie (Big bluestem type)	1322	461	462	151	......	......	......	......
Early stage of degeneration	1091	346	333	94	17.4	24.9	27.9	37.7
Medial stage of degeneration	929	256	277	72	29.7	44.4	40.0	52.3
Late stage of degeneration	394	133	107	39	70.2	71.1	76.8	74.1

Examination of the upland types shows that the decrease in both volume and weight of samples from pastures in the early stages of degeneration, when compared with the native bluestem (table 3), is quite marked. In volume it is 28 and 23 per cent and in weight 35 and 22 per cent. Thus in both cases the greatest decrease is in the surface layer of soil. Conversely, the decrease from the early to the medial stage is small: in volume it does not exceed 2 per cent; in weight it is only 1 to 7 per cent. There are two definite explanations for this. In the first place some of the pastures in the "early stage" are really somewhat advanced towards the medial stage. Secondly, the last two samples (table 5, section 2) supported unusually good stands of bluegrass because

FIG. 10.—Average amount of plant materials from the surface 0-4 inches of soil, each lot spread over an area of one-half square meter which is the same soil area from which it was secured. 1, Big bluestem; 2, little bluestem; 3, needle grass; 4, buffalo grass; 5, blue grama grass; and 6, bluegrass. Note that the short grasses and bluegrass have roots of finer texture.

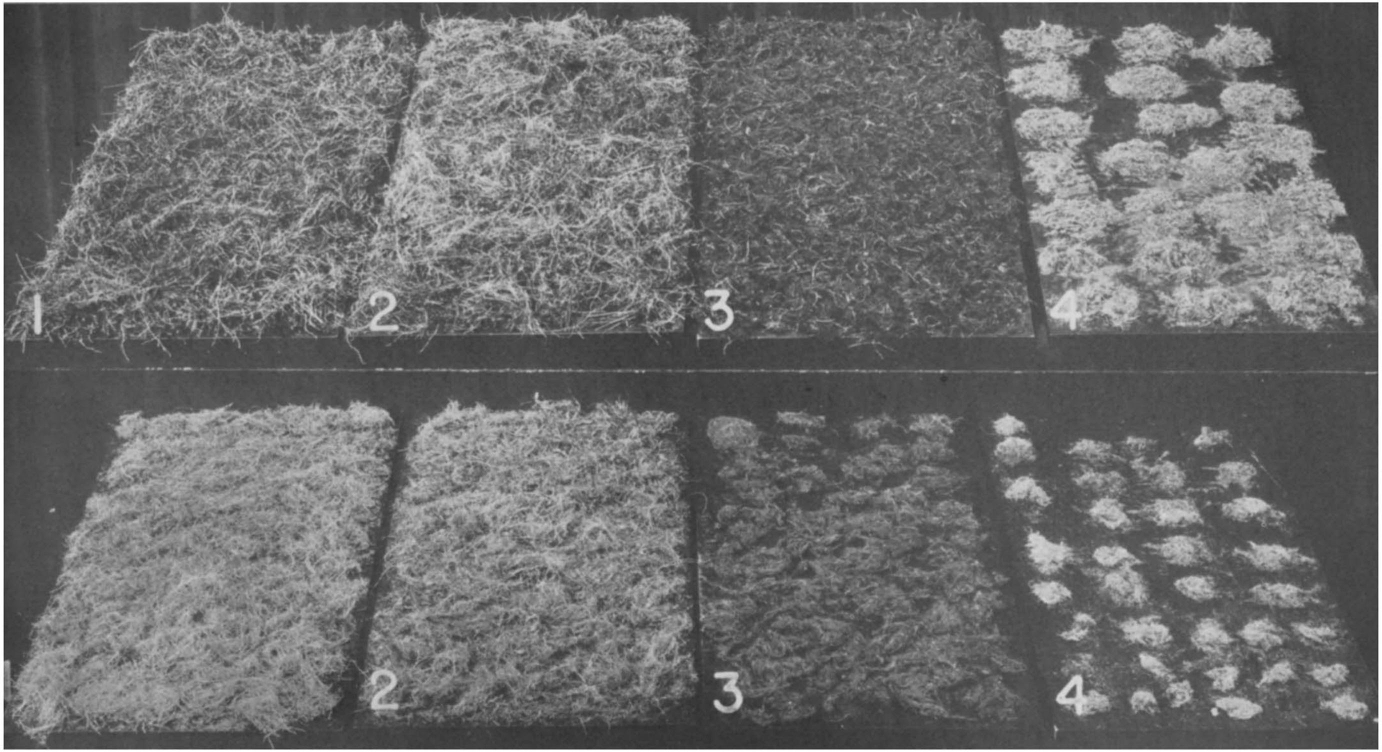

FIG. 11.—Underground parts of grasses from 0 to 4 inches depth (upper row) and 4 to 12 inches depth (lower row) each spread over the same area (one-half square meter) from which they were obtained. 1, Big bluestem; 2, little bluestem; 3, bluegrass; and 4, annual grass type. Samples illustrate average for each condition.

of slight depressions permitting water to run in. On the lowland, which was somewhat closely pastured, the decrease from the early to the medial stage is well marked, being 15 to 26 per cent in volume and 17 to 23 per cent in weight.

Once the medial stage is reached, whether it is characterized by bluegrass, grama grass, or buffalo grass, further degeneration resulting from heavy pasturing is accompanied by very small amounts of living materials in the soil. Table 5, section 3, shows that the maximum volumes in the two levels did not exceed 701 and 232 c.c. respectively, and dry materials 198 and 91 grams. It should be made clear that in these samples the roots of the forbs are also included. This seemed expedient since these annuals have fibrous branch roots which are separated from the grasses only with great difficulty.

The percentage decrease from the medial to late stage was 55 and 63 per cent in volume and 53 and 59 per cent in dry weight. At this stage in deterioration the soil had lost a total of 67 to 72 per cent of the original volume of living materials and 72 to 69 per cent of the original weight, depending upon depth. If we assume that the late stage on the lowland was similar to that on upland—as is often the case, depending upon the severity of grazing—the losses were even greater (table 6). Cf. fig. 11.

Fortunately the disappearance of dead organic matter from the soil is very slow, and even in bared soil it may remain during a long period of years. Hence, if the denuded soil is not eroded, its fertility and good structure are maintained over a sufficient period of time to permit nature, if undisturbed, to repair the damage due to overgrazing by developing a new cover of vegetation.

Summary.—A summary of amount of plant materials in the various types is given in both cubic feet and pounds per acre in table 7.

TABLE 7.—*Amount of plant materials per acre in the various types of prairies and pastures.*

Type	Cu. ft. per acre 0-4″	Cu. ft. per acre 4-12″	Tons per acre 0-4″	Tons per acre 4-12″
Andropogon furcatus	378	132	4.122	1.347
Andropogon scoparius	346	137	3.355	1.115
Stipa spartea	245	128	1.874	0.892
Poa pratensis (lowland)	269	50	2.516	0.437
Poa pratensis (upland)	224	92	2.052	0.848
Bouteloua gracilis	334	120	2.436	0.901
Bulbilis dactyloides	260	112	2.391	0.981
Early stage (upland)	250	105	2.177	0.865
Medial stage (upland)	249	104	2.016	0.857
Late stage (upland)	113	38	0.955	0.348
Early stage (lowland)	312	99	2.971	0.839
Medial stage (lowland)	266	73	2.471	0.642
Late stage (lowland)	113	38	0.955	0.347

From these data it may be seen that the amount of plant materials per acre far exceeds the tonnage of hay produced. In the little bluestem prairies the annual yield usually ranges between 0.5 and 1.5 tons per acre; in the big bluestem type of lowlands it usually varies from 1.5 to a little more than 2 tons per acre.

EXPERIMENTS ON WASHING AWAY THE SOIL

The effect of plant parts on preventing erosion may be determined directly by applying water to the soil. Since it was not expedient to haul the necessary large quantities of water into the various areas, samples of undisturbed sod were brought into the greenhouse where the water could be applied under controlled conditions. These studies were made in the fall of 1934.

METHODS

Stout frames one meter long, one-half meter wide, and 10 cm. deep were made of lumber one inch thick. These were taken to the prairie or pasture and placed over samples selected as representative of different types. A spade with a straight blade was used in cutting the sod to a depth of 4 inches around the frame and in such a manner that the frame could be forced to this depth in the soil. Several cross pieces were then nailed to the top of the frame to keep the sod in place when it and the enclosed sod were inverted. This was accomplished by digging away the soil on both sides under the frame and then turning it over. The one-half square meter of sod was then cut off evenly with the lower edge of the frame to which a wooden bottom was now tightly nailed. The sod was then returned to its normal position for transportation to the greenhouse. It fit very tightly into the frame and no portion was loosened or lost.

The frame and sod were placed lengthwise on a washing rack with a slope of 10°. The cross pieces were removed from the top and all vegetation was cut to the surface of the soil and removed. A lath was nailed along each side of the top so that it projected over the soil about one inch and kept the stream of water used in washing from striking directly the sides of the box. Moreover, three one-inch holes were bored in the lower end of the box to furnish an exit for the water and eroded soil after the top of the sod had been worn away.

Water was always applied from the same hydrant with the same hose and nozzle and at a distance of 2.5 feet from the sample. Care was taken to move the hose slowly back and forth in a regular manner so that the stream played for only an instant on any one spot. In every case the first hour of washing was done without a nozzle and the second with the nozzle set so as to throw an approximately uniformly circular stream 4 inches in diameter. Washing was then continued until all of the soil was removed with a stream only three-eighths inch in diameter and, consequently, with greatly increased force.

Under the first condition 12.73 gallons of water were delivered per minute under a total force of approximately 1.0 pound. The second condition delivered 4.80 gallons of water per minute which struck the soil with a total force of 1.95 pounds. Under the third condition the volume of water was reduced to 3.42 gallons per minute, and the force of 1.39 pounds was concentrated within an area of only about 0.11 square inch and, consequently, had a great erosive effect.

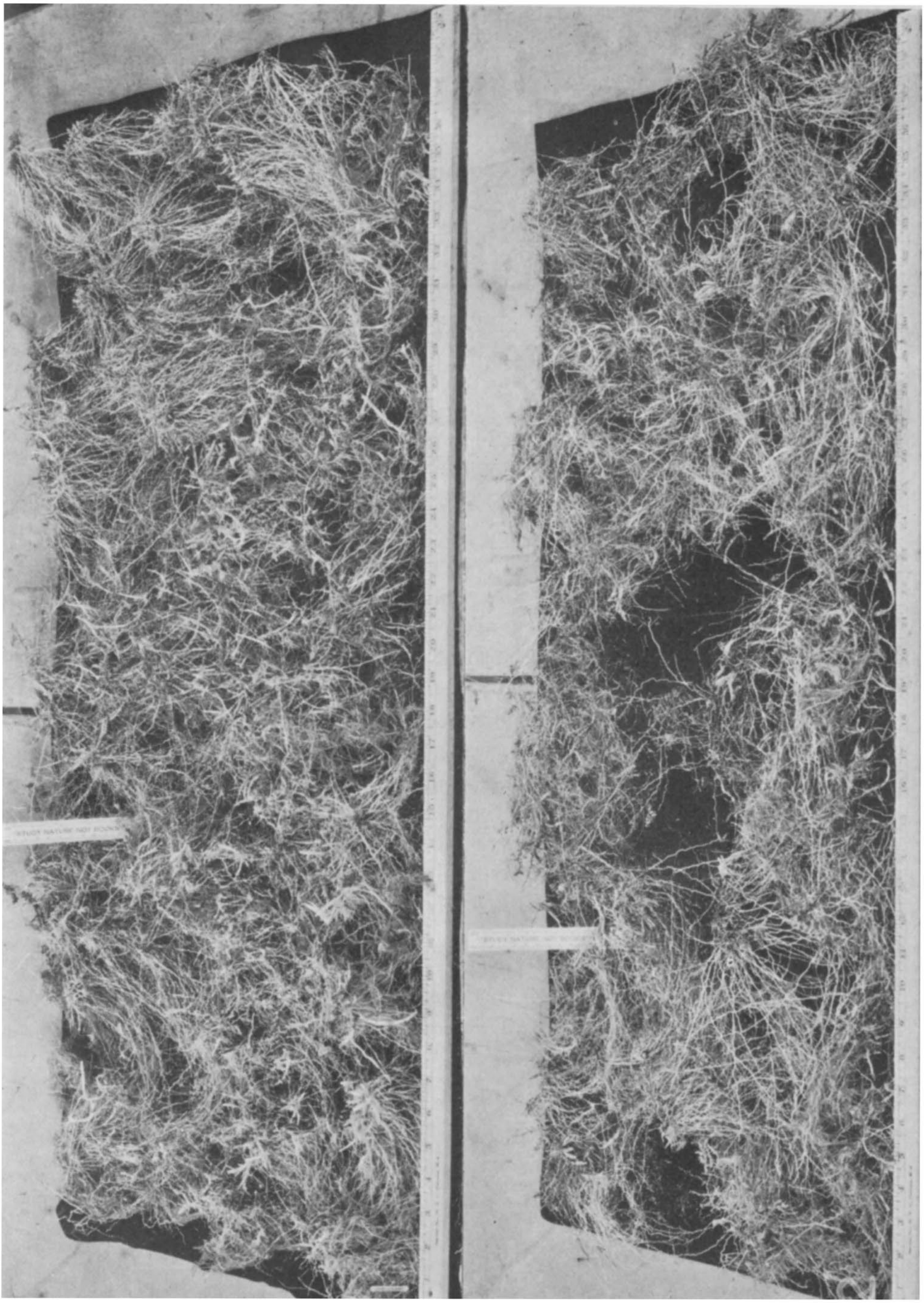

FIG. 12.—Underground parts of big bluestem from closely adjacent areas on level land of the same soil type. Area 1 was undisturbed, area 2 was closely grazed for 2 years. Each lot of material is in its natural position in the one-half square meter after the soil was washed away.

These forces were measured directly by directing the stream from the hose on the pan of an appropriate balance sensitive to 1 gram.

RESULTS

Big Bluestem.—A typical sod of *Andropogon furcatus* was obtained from a rather heavy Wabash silt loam soil. When water was applied it became muddy for a period of 5 to 8 minutes, after which it remained clear throughout the first hour. This phenomenon occurred with nearly all the sodded soils and resulted from the fact that the surface 0.5 to 1 inch of soil has few roots and rhizomes. Once this loosely held earth is removed the sod resists this simple flooding for very long periods of time. Even by the end of the second hour the mass of soil had not been greatly reduced. The compacted rhizomes and tough wiry roots maintained their position and formed an effective barricade between the force of the water and the soil. Only after a period of 2 hours and 40 minutes with the small stream of water were the underground parts freed from the soil (Fig. 6).

A second sample of big bluestem sod, intermixed with considerable Indian grass, was secured from a colluvial phase of Wabash silt loam. This sample was ungrazed. In an adjoining area, only 8 feet distant, a sample that had been heavily grazed for two years was also secured.[1] These samples were selected for uniformity of basal cover. The soil was washed from the ungrazed sample in 3 hours and 28 minutes; from the grazed one in 2 hours and 35 minutes. Differences in the quantities of underground plant materials were quite striking. In the first case there was an almost continuous mat of sod; in the second openings occurred in which few or no roots were present. It was here that the soil washed away readily and permitted the undermining of the sod (Fig. 12).

Little Bluestem.—Samples of *Andropogon scoparius* sod were obtained for uniformity of ground cover in Lancaster loam. One had never been grazed, but mowed annually, the second had been closely grazed for two years. The first sam-

[1] Actually close cutting 5 or 6 times each growing season was employed to simulate grazing.

ple was eroded during the first hour in a manner similar to the big bluestem. The second, with weakened stem bases and rhizomes, permitted the loss of 1.5 inches of surface soil, when a depth was reached where the roots were well matted. In this sample the water remained turbid much longer than in the first. The great mass of materials, once exposed, well protected the soil from the force of the water. It was only after 3 hours and 32 minutes that the soil was washed from the ungrazed sample; from the one weakened by grazing, 2 hours and 40 minutes washing was required (Fig. 13).

Needle Grass.—A representative sample of *Stipa spartea,* intermixed, as is usual, with considerable little bluestem, and smaller amounts of big bluestem, was taken from a Carrington silt loam soil in ungrazed prairie. This is a heavier soil type than the preceding. The bunches were well developed. That the Stipa type of vegetation does not occupy the soil so completely as that of the bluestems is shown in figure 14. The large bunches of needle grass, however, remained in position even after the soil was removed and throughout the process of erosion formed a bulwark to hold the soil in place. The time required to remove the soil was 3 hours and 20 minutes. Thus this sample of needle grass compared very favorably in its resistance to erosion with that of little bluestem (table 8).

Bluegrass.—A fine sample of *Poa pratensis* was obtained near the head of a ravine in a half-degenerated pasture. It appeared to be a pure stand, but later two clumps of big bluestem rhizomes and roots were found. During the process of washing a few roots broke and were washed away from the general mass. The exposed roots and long slender rhizomes formed an efficient barrier against the force of the water. As the soil was very gradually removed the mat sank with the soil, quite unlike that of the coarser bluestems and *Stipa* (Fig. 15). The resistance of the silt loam soil, held by the cover of grass, was marked until the first 3 inches were washed away. This required a period of 4 hours and 20 minutes. At greater depths rhizomes were few and the

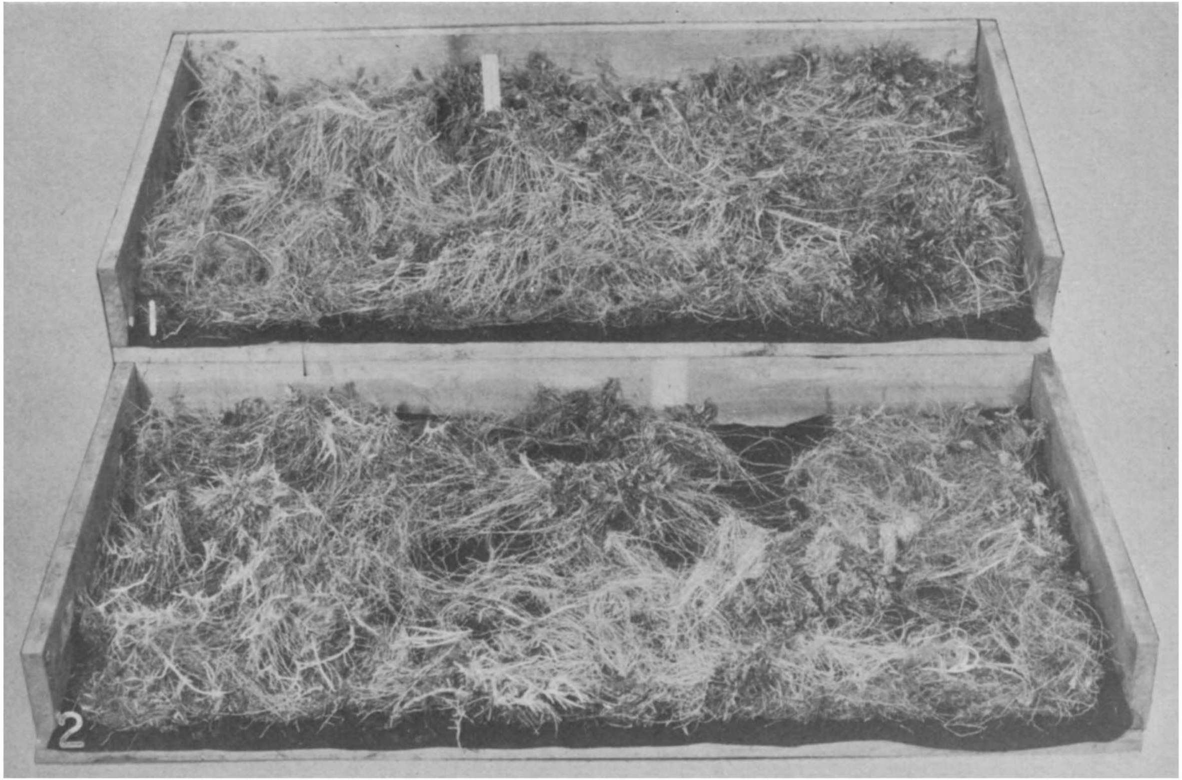

FIG. 13.—Underground parts of little bluestem taken 4 feet apart. 1, ungrazed; 2, closely grazed for two years. Both have a small admixture of Indian grass.

holding power of the grass greatly decreased. Hence the fourth inch of soil was removed in an additional 25 minutes. Undoubtedly this sample was somewhat better than the average from lowland pasture, but it illustrates well the remarkable binding power of bluegrass sod.

Annual Weed Stage.—A sample of Lancaster loam was taken in an old pasture. It supported a moderate growth of annual wire grass (*Aristida oligantha*), annual drop seed (*Sporobolus neglectus*), stink-grass (*Eragostis major*), fetid marigold (*Boebera papposa*), and a single plant of sand drop seed (*Sporobolus cryptandrus*). The water was muddy from the beginning to the end of the washing process. The roots easily became dislodged and fragmented, floating away either as individual root systems or in parts. Little resistance was offered to soil erosion. All the soil was washed away in 41 minutes.

Bare Soil.—Finally, a sample of Lancaster loam was obtained from a cornfield only a few rods from where the samples of little bluestem were taken. This field had been broken and planted to corn for a period of 7 years. The bases of two or three stalks of corn of the current year were included in the sample. The field was practically free from weeds. The corn stubble soon floated away and the entire sample was washed from the frame in a period of only 18 minutes.

Summary.—A summary of these data is given in table 8. A comparison of results shows the efficiency of the various types of vegetation in holding the soil against the forces of erosion. Although the native grasses can not be directly compared because of variations in soil type, these data indicate but slight differences in fairly comparable soil types. The cover of bluegrass is perhaps most efficient in the surface 3 inches, but becomes less so at greater depths. When, after long abuse of pastures, the annual weed stage is attained, the soil is very loosely held by the underground parts. But even this annual vegetation has some binding effect when compared with the rate of erosion of bare, cultivated soil.

TABLE 8.—*Summary of experiments on rate of erosion.*

Type	Soil type	12.7 gal. per min. 1 lb. on 2 sq. in. Hrs.	Min.	4.8 gal. per min. 1.9 lbs. on 12.5 sq. in. Hrs.	Min.	3.4 gal. per min. 1.4 lbs. on 0.11 sq. in. Hrs.	Min.
Andropogon furcatus	Heavy Wabash silt loam	1	....	1	....	2	40
Andropogon furcatus	Colluvial phase Wabash silt loam	1	....	1	....	1	28
" (grazed 2 yrs.)	"	1	....	1	....	..	35
Andropogon scoparius	Lancaster loam	1	....	1	....	1	32
" (grazed 2 yrs.)	"	1	....	1	....	..	40
Stipa spartea	Carrington silt loam	1	....	1	....	1	20
Poa pratensis	Wabash silt loam	1	....	1	....	2	45
Annual weeds	Lancaster loam	..	41	..	....	..	....
Bare soil	"	..	18	..	....	..	....

DISCUSSION

The living plant materials form a wonderfully efficient anchorage system for the soil, especially the surface layer. This living network, which holds the soil in place, constitutes about one-tenth, by weight, of the total organic matter in the surface 6 inches (Weaver, Hougen, and Weldon, 1935). Because of the wide distribution into thousands of cable-like structures with which the soil is everywhere ramified, and because of the intimate contact of the absorbing roots with the soil particles, the binding efficiency of these threads of great tensile strength is greatly increased. Approximately 60 per cent of the underground parts in the little bluestem type occur in the first 6 inches of soil. In big bluestem sod, 60 per cent of the entire root system, by weight, occurs in the surface 6 inches of soil (*loc. cit.*).

The binding action and other favorable soil conditions were shown in a remarkable manner during the recent great drouth. In the bluestem prairie the surface soil was so firmly held in place that no cracks occurred. But where the bluestems had been replaced by bluegrass or other grasses, as a result of grazing, great fissures in the soil were common. These extended deeply and greatly increased the direct loss of soil water by evaporation, since it permitted the vapor to diffuse outward directly from the subsoil. Moreover, these soil crevices may be the beginnings of gully erosion.

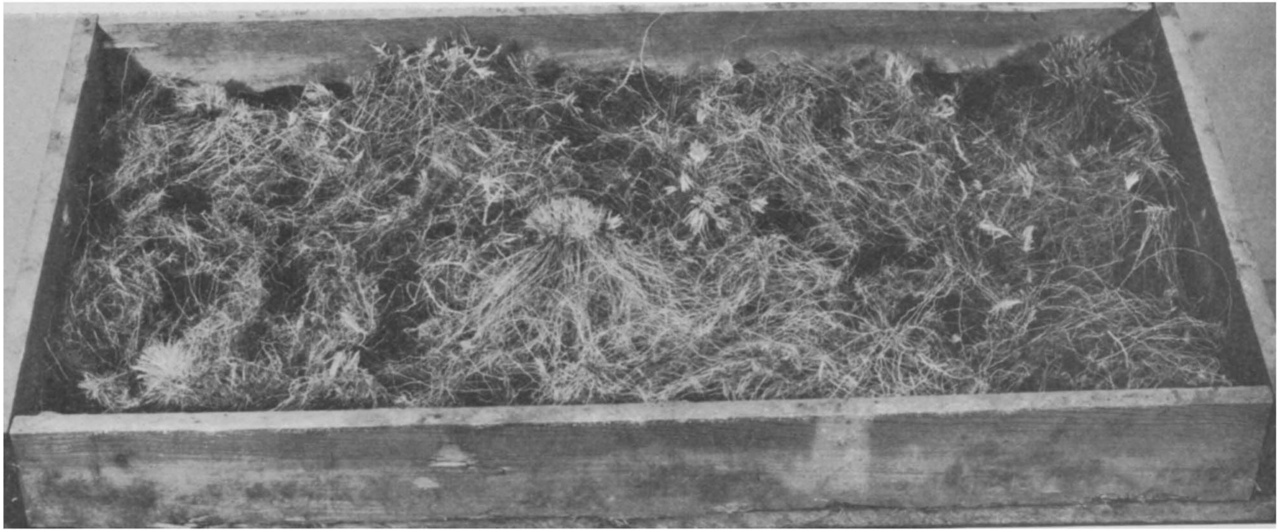

FIG. 14.—One-half square meter of needle grass after the soil was washed away. It also contains numerous small tufts of little bluestem.

Underground plant parts slowly deteriorate, die, and decay with the passing of the years only to be replaced by new ones. The channels made by roots and rhizomes in pressing aside the soil remain for a long time, greatly increasing the pore space, and consequently the absorption of water. They may readily be traced for many feet, especially below the first 4 inches (Weaver, 1919, 1920). Pore space in the surface 6 inches of Lancaster loam prairie sod constituted 57 per cent of the volume of the soil. During a year of approximately average precipitation 25 per cent was occupied by water and 32 per cent by air. Pore space decreased with depth to 39 per cent at 4 feet. An equally large pore space was determined in Wabash clay loam in big bluestem sod. Here it occupied over one-half of the soil volume even at a depth of 7 feet (Weaver, *et. al.*, 1935).

The structure of the soil is also greatly benefited and the fertility increased by the incorporation of decayed plant materials. Grassland soils are high in organic matter, between 4 and 5 per cent occurring in both upland and lowland virgin prairie soil. The low percentage by weight is due to the fact that the mineral soil matrix has a density about three times as great as that of the humus. By volume the figures would be much more impressive.

Abundant plant materials in the soil are associated with an abundant yield of forage. This varies with climate and species. Where bluestem pastures have been replaced by either bluegrass, buffalo grass, or grama grass it has been shown that the materials below ground also decreased. Decreases in yields of forage have been determined to exceed these decreases in underground parts. This is to be accounted for by the fact that bluegrass is a somewhat mesic species. This is illustrated by its death in thousands of pastures in eastern Nebraska during the past summer of great drouth, although the subsoil below 4 feet was often moist. Normally it grows poorly during the hot summer when the bluestems thrive. The short grasses, migrating from the arid west, have retained their habit of developing much more extensive roots than tops as compared with the bluestems. Changes

FIG. 15.—Matted roots and rhizomes of bluegrass which settled to the bottom of the frame as the soil was removed by washing.

from these perennials to the annual grasses described is accompanied by marked decreases in both roots and tops.

The relation of grass roots to soil structure and productivity and also to erosion has been succinctly stated. When the virgin prairie sod is first broken, the soil is mellow, moist, and rich and produces abundant crops. But after a few years of continuous cropping and cultivation, there occurs a great change in its physical condition. It becomes more compact and harder to till, dries more quickly than formerly, bakes more readily, and when plowed, often turns over in hard lumps and clods. After a clayey soil has been cropped for a long time, it tends to run together. It is very sticky when wet, but when dry, the adhesive characteristic almost entirely disappears. The grass roots and humus which formerly held it together are decayed and gone. When loosened by the plow, it is often easily drifted and blown away. But when sowed to grass, marked improvement occurs, for grass is a soil builder, a soil renewer, and a soil protector. Covering the land with grass is nature's way of restoring to old, worn-out soils the productivity and good tilth of virgin ones. The perfect tilth and freedom from clods, so characteristic of virgin soils, are always more or less completely restored wherever the land has supported a cover of grass for a number of years. The covering of sod prevents the puddling action of rain. As the roots develop, the soil particles are wedged apart in some places and crowded together in others. The small soil grains become aggregated into larger ones. Each year, many of the old roots die and are constantly replaced by new ones. The soil is filled with pores of the old root channels; the humus from the decaying roots helps cement soil particles into aggregates and thus lightens and enriches it. In this way, the mellow texture of the virgin soil is restored, and the accumulation of organic debris, largely from the decayed masses of old roots, adds greatly to its fertility.*

SUMMARY

A quantitative study was made of the amounts of living plant materials in prairies and pastures of eastern Nebraska.

* Rewritten from Ten Eyck, Kan. Agr. Exp. Sta. Bul. 175. 1911.

Samples of soil one-half square meter in surface area were taken at depths of 0 to 4 and 4 to 12 inches, respectively. The underground plant materials were obtained by washing away the soil. Large samples were necessary because of the irregularity of distribution of the underground parts.

Big bluestem type is the most important of lowland prairie. *Andropogon furcatus* alone constitutes about 78 per cent of the vegetation. The basal cover of this sod-forming grass averages only about 13 per cent. The coarse roots grow rapidly and usually reach a depth of 5 to 7 feet. About 60 per cent of the root system, by weight, occurs in the surface 6 inches of soil.

Big bluestem prairie yielded the largest volume and dry weight of underground plant parts. Dry weight averaged 462 gm. per sample in the surface 4 inches and 151 gm. in the 4 to 12 inch depth. This was 4.1 and 1.3 tons per acre, respectively. The root-rhizome system forms a continuous framework throughout the soil.

Little bluestem is the chief grass of the *Andropogon scoparius* type which is the most extensive of upland prairie. It exceeds in importance all other upland species combined. Basal cover in this sod-mat or bunch-grass type is only about 15 per cent. Yet the fine, tough roots thoroughly occupied the soil to the depth of sampling, and extended to a depth of 4 to 5 feet.

Little bluestem prairie ranked second in yield of underground materials averaging 376 gm. in the surface 4 inches and 125 gm. in the deeper layer. This was 3.3 and 1.1 tons per acre, respectively. The entire soil mass is ramified by roots which anchor it in place.

Needle grass dominates a second, drier type of smaller extent. *Stipa spartea* alone may constitute 40 or more per cent of the vegetation. The bunches are widely spaced and basal cover is about 11 per cent. Underground materials are less in the drier soil, but well distributed throughout. They averaged 210 and 100 gm. per sample, or 1.87 and 0.89 tons per acre.

Under continued close grazing the native grasses are replaced by bluegrass, blue grama grass, or buffalo grass.

Poa pratensis forms a compact sod, the long, tough rhizomes binding the surface soil. Roots are much finer, have less tensile strength, and extend less deeply than those of the bluestems. Few penetrated beyond 32 inches in depth. Plant materials in the upland (2.0 and 0.84 tons per acre, respectively) were 39 and 24 per cent less than those of little bluestem; on lowland (2.5 and 0.43 tons per acre, respectively) they were 39 and 68 per cent less than those of big bluestem.

Underground materials of the finely and deeply rooted short grasses were less than those of the grasses they replaced. *Bouteloua gracilis* yielded 27 and 19 per cent less by weight than the little bluestem, and *Bulbilis dactyloides* 42 and 27 per cent less than big bluestem.

Continuously overgrazed native pastures show several distinct stages of degeneration each being indicated by the dominance of certain grasses or forbs.

Samples from pastures in early, medial, and late stages of degeneration showed consistent decreases in underground plant materials. These were clearly apparent, often after only two years of overgrazing. On uplands decreases in dry weight were 35, 40, and 72 per cent respectively, from the original sod in the surface 4 inches, and 22, 23, and 69 per cent in the 4 to 12 inches. Total decrease from early to late stage was from 2.17 tons to 0.95 per acre at 0 to 4 inches depth, and from 0.86 to 0.34 ton at 4 to 12 inches depth.

On lowlands decreases of 28, 40, and 77 per cent were found in the surface layer and 38, 52, and 74 in the deeper one. This was a decrease from 2.97 tons to 0.95 in the surface layer and 0.83 to 0.34 in the deeper one from the early to the late stage.

One-half square meters of sod were secured intact in frames to a depth of 4 inches, placed at an angle of 10 degrees, and the soil washed away under controlled conditions. Big bluestem in Wabash silt loam resisted erosion longest, but bluegrass in similar soil almost equally well. Needle grass was somewhat less effective in holding the soil than was little bluestem.

The rhizome-root framework of the native grasses was retained practically in place after the soil had been removed;

that of bluegrass sank to the bottom of the frame. Holding power of bluegrass was clearly less after the first 3 inches of soil were eroded.

Soil held only by plants of the late weed stage rapidly washed away, but not so quickly as similar soil from an adjacent cornfield.

A cover of grass conserves both rainfall and soil.

The plant cover is discussed in relation to rainfall interception, decrease in run-off, and promotion of absorption; and underground parts in relation to pore space, soil structure, and erosion.

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