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Washington, D. C. ▼ October 6, 1924

FOREST TYPES IN THE CENTRAL ROCKY MOUNTAINS AS AFFECTED BY CLIMATE AND SOIL

By

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CONTENTS.

INTRODUCTION.

In "Physiological Requirements of Rocky Mountain Trees," (*6*) [1] by the writer, published in the Journal of Agricultural Research (Apr. 14, 1923), the relative physiological requirements of the species composing the various forest types of the central Rocky Mountains have been discussed. The present work on climatic and soil conditions affecting the same forest types supplements that discussion. The two papers are, indeed, so closely related that the one is indispensable to the understanding of the other.

In the earlier paper the results of a number of laboratory studies were presented, in the hope that such comparisons, made under controlled conditions equally affecting all of the species involved, might permit judgment of the relative physiological requirements, and thereby make it possible more definitely to decide what conditions of the environment are really important in controlling distribution and what are merely variable concomitants of these controlling conditions. If the ensuing discussion presented from the standpoint of field observations does no more than reconcile the two

[1] Parenthetical figures (*italic*) placed in the text refer to corresponding numbers under "Literature cited" on page 152 of this bulletin.

points of view and make clear what conditions of environment respond directly to physiological requirements and thus most vitally affect the composition of the forest, and in what terms these conditions must be measured and expressed, it is felt that an advance will have been made. But it is believed that a further progress has been made. In these two approaches to the subject the understanding of the relative qualities of the forest trees considered may become clarified for the reader, and thus assist foresters in reaching a proper understanding of the technical problems which are met almost daily. This belief is held notwithstanding the fact that the methods in ecological study of the environment are in some respects very crude and in these respects still afford opportunity for much intensive and fruitful work.

A brief review of the physiological work and of the conclusions which have already been presented is here given.

The historic concept of a difference between tree species as to "shade tolerance" or photosynthetic capacity has been borne out by observations on the growth rate during growing seasons and the sap densities at the end of these seasons, in which the several species were subjected to identical conditions. The six species considered seem to be photosynthetically effective in the following decreasing order: Engelmann spruce, Douglas fir, lodgepole pine, bristlecone pine, yellow pine, and limber pine.

As a direct result of greater photosynthetic activity, the water use per unit of growth is reduced; or, in other words, in relative "water requirements" the most "tolerant" or effective species take the lowest positions.

This also affects the absolute requirements, as expressed by transpiration per unit of leaf area or exposure, indirectly, through the relative evaporating rates of solutions of different densities, so that in a general way the most active species are absolutely the smallest users of water. It also appears in this connection that certain species may be much better adapted than others to resist transpiration on account of the thickening of the epidermis and the reduction of the stomata. This places them in a lower category with respect to the absolute transpiration rate, but does not appreciably affect their water requirements, because such economies can be effected only through means which exclude carbon dioxide or light from the functioning cells. Thus, Engelmann spruce, Douglas fir, and yellow pine appear in increasing order as absolute water users; but limber pine, bristlecone pine, and, to a lesser extent, lodgepole pine, take lower positions than would be expected, all being "weedy" trees which sacrifice growth rate for protection against great water losses.

In view of the behavior of weaker and denser solutions, it is conceived that the species which are most effective photosynthetically may be satisfied with the coolest environments, because, with their relatively dense cell saps a smaller proporation of the energy of the absorbed sunlight is used in the process of evaporation. In other words, a dense solution is not so rapidly cooled by its own evaporation as a lighter solution. Hence the possessor of the dense solution may more readily maintain leaf temperatures which will be conducive to effective photosynthesis. That the temperature of the leaf is important in this process can hardly be questioned. Thus the relative light requirements and heat requirements of the several species are seen to be identical. On the basis of light requirements the species would be zonated in the order already given, with spruce occupying the situations of lowest air temperatures.

It is also conceived that, as the most effective species is least readily cooled by the evaporation of its cell sap, it may not only require less heat for effective growth, but may most readily become superheated to the point at which direct protoplasmic injury results. For this reason no species may become established in a temperature zone or in an exposed site whose temperatures exceed a certain maximum. It must, however, be admitted that the direct evidence on this point is extremely meager. It is also apparent that the maximum temperatures encountered in nature, namely, those at the surface of insolated soils, are so intimately connected with the dryness of that layer and with the water supply and transpirational losses of young seedlings that evidence of direct heat injury, apart from injury through water loss, may be very difficult to obtain.

At this stage it is not unimportant whether the high temperatures of the surface soil react directly or indirectly, but it is of greater importance to recognize that the combined effects may be the most common cause of the death of forest-tree seedlings in the region under consideration. The present evidence is that the action is most commonly indirect; that spruce and lodgepole pine seedlings are most sensitive to excessive heat and drying, because their poorly developed roots and thread-like stems do not permit them to push the necessary supplies of water past the superheated section of the stem; that Douglas fir and yellow pine are relatively resistant, because they are much stronger both as to length of root and size of stem.

It would seem that the species which creates carbohydrates most readily, maintaining the sap of greatest density and osmotic pressure, would, by reason of the last-named quality, extract water from the soil to the lowest point, and there is no reason to believe that this is not the case. Even in carefully controlled pan tests, however, and more markedly in the field, drought resistance is much more than extracting the water from the soil particles with which the roots may be in contact. It is the ability to reach with the roots the supply of water that very largely determines which seedlings will last the longest. Thus although Engelmann spruce seedlings do resist drought remarkably well when the losses by transpiration are at a very low rate and when slow capillary action may assist in bringing water to the roots, yet ordinarily they succumb before Douglas fir or yellow pine seedlings, because the latter at the outset develop roots nearly twice as long. On the contrary, spruce trees of greater age, having developed a great many root branches, evidently have at their command a larger proportion of the water supply of a given soil space than either yellow pine or fir, whose roots are then coarse and few in number. Both because lodgepole pine develops a root as slowly as spruce, and because it apparently exerts a relatively low osmotic pressure, its seedlings stand out prominently as the least drought-resistant of those considered.

As a result of the various investigations upon the relative physiological functioning of the species named, Engelmann spruce (*Picea engelmanni*) and Douglas fir (*Pseudotsuga taxifolia*) may be considered to be the most highly developed plant organisms, in the sense of effecting most readily the processes on which growth is dependent; and at the other extreme are found western yellow pine (*Pinus ponderosa*) and limber pine (*P. flexilis*). Although further investigation may tend to alter the relative positions of the four pines, it is believed that acceptance of the order first given above will not be seriously misleading.

But apart from this physiological development, which is considered most fundamental, there are two lines of adaptation which evidently affect distribution. In the bristlecone (*Pinus aristata*) and limber pines, both of which are "weedy" or below the stature of true forest trees, and perhaps more facultative in adapting themselves to site, the stomata are greatly restricted in size. This inevitably reduces growth rate by making carbon dioxide less available. These trees are certainly resistant to the evaporation which might result from strong wind, but it is not believed that they are drought-resistant in the sense of exercising a strong osmotic control over their water supplies. This distinction is important, for, although the property of being resistant to evaporation makes them valuable on wind-exposed sites, it does not equip them for enduring the actual drought of the soil, which results, for example, from competition between trees.

On the other hand, in the early and vigorous root development of yellow pine and Douglas fir, as contrasted with lodgepole pine (*Pinus contorta*) and spruce, there is an effort on the part of the former to adapt themselves to the meager moisture supplies which usually obtain in the localities where these species find their proper heat conditions. It is believed that the heat conditions are fundamentally controlling, and that the moisture conditions have been met by this adaptation as the need arose.

As between spruce and lodgepole pine there is plainly a distinction. The former is evidently under no stress to root vigorously, for under the temperature conditions to which it is adapted exhaustion of the surface moisture is a very slow process. Furthermore, according to the present interpretation, the species is capable of coping with a considerable degree of drought. It seems almost certain that lodgepole thrives best with relatively high temperatures, yet the root development is adapted only to existence in perpetually moist sites. The sluggish germination of lodgepole pine seeds, except when exposed to wide temperature ranges, suggests adaptation to open, exposed situations without other cover. From this and other bits of evidence it may be concluded either that lodgepole pine is a recent migrant to the central Rocky Mountains and is poorly adapted to a region of great atmospheric dryness, or is capable of developing only in the early stage of a succession, when competition for moisture is lacking.

With these facts and theories as a working hypothesis, it is now intended to examine the environmental conditions for evidence as to the factors which must be controlling in the formation of each forest type.

THE METHOD OF STUDY.

The primary data to be presented in this bulletin are records of climatic and soil conditions in different forest types. The main object of such a presentation must be to show that differences in climatic and soil conditions between the forest types either do or do not exist in sufficient degree to account for the varying phenomena of occurrences and growth.

As the special data collected by the Forest Service do not cover periods long enough to establish the "normal" conditions of any of the forest types (and by this is meant the average conditions for a period of at least 20 years), and since even the average conditions for a period of 10 years may vary considerably from "normals," it is necessary to assume that important differences between forest types are fairly constant, and will be brought to light by the consideration of short-period records. Such bases can not be fraught with any serious dangers, moreover, when, as in this case, the forest types to be compared are in the same general locality, that is, in the path of the same air currents and storm centers. Any considerable separation of the stations, however, especially in a rugged mountainous region, is likely to introduce temporary variations in certain conditions which are not "normal," and particularly in those conditions which are most directly influenced by the path of storm centers. Thus at the time of this writing it appears that the storm centers have for some time been passing considerably to the north of the Pikes Peak region, giving that locality unusual westerly winds and leaving it without its usual amount of moisture. Consequently as early as the end of May an unprecedented shortage of water exists, while scarcely 100 miles to the north unusually large accumulations of snow are reported.

Again, the moisture factor is most variably influenced by the restricted character of many of the summer showers; especially are

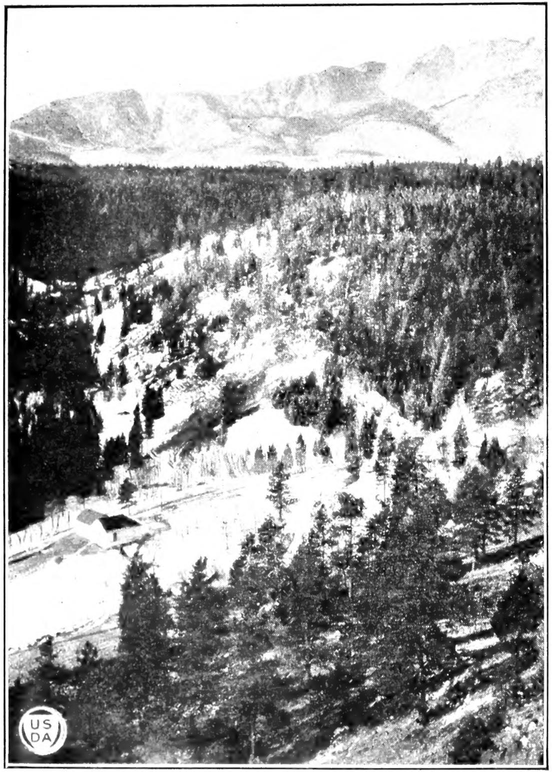

FIG. 1.—GENERAL VIEW OF SURROUNDINGS OF CONTROL STATION (F-1) MIDWAY BETWEEN THE TWO HOUSES.

Note lack of tree growth on crest of the ridge. January 5, 1911.

FIG. 2.—STATION F-3. ON THE RIGHT IS THE SOIL WELL, AND ON THE LEFT THE TOWER USED FROM 1910 TO 1912. GROUND CONDITIONS ARE RECORDED BEHIND THE CLUMP OF SAPLINGS IN THE CENTER.

In the foreground is a small reservoir holding the water of a spring which appears in the gulch bottom. July 7, 1918.

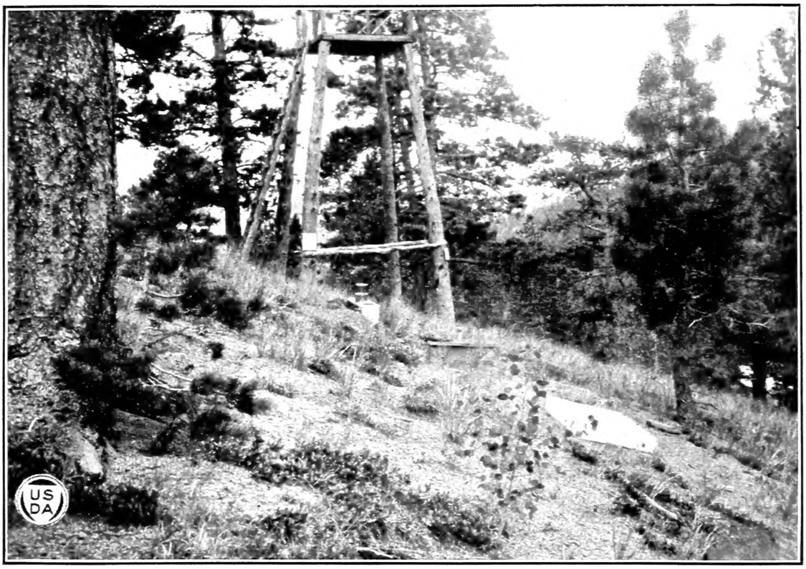

FIG. 1.—STATION F-2, SHOWING THE FOREGROUND SOIL WELL, THERMOMETER PIPES, AND EVAPORIMETER, AND IN THE BACKGROUND, TOWER ON WHICH OBSERVATIONS WERE MADE FROM 1910 TO 1912. JULY 7, 1918.

FIG. 2.—STATION F-6, LOOKING ACROSS THE SLOPE.

Note the sparseness of the vegetation in the foreground where it has not been disturbed. July 7, 1918.

the heaviest downpours in a given locality likely to affect only very small areas. Temperatures are generally not so directly affected by local conditions. Thus the month of December, 1917, was an unusually warm month not only at the Fremont Forest Experiment Station, but over most of the western part of the United States. January, 1918, likewise, was generally cold to an unusual degree. It seems safe, therefore, to compare the records of any two near-by stations for short periods, whatever the factors under consideration, and an increasing period will be demanded as the distance between stations increases.

Fortunately the dozen or more stations located in the vicinity of Fremont all come under the same general influences. This is true of the entire area from the plains to the summit of Pikes Peak, with the exception that summer rains frequently fall in one part of the area and not in others. Winter snows may also be so localized, but usually in conformity with altitudinal zones. It is true that two stations not 100 yards apart may on a given day have temperatures varying by 2° F. in one direction, and on the next day varying in the opposite direction. Such variations from a consistent relation are, however, always small, and there is every reason to believe that the means of a single month usually express essentially the normal temperature relation between two stations for that month of any year.

Therefore the method of presenting results in this bulletin is to compare each condition at any outlying station, for whatever period observations may have been taken, with the corresponding condition recorded during the same period at the so-called "control station." The latter is merely a single point, near the headquarters of the Fremont Forest Experiment Station, at which all of the factors to be considered have been measured almost continuously from 1910 to 1921, or later, with the important exception of the evaporation factor for which satisfactory measurements were not obtained until 1916.

In the study of air temperatures, several attempts have been made to cover the somewhat distinct sets of conditions which may exist at any station—that is, to measure both the very local air temperatures near the ground and those well above the ground, which may represent the mean for the locality, obtained by the mixing of the warmer and cooler strata of air. On a breezy day, of course, this mixing is constant and effective and even brings together the warm air near the earth and the much cooler air of high strata in the atmosphere. On quiet days such mixing may be very incomplete, so that even at 20 feet above the ground temperature records may reflect local rather than general conditions. Sudden changes of temperature are then likely to be recorded when a stronger movement of air begins.

The temperature of the air close to the ground is a condition in which foresters are greatly interested because of its relation to seedlings and young growth. A number of observations have been made at an elevation of 1 foot from the ground surface, and these will hereafter be spoken of as "ground temperatures" in contrast with temperatures in the soil, on the one hand, and the temperature of mixed air at higher levels, on the other. At the "ground" elevation the rate of air movement is low, and, unless brisk breezes are blowing, is such as to permit the air to attain almost the temperature of the ground and of the vegetation with which it comes in contact. An elevation of 1 foot was adopted for ground temperatures, because it was the lowest elevation at which maximum and minimum thermometers could be conveniently operated without seriously disturbing the snow blanket, and because it was thought adequate to represent purely local conditions of absorption and radiation. An elevation of 4½ to 6 feet, which is very convenient, may represent a good degree of air mixing without nullifying local character, except to modify daily extremes. With greater elevations, which have been used in a few instances to measure the conditions affecting the crowns of trees, it will be seen that the local character of the temperatures partly disappears.

In securing temperature records at these elevations the ordinary method of exposing thermometers is not satisfactory where wind is very light. Unless there is considerable wind to cause constant change of air within a standard thermometer shelter, the temperatures recorded are certain to reflect the heat absorption of the walls of the shelter itself during the day, and at night the degree of heat retention by the same walls, rather than the absorption and radiation of natural objects. Although, because of the free air movement, this influence is not very potent at considerable elevations above the ground, special precautions must be taken in exposing thermometers for ground temperatures. Direct insolation of the thermometers must of course be prevented. At the risk, however, of some reflected radiation striking the instruments, it has been found best to attach them to the north faces of boards and to protect them from the sun above and on the east and west, leaving them open to air currents on the north. There is nothing below them to interfere with ground-and-air cooling at night. Where standard shelters have been used on the ground, their doors have been constantly open to the north except for short periods, and usually the floors have been partly open. Although by no means all obstacles to proper temperature recording have in this manner been removed, it is believed that the records presented contain only occasional errors due to improper exposure.

Records of evaporation have been obtained with a variety of instruments and methods, omitting evaporation from free-water surfaces, but while an attempt has been made to compare the results obtained by different methods, it must be recognized as a general principle that such comparisons are of little value. Inasmuch as the rate of evaporation at any time is dependent not only upon the heat supplied by the sun and the air in contact with the evaporating surface, but also upon the rate of diffusion of the vapor as influenced by wind movement and atmospheric humidity, it is irrefragable that two different evaporating instruments or surfaces, with constant variations in each of these four contributing factors, can not maintain constant relative evaporating rates (*5*). Furthermore, it is hopeless to expect that the response of any instrument or evaporating surface will bear a constant relation to the response of any given plant, which must be differently affected by each of the four factors. The problem is made even more intricate by the variation in the capacity of different plants for sunlight absorption and for transpiration. For these reasons, the comparisons of types are based almost wholly on records of Type 4 evaporimeters, although some of these records were not obtained until the early part of 1921.

Methods of soil study are so far from being standardized, and the methods used by agricultural investigators are in some respects so inapplicable to mountain soils, that considerable ingenuity has been required to develop suitable procedure for this study. The aim has been to obtain an accurate measure of soil temperature on the one hand and on the other to determine the moisture content of the soil throughout the growing season. At the same time measurements have been made of those more or less stable soil qualities which have an influence upon the availability of soil moisture. After considerable observation and experiment the conclusion has been reached that soil-moisture data can be directly valuable in such a study as this only if they are reducible to terms of exterior osmotic pressure, which is opposed to the osmotic pressure in the plant itself. Although soil-moisture quantities have not been measured in exactly these terms, in the data certain guides are found by which the relative osmotic pressures may be approximated. There remains, however, a great need for further refinement of the data and for new methods especially applicable to the surface of the soil.

The special conditions affecting the value of the soil moisture and temperature data will be described under these respective captions just before the presentation of the results.

DESCRIPTION OF THE LOCALITIES STUDIED.

For the purpose of compilation the stations have been arranged in alphabetical and numerical series, rather than according to the forest types which they represent. The letter represents the initial of the geographic name by which the station is likely to be known, and the number indicates simply the serial order under each letter in this particular study. As the reader is not likely to hold these descriptions in mind and may wish to refer to them frequently, the indexing idea will prevail in their arrangement, except that the control station at Fremont will be first described.

F-1: Control station.—Elevation, 8,836 feet; aspect, S. 15° W.; slope, 21 per cent. Whether this station represents any forest type or will for ages remain a grassy park is very uncertain. It is situated practically on the crest of a narrow east-west ridge, lying only a few feet above stream channels on either side. The ridge represents granite in situ, however, rather than stream deposit. At the exact spot where the instruments are located there were no tree specimens, but a very compact sod. Within 30 feet, on the southerly slope, aspen, limber pine, and yellow pine seedlings were found, the aspen particularly being of very poor development, the nearest trees not over 10 feet high. On the northerly slopes of the same ridge yellow pine, limber pine, and Engelmann spruce form a poorly defined stand. Irregularities in conformation also give room for birch and aspen on this slope.

In the light of both topographic and vegetational evidence, the exact spot at which the station is located must be considered to represent conditions most conducive to a growth of yellow pine or perhaps limber pine. This classification, however, is not so important, since the station was designed primarily to secure data for the general atmospheric conditions of the Douglas fir zone in which it lies; and for the study of either atmospheric conditions or soil conditions one common point of comparison is perhaps as good as another. The records of this station are used in all comparisons of type conditions.

To make the records as free as possible from purely local influences, all atmospheric conditions have been observed on a tower so constructed that the thermometers, anemometers, evaporimeters, and other apparatus could be placed about 20 feet above the ground. (See Pl. I, fig. 1.) At this height no artificial influence acts upon any of the instruments, and even the nearest trees are too distant to have any appreciable effect upon wind movement or direction, although both movement and direction are strongly influenced by the configuration of the larger valley in which this small ridge lies. In 1917 a house was erected about 30 feet to the northwest of the tower, with the roof comb slightly higher than the instruments on the tower; but no effect from this structure has been noted in any of the records, and it is not thought that an appreciable effect can be produced by it, either upon temperature or wind movement.

In addition to the records obtained on this tower, it was thought desirable, in 1916, to measure air temperatures near the ground, as was being done at many of the outlying stations, in order that knowledge might be had as to the influence of elevation on temperatures. These ground temperatures go under the station number 1–G to distinguish them from the records designated 1–A. The equipment of this station, where most of the observations have been continued to date, has been as follows:

Tower (F–1A):

Maximum and minimum thermometers, in standard shelter. Standardized U. S. Weather Bureau instruments used, January, 1910, to April, 1920.

Air thermograph, March, 1910, to April, 1920.

Anemometer, standard, with register, February, 1910, to date.

Wind vane, with register, February, 1910, to date.

Sunshine recorder, electric themometric, with register, February, 1910, to date.

Psychrometer, January 21, 1910, to April, 1920.

Evaporimeter, inner-cell, Type 2, March 22, 1916, to January 1, 1917; inner-cell, Type 4, January 1, 1917, to date.

Ground (F–1G):

1-foot soil thermometer, in iron pipe, February 10, 1910, to September, 1918.

2-foot soil thermometer, in iron pipe, February 10, 1910, to June 30, 1914.

4-foot soil thermometer, in iron pipe, July 1, 1914, to date.

1-foot soil thermometer, in wooden tube, February 20, 1918, to June 10, 1920.

Maximum and minimum thermometers, on shielded board, April 1, 1916, to February 20, 1918.

Maximum and minimum thermometers, in standard shelter, February 20, 1918, to September, 1918.

Air thermograph, in standard shelter, February 20, 1918, to September, 1918.

8 and 12 inch rain gages, with register, January, 1910, to date.

Soil well in operation from June 29, 1914, to 1918. Determinations of moisture during growing season at depths of 1, 2, and 3 feet, and for 1917 at surface.

No records whatever for any of the above-described equipment were obtained during the periods from January 21 to March 20, 1914; from December 11, 1914, to February 28, 1915; and from September 21, 1918, to May 1, 1919. For some conditions, the record obtained up to 1918 seems adequate for establishing practically normal values; for others, the two succeeding years introduce very different values, and their records are therefore used.

C–1: Colorado Springs plains.—Elevation, 6,098 feet. On flat plains about 100 feet higher than the valley of Monument Creek, immediately adjacent on the west. The observations here were taken on the roof of one of the buildings on the campus of Colorado College, possibly 50 feet above the ground. The building is practically on the break between the flat plains which lie to the east and the valley of

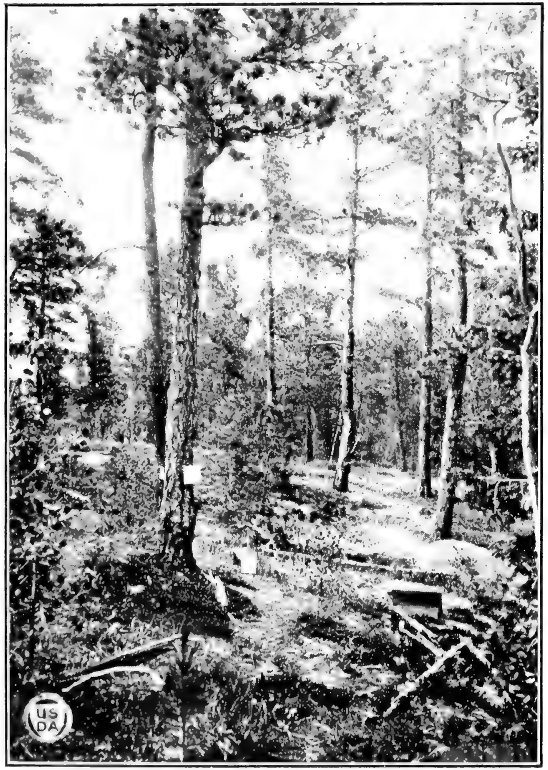

FIG. 1.—STATION F-4, LOOKING NORTHWARD, SHOWING THE CHARACTER OF THE WESTERN YELLOW PINE TIMBER WHICH FORMS THE MAIN CANOPY. JULY 7, 1918.

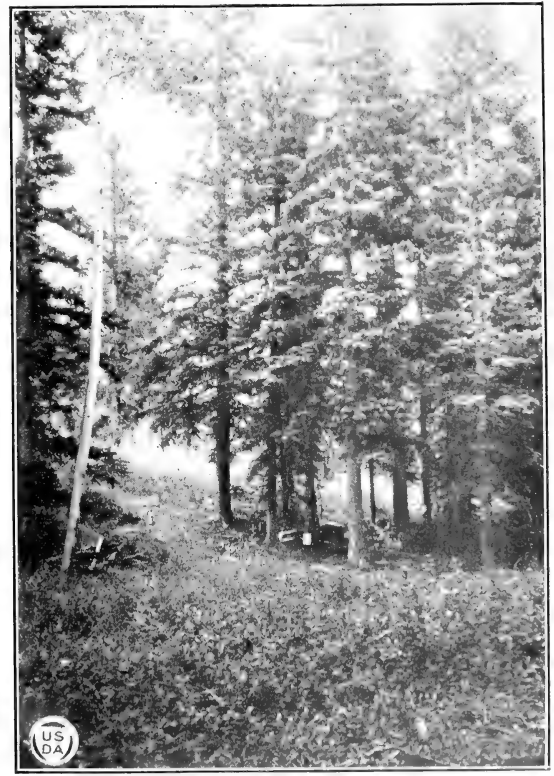

FIG. 2.—STATION F-5, SHOWING THE CLUMP OF SPRUCE TREES WHICH SHIELDS THE GROUND EQUIPMENT.

A few aspens have been cut from the space in the foreground. July 7, 1918.

FIG. 1.—STATION F-7, PRIOR TO REMOVAL OF LOGS FROM THE GROUND, LOOKING TOWARD UNCUT SPRUCE AND FIR BELOW AND IN THE ADJACENT PLOT WHERE STATION F-9 IS LOCATED. JULY 7, 1914.

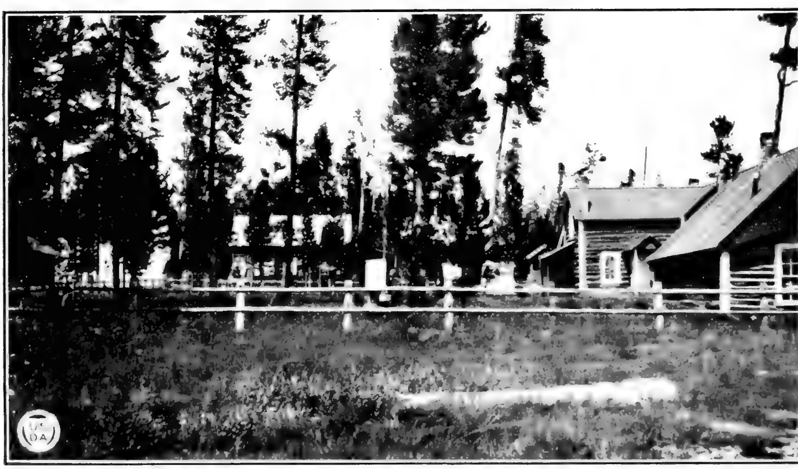

FIG. 2.—STATION F-11, FOXPARK, WYO., AT THE SOUTH EDGE OF A THINNED STAND OF LODGEPOLE. AUGUST 9, 1914.

Monument Creek. Other buildings are not close enough to affect the records in any way. The free sweep allowed the prevailing westerly winds probably accounts for some of the phenomenal velocities recorded at this station. In addition, the southward sloping creek valley tends to introduce an air drainage factor in the form of northerly breezes, which are not at all felt on the mountain slopes, and the north and northeast winds accompanying cyclonic storms are also not at all interfered with. Colorado Springs lies 4½ miles from the first abrupt rise of the mountains at Manitou, and 6 miles in an air line from the Fremont Forest Experiment Station.

The equipment of this station is that of a first-class weather bureau station, namely, maximum and minimum thermometers, thermograph, anemometer, psychrometer, sunshine recorder, rain gages, and triple register. No observations of ground or soil conditions are made. The station has been maintained by the faculty and students of Colorado College for about 35 years. The station is principally valuable as forming a base for the whole Pikes Peak series, which extends from this elevation to timberline at 11,500 feet.

D–1: Black Hills western yellow pine.—Elevation, 4,535 feet. Valley situation. Deadwood, S. Dak., is situated in the higher and moister portion of the Black Hills but in a valley surrounded by relatively high ground. It is therefore doubtful whether the station receives greater precipitation than the average for the Black Hills region. The record of precipitation and temperatures has been obtained for a great many years, under a variety of conditions, and while the conditions surrounding the taking of the late record used in this study have not been investigated, it is believed that in distribution of precipitation at least, which is the more important feature, the record will be properly indicative.

Due to artificial influences, the yellow pine forest immediately surrounding this station is far from representative of the Black Hills. However, this locality seems capable of producing the same dense reproduction and the same excellent development of pure yellow pine stands as any other portion of the hills, provided the soil is favorable; but everywhere these qualities seem to be strongly influenced by soils, and especially unfavorably by soils of limestone origin.

F–2: Fremont south slope western yellow pine.—Elevation, 8,921 feet; aspect, S. 35° W.; slope, 34 per cent. This station is situated but 400 feet from the control station, and as it occupies the south exposure of the same main valley it is subject to the same air currents.

The forest is the typical western yellow pine stand of semiarid regions, consisting of not over 20 or 30 trees per acre, with a maximum height of 60 feet. Occasional specimens of limber pine are found, but none of them attains a height equal to that of the yellow pine. The station is quite strongly shaded on the east, but is more open to the south and southwest. This fact, with the southwesterly aspect, accounts for a very late maximum temperature each day, and in part for the high soil temperatures recorded in the morning. (See Pl. II, fig. 1.)

During the two-year period, March, 1910, to February, 1912, this station was visited daily a few minutes later than the control station. As at the control station, all observations except soil temperatures, were made on a tower 20 feet above the ground. During later years some additional records of ground temperatures and evaporation have been secured for short periods. This station, with the following one, furnished the main part of the data presented in the preliminary report (*3*) on this study.

The full equipment is as follows:

Tower (F–2A):

Maximum and minimum thermometers, in standard shelter, March 1, 1910, to February 28, 1912.

Air thermograph, February 1, 1911, to February 28, 1912.

Anemometer, March 1, 1910, to February 29, 1912.

Psychrometer, March 1, 1910, to February 29, 1912.

8-inch rain gage, March 1, 1910, to February 29, 1912.

Ground (F–2G):

1-foot soil thermometer, in iron pipe, February 10, 1910, to February 29, 1912.

2-foot soil thermometer, in iron pipe, February 10, 1910, to February 29, 1912.

(In addition, these points were observed in spring and fall of 1913, and in 1914 from May to July, when the 4-foot depth was substituted for the 2-foot depth.)

1 and 4 foot soil thermometers, in iron pipes, July 9 to December 12, 1914; March 1, 1915, to February 29, 1916; and May 11, 1917, to September, 1918. On April 26, 1918, a wooden tube was substituted for the iron pipe at the 1-foot depth.

Soil samples at random during growing season July, 1910, to October, 1911.

Soil well in operation during growing seasons after June 29, 1914, and excluding 1916. Regular determinations at 1, 2, and 3 feet, and in 1917 at surface.

Piche evaporimeters, as modified by Weather Bureau, May 5, 1914, to February 29, 1916.

Evaporimeter, inner-cell, Type 4, February to September, 1918; May, 1919, to April, 1920.

Maximum and minimum thermometers, on shielded board, March 2, 1915, to February 29, 1916.

F–3: Fremont Canyon spruce.—Elevation, 8,860 feet; aspect, N. 44° E.; slope, 54 per cent. This station, like the preceding, is only about 400 feet from the control station. It is situated at the foot of a steep northeasterly slope, only a few feet above one of the small streams. (See Pl. I, fig. 2.) It is cut off from the air currents which principally affect Stations 1 and 2 by the westward extension of the ridge on which Station 1 is located, and which becomes considerably higher opposite Station 3. The ground at Station 3 is so close to the stream as to feel very markedly the cold-air stream at night, which on the 20-foot tower is much less apparent.

This type is strictly Engelmann spruce at the station, although as one ascends the slope to a more exposed situation the forest quickly changes to one of Douglas fir. For this reason, in an earlier report (*3*), this station was described as representing a spruce-fir type. The predominance of spruce at the very foot of northerly slopes at this elevation is typical, and the purely local condition should here be considered. The stand has come in since a fire which occurred about 60 years ago.

This station has had the same equipment and has been under observation during the same periods as F–2, with a few insignificant exceptions.

F-4: Fremont east slope pine-fir.—Elevation, 9,117 feet; aspect, N. 88° E.; slope, 27 per cent. This station is placed on a moderate east slope, where it receives the full effect of the morning sun, which, especially during the warmer months, is usually unobscured. The station lies between two very shallow depressions, not over 20 feet apart, which possibly gives the soil moisture a trifle more than the average value for the slope as a whole. (See Pl. III, fig. 1.)

The site represents a somewhat common condition in the yellow pine forests of the region, which, when not too strongly insolated, give way to Douglas fir as a climax, in agreement with Clements' description (*10*). Here it appears that the succession may have been arrested by the fire which burned over the whole territory about 60 years ago, but on this area merely scarred the mature yellow pine trees. These are now in a decadent condition and somewhat infected by mistletoe, which, through its attacks on the yellow pine saplings, seems to be an important factor in hastening succession. In the tally of the trees within a radius of 50 feet of the station center, it will be noted, the Douglas fir does not hold so prominent a place in the younger reproduction as in the class from 2 to 5 inches in diameter at breast height.

Class.	Yellow pine.	Douglas fir.	Limber pine.
Reproduction under 4.5 feet	20	6	20
Saplings, 0 to 2 inches	15	7	5
Saplings, 2.1 to 5 inches	4	9	5
Trees over 5 inches	17	3	4

The site then is evidently such that the slightest disturbance might cause a swing toward either Douglas fir or yellow pine predominance. The occurrence of considerable aspen (*Populus tremuloides*) and limber pine is not considered significant.

All observations have been taken at or in the ground. The equipment has been as follows:

1 and 4 foot soil thermometers, in iron pipes, July 9, 1914, to December 12, 1914; March 3, 1915, to March 1, 1916; and May 11, 1917, to September, 1920. 1-foot iron pipe replaced by wooden tube, April 26, 1918.

Ground and soil-surface temperatures, May to September, 1920.

Soil well after July, 1914, with soil-moisture samples taken during the open seasons of 1914, 1915, and 1917.

Evaporimeter, inner-cell, Type 4, February to September, 1918, May, 1919, to September, 1920.

F.-5: Fremont Canyon spruce.—Elevation, 9,044 feet; aspect, S. 20° E.; slope, 10 per cent. Conditions here are very similar to those of Station F-3, except that Station F-5 is in the creek bottom, about 10 feet north of the east-west channel. There is no surface stream here, but the underground seepage must be considerable. The soil is alluvial and contains considerable granitic gravel.

The spruce stand forms only a narrow band along the stream channel and the base of the north slope. Aspen reaches better development here, perhaps, than anywhere else in the vicinity. The station is practically at the base of a spruce 18 inches in diameter by 70 feet high. (See Pl. III, fig. 2.) It is strongly shaded except on the southwest, where an artificial opening permits some light to enter. A natural opening also permits sunlight to reach the ground for an hour or more before noon.

The equipment and observations have been the same as for the preceding station.

F.-6: Fremont west slope limber pine.—Elevation, 9,060 feet; aspect, N. 48° W.; slope, 32 per cent. Situated near the top of a steep northwest slope, with a wide canyon to the west, this station gets the full sweep of the desiccating winter winds from the west. At this point the slope is less steep than below, and the type is less completely one of limber pine, for it contains some yellow pines, which form the main stand on the ridge just to the east. However, at the station the limber pine strongly predominates. Like all exposed westerly slopes in the Pikes Peak region, this one shows the effect of the winter blasts. The ground is swept bare, and practically no ground cover appears even for short periods in the summer. (See Pl. II, fig. 2). In spite of its apparent poverty, however, the soil at the station was found to contain an unusual amount of fine mineral material and humus. Pure stands of limber pine are extremely rare in the central Rockies, and for this reason the study of the conditions which might have brought this one into being was begun with great interest.

The equipment of Station 6 has all been placed at the ground, as follows:

1 and 4 foot soil thermometers, July 9, 1914, to December 12, 1914; March 3, 1915, to February 29, 1916; and May 11, 1917, to September, 1920. Iron pipe at 1 foot replaced by wooden tube April 26, 1918.

Ground and soil-surface temperatures, May to September, 1920.

Soil well, with moisture determinations for 1, 2, and 3 feet, established July, 1914, and operated during open seasons of 1914, 1915, and 1917.

Maximum and minimum thermometers, in shelter, March 15, 1915, to February 29, 1916.

Anemometer (elevation, 18 inches), March 5, 1915, to February 29, 1916.

Evaporimeter, inner-cell, Type 4, February to September, 1918; May, 1919, to September, 1920.

F-7: Fremont north slope spruce-fir, clear-cut.—Elevation, 9,105 feet; aspect, N. 16° E.; slope 34 per cent. This station is situated near the middle of a north slope whose total width is about 400 feet. It lies 60 feet higher than the stream channel directly below, where Station 5 is situated.

Station 7 is in the lower third of an opening about 250 feet square which was made by clear-cutting the forest. At this level the original stand was a dense mixture of Engelmann spruce and Douglas fir in almost equal proportions, with occasional specimens of limber pine and yellow pine and a few subordinate and decadent aspens. The area was cut over in the fall of 1913, and up to the present there is practically no cover except aspen sprouts, 3 to 5 feet high, and herbs.

This station, together with Stations 8, 9, 14, and 15, represents the conditions on four near-by identical acre plots from which the timber has been cut in different ways. Because of a break in the slope just above the middle of plot 1, two stations, 7 and 8, were thought necessary to represent its soil conditions; but a single station at the center, known as 7–8, was considered adequate for atmospheric measurements. Thus together, Stations 7, 7–8, and 8 are the counterpart of Station 9 in the uncut plot (2) to the east, and of Stations 14 and 15 at the centers of the two additional plots from which only a portion of the timber was removed. These will be described later. It is important to remember that these four stations (or six, considered individually) represent essentially the

FIG. 1.—STATION F-12, WESTERN YELLOW PINE RIDGE TYPE AT THE FREMONT FOREST EXPERIMENT STATION.

In the view are also shown limber pine and Douglas fir saplings, and in the background large Douglas firs. July 7, 1918.

FIG. 2.—STATION F-13, LOOKING SOUTH, SHOWING A PORTION OF THE HIGH ROCKY KNOB WHICH TERMINATES THE RIDGE ON THE EAST. MAY 21, 1915.

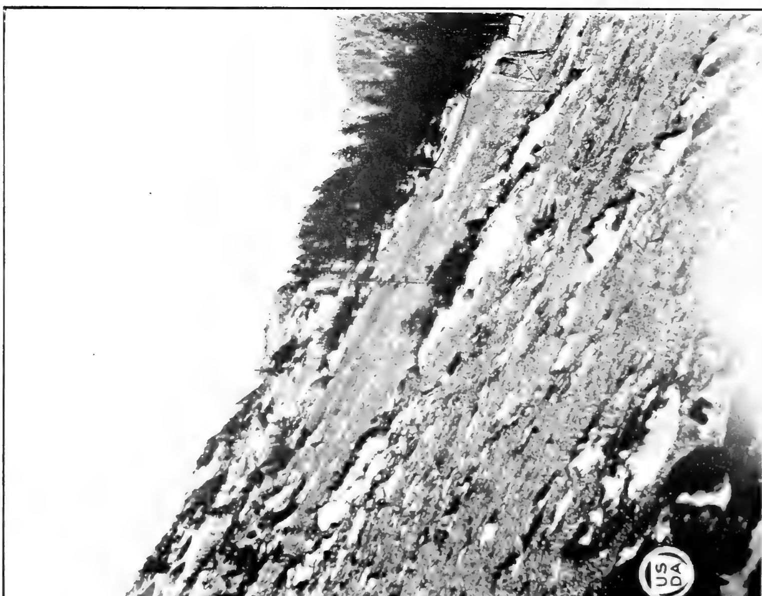

FIG. 1.—STATION F-16, AT TIMBER LINE ON PIKES PEAK.

Note that to the west the spruce attains a higher elevation in the shelter of a rocky ridge. October, 1916.

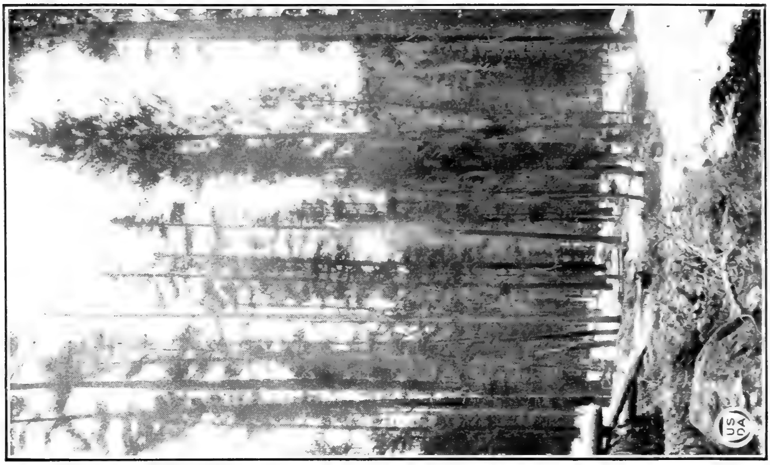

FIG. 2.—FIRST-QUALITY LODGEPOLE PINE IN THE VICINITY OF FRASER, COLO., ON TRANSPORTED SOIL CONTAINING MUCH CLAY. JUNE 3, 1914.

same original conditions, now changed by disturbance of the forest cover. (See Pl. IV, fig. 1.)

At this station the following equipment has been used:

1 and 4 foot soil thermometers, in iron pipes, July 9, to December 12, 1914, and March 3, 1915, to April, 1920, with the exception of March, 1916. 1-foot pipe replaced by wooden tube April 26, 1918.

Soil well in use from July 13, 1914, during open seasons, to end of 1917, weekly determinations being made of moisture at 1, 2, and 3 foot depths, and during 1917 at the surface.

Evaporimeter, Piche, July 7, 1914, to December 12, 1914, and June 8, 1915, to October 24, 1915. Later evaporation records made at Station 7–8.

F–7–8: Fremont north slope Douglas fir, clear-cut.—This station lies midway between Stations 7 and 8 in a clear-cut plot. At this elevation, which is only 16 feet higher than Station 7, the Douglas fir in the original stand was clearly predominant, while at Station 8 it had practically no competition. This location was selected in the center of the clear-cut plot to represent atmospheric conditions for the plot as a whole.

The equipment has been as follows, all placed about 1 foot above the ground:

Maximum and minimum thermometers, on shielded board, September, 1915, to September, 1918, excepting March, 1916.

Air thermograph, on shielded board. Psychrometer (beginning May 1, 1916). Anemometer, with register. Evaporimeter, Type 2, 1916; Type 4, 1917.	April 1, 1916, to December 31, 1917. Rotated with Stations 14 and 15, this station being reached the first decade of each month.

Evaporimeter, Type 4, January 1, 1918, to April, 1920.

Sunshine recorder, electric thermometric, with register, during first third of each month from July to October, 1917.

8-inch rain gage, April 6, 1916, to December 31, 1917.

F–8: Fremont north slope Douglas fir.—Elevation, 9,137 feet; aspect, N. 22° E.; slope, 26 per cent. The conditions surrounding this station are very similar to those at Station 7, except that the slope to the north is 8 per cent less steep, and Station 8 is at a higher position on the slope. This difference was sufficient to introduce a marked difference in the original forests at the two stations, the forest at Station 8 being almost pure fir, while at Station 7 Engelmann spruce comprised half the stand. The possible insolation of the soil at Station 8 is probably made greater by the nearness of the station to the top of the ridge, with reduced opportunity to secure seepage water and transported soil. The evaporation records of 1914 also indicate that the higher position gives Station 8 somewhat greater exposure to drying influences.

The equipment of this station has been identical with that of Station 7, except that the Piche evaporimeters were used here only during 1914. The conditions recorded here may properly be averaged with those at Station 7 to obtain data representing the clear-cut area as a whole.

F–9: Fremont north slope Douglas fir, uncut.—Elevation, 9,099 feet; aspect, N. 10° E.; slope, 33 per cent. It is seen that this location is practically identical with that of Station 7, except that the slope does not bear quite so much away from the north and is protected by a virgin forest cover, while Stations 7 and 8 are in an artificial opening of the same stand. (See Pl. IV, fig. 1.)

The forest surrounding Station F-9 may be depicted by reference to a tabular statement for an area of 0.942 acres, at the center of which the station is situated. This shows a total of 1,143 trees over 4.5 feet in height, of which 367, or 32.1 per cent, are Douglas firs. The firs comprise 68.6 per cent of all the trees over 4 inches in diameter at breast height, but only 18.8 per cent of those below this size. In contrast, Engelmann spruce comprises only 22.6 per cent of the larger trees, but 47.4 per cent of the smaller ones. This relative status of the two species would indicate, without further evidence, that Douglas fir is unable to hold its own under the dense canopy of the larger trees. That this crowding out of the Douglas fir is not due to lack of seeds, is repeatedly shown by the comparatively large number of fir seedlings which germinate, but soon die. For example, in the new crop of seedlings in 1916 there were 1,183 Douglas firs and only 334 Engelmann spruces. After a few years only about a 3:2 ratio of the two species exists among the small seedlings. In the half-cut plots adjacent, where the canopy is not over one-third as dense, there were practically no spruce seedlings, but there was about the same number of firs. This may be due either to the differences in physical conditions, or to the complete removal of spruce seed trees from the cut-over plots, though it would seem that considerable spruce seed might be blown in. Although fir, because of its control of the canopy, may initiate a large part of the new seedlings each year, there is little doubt that the survivors are mainly of spruce. In other words, the conditions being measured at Station 9 are those conducive to spruce survival.

The equipment of Station 9 has been maintained almost continuously, so that the conditions at Stations 7–8, 14, or 15 might be compared with the conditions at this station, as a secondary control for any period. The record follows. All atmospheric observations have been at an elevation of 1 foot.

1 and 4 foot soil thermometers, in iron pipes, July 10, 1914, to April, 1920, with the exception of March, 1916. 1-foot iron pipe replaced by wooden tube April 26, 1918.

Soil well in use from July 13, 1914, to end of 1917, during open season, giving weekly records of soil moisture at 1, 2, and 3 foot depths, and during 1917 at the surface.

Maximum and minimum thermometers, on tree, September, 1915, to September, 1918, excepting March, 1916.

Air thermograph, under partial shelter, April 1, 1916, to December 31, 1917.

Psychrometer, April 23, 1916, to December 31, 1917.

Anemometer, April 23, 1916, to December 31, 1917, with register most of time.

8-inch rain gage, April 6, 1916, to December 31, 1917.

Evaporimeter, inner-cell, Type 2, April 1 to December 31, 1916.

Evaporimeter, inner-cell, Type 4, January, 1917, to April, 1920.

F-11: Foxpark Plateau lodgepole pine.—Elevation, 9,000 feet; aspect, S.; slope, about 5 per cent. The station is situated within the forest, but only about 50 feet from the edge of it, where it opens out abruptly into a grassy bog or park bordering Foxpark Creek. This station is barely 10 feet above the creek level. As the cover has been considerably lightened by the cutting of trees in the ranger station yard, it is altogether probable that the summer temperatures represent about a mean between those of the dense lodgepole forest and those of the much warmer glades. As winter temperatures are more largely controlled by strong winds and a deep snow blanket, they would be little affected. (See Pl. IV, fig. 2.) The soil at this point is a decomposed gneiss which forms a grayish, gravelly sand not wholly devoid of clay. On account of the heavy snows which lie until summer, and the presence of the water table at a depth of 6 to 8 feet, the soil is usually saturated during the early part of the growing season, but gradually dries out to a low point. This seems to be true of a considerable area about Foxpark, though the moisture is perhaps greater at the station than in the forest as a whole.

This station is the only one in the lodgepole pine type for which soil data are recorded. It is located very close to Foxpark post office, almost on the line between Colorado and Wyoming, in longitude 106° W. The entire plateau about Foxpark bears an almost unbroken forest of lodgepole of very good quality, but a few high points projecting out of the plateau bear mixed stands of spruce and lodgepole. About 5 miles to the east of Foxpark the plateau breaks off abruptly to the plains, and on these slopes are found a few specimens of yellow pine and Douglas fir.

The Weather Bureau installed maximum and minimum thermometers and an 8-inch rain gage at this station in March, 1911, and the earlier record of temperatures as used in this report is taken directly from Weather Bureau summaries. In March, 1916, the Forest Service supplemented this equipment with the following, which was in use through August, 1918:

Psychrometer.

Anemometer.

Evaporimeter, inner-cell, Type 2. This was replaced by Type 4 evaporimeter, January 15, 1917.

Still earlier, in August, 1914, soil thermometers had been installed, in iron pipes, at depths of 1 and 2 feet, the latter being lowered to 4 feet on March 15, 1916.

A soil well was prepared in July, 1916, and weekly soil samples at the surface and at depths of 1, 2, and 3 feet have been taken during the open season since August 1, 1916.

It is to be noted here that the observations for the Foxpark station have been more or less irregular, owing to the frequent absence of the observer for several days at a time. However, the air temperatures, which would be most affected, have now been observed for a sufficient number of years so that the uncompensated error should be quite small.

F-12: Fremont Ridge western yellow pine.—Elevation, 9,164 feet; aspect, S. 20° E.; slope, 8 per cent. This point is on a broad, well-rounded ridge that has a general east-west bearing, but very little slope for a considerable distance east or west of the station. (See Pl. V, fig. 1.) It is thus very evenly exposed on all sides, and at the outset the exposure to wind from all directions was thought to account largely for the very scrubby growth of the yellow pine.

The stand immediately surrounding the station is, for the most part, young, having probably originated after a fire about 60 years ago. The trees range from a height of about 20 feet down to tiny seedlings. Yellow pine strongly predominates in numbers, but Douglas fir and limber pine are also coming in, and these two species likewise occur in all sizes. The yellow pine was very badly infected with mistletoe, which was seriously retarding the growth of most trees and gradually claiming victims. The elimination of diseased trees during the winter of 1917–18 has markedly improved appearances and the general rate of growth. No cutting was done close to

Station 12. The soil at this site is extremely thin and poor. In fact, there is so little accumulation of organic matter, and the granite is so slightly disintegrated that it can hardly be said that there is any soil.

The equipment of this station consisted of:

Maximum and minimum thermometers, in standard shelter, on the ground, March 3, 1915, to February 29, 1916.

Air thermograph, same location and period.

Anemometer, 8 feet from ground, with register, same period.

Sunshine recorder, electric thermometric, March 7, 1915, to September 10, 1915.

Evaporimeter, inner-cell, Type 4, 1 foot above ground, February 16, 1918, to September, 1920.

1 and 4 foot soil thermometers, in iron pipes, the former from May 22, 1915, and the latter from June 19, 1915, to February 29, 1916. Both from August 1, 1917, to September, 1920. One-foot iron pipe replaced by wooden tube, April 26, 1918.

Ground and soil-surface temperatures, May to September, 1920.

Soil well, furnishing moisture samples at 1, 2, and 3 feet, from July 7, 1915, to end of season, and also surface samples during season of 1917.

F–13: Fremont high-ridge limber pine.—Elevation, 10,300 feet; aspect, flat. This station presents the conditions existing on an exposed ridge at the northeast base of Pikes Peak, where much of the original forest was destroyed by fire many years ago. For the most part this forest was of spruce. Limber pine is now coming in all over the burned area, and in the more sheltered spots the spruce followers are already appearing. At present the stand of limber pine about Station 13 is not sufficient to furnish any protection. The chief characteristic of the site, therefore, is an intense exposure to both sun and wind. (See Pl. V, fig. 2.) It is interesting to note that a few specimens of western yellow pine may be found in the vicinity of this station where the exposure is less severe. Apparently they are of the same age as the first group of limber pines gaining a foothold after the fire. Observations at this point were at 5-day intervals. No soil-moisture determinations were made.

This station was equipped with:

Maximum and minimum thermometers in shelter 5 feet above the ground May 21, 1915, to October 1, 1916.

Air thermograph, same location and period.

Psychrometer.

Anemometer 7 feet above ground. In addition to dial readings at 5-day intervals, the velocity was observed during about an hour for each period from May 21, 1915, to March 5, 1918. Even with this aid, however, it was impossible to determine the 5-day movements with any certainty when high velocities prevailed.

Evaporimeter, wick Type 1, August 26, 1915, to February 11, 1916.

Evaporimeter, inner-cell, Type 2, April 1 to October 1, 1916.

Eight-inch rain gage, May 21, 1915, to October 1, 1916.

Soil thermometers, at depths of 1 and 2 feet in iron pipes, from May 21, 1915, to October 1, 1916.

Soil thermograph, at 1 foot depth, September 1, 1915, to October 1, 1916.

F–14: Fremont north slope Douglas fir, half cut.—Elevation, 9,087 feet; aspect, N. 3° E.; slope, 35 per cent. This station and the following are counterparts of Station 7–8 in clear-cut and of Station 9 in uncut Douglas fir. Station 14 represents conditions under a half canopy of the taller trees of the original stand with all undergrowth removed. The character of the cutting carried out in 1913 was that known to foresters as the "shelterwood system." The

FIG. 1.—ROLLING SAND-HILL LAND, HALSEY, NEBR.

Extreme right of picture corresponds to situation of Station H-3 on southerly exposure.

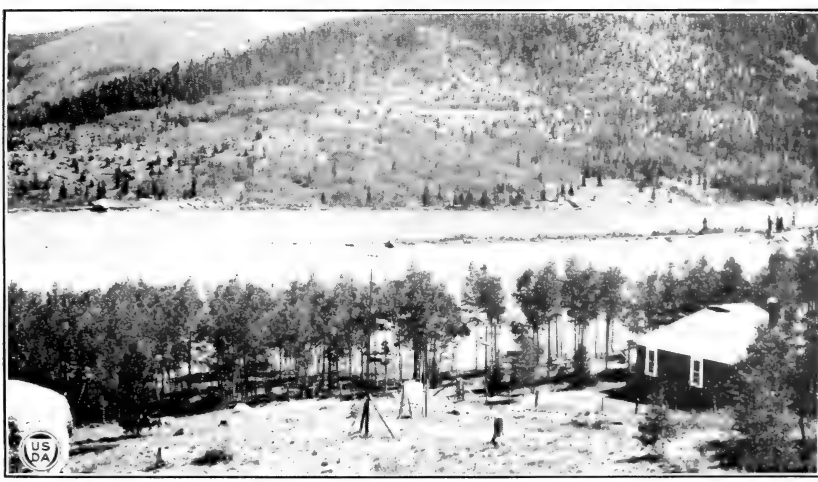

FIG. 2.—WEATHER STATION AND SURROUNDINGS AT LAKE MORAINE, NEAR PIKES PEAK, COLO. (STATION L-1). AUGUST, 1918.

FIG. 1.—STATION M-1, SHOWING IMMEDIATE SURROUNDINGS OF INSTRUMENT SHELTER.

The soil well is just to the left of the anemometer at the foot of the oak clump. May 23, 1915.

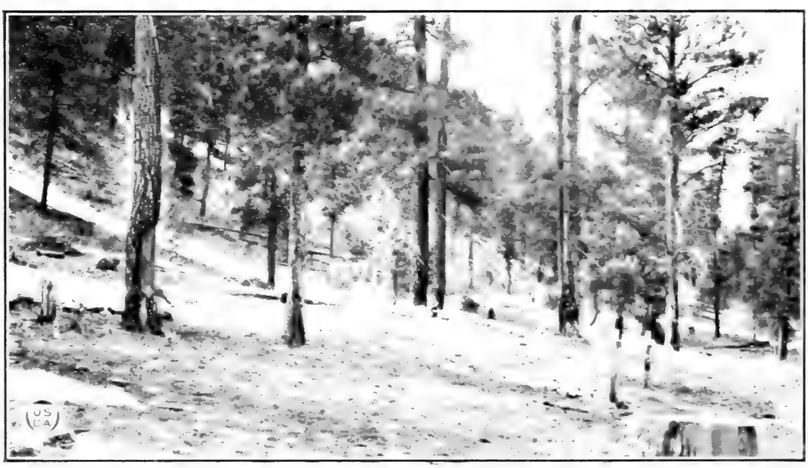

FIG. 2.—WESTERN YELLOW PINE FOREST NEAR PAGOSA SPRINGS, COLO., AT THE FOOT OF AN EAST SLOPE, IN SANDSTONE. APRIL, 1917.

object of this kind of cutting is to leave at the first cut only such trees as will be merchantable in a few years, and these for the value of their protection to the new growth, whose development determines the time when the old trees shall all be removed. Inasmuch as the original stand was not single-aged, though it was mainly so, this process involved forced cutting of material not merchantable except for fuel. All trees except those of Douglas fir were removed in the cutting, and of the latter about 83 trees of an average diameter of 9.7 inches and an aggregate basal area of 43 square feet were left on the acre plot. This represents just one-fourth the basal area of the original stand. Presumably, therefore, the crown density is not over one-fourth of the virgin crown density nor of that now sheltering Station 9.

Although a few observations of minimum temperatures were made at this point in the fall of 1915, the more important records do not begin until 1916. The equipment used was as follows:

Maximum and minimum thermometers, in standard shelter, 1 foot above ground, April 1, 1916, to December 31, 1917.

Air thermograph, in shelter. Psychrometer. Anemometer, 1 foot above ground, with register. vaporimeter, inner-cell, Type 2, in 1916. Evaporimeter, inner-cell, Type 4, in 1917.	April 1, 1916, to December 31, 1917. Rotated with Stations 7–8 and 15, this station being reached the second decade of each month.

Evaporimeter, Type 4, January 1, 1918, to April, 1920.

One and 4 foot soil thermometers, in iron pipes, April 1, 1916, to April, 1920; 1-foot iron pipe replaced by wooden tube, April 26, 1918.

Soil well furnishing samples for moisture determination at depths of 1, 2, and 3 feet, from May 23 to end of season, 1916, and also from the surface during the whole season of 1917.

F–15: Fremont north slope Douglas fir, half cut.—Elevation, 9,080 feet; aspect, N. 8° W.; slope, 28 per cent. This station is only 250 feet east of the preceding and practically on the same contour. However, it will be noticed that the slope is slightly less steep, and this location has a very slight bearing to the west of north. The difference in slope, giving somewhat more direct insolation at Station 15 than at Station 14, is probably a little more than counterbalanced, for the general area in which Station 15 is located, by a somewhat greater density of cover. At the station, however, the cover is fairly heavy on the east but relatively open to the west and southwest, permitting sun action in the afternoon, and this will fully account for the slightly higher soil temperatures here than at Station 14.

The plot in the center of which Station 15 lies, like that surrounding Station 14, has been heavily cut over, but with the object here of leaving trees of all sizes, or in other words, of producing a "selection" forest. Again, this cutting was forced, as the original stand was far richer in mature than in immature sizes. This was especially true of the Douglas fir, and as the cutting completely removed all other species, the number of healthy young trees left could not be very great. However, the number of trees is somewhat greater than in the "shelterwood" forest, both of large and small sizes. The principal shortage is in trees 4 to 6 inches in diameter. In the stand left after cutting there are 110 trees of an average diameter of 10.2

inches and 160 trees of an average diameter of 2 inches, making a total basal area of 66 square feet, or 50 per cent more than in the "shelterwood" plot.

The equipment and operation of this station has been the same as of Station 14, except that the periodic use of recording instruments fell here on the third decade of each month.

F-16: Timberline.—Elevation, about 11,500 feet; aspect, N. 10° E.; slope, 40 to 45 per cent. This station represents conditions on the north slope of Pikes Peak, at the upper limits of the Engelmann spruce type, limber pine and bristlecone pine, as well as spruce, being found in the edge of the forest. It is just a few feet outside the timbered zone, which here ends very abruptly. (See Pl. VI, fig. 1.) Presumably, on account of local wind exposure, the point represents one of the lowest dips in the timberline, and was chosen for the observations because of its accessibility.

Owing to the difficulty of the trip, the station has been visited only at 5-day intervals since its installation in October, 1916. For air temperatures such a program necessitates more than the usual dependence upon the thermograph record, as but one correction of the maximum and one of the minimum is secured for each 5-day period. The system has been to apply these corrections to the trace for each day of the five, with slight modification, and then to obtain from the trace the maximum and minimum temperature for each day, calculated from midnight to midnight. This, it is thought, would have permitted no serious error over a long period had the recording thermometers been perfectly reliable. Owing to the high wind velocities it was found impossible to obtain a correct record of minimum temperatures in the shelter where the other instruments were located, and as a final resort two other minimum-registering thermometers were placed on more substantial supports. Although these did not fail to register properly, they did not of course register the temperatures prevailing in the shelter. The entire temperature record, therefore, presents a combination of values, all of which are not representative of the same point, but doubtless represent the locality well enough.

The thermometer shelter, anemometer, and evaporimeter were so placed on a tower that an elevation of about 10 feet above the ground was secured for each instrument. The periodic psychrometer readings, which of course do not have great value, were likewise secured at this elevation. The precipitation record during most of the first year was secured by means of an 8-inch gage placed in the shelter of spruce trees 100 feet from the other equipment. It was thought that the trees afforded no more than enough protection from wind to insure a good snow catch. With rain and little wind, however, it was found that a 12-inch gage in the open gave much higher values. For this reason the entire precipitation record, except for August and September, 1917, is questionable and has not been used. No soil moisture determinations have been made at this station.

The following equipment was used:

Maximum and minimum thermometers, in standard shelter, October 1, 1916, to February 28, 1918.

Air thermograph, in shelter, October 1, 1916, to February 28, 1918.

Psychrometer, in shelter, October 1, 1916, to February 28, 1918.

Anemometer, with register, October 1, 1916, to February 28, 1918.

Evaporimeters, inner-cell, Type 2, October 1, 1916, to December 31, 1916.

Evaporimeters, inner-cell, Type 4, January 1, 1917, to September, 1918.
1 and 4 foot soil thermometers, in iron pipes, October 1, 1916, to September, 1918.
Soil thermograph, October 1, 1916, to October 16, 1917.
8-inch rain gage, under shelter of trees, October 1, 1916, to February 28, 1918.
12-inch tipping-bucket rain gage, with register, August 1, 1917, to September 21, 1918.

F–17: Frances Douglas fir.—Elevation, 9,300 feet; aspect, easterly. This station is situated near Frances, Colo., on a steep mountain side, in the bottom of a gulch opening to the east. The ground in the immediate vicinity of the station is not far from level, but it rises precipitously a few rods to the west. The situation is apparently such as to give marked air-drainage effect at night, and to cause stagnation of the air during the day. The temperature records of this station are thought to have considerable comparative value, because the station is at almost the same elevation as Fremont, and similarly situated on the east slope in the Douglas fir zone.

The forest surrounding the station was at one time a fairly even stand of comparatively small Douglas firs. It has been almost completely destroyed by cutting and fires over a large area, and in this locality there is almost no reproduction. A little higher the granitic and glacial soils are being occupied by lodgepole pine.

F–18: Fraser Basin lodgepole pine.—Elevation, 8,560 feet; aspect, northerly; slope, 1 to 2 per cent. This station, in north-central Colorado, is situated in the broad valley of the Fraser River, which at this point runs slightly west of north. The drainage area to the south of Fraser comprises about 100 square miles, and the valley at this point has widened out into a meadowlike basin of very little slope, having a width of fully a mile between the forest-covered slopes on either side. Although it is thus considerably removed from the forest, there appears no reason for any great difference between the atmospheric conditions over the station and those over the forest. The locality is characterized by precipitation so well distributed over the entire year that, although the month of June is usually about the driest, the melting snow furnishes abundant moisture for the early part of the growing season. The winter temperatures are extremely low, but always accompanied by a good snow blanket. Under these conditions lodgepole pine attains the best development noted anywhere in Colorado, both as to stature of trees and density of stands. (See Pl. VI, fig. 2.)

The character of the soil, considered in connection with the well-distributed precipitation, probably is an important factor in this development. The soil in the forest is of granitic origin but is so thoroughly broken down as to contain a high percentage of clay, and consequently to have a high water-retaining capacity.

The lodgepole forest about Fraser comes down on all slopes practically to the edge of the valley and to an elevation within 100 feet of that of the station; to the south, where the valley is narrower, the forest extends entirely across it. This fact might lead to the conclusion that the forest does not reach the station on account of the forbidding conditions of an alluvial soil. It is also interesting to note that there is no transition zone between the mesophytic conditions of the slopes and the "desert" conditions of the valley. To be sure, a very few specimens of western yellow pine may be found on the lower hills, while somewhat more frequently a clump of

Douglas fir occupies some low, rocky point. The occurrence of Douglas fir seems always to be the result of natural protection from fire, and we may conclude, as in most of the lower lodgepole regions, that Douglas fir originally controlled the situation.

H–2: Nebraska sandhills.—Because of the marked success of the planting of yellow pine and jack pine (*Pinus banksiana*) in the Nebraska sandhills, it has been deemed advisable to observe to what extent the conditions here differ from those of the yellow pine type in the mountains. Since the establishment of the Halsey Nursery in 1903, temperature and precipitation records have been secured in a river-bottom situation (H–1). In October, 1918, an additional primary station (H–2) was established on the hills 80 or 90 feet higher than the river bottom, on a gentle northerly slope. A station (H–3) for the observation of soil temperatures on a steep southeasterly slope was also installed only 200 to 300 feet from H–2. (See Pl. VII, fig. 1.)

In considering the conditions shown by the records for these stations it should be borne in mind that the locality does not produce yellow pine naturally, and that no success has been had from direct seeding. This may be due to the very sandy soil as much as to any atmospheric conditions observed. The latter, apparently, are favorable for a very high growth rate of established trees.

L–1: Lake Moraine Basin spruce.—Elevation, 10,265 feet; aspect, southeast; slope, about 20 per cent. This station is next to the highest in the Pikes Peak series. It is operated by the officials of the city water department of Colorado Springs in cooperation with the Weather Bureau, and the record of precipitation and air temperatures has been obtained for 24 years. This site is on a gentle slope not far from the west bank of Lake Moraine, 20 feet above the water and just outside a thick clump of aspen. (See Pl. VII, fig. 2.) The body of water probably modifies temperature extremes to a slight extent. The station is not protected by forest, for this consists only of scattered specimens of limber pine, 4 to 8 feet high, which followed a destructive fire 60 years ago. Some protection from winter wind is furnished by the steep hill to the northwest.

L–2: Leadville flat spruce.—Elevation, 10,248 feet; aspect, southwesterly; slope, 5 to 10 per cent. The surroundings of this station are on the west, an almost flat bench sloping very gradually to the Arkansas River, 3 miles away, and on the east the higher mountains. The station is near the top of a ridge within the town of Leadville. Most of the ground outside the town is clothed with a young, somewhat open growth of lodgepole pine, which apparently has replaced the virgin forest since the first mining activity in this region disturbed the natural conditions. This, however, has not been closely investigated.

The most striking conditions of the locality are the severe wind exposure afforded by the high elevation and the free sweep over a broad basin to the west, and the apparent poverty of the soil, which is composed of a gravelly sand. This soil, which is of the general character often chosen by lodgepole, may account for the openness of the stands and the not too vigorous growth. On the other hand, openness of the stands may be due to artificial factors, such as smelter fumes, which have been fatal to some of the hill forests nearby.

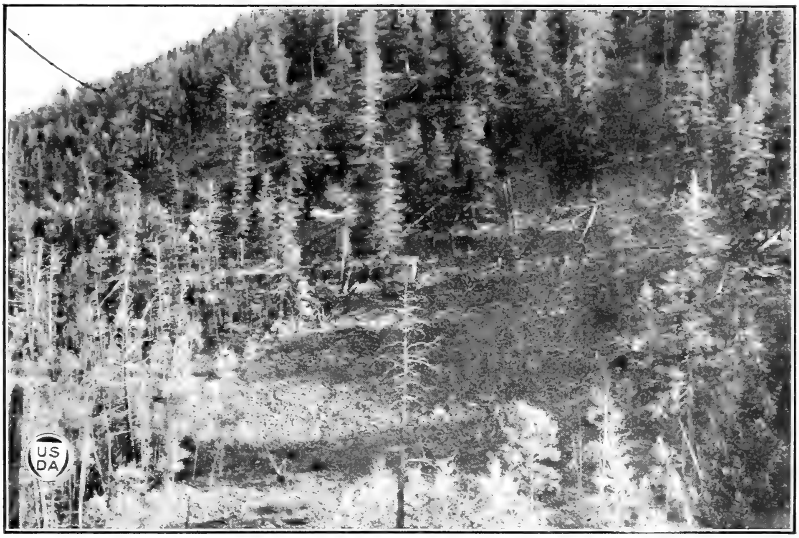

FIG. 1.—STATION W-A1, WAGON WHEEL GAP, IN NORTH-SLOPE DOUGLAS FIR.

The instrument shelter may be seen just within the timber on left (east) of rock slide. 1910.

FIG. 2.—LOCATION OF INSTRUMENT SHELTER AT STATION W-C, IN BORDERLAND BETWEEN THE FORESTED SLOPE AND THE FLATTER "PARK."

FIG. 1.—SOUTH-SLOPE DOUGLAS FIR, VERY SIMILAR TO THAT AT STATION A 2, WAGON WHEEL GAP.

This photo is at Station B-2. 1910.

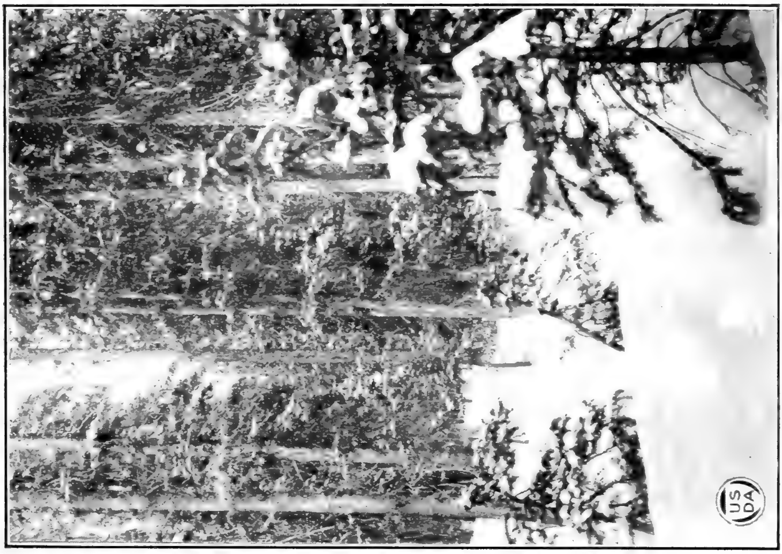

FIG. 2.—TYPE OF ENGELMANN SPRUCE FOREST ON NORTH SLOPE STATION W-F, AT 11,500 FEET ELEVATION. APRIL 23, 1913.

The station, of course, does not exactly represent the conditions of the forest. It is thought to be advisable to use the records as showing the conditions at the upper limit of lodgepole growth, in contrast with the more nearly optimum conditions of Nast, on the western slope of Colorado, of Foxpark, on the eastern slope in Wyoming, and of Fraser, in an interior basin.

M–1: Foothills western yellow pine.—Elevation, 7,200 feet; aspect, easterly; slope, 3 to 4 per cent. This station is located at the Monument Nursery, 2 miles west of the railroad station of the same name, and about 20 miles north of Colorado Springs. It may well be compared with other stations in the Pikes Peak series. It represents the foothills type of yellow pine forest, this type being characterized by scrub oak as a secondary cover, which appears to be able to drive yellow pine to the rocky situations, poorer soils, and the banks of eroding gulches.

The station is scarcely more than 100 feet higher than the valley of Monument Creek, which is devoid of forest growth. The pine forest, however, appears on the first hills above the creek. Elsewhere, under similar circumstances, the pine occurs at elevations below 6,000 feet, along ravines and bluffs; hence this station site represents the lower limit of pine growth only as determined by local topography and soil. The present site of the station is on a flat, east-west ridge or bench about 20 feet higher than the parallel gulch just to the north. Prior to January, 1915, temperature and precipitation records were obtained in this gulch, where cold-air drainage is much more pronounced.

The station is surrounded by oak brush. (See Pl. VIII, fig. 1.) In this brush a few yellow pine seedlings of various ages are making headway. The nearest mature pines stand 40 or 50 feet to the south on an elevated part of the ridge and do not shade the station.

The soil is a very rocky mixture of granitic origin. In the first foot the fragments of granite occupy only a small part of the space, while at a depth of 2 or 3 feet the grayish sandy soil claims only about 60 per cent of the space. The soil contains nearly equal parts of gravel, sand, and finer material. It is evidently a transported soil deposited here before the beginning of the secondary erosion, though its coarse texture suggests glacial rather than water action.

The following equipment has been in use in connection with the daily observations since January, 1915:

Maximum and minimum thermometers, in shelter, 5 feet above the ground.

Air thermograph, until January 1, 1920.

Psychrometer, April 8, 1916, to June, 1919.

Anemometer, on pole, 7 feet above the ground. This height gives some freedom from the protection of the oak brush, most of which is 5 to 7 feet high.

Evaporimeters, Type 2, 5 feet above ground, April 3, 1916, to December 30, 1916.

Evaporimeters, Type 4, 5 feet above ground, January 27, 1917, to date.

Soil thermometers, at depths of 1 and 4 feet, in iron pipes.

Soil well. Samples taken weekly during growing seasons from 1915 to 1918. Sent by mail to Fremont Experiment Station, usually involving about two days in transit before moist weight is taken.

8-inch rain gage.

N–1: Nast western slope lodgepole pine.—Elevation, 8,800 feet; aspect, westerly. This station is situated on the Colorado Midland Railroad between Hagermann Pass and Thomasville, and lies only a few miles west of the highest comb of the Rockies, on a slope dropping rapidly to the west. It represents a region that once, in all probability, bore a heavy forest of Douglas fir, of which only a few relics remain. The lodgepole pine forest which now clothes the slopes is, for the most part, young and vigorous. No particular study has been made of this locality. The temperature data for the station are introduced simply to show that the temperature conditions conducive to a successful invasion by lodgepole pine are quite uniform throughout the range of the species in this region.

P–1: Southern Colorado western yellow pine.—Elevation, 7,108 feet; nearly flat river valley. Although the pine forest has been almost completely removed from the vicinity of Pagosa Springs, this station may still represent in a fair way the temperature and moisture conditions favorable to the optimum growth of yellow pine in southern Colorado. (See Pl. VIII, fig. 2.) A valley forest about 20 miles from Pagosa is typical of the forest found here. This type is distinctly not the mesa type so characteristic of Arizona and New Mexico. It is a hilly type in which the best development is reached only on the moister ground along stream courses, and the strongly sloping hillsides. The conditions of this region approach those of Arizona in the amount of the winter precipitation, but at corresponding elevations the Colorado type is deficient both in snow and in the volume of the summer rains. It is probably for this reason that the higher, nearly level ground corresponding to the mesas of Arizona bears only a meager stand of pine.

W-A1: Wagon Wheel Gap north slope Douglas fir.—Elevation, 9,610 feet; aspect, north; slope, 40 per cent. This station is one of a series which has been very carefully and consistently operated since 1910, in connection with the stream-flow study conducted by the Forest Service and the Weather Bureau. The meteorological records are of the highest order, although it has not been possible to reach some of the more inaccessible stations for daily observations. The equipment of this station, as of Stations W-D and W-G, has been about as complete as possible. There was, however, no sunshine record, no recording apparatus for anemometer, nor any record of evaporation until August, 1919.

The site represented is a steep north slope bearing in general a Douglas fir stand badly damaged by fire some 25 years ago, and here and there replaced by aspen. (See Pl. IX, fig. 1.) About the instrument shelter there is a fairly dense stand of firs about 40 feet high, but the anemometer and rain gages have been exposed in an opening a few rods to the west where there is an almost bare rock-slide about half an acre in extent. In some places the reproduction is about equally of spruce and of fir, but in general at this elevation the spruce is not of sufficient weight to warrant calling the site a fir-spruce type. On the whole, the struggle between spruce and fir is in almost the same stage as at the corresponding station at Fremont, F–9.

In every respect except that of wind velocity, the records of this station agree so closely with those of W-B1, similarly situated on another drainage area one mile north, that the statement of conditions at the latter point would mean sheer duplication. This similarity gives further assurance that the records fairly represent the type.

The equipment of this station has been maintained essentially in the same status since September, 1910, and is as follows:

Maximum and minimum thermometers in shelter, 8 feet above ground.
Air thermograph, 8 feet above ground.
Hygrograph, 8 feet above ground.
Psychrometer, read daily at 9 a. m.
Anemometer, on post in opening, 4½ feet above ground.
8-inch rain gage, on post in opening.
Marvin shielded gage in opening, since 1913.
1-foot soil thermometer is bulb of telethermoscope having no direct connection with the air above. This has been compared at various times with thermometers in iron, wood, and porcelain tubes. The porcelain tube is retained for frequent checking.
4-foot soil thermometer, in iron pipe, beginning August, 1913.
Soil well, with moisture determinations weekly, at depths of 1, 2, and 3 feet, during open seasons since 1913.

W–A2: Wagon Wheel Gap south slope Douglas fir.—This station is directly opposite A1 on the same watershed, the elevation and slope being almost identical, but the aspect almost south. The stand is here also predominantly one of Douglas fir, but is more open than on the north slope. The trees have attained much larger size. (See Pl. X, fig. 1.) Aspen is restricted to the base of the slope below the station, or to gullies, and only bristlecone pine among conifers competes with the fir. Specimens of the pine are here rare, and become numerous only on the more rocky ground at the top of the slope. Limber pine is relatively rare in the Rio Grande region, and bristlecone pine appears largely to replace it on rocky ground and wind-exposed points.

Although air temperatures were recorded at this station during its earlier years, the longer record covers only soil temperature and soil moisture. The soil temperature at 1 foot has been determined by a thermometer in a wooden tube since January, 1913, and at 4 feet by the one in an iron pipe since October, 1913.

W–C: Wagon Wheel Gap pine-fir.—Elevation, 9,360 feet; aspect, east; slope, 30 per cent. At the initiation of the stream-flow experiment, the point here mentioned was established as a control station with whose conditions those on the two watersheds might be compared. It lies on an east slope between them, and is not affected by forest cover of any kind except as a few aspens form a windscreen for the rain gages. It is, then, spoken of as a pine-fir type only because it lies about on the line between the Douglas fir forest on the higher slopes and the occasional yellow pines which occur on warm, exposed breaks below. (See Pl. IX, fig. 2.) In fact, the soil conditions here, and more markedly on the flatter ground just below, seem to be prohibitive of coniferous growth by reason of the presence of a considerable amount of alkali (carbonate of soda).

The plan at this station has been to measure particularly those conditions which are more or less general for the locality, and which could not be conveniently recorded at points farther from headquarters. The equipment has consisted of:

Maximum and minimum thermometers, in shelter, at 10 feet above ground.
Air thermograph, in shelter, at 10 feet above ground.
Psychrometer.
Anemometer, on tower, about 15 feet above ground, with register.
Wind-vane, on tower, about 18 feet above ground, with register.
Sunshine recorder, electric thermometric, with register.
Tipping-bucket rain gage, 3 feet above ground, with register.

Soil thermometers, 1 foot in wooden tube,[2] and 4 foot in iron pipe.

All records at this station except those for sunshine, rainfall, and soil temperatures were discontinued about the end of 1913.

W–D: Wagon Wheel Gap burned bench spruce.—Elevation, 11,000 feet; aspect, east; slope, 5 per cent. This point is typical of much of the best spruce land in southern Colorado and represents a high, well-watered bench of deep, transported soil, partially protected on the west by a higher ridge and fully open to the sun. (See Pl. XI, fig. 1.) The stand, evidently a very heavy one, was completely killed, probably by the fire which swept this region 25 years ago. The occasional spruce seedlings which have come in do not affect present conditions as measured. The ground is covered by a heavy sod, mainly of sedges. Dead trees, standing and down, furnish considerable protection, but can hardly affect the wind record of the station, which has been taken at a point 20 feet above the ground, in order to eliminate purely local influences.

The station has been equipped with:

Maximum and minimum thermometers, in shelter, about 8 feet above ground, read at 6-day intervals.

Air thermograph, in shelter.

Psychrometer.

Anemometer, on pole 20 feet above ground, connected with register at headquarters.

Eight-inch rain gage.

Tipping-bucket rain gage, connected with register.

Marvin shielded rain and snow gage.

Soil thermometers, 1 foot in wooden tube,[3] and 4 foot in iron pipe, read every 6 days.

Soil well, for moisture determinations, at depths of 1, 2, and 3 feet, every 6 days during open season.

W–G: Wagon Wheel Gap high-ridge spruce.—This station is located at 11,580 feet, on an east-west ridge. The soil thermometers are on ground sloping almost inappreciably to the south. This slope is hardly sufficient to affect any other condition measured. Although the station is within about 500 feet of timberline, and the soil of the ridge is very rocky, the spruce is of remarkably good quality, running up to 70 feet in height, while even on better soils near by it rarely attains more than 80 feet. (See Pl. X, fig. 2, and Pl. XI, fig. 2.)

An opening in the forest of about 1 acre was made in 1913, when this station was established, in order that atmospheric conditions and sunshine might be recorded free from the direct effect of the forest. This record is supplemented by soil temperature and moisture data from Stations E and F, located only a few hundred feet away, at the same elevation, on northerly slopes in the heart of the forest. Stations E, F, and G were abandoned at the end of December, 1917.

The equipment of Station W–G consists of:

Maximum and minimum thermometers, in shelter, 8 feet above ground, read at 6-day intervals.

Air thermograph, in shelter.

Sunshine recorder, operated only during winter season.

Tipping-bucket rain gage, operated only during summer season.

Marvin shielded rain and snow gage.

Soil thermometers, 1 foot in wooden tube,[3] and 4 foot in iron pipe, read every 6 days.

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[2] Except when snow becomes deep, when iron pipe with aerial extension is used.

[3] Except when snow becomes deep.

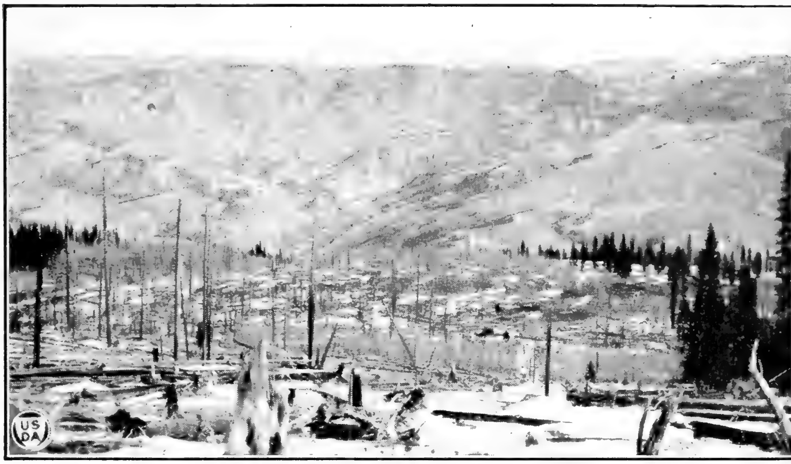

FIG. 1.—LOOKING DOWN ON STATION W-D FROM THE HILL ON THE WEST.

Note small extent of reproduction in this spruce area 25 years after fire. November 5, 1914.

FIG. 2.—STATION W-G, IN AN ARTIFICIAL OPENING OF THE HIGH SPRUCE FOREST, RIDGE TYPE, 500 FEET BELOW TIMBERLINE. JULY 28, 1914.

Soil wells, representative of the high spruce type, were located at Stations E and F, but none here. Moisture determinations every 6 days during open season.

Summary.—In Table 1 is given a summary of the stations which have been enumerated, the arrangement being in the general altitudinal order in which the types appear. Within each group the stations appear in the order of their absolute elevations. Station F-9 has been designated as representing a transition zone between fir and spruce for the reason, already stated, that the conditions under the dense cover here, as shown by the reproduction, are more favorable to the growth of spruce than of Douglas fir. The other stations on the same slope, which are not so heavily shaded, and which seem likely to reproduce to limber pine and fir, have been classed as Douglas fir sites.

TABLE 1.—*List of stations from which data are drawn.*

Vegetative type represented.	Station number.	General locality.	Geographic name.	Elevation.	Character of record.[1]		
					Temperature and precipitation only.	More extensive meteorological.	Soil data.
				Feet.			
Plains	C-1	Pikes Peak	Colorado Springs, Colo.	6,098	....	*x*	None.
Western yellow pine.	D-1	Black Hills	Deadwood, S. Dak.	4,535	*x*	....	None.
	P-1	Southern Colorado	Pagosa Springs, Colo.	7,108	*x*	....	None.
Western yellow pine.	M-1	Pikes Peak	Monument, Colo.	7,200	....	*x*	M.&T.
	F-2	.....do	Fremont Station, Colo.	8,921	....	*x*	M.&T.
	F-12	.....do	.....do	9,164	....	*x*	M.&T.
Limber pine	F-6	.....do	.....do	9,060	....	*x*	M.&T.
	F-13	.....do	.....do	10,300	....	*x*	Temp.
Pine-fir	F-1	Pikes Peak (control).	.....do	8,836	....	*x*	M.&T.
	F-4	Pikes Peak	.....do	9,117	....	*x*	M.&T.
	W-C	Rio Grande Valley	Wagon Wheel Gap, Colo.	9,360	....	*x*	Temp.
Douglas fir	F-7-8[2]	Pikes Peak	Fremont Station, Colo	9,121	....	*x*	M.&T.
	F-17	Northern Colorado	Frances, Colo.	9,300	*x*	....	None.
	W-A1	Rio Grand Valley	Wagon Wheel Gap, Colo.	9,610	....	*x*	M.&T.
	W-A2	.....do	.....do	9,600	*x*	....	M.&T.
Lodgepole pine	F-18	North Central Colorado.	Fraser, Colo.	8,560	*x*	....	None.
	N-1	Western Slope, Colo.	Nast, Colo.	8,800	*x*	....	None.
	F-11	Southern Wyoming	Foxpark, Wyo.	9,000	....	*x*	M.&T.
	L-2	Continental Divide, Colo.	Leadville, Colo.	10,248	*x*	....	None.
Fir-spruce	F-9	Pikes Peak	Fremont Station, Colo.	9,099	....	*x*	M.&T.
Engelmann spruce.	F-3	.....do	.....do	8,860	....	*x*	M.&T.
	F-5	.....do	.....do	9,044	....	*x*	M.&T.
	L-1	.....do	Lake Moraine, Colo.	10,265	*x*	....	None.
	W-D	Rio Grande Valley	Wagon Wheel Gap, Colo.	11,000	....	*x*	M.&T.
	W-G	.....do	.....do	11,580	....	*x*	M.&T.
Timberline scrub	F-16	Pikes Peak	Fremont Station, Colo.	11,500	....	*x*	Temp.

[1] In the first two columns under this caption the letter *x* is used as an affirmative sign with reference to the subheadings. In the third column the abbreviation "M. & T." means that both soil moisture and soil temperature data have been secured.
[2] Also F-14 and F-15 under different conditions of forest cover.

THE GROWING SEASON.

In the study which attempts to detail the climatic conditions of a region in relation to vegetation, one can hardly fail to realize the necessity for distinguishing between those conditions which characterize the growing season and those which occur during the period of rest.

In a study of annual or perennial herbs and of deciduous trees it may be possible to draw a fairly sharp line between the growing season and the dormant period, if only on the basis of the period each year in which the plant is in foliage or of that period which is free from killing frosts. With conifers, however, or in fact any evergreen vegetation, the problem is a difficult one; first, because it is next to impossible to determine, in the field, when the period of height or diameter accretion begins and ends; and, secondly, because it is by no means certain that evergreen plants do not lay up carbohydrates necessary for growth whenever light, temperature, and moisture conditions make photosynthesis possible, in winter as well as summer. It is fairly apparent that photosynthetic activity in conifers may occur for short periods of warm winter days. Although we do not know the actual internal leaf temperature necessary for photosynthesis in any plant, it is readily seen, from the melting of the snow, for example, that the leaf temperature may be several degrees higher than that of the air, and that the minimum temperature for photosynthesis may be reached in bright sunlight when the atmospheric condition seems very forbidding. The temperature of light-absorbing bodies, with little wind, may well be as much as 40° F. above that of the air. On January 10, 1918, at 2 p. m. snow was observed melting on the edge of a black shingled roof, where there was reflected as well as direct sunlight, but which was entirely removed from artificial heat, at an air temperature of −6° F. (−21° C.).

From the consideration of such facts it becomes apparent that any "growing season" for evergreen trees or herbs must be set apart on a purely arbitrary basis. We may better speak of a period of maximum or optimum growth, if it is desirable, rather than convey the impression that growth is restricted to the warmer portion of the year. In this bulletin the term "growing season" will be used in this sense.

In the preliminary report (*3*) on this study the writers did not attempt to divide the data between growing season and dormant period, but presented some facts to show that, considering a soil temperature of 41° F. (5° C.) essential to the growth of any of the Rocky Mountain trees, there is a marked difference in the length of the growing season as between different slopes and different forest types. The soil of a south exposure, for example, at a depth of 1 foot was found to be above this temperature for about 220 days, and that of a north exposure for only 133 days. But while there is no occasion for minimizing the importance of this difference the assumption that growth is dependent upon a soil temperature of 41° F. is not substantiated by the facts. The phenological observations of a number of years show that the first swelling of the buds of Douglas fir may occur at soil temperatures as low as 39° F., or as high as 50° F. So far as can be determined by this crude method of observation, soil temperature and moisture are strongly interdependent, and it is the molecular activity of the soil water, as determined by its temperature and amount, and as well by the solutes it contains, which controls the beginning of new growth.

The time at which the first growth of a given tree may be noted in successive years is so variable as to make the fixing of even a mean date almost impossible. When the variations between different sites and elevations and the different species on the same site are brought into the problem it becomes so involved that its significance is likely to be obscured.

For all of the above reasons it has been decided to consider the "growing season" as synonymous with "summer," or the months of June, July, and August, and the first decade [4] in September. The three months stand quite apart from the remainder of the year. At the low elevations, of course, much vegetative activity begins before June 1; at very high elevations deep banks of snow remain until after July 1. But at all elevations in or very close to the high mountain ranges the cooling effect of a general snow covering disappears soon after June 1, and this causes a very abrupt change in the temperature conditions. The first decade of September is included because it is nearly always as warm as if not warmer than the much cloudier decade preceding. Thus a comparison of temperatures for these 10 decades may be quite as valuable as a comparison of mean temperatures or temperature sums for growing seasons of variable length, as we have practically no knowledge of what temperatures are growing temperatures for the plants under consideration. It may be said quite safely for the limited latitudinal range covered by this discussion that, if the summer temperature of a given site is found to be relatively high, the season during which it has favorable temperatures for growth must also be relatively long. It is therefore thought worth while in this bulletin to give summer or "growing season" means for all data, as well as annual means. Any greater refinement of the distinction between periods of growth and rest does not appear justified.

ABSOLUTE AND COMPARATIVE CONDITIONS IN THE VARIOUS FOREST TYPES.

AIR TEMPERATURES.

In taking up the study of atmospheric conditions which may cause the differentiation of mountain forests into types dominated by different species it is natural to turn first to the subject of air temperatures for two reasons, viz:

(1) The decrease in temperature with an increase in altitude is the most obvious change which occurs between plains and mountain tops, and hence has the appearance, at least, of being a primary cause for the zonal distribution of each species of the forest. The difference in the warmth of north and south exposures is equally perceptible and suggests a primary cause for the difference in forest cover which usually characterizes opposing slopes at the same elevation.

(2) Air temperatures are more readily measured, perhaps, than any other conditions, and this has given rise to more records of air temperatures than of other conditions except possibly precipitation. This fact makes it possible to draw upon several localities besides

[4] Throughout this bulletin the term "decade" is used to denote a third of a month, ordinarily a period of 10 days, but varying from 8 to 11 days when the last decade of a month is referred to.

those especially covered by the present study in considering air temperatures of the various forest types.

As already stated, the air temperature observations in this study fall into two groups, namely, (1) those referring to conditions several feet ($4\frac{1}{2}$ or more) above the ground, and hence more or less representative of an extensive locality; and (2) those applying to conditions within a foot of the ground and reflecting the local influences of insolation and radiation. Data of the second class will be referred to as "ground temperatures" and are available for only a few of the special stations where the conditions directly affecting forest reproduction seemed very important.

By agreement the mean temperature for any period of 24 hours may be computed by adding the highest and lowest temperatures in that period and dividing the sum by 2. It is well understood that for any single period this method is not at all likely to give a true mean temperature. But common experience shows that over a number of daily periods (for example, a month) the mean temperature so computed will be practically the same as the mean computed from hourly temperatures. The latter, of course, can be had only where a thermograph is employed, and to make use of the many records obtained from maximum and minimum registering thermometers it is necessary to employ the simpler method. It seems desirable, therefore, to keep all records to the same standard, even where hourly temperatures might be secured from thermograph traces.

In addition to the convenience of the method the mean temperature derived from the maximum and minimum temperatures has this virtue—that it involves no element of judgment in the computation. Without going into the mechanics of the thermograph, it may simply be said that the correction to be applied to different portions of a thermograph trace can not properly be determined by rule-of-thumb as is usually done. The character and amount of such corrections must rest upon the question of whether or not the observable errors in the trace are due to the natural inertia of the instrument or to improper adjustment of its mechanism. Hence slightly variable results may be obtained in reading hourly temperatures from the thermograph trace, and this fact detracts greatly from the value of hourly records as ordinarily prepared.

The temperature records of the control station at Fremont have been prepared by computing the maximum and minimum temperatures for each midnight-to-midnight period from the thermograph trace as corrected from thermometer registrations. The daily range is the difference between the highest and lowest temperature from one midnight to the next and the daily mean the average between the highest and lowest temperatures. To obtain records for other stations exactly comparable with the control station as to period, the same method has been followed where thermograph traces made it possible. For those stations having no thermographs the method has always been to make observations in the morning, tabulating the minimum temperature as of the day on which recorded and the maximum temperature as of the day previous.

Temperatures at the control station.—The air-temperature record for the control station, representing atmospheric conditions 20 feet above the ground and in all probability mean conditions for this elevation (8,836 feet) and locality, little affected by local exposure and other circumstances, extends from January, 1910, to April, 1921, inclusive, with the exceptions already noted. For the most part these records were compiled and comparisons between the types were made on the basis of data secured to the end of March, 1918. Such comparisons seem quite adequate but to arrive more nearly at normal absolute temperatures records secured since March, 1918, will sometimes be used. The constant use of a thermograph and of standardized thermometers has made this a very satisfactory record. It has been very carefully checked over since its compilation, as secured month by month, so that little error is likely to remain in it except that inherent in the short method of computing means.

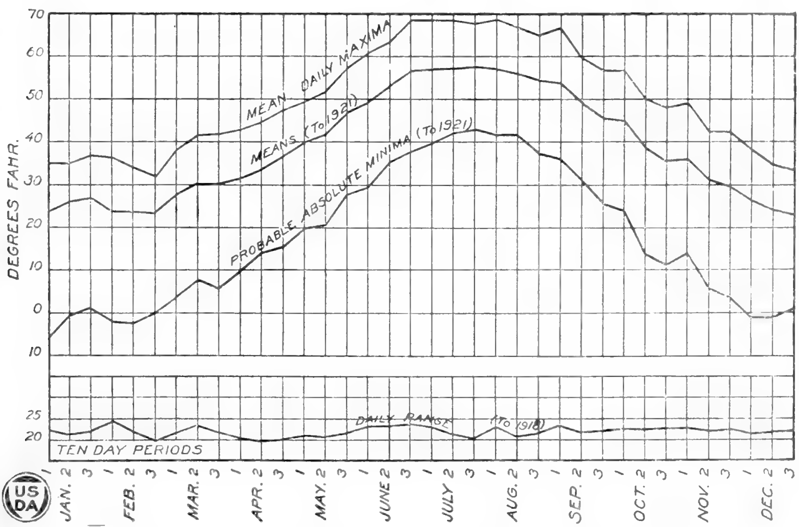

FIG. 1.—Air temperatures at control station by 10 day periods. (F–1) Elevation 8,836 feet.

Mean air temperatures.—The complete record of mean air temperatures for the control station is given in Table 2, by decades and months, for the purpose of showing the possible variation in corresponding periods of different years, as well as the constancy of certain conditions which are of interest. The average temperatures are shown in Figure 1.

NOTE.—All original records of air temperatures for decades, months, and years are carried to two decimal places. Hence, some of the means given in the following tables, do not agree precisely with the 1-place figures from which they are apparently derived. In dropping hundredths to save space in these tables, the rule is followed of throwing 0.05 to the nearest even tenth. Thus 0.45 becomes 0.4 and 0.55 becomes 0.6.

TABLE 2.—*Mean air temperatures at the control station (20 feet above the ground).*[1]

Year.	Decade.	Record by decades and months in degrees Fahrenheit.													
		January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Annual.	Mean growing season.
1910	1	17.6	18.7	36.9	35.6	39.9	53.1	58.8	58.3	56.4	50.4	39.5	33.7	......	......
	2	28.4	15.6	38.3	36.5	40.2	58.3	63.0	57.6	55.7	42.4	31.2	30.8	......	......
	3	31.0	28.2	38.6	43.1	46.3	57.4	61.8	56.6	49.7	39.8	37.7	22.2	......	......
	Month	25.8	20.3	37.9	38.4	42.3	56.3	61.2	57.4	53.9	44.1	36.1	28.7	41.88	58.12
1911	1	24.4	29.1	35.6	36.5	44.9	56.3	55.3	59.2	54.3	45.1	29.2	30.2	......	......
	2	36.4	21.6	30.7	31.5	45.7	53.2	55.3	61.2	52.6	36.8	32.0	14.4	......	......
	3	33.6	11.2	32.1	39.5	47.0	58.8	54.0	51.7	53.1	31.0	22.7	14.9	......	......
	Month	31.5	21.3	32.8	35.8	45.9	56.1	54.8	57.2	53.3	37.4	28.0	19.7	39.49	55.92
1912	1	19.4	23.7	24.2	35.4	38.7	50.3	55.9	54.9	54.5	42.6	36.2	19.8	......	......
	2	28.2	23.2	25.3	28.7	39.5	43.4	56.8	54.5	39.5	40.6	35.4	24.5	......	......
	3	29.8	14.2	23.3	34.2	51.1	52.1	57.4	58.3	36.0	34.4	30.4	20.6	......	......
	Month	25.9	20.6	24.3	32.8	43.4	48.6	56.7	56.0	43.3	39.0	34.0	21.6	37.18	53.80
1913	1	13.6	18.4	26.7	31.1	39.4	46.2	62.3	59.6	54.6	41.6	36.5	24.0	......	......
	2	23.9	22.6	24.7	40.6	45.2	52.2	56.8	58.9	45.0	35.2	39.2	24.6	......	......
	3	27.1	12.2	28.4	38.4	51.4	56.0	53.4	57.3	37.0	31.3	30.5	21.1	......	......
	Month	21.7	18.1	26.7	36.7	45.5	51.5	57.4	58.6	45.6	35.9	35.4	23.2	38.02	55.73
1914	1	32.0	.....	.....	30.3	42.0	52.1	54.1	58.2	56.4	45.1	40.8	.....	......	......
	2	31.3	.....	.....	34.0	39.0	53.6	57.1	59.6	52.7	42.9	31.6	.....	......	......
	3	.....	.....	.....	36.5	49.3	57.0	56.8	53.4	48.9	39.0	34.7	.....	......	......
	Month	.....	.....	.....	33.6	43.6	54.2	56.0	57.0	52.7	42.2	35.7	.....	......	55.82
1915	1	.....	.....	16.2	34.5	32.4	44.2	53.0	52.6	52.9	41.9	41.4	34.1	......	......
	2	.....	.....	23.3	38.3	42.7	50.3	57.2	51.8	49.2	37.5	25.6	22.3	......	......
	3	.....	.....	28.0	39.9	42.6	51.3	53.6	51.3	46.3	47.5	29.2	23.4	......	......
	Month	.....	.....	22.7	37.6	39.3	48.6	54.6	51.9	49.5	42.5	32.1	26.5	......	51.83
1916	1	31.9	24.9	30.8	28.4	44.3	46.8	59.9	58.1	55.4	45.3	38.1	24.7	......	......
	2	18.3	33.8	40.8	36.4	35.1	52.0	57.5	55.8	44.8	35.4	19.8	18.4	......	......
	3	21.4	27.2	31.7	36.8	48.8	58.6	59.7	51.0	47.0	37.7	28.1	15.9	......	......
	Month	23.8	28.7	34.4	33.9	42.9	52.5	59.1	54.8	49.1	39.4	28.6	19.5	38.89	55.48
1917	1	28.1	24.1	18.2	27.6	27.7	45.7	56.5	57.0	55.9	46.9	40.2	23.4	......	......
	2	17.0	22.0	20.1	32.8	42.6	51.2	57.4	51.4	49.0	40.0	33.6	33.6	......	......
	3	19.8	27.4	28.7	32.8	36.8	59.8	61.6	53.0	47.9	31.9	35.3	35.3	......	......
	Month	21.5	24.3	22.5	31.0	35.7	52.2	58.6	53.8	51.0	39.3	36.4	30.9	38.11	54.95
1918	1	23.7	28.2	33.0	28.6	42.7	52.2	56.1	59.1	47.2	.....	.....	.....	......	......
	2	11.2	22.4	33.9	28.0	44.2	61.0	54.8	55.8	47.4	.....	.....	.....	......	......
	3	18.0	32.2	34.7	34.5	46.0	56.5	57.0	54.4	.....	.....	.....	.....	......	......
	Month	17.7	27.2	33.9	30.4	44.4	56.5	56.0	56.4	.....	.....	.....	.....	......	55.36
1919	1	.....	.....	.....	.....	39.1	41.9	60.0	57.0	57.9	38.4	31.4	21.8	......	......
	2	.....	.....	.....	.....	43.6	54.5	57.5	58.9	52.0	37.1	33.6	28.2	......	......
	3	.....	.....	.....	.....	46.6	59.2	60.0	60.2	46.8	34.0	25.1	35.5	May-	April.
	Month	.....	.....	.....	.....	43.2	51.8	59.2	58.8	52.2	36.4	30.1	28.7	39.01	56.70
1920	1	19.4	28.0	21.6	28.1	45.3	51.8	58.2	58.1	48.5	53.4	30.3	29.9	......	......
	2	36.0	24.0	25.8	27.8	39.0	52.1	60.1	53.0	59.8	43.2	29.5	24.1	......	......
	3	33.9	20.7	29.2	27.5	51.1	56.6	61.3	52.9	47.8	32.0	28.8	21.7	May-	April.
	Month	29.9	24.4	25.6	27.8	45.3	53.5	59.9	54.6	52.0	42.5	29.6	25.1	40.56	55.25
1921	1	27.5	21.3	34.6	31.6	.....	.....	.....	.....	.....	.....	.....	.....	......	......
	2	29.3	28.0	40.3	33.3	.....	.....	.....	.....	.....	.....	.....	.....	......	......
	3	28.9	37.3	28.7	34.4	.....	.....	.....	.....	.....	.....	.....	.....	......	......
	Month	28.6	28.2	34.3	33.1	.....	.....	.....	.....	.....	.....	.....	.....	......	......
Average	1	23.8	24.0	27.8	31.6	39.7	49.1	57.3	57.5	54.0	45.1	36.4	26.8	......	......
	2	26.0	23.7	30.3	33.4	41.5	52.9	57.6	56.2	49.8	39.1	31.2	24.5	......	......
	3	27.1	23.4	30.3	36.1	47.0	56.7	57.9	54.6	46.0	35.9	30.2	23.4	......	......
	Month	25.7	23.7	29.5	33.7	42.9	52.9	57.6	56.0	49.9	39.9	32.6	24.9	39.11	55.35

[1] See Note, p. 29.

The following points in Table 2 are worthy of note: (1) In all but the summer months, temperatures in consecutive decades are subject to very radical changes. Even the mean monthly temperatures are very dissimilar in different years, and, in any one year, for example, April may be cooler than March. Such discrepancies point to the need for a long record to insure even approximate "normals" for any given period, but more particularly in this study to the absolute necessity for comparing temperatures of different stations for identical periods only.

(2) The first decade of June is seen to attain a temperature of almost 50° F., and temperatures above 50° F. prevail from then until after the first decade of September. It will later be seen that these ten decades, except the first one, are also free from the liability of frost. They form, then, a fairly logical as well as convenient basis for separating the growing season from the remainder of the year, at least at this middle elevation. In other localities the winter snow may remain considerably after June 1, and this necessarily means a shortening of the frost-free period for all adjacent areas.

(3) The highest temperatures occur from the middle to the end of July. Thereafter the probability of cloudiness and rain increases, until about September 1, when a rise in temperature may again occur with clear weather. It will be noted that in 5 years out of 11, this first decade of September is markedly warmer than the last of August Thus, while much of the temperate United States is feeling its most oppressive heat in August, the mountain area subject to the "summer rainy spell" avoids any excess at that time. The cloudy weather depresses the minima quite as much as or possibly a little more than the maxima, which may be reached, on many rainy days, before the afternoon clouds gather. That the minima are not held up is evidently due to the quick clearing away of the clouds and to the rapid evaporation after each shower.

It will be noted that the normally highest decade has a temperature of only 58° F. and that the highest single decade of record showed a temperature of only 63° F. (July, 1910). Detailed examination of the records shows only a few individual days attaining to the height of 66° F., which, according to Baker (*1*), is approximately the mean summer temperature required for the proper development of corn. The failure of the mountains to produce agricultural crops is, on this basis alone, quite fully explained.

(4) The winter temperatures are not extremely low. The total range from summer to winter temperatures is, in fact, much less than in the lowlands of the northern United States, and the winter temperatures are actually higher in the mountains. It will later be shown that they are somewhat higher in the Pikes Peak region than elsewhere at corresponding elevations. This fact alone augurs unfavorably for vegetation, and especially for vegetation which retains its foliage through the winter. When, however, it is noted that the lowest winter temperatures are synchronous with periods of calm (February), and the warmer periods always associated with high westerly descending winds, the full importance of this period begins to be apparent. The table shows that the temperatures do not decrease in normal fashion to about February 1, but reach practically their lowest point at the end of December, then rise during the January windy period, to find a second depression in the calm of February

and again an unseasonable rise with the recurring winds of March. April brings much less wind and the heaviest snows; hence the low temperatures.

(5) The autumn temperatures contain little of interest unless it be in the somewhat sharp depressions for the second decade of September and the second of October, which are very often periods of heavy, wet snows.

Range of air temperatures.—It is very doubtful whether the range of air temperatures is of much biological significance, at least in connection with plants so "hardy" and so accustomed to a great variety of conditions as the coniferous trees. For this reason it seems necessary only to show the normal values, by decades, as computed up to March, 1918. (Table 3). These have a value also in connection with the table of mean temperatures in indicating the maxima and minima, which may be directly computed by use of the two tables and which, therefore, will be omitted.

Table 3 shows that the mean daily range at the control station is 22.3°; and, although it varies for individual decades by as much as 7° and is greatly influenced by cloudiness, wind, and other circumstances, the maxima and minima, respectively, may be approximated if 11° are added to or subtracted from the mean temperature for any period.

TABLE 3.—*Mean daily range of air temperatures at the control station (averages to March, 1918).*

Decade.	Record by decades and months in degrees Fahrenheit.												Mean annual.	Mean growing season.[1]
	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.		
1	22.5	24.4	21.9	20.9	21.2	23.6	23.3	23.4	23.4	23.2	23.6	22.2	......	......
2	21.2	22.0	23.2	19.6	20.8	23.7	21.8	21.4	22.2	23.0	22.6	22.5	......	......
3	22.2	19.8	22.0	20.4	21.8	24.4	20.9	22.1	22.4	23.5	23.0	23.1	......	......
Month	22.0	22.2	22.3	20.3	21.3	23.9	22.0	22.3	22.7	23.2	23.1	22.6	22.32	22.80

[1] See note, p. 29.

From the purely meteorological standpoint, the shortening of the daily range in the stormy period of April is of some interest. Of even greater interest is the decrease during the windy winter months, which does not show up in the means because here the action and reaction are about equal. A west wind may have any one of several effects on the temperature curve, but nearly always gives it an abnormal shape, because the wind rarely attains its greatest force during the warmer part of the day. Arising in the evening, after a cloudy day, it may bring the maximum temperature at midnight. If the following day witnesses a dying of the wind, its maximum temperature may be recorded at the beginning and its minimum at the end of the midnight to midnight period. A steady wind may hold the daily range down to 8° or 10°, but a sudden rise or cessation will elevate it to 40°. There are, of course, other cosmic conditions at the source of such winds, which accentuate their effect on temperature.

From the average values it is seen that the daily range is slightly greater during the growing season than for the year as a whole. However, only the year 1910 shows this character in a marked degree. If this year were eliminated, the growing season and annual means would be almost identical. The peculiarity of the season of 1910 deserves consideration. The very high mean temperatures for that year, as well as the high daily ranges, it was at first conceived, might have been due to some condition in the exposure of thermometers which was later altered. However, no such factor could be recalled except that during 1910, and 1911 as well, extra observations were taken at 1 p. m., and the opening of the shelter at that hour very frequently resulted in a slight jump of the thermometers and thermograph. Allowance was always made for this when the maximum at this moment exceeded that of any other hour, which it rarely did. On examining all the conditions for 1910, however, it is found that that year was one of the driest on record, both as to precipitation and atmospheric humidity, and had a very high percentage of sunshine. As these conditions are associated with great daily ranges for short periods, so they may be seen to account for the general character of the year 1910, and for the somewhat high ranges of 1917.

Absolute minimum air temperatures.—The Pikes Peak region is not subject to extremely low temperatures in winter, even for short periods, nor is it evident that where very great extremes do occur, in other parts of the central Rockies, they have any but a beneficial effect on established forests. However, a discussion of minimum temperatures (Table 4) is of interest in connection with forest reproduction, especially in a locality where late germination is induced by especially favorable conditions in July and August. Pearson (*16*) concluded that young reproduction of yellow pine is extremely susceptible to frost injury, and indeed there is evidence to indicate that lodgepole pine, spruce, and Douglas fir seedlings succumb to fall frosts if they are not fully matured. The forester is in the habit of saying that the seedling must be "lignified," that is, its tissues must be solidified, before it can withstand freezing. It would probably be more correct to say that it is necessary for the young plant to carry on photosynthesis and by the accumulation of soluble carbohydrates make the sap so dense that it will not freeze with the first frost or freeze firmly at any temperature. Lignification would naturally be an immediate sequel to this accumulation of building material.

In Table 4 the lowest temperature for each decade of the record has been set down, and these temperatures have been averaged at the foot of the table in such a way as to show the probable (not the possible) minimum for any period of the year, in so far as a record of this length may indicate probabilities. Because of very unusual occurrences since March, 1918, it has seemed desirable to extend this record to April, 1921. The data recorded since May, 1920, are for a site where the probable minimum appears to be 1° to 2° higher than at the control station. However, this will not affect the averages more than 0.1° or 0.2°, and the additional record assists in eliminating irregularities.

73045°—24——3

TABLE 4.—*Absolute minima at the control station (20 feet above ground).*

Year.	Decade.	Record in degrees Fahrenheit by decades and months.												Annual.	Growing season.
		January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.		
1910	1	−14.0	− 3.0	10.1	12.5	19.0	30.5	40.0	40.0	36.0	24.0	16.5	8.0	.....	.....
	2	7.0	−20.5	20.5	11.0	17.0	39.0	42.0	41.0	36.0	5.0	11.0	13.0	.....	.....
	3	8.0	6.5	10.5	25.0	24.5	37.0	43.0	28.5	32.0	11.0	9.0	2.0	.....	.....
	Month	−14.0	−20.5	10.1	11.0	17.0	30.5	40.0	28.5	32.0	5.0	9.0	2.0	−20.5	28.5
1911	1	−22.5	8.0	16.5	13.0	20.0	36.0	39.0	36.0	33.5	28.0	0.5	4.2	.....	.....
	2	15.0	−10.5	13.0	9.5	21.0	37.0	42.0	45.0	29.0	−1.0	− 2.5	− 4.5	.....	.....
	3	4.0	−11.0	6.0	19.0	26.0	41.5	40.0	34.5	33.0	8.0	− 2.0	− 6.0	.....	.....
	Month	−22.5	−11.0	6.0	9.5	20.0	36.0	39.0	34.5	29.0	−1.0	− 2.5	− 6.0	−22.5	33.5
1912	1	− 4.5	− 2.0	− 1.0	15.0	21.6	30.0	33.0	38.0	33.5	25.0	15.9	− 6.5	.....	.....
	2	2.5	3.0	− 1.0	17.0	21.0	25.0	42.5	42.0	22.0	22.0	17.5	− 4.0	.....	.....
	3	6.4	− 7.0	3.5	11.5	30.2	32.5	45.0	41.5	17.0	14.0	− 2.5	− 4.5	.....	.....
	Month	− 4.5	− 7.0	− 1.0	11.5	21.0	25.0	33.0	38.0	17.0	14.0	− 2.5	− 6.5	− 7.0	25.0
1913	1	−23.0	− 8.0	11.0	10.0	22.0	34.5	42.0	41.5	39.0	20.0	14.5	7.7	.....	.....
	2	− 3.5	− 4.2	− 2.0	16.5	28.0	36.0	41.0	43.5	26.0	13.2	21.5	1.7	.....	.....
	3	8.0	− 8.5	− 7.0	10.0	29.0	38.0	38.0	43.5	18.5	5.6	14.4	0.0	.....	.....
	Month	−23.0	− 8.5	− 7.0	10.0	22.0	34.5	38.0	41.5	18.5	5.6	14.4	0.0	−23.0	34.5
1914	1	6.5	.....	.....	5.3	22.5	35.5	40.6	42.1	34.0	25.8	22.0	.....	.....	.....
	2	7.5	.....	.....	12.0	24.0	37.8	43.0	43.2	32.0	18.4	3.5	.....	.....	.....
	3	.....	.....	.....	18.4	38.0	41.5	44.5	39.1	28.0	24.2	15.9	.....	.....	.....
	Month	.....	.....	.....	5.3	22.5	35.5	40.6	39.1	28.0	18.4	3.5	.....	.....	34.0
1915	1	.....	.....	2.0	17.0	13.3	23.2	33.5	37.8	36.0	18.0	21.7	9.7	.....	.....
	2	.....	.....	− 0.3	26.0	17.6	30.1	41.7	39.2	30.3	21.9	− 1.2	1.0	.....	.....
	3	.....	.....	7.5	28.1	24.8	36.7	42.0	35.4	30.0	25.2	− 0.9	− 5.5	.....	.....
	Month	− [1]20	.....	− 0.3	17.0	13.3	23.2	33.5	35.4	30.0	18.0	− 1.2	− 5.5	−20.0	23.2
1916	1	10.0	−16.6	0.4	6.7	11.0	29.8	45.0	44.4	37.0	26.0	12.3	− 9.3	.....	.....
	2	− 9.1	14.5	11.4	15.5	12.0	34.7	43.0	41.6	27.6	6.2	−18.1	− 7.8	.....	.....
	3	−15.3	8.5	9.6	12.1	29.3	36.0	45.3	36.5	23.4	14.7	4.2	− 5.5	.....	.....
	Month	−15.3	−16.6	0.4	6.7	11.0	29.8	43.0	36.5	23.4	6.2	−18.1	− 9.3	−18.1	29.8
1917	1	11.4	−14.7	−11.0	2.7	11.7	24.1	39.0	41.6	38.8	24.4	22.6	− 5.3	.....	.....
	2	−16.0	0.7	0.6	18.0	20.0	32.7	40.4	40.4	32.7	7.9	18.2	6.0	.....	.....
	3	−11.0	2.5	0.4	7.6	22.3	40.2	46.3	36.1	27.7	−6.8	14.4	18.0	.....	.....
	Month	−16.0	−14.7	−11.0	2.7	11.7	24.1	39.0	36.1	27.7	−6.8	14.4	− 5.3	−16.0	24.1
1918	1	−22.5	− 3.8	14.5	12.6	18.2	32.0	40.0	41.1	31.0	.....	.....	.....	.....	.....
	2	10.7	− 4.0	6.5	5.0	21.4	46.2	40.6	44.2	29.0	.....	.....	.....	.....	.....
	3	− 9.4	− 4.6	15.5	17.8	28.3	34.1	40.5	36.7	.....	.....	.....	.....	.....	.....
	Month	−22.5	− 4.6	6.5	5.0	18.2	32.0	40.0	36.7	.....	.....	.....	.....	−22.5	31.0
1919	1	.....	.....	.....	.....	26.7	18.7	44.1	44.8	42.9	16.1	9.7	−26.2	.....	.....
	2	.....	.....	.....	.....	26.6	37.7	44.9	43.3	36.6	20.6	11.0	−10.0	.....	.....
	3	.....	.....	.....	.....	23.9	43.7	44.3	43.8	26.8	7.1	−15.9	14.0	.....	.....
	Month	.....	.....	.....	.....	23.9	18.7	44.1	43.3	26.8	7.1	−15.9	−26.2	−26.2	18.7
1920	1	− 6.5	13.0	−11.2	− 2.8	30.4	30.8	40.8	47.0	36.8	35.5	9.4	13.2	.....	.....
	2	2.6	− 3.5	8.0	11.1	17.8	36.3	45.4	38.0	46.6	26.5	9.2	0.0	.....	.....
	3	11.2	0.4	7.9	7.1	31.0	38.2	46.0	37.1	27.6	11.8	7.9	− 1.0	.....	.....
	Month	6.5	− 3.5	−11.2	2.8	17.8	30.8	40.8	37.1	27.6	11.8	0.2	− 1.0	−11.2	30.8
1921	1	4.5	3.2	3.7	9.5	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	2	0.5	1.5	19.0	9.4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	3	10.2	10.0	8.2	13.7	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
	Month	[illegible]	1.5	3.7	9.4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Average probabilities	1	[illegible]	2.7	[illegible]	9.2	19.6	29.6	39.7	41.3	36.2	24.3	11.5	− 0.5	.....	.....
	2	[illegible]	2.6	7.6	13.7	20.6	35.7	42.4	41.9	31.6	14.1	6.1	− 0.5	.....	.....
	3	1.0	0.4	6.2	15.5	27.9	38.1	43.2	37.5	26.4	11.5	4.4	1.3	.....	.....
	Month	[illegible]	[illegible]	0.4	7.8	18.0	29.1	39.2	37.0	26.0	7.8	0.1	− 6.4	−18.7	28.5

[1] Minimum for the period from December to February, inclusive.

The probability of freezing temperatures in the first decade of June has already been mentioned in the discussion of the "growing season." Nevertheless, it is difficult to see how the factor of frosts at this time can have much effect on the problem of what causes the survival of one species and the failure of another. New seedlings have rarely appeared at this time, and those from previous seasons which have survived the winter should hardly be susceptible to injury at so late a date. New growth on older trees will barely have started by June 10, and shows no injury from the snows which may occur at this time. Even young aspen leaves just emerging from the bud withstand temperatures considerably below 32° F. without apparent injury. Observation at a more advanced stage has not yet been possible. The great certainty of freedom from frost in the first decade of September fully justifies extending the growing season over this period. The second decade is equally certain to record a thorough freezing.

The lowest temperatures of the year are almost certain to be recorded in January, notwithstanding the fact that the lowest mean temperatures occur in February. This is made possible by the fact that the absolute minima fall in periods of calm, when the protection (if such it may be called) of the westerly winds is temporarily withdrawn. It will later be seen that the high, rather than the low, temperatures of January have the greater significance.

Classification of days according to temperature.—The computation of mean temperatures even for so short a period as a decade tends to hide the fluctuations and smooth over the extremes. In a biological study it may be of interest to know, for example, that in a January having a mean temperature of 17.7°, whose warmest decade was 23.7°, there might be two days having mean temperatures above 41°, and to consider whatever possibilities this may present in the matter of the photosynthetic activity of trees, and also the more important probability of damaging transpiration.

Therefore, to present most strikingly the temperature conditions at the control station, Table 5 has been prepared, showing for each month up to March, 1918, the number of days of the following arbitrary classes, based on mean temperatures:

No thawing: Mean and maximum, 32.0° F. or less.
Freezing: Mean below 32°, and maximum above 32°.
Cold: Mean temperature, 32.1° to 41°.
Cool: Mean temperature, 41.1° to 50°.
Moderate: Mean temperature, 50.1° to 60°.
Warm: Mean temperature, 60.1° to 72.°

It should, of course, be realized that thawing or melting of snow is not precluded on days whose maximum air temperatures are below 32 degrees. In bright sunlight, thawing may take place with temperatures as low as 0° F.

TABLE 5.—*Classification of days according to air temperatures.*

Year.	Class.	Record by months in degrees Fahrenheit.												Total annual.	Total growing season.
		January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.		
1910	No thawing	11	14	2	2	2	0	0	0	0	3	2	6	42	
	Freezing	10	9	3	3	3	0	0	0	0	1	8	13	50	
	Cold	7	5	15	17	5	0	0	1	1	4	9	12	76	1
	Cool	3		11	6	15	4	1	1	5	11	10		67	7
	Moderate				2	6	18	9	19	21	12	1		88	53
	Warm						8	21	10	3				42	41
1911	No thawing	3	11	3	2	0	0	0	0	0	4	4	17	44	
	Freezing	9	11	13	6	1	0	0	0	0	5	15	11	71	
	Cold	15	6	13	14	8	0	0	0	0	11	9	3	79	
	Cool	4		2	8	10	5	4	6	5	8	2		54	16
	Moderate					12	20	27	14	24	3			100	70
	Warm						5	0	11	1				17	16
1912	No thawing	8	11	9	1	2	0	0	0	4	3	2	13	53	
	Freezing	14	17	19	13	4	1	0	0	4	1	9	15	97	1
	Cold	9	1	3	13	6	2	0	0	3	12	14	3	66	2
	Cool				3	11	11	3	3	10	14	5		60	19
	Moderate					8	16	24	22	9	1			80	70
	Warm							4	6					10	10
1913	No thawing	14	14	8	3	0	0	0	0	1	4	2	16	62	
	Freezing	12	11	12	7	1	0	0	0	2	6	9	11	71	
	Cold	5	3	9	8	10	3	0	0	5	8	11	4	66	3
	Cool			2	12	11	8	4	0	10	13	8		68	12
	Moderate					9	16	18	21	12				76	65
	Warm						3	9	10					22	22
1914	No thawing	[1] 5			6	2	0	0	0	0	0	2			
	Freezing	9			7	1	0	0	0	0	3	5			
	Cold	14			8	9	1	0	0	2	8	15			1
	Cool	3			9	11	3	1	0	5	16	8			5
	Moderate					8	22	25	22	21	4			102	76
	Warm						4	5	9	2				20	20
1915	No thawing			18	0	3	0	0	0	0	0	5	9		
	Freezing			9	4	6	1	0	0	0	4	8	8		1
	Cold			4	17	7	4	0	0	5	9	8	12		4
	Cool				9	10	10	7	9	8	13	9	2		28
	Moderate					5	15	18	22	17	5			82	63
	Warm							6						6	6
1916	No thawing	11	3	3	7	2	0	0	0	0	4	7	17	54	
	Freezing	13	14	9	4	2	0	0	0	1	3	10	8	64	
	Cold	3	12	5	11	6	2	0	0	3	9	8	6	65	2
	Cool	4		14	8	12	9	1	5	9	10	5		77	16
	Moderate					9	15	13	22	15	5			79	57
	Warm						4	17	4	2				27	27
1917	No thawing	11	11	12	5	5	0	0	0	0	1	2	5	52	
	Freezing	14	10	13	9	8	1	0	0	0	7	5	9	76	1
	Cold	6	6	5	9	11	2	0	0	1	7	15	13	75	2
	Cool		1	1	7	5	8	0	6	11	10	8	4	61	15
	Moderate					2	13	18	21	18	6			78	61
	Warm						6	13	4					23	23
1918	No thawing	19	6	2											
	Freezing	6	11	10											
	Cold	4	9	12											
	Cool	2	2	7											
	Moderate														
	Warm														
Average	No thawing	10.2	10.0	7.1	3.2	2.0	0.0	0.0	0.0	0.6	2.4	3.3	11.9	50.7	
	Freezing	10.9	11.9	11.0	6.6	3.2	0.4	0.0	0.0	0.9	3.7	8.6	10.7	67.9	.4
	Cold	7.9	6.0	8.2	12.1	7.8	1.8	0.0	0.1	2.5	8.5	11.1	7.6	73.6	1.9
	Cool	2.0	0.4	4.7	7.8	10.6	7.2	2.6	3.8	7.9	11.9	6.9	0.8	66.6	14.7
	Moderate				0.3	7.4	16.9	19.0	20.4	17.1	4.5	0.1		85.7	64.4
	Warm						3.7	9.4	6.7	1.0				20.8	20.6
														365.3	102.0

[1] January, 1914, based on record of Jan. 1-20 expanded.

It is seen that considerably more than half the days of the growing season have a moderate mean temperature, and that their number does not vary greatly from year to year. On the other hand, the number of warm days, practically all of which occur in the growing season, has varied in 8 years from 6 to 41 per year. Whether or not such days are favorable to the growth of conifers, or whether, for the Rocky Mountain species, they may not represent excessive heat, might possibly be determined by growth studies; but nothing can be said on the subject at present.

No less interesting is the fact that January and March show not only a number of days with mean air temperatures above freezing, but the probability of a few days when the mean will be above 41°, the minimum scarcely below 32°, with the possibility of very effective thawing of the soil on well-insolated sites, and of some snow melting on any site at this elevation.

Ground temperature at control station.—The temperature of the atmosphere at the control station has been shown in considerable detail for the purpose of depicting prevailing conditions at a middle elevation in the mountains. In addition to this the temperatures at the control station are to serve as a base with which all other temperature records will be compared for their respective periods. At a number of the compared stations in various forest types only ground temperatures have been recorded, and at practically all these stations the elevation of the thermometers is considerably less than 20 feet. It is desirable, therefore, to know how the ground temperatures at the control station may compare with those of the higher aerial position.

As the control station is on a southerly exposure, though the gradient is very slight, it is to be expected that the purely local temperatures will be somewhat higher than the mean temperatures for the locality, recorded 20 feet above the ground. This proves to be true. In Table 6 are given, in condensed form, the results of a comparison of the two for two years ending March 31, 1918. In this period the maximum and minimum registering thermometers for the ground location were placed on a shielded board, which did not entirely protect them from reflected light and heat, but allowed very free cooling at night, as already described under "The Method of Study." As no thermograph was employed, the ground temperatures are not synchronous with those of the tower station, but they always represent periods about 8 hours later.

TABLE 6.—*Departure of ground temperatures from temperatures 20 feet above ground at the control station (with dissimilar exposure of instruments).*

Datum.	Record by months in degrees Fahrenheit.												Mean annual.	Mean growing season.
	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.		
Mean temperature	+0.4	+0.5	+1.3	+2.3	+1.5	+0.9	+0.8	+1.1	+0.9	+1.5	−0.1	+1.1	+1.0	+0.9
Mean maxima	+1.7	+2.1	+3.0	+5.3	+4.5	+4.5	+4.1	+3.9	+4.2	+3.4	+2.2	+2.6	+3.5	+4.2
Mean minima	− .9	−1.2	− .4	− .7	−1.4	−2.6	−2.4	−1.7	−2.4	− .4	−2.3	− .5	−1.4	−2.3
Absolute minima	−1.8	−3.5	−1.8	−3.9	−1.2	−2.2	−2.8	−1.8	−1.0	− .7	−1.2	−2.1	−2.0	−2.2
Daily range	+2.3	+3.3	+3.4	+6.0	+5.8	+7.1	+6.5	+5.6	+6.6	+3.8	+4.5	+3.0	+4.9	+6.4

[1] See note, p. 29.

It is seen that the maxima are always higher and the minima always lower near the ground than at the 20-foot elevation. This results, of course, in a much greater daily range, and in a slightly higher mean temperature close to the ground. The difference seems to be greatest in April and May, possibly because at that time the higher air is cooled by passing over snow fields, while locally the ground may be bare. The daily minima, it is found, are likely to show the greatest depression at the ground, in the coolest periods with extremely calm nights.

As has been indicated, the exposure of the thermometers at the ground was not such as to insure their recording strictly the temperature of the air itself at the time of the highest temperatures each day. Because this was realized, at the end of the period above described, the equipment, with thermograph added, was placed in a standard shelter, free from direct insolation or reflected insolation, and well ventilated through the floor to insure radiation at night. The site of the shelter was only a few feet from the other site, but was more fully clothed with vegetation. Since this change was made the higher maxima near the ground have been at all times just about counterbalanced by the lower minima, and the result has been, as before, a higher daily range for the ground position, but essentially the same mean temperature. The data for April, 1918, are especially interesting, because during this month, in the earlier arrangement, the greatest excess of ground heat was recorded. (See Table 7.)

TABLE 7.—*Departure of ground temperatures from temperatures 20 feet above ground at the control station (with similar exposure of instruments).*

	April, 1918.	July, 1918.
Mean temperature[1]	+0.2	+0.2
Mean maxima	+1.6	+2.2
Mean minima	−1.3	−1.9
Absolute minima	−1.8	−2.0
Mean daily range	+2.9	+4.1

[1]See note, p. 29.

Although these data are hardly extensive enough to invalidate those previously presented, it is probably safe to state that in an open situation of practically neutral aspect there is no important difference between the mean temperatures near the ground and those 20 feet above the surface; but that the ground location may easily show daily ranges exceeding by 3° or 4° those of the atmosphere above. Hence, of course, the probability of frost is much greater at the ground than on the tower where our main temperature record has been secured. It is seen from Table 4 that the probable minimum for the second decade of June, when expressed in terms of ground temperatures, may be as low as 32° F., and for the first decade of September as low as 34° F. It is thus apparent that the frost-free season may actually be 10 or 15 days shorter at the ground than would be indicated by Table 4; and of course it is the seedling at the ground level that is most sensitive to frost. On the morning of September 7, 1918, for example, the ground temperature was 30.2° F., and the frost was severe enough to kill tomatoes but not other garden vegetables. The minimum temperature 20 feet above ground was 32.5°.

These facts evidently do not apply to sites of decided northerly or southerly aspect, where the amount of insolation received may appreciably affect the local mean temperature. (Compare Stations 3A and 3G, 2A and 2G, in Table 9.)

Temperatures at various elevations in the Pikes Peak region.—The control station in this project, the Weather Bureau station at Colorado Springs, the Forest Service station at the Monument Nursery, the Weather Bureau cooperative station at Lake Moraine, and the special station at timber line, operated for 17 months, comprise an

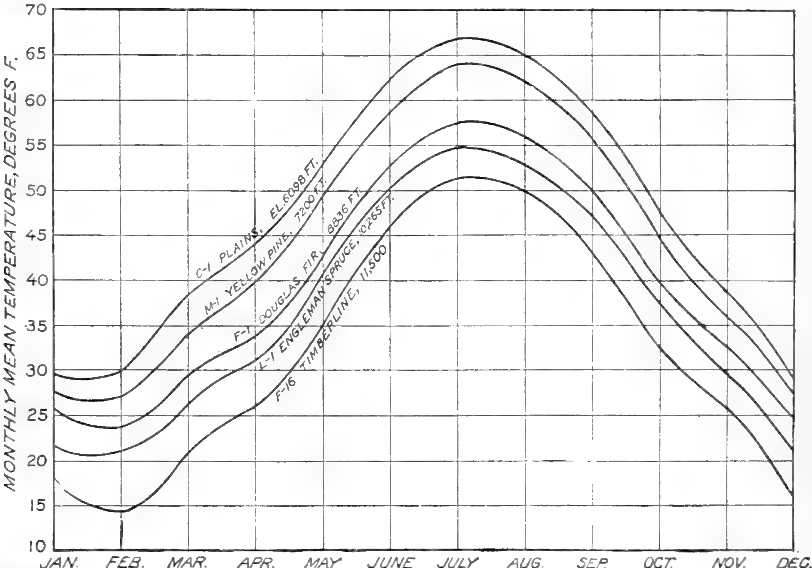

FIG. 2.—Monthly mean temperature for different elevations in the Pikes Peak region series.

altitudinal series (Table 8) from which a very definite idea may be obtained of the primary cause of forest zonation, if, indeed, temperature is a cause, as it appears to be.

In Table 8 the mean temperature of each of these stations, by months, is expressed by the difference between the temperature of the station in question and that of the control station, for the period indicated in column 4. The mean temperatures at the control station for the period up to April, 1921, are given in the center of the table, so that those for any other station may readily be computed to the same basis. In Figure 2 the absolute temperatures computed in this manner are shown.

TABLE 8.—*Comparative mean temperatures in Pikes Peak series.*

[Departures from control station temperatures during periods indicated and average temperatures for the control station.]

Station No.	Zone or type.	Elevation.	Period of record.	Record by months in degrees Fahrenheit.												Mean annual.[1]	Mean growing season.
				Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.		
		Feet.															
C-1	Plains	6,098	Jan., 1910, to Mar., 1918	+3.9	+6.1	+8.9	+10.1	+9.8	+9.4	+9.4	+9.2	+9.0	+7.9	+6.4	+4.4	+7.86	+9.28
M-1	Yellow pine type	7,200	Jan., 1911, to Mar., 1918[2]	+2.0	+3.0	+4.4	+6.2	+6.3	+5.9	+6.6	+6.2	+6.0	+5.1	+3.5	+2.9	+4.85	+6.21
F-1 control	Douglas fir zone	8,836	Jan., 1910, to Apr., 1921[3]	25.7	23.7	29.5	33.7	42.9	52.9	57.6	56.0	49.9	39.9	32.6	24.9	39.11	55.35
L-1	Spruce zone, limber pine type.	10,265	Jan., 1910, to Mar., 1918	−4.1	−2.8	−3.3	−2.9	−2.2	−2.6	−2.9	−3.3	−2.5	−2.1	−3.1	−3.5	−2.95	−2.91
F-16	Timber line	11,500	Oct., 1916, to Feb., 1918	−7.6	−9.3	−8.5	−7.8	−7.8	−7.0	−6.1	−6.0	−6.6	−7.6	−6.6	−8.8	−7.48	−6.39

[1] See note, page 29.
[2] Same omissions as control.
[3] With omissions.

For the stations below the control station the greatest excess of temperature is recorded in the spring and summer months and the least in winter; for the two stations at higher elevations the least deficiency is recorded in the summer months and the greatest in winter. This may be expressed more concretely. Although the control station is almost midway between the highest station and the lowest station in the series, its January temperature is 1.8° higher than the mean of the two and its July temperature is 1.6° lower. This is probably because of the high position of the thermometers at the control station, although it may have a broader significance than has been detected. Figure 3 shows the January gradient as a slightly convex curve, but the July gradient is not concave, the control station only being depressed.

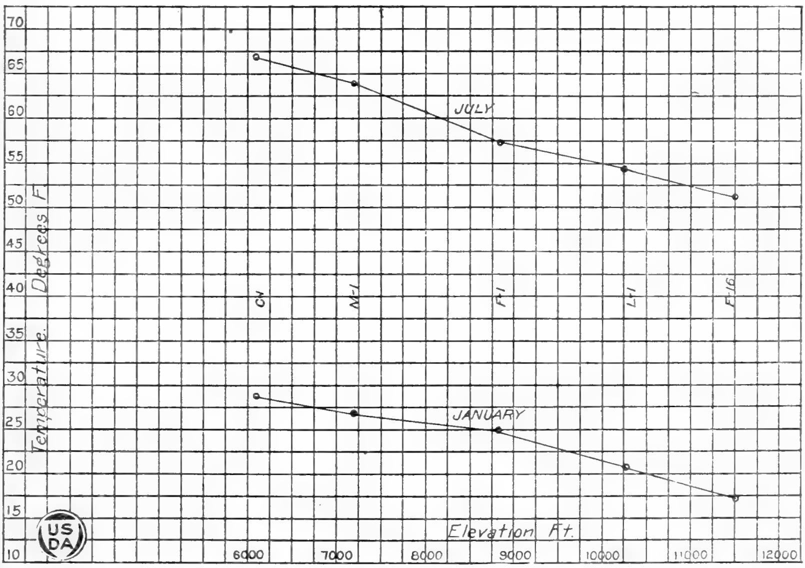

FIG. 3.—Temperature gradients in Pikes Peak region.

More important is the fact that the altitudinal temperature difference is least in the winter months, reaching a minimum of 11.5° in January and a maximum of 17.9° in April. The latter is plainly due to the quick disappearance of any snow that may fall at the lower elevations, while the high elevations suffer a handicap from the snow blanket, which is only nullified through the summer. The small difference in winter is probably due to the tendency of cold air to settle at lower levels, which sometimes results in an inversion of temperatures in the coldest weather.

The January gradient amounts to 2.1° per thousand feet elevation, the April gradient to 3.3°, and the mean for the year is 2.9°. It should not be considered that these figures have any general value, though they agree closely with the average of 10 Colorado watersheds as computed by Robbins (*20*).

TABLE 9.—*Comparative temperatures in different types at middle elevation, Pikes Peak region.*

[Departures from control station temperatures during periods indicated and average temperatures for the control station.]

Station No.	Type.	Elevation.	Aspect.	Height of thermometers.	Period of record.	Datum.	Records by months in degrees Fahrenheit.												Mean annual.[1]	Mean growing season.
							Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.		
		Feet.		Feet.																
F-1A	Control	8,836	S.	20	Jan., 1910, to Apr., 1921.[2]	True mean temperature.	25.7	23.7	29.5	33.7	42.9	52.9	57.6	56.0	49.9	39.9	32.6	21.9	39.11	55.35
F-2A	Yellow pine slope	8,921	SW.	20	Mar., 1910, to Feb., 1912.	Comparative temperature.	+ .9	+2.0	+2.2	+1.9	+2.1	+2.0	+1.5	+2.0	+2.0	+2.5	+1.2	+1.7	+1.84	+1.80
F-2G	do	8,921	SW.	1	Mar., 1915, to Feb., 1916.	do	+2.6	+4.3	+4.8	+4.7	+4.6	+4.8	+5.4	+4.2	+4.0	+4.6	+5.0	+3.9	+4.41	+4.81
F-12	Yellow pine ridge	9,161	[3] S.	1	Apr., 1915, to Mar., 1916.	do	− .4			+ .7			+2.9			+ .3			+ .87	
F-4	Yellow pine slope	9,117	E.	1	June to Sept., 1920.	do						−1.1	−1.5	−1.3	−1.8					−1.30
F-6	Limber pine slope	9,060	NW.	1	Apr., 1915, to Mar., 1916.	do	+ .2			+3.2			+6.4			+1.4			+2.81	
F-13	Limber pine high ridge.	10,300	Flat.	5	June, 1915, to Sept., 1916.	do	−2.0	−2.5	−3.4	−2.5	−2.2	− .3	− .7	−1.7	−1.6	−2.7	−2.7	−2.7	−2.10	− .96
F-7-8	Douglas fir opening.	9,121	N.	1	Oct., 1915, to Dec., 1917.	do	−1.6			+1.4			+2.2			+ .3			+ .58	
F-14	Douglas fir part cover.	9,087	N.	1	Apr., 1916, to Dec., 1917.	do	−2.2			+ .6			+2.1			0.0			+ .12	
F-15	do	9,080	N.	1	Apr., 1916, to Dec., 1917.	do	−1.6			+ .8			+2.6			+ .1			+ .47	
F-9	Douglas fir-spruce, virgin stand.	9,099	N.	1	Oct., 1915, to Dec., 1917.	do	−2.2			− .2			+2.4			− .9			− .22	
F-5	Canyon spruce	9,044	E.	1	June to Sept., 1920.	do						−3.2	−5.1	−4.4	−5.6					−4.26
F-3A	do	8,860	NE.	20	Mar., 1910, to Feb., 1912.	do	−1.1	+ .2	+ .2	+ .6	+ .7	−1.0	+ .3	+ .9	+ .2	− .6	− .8	−1.5	− .15	+ .08
F-3G	do	8,860	NE.	1	Mar., 1915, to Feb., 1916.	do	−2.5	+3.0	+ .8	+ .1	+1.6	+2.4	+1.7	.0	−1.2	−3.5	−1.0	−2.1	− .54	+1.08

[1] See note, page 29.
[2] With omissions.
[3] Nearly flat.

Other temperatures in the Pikes Peak Region.—The remaining temperature records for the Pikes Peak region (Table 9) are those obtained at the special stations in the vicinity of the control station, all but one at practically the same elevation, and designed to show the difference between types on slopes of different exposure. It is shown that a difference of exposure may create as great a difference in local air temperature as a difference of 1,000 or 2,000 feet in elevation; hence, so far as air temperatures determine, almost any species may find the proper conditions for initiation at a middle elevation.

In Table 9 the same plan has been followed as in Table 8, the records being for a variety of periods and none covering the whole period during which the control station has been operated. Several of the records do not have sufficient individual value to warrant the computation of means for every month. In these records one month in each quarter has been considered, and the annual means have been derived from these four months, a comparison being made, of course, with the same months at the control station.

It is seen from Table 9 that the growing season excesses of the outlying stations are somewhat greater than the excesses for the whole year, where both have been computed, except at Station F–2A, which, like the control station, represents conditions 20 feet above the ground. These facts may account for the low summer temperatures of the control station, as compared with other stations in the Pikes Peak series.

When the most typical pine and spruce stations shown in Table 9 are compared with corresponding types at different elevations, as shown in Table 8, namely, F–2 with M–1, and F–3 with L–1, it is found that the air temperatures of corresponding forest types vary in the same direction, but that the local variations are not so great as those in which a difference in elevation is involved. The pine type locally may be 4.4° warmer than the control station, if the ground conditions for the whole year are considered, but at a lower elevation the pine type is 4.8° warmer. Here the agreement is close.

One of the local spruce types is decidedly cooler than the control station for the summer period in which record has been secured, but the other is cooler only during the winter. In the first spruce type there is a very marked depression of the minima, undoubtedly due to cold air drainage; but in the second type the summer maxima are so high as to lead to the belief that the poorly sheltered thermometers received some direct insolation, the possibility of which was not suspected during the observations. It is to be noted that insolation, reaching the ground through breaks in a heavy canopy, produces very sharp effects on account of the stagnation of the air. Because of the factors possibly affecting the record for F–3, more significance should be attached to the soil temperatures, which more clearly show the general coolness of this site.

It is noted that the western yellow pine ridge (F–12), like the control station, is freely exposed to wind and is practically no warmer than the control station. It will also be remembered that this site is reproducing to Douglas fir and limber pine, as well as to yellow pine, and that the yellow pine is in a very unhealthy condition. This condition is equally well brought out by the soil temperatures. In the summer, at least, lower air temperatures occur at F–4, where the maxima are not high on account of the easterly exposure, and where the minima are relatively low after the long period of radiation, and possibly somewhat affected by air drainage in the slight depression.

The temperature record of the local limber pine type (F–6) is a wholly dependable one, and is, perhaps, significant of the requirements of this species. It is especially noteworthy that the winter temperatures, in spite of the fact that they represent ground conditions, are slightly higher than those of the control station, and there can be little doubt that this is due to direct exposure to west winds. As the slope is a northwest one, the high summer temperatures may be accounted for only by the fact that such insolation as is received locally, coming late in the day when the general air temperatures are already high, causes high and late maxima and hence high minima.

The record of the higher limber pine type (F–13) does not seem to bear out the assumption that this species demands a great deal of heat. Although the mean temperatures are always considerably lower than for the control station, it is, however, possible to conceive that during the summer months, when the difference is rather slight, this site experiences a few hours of high temperatures satisfactory to a heat-demanding tree, and that the growth of limber pine is restricted to such short periods. Even so, the maxima are considerably lower than for the control station, especially during the winter months. The maxima for the growing season are 1.7° lower than at the control station, the minima 1.8° higher, and the mean daily ranges 3.5° less. For this period the station would compare favorably with ground temperatures at the control station. The daily ranges at the higher station are relatively the least during the winter months. The decade minima are usually higher during the coldest months when they are most affected by wind. For the growing season they are 0.8° lower, on the average, and only very rarely higher than at the control station.

On the whole, no plausible explanation is found for the occurrence of limber pine in burns of the spruce zone except on the assumption that ground temperatures during the growing season may be about the same as at lower elevations, at least giving short periods of favorable temperature. Having no competition, the limber pine is able to survive even with a very small annual accretion.

The temperatures of the four north-slope stations that represent different weights of cover in the Douglas fir type, are worthy of note. The mean temperature in the fully open position is slightly in excess of that of the control station—about as much in excess as the ground temperatures at the control station might be expected to be. The two stations under partial cover are almost identical with the control station for the year as a whole; however, they are decidedly cooler in winter and warmer in summer. These high temperatures on a north slope are to be accounted for only by air stagnation, the wind movement being much less here than at the control station, even if velocities at the latter point are reduced to ground conditions. The whole-cover station (F–9) is appreciably cooler than the others during most of the year.

The mean temperatures, however, do not tell the story for these four stations. In Table 10 the extremes and daily ranges for the control station and the four north-slope stations are shown. The absolute figures given for the control station are for the longer period corresponding to Station 7–8, namely, October, 1915, to December, 1917.

For the most part, the variations from the control station, whatever the condition measured, progress rather regularly through the four stations, that is, become greater or smaller, as the case may be, with increase in density of the cover. The influence of cover may then be directly measured by comparing Station 9 with 7–8. In July, the complete canopy reduces the maxima 2.2° and raises the minima 2.5°; in January the effect on the minima is similar, but, as almost no January sunlight reaches the ground under the canopy, the maxima also are reduced about 3.1°.

TABLE 10.—*Actual temperatures at the control station and departures therefrom on north-slope Douglas fir sites, with different weights of cover.*

Station.	Datum.	Record in degrees Fahrenheit.				Mean annual.[1]
		January.	April.	July.	October.	
Control, Oct., 1915, to Dec., 1917.	Mean maximum	33.86	42.84	70.14	52.67	49.88
	Mean minimum	11.46	22.09	47.52	28.15	27.30
	Daily range	22.40	20.76	22.62	24.51	22.57
	Absolute minimum	−15.65	4.70	41.0	5.80	8.96
F-7-8, open	Mean maximum	− 1.9	+2.8	+6.3	+1.5	+2.2
	Mean minimum	− 1.4	0	−1.8	−1.0	−1.0
	Daily range	− .5	+2.8	+8.1	+2.5	+3.2
	Absolute minimum	− 1.0	−3.4	−1.3	−1.7	−1.9
F-14, part cover	Mean maximum	− 4.0	+ .5	+5.0	− .1	+ .3
	Mean minimum	− .3	+ .7	− .6	+ .2	0
	Daily range	− 3.7	− .2	+5.6	− .2	+ .4
	Absolute minimum	− .2	+1.2	− .6	−1.0	− .1
F-15, part cover	Mean maximum	− 3.8	+ .1	+4.9	−1.0	0
	Mean minimum	+ .6	+1.5	+ .2	+1.2	+ .9
	Daily range	− 4.4	−1.4	+4.7	−2.2	− .8
	Absolute minimum	+ .2	+2.4	− .2	0	+ .6
F-9, virgin stand	Mean maximum	− 5.0	−1.1	+4.1	−3.3	−1.4
	Mean minimum	+ .7	+ .7	+ .7	+1.5	+ .9
	Daily range	− 5.7	−1.8	+3.3	−4.8	−2.2
	Absolute minimum	+ 3.4	+ .4	− .2	+1.0	+1.2

[1] See note, p. 29.

October is doubtless the most important month with respect to the fate of new, poorly developed seedlings. Its temperatures are similar to those of September, when the first frosts are to be expected. In October the complete canopy has the effect of raising the mean minima 2.5° and the absolute minima 2.7°. This is sufficient to postpone freezing under the canopy for several days, the mean rate of cooling, figuring from September to October, being 1° every 3 days. Frost may, then, "normally" be postponed a week through the protection of the canopy. This should be of some slight benefit to seedlings. However, it should tend to favor the less hardy species, Douglas fir, as against the species, Engelmann spruce, which in many of its habitats is subject to frost every month in the year. This it does not do. The canopy tends to favor spruce, but fir and limber pine flourish more abundantly in the open. It may, therefore, be conceived that the influence of the canopy in reducing extremely high temperatures, or mean temperatures for the year as a whole, has more importance in selecting the successful species.

Other air temperatures at more distant points.—The mean air temperatures for a number of stations in the central Rocky Mountain region, believed to be representative of its different localities are shown on a comparative basis in Table 11. With a few exceptions the records of these stations cover the period during which the control station has been operated, up to March, 1918, and all the comparisons are made between identical months of the eight years, or parts thereof.

TABLE 11.—*Average mean temperatures for the control station and departures therefrom for scattered stations in the central Rocky Mountain region.*

[Actual mean temperatures given for the control station.]

Station No.	Type.	Period.	Comparative temperatures in degrees Fahrenheit.												Year.[1]	Growing season.
			Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.		
F-1	Control station	Jan., 1910, to Apr., 1921 [2]	25.7	23.7	29.5	33.7	42.9	52.9	57.6	56.0	49.9	39.9	32.6	24.9	39.11	55.35
H-2	Nebraska sandhills	May, 1919, to Apr., 1921	− 1.2	+ 3.5	+ 8.4	+12.8	+12.3	+15.5	+16.3	+14.5	+13.7	+ 9.1	− .1	− 4.7	+ 8.36	+15.46
P-1	Southern Colorado western yellow pine	Jan., 1910, to Dec., 1916 (2) [3]	− 7.4	+ .1	+ 2.7	+ 6.7	+ 5.8	+ 4.4	+ 6.4	+ 5.7	+ 6.0	+ 3.6	+ 1.3	− 4.2	+ 2.58	+ 5.53
D-1	Black Hills western yellow pine	1910 to 1918, except 1915 (12)	− 4.8	− .2	+ 3.0	+ 7.4	+ 7.2	+ 8.2	+10.1	+ 7.1	+ 6.2	+ 3.8	+ 2.5	+ .9	+ 4.28	+ 8.25
F-17	Northern Colorado Douglas fir (east)	1910 to 1918	− 4.1	− .4	0	+ 1.8	+ 1.5	+ 1.9	+ 2.3	+ 2.6	+ 1.3	+ .2	− .4	− 1.0	+ .47	+ 2.15
W-A1	Southern Colorado Douglas fir (north)	Nov., 1910, to Dec., 1917	− 9.1	− 4.2	− 3.0	− .9	− .4	− .5	− 1.0	− 1.7	− 2.1	− 2.8	− 6.4	− 8.0	− 3.35	− 1.17
F-18	Fraser River lodgepole pine	1910 to 1918 (1)	−13.9	− 9.9	− 7.8	− 4.2	− 5.1	− 4.9	− 4.8	− 5.2	− 5.5	− 6.1	−10.0	−13.0	− 7.56	− 5.05
N-1	Western slope lodgepole pine	1910 to 1918	− 8.7	− 5.2	− 3.6	− .2	+ 1.2	− .5	− .5	− .6	− .9	− 1.4	− 4.9	− 7.6	− 2.74	− .56
F-11	Southern Wyoming lodgepole pine	Mar., 1911, to Mar., 1918 (12)	− 9.5	− 7.1	− 7.4	− 4.7	− 5.4	− 5.8	− 5.1	− 5.0	− 6.4	− 5.7	− 6.5	−10.8	− 6.62	− 5.41
L-2	Continental Divide lodgepole pine	1919 to 1918	− 9.4	− 5.2	− 5.4	− 3.2	− 2.8	− 3.3	− 2.8	− 2.9	− 3.0	− 4.3	− 6.5	− 7.6	− 4.68	− 2.98
W-G	Southern Colorado high spruce	Oct., 1913, to Dec., 1917	−10.2	− 7.3	− 7.3	− 6.4	− 7.2	− 5.8	− 6.1	− 5.2	− 7.0	− 6.1	− 6.7	− 8.5	− 6.98	− 5.84

[1] See footnote (6), p. 29.
[2] With exceptions already noted under description of this station. Comparisons are made on basis of period up to March, 1918, except for Station H-2.
[3] Number in parentheses indicates number of months missing in inclusive period, in addition to omissions for control station.

The observations at all outlying stations, it is believed, have been made at an elevation of about 5 feet above the ground as compared with 20 feet for the control station, but, as has been shown, this factor can not materially affect the mean temperature for any month. An examination of such data as are readily available on the daily range of air temperatures for other localities shows that a range of about 20° to 22° is characteristic throughout the region under discussion, except in the Nebraska sandhills. The relation of maxima and minima to means will be, therefore, almost the same as the relation at the control station.

Air temperatures compared by forest types.—1. The yellow pine station in southern Colorado shows less excess over the control station than does a station 400 feet distant, and less than the Monument station at the foot of the Pikes Peak series, if the comparison is made for the whole year. For the growing season, however, the southern Colorado station is slightly warmer than the local yellow pine type, but not equal to the Monument station. In both southern Colorado and the Black Hills yellow pine endures much lower winter temperatures than occur at any but the highest elevations in the Pikes Peak region. The fact must not be lost sight of, however, that these low temperatures are endured in the presence of a deep blanket of snow which may largely prevent soil freezing.

All of the data for the western yellow pine sites may be briefly summarized and reduced to absolute temperatures, in the order of growing-season temperatures, as follows:

	Growing season.	Year.	Locality.
	°*F.*	°*F.*	
Highest	63.60	43.39	Black Hills.
	61.56	43.96	Pikes Peak, M-1.
	60.88	41.69	Southern Colorado.
	[1] 58.65	42.23	Fremont, south slope.
	[2] 56.65	39.98	Fremont, ridge.
Lowest	54.05	....	Fremont, east slope.
Total range	9.55	3.98	

[1] Averaging ground and air conditions.
[2] Based on May, July, and October differences.

It is then seen that the Black Hills station, in a low-lying region where other forest species are practically excluded, has the highest growing-season temperatures of any of the western yellow pine types, and with this condition and fairly high rainfall the species reaches its optimum development, at least in reproduction. Where the lowest growing-season temperatures of yellow pine types are found Douglas fir and limber pine also appear in considerable proportions.

Establishment of yellow pine by planting has been successfully accomplished in the Nebraska sandhills, where the mean temperature for the growing season is in excess of 70°, and for the year is nearly 48°. The former is about 7° in excess of the Black Hills yellow pine type. These conditions, however, not only have prohibited natural extension of pine to this region, but have caused considerable losses in plantations; furthermore, they have precluded direct seeding. Although, of course, all the conditions which accompany these temperatures must be referred to, still the more this matter is studied, the greater is the conviction that temperatures do very largely control the distribution of species, although the air temperatures as measured may fall far short of showing the really critical conditions which must ultimately be examined. In considering these Nebraska temperatures, the effects of a scantily covered and strongly mineral soil are apparent in the high daily ranges, which in clear weather often go to 40° and occasionally to 50°, while averaging 27.6° for the year and 30.4° for the growing season. Thus, for the growing season the mean maxima are 20.7° in excess of those at the control station, while the minima are only 11° in excess, the difference becoming less in late summer. These facts, considered with those of distribution, are at least strongly suggestive that, although yellow pine may make vigorous growth with temperatures which are both theoretically and actually very favorable for corn, yet the seedlings at their most sensitive stage must have much more moderate conditions. The relation of these high temperatures to surface drought in such a sandy soil must not be overlooked, especially when it is noted that seeding fails even in well-shaded situations.

2. The northern Colorado Douglas fir site (F–17) should possess characteristics somewhat similar to those of the control station, as it is similarly situated on the east slope of the mountain range. Its considerably lower winter temperatures, however, indicate that it is not so potently affected by descending winds, and that these may be peculiarly developed in the Pikes Peak region. On the other hand, the southern Colorado station (W–A1) is very much colder than the control station during the winter—the locality being peculiarly free of wind at all times—and appreciably cooler also throughout the growing season, although the latter difference is not a serious one.

If the north slope open and covered stations are used to represent Douglas fir in the Fremont locality, the temperatures for this type, as computed, may be summarized in the following order based on the growing season:

	Growing season.	Year.	Locality.
	°*F.*	°*F.*	
Highest	57.50	39.58	Northern Colorado.
	[1] 56.65	39.59	Fremont, cut-over.
	[1] 55.78	38.89	Fremont, closed stand.
Lowest	54.18	35.76	Wagon Wheel Gap, north.
Total range	3.32	3.82	

[1] Based on April, July, and October differences.

The Douglas fir temperatures, which happen to have been taken entirely at middle elevations, do not show so great a range as those of the yellow pine type. In either annual or growing-season requirements, the species seems to have a somewhat limited range, giving way appreciably to spruce under the lowest temperatures here recorded. Even if the brief record for the south-slope station at Wagon Wheel Gap (W–2A) be considered, temperatures in excess of those noted are not found. The south slope here shows an excess of about 1.8° over the corresponding north-slope site, and the conditions thus produced seem to be about the maximum that fir will bear, if the large summer mortality among seedlings may be taken as evidence. Further evidence of the lack of adaptive qualities in fir is found in the fact that in the Pikes Peak region, as observed by the writer, Douglas fir does not go to such high elevations as the western yellow pine occasionally does.

3. The lodgepole-pine type, wherever found, seems to be characterized by very low winter temperatures and also by growing-season temperatures considerably lower than those of the control station. It is believed that the low winter temperatures of this type are always accompanied by heavy snowfall, which, at least at the southern Wyoming station, arrives so early as to prevent deep soil freezing. These facts suggest that the most obvious requirement for reproduction of lodgepole pine is a winter climate of such low temperatures and with such an abundance of snow that the evaporation factor is essentially nullified. This would seem to explain the absence of lodgepole pine from the Pikes Peak region, but not its ability to grow there when planted. As has been shown by the physiological studies, it is more probable that in the Rocky Mountains it is crowded out of its normal temperature zone by demands for moisture which can be met only at elevations where the snowfall is heavy and well conserved throughout the winter. The mean temperatures indicated by these data are:

	Growing season.	Year.	Locality.
	° *F.*	° *F.*	
Highest	54.79	36.37	Western slope.
	52.37	34.43	Continental Divide.
	50.30	31.55	Fraser Basin.
Lowest	49.94	32.49	Southern Wyoming.
Total range	4.85	4.82	

It will be noted that these maxima overlap somewhat into the zone of Douglas fir temperatures. It will also be noted later that the temperatures enjoyed by lodgepole pine come within the range of temperatures enjoyed by spruce.

4. The single spruce station listed in this table (W–G) shows a January temperature scarcely lower than the Douglas fir station (W–A1) of the same region, but for the remainder of the year the high spruce type is much cooler. The annual and growing-season means of this station are also remarkably close to those of the timber-line station (F–16, Table 8) of the Pikes Peak region, the two being at almost the same elevation, and the former not more than 500 feet below timber line for its locality. This suggests that an annual mean of slightly less than 32° F. may be the limiting factor for all forest growth in the central Rockies. It is suspected, however, that such a limitation is placed upon growth only indirectly if at all.

All of the spruce temperatures may be summarized as follows:

	Growing season.	Year.	Locality.
	° *F.*	° *F.*	
Highest	[1] 55.93	[1] 38.77	Fremont, canyon type.
	52.44	36.16	Fremont, middle zone.
	51.09	....	Fremont, canyon type.
	49.53	32.13	Wagon Wheel Gap, near timber line.
Lowest	48.96	31.63	Fremont, timber line.
Total range	6.97	7.14	

[1] Average of ground and air conditions at F–3.

73045°—24——4

Summary of mean air temperatures.—To bring all the preceding data together for closer study, the average temperature of each type, as studied, and the differences within each type, may be shown as follows:

Type.	Number of stations.	Mean temperatures.			
		Growing season.		Year.	
		Range.	Average.[1]	Range.	Average.[1]
		° F.	° F.	° F.	° F.
Plains	1	....	64.6	....	47.0
Sand hills	1	....	70.8	....	47.5
Western yellow pine	6	9.6	59.2	4.0	42.2
Limber pine	3	6.6	55.2	5.8	38.4
Douglas fir	4	3.3	56.0	3.8	38.5
Lodgepole pine	4	4.8	51.8	4.8	33.7
Engelmann spruce	5	7.0	51.6	7.3	34.7

[1] Of stations listed in four tables just preceding.

CONCLUSIONS REGARDING AIR TEMPERATURES.

As has already been pointed out, from the physiological standpoint the air temperatures per se may mean very little. It has been made apparent by the preceding studies that the several species here considered show wide differences in photosynthetic capacity, and it is logical to assume that the species which makes the most effective use of sunlight will succeed best in a cool environment. On this basis alone the upward extension of any species would be plainly limited by competition with another species of greater shade tolerance and correspondingly low heat requirements for effective growth. In this consideration it seems that the mean air temperatures for the growing season serve as well as any other criteria to explain both the altitudinal zonation of the mountain forests and the sharp contrasts in cover as between opposing slopes. In fact, as regards mean air temperatures, it has been shown that the same differences may be produced locally as well by change of aspect as by great differences in altitude.

But even if the zones and aspect types are accepted as temperature types primarily, and as sufficiently well described and limited by the growing-season means, an explanation has not been provided, in agreement with physiological theory, for the fact that each species has a lower altitudinal limit and an apparent maximum-temperature limit. The mean air temperatures can of course give only a suggestion of what such limits might be, and even the maximum air temperatures, it is believed, would fall so far short of depicting the really critical conditions that it does not seem worth while to tabulate them for this purpose. When one considers all the facts of forest distribution, together with such phenomena as the marked success of yellow-pine planting in the Nebraska sand hills and the vigorous growth of the species there, the conclusion is unavoidable that the only conditions worth studying, in the attempt to explain the natural limitations of the forest types, are those which have the most acute bearing on seedlings in the infant stage. Even the matter of germination may confidently be put aside, for year after year great numbers of seedlings are germinated, but few of them survive even to the end of the first growing season.

To understand the limitations of the forest types, therefore, it seems essential that there should be knowledge of the maximum temperatures to which seedlings are subjected, and by this is meant the maxima at the surface of the soil, where injury to seedlings is first apparent. These will not wholly tell the story, as the fatal effects are probably produced by lack of moisture; but the maximum temperatures would probably be a very fair criterion as to the degree of drought produced if some allowance were made for the type of soil.

Considering the matter in its broader aspects, it is fairly apparent, even before the other conditions of the forest types have been considered, that temperatures are primarily and closely controlling in the natural distribution of each species. It is to be expected that each would show some range of requirements, and that, as indicated by the data, spruce and yellow pine might show a somewhat greater range than the other species, because, occupying the edges of the stands, they are not so closely limited by competition. It may be, of course, purely accidental that the data do show this quality. And in considering the range of temperatures under which any species thrives it should be apparent that different temperatures, as they are measured, may be physiologically alike. Thus, it may be said, atmospheric humidity modifies the apparent temperatures for plants as it does for animals. The plant temperature must be relatively higher in a moist than in a dry atmosphere. On the contrary, in the critical connection mentioned as affecting seedlings, the greater the humidity, no doubt, the higher the temperature that may be tolerated.

These considerations explain fully enough why the absolute temperatures enjoyed may cover a wide range, and especially why the temperature requirements in different regions may be markedly different. In this connection, however, it should be remembered that different races of the same species are now being dealt with. The behavior of the Montana and Arizona forms of yellow pine has been briefly described in the earlier physiological paper. The functioning of the Arizona form would lead one to expect that it would tolerate higher temperatures than the Colorado variety. Pearson (*19*) shows that the mean temperatures of the type in Arizona during the growing season—June to September—range from 59.5° to 65.6° F., the highest (Williams) being a little in excess of the Black Hills temperature, and being accompanied by a daily range of 33°, and with less precipitation than is characteristic of the Black Hills. The Arizona forest, however, reproduces itself with the greatest difficulty, while in the Black Hills reproduction is very abundant.

The temperatures given by Larsen (*13*) for an even longer growing season—May to September—are 61.2° for the Washington-Idaho section, 59.8° for the intermontane region of Idaho and Montana, and 64.7° for eastern Montana. It is believed that the intermontane region with the lowest temperature is the most favorable as regards moisture. The relatively high value for the type in eastern Montana may be determined by summer dryness, but there is a possibility, at least, that the Chinook of that region may have some influence in confining the type to warm sites where the danger of soil freezing is least.

Pearson's (*19*) Douglas fir type in the San Francisco Mountains, at an elevation of 8,900 feet, has a growing-season temperature almost identical with the average, but the annual mean is about 3° higher than the average in Colorado.

There are, then, no surprising differences even when widely separated types are compared. It seems evident that the temperature requirements of the three principal forest trees of the region—yellow pine, Douglas fir, and spruce—are in accord with their physiological properties, but that lodgepole pine, which theoretically would grow much better in conditions similar to those enjoyed by yellow pine, is compelled to take a much cooler site because of its inability as a seedling to cope with drought. Its ability to tolerate the extreme heat of fresh burns and to thrive here where competition has been destroyed is entirely in keeping with its physiological properties, and the inability to reproduce in its own shade is further evidence that the low temperatures are merely tolerated, not enjoyed.

Somewhat similarly, limber pine, although sometimes extending almost to timber line, is plainly a tree of the open. Its occupation of the wind-swept northwest slope, the warmest site here studied, may be temporary, but it is believed to result from a greater resistance to wind drying than is possessed by species which function more vigorously. Thus it seems safe to say that none of the species chooses warmer sites than, relatively speaking, its physiological conditions dictate, and that, when driven by other considerations to sites relatively too cool, the tenancy is only temporary.

WIND, HUMIDITY, AND EVAPORATION.

It would appear logical to follow the discussion of air temperatures by that of soil temperatures, for the two must be somewhat closely related, and their consideration in direct sequence would facilitate fixing in mind the temperature conditions, as a whole, for various kinds of sites. There is, however, one very potent reason for postponing the consideration of soil temperatures until all of the atmospheric conditions have been carefully weighed. This is the fact that the soil-temperature data which we are enabled to present here are not, perhaps, so important as temperatures as they are for expressing the physical status of the soil and the availability of its moisture. How important it is that the soil should be frozen one or six months is, obviously, not to be determined until we have first considered the atmospheric conditions and measured, in a rough way, the demand to give up moisture by transpiration which may be made upon trees during the period of soil freezing. It is therefore desirable and in fact necessary to proceed with the consideration of atmospheric conditions before taking up the subject of soil factors.

WIND MOVEMENT.

Wind movement at the control station.—The topographic position of the control station has already been described in general. The station lies in a fairly wide valley formed by the junction of three stream channels. It is not in the bottom of the valley, but on a low ridge lying between two of the streams. As the anemometer is placed on a tower 20 feet above the ground, the air movement is not strictly that of the valley bottom, but represents a slight gradation toward the freer movement of the higher air strata. Nevertheless, the elevation of the anemometer, 50 feet or less above the lowest adjacent ground in the valley, is inconsiderable in comparison with the elevation of the walls of the valley. At this point these rise some 300 feet higher on the north, at an angle of 18 degrees, and about

200 feet higher on the south, at an angle slightly less. Toward the head of the more open of the three stream channels, in a northwesterly direction, the elevation is somewhat less than 200 feet, and the angle is 7 degrees. Down the valley the immediate negative elevation is still less.

The control station is thus appreciably affected only by air currents paralleling the main axis of the valley, namely those from the southeast or the northwest. Only rarely do currents from the southwest or south reach the station through the valley having its origin in that direction, as the station is somewhat west of the axis of that valley. Due to this influence of local topography there is every reason to believe that the full velocity of the prevailing winds is not recorded. The prevailing wind direction is always southeast during the periods when valley breezes constitute the chief element of air circulation, that is, during the summer; and always northwest or west, the former predominating, when mountain breezes or anticyclonic winds dominate the atmosphere. Cyclonic winds, which are usually of northeasterly origin, are rarely recorded as such at this station, and may appear as east or southeasterly winds. It must, therefore, be recognized that winds from the northeast or north, and to a less extent those from the south and southwest, must conform to the configuration of the valley to become effective at this station.

Further evidence of local influences is given in the gusty character of winds, whenever the velocity is at all high. This is not shown by records, since the gusts of wind are usually so short that any individual mile recorded may be made up of several squalls and intermediate calms. From extended observation the writer has estimated that the momentary velocity of the wind gusts is fully twice the rate of movement indicated by the anemometer records. In any study of the mechanical effects of wind this discrepancy would be very important, and only the pressure-tube anemometer or some similar contrivance could possibly depict the actual conditions. For the purposes of this study, on the other hand, momentary velocities are of no importance, and, it may as well be stated at this point, the mechanical effects of wind in the region under study are quite negligible. The soil is of such firm texture and the trees are so short-boled as to preclude windfalls—except, of course, when trees have become badly decayed—and even the breaking of limbs is extremely rare. On one occasion in eight years, at a time when intense cold was accompanied by high wind, considerable snapping of twigs was noted. Even this was confined to the especially long side branches whose rapid, slender development subjected them to unusual exposure.

At timberline, of course, the mechanical effects of wind are always apparent in the distortion of limbs and the one-sided development of trees as a whole. At lower elevations that which appears to be a similar mechanical distortion of form has been traced by the writer (*6*) to winter-killing of limbs on the most exposed portions of the trees.

With these facts in mind, the recorded wind movements at the control station, as shown in Table 12, may be considered. As this record is an almost perfect one, it can be quite positively stated that apparent discrepancies between succeeding decades or corresponding periods of different years are true to the facts. The credit belongs to the designer of the thoroughly practical Robinson anemometer, and to the fact that the daily dial readings are compared with an almost unbroken automatic record.

TABLE 12.—*Total wind movement at the control station, beginning and ending at 8 a. m.*

Year.	Decade.	Record in miles per decade and month.												Total annual.	Total growing season.
		January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.		
1910	1	...	1,090	1,273	1,265	1,216	1,386	1,188	1,058	1,240	1,081	1,155	1,918	...	...
	2	...	1,811	1,032	1,261	1,143	1,328	1,162	965	996	1,168	828	848	...	...
	3	...	1,589	1,775	1,151	1,234	1,231	1,202	1,174	968	1,187	1,853	1,334	...	...
	Month[1]	...	4,489	4,080	3,677	3,592	3,945	3,552	3,197	3,203	3,436	3,836	4,100	[2] 46,508	11,933
1911	1	2,038	1,816	2,270	1,580	1,359	1,365	940	1,130	1,087	1,078	1,515	894	...	...
	2	2,349	1,085	1,009	1,397	1,445	1,110	852	1,051	1,155	1,206	2,169	645	...	...
	3	1,961	822	1,760	982	1,543	1,154	1,115	1,090	948	881	1,173	1,544	...	...
	Month.	6,348	3,722	5,039	3,958	4,346	3,629	2,907	3,272	3,190	3,165	4,858	3,084	47,518	10,895
1912	1	2,682	1,183	1,171	1,417	1,434	1,133	1,253	982	1,223	1,325	1,079	982	...	...
	2	1,474	1,578	1,710	1,750	986	942	1,047	893	928	1,111	1,013	1,470	...	...
	3	1,328	946	1,151	1,375	1,790	1,168	1,032	1,148	877	1,334	1,254	1,807	...	...
	Month.	5,484	3,707	4,033	4,543	4,210	3,242	3,332	3,022	3,028	3,770	3,347	4,259	45,977	10,820
1913	1	1,862	1,111	1,168	1,325	1,112	1,147	1,226	1,192	956	1,311	1,073	1,052	...	...
	2	2,949	907	1,523	1,088	1,203	1,172	1,117	924	978	965	926	916	...	...
	3	1,329	982	1,766	1,179	1,343	1,140	1,109	1,018	872	1,185	873	1,219	...	...
	Month.	6,140	3,000	4,458	3,592	3,658	3,460	3,453	3,134	2,806	3,461	2,872	3,187	43,220	11,063
1914	1	1,543	...	...	827	1,209	1,447	908	947	1,004	1,201	854	768	...	...
	2	2,017	...	...	1,151	877	1,061	945	1,023	1,360	1,025	1,000	...	...	...
	3	...	...	...	1,280	1,366	1,222	985	1,207	1,131	1,141	873	...	...	...
	Month.	...	...	...	3,258	3,452	3,730	2,838	3,177	3,495	3,366	2,727	...	...	10,749
1915	1	...	...	831	1,252	1,267	1,084	1,202	946	1,006	1,131	1,310	834	...	...
	2	...	...	1,149	998	1,213	1,557	1,137	886	1,231	962	1,708	1,925	...	...
	3	...	...	1,194	1,136	1,236	1,096	1,043	1,036	1,188	1,168	1,788	2,128	...	...
	Month.	...	...	3,173	3,386	3,715	3,737	3,382	2,868	3,425	3,261	4,805	4,888	...	10,993
1916	1	2,388	1,571	2,622	1,145	1,464	1,244	1,350	1,032	1,173	1,410	1,324	1,594	...	...
	2	1,387	932	1,530	1,483	1,191	1,173	1,015	955	1,046	1,299	914	2,166	...	...
	3	1,524	1,058	1,588	1,053	1,940	1,281	1,068	1,010	1,144	1,196	1,222	1,916	...	...
	Month.	5,299	3,561	5,740	3,681	4,595	3,699	3,433	2,997	3,364	3,906	3,459	5,676	49,410	11,302

1917	1	1,570	1,404	1,574	1,293	970	1,358	1,115	1,166	917	1,092	960	1,824		
	2	1,389	1,467	1,478	1,328	1,166	1,163	1,076	915	896	1,443	1,059	1,588		
	3	2,328	1,881	2,130	1,006	1,132	1,314	1,266	1,059	1,045	1,943	1,207	1,369		
	Month.	5,288	4,752	5,181	3,627	3,269	3,835	3,456	3,140	2,858	4,478	3,226	4,781	47,892	11,349
1918	1	1,153	1,740	1,970	1,146	1,464	1,124	953	1,026	942					
	2	1,243	1,891	1,665	1,241	1,312	1,199	944	924	985					
	3	1,616	1,785	1,341	1,173	1,765	1,180	1,090	1,251						
	Month.	4,012	5,416	4,977	3,561	4,541	3,502	2,987	3,201						10,632
1919	1					1,489	1,180	1,035	1,055	1,064	1,094	1,517	2,268		
	2					1,068	1,110	1,005	1,223	860	1,097	988	1,330		
	3					1,330	1,201	1,191	1,236	1,156	1,579	1,041	1,381		
	Month.					3,886	3,491	3,231	3,514	3,081	3,770	3,545	4,979		11,300
1920	1	899	933	1,035	1,946	1,321	1,118	1,072	942	895	1,323	955	1,407		
	2	1,893	1,280	2,009	1,449	905	1,161	1,017	953	1,017	1,291	885	1,626		
	3	995	875	1,708	1,364	1,226	982	1,288	1,197	1,456	1,161	1,230	1,438		
	Month.	3,787	3,088	4,752	4,759	3,452	3,260	3,377	3,092	3,367	3,775	3,070	4,471	44,250	10,624
1921	1	1,589	1,071	1,082	1,113										
	2	2,061	1,319	1,385	1,230										
	3	1,271	1,020	1,529	1,406										
	Month.	4,920	3,410	3,996	3,749										
Average[3] to Apr. 30, 1921	1	(9) 1,747	(9) 1,324	(10) 1,500	(11) 1,301	(11) 1,300	(11) 1,235	(11) 1,113	(11) 1,043	(11) 1,046	(10) 1,205	(10) 1,174	(10) 1,354		
	2	1,862	1,363	1,449	1,307	1,137	1,180	1,029	974	1,041	1,157	1,149	(9) 1,390		
	3	(8) 1,544	1,218	1,594	1,191	1,446	1,179	1,126	1,130	(10) 1,079	1,278	1,251	1,571		
	Month.	5,154	3,905	4,543	3,799	3,883	3,594	3,268	3,147	3,166	3,639	3,575	4,315	45,987	11,055
Average miles per hour.	1	7.3	5.5	6.2	5.4	5.4	5.1	4.6	4.3	4.4	5.0	4.9	5.6		
	2	7.8	5.7	6.0	5.4	4.7	4.9	4.3	4.1	4.3	4.8	4.8	5.8		
	3	5.8	6.1	6.0	5.0	5.5	4.9	4.3	4.3	4.5	4.8	5.2	6.0		
	Month.	6.9	5.7	6.1	5.3	5.2	5.0	4.4	4.2	4.4	4.9	5.0	5.8	5.2	4.5

[1] See footnote, p. 29.
[2] Assuming January to have been average (5,401.6 miles) as averaged to 1918.
[3] Numbers in parentheses indicate number of records on which average is based. Monthly normal is sum of decade averages.

It is, perhaps, of first importance to note that the total wind movement by years varies only within somewhat narrow limits. For the seven years for which there are almost complete records the mean variation from normal is only 3.7 per cent of the total movement, while the Colorado Springs station shows an average variation of 5.1 per cent during the eight years 1910 to 1917, inclusive. The variation between growing seasons is even less important. For the 11 complete growing seasons the local station shows an average variation of 2.7 per cent of the total movement, while Colorado Springs for eight years shows an average variation of 7.5 per cent, the growing season on the plains being thus more variable than the year as a whole. The similarity of different growing seasons speaks for the importance and stability of the mountain and valley breezes, as well as for the practical immunity of the station to cyclonic influences which express themselves during the summer in the form of southerly winds. Apparently the least variation is to be expected in the last decade of June, when the influence of insolation is probably the greatest.

It is noted that the period of greatest calm, when the wind drops to an average velocity of 4.1 miles per hour, is at the middle of August, which also represents the climax of the summer rainy period, or at least a period when rains seldom fail. The cloudiness at this season reacts, of course, to retard the convectional flow of the mountain and valley breezes, while the cumulative effects of summer temperatures have doubtless at this time brought about the nearest approach to equilibrium of mountain and valley radiation.

From the middle of August to the end of the year the wind velocities gradually increase without important variation, and the maximum velocities are recorded during the second decade of January. This must be related to the general cosmic conditions. These are "anticyclonic" winds, blowing toward the centers of low-pressure areas, which during the winter almost invariably take a route across the southern portion of the United States. Anticyclonic winds are generally more violent than those in advance of the storm area, and only the anticyclones are of importance at the control station, because cyclonic winds during the winter season are locally opposed to prevailing mountain breezes, which result from higher temperatures on the plains.

Further evidence of the character of the winter winds at Fremont is found in the fact that they suffer a decline during February and are again important in March. In other words, they reach, locally, their greatest strength just before and just after the cyclonic storms have reached their southernmost course, which is normally in February. And they are probably less violent winds in February than in January or March, because the storm centers are farthest away in February. Their more northerly origin in February might be thought to affect their local force at the control station, but when other stations show the same feature this point loses significance.

The important biological fact is, then, that the winds coming during the coldest part of the winter, when practically all mountain soils are frozen, are most violent and incessant of any during the whole year, are dry because they are anticyclonic, and are of an especially injurious character on the eastern slope of the Rocky Mountains, because in descending the slope they increase in temperature and in desiccating power. These winds not only fail to bring moisture with them or to precipitate any on the eastern slope, but they sometimes melt and always evaporate the snow which may have fallen in advance of their occurrence. Vegetation, then, is not only exposed, but the soil is denied the protection of a snow blanket which might retard its freezing, and the soil-building humus of the previous season's accumulation is frequently moved from exposed slopes to easterly slopes or canyon bottoms.

There is not the slightest doubt that this combination of conditions, in which anticyclonic winds are the chief element, comprises a very serious obstacle to forest growth in the Pikes Peak region, and that its analysis in relation to forest types may be of prime importance. Elsewhere along the eastern slope of the Rockies similar conditions may prevail, though it is doubted whether any locality can show such a powerful combination existing as a normal winter condition. Further back from the plains, at higher elevations, and on the western slope of the main range the westerly winter winds combine far less effectually for the destruction of vegetation and soils.

Considering the winter periods during which evaporation, as well as wind movement, has been measured, it is found that evaporation is not always rapid when wind velocities are high. When the mean temperatures are below freezing the amount of evaporation is so strongly influenced by the length of thawing periods that at this season, more perhaps than at others, the temperature may be said to affect the rate of evaporation more strongly than does the wind. In order to show, therefore, that high winds do cause excessive evaporation it is necessary only to show that they do not have a depressing effect on temperatures. This has been done by comparing the wind movements and temperatures for the 78 decades of record during December, January, and February. It has already been shown in Table 2 that the average mean temperature for these three months is essentially uniform. The comparison indicates that with mean wind velocities of 100 miles per day the mean temperature is 23.5°; for velocities of 150 miles, 25.0°; and for velocities of 200 miles, 26.1°. No doubt this power of winter winds to increase the temperature would be much more apparent if individual days were considered, as the decade which witnesses a very strong anticyclone may also cover the cyclone and the very low temperatures which often follow snowfall. It is, however, very certainly the tendency for higher temperatures to accompany the higher wind velocities, even though exceptions to this rule are very numerous.

The important thing is, then, that sometime during each winter wind movements occur which approximate velocities of 10 miles per hour over a period of a decade, and that these winds are always of westerly origin. Such velocities do not appear excessive, and, indeed, examination of the automatic record shows that excessive velocities seldom occur. A maximum of about 27 miles per hour is the highest record that thas been specifically noted, and over a period of 12 or 24 hours an average of 20 miles per hour is unusual. Even excessive movement for a day or two at a time is not likely to induce sufficient evaporation to cause any apparent injury to trees. It is the continuity of these winds that makes them dangerous, and probably the decade is the shortest period that need be considered in this connection.

Only one additional feature of the record need be noted. Although there is a general decline in the average velocities from the end of April to August, there is a somewhat sharp rise at the end of May, continuing into June, which is nearly always associated with lack of precipitation. Whether the dry winds occurring at this season are actually injurious or not depends, no doubt, primarily on the reserve moisture of the soil. On the other hand, if the dryness occurs when the season, so far as temperature is concerned, is well advanced, as in 1917, a day or two of even moderately high winds with a high evaporating rate may have a very noticeable influence. On June 29, 1917, wilting of herbaceous vegetation, in general, and of some new shoots on conifers, was noted, although the soil was by no means dry, and the recorded velocity for the day was only 6.2 miles per hour.

This late spring dry period, with moderately high winds, is especially injurious to newly planted trees, and it may well be concluded that it has an indirect relation to forest types in so far as it tends to preclude the germination of seeds early in the season. It can not be said that any difference in this respect has been noted between different sites and exposures. When the atmosphere is lacking in moisture and is freely circulating, even the most protected situations seem to suffer superficial drying so quickly that germination is postponed until the beginning of the frequent summer rains, usually about July 15. This fact may create special problems in comparing the species in the Pikes Peak region, and it may be said that spring dryness has a bearing on the selection of the species which shall survive through the autumn drought.

Wind movement in the various forest types.—In Table 13 all the available data on wind movements are given. As the stations having this record are relatively few in number, it has not been thought necessary to consider the local stations apart from those lying at a greater distance from the control station, and hence subject to altogether different influences. Neither is it necessary to separate those stations at which the anemometer has been placed a considerable distance above the ground from those at which for a special reason the surface circulation has been measured, although in comparing the results this factor should be kept in mind. Inasmuch as the period of observation is very different for different stations, and at most of them is not over 2 or 3 years in length, the method has been followed throughout of giving the actual mean monthly movement for each station, and the percentage relation which this bears to the movement at the control station for the same period. These percentages might then be related to the "average" movement for the control station, as shown in Table 12, but it is doubted whether this computation would have any additional value. As the matter of primary interest is not wind, but rather its influence on evaporation, the main intent at this stage of the discussion is to show relative wind movements in a rough way only.

TABLE 13.—*Comparative wind movements.*

Station No.	Type.	Locality.	Elevation above ground.	Period of observations.	Datum.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Total annual.	Total growing season.[1]
			Feet.																
C-1	Plains	Pikes Peak	50	Feb. 1, 1910, to Jan. 31, 1918.	Miles	6,014	5,473	6,715	6,166	6,076	5,031	4,378	4,387	4,377	5,255	4,740	5,643	64,255	15,282
					Percent.	111	141	148	166	158	138	133	141	138	146	130	134	139.5	137.3
M-1	Western yellow pine	do	8	Mar. 1, 1915, to July 20, 1918.	Miles	4,018	3,497	3,954	2,862	3,187	2,473	2,204	2,089	2,313	3,055	3,395	4,330	37,375	7,522
					Percent.	83	76	83	80	79	67	66	70	72	79	89	85	78.0	68.1
F-2A	do	do	20	Mar. 1, 1910, to Feb. 29, 1912.	Miles	6,244	3,384	4,093	3,222	3,155	3,076	2,287	2,548	2,434	2,498	4,128	3,123	40,192	8,854
					Percent.	106	91	90	84	80	81	71	79	76	75	95	87	86.1	77.6
F-12	do	do	7	Mar. 4, 1915, to Feb. 29, 1916.	Miles	5,152	2,939	2,052	2,350	2,845	2,868	2,525	1,797	2,509	2,347	4,413	4,406	36,204	7,881
					Percent.	97	83	71	69	77	77	75	63	73	72	92	90	80.1	71.7
F-6	Limber pine	do	1½	Mar. 11, 1915, to Feb. 29, 1916.	Miles	3,330	2,071	2,335	1,406	1,666	1,574	1,360	912	1,167	1,470	3,788	3,793	24,871	4,140
					Percent.	63	58	74	42	45	42	40	31	34	44	83	78	54.8	37.4
F-7-8	Douglas fir (open).	do	1	Apr. 1, 1916, to Mar. 4, 1918.[2]	Miles	715	842	830	452	364	564	308	209	484	423	551	852	19,783	3,728
					Percent.	52	54	53	37	30	43	25	17	43	34	48	50	41.5	30.3
F-9	Douglas fir (uncut).	do	1	do	Miles	1,100	1,167	468	452	612	669	261	224	244	842	553	1,371	7,962	1,225
					Percent.	24	22	9	12	16	18	8	7	8	20	17	26	16.3	10.8
F-14	Douglas fir (half cut).	do	1	do.[3]	Miles	498	576	0	436	295	339	166	100	196	458	265	803	12,396	2,011
					Percent.	38	34	0	31	25	29	16	11	20	33	27	43	26.8	19.3
F-15	do	do	1	do.[4]	Miles	956	720	99	308	582	405	197	209	357	725	545	752	17,566	2,789
					Percent.	48	36	5	33	33	31	17	20	33	46	45	46	33.1	24.1
W-A1	Douglas fir, north.	Rio Grande	5	Nov. 1, 1910, to Aug. 31, 1918.	Miles	1,488	1,447	1,787	1,896	2,167	1,983	1,657	1,544	1,431	1,488	1,370	1,354	19,612	5,661
					Percent.	27	36	38	51	55	55	51	50	45	41	38	32	42.2	51.6
F-3A	Engelmann spruce, canyon.	Pikes Peak	20	Mar. 1, 1910, to Feb. 29, 1912.	Miles	2,742	1,660	2,081	1,788	1,730	1,649	1,256	1,339	1,294	1,359	2,100	1,603	20,601	4,741
					Percent.	46	45	46	47	44	44	39	41	40	41	48	45	44.2	41.5
F-16	Timber line	do	10	Oct. 1, 1916, to Feb. 28, 1918.	Miles	12,933	10,579	11,640	8,324	5,877	6,085	4,459	4,813	5,160	9,924	8,452	15,477	103,722	17,003
					Percent.	278	208	224	230	255	159	129	153	181	237	253	296	216.7	150.0
W-D	Engelmann spruce, burn.	Rio Grande	20	June 1, 1913, to Aug. 31, 1918.	Miles	5,685	4,678	6,069	5,128	5,015	4,387	3,556	3,360	3,562	4,765	4,262	5,034	55,441	12,490
					Percent.	117	102	127	146	128	120	109	109	112	129	123	109	119.0	113.3
F-11	Lodgepole pine.	Southern Wyoming.	6	Mar. 21, 1916, to Sept. 10, 1918.	Miles	4,944	4,965	4,679	3,269	2,998	2,528	2,181	2,146	2,322	3,431	3,338	5,469	42,270	7,611
					Percent.	106	96	93	90	73	69	66	69	76	82	100	105	87.3	68.6

[1] Growing-season totals secured by considering first decade of September only, except stations F-14 and F-15, where the single available record for September is used. Fractional miles in original records throughout rounded off.

[2] First decade of each month only. Annual totals approximated by multiplying decade sums by 3.

[3] Second decade only.

[4] Third decade only.

If an examination is made first of the Colorado Springs station, which may perhaps give a better conception of the wind movements of the region than even the control station, because of the free exposure of the former, it is seen that, for the whole year, the wind movement is much greater than that at the control station, and greater than that of any of the mountain stations, except that at timber line on Pikes Peak. The growing-season total bears almost the same relation to the control station as the total for the whole year. The Plains station has a low ratio to the control station during the early winter months, November to January, which may mean that the location of the control station gives winds at that time a magnified local effect. The Plains station has relatively the highest winds during the spring, probably because it is more susceptible to the winds which blow from all directions toward storm centers during the spring period. Actually, the most severe season on the Plains must be just before the end of winter and before thawing has become general.

The Monument yellow-pine station is only 20 miles from Colorado Springs, but being in the edge of the hills is fairly well protected from north-south currents. This station shows distinctly mountain characteristics, but scarcely more than half the total movement recorded on the Plains. Part of this difference is no doubt due to the elevation of the anemometer, which is barely above the top of the surrounding oak-brush clumps. The relatively high values at this station throughout the entire winter period define the degree of exposure on the west. It is not doubted that, with a similar local exposure of the anemometer, this station would show winter values just about the same as the control station. The evaporation attending such winds would be augmented by the higher temperatures in the pine belt, but their effect on vegetation would be decreased by the shortness of the soil-freezing period.

The local yellow-pine station (F–2) shows no great variation from the control station, such difference as exists being explicable, probably, by the wind-breaking power of the surrounding trees, which run up 30 to 40 feet higher than the anemometer. No doubt the high January ratio at this station was due to the wind blowing from certain directions so that the currents reached the anemometer unbroken. On the whole, it would be best to assume that the exposure, if the trees were not present, would correspond closely to that of the control station.

The record at the yellow-pine ridge station (F–12) is difficult to explain, inasmuch as both the soil of the ridge and the character of the growth thereon are suggestive of the most extreme wind exposure. Indeed, a few isolated days may be found when the velocities of west winds recorded here exceed those at the control station. On the whole, however, the movement is considerably less. The anemometer was placed high enough to be practically free from the influence of the surrounding trees, which are short and widely scattered. The deficit can be accounted for only by the position of the station on a bench of considerable area, which does not directly contribute to and in fact is out of the paths of the local convectional currents, which naturally hug the slopes and valley bottoms. The station can not be considered to represent so severe a wind exposure as the control station; but, if its longer period of soil freezing is considered, it represents, as will be seen later, a closer approach to the limiting conditions for yellow pine.

The west-slope limber pine station (F–6) shows scarcely more than half the movement recorded at the control station. The ratio is very low during the summer months when the prevailing winds are of easterly origin. The values of 74 to 83 per cent during some of the winter months are high, when it is considered that the anemometer was placed only 18 inches above the ground surface in a fairly dense forest. As the strongest winds blow against the face of this slope, this does not indicate any unusual velocities overhead, but it does indicate extremely severe conditions for reproduction.

The four north-slope Douglas fir stations (F–7–8, 9, 14, and 15), differing only in the weight of their forest cover, show clearly the ability of the forest to check surface-air movements. The ratios of each station to the control station are quite irregular, on account of the short periods involved, and because of the fact that during the winter months the anemometers at an elevation of only 1 foot may be completely stopped by accumulated snow. This rarely occurs for more than a short period, but of course may obliterate some of the highest wind movements. On the whole, the movement in the forest is seen to be scarcely more than one-third of that in the open; in the partly-cut forest it is two-thirds. The winter values are the highest, both absolutely and when related to the control station, because this slope is hardly at all sheltered from northwest winds. It is not difficult to believe that the wind that blows over the tops of the trees is here quite as strong as at any similar elevation in the locality.

The local spruce canyon site (F–3) shows much more wind than would be expected, even with the anemometer 20 feet above the ground and well into the tops of the young spruce trees. The ratios of movements here to those at the control station are perhaps more constant than for any other station. This site is scarcely more than 400 feet from the control station, but in a narrow V-shaped canyon bottom, which could not possibly be called "exposed." The fairly good velocities attained here show clearly the importance of the mountain and valley breezes, of which the former particularly is always most noticeable in a canyon bottom. This canyon, moreover, appears to receive its due share of pressure from the stronger west winds of winter.

The timber-line station (F–16) gives a fair impression of the movements in the higher atmosphere. Pikes Peak to the south rises at a sharp angle nearly 3,000 feet higher than this station, and the slope is by no means rounded. The site, however, does not seem to be exempt from the influence of winter winds, although the movement in the summer is relatively moderate. West and northwest winds obtain a perfectly free sweep over all topographic features on that side. The resultant velocities at the station, which is unprotected by any timber, tax the credulity. The January ratio of 278 per cent would mean, when related to the control station averages, a mean velocity of about 20 miles per hour for that month. The following data have been picked from the record of 17 months:

	Velocity, miles per hour.
Highest 10 days, Dec. 11 to 21, 1916	26. 0
Highest 5 days, Dec. 21 to 26, 1916	31. 4
Highest single day, Jan. 27, 1917	42. 0
Highest six hours, Nov. 30, 1917	44. 9
Highest single hour, Dec. 3, 1916	49. 0

It is seen from these special data, as well as from Table 13, that this station, except for the four summer months, is exposed to wind forces more than twice as strong as those at the control station. Hence these winds are strong enough to move snow and soil and actually blast off the exposed portions of trees as with a sand-blast. There is no doubt in the mind of the writer that here the upper limit of timber growth is set by the mechanical effects of the wind and only indirectly by temperature conditions. The spruce and bristlecone pine trees which form the upper fringe of the forest are severely exposed during eight months of the year, and during much of this time they are cut off from soil moisture by the freezing of the ground. Although low temperatures greatly modify the drying power of the violent winds, it will be seen later that these winds are by no means incapacitated for doing damage.

The high spruce station at Wagon Wheel Gap (W–D), though fully exposed in an old burn, shows by no means the wind velocities that have just been described. Its velocities are only a fifth greater than those at the control station, the lowest ratios occurring at midsummer. The immunity to high wind is doubtless characteristic of the vicinity of Wagon Wheel Gap, and not due to any special features of the exposure, for even at an elevation corresponding to F–16 (namely 11,500 feet) no excessive velocities have been recorded, and at 12,000 feet, on the highest ridge of the locality, the evidences of injury from wind are confined to a small flat at the very top, where the movement of snow is most easily accomplished.

Turning now to the Douglas fir station in this locality (W–A1), protected by the walls of a basin which drains to the east, it is seen that the annual movement corresponds closely to that of the fully exposed north-slope station at Fremont (F–7–8), but that the winter velocities of the former are much lower and are counterbalanced by greater movement during the spring and summer. In fact, Station W–A1 is the only one in the list which shows higher velocities in summer than in winter, relative to the control station. Only the winter velocities are of any import. It will later be seen that, in combination with low temperatures but a drier atmosphere, these light winds have considerable power for evaporation; but during the winter months there is less of this influence than is shown at the control station.

Finally, a glimpse may be had of the conditions which characterize the lodgepole forest of southern Wyoming (F–11). This station is only partly exposed and receives a great deal of protection from the forest on the north and west. Hence the relatively high velocities of December and January bespeak a very great disturbance of the atmosphere; and, even though the ratios decline during the latter part of the winter, it is difficult to concede that the exposure of trees is any less severe in this locality than at the control station. During the summer the wind movement might best be compared with that of the yellow pine type at Monument. However, it must be remembered that this lodgepole locality, and every other lodgepole locality which was examined in connection with air temperatures, is characterized by very cold winters, and it will be seen later that, by actual test, this practically nullifies the evaporation at Foxpark.

It should be brought to attention that the data presented in no case refer to wind conditions at the level of the tree top, and that, for the most part, direct comparisons of the sites are only approximate because of the varying elevations of the exposed anemometers. Every such consideration would lead to the belief that the several sites in the vicinity of Fremont would be quite closely comparable as regards total wind movement 40 or 50 feet above the ground, and therefore that the exposure of the growing tops of the trees, the portion most sensitive to desiccating influences, is not essentially different in different sites. The general air movement which characterizes the locality, considered in connection with soil freezing, is probably more important in fixing the types of forest than are the specific velocities which have been measured. On the other hand, high elevations doubtless experience much stronger winds than do the middle elevations; the Plains region, slightly stronger; the Wyoming locality, stronger winter winds; and the Wagon Wheel Gap locality, winter winds of less importance, when like exposures are compared.

ATMOSPHERIC HUMIDITY.

Atmospheric humidity is doubtless of some importance in any ecological study, but nowhere more so than in a study of evergreen trees, which are influenced by evaporation and transpiration during the winter as well as the summer. In this relation, the saturation deficit is a much more valuable criterion than either vapor pressure or relative humidity, as the "deficit" expresses at once the capacity of the atmosphere for additional moisture, without further reference to temperature. In other words, a lack of vapor in the atmosphere, amounting, for example, to 0.100 inch (this being the difference between the actual and possible pressures) should induce about the same rate of evaporation whether the air temperature be 40° or 100°. The greater deficits are, of course, likely to be encountered at high temperatures.

The correct measurement of the moisture of the atmosphere is one of the most difficult which a meteorologist is called upon to perform. It is almost impossible to eliminate the personal element in securing a depression of the wet bulb of the psychrometer, for there is constantly a tendency to fail to secure the greatest possible depression. To make the situation more difficult, there is no hygrograph, or automatic instrument for this purpose, which is at all precise. One is compelled to depend upon such psychrometer readings as can be taken in estimating the mean moisture for whole days or longer periods, and must never forget that even these observations are fallible. In spite of the most conscientious effort in the field, therefore, the humidity data here presented can show only approximate mean conditions.

Although the ultimate interest is in vapor deficits, as related to evaporation, it will be worth while to examine first the absolute-humidity or vapor-pressure data, to determine whether there is any essential difference between adjacent sites other than that induced by variations in air temperature. Even this is difficult to determine, as is realized when one notes the rapid changes in vapor pressure with changes in temperature at a given point. However, as vapor is distributed through the atmosphere very rapidly, local excesses or deficits tend to be nullified. Hence it is to be expected, at least for the several sites immediately adjacent to the Fremont station, that there will be little variation in absolute humidity.

TABLE 14. —*Mean vapor pressures at the control station, from psychrometer readings at 7 and 8 a. m.*

[From table for 21.42 inches barometric pressure prepared by B. C. Kadel, United States Weather Bureau.]

Year.	Decade.	Vapor pressure in inches of mercury.													
		January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Mean annual.	Mean growing season.
1910	1	....	....	[1] 0.1067	[1] 0.1259	0.1460	0.2092	0.2145	0.3007	0.1828	0.1371	0.0939	0.0808	....	....
	2	....	....	.1079	.1320	.1508	.2272	.2572	.2932	.2715	.1454	.1000	.0743	....	....
	3	....	....	[1] .1235	.1870	.2012	.2636	.2920	.2347	.1872	.1038	.0909	.0733	....	....
	Month.	....	....	.1130	.1483	.1671	.2333	.2654	.2749	.2138	.1280	.0949	.0760	....	0.2505
1911	1	[1] 0.0490	0.0529	.0867	0.1269	0.1588	0.1579	0.2896	0.2649	0.2657	0.1842	0.0937	0.0515	....	....
	2	.0866	[1] .0645	.0889	.0912	.1256	.2647	.3279	.3386	.2536	.1315	.0883	.0510	....	....
	3	.0893	.0457	.0942	.1437	.1795	.2373	.2935	.2473	.2258	.1145	.0477	.0348	....	....
	Month.	.0754	.0550	.0901	.1206	.1554	.2199	.3033	.2824	.2484	.1424	.0766	.0454	0.1512	0.2687
1912	1	0.0263	0.0512	0.0848	0.0697	0.1907	0.2493	0.2813	0.3197	0.2035	0.1508	0.0887	0.0455	....	....
	2	.0486	.0582	.0766	.0980	.1617	.2284	.3361	.3198	.1493	.1023	.0681	.0485	....	....
	3	.0425	.0434	.0750	.1099	.2011	.2974	.3779	.2640	.1260	.1113	.0455	.0304	....	....
	Month	.0392	.0512	.0787	.0925	.1850	.2584	.3333	.3000	.1596	.1211	.0674	.0411	0.1140	0.2877
1913	1	0.0412	[1] 0.0437	.0660	0.0793	0.1323	0.2149	[1] 0.3090	[1] 0.2741	0.2817	0.1347	0.0958	0.0749	....	....
	2	.0389	.0548	.0615	.1001	.1366	.2304	[1] .3060	.2434	.1927	.1057	.1109	.0601	....	....
	3	.0515	.0457	.0675	.0983	.2050	.2339	.2368	.2428	.1375	.0904	.0744	.0474	....	....
	Month.	.0441	.0482	.0650	.0926	.1595	.2264	.2824	.2531	.2039	.1093	.0937	.0604	0.1339	0.2573
1914	1	0.0701	....	....	0.1121	0.1515	[2] 0.2145	0.3328	[1] 0.3426	0.3076	0.1420	0.0868	0.0713	....	....
	2	.0801	....	....	.1149	.1895	.2735	.3441	.3021	.2208	.1081	.0569	....	....	....
	3	....	....	....	.1434	.1996	.2163	.3549	.2412	.1500	.1400	.0780	....	....	....
	Month.	.0751	....	....	.1235	.1808	.2348	.3443	.2935	.2261	.1301	.0739	....	....	0.2930
1915	1	....	....	[1] 0.0742	0.1503	0.1336	0.2014	0.2409	0.2724	0.2236	0.1453	0.1147	0.1070	....	....
	2	....	....	.0736	.1516	.1428	.1895	.2667	.2945	.2078	.1470	.0738	.0759	....	....
	3	....	....	.1183	.1824	.1735	.2744	.2860	.2576	.1934	.1169	.0859	.0934	....	....
	Month.	....	....	.0896	.1614	.1507	.2218	.2652	.2743	.2083	.1358	.0915	.0921	....	0.2507

1916	1	0.0898	0.1040	0.0906	.0900	0.0908	0.1661	0.2683	0.2844	0.2243	0.1718	0.0741	0.0645	....	....
	2	.0754	.0824	.0564	.0939	.1393	.1938	.2789	.3022	.1649	.1539	.0656	.0478	....	....
	3	.0942	.0846	.0731	.1306	.1075	.1532	.2770	.2642	.1333	.1045	.0455	.0428	....	....
	Month.	.0867	.0905	.0734	.1048	.1124	.1710	.2748	.2829	.1742	.1421	.0617	.0514	0.1355	0.2412
1917	1	0.0575	0.0640	0.0504	0.0790	0.1260	0.1477	0.2295	0.2513	0.2440	0.1455	0.0628	0.0698	....	....
	2	.0550	.0629	.0612	.1365	.1543	.1692	.2408	.2783	.2110	.0885	.0880	.0779	....	....
	3	.0415	.0696	.0599	.1058	.1685	.1837	.2710	.1895	.1547	.0854	.0758	.0648	....	....
	Month.	.0510	.0652	.0573	.1071	.1502	.1669	.2478	.2381	.2032	.1058	.0755	.0706	0.1282	0.2205
1918	1	0.0700	0.0553	0.0912	0.0901	0.0985	0.1940	0.2950	0.2720	0.2120	....	....	....	....	....
	2	.0536	.0490	.0799	.1094	.0942	.2423	.2872	.2582	.1855	....	....	....	....	....
	3	.0710	.0706	.1090	.1005	.1469	.2576	.2670	.1955	....	....	....	....	....	....
	Month.	.0652	.0574	.0938	.1000	.1143	.2313	.2825	.2404	....	....	....	....	....	0.2481
Average to Sept. 20, 1918	1	0.0577	0.0618	0.0813	0.1026	0.1365	0.1950	0.2768	0.2869	0.2384	0.1514	0.0888	0.0707	....	....
	2	.0626	.0620	.0758	.1204	.1439	.2243	.2939	.2923	.2063	.1228	.0814	.0622	....	....
	3	.0650	.0599	.0901	.1335	.1759	.2353	.2951	.2374	.1635	.1084	.0680	.0553	....	....
	Month.	.0619	.0613	.0826	.1188	.1529	.2182	.2888	.2711	.2027	.1269	.0794	.0625	0.1439	0.2575

[1] Contains element of estimate because of the omission of some of the daily observations.
[2] Beginning of 8 a. m. observations.

Vapor pressures at the control station.—In Table 14 are presented the records of vapor pressures for the control station, by decades, up to September, 1918. These vapor pressures have been computed from a table prepared in 1911 by B. C. Kadel, of the Weather Bureau, for a barometric pressure of 21.42 inches, which is the mean for Wagon Wheel Gap, but slightly below the mean for Fremont.

It will be noted that up to June, 1914, these records pertain to conditions prevailing at 7 a. m., while thereafter the psychrometer readings were taken at 8 a. m. This change has probably had a very slight effect on the values, increasing the later ones by about 0.0050 inch.

As these data are only of indirect interest in the study, their detailed consideration is hardly necessary. However, a few interesting facts from the meteorological standpoint may be noted.

(1) The amount of vapor in the air varies greatly at times from one decade to the next. This is not surprising in view of variations in cloudiness, wind direction and velocity, and other conditions which are related. However, it is surprising to find that different years may vary by a margin as great as 25 per cent. In general, these variations show little relation to mean temperatures; or, if they show any such relation, they indicate that high vapor pressures tend to lower temperatures, rather than that high temperatures permit high humidity. This is more plainly true of growing seasons than of whole years. Some of this variation may be ascribed to changes in observers and to consequent changes in the standard of psychrometer readings.

(2) The seasonal variation, as indicated by the averages for eight years, or indeed by most of the individual years, keeps pace with the rise and fall of temperature, but is to some extent modified by prevailing wind directions and velocities. The highest humidities are recorded in the latter half of July, with the highest temperatures; but the middle of August is likewise a moist period, with low winds and prevailing cloudiness, as previously mentioned.

As humidity readings at other stations in the same locality as the control station have always followed those at the control station by an interval varying from a few minutes to two hours, and as it is proposed to use the 8 a. m. humidity as a measure of the mean humidity for whole days, it is necessary to determine to what extent the humidity varies during the day. In Table 15 the data are given for representative months from March, 1910, to February, 1912, during which time observations were made daily at 7 a. m., 1 p. m., and 7 p. m.

TABLE 15.—*Vapor pressures at the control station at various hours, April, 1910, to January, 1912.*

[Average vapor pressures in inches.]

Hour.	January.	April.	July.	October.	Mean annual.	Increase over pressure at 7 a. m.	
						Amount.	Per cent.
7 a. m.	0.0573	0.1344	0.2844	0.1352	0.1528	....	....
1 p. m.	.0800	.1594	.3128	.1726	.1812	0.0284	19
7 p. m.	.0670	.1393	.3022	.1457	.1636	.0108	7

Table 15 indicates that there is an increase in the vapor pressure, corresponding to the rise in temperature from 7 a. m. to 1 p. m., and amounting on the average to 0.0284 inch, or 0.0047 inch per hour, and that most of the increase has been lost by 7 p. m. There is every reason for supposing that the lowest vapor pressure of the day would be recorded with or shortly following the minimum air temperature, for, if this is lower than the dew point, some of the atmospheric moisture is certain to be precipitated as dew or frost. The humidity at 7 a. m. is, then, probably less than the mean humidity for the day, as the temperature at that hour is slightly below the mean temperature. The 8 a. m. humidity, however, can not miss the mean for the day by a very wide margin.

To estimate the probable increase from 7 a. m. until 1 p. m., at any other station, it is best to use the average figure, 0.0284 inch, representing the whole year; for, though October and January do not agree in the amount of this change, October, 1910, and October, 1911, were by no means uniform in this respect.

Vapor pressures at other stations near the control station.—Stations F–2 and F–3, which are situated only a few hundred feet from the control station, but represent very different sites, were observed daily during the first two years of this project and only a few minutes later than the control station. Hence their humidities are comparable, with little or no correction for time. The variations from the control station, by months, are shown in Table 16.

TABLE 16.—*Departure of vapor pressures at two near-by stations from those at control station, 1910–1912, in inches of mercury.*

[All records obtained 20 feet above ground.]

Station No.	Type.	January.	February.	March.	April.	May.	June.	July.
F-2A.....	Yellow pine, south slope.	−0.0015	−0.0021	−0.0007	−0.0054	−0.0056	−0.0080	−0.0071
F-3A.....	Canyon spruce......	+.0045	+.0031	+.0063	+.0193	−.0036	−.0195	−.0070

Station No.	Type.	August.	September.	October.	November.	December.	Year.	Growing season.[1]
F-2A.....	Yellow pine, south slope.	−0.0097	−0.0085	−0.0158	+0.0007	−0.0008	−0.0053	−0.0082
F-3A.....	Canyon spruce......	−.0186	+.0043	−.0102	−.0005	+.0021	−.0016	−.0158

[1]Based on arithmetic means of 10 decades.

It is indicated that the atmospheric humidity over the south-slope station is always less than at the control station, with the possible exception of November. The same is true of the canyon site which has developed spruce, if the year as a whole is taken; but from December to April this site consistently shows higher humidity than the control station. The amount of excess is generally more than could possibly be accounted for by the difference in time between the observations.

For the growing season at least, it is safe to say that the vapor pressure 20 feet from the ground in the pine stand is less than at the control station, and in the spruce stand less than in the pine. Whether the forest growth has any direct relation to this fact may be seriously questioned. It is believed that marked deficits during the growing season are due simply to the fact that these sites do not feel the effect of the diurnal valley breeze quite so early as the control station, these breezes carrying somewhat more moisture than the local air.

Certain data are given in Table 17 for somewhat more distant stations covering a later period of two years, when observations at the control station were taken at 8 a. m., and those at the outlying stations from one-half to one and one-half hours later, the interval being longer in winter than in summer. At all these outlying stations the psychrometer was swung as close to the ground as possible.

TABLE 17.—*Departure of vapor pressures near the ground, in north-slope Douglas fir type, from those at the control station, in inches of mercury.*

Station No.	Cover condition.	January.	February.	March.	April.	May.	June.	July.
F-7-8	Clear cut	−0.0036	+0.0050	+0.0046	+0.0038	+0.0108	+0.0019	+0.0064
F-14	Half cut	−.0013	−.0014	−.0036	−.0032	+.0055	+.0112	+.0305
F-15	do	−.0027	+.0005	+.0026	−.0028	+.0021	−.0007	+.0243
F-9	Uncut	+.0001	+.0036	+.0013	−.0053	+.0087	+.0041	+.0146
Average		−.0019	+.0019	+.0012	−.0019	+.0068	+.0041	+.0190

Station No.	Cover condition.	August.	September.	October.	November.	December.	Year.	Growing season.[1]
F-7-8	Clear cut	+0.0309	+0.0214	+0.0067	+0.0089	−0.0088	+0.0073	+0.0139
F-14	Half cut	+.0321	+.0060	−.0006	+.0031	−.0081	+.0058	+.0227
F-15	do	+.0065	+.0083	−.0091	+.0082	−.0028	+.0029	+.0099
F-9	Uncut	+.0210	+.0126	+.0026	+.0078	−.0014	+.0058	+.0132
Average		+.0226	+.0121	−.0001	+.0070	−.0053	+.0054	+.0149

[1] Growing-season means computed by adding three times the June, July, and August differences to the September difference and dividing the total by 10.

The great irregularity of the relations indicated by the above data is difficult to account for. It should be understood that humidity at each of the first three stations was measured during different decades of each month; that is, during one decade a month for each station. The record for Station F-9 is complete, and therefore might be compared with the average of the first three stations. However, even this comparison does not help to clarify the results. Every effort was made to eliminate discrepancies by using the same psychrometer at all stations, and by daily reversal of the order of observations. Hence the average time is essentially the same for each of the four stations.

All of the annual differences show higher humidity at these stations than at the control station. The increase in humidity during the morning hours is due to the rise in temperature, or to the setting up of the mountain breeze, or to both. In either case the greatest change is likely to occur in the early part of the day, and especially in summer between 8 and 9 a. m. Hence, the generally higher humidity at these stations, as well as the great excess during the growing season, may be wholly accounted for by the difference in time between these stations and the control station. On the other hand, the variations between the four stations are unaccountable, except on the ground of variations in the amounts of sunlight at the points of observation and of the impossibility of entirely shielding the psychrometer from this influence. Sunlight on the psychrometer has the effect of lessening the wet-bulb depression and thereby making the humidity appear higher than it is.

On the whole, there is no indication that the humidity at these forest stations near the ground is measurably different from that 20 feet above the ground in the open position of the control station.

Vapor pressures in central and southern Colorado.—The control station may now be compared with the only other station in this series for which dependable humidity records are available (Table 18). The stations are at similar elevations, and the record covers nearly seven years. The later time of observations at Wagon Wheel Gap—9 a. m.—should tend to bring out higher vapor pressures than at the control station.

TABLE 18.—*Absolute and comparative humidity at W–A1 (Wagon Wheel Gap north-slope Douglas fir).*

Datum.	January.	February.	March.	April.	May.	June.	July.
Actual 9 a. m. vapor pressure	0.0537	0.0562	0.0734	0.0995	0.1165	0.1849	0.2792
Compared with 8 a. m. at control station	−.0066	−.0050	−.0049	−.0133	−.0345	−.0314	−.0099

Datum.	August.	September.	October.	November.	December.	Year.	Growing season.
Actual 9 a. m. vapor pressure	0.2605	0.1894	0.1149	0.0735	0.0506	0.1294	0.2363
Compared with 8 a. m. at control station	−.0101	−.0140	−.0118	−.0059	−.0118	−.0132	−.0168

The greatest difference between the two localities is seen to exist during May and June, when their temperature difference is least. This great deficit at Wagon Wheel Gap is due to the fact that the rainless period in May or June, or both, is much more marked than it is farther north and corresponds more closely to the conditions in the Southwest.

During other portions of the year the deficit at Wagon Wheel Gap is relatively uniform. It should, however, be pointed out that this deficit may not mean much higher evaporation rates at Wagon Wheel Gap, because the general temperature is here lower than at Fremont. An examination of the different years at Wagon Wheel Gap, which are comparable with whole years at Fremont, shows that the variations from year to year are of almost the same magnitude as those at Fremont, but that the two series are by no means parallel.

Saturation deficits.—The question of humidity in combination with air temperatures may now be considered. It has been stated that the most direct expression for humidity, to bring out the relation of this condition to evaporation and transpiration, is the vapor deficit. In the following tabulation the vapor deficit has been computed by deducting the mean decade vapor pressure, determined by the daily observations at 8 a. m., from the saturation pressure, determined by reference to the mean temperature for the decade. If applied to single days, this method would be far from precise, because the humidity might strongly increase or decrease during a whole day. It is believed, however, that the 10 morning determinations of humidity in a decade give a very close approximation to the true mean humidity, and that the mean temperature is a sufficiently close measure of the mean saturation pressure for the whole decade. Of course, this method would err seriously if the temperature variations in a decade were very great.

TABLE 19.—*Mean saturation deficits at the control station, by decades (based on 8 a. m. vapor pressures and mean air temperatures).*

Year.	Decade.	Saturation deficits, in inches of mercury. January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Mean annual.	Mean growing season.
1910	1	([1])	([1])	[2] 0.1123	[2] 0.0818	0.0998	0.1946	0.2515	0.1859	0.2708	0.2275	0.1481	0.1118		
	2			.1227	.0829	.0977	.2592	.3178	.1812	.1719	.1251	.0736	.0963		
	3			[2] .1095	.0906	.1124	.2073	.2582	.2225	.1691	.1411	.1341	.0411		
	Month.			.1146	.0851	.1036	.2204	.2752	.1974	.2039	.1638	.1186	.0817	0.1564	0.2349
1911	1	[2] 0.0773	0.1044	0.1209	0.0881	0.1381	0.2959	0.1468	0.2384	0.1551	0.1150	0.0643	0.1140		
	2	.1278	[2] .0463	.0807	.0847	.1808	.1403	.1089	.2001	.1420	.0869	.0919	.0278		
	3	.1028	.0213	.0868	.0986	.1420	.2573	.1237	.1356	.1769	.0577	.0691	.0459		
	Month.	.1026	.0599	.0958	.0905	.1532	.2312	.1264	.1896	.1580	.0856	.0751	.0620	0.1192	0.1802
1912	1	0.0735	0.0711	0.0408	0.1368	0.0432	0.1149	0.1646	0.1117	0.2202	0.1207	0.1240	0.0562		
	2	.1025	.0616	.0553	.0569	.0807	.0525	.1251	.1041	.0929	.1493	.1376	.0787		
	3	.1202	.0344	.0454	.0866	.1742	.0908	.0926	.2230	.0846	.0872	.1213	.0750		
	Month.	.0996	.0564	.0471	.0934	.1018	.0861	.1263	.1423	.1326	.1220	.1276	.0701	0.1004	0.1300
1913	1	0.0345	[2] 0.0515	0.0751	0.0935	0.1088	0.0967	[2] 0.2526	[2] 0.2367	0.1448	0.1275	0.1188	0.0494		
	2	.0846	.0613	.0670	.1523	.1646	.1602	[2] .1550	.2540	.1051	.0983	.1284	.0677		
	3	.0921	.0248	.0851	.1336	.1734	.2139	.1702	.2264	.0818	.0840	.0937	.0606		
	Month.	.0711	.0500	.0760	.1265	.1497	.1569	.1919	.2386	.1106	.1026	.1136	.0592	0.1206	0.1910
1914	1	0.1093	([1])	([1])	0.0545	0.1141	0.1741	0.0852	[1] 0.1426	0.1464	0.1574	0.1677	0.0265		
	2	.0942			.0798	.0475	.1365	.1215	.2081	.1764	.1671	.1196	([1])		
	3	([1])			.0712	.1515	.2481	.1063	.1669	.1954	.0965	.1222	([1])		
	Month.	.1018			.0685	.1059	.1862	.1044	.1724	.1727	.1389	.1365			0.1536
1915	1	([1])	([1])	[2] 0.0114	0.0483	0.0491	0.0918	0.1614	0.1241	0.1762	0.1200	0.1453	0.0890		
	2			.0465	.0792	.1304	.1746	.2011	.0893	.1418	.0771	.0601	.0387		
	3			.0316	.0639	.0984	.1026	.1253	.1191	.1193	.2108	.0725	.0272		
	Month.			.0299	.0638	.0928	.1230	.1614	.1111	.1458	.1384	.0926	.0508		0.1366

1916	1	0.0892	0.0257	0.0798	0.0623	0.2006	0.1539	0.2469	0.1985	0.2136	0.1301	0.1547	0.0638	...	...
	2	.0190	.1110	.1975	.1204	.0647	.1929	.1933	.1422	.1308	.0522	.0358	.0475	...	...
	3	.0158	.0594	.1041	.0878	.2361	.3382	.2354	.1098	.1890	.1206	.1046	.0416	...	...
	Month.	.0405	.0655	.1264	.0902	.1694	.2283	.2255	.1488	.1778	.1016	.0983	.0507	0.1269	0.2025
1917	1	0.0928	0.0607	0.0438	0.0679	0.0215	0.1579	0.2262	0.2142	0.2028	0.1751	0.1851	0.0509	...	...
	2	.0339	.0500	.0418	.0492	.1173	.2070	.2304	.1001	.1361	.1585	.1042	.1144	...	...
	3	.0599	.0758	.0949	.0801	.0490	.3291	.2770	.2115	.1784	.0934	.1294	.1399	...	...
	Month.	.0621	.0612	.0614	.0657	.0621	.2313	.2456	.1823	.1724	.1407	.1396	.1029	0.1273	0.2156
1918	1	0.0526	0.0955	0.0960	0.0641	0.1749	0.1957	0.1550	0.2292	0.1120	...	...	...	...	...
	2	.0153	.0662	.1145	.0402	.1945	.2927	.1422	.1866	.1415	...	...	...	...	...
	3	.0226	.1104	.0914	.0989	.1632	.1983	.1970	.2279	...	...	...	...	...	...
	Month.	.0299	.0806	.1003	.0677	.1770	.2289	.1658	.2150	...	...	...	...	...	0.1937
Average to Sept. 20, 1918	1	0.0756	0.0681	0.0725	0.0775	0.1056	0.1639	0.1878	0.1868	0.1824	0.1467	0.1385	0.0702	...	...
	2	.0682	.0611	.0908	.0828	.1198	.1795	.1773	.1629	.1376	.1143	.0939	.0673	...	...
	3	.0689	.0544	.0811	.0901	.1445	.2206	.1762	.1825	.1493	.1114	.1059	.0616	...	...
	Month.	.0708	.0617	.0814	.0835	.1240	.1880	.1803	.1775	.1564	.1237	.1130	.0662	0.1189	0.1820

[1] No observations.
[2] Record not complete and in part estimated.

Another method, which was practiced in compiling the records at Fremont for a number of years, is to compute the saturation deficit directly from each psychrometer reading, using vapor pressure and saturation pressure tables, or a special table in which the saturation deficits are shown directly. This method, however, is probably less precise than the one described above, and gives very different results, because the saturation deficit varies much more widely with changes in temperature than does the vapor pressure. Hence this method is not to be recommended where dependence must be placed on single daily observations at a fixed hour.

The saturation deficit data for the control station up to September, 1918, are given in Table 19.

It will, perhaps, be of interest to note that during the winter months the saturation deficits are of about the same magnitude as vapor pressures for the control station (Table 14) and indicate a relative humidity of about 50 per cent. From April onward, through the growing season, vapor deficits are scarcely more than two-thirds of the magnitude of vapor pressures and indicate relative humidities nearer to 60 per cent. This general change results from the cessation of the strong mountain and anticyclonic winds.

At Wagon Wheel Gap (W–A1) the winter deficits are always of less magnitude than vapor pressures, probably because of the lack of any direct mountain-breeze effects. They are also of less magnitude at all other times, except in May and June, when the relative humidity is 40 or 45 per cent. Thus the dependence of vapor deficits on temperatures as well as on vapor pressures is clearly brought out.

EVAPORATION.

Evaporation observations were begun at the control station and at several other local stations as early as July, 1914. The instrument then in use was the Piche, as modified by the United States Weather Bureau [5] fitted with 10-centimeter glass plates and with 9-centimeter filter papers [6] as a standard. Great difficulty is always experienced in operating these instruments on a basis of daily observations, because of the necessity for frequent adjustments, according to temperature and dryness, to prevent overflowing or drying of the papers. As the capacity of these instruments—40 cubic centimeters—was found to be insufficient for a day's evaporation at midsummer, extra fillings were immediately necessary, and smaller papers were soon adopted. The results were corrected to the standard papers on the basis of the exposed areas of the two kinds.

These observations, unsatisfactory as they seemed at the time, were continued through 1914 and again taken up in April, 1915. During the colder part of this period, to prevent injury to the glass vessels from freezing, various mixtures of alcohol and water were used. It is evident that the alcohol would accelerate losses, and it is equally evident that evaporation of the alcohol would continue freely at temperatures below 32°. Hence this expedient was in nowise satisfactory, even though the mixtures were compared with distilled water to determine relative evaporation rates at temperatures above freezing.

[5] While the modified Piche evaporimeter was employed by the Weather Bureau for a time in comparisons with other instruments, its indications have always been regarded as most untrustworthy.

[6] Schleicher & Shull's No. 595.

An effort on the part of the writer to overcome the difficulties due to the small capacity and fragility of the container, by substituting a larger metal container for the glass tubes, was also unsuccessful, although this instrument was used for several months in 1915 at the control station. The experiment showed at least that the volumetric method with evaporimeters could never be satisfactory for year long observations, because of the very great changes in volume at the freezing point, and for that matter with every change of temperature. Often these volume changes were sufficient entirely to obscure the water loss for a period of several days in cold weather.

As a result of this experience, four types of wick evaporimeters have been devised and tested, in which evaporation losses were determined by weighing. Type 4 has proved so satisfactory under all conditions that an effort has been made to determine the evaporation rates for all stations by means of this instrument. Types 2 and 4 have been described by the present writer (*5*) as have also the fundamental principles on which they are based. Type 2 was put in service in April, 1916, and gave fairly satisfactory records at several stations during that year. It was an objectionable feature of this type that rain and snow were not entirely excluded from the water chamber, although in the so-called "shade" instrument of each pair this was partly accomplished. The records of this instrument are, therefore, preferred to those of the "sun" instrument, which might absorb the precipitation of an area about one-twentieth as great as the exposed wick. The several instruments in use in 1916 were never standardized, but this objection was in part overcome by rotation among the several stations.

The usable evaporation record, then, begins with 1916, and a large part of it has been secured during the years 1919, 1920, and 1921. At one station (F–13), however, where types 2 and 4 were not used for a whole year, it seems advisable to complete the record for 12 months by reference to the data obtained by the use of type 1 instruments. This type will not be described, except to say that its evaporation surface was a cotton wick, fully exposed to the air and sun, in a horizontal plane. Like the Piche and Livingston instruments, it gave relatively too high values for high wind velocities.

Evaporation at the control station.—The evaporation values obtained with instruments of type 2 in 1916 and of type 4 in 1917 to 1921 are not closely comparable because of differences in shape and in the size of the evaporating areas. They are given together in Table 20, however, because the comparative data for two stations are in part dependent on this 1916 record from the type 2 instrument.

Although the evaporation record of Type 4 instruments has been secured only for parts of four years, and the averages by decades and months can not be considered even as close approximations to "normals," still this record is considered very valuable in several respects, viz:

(1) It shows the magnitude of the evaporation factor during the winter months, due primarily to the somewhat warm and dry character of the descending anticyclonic winds. As already suggested, these winds give the Pikes Peak region a peculiar character, and an examination of the other evaporation records shows that no other region studied has winter conditions so severe.

TABLE 20.—*Actual evaporation at the control station.*

Year.	Decade.	Total evaporation in grams per 100 square centimeters surface.												Total year.	Total growing season.
		January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.		
1916	1				[1] 52.9	153.0	101.5	138.5	114.5	135.1	109.4	73.4	67.3		
	2				75.5	32.7	113.0	68.8	65.6	82.9	51.2	30.0	76.3		
	3				52.6	208.9	205.5	84.0	76.1	113.9	86.0	70.2	62.2		
	Month				181.0	394.6	420.0	291.3	256.2	331.9	246.6	173.6	205.8		1,102.6
1917	1	[2] 39.3	39.4	27.7	54.4	24.2	158.8	169.8	199.8	100.4	117.2	68.7	38.7		
	2	24.1	22.6	33.5	46.1	75.9	178.2	207.8	55.3	75.6	122.9	36.5	54.8		
	3	49.4	48.6	69.5	59.7	35.4	274.4	280.2	119.0	111.6	106.4	[3] 66.2	62.1		
	Month	112.8	110.6	130.7	160.2	135.5	611.4	657.8	374.1	287.6	346.5	171.4	155.6	3,254.2	1,743.7
1918	1	[4] 41.5	68.4	110.0	32.6	102.0	114.4	101.1	106.6	47.4					
	2	10.0	53.9	131.1	27.3	120.8	154.1	86.8	96.9	70.9					
	3	41.4	101.2	74.6	67.3	146.9	145.8	129.0	139.3						
	Month	92.9	223.5	315.7	127.2	369.7	414.3	316.9	342.8						1,121.1
1919	1					46.5	62.8	114.0	139.2	103.2	52.5	54.1	58.5		
	2					82.2	126.3	156.6	147.6	57.2	50.4	48.3	43.7		
	3					95.9	146.3	146.2	148.4	95.6	77.8	36.4	68.3		
	Month					224.6	335.4	416.8	435.2	256.0	180.7	138.8	170.5		1,290.6
1920	1	15.1	28.9	26.6	62.1	78.1	100.1	107.2	75.7	58.1	123.6	30.0	45.6		
	2	108.6	35.0	64.4	49.3	54.4	88.6	109.0	74.7	123.6	88.9	38.9	28.9		
	3	59.5	27.8	70.9	45.6	120.9	98.2	137.8	108.0	121.8	38.6	41.5	40.8		
	Month	183.2	91.7	161.9	157.0	253.4	286.9	354.0	258.4	303.5	251.1	110.4	115.3	2,526.8	957.4
1921	1	58.3	25.3	57.2	56.0										
	1	84.1	39.9	88.8	53.0										
	3	27.7	60.9	47.9	72.0										
	Month	170.1	126.1	193.9	181.0										
Average to Apr. 30, 1921 (type 4 only)	1	38.6	40.5	55.4	51.3	62.7	109.0	123.0	130.3	77.3	97.8	50.9	47.6		
	2	56.7	37.8	79.4	43.9	83.3	136.8	140.0	93.6	81.8	87.4	41.2	42.5		
	3	44.5	59.6	65.7	61.2	99.8	166.2	173.3	128.7	109.7	74.3	48.0	57.1		
	Month	139.8	137.9	200.5	156.4	245.8	412.0	436.3	352.6	268.8	259.5	140.1	147.2	2,896.9	1,278.2

[1] Type 2 wick, "shade" only.
[2] Type 4, "sun" only.
[3] Type 4, "shade" only ("sun" instrument out of order).
[4] Average of two "sun" instruments, standardized, most of time after Jan. 1, 1918.

(Type 2, 1916, 189 square centimeters, in cylinders; type 4, 1917–1921, 100 square centimeters, horizontally.)

(2) It indicates the marked differences that are possible between succeeding years and between growing seasons, the latter explaining far more completely than the records of precipitation do, the variations in growth rates of trees from year to year. The growing seasons of 1917 and 1920 are especially to be contrasted.

(3) It gives a basis on which, in the absence of a long-term record, the evaporation may be computed for other years, in order to show more clearly the cyclic character of growing conditions.

If the indicated annual evaporation is reduced to depths, a figure of 28.96 centimeters or 11.4 inches, is found to be the approximate yearly loss. As the normal precipitation is 21.1 inches, the evaporation represents 54 per cent of the precipitation. At a corresponding elevation at Wagon Wheel Gap, streamflow measurements indicate that about 74 per cent of the total precipitation escapes as evaporation from snow, soil, and vegetation. For the 20 months of observation, the measured evaporation is only 25.9 centimeters per year, or only about 47 per cent of the normal precipitation when entirely unaffected by trees. The instrumental measurements, therefore, are evidently conservative. Evaporation records from open pans usually show more evaporation than precipitation in arid climates.

Evaporation record extended by formula.—In a general way the rate of evaporation from any type of evaporimeter or vessel of water is determined by the capacity of the atmosphere for additional vapor, which affects the rate of diffusion from the evaporating surface, and by the rate of wind movement, which not only assists diffusion but may be the principal source of heat for continuing evaporation. If the evaporating surface is well heated by sunshine, however, it may be warmer than the air; the wind will then be not a source of heat but a means for loss. As evaporation is further complicated by other factors, precise formulæ for computing it, even from free-water surfaces, have never been devised. However, for approximate purposes in this study, to obtain a better idea of the relative evaporation for different years, it seems advisable to determine the ratio between the actual evaporation of Type 4 instruments during 1917 and 1918 and the evaporation which may be computed from the wind, humidity, and sunshine data combined in a manner to give the most consistent results. The coefficient so obtained will then be applied to the corresponding atmospheric conditions for other years, to elaborate the evaporation record for the control station.

Admittedly, because the sunshine record does not indicate the intensity of sunlight as determined by its angle of incidence on a horizontal surface, the coefficient should vary according to the elevation of the sun. It has been considered sufficient to calculate C for each month, assuming that the variable atmospheric conditions affecting intensity would probably be fairly well compensated in the records of twenty months.

The formula used, after three other trials, to compute the coefficient for each decade of the 20 months is as follows:

$$C = \frac{E}{(W + VD)\ SS}$$

in which E is the evaporation in cubic centimeters, W the wind movement in total miles for the same period, VD the sum of the daily saturation deficits, in inches, times 1,000; and SS the average minutes of sunshine per day, divided by 10,000.

Conversely, to calculate the rate of evaporation when C has been determined—

$$E = C \times SS(W + VD).$$

As these data are lacking in precise value, it is necessary only to state that the coefficients vary widely for corresponding periods of the year, and that on the average they vary, according to the sun's elevation and other factors, from 0.477 in January to 1.336 in July.

The evaporation computed by decades for all periods of record from March, 1910, to December, 1916, is summarized in Tables 21 and 22, with the actual record since January, 1917. (See fig. 4.)

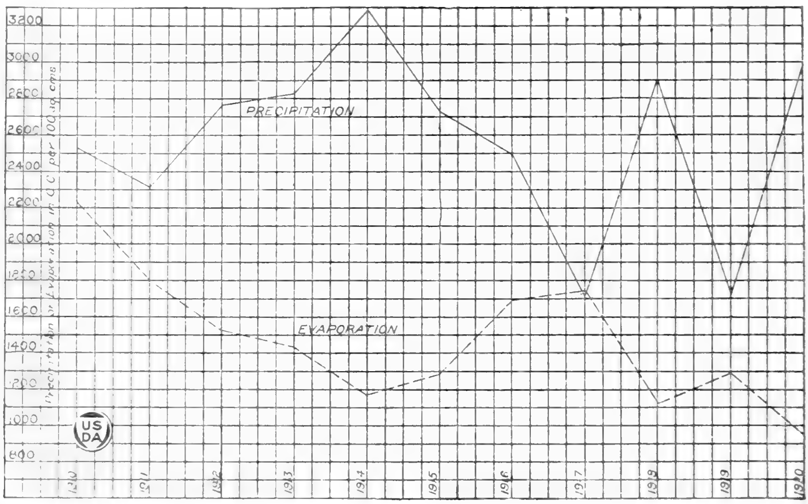

FIG. 4. Variations in the relation between precipitation and evaporation for growing seasons. Control station.

The principal value of Table 21 is that it shows the maximum evaporation that may occur during the winter, the maximum rates at this time being those which may cause injury to trees. On the whole, however, this has little advantage over Table 20, for it is seen that the maxima during the winter do not go to such great extremes, relative to average rates, as, for example, they do during June.

On the other hand, Table 22 brings out certain facts which can not be reached from a consideration of any single climatic condition. In the evaporation data alone it is seen that the variations as between years and growing seasons are much greater than might be expected from a consideration of air temperatures or wind movements, and that saturation deficits (Table 19) are not always fully reflected in the evaporation quantities. In a general way, when precipitation and atmospheric humidity are high, evaporation is low, and vice versa; but as there are some exceptions to this rule, to measure the moisture conditions it is really necessary to establish the ratio between water supply (precipitation) and water loss (evaporation).

TABLE 21.—*Maximum probable evaporation rates as indicated by computed values, March, 1910, to December, 1916; actual evaporation, January, 1917, to April, 1921.*

Decade.	Total evaporation per decade. [Cubic centimeters per 100 square centimeters horizontal surface.]												Year.	Growing season.
	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.		
1	76.9	74.9	110.0	120.3	203.0	346.4	284.5	199.8	237.7	144.8	82.6	58.5		
2	108.6	54.4	131.1	95.6	209.0	291.0	274.9	147.6	129.5	133.5	61.3	54.8		
3	61.7	101.2	97.8	88.3	291.3	316.3	280.2	215.0	121.8	153.0	66.2	68.3		
Month.	199.6	223.5	315.7	298.7	564.3	802.8	826.9	433.7	448.8	358.9	196.1	170.5	4,062.8	2,232.3

TABLE 22.—*Variations in annual and growing-season evaporation and their relation to precipitation.*

[Amounts for an area of 100 square centimeters. Evaporation computed by formula prior to 1917.]

Year.	Annual evaporation.		Precipitation for corresponding year.		Growing-season evaporation.		Growing-season precipitation.	
	Amount.	Variation from average.	Amount.	Ratio to evaporation.	Amount.	Variation from Average.	Amount.	Ratio to evaporation.
	C. c.	*Per cent.*	*C. c.*		*C. c.*	*Per cent.*	*C. c.*	
1910	[1] 4,063	+27	4,704	1.16	2,232	+51	2,530	1.13
1911	3,837	+20	5,002	1.30	1,804	+22	2,315	1.28
1912	3,446	+8	4,990	1.45	1,528	+3	2,763	1.81
1913	2,806	−12	6,740	2.40	1,433	−3	2,828	1.97
1914	[2] 2,934	−8	6,322	2.15	1,174	−21	3,291	2.80
1915	[3] 2,801	−12	5,718	2.04	1,284	−13	2,729	2.12
1916	3,657	+14	4,990	1.36	1,694	+15	2,492	1.47
1917	3,254	+2	4,374	1.34	1,744	+18	1,703	0.98
1918	[4] 3,106	−3	4,995	1.61	1,121	−24	2,902	2.59
1919	[5] 2,752	−14	3,771	1.37	1,291	−13	1,734	1.34
1920	2,527	−21	5,406	2.14	957	−35	2,982	3.12
Average	3,198	±13	5,183	[6] 1.665	1,478	±20	2,570	[7] 1.874

[1] Year from March, 1910, to February, 1911.
[2] Assuming missing periods, January to March, to have been "normal."
[3] Year from March, 1915, to February, 1916.
[4] Year from September 21, 1917, to September 20, 1918.
[5] Year from May, 1919, to April, 1920.
[6] ± 0.100.
[7] ± 0.157.

In point of actual evaporation and relative shortage of precipitation, the year 1910 has probably been the most severe our records have known, followed by 1911, both years having unusually high temperatures and much sunshine. The whole year 1917, with moderate evaporation and lowest precipitation (excepting 1919), was only moderately severe. The year 1913, which was especially deficient in sunshine, seems to have presented the most abundant surplus of moisture.

One may turn with more interest to the growing-season data, and also with more confidence, because here both extremes are found within the period of actual evaporation measurements, and also because no shifting of the period limits is necessary. Here it is seen that the lowest evaporation, that for 1920, is less than 45 per cent of that for 1910, and that the most severe growing season (1917), as shown by the ratio of precipitation to evaporation, is not one in which the evaporation was itself excessive. Although these years are only partly covered by soil-moisture records, it should be noted that the exhaustion of soil moisture was in 1917 more complete than in any other year of which there is knowledge.

On the other hand, it should not be construed that the low evaporation and relatively great precipitation of 1920 constituted particularly favorable growing conditions. The size of rings formed has not been determined, but other evidence points to a very serious deficiency in the growth activity, with a resultant lack of vigor in the new growth of 1921, notwithstanding an unusual abundance of water in 1921.

It would seem that for the region and flora that are being described, an increasing ratio of precipitation to evaporation might be considered favorable until the ratio reaches about 2:1, after which any increase is probably detrimental. This should be definitely determined by a study of the width and structure of rings.

A succession of years such as 1916 and 1917 is evidently a very serious strain on the forest, and probably this period has done more toward weeding out mature trees in the Pikes Peak region than any other set of conditions covered by this series of observations. This has been particularly noted in relation to yellow pine, both in pure stands and where the tree competes with Douglas fir. The yellow pine suffered more than any other species from the unusual drying winds of January and March, 1916. Further weakening through two seasons of drought no doubt gave its natural enemy, the mistletoe, a very decided advantage, and the attacks of this parasite became most evident in 1920 in a very marked deterioration of old trees, wherever mistletoe was at all abundant. As elsewhere pointed out, this loss of yellow pine is giving Douglas fir in many places a decided advantage. These casually observed facts are stated in order to show the importance of unusual conditions in the life of the forest, and the danger arising from short-period comparisons of the conditions in the several forest types. Without doubt this comparison of years, which has been attempted, demands as much consideration in drawing conclusions as any direct comparison of conditions in various forests which it is possible to make.

Relative evaporation rates at other stations.—Prior to 1916 the efforts to measure evaporation continuously were largely unsuccessful, and during 1916 satisfactory instruments were available for only a few stations. In 1917 practically the same line-up was secured with the latest type of instruments. After this trial the number of instruments was greatly increased, and more satisfactory records were secured through calibration of the instruments and through their frequent shifting from one station to another. From March to the cessation of observations in September, 1918, all the local stations were covered, with systematic rotation of instruments among them; hence this portion of the record is very satisfactory. The record was further rounded out from May, 1919, to September, 1920, a special effort being made to cover the winter period at all stations.

As there are no long records for any of the stations that were secured with a single type of instrument, it has seemed best to express the evaporation at an outlying station as a percentage of that for the control station, for each month of record, regardless of the type of instrument currently in use. When, however, the same month has been covered during more than one year, the arithmetic means for the control station and the outlying station have been similarly compared. The ratios for years and growing seasons are based on the mean total amounts of evaporation for the respective periods.

In Table 23 the comparative evaporation rates, so far as any approximate basis will permit, are shown.

TABLE 23.—*Comparative evaporation.*

[Ratios to Station F-1; Type 4 evaporimeters unless otherwise specified.]

Station No.	Type.	Locality.	Height above ground.	Period.	Number months record.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual.[1]	Growing season.[1]
			Feet.			Mean total evaporation, in cubic centimeters.													
F-1	Control	Pikes Peak.	20	Jan., 1917 to Apr., 1921.	45	140	138	200	156	246	412	436	353	269	260	140	147	2,897	1,278
						Comparative evaporation, ratios to F-1.													
H-2	Sandhills	Nebraska	6	May, 1919 to Apr., 1921.	24	0.25	0.57	0.73	0.92	0.81	0.89	0.88	0.88	0.75	0.55	0.36	0.24	0.713	0.888
M-1	Western yellow pine.	Pikes Peak.	5	Feb., 1917 to Apr., 1921.	44	1.02	1.12	1.30	1.26	1.40	1.14	1.12	1.39	1.56	1.20	.89	.99	1.217	1.243
F-2G	do	do	1	Mar., 1918 to Apr., 1920.	19	.67	.88	.79	.76	.95	.87	.81	.86	.95	.81	.64	.79	.795	.852
F-12	do	do	1	Mar., 1918 to Feb., 1920.	17	.58	.80	.73	.83	1.07	.97	.97	.93	.86	.71	.54	.54	.841	.950
F-4	Pine-fir	do	1	Mar., 1918 to Sept. 1920.	24	.31	.42	.49	.71	.61	.70	.76	.65	.83	.54	.30	.34	.602	.724
F-7-8	Douglas fir, clear cut.	do	1	Jan., 1917 to Apr., 1920.	32	.41	.40	.52	.70	.92	.85	.81	.85	.82	.62	.44	.28	.704	.841
F-14	Douglas fir, half cut.	do	1	Jan., 1918 to Apr., 1920.	20	.18	.23	.34	.57	.70	.65	.57	.71	.60	.47	.30	.09	.512	.641
F-15	do	do	1	Jan., 1918 to Feb., 1920.	20	.17	.22	.22	.36	.65	.70	.57	.62	.56	.43	.23	.07	.470	.623
F-9	Douglas fir, uncut.	do	1	Jan., 1917 to Apr., 1920.	32	.14	.17	.14	.30	.38	.36	.30	.39	.29	.24	.27	.21	.292	.345
W-A1[2]	Douglas fir, north.	Rio Grande	5	Aug., 1919 to Mar., 1921.	20	.08	.14	.33	.69	.78	1.20	1.02	.93	.56	.49	.18	.05	.648	1.016
W-B2	South slope, clear cut.	do	5	Aug., 1919 to Mar., 1921.	20	.31	.66	.65	.97	1.68	1.80	1.37	1.20	1.13	.94	.73	.37	1.104	1.423
F-6	Limber pine	Pikes Peak.	1	Mar., 1918 to Sept., 1920.	24	.50	.49	.46	.64	.69	.71	.57	.66	.66	.48	.54	.56	.599	.642
F-13[3]	do	do	5	Sept., 1915 to Sept. 1916.	11	1.94	......	......	1.12	1.22	1.32	1.56	1.08	1.17	1.38	1.26	.91	1.258	1.318
F-11	Lodgepole pine	Southern Wyoming	5	Jan., 1917 to Sept., 1918.	20	.16	.11	.23	.80	.64	.77	.75	.77	.92	.67	.60	.31	.638	.767
F-3G	Engelmann spruce.	Pikes Peak.	1	Mar. 1918 to Apr., 1920.	17	.07	.04	.15	.26	.39	.48	.36	.32	.36	.22	.15	.05	.281	.348
F-5	do	do	1	Mar., 1918 to Sept., 1920.	24	.26	.30	.28	.28	.36	.35	.29	.35	.39	.38	.25	.17	.317	.343
F-16[4]	Timberline	do	10	Oct., 1916 to Aug., 1918.	23	.17	.10	.20	.40	.72	.62	.67	1.09	1.72	1.22	1.01	.30	.773	.843
W-D	High spruce, burn.	Rio Grande	5	Nov. 1919 to Mar., 1921.	17	.46	.74	.52	.52	1.08	1.37	1.54	1.18	1.50	1.18	.49	.41	1.048	1.430

[1] Annual and growing-season mean ratios are algebraic, total quantities being compared with totals for control station in same period.

[2] Value for July estimated from other records obtained near by.

[3] Type 1 September to January; type 2 April to September.

[4] Type 2 in 1916; type 4 later.

Table 23 contains a number of surprises and brings out certain relationships of the types and localities studied, the knowledge of which could hardly have been obtained through the examination of the several conditions affecting evaporation—sunshine, humidity, wind, and temperature. The desirability of a direct measure of evaporation is therefore apparent, and the importance of a method which gives the most probable weight to each of the component factors in evaporation must not be minimized.

One of the first points to be noted is that, with the exception of one or two of the very open situations, the winter ratios for the outlying stations are much lower than the summer ratios to the control station. This is partly due to the effect of cover and to the fact that there is some slope, which may cut off insolation much more completely in winter than in summer. A still more important point is that when the air temperatures are below freezing there can be practically no evaporation without sunlight to thaw the instrument (or, for that matter, the leaf), but, when the air is everywhere warm, insolation is by no means so important a factor. It is well to bear in mind that under very arid conditions shading is by no means a preventive of water losses.

The following observations may be made with regard to conditions of the several forest types:

(1) It is readily seen that, of the yellow pine sites examined, the most severe is by no means the planting site in the Nebraska sandhills, but is found at the foot of the Pikes Peak region (M–1), where the low humidity of the mountains is combined with the relatively high temperatures of the low elevations. The ratio for Station M–1 is uniformly high throughout the year, the depression in November and December not being accounted for by any of the factors which have been more extensively studied. On the other hand, because of the low wind movement and higher humidity, the Nebraska sandhills present a far less severe condition, except during the summer when the temperature contrast is greatest. It is possibly of some significance that the highest relative rate occurs here about September 1. Of the several yellow pine sites examined, that which approaches a condition favorable for Douglas fir (F–4) is seen to be most moderate in its evaporation stresses. The low values denote the influence of shade more than anything else.

(2) The contrast between open and shaded Douglas fir sites is brought out very clearly. Thus the four local north-slope stations show a marked grading down from the clear-cut to the virgin stand, the latter, for the year as a whole, having only two-fifths the evaporation rate of the former. Whether or not the high evaporation rate in the open area is a prohibitive factor for any of the species, there is presented, at a single glance, a striking picture of the changed conditions for reproduction which necessarily follow cutting of the parent forest. Again, in this group a surprise is met with in the high evaporation rate for the Wagon Wheel Gap stations, where, as already shown, the temperatures and wind movements are generally lower than at Fremont, and the vapor pressures markedly lower. Thus at Station W–A1, which probably receives less than half the direct insolation received at the control station, evaporation goes appreciably higher during the early part of the summer but dwindles almost to nothing in the coldest winter months. Where atmospheric

dryness plays such an important part, the contrast between a shaded north-slope site and an open south exposure is far less marked than at Fremont, except for the coldest part of the year.

(3) The high spruce burn at Wagon Wheel Gap (W–D) shows, for the growing season, the highest ratio to the control station of all the stations studied. During the winter months its ratios are relatively much higher than those for the timberline station on Pikes Peak, due no doubt to the fact that the latter receives negligible insolation. It has already been noted that Station W–D shows at all times somewhat greater wind movement than the control station. The importance of this factor, combined with full insolation and acting in the presence of low air temperatures, is plainly shown in the not insignificant evaporation of the winter period.

The very low evaporation rates in the two local spruce stands (F–3 and F–5) reflect the influence both of heavy shade and of the close growth of the stand which reduces the air movement almost to nothing. Here again, however, the potent effect of atmospheric humidity may be observed; for, although the insolation at either station is probably not more than 10 per cent of that received at the control station and the wind velocity is reduced in almost as great proportion, the evaporation is about three-tenths as great as at the control station. It should be noted that at Station F–3, as at the north-slope fir stations, the evaporimeter is sometimes completely covered by snow. This does not occur at Station F–5.

(4) The single lodgepole pine station (F–11) is marked by moderate evaporation at all periods. The winter rate is not excessively low, as the temperatures might suggest, because the wind is at this time a very strong factor.

(5) The local limber pine type (F–6) shows clearly the effects of winter winds which strike the slope very squarely, the winter evaporation rates being among the highest notwithstanding the lack of sunlight on this northwest slope. The higher limber pine site (F–13), which has been depicted as presenting nearly timberline conditions, is, so far as the available record can be depended upon, even more severe in winter than is the actual timberline site, the former being considerably warmer and better insolated.

(6) If the three major types are compared, for which the data are adequate, it is seen that, with anything like normal cover, there is a decided tendency for the evaporation rate to grade down from pine to Douglas fir and from the latter to spruce. This decrease accompanies the decreasing temperatures which are characteristic of the types. It is undoubtedly augmented by the reduction of insolation due to increasingly dense stands in the higher zones. Although free air movement evidently increases generally with increase in elevation, the greater density of the stands tends to nullify any effect from this source.

It may, then, safely be said that the typical conditions for the reproduction of the species are evidently less severe, as regards the tendency toward evaporation, in the spruce than in the fir or pine types. This statement is not in the least weakened by the fact that in very open situations there is practically as much evaporation in one zone as in another, as is evidenced by comparing Station M–1 with the control station, or Station W–B2 with Station W–D. It is known that in these very open situations the reproduction is never abundant and often is not typical of the climax forest. In the Pikes Peak region there is a strong tendency for limber pine to invade every open site; in the Wagon Wheel Gap region bristlecone pine is the pioneer.

Although, then, it may be seriously questioned whether the evaporation stress is the controlling or limiting condition in many instances, still there can be little doubt that this measurement, sensitive as it is to every atmospheric condition, gives an extremely convenient and valuable index to site conditions, and particularly as it reflects in a simple term the general temperature and sunlight conditions.

The evaporation measure seems particularly useful in expressing the broader differences between regions. Thus, only a confused picture of the Nebraska sandhills is obtained by determining that the temperatures are higher, the humidity higher, the wind movement lower, and the sunshine (this is said for illustrative purposes only) less than at the control station. Orientation is, however, immediately possible when it is found that all these differences are algebraically summed up in less evaporation in Nebraska. When this result is considered in connection with each of the individual factors, the phenomena of tree growth become very clear.

On the other hand, the high evaporation rates which are found at the Wagon Wheel Gap stations, in comparison with the control station, demand an explanation. If the evaporation rate has any direct bearing on the choice of species, how is it that unity evaporation gives essentially the same result in the one locality (compare Stations F–9 and W–A1) as three units of growing-season evaporation in the other? It should be noted that even the highest rate recorded in these data is probably not excessive for established vegetation; with a reasonable water supply, the highest rate may, possibly, represent the most favorable and not the least favorable growing conditions. As the high rate in the Wagon Wheel Gap locality is induced primarily by a dry atmosphere, which represents a normal condition, it seems probable that that region is not, in the long run, subject to any more extreme maxima than the Pikes Peak region, where sunshine, humidity, and temperatures suffer greater fluctuations from year to year. This can be certainly determined only by much longer study.

It seems, therefore, that, if evaporation rates bear directly on the composition of forest types, this can be determined in only two ways. It may be determined by a more intensive study of evaporation rates as they affect young seedlings, in close correlation with the determination of the moisture supplies of those seedlings. This points to the same situation that has been reached in the study of air temperatures and soil temperatures, namely that the conditions which must be critical in the early establishment of forest trees are special, perhaps short-term, conditions, and are not covered by these general comparisons.

On the other hand, if evaporation is measured as in these tests but through a longer term of years, it is probable that extreme conditions in the various forest types, particularly for the more widely separated localities, will be brought to light, which, although not necessarily constituting criteria of the resistance of the species, will give a better conception of the relative stresses which each species is compelled to tolerate before it can come fully into possession of the site. To attempt now to compare the extreme conditions in the various types on the basis of records for only two or three growing seasons, does not promise fruitful results. Even the somewhat serious drought conditions presented in the late growing season of 1917 can not be used in this manner, as there were at that time only a few evaporimeters in operation, and no special observations on the mortality of seedlings were made. It is probable that the soil-moisture conditions to be discussed later, are more significant in this connection than any evaporation rates could possibly be.

There is, however, in the whole region under discussion an annual drought which is absolute, and which results from the freezing of the soil. As the duration of this freezing is so different in the different forest types, it has always seemed probable that this drought period might have a very direct bearing on seedling establishment. It may be said at this point that a consideration of the possibilities of winter drying does not materially alter the conception of the relative positions of the types, except in showing that typical warm yellow pine sites are least liable to winter drying. On the other hand, the evaporation at this season still further emphasizes the severity of any strictly open site. The high evaporation rate which seems characteristic of the Rio Grande region does not seem to be at all compensated for by a warmer soil; in fact, the period of freezing there is a little longer than at Fremont.

It has seemed desirable to discuss this evaporation problem somewhat carefully, and to accept the comparative data cautiously, because of the dual rôle which evaporation plays, or, to be more specific, because of the double function of the evaporation rate as a measure of growing conditions. It is evident that loss of water by the plant is rarely, if ever, advantageous per se, yet that it is inevitable if the plant is to enjoy the benefits of light and is to be able to absorb carbon dioxide. A good rate of evaporation in the growing season may, therefore, indicate the optimum growing conditions, in other respects, for the more light-demanding and heat-demanding of the plants. Likewise, a relatively lower rate is likely to accompany the light and temperature conditions which are best for the less demanding or more "tolerant" plants. Therefore, although there may be little hesitancy in declaring the facts as to evaporation to be so and so with respect to the several forest types, there is hesitation about saying that these facts indicate anything as to the ability of the species to withstand evaporation or to balance it with equal intake. This, of course, is the point on which information is most needed, that of the drought-resisting relations.

It is greatly to be regretted that, because of their use of a different atmometer, comparison can not be made with the evaporation records of Pearson (*19*), Shreve (*21*), Weaver (*23*), and others. A broader comparison would be valuable in indicating the importance or the probable lack of importance of absolute evaporation rates. It is to be noted, however, that the results obtained by these investigators are uniformly in agreement with the results described in this paper, namely, that the evaporation rate is always highest in the more open situations and in the most xerophytic plant types. Further, those authors lay considerable stress on the probability that high evaporation directly drives out the more mesophytic plants.

SOIL TEMPERATURES.

Before the initiation of this project it had been observed that the surface temperature of sandy soils in Nebraska might be high enough at midday to injure young planted trees of yellow pine and jack pine and that they apparently had the effect of drying the lightly protected stems just at the root collar. It was also thought, after observation of the vegetational difference between north and south exposures in the Rocky Mountain region, that soil temperatures might express more fully than any other measure the cause of this difference, which results primarily from the amounts of insolation received. In the preliminary report (*3*) on this project, soil temperatures were considered only as climatic elements expressing the possible length of the growing seasons. There is still much doubt among ecologists as to whether these temperatures have the greater significance in connection with climatic or with soil conditions; but it is now evident that a complete separation of the two sets of conditions is out of the question, and that soil temperatures form an important link between them. That they have been looked upon as results of rather than features of the weather conditions is indicated by the fact that the Weather Bureau has never recorded soil temperatures on an extensive scale except in connection with a few special studies, such as the study of streamflow now being conducted at Wagon Wheel Gap, Colo.

The factors influencing soil temperatures, at a given time and place, have been investigated, notably by Bouyoucos (*7*). The Wyoming Agricultural Experiment Station has for a few years recorded soil temperatures at Laramie. A great many other records have no doubt been obtained, but nothing comparable to the great organized mass of air temperature records. During the last four years the Ecological Society of America has lent its influence to the organization of a more or less complete soil-temperature survey of the United States; and as a great many competent observers have thus become interested in the subject it is to be hoped that comparable data will soon be available for different regions.

Pearson (*17*), in his study of the yellow-pine forest and parks, made comparative observations for only four months, July to October, during which time, at a depth of 2 feet, he found the forest soil to be 5.1 degrees cooler than the open park. In February, 1913, he also made some examinations which are of interest here. The day was warm, and all snow had been melted by the direct and reflected light on the south side of a pine tree, while on the north side, and in an opening, the snow cover was from 6 to 8 inches deep. In the first position there was no trace of frost in the soil; in the second it extended down 13½ inches, and in the open park 23 inches. This single observation, whose general import is indicated by data to be presented, is of principal interest in showing the conditions which young seedlings must contend with before the forest is established; for Pearson (*16*) has also shown that seedlings in the pine type are compelled by summer heat and drought to adhere very closely to the shaded spots. In a later report Pearson (*19*) has given more complete data for all of the forest types, and these will later be compared with the data of the present investigation.

Shreve (*21*), in his study of mountain vegetation, has given only slight attention to soil temperatures. The few records of minima which were obtained seem to have no bearing on the present study.

Larsen (*13*), in his companion report on the types of Idaho and vicinity, gives the results of systematic soil-temperature observations, at depths of ½, 1, and 2 feet, extending over a period of several years. One of the most interesting features of these data is that the soil of the white pine type, in the vicinity of the Priest River Forest Experiment Station, which occupies a northeast slope that is almost without insolation for several months, barely freezes to a depth of one foot. This is apparently due to the fact that early snows are retained, the winter blanket becomes very heavy, and radiation is so checked that much of the summer heat is retained. (See Bouyoucos (*8*).)

It will be shown that lodgepole pine, in its optimum environment, is similarly protected. It appears to be of great significance that western white pine, perhaps the nearest relative of any of the eastern conifers attaining a good development in the Rocky Mountain region, does so under very low atmospheric temperatures, but with the resultant protection of a high relative humidity, and with its moisture supply probably never completely cut off by the freezing of the soil. A southwest slope, also in the vicinity of the Priest River Forest Experiment Station, shows about the same soil minimum at 12 inches; but its mean temperature for the whole "rest period" is 3.3° F. higher than that of the northeast slope, and for the entire year 4.6° higher. In neither place does the soil freeze to a depth of 24 inches. This southwest slope, occupied by western yellow pine and Douglas fir, shows a mean annual temperature at 12 inches depth of 47.9° F., and a January temperature of 34.1°, both of which are 3.1° higher than the corresponding temperatures at Fremont (Station F-2). The midwinter air temperatures, however, are lower in the Idaho region.

Special conditions affecting soil temperatures in this study.—Soil temperatures have been observed at each of the special stations for this study, including Monument and Foxpark, practically during the entire period of the operation of the stations. In addition they have been recorded at each of the meteorological stations at Wagon Wheel Gap, three of which are mentioned in this phase of the study. A few scattered observations taken in connection with other projects will also be called into use. For the most part these were made without any special preparation, that is, a thermometer was simply inserted into a hole of the desired depth and protected from direct air circulation. These observations are mainly for a depth of 12 inches.

Prior to 1914 the three stations under observation at Fremont were equipped with 1 and 2 foot soil thermometers. In 1914 it was decided that the 2-foot depth had no individual significance, and with the installation of several new stations the new ones and the older ones were equipped for readings at 1 and 4 feet. This arrangement has been standard since 1914.

The stations at Wagon Wheel Gap were at first equipped with 1-foot thermometers only. During 1913, 4-foot thermometers were added at all stations then in operation and the standard equipment was placed at stations established in the fall of that year. The 1-foot thermometers have been in wooden tubes a greater part of the time. The Foxpark station had 1 and 2 foot thermometers from 1914 to April, 1916. The 4-foot thermometer was placed when more extensive observations were begun in 1916. Local Station F-13 (limber pine) had only 1 and 2 foot thermometers during the period of its operation, because of the impenetrable soil encountered below a depth of 2 feet. Little use has been found for the temperature records for a depth of 2 feet, but they will be mentioned where they appear to give additional information of value.

For the most part, soil thermometers have been placed in iron pipes. Standard 1-inch galvanized pipe has always been used, the lower end being sealed either by a threaded cap or by welding. The practical advantages of this arrangement over any other type of tube, or over long-stemmed thermometers which may be read without moving, are obvious—namely, durability, dryness, convenience, and cheapness. In fact, temperatures at a depth of 4 feet can hardly be measured in any other way. The exposed end of the pipe is capped, the suspending cord for the thermometer being sealed to the inside of the cap. The standard Weather Bureau "mercurial thermometer," Fahrenheit scale, with cylindrical bulb, has been used mainly. To prevent any immediate change when the thermometer is raised for reading, the bulb is inserted in a cork or a vial of alcohol. The cork is a good non-conductor and serves as a cushion when the thermometer is placed at the bottom of the pipe. There is no doubt as to the accuracy of the readings at 4 feet when obtained in this way, since, with the bulb protected, no change in the mercury is noted for 20 to 30 seconds, as a general rule, while the reading may be taken in 3 to 5 seconds after removal of the thermometer from its seat.

It is, however, greatly to be regretted that in the soil-temperature observations at a depth of 1 foot iron pipes have been used, since at this depth these introduce an avoidable error into the temperatures recorded. The technical problems encountered in measuring soil temperatures have been discussed in detail in Research Methods (*24*), but for the sake of clarity it is desirable to explain the influence of the iron pipe on the temperature records here presented. The iron pipe is a good conductor of heat, and, especially if the exposed portion becomes insolated, may conduct heat to a depth of 1 foot more rapidly than would the soil itself. Likewise, at night, the pipe may carry away heat to the air which is cooler than the soil. The soil thermometer in an iron pipe, therefore, goes through a greater daily range than the soil itself. For the well-insolated control station, in September, at a depth of 1 foot, the range in the iron pipe was found to be 7.93°, as compared with 3.41° in a wooden tube, in which the temperatures always corresponded closely to those of the soil itself.

It is not admitted, however, that the use of iron pipes has any appreciable influence on temperatures recorded at a depth of 4 feet; in view of the very gradual changes in such temperatures and the absence of appreciable daily oscillations, it is evident that the usual morning observations give a satisfactory basis for calculating mean temperatures. Also, this influence of the iron pipe is probably, in the long run, completely balanced; that is, the mean temperature in the iron pipe would be the same as in the soil proper, because absorption and radiation by the pipe must be just about equal. The pipe would, however, raise the temperatures in spring and summer, and lower them in fall and winter—the general cooling period. Even this is relatively unimportant, compared with its effect on the single daily temperature recorded. The great number of soil-temperature observations in this study have been made between 8 and

10 a.m., and a few as early as 7 a.m. The minimum soil temperature occurs usually several hours later than the minimum air temperature, but for most sites it occurs some time between 8 a.m. and noon. It is, therefore, readily seen that the tendency has been to record, for 1-foot temperatures, the minima rather than the mean temperatures for the days of record. The conductivity of the iron pipe has an influence in making these minima lower than they actually were in the soil, unless the insolation of the current day has proceeded long enough to be felt at the base of the pipe, as, for example, on an easterly exposure.

The mean temperature of the soil of a given site may be almost constantly either higher or lower than the mean air temperature, depending on the amount of insolation received. The air temperature in a large measure reflects the average soil temperature of all the sites in a region of considerable extent. According to Moore (*15*), however, the more or less constant difference between the temperatures of sites in the same locality disappears when great depths are considered. Indeed, it is sometimes said that at a depth of about 50 feet the soil temperature does not change and is, at any time, an accurate index to the mean annual air temperatures above.

At a depth of 4 feet the soil temperatures, although not subject to rapid changes, appear to show in their year-long values the amount and effectiveness of the insolation received locally. It is, therefore, believed that a comparison of the 1-foot and 4-foot temperatures for entire years is the simplest means of determining the probable extent to which the factors mentioned above—that is, the use of iron pipes and the prevalence of morning observations—have tended to give values for the 1-foot depth lower than the true means.

Table 24 shows the probable mean error in the 1-foot soil temperatures as determined by comparison with the 4-foot temperatures for corresponding periods. It must be recognized that the mean corrections so indicated are not equally applicable at all seasons, and may not be absolutely right, even though relatively so for the several stations. It should be noted also that the periods of comparison here considered are not identical with those for which the average temperatures for each station and depth have been computed.

TABLE 24.—*Probable mean error in 1-foot soil temperatures.*

[Determined by comparison with 4-foot temperatures for corresponding periods.]

Station.	Probable depression of temperature in pipe below the mean, at hour of observation.	Station.	Probable depression of temperature in pipe below the mean, at hour of observation.
	° *F.*		° *F.*
F-1	[1] 2.92	F-13	No data.
F-2	1.01	F-14	1.11
F-3	0.71	F-15	0.97
F-4	0.34	F-16	1.38
F-5	1.40	H-2	1.05
F-6	1.17	M-1	0.64
F-7-8	1.10	W-A1	0.38
F-9	0.94	W-A2	[2] 3.16
F-11	1.19	W-D	0.05
F-12	0.78	W-F	0.34

[1] 1916-17 only. [2] 1914-1917.

All other stations in the Pikes Peak locality should be subject to less error than the control station, both because nearly all are better protected from direct insolation and radiation, and because the observations have been taken at later hours, when, ordinarily, the minimum temperature in the iron pipe will have been passed. Both the time and the amount of insolation, however, are probably important in determining the amount of the depression at the observation hour.

One of the Wagon Wheel Gap stations (WA–1), which has a telethermoscope for its 1-foot temperatures, should have no error in the 9 a. m. readings, but these may be lower than the mean temperatures. The corresponding south-slope station (A–2), although its thermometer has always been in a wooden tube, is subject to full radiation and insolation all the year, but this is not received until late in the day, which probably accounts for the low 1-foot temperatures at 9 a. m. However, in illustration of the variability of this correction with season and time of insolation, it should be mentioned that at midsummer the 9 a. m. temperatures were found to be about 0.9° F. above the daily means, while in the winter they must be several degrees below the means. The data for the high spruce stations should be fairly close to true mean temperatures, because their readings have been taken about midday. As the Foxpark and Monument stations have been regularly visited at 8 a. m. or earlier, practically minimum temperatures in the iron pipes may be expected, except that the Monument station, like Station F–4, may receive insolation very early. The sandhills station (H–2) has had only a wooden tube at its 1-foot depth, and is on a northerly slope, both of which factors would tend toward low corrections.

Seasonal soil temperatures at the control station.—In Tables 25 and 26 are presented the results of soil-temperature observations at the control station, by 10-day periods up to 1918, for the 1, 2, and 4 foot depths. Although considerable data have been added at this and other stations since 1918, it is not felt to be necessary to extend the averages; moreover, the use of such data would further complicate the problem of accounting for the 1-foot depressions as described above, since at a number of the stations wooden tubes have been substituted for iron pipes in this later period.

The following points are noteworthy:

(1) The mean soil temperature for 1 foot is 3.1° higher than the mean air temperature for this station, and 6° higher if the correction indicated by Table 24 is used. For 2 feet it is 5.4° higher and for 4 feet it is 5.7° higher, only corresponding periods being compared.

(2) In the six years that have practically complete records, the 1-foot annual mean temperature shows an average variation from the normal of 1.07°. The first two years of observation were doubtless warmer than any since that time, although 1914 had a very warm growing season, and may have been on the whole as warm as 1911.

(3) The greatest variation between corresponding decades occurs about the 1st of June, when it amounts to an average for nine years of 3.16°. This is on account of the effectiveness of insolation at this time, and because of the fact that in some years the soil may be very dry by June 1; but in other years snows may be occurring at this time.

(4) The least variation in corresponding decades is found at the end of the growing season, the first decade of September showing an

TABLE 25.—*Mean soil temperatures at the control station (F–1)—1 foot.*

Year.	Decade.	January.	February.	March.	April.	May.	June	July.	August.	September.	October.	November.	December.	Mean annual.	Growing season.
1910	1	.....	.....	32.44	39.12	43.02	55.94	58.48	56.91	57.73	52.14	41.29	34.07	.....	.....
	2	.....	28.01	34.65	39.04	44.50	57.88	60.01	56.53	57.91	49.39	38.62	32.83	.....	.....
	3	.....	29.80	40.25	43.42	47.25	60.77	61.11	56.29	52.89	41.52	37.75	28.60	.....	.....
	Month.	(1)	28.90	35.93	40.53	45.00	58.20	59.91	56.57	56.18	47.48	39.22	31.73	43.96	58.16
1911	1	26.38	34.01	32.35	38.34	43.75	56.04	56.33	59.57	53.43	50.05	35.10	30.64	.....	.....
	2	32.12	33.68	34.02	37.42	49.78	56.87	56.45	59.88	55.74	46.78	35.67	28.04	.....	.....
	3	33.59	30.59	35.06	41.09	49.25	57.77	54.88	52.83	55.13	38.79	31.38	27.99	.....	.....
	Month.	30.79	32.92	33.85	38.95	47.65	56.89	55.85	57.28	54.77	45.00	34.05	28.86	43.07	56.40
1912	1	23.29	27.68	28.90	35.20	40.23	49.93	56.23	55.90	57.11	44.79	35.77	30.97	.....	.....
	2	27.08	29.08	31.55	35.75	37.33	45.68	57.39	56.42	52.81	42.74	35.35	29.29	.....	.....
	3	30.05	27.48	32.02	35.11	51.25	50.25	56.79	58.15	43.56	40.19	33.16	23.62	.....	.....
	Month.	26.91	28.10	30.86	35.35	43.20	48.62	56.80	56.86	51.16	42.49	34.76	27.82	40.24	54.38
1913	1	25.61	26.80	29.88	35.72	42.91	50.46	62.49	61.12	56.55	45.41	37.47	33.51	.....	.....
	2	25.53	29.20	31.93	36.83	45.59	49.91	61.61	58.47	50.19	42.52	37.83	32.98	.....	.....
	3	26.46	29.69	32.07	39.76	51.05	54.68	55.75	57.36	44.19	39.15	34.92	31.98	.....	.....
	Month.	25.89	28.48	31.32	37.44	46.67	51.68	59.81	58.93	50.31	42.26	36.74	32.80	41.86	56.84
1914	1	32.04	.....	.....	36.00	38.72	53.08	56.35	56.96	58.21	52.79	40.11	32.62	.....	.....
	2	31.76	.....	.....	35.02	42.81	55.54	57.83	58.94	56.78	46.77	36.70	.....	.....	.....
	3	.....	.....	32.69	38.74	48.89	61.10	57.42	55.26	55.27	41.95	35.24	.....	.....	.....
	Month.	.....	.....	.....	36.58	43.65	56.57	57.21	56.99	56.75	47.00	37.35	.....	.....	57.07
1915	1	.....	.....	27.53	32.83	37.72	44.35	54.93	53.23	55.65	43.81	44.33	33.05	.....	.....
	2	.....	.....	29.45	37.27	45.20	52.22	60.81	52.10	53.66	40.34	34.97	31.08	.....	.....
	3	.....	.....	31.51	39.39	43.43	53.52	54.70	52.19	51.33	43.15	36.38	30.33	.....	.....
	Month.	.....	.....	29.50	36.50	42.16	50.03	56.75	52.50	53.55	42.45	38.56	31.38	.....	53.37
1916	1	30.60	26.71	34.00	34.65	41.01	53.03	62.19	56.52	56.05	50.91	39.63	32.61	.....	.....
	2	27.31	32.09	39.91	36.78	43.13	54.09	56.67	56.04	47.63	42.71	31.40	25.37	.....	.....
	3	28.43	32.87	39.74	39.44	46.64	57.70	60.24	52.57	50.48	38.72	31.05	20.68	.....	.....
	Month.	28.77	30.48	37.94	36.96	43.69	54.94	59.72	54.94	51.39	43.94	34.03	26.04	41.90	56.51
1917	1	27.55	27.05	27.53	33.30	35.27	42.25	58.03	59.57	53.71	49.39	39.17	31.64	.....	.....
	2	24.92	28.37	27.18	34.96	39.42	53.12	59.79	52.93	50.79	46.71	35.80	30.96	.....	.....
	3	24.96	30.47	32.39	38.20	38.84	58.73	62.10	51.57	47.87	39.91	34.99	33.83	.....	.....
	Month.	25.78	28.50	29.14	35.49	37.88	51.37	60.04	54.59	50.79	45.16	36.65	32.20	40.63	55.18
1918	1	31.96	27.33	[2]35.29	36.72	44.06	50.70	59.07	59.18	54.07	.....	.....	.....	.....	.....
	2	24.29	28.50	37.33	36.61	46.50	58.24	57.50	57.09	50.44	.....	.....	.....	.....	.....
	3	24.45	34.30	37.95	37.13	50.35	57.58	57.62	58.75	.....	.....	.....	.....	.....	.....
	Month.	26.82	29.58	36.89	36.82	47.08	55.51	58.05	58.35	.....	.....	.....	.....	.....	56.98
Average to July 10, 1918	1	28.20	28.26	30.99	35.76	40.74	50.64	58.23	57.47	56.06	48.66	39.11	32.39	.....	.....
	2	27.57	29.85	33.26	36.63	43.81	53.73	58.73	56.41	53.19	44.74	35.79	30.08	.....	.....
	3	27.99	30.74	34.85	39.14	47.44	56.90	57.87	54.53	50.09	40.42	34.36	28.15	.....	.....
	Month.	27.92	29.54	33.09	37.18	44.11	53.76	58.26	56.08	53.11	44.47	36.42	30.14	42.01	56.06

[1] January assumed to be normal. [2] Began using wooden tube.

average variation for eight years of only 1.34°. From this time on, the variation is somewhat greater, owing to the uncertainty of the snow cover; but the variation decreases somewhat at the end of the winter.

(5) The eight growing seasons for which complete records at 1 foot are available show a slightly greater variation—1.24°—than the six whole years; but the six growing seasons corresponding to the six whole years show practically the same variation, 1.04°.

(6) The annual oscillation of soil temperatures, as determined from the decade means, is for 1 foot 31.4°, and for 4 feet 22.7°; but the corresponding oscillation of air temperatures is 35.9°, this greater oscillation of the air being due to winter depression when the soil is more or less blanketed with snow. The lowest average soil temperatures occur in the second decade of January, while the lowest mean

TABLE 26.—*Mean soil temperatures at the control station (F–1)—2 and 4 feet.*

Year.	Decade.	January.	February.	March.	April.	May.	June	July.	August.	September.	October.	November.	December.	Mean annual.	Growing season.
	1	.....	.....	31.98	40.51	44.47	55.25	59.27	59.07	59.22	55.53	45.92	38.54	.....	.....
	2	.....	30.64	34.82	40.20	46.18	57.59	60.24	58.28	59.62	54.03	43.37	37.04	.....	.....
1910	3	.....	30.93	40.83	43.64	47.53	60.72	62.01	58.44	56.55	47.33	41.44	33.94	.....	.....
	Month.	(1)	30.75	36.04	41.25	46.11	57.85	60.55	58.59	58.46	52.14	43.58	36.42	46.10	59.01
	1	31.21	36.68	33.70	40.27	44.74	55.47	58.29	60.67	56.85	55.37	40.49	34.37	.....	.....
	2	32.96	35.77	35.90	39.58	50.59	58.03	58.43	61.51	58.60	52.45	39.99	33.11	.....	.....
1911	3	34.80	33.83	36.85	42.83	50.85	58.41	57.33	57.07	58.04	45.22	37.81	32.19	.....	.....
	Month.	33.05	35.54	35.53	40.89	48.80	57.30	57.99	59.66	57.83	50.83	39.43	33.19	45.84	58.21
	1	29.62	31.27	30.86	35.82	41.66	51.94	56.52	58.31	59.92	48.83	39.93	34.52	.....	.....
	2	30.23	31.54	31.80	38.10	39.14	48.61	58.22	58.09	54.18	47.15	38.91	33.05	.....	.....
1912	3	31.35	30.57	32.06	36.49	50.22	51.10	58.05	59.76	49.31	45.07	36.73	30.10	.....	.....
	Month.	30.43	31.14	31.59	36.80	43.56	50.55	57.61	58.75	54.47	46.95	38.52	32.48	42.74	56.05
	1	29.43	29.44	30.71	36.19	44.07	52.09	61.51	61.94	58.89	48.49	40.28	35.82	.....	.....
	2	28.65	30.33	31.92	37.40	46.17	51.12	61.94	59.68	54.52	46.21	40.45	35.09	.....	.....
1913	3	29.19	30.96	32.02	40.33	51.05	55.01	58.07	59.10	48.71	42.52	38.11	34.13	.....	.....
	Month.	29.13	30.19	31.56	37.97	47.22	52.74	60.43	60.20	54.04	45.64	39.61	34.98	43.64	57.94
	1	33.80	.....	.....	36.75	39.12	53.33	57.84	.....	.....	.....	.....	.....	.....	.....
	2	33.50	.....	.....	35.97	43.66	56.39	.....	.....	.....	.....	.....	.....	.....	.....
1914	3	.....	.....	33.49	39.41	49.19	61.63	.....	.....	.....	.....	.....	.....	.....	.....
	Month.	.....	.....	.....	37.37	44.16	57.12	.....	.....	.....	.....	.....	.....	.....	.....
	1	31.02	32.46	31.81	37.91	42.81	53.62	58.69	60.00	58.72	52.06	41.66	35.81	.....	.....
	2	31.34	32.07	33.61	28.25	45.15	54.35	59.71	59.39	56.73	49.96	40.68	34.57	.....	.....
Average [2]	3	31.78	31.57	35.04	40.54	49.77	57.37	58.86	58.59	53.15	45.04	28.52	32.59	.....	.....
	Month.	31.39	32.02	33.54	38.90	46.03	55.11	59.08	59.10	56.20	48.89	40.29	34.27	44.57	57.93
	1	.....	.....	.....	.....	.....	.....	.....	56.68	56.51	56.04	47.33	40.78	.....	.....
	2	.....	.....	.....	.....	.....	.....	[3]55.98	57.11	56.95	53.63	45.37	.....	.....	.....
1914	3	.....	.....	.....	.....	.....	.....	55.93	57.01	56.85	50.76	42.60	.....	.....	.....
	Month.	.....	.....	.....	.....	.....	.....	56.56	56.92	56.77	53.40	45.10	38.50	.....	.....
	1	.....	.....	32.36	32.97	39.41	43.84	50.83	53.64	54.04	50.65	46.85	40.01	.....	.....
	2	.....	.....	32.22	35.53	41.14	46.53	53.95	53.25	54.16	48.09	44.07	38.70	.....	.....
1915	3	.....	.....	32.43	37.68	42.88	49.89	54.20	52.91	53.78	46.55	41.90	36.84	.....	.....
	Month.	.....	.....	32.34	35.39	41.20	46.75	53.03	53.26	53.99	48.37	44.27	38.52	.....	51.31
	1	35.70	33.27	35.66	39.41	40.77	48.89	55.40	57.08	55.98	53.99	47.28	39.81	.....	.....
	2	35.01	33.22	38.1ō	38.83	43.94	50.72	56.42	57.18	55.11	51.95	44.22	38.06	.....	.....
1916	3	34.02	34.55	40.63	40.27	44.35	52.93	57.05	56.35	53.80	48.35	41.42	35.38	.....	.....
	Month.	34.88	33.65	38.19	39.50	43.06	50.85	56.32	56.85	54.96	51.33	44.31	37.67	45.13	54.80
	1	34.00	32.89	33.16	33.78	38.13	40.96	52.95	56.70	54.00	52.43	46.50	41.46	.....	.....
	2	33.96	33.00	32.92	35.58	37.84	46.20	53.86	55.41	54.16	51.94	45.36	38.84	.....	.....
1917	3	33.09	33.04	32.82	37.92	40.37	50.09	55.66	54.13	52.97	49.23	42.95	38.96	.....	.....
	Month.	33.66	32.97	32.96	35.76	38.84	45.75	54.21	55.37	53.71	51.14	44.94	39.73	43.25	52.00
	1	39.24	33.75	36.04	38.39	40.80	48.72	55.92	56.90	56.09	.....	.....	.....	.....	.....
	2	36.59	34.23	37.53	38.14	43.98	51.76	55.67	56.35	53.59	.....	.....	.....	.....	.....
1918	3	34.65	35.05	38.39	37.53	47.45	54.35	55.87	56.92	.....	.....	.....	.....	.....	.....
	Month.	36.75	34.29	37.35	38.02	44.15	51.61	55.82	56.73	.....	.....	.....	.....	.....	54.86
	1	36.51	33.30	34.30	36.14	39.78	45.60	53.78	56.02	55.13	53.28	46.99	40.52	.....	.....
	2	35.19	33.18	35.20	37.02	41.72	48.80	55.05	55.74	55.10	51.40	44.76	38.53	.....	.....
Average to July 10, 1918	3	33.92	33.96	35.81	38.35	43.76	51.82	55.71	55.10	54.35	48.97	42.22	37.06	.....	.....
	Month.	35.10	33.55	35.13	37.17	41.82	48.74	54.87	55.60	54.86	51.14	44.66	38.65	44.27	53.28

[1] January assumed to be normal.
[2] Average (2 feet) February, 1910, to July 10, 1914.
[3] Record at 4 feet begins.

air temperatures are not to be expected until four decades later, an unusually late time, as has been explained in the discussion of air temperatures. The highest average soil temperatures occur one decade earlier than the highest mean air temperatures, the former being slightly in excess of the latter, a fact which is made the more certain by considering the low value of the soil temperatures recorded at 8 a. m. The extremes at 4 feet occur two decades later than those at 1 foot.

(7) At this station and at practically all others the soil temperature rises in the first or second decade of September. This results from the usual cessation of rains and cloudiness near the end of August. Six years out of eight show this characteristic.

Soil temperatures evidently vary by years in about the same manner and degree as air temperatures, and corresponding periods of different years may exhibit quite different characteristics. Notwithstanding these facts, it has been decided to accept each soil-temperature record from the other stations at its face value, without attempting, as was done with air temperatures, to compare it with the control station for the same period. The reasons for this decision may be stated as follows:

(1) Most of the records here presented cover periods of three years or more, with the consequent opportunity for partial compensation of variations.

(2) The failure to determine mean 1-foot temperatures more directly makes great precision in this phase of the study impossible.

Absolute soil temperatures of the types.—The records for each of 20 stations, by months, are accordingly presented in Tables 27 and 28, the period of observation for each station being shown. Figures 5 and 6 show some typical soil-temperature relations.

Table 27 discloses that considerable differences in soil temperatures may exist between sites which are similar as to forest cover. These are equal to or greater than the air-temperature differences between the same sites. Since it is apparent that soil temperatures at a depth of a foot or more can have little direct bearing on growth, as temperature factors, there will at first be an inclination to say that soil temperatures are not so good criteria of the possibilities of the site as air temperatures are, provided the latter are taken close enough to the ground to represent those conditions most directly affecting germination and seedling growth. As has been said, however, the tables show that mean soil temperatures, even for whole years, do not bear a constant relation to the air temperatures of the respective sites. When it is also considered that the latter have not always been measured where they would best show the conditions surrounding seedlings, and as the soil-temperature measurements do bear a certain fairly definite relation to surface conditions, it is seen that soil temperatures may have a special significance, at least in indicating the degree of insolation of the site, and the maximum temperatures which the seedlings will encounter. It is now believed that the maximum temperatures near the surface of the soil are of the greatest importance in the distribution of the species, and it is for this reason that the 1-foot temperatures during the growing season will be considered in the greatest detail.

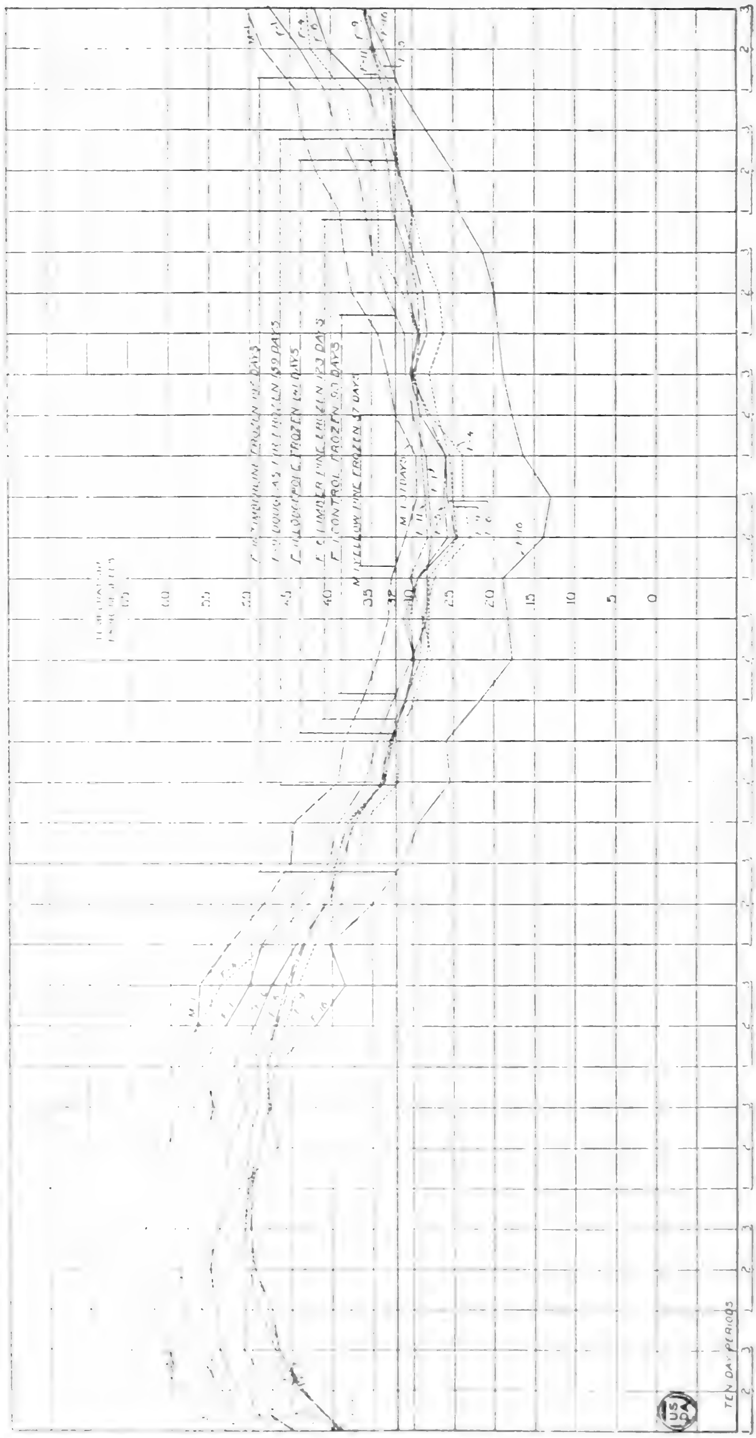

FIG. 5.—Average soil temperatures, depth 1 foot, by 10-day periods. (Observed temperatures, not corrected.)

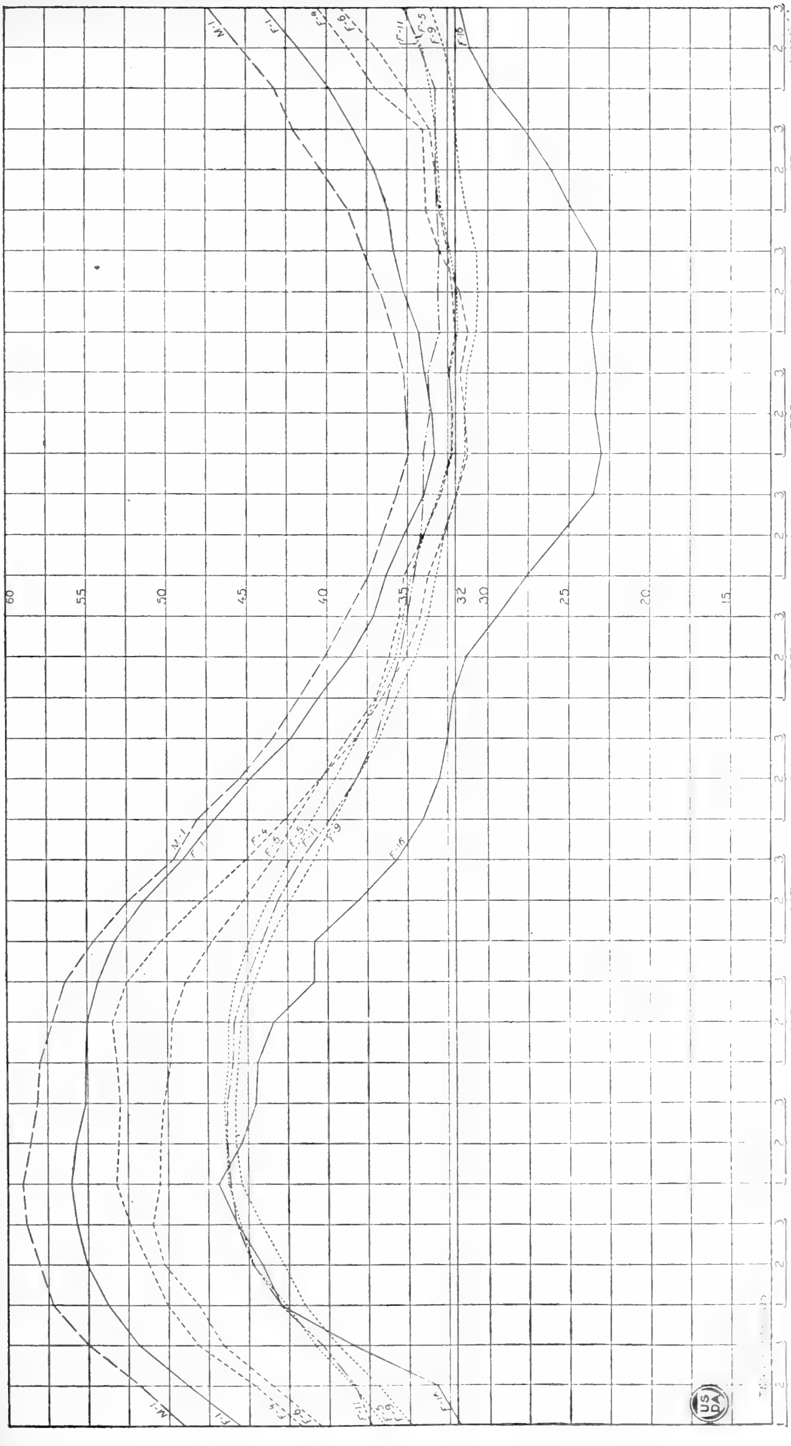

FIG. 6.—Average soil temperatures, depth 4 feet, by 10-day periods.

TABLE 27.—*Summary of mean soil temperatures for all stations—depth, 1 foot.*

[Parenthetical figures indicate number of decade in which highest or lowest temperature is reached.]

Station No.	Locality.	Forest type.	Period of observations.	Record, by months, in degrees Fahrenheit.												Mean annual.[1]	Mean growing season.[1]	Corrected according to Table 24.	
				Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.			Mean annual.[1]	Growing season.[1]
F-1	Pikes Peak	Control	Jan., 1910, to July, 1918.	(2) 27.9	29.5	33.1	37.2	44.1	53.8	(2) 58.3	56.1	53.1	44.5	36.4	30.1	42.01	56.06	44.93	58.98
H-2	Nebraska	Sandhills	Nov., 1918, to June, 1921.	(3) 30.3	30.1	35.5	43.8	56.7	67.5	(3) 75.0	72.5	65.9	50.5	36.7	32.3	49.73	71.32	50.78	72.37
M-1	Pikes Peak	Western yellow pine.	Jan., 1915, to July, 1918.	(3) 30.9	31.4	36.7	41.4	47.8	57.2	(3) 62.7	60.3	57.6	48.6	40.7	34.4	45.82	60.06	46.46	60.70
F-2	do	do	Feb., 1910, to Feb., 1912; Mar., 1913, to Dec., 1913; May to Dec., 1914; Mar., 1915, to Feb., 1916; May, 1917, to July, 1918.	(1) 31.0	32.9	36.6	39.8	45.1	55.5	(2) 58.4	57.1	57.2	48.3	40.8	34.2	44.75	57.15	45.76	58.16
F-12	do	do	June, 1915, to Feb., 1916; May, 1917, to July, 1918.	27.8	(1) 28.4	30.2	35.1	41.6	51.4	(2) 58.3	54.8	52.0	42.4	36.0	30.9	40.74	54.80	41.52	55.58
F-4	do	Pine-fir	July, 1914, to Feb., 1916; May, 1917, to July, 1918.	(2) 24.6	27.0	31.6	35.4	41.4	51.0	(2) 58.4	57.9	56.4	43.4	34.8	28.5	40.86	56.09	41.20	56.43
F-6	do	Limber pine	July, 1914, to Feb., 1916; May, 1917, to July, 1918.	(2) 26.5	28.1	30.2	33.0	39.3	50.0	(2) 54.4	52.2	49.7	41.0	34.9	30.5	39.15	52.23	40.32	53.40
F-7-8	do	Douglas fir, open.	July, 1914, to July, 1918.	(2) 20.9	22.5	27.3	32.5	38.1	49.6	(3) 56.2	53.7	48.6	38.9	29.9	23.9	36.84	53.04	37.94	54.14
F-14	do	Douglas fir, half cut	Apr., 1916, to July, 1918.	(2) 23.8	24.9	28.1	31.6	35.1	45.4	(3) 52.1	51.1	46.3	38.5	30.7	26.4	36.17	49.51	37.28	50.62

F-15	do	do	do	(2) 24.1	25.3	28.2	31.5	35.5	47.3	(3) 53.5	51.0	45.5	38.3	31.2	27.2	36.56	50.42	37.53	51.39
W-A2	Rio Grande	Douglas fir, south.	Jan., 1913, to July, 1918.	28.9	(1) 28.7	30.6	33.9	39.8	50.0	(2) 54.6	52.8	48.9	43.5	38.8	32.6	40.26	52.38	43.42	55.54
W-A1	do	Douglas fir, north.	Apr., 1912, to July, 1918.	19.3	(2) 19.3	21.4	26.4	31.9	37.5	45.7	(1) 47.2	40.7	33.3	28.1	21.0	30.97	43.56	31.35	43.94
F-9	Pikes Peak	Douglas fir-spruce, uncut.	July, 1914, to July, 1918.	(2) 25.7	26.6	27.2	31.2	34.9	43.0	(3) 49.3	49.0	46.0	39.0	33.1	28.6	36.14	47.23	37.08	48.17
F-11	Southern Wyoming.	Lodgepole	Aug., 1914, to July, 1918.	(2) 28.9	29.1	29.6	31.6	34.7	43.3	(3) 50.0	50.0	47.1	40.6	34.3	29.4	37.37	47.88	38.56	49.07
F-13	Pikes Peak	Limber pine	June, 1915, to Sept., 1916.	(3) 23.1	26.3	33.5	33.8	41.0	51.0	(1) 57.5	50.2	48.4	37.4	32.0	25.8	38.34	52.81	......	......
F-5	do	Engelmann spruce, canyon.	Same as F-2	26.4	(1) 26.4	29.9	32.0	36.3	47.6	(2) 52.1	50.4	46.9	38.4	32.6	28.7	37.31	49.92	38.02	50.63
F-5	do	do	June to Dec., 1914; Mar., 1915, to Feb., 1916; May, 1917, to July, 1918.	27.0	(1) 27.8	28.9	31.7	34.4	42.9	(3) 49.0	48.7	46.9	41.0	34.5	30.2	36.93	46.97	38.33	48.37
W-F	Rio Grande	Engelmann spruce, north slope.	Nov., 1913, to Dec., 1917.	(1) 26.9	27.5	27.6	29.1	31.0	33.6	42.0	(1) 44.5	39.8	32.9	29.3	26.7	32.56	40.00	32.90	40.34
W-D	do	Spruce burn, flat.	Dec., 1913, to Nov., 1918.	(2) 28.0	28.6	29.5	31.1	33.1	44.8	(3) 53.3	52.7	47.6	40.6	32.9	28.8	37.58	50.01	37.63	50.06
F-16	Pikes Peak	Timber line	Oct., 1916, to Feb., 1918.	(3) 15.2	17.6	20.2	25.9	33.5	45.9	(3) 51.8	48.5	42.4	35.3	26.8	19.2	31.86	48.55	33.24	49.93

[1] Annual and growing-season means computed from decade and monthly values carried to hundredths. Growing season is arithmetic mean of 10 decades, except Stations W-D and W-F.

TABLE 28.—*Summary of mean soil temperatures for all stations—depth, 4 feet.*[1]

Station No.	Locality.	Forest type.	Record, by months, in degrees Fahrenheit.												Mean annual.[2]	Mean growing season.[2]
			January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.		
F-1	Pikes Peak	Control	35.1	33.6	35.1	37.2	41.8	48.7	54.9	55.6	54.9	51.1	44.7	38.6	44.27	53.28
H-2	Nebraska	Sandhills	36.8	35.5	37.2	43.5	52.2	61.1	67.4	68.3	65.5	57.6	45.2	39.1	50.78	65.67
M-1	Pikes Peak	Western yellow pine	36.5	35.1	36.8	40.3	45.3	51.9	58.1	58.6	57.2	52.1	45.6	40.1	46.46	56.38
F-2	do	do	37.5	36.5	37.0	38.8	42.4	48.3	53.8	55.0	55.6	52.2	47.1	41.6	45.49	52.66
F-12	do	do	34.3	32.6	32.9	35.4	39.4	45.2	50.8	51.7	51.0	46.4	41.6	37.0	41.52	49.41
F-4	do	Pine-fir	32.8	31.4	32.0	33.9	38.8	44.9	51.2	53.1	53.0	47.7	40.4	35.2	41.20	50.07
F-6	do	Limber pine	31.0	32.3	32.2	33.3	37.1	43.6	49.8	50.4	49.5	45.2	40.4	36.2	40.32	48.12
F-7-8	do	Douglas fir, open	30.3	29.0	30.1	31.8	33.2	41.1	48.2	50.2	48.6	43.3	37.0	33.0	37.94	46.78
F-14	do	Douglas fir, half cut	30.7	29.6	30.2	31.7	32.3	38.8	46.1	48.8	46.9	42.4	36.4	33.1	37.28	45.00
F-15	do	do	31.5	30.2	30.6	31.9	32.4	39.7	46.9	48.6	46.2	42.0	36.7	33.6	37.53	45.29
W-A2	Rio Grande	Douglas fir, south	36.8	35.2	35.3	37.1	40.9	46.5	51.8	52.8	51.9	48.7	45.2	40.2	43.54	50.57
W-A1	do	Douglas fir, north	26.4	25.2	25.2	26.4	31.3	32.6	36.6	40.6	38.7	33.3	30.8	29.4	31.39	36.98
F-9	Pikes Peak	Douglas fir-spruce, uncut	32.6	31.4	30.7	31.7	32.8	37.1	42.9	45.7	45.2	42.2	38.1	34.6	37.08	42.26
F-11	Southern Wyoming	Lodgepole pine	34.3	33.8	33.0	33.2	34.3	38.8	44.5	46.3	45.6	42.9	38.3	35.5	38.35	43.43
F-13	Pikes Peak	Limber pine	28.6	28.6	32.4	33.6	39.9	49.3	54.6	51.2	49.2	40.2	35.6	30.2	39.45	51.65
F-3	do	Engelmann spruce, canyon.	33.6	32.0	31.6	32.6	34.2	40.2	45.5	46.8	45.8	42.0	38.0	34.8	38.08	44.36
F-5	do	do	33.9	32.3	32.0	33.0	34.3	38.7	44.3	46.4	46.0	43.6	39.5	35.9	38.33	43.42
W-F	Rio Grande	Engelmann spruce, north slope.	31.8	31.4	31.3	31.4	31.6	32.0	32.3	35.7	37.4	35.0	32.8	32.2	32.90	33.73
W-D	do	Spruce burn, flat	33.3	32.6	32.3	32.3	32.3	35.8	43.8	47.3	46.2	43.2	37.9	34.6	37.63	42.69
F-16	Pikes Peak	Timberline	25.4	23.2	23.4	26.2	30.9	34.6	44.3	45.6	42.8	38.1	33.2	31.0	33.24	41.79

[1] Period of observations same for 4 feet as for 1 foot, except that former do not begin until July, 1914, for local stations; July, 1913, for Wagon Wheel Gap stations; and April, 1916, for F-11.

[2] See footnote to Table 27.

Extremely low air temperatures in winter may be made more severe by melting snow in the vicinity, which, as it melts, tends to absorb most of the sun's heat. On the other hand, the snow blanket tends to hold up the soil temperatures and to prevent deep freezing. Thus, although the lodgepole pine type in Wyoming (Station F–11) has a mean air temperature practically equivalent to that of timber line at Pikes Peak, its mean soil temperature is some 5° higher and its winter soil temperature is 11° higher. Again, the high-altitude spruce station at Wagon Wheel Gap has practically the same mean annual air and soil temperatures as the timber line station on Pikes Peak; but while the latter's January soil temperature drops to 15.2° F. the former reaches a low point of only 26.9° F. The difference is due to lack of snow cover at the timber line station, and, similarly, the lack of forest cover gives this station much higher summer soil temperatures.

In Table 29, both air temperatures and 1-foot soil temperatures have been summarized in such a way as to bring out the contrasts which exist at different seasons, and to show that soil temperatures and air temperatures do not give similar measures of site conditions. The differences between soil and air temperatures are to some extent illustrated in Figures 7 and 8. It must, of course, be borne in mind that the air temperatures given in this table are approximations to the "normals" for the period 1910 to 1918, by comparison with the control station, but that the soil temperatures represent shorter periods, and somewhat different periods for different stations.

TABLE 29.—*Comparative air and soil temperatures.*

[Soil temperatures in degrees Fahrenheit at 1 foot, corrected for year and growing season by amounts indicated in Table 24; for winter, by one-half of these amounts.]

Station No.	Forest type.	Annual temperatures.			Growing-season temperatures.			Winter (Jan.–Mar.) temperatures.		
		Air.	Soil.	Difference.	Air.	Soil.	Difference.	Air.	Soil.	Difference.
H-2	Sandhills	47.47	50.78	+3.31	70.81	72.37	+ 1.56	29.87	32.00	+ 2.13
M-1	Western yellow pine.	43.96	46.46	+2.50	61.56	60.70	− 0.86	29.43	33.32	+ 3.89
F-2	do	42.23	45.76	+3.53	58.65	58.16	− 0.49	29.10	34.02	+ 4.92
F-12	do	39.98	41.52	+1.54	56.65	55.58	− 1.07	25.84	29.19	+ 3.35
F-4	Pine-fir	....	41.20	....	54.00	56.43	+ 2.43	....	27.90	....
F-7-8	Fir with pine	39.69	37.94	−1.75	56.68	54.14	− 2.54	25.70	24.12	− 1.58
W-A2	do	37.54	43.42	+5.88	55.98	55.54	− 0.44	22.67	30.98	+ 8.31
F-15	Douglas fir	39.58	37.53	−2.05	56.52	51.39	− 5.13	25.50	26.36	+ 0.86
F-14	do	39.23	37.28	−1.95	56.58	50.62	− 5.96	25.03	26.16	+ 1.13
F-9	Fir with spruce	38.77	37.08	−1.69	55.78	48.17	− 7.61	24.77	26.97	+ 2.20
W-A1	do	35.76	31.35	−4.41	54.18	43.94	−10.24	20.87	20.19	− 0.68
F-3	Engelmann spruce.	38.91	38.02	−0.89	55.95	50.63	− 5.32	25.40	27.92	+ 2.52
F-5	do	....	38.33	....	50.98	48.37	− 2.61	....	28.60	....
W-F	do	32.13	32.90	+0.77	49.53	40.34	− 9.19	18.03	27.50	+ 9.47
F-16	Timberline	31.63	33.24	+1.61	48.96	49.93	+ 0.97	17.83	18.36	+ 0.53
F-11	Lodgepole pine	32.49	38.56	+6.07	49.94	49.07	− 0.87	18.30	29.80	+11.50
F-6	Limber pine	41.92	40.32	−1.60	59.02	53.40	− 5.62	27.50	28.86	+ 1.36
F-13	do	37.01	38.34	+1.33	54.39	52.81	− 1.58	23.67	27.63	+ 3.96

In Table 29, certain relations stand out in bold relief, as, for example, the ability of the soil of well-insolated sites to equal or even exceed the air temperatures during the growing season, although the north slopes and those covered by the denser stands fail to do this by 2.5° to 10.2°. It is significant that all of the warmer sites encourage pines in some degree. These and other relations will be further analyzed in the following discussions of the types.

(1) The yellow pine sites—M–1 at 7,200 feet elevation and F–2 1,700 feet higher—show nearly the same soil temperatures at all seasons, although the constant difference between the two is even greater than the difference in air temperatures near the ground. These two stations are almost in a class by themselves. However, it is to be noted that F–1, the control station, practically measures up to yellow pine standards, its 4-foot mean being as high as that at Station F–2. Stations F–12 and F–4, both representing sites in which the yellow pine tends to give way to Douglas fir and limber pine, show soil temperatures a little below the yellow pine standard.

That the growing-season temperatures indicated above as being favorable to yellow pine will not fall far short of those occurring in

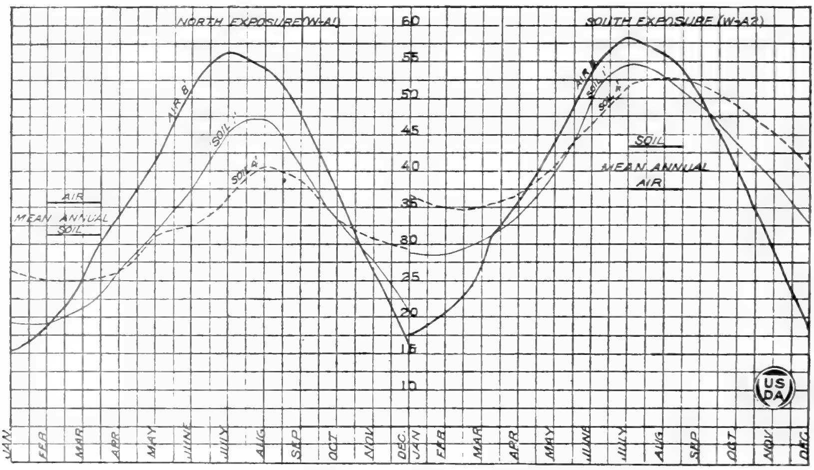

FIG. 7.—Relation of soil and air temperatures on opposing slopes.

any of the yellow-pine sites of this region is indicated by numerous measurements made in the Black Hills region in 1914, when, during June, July, and August, soil temperatures at 1 foot ranging from 56° to 65° were continually encountered.[7] Although measurements are lacking, there is little doubt that winter soil temperatures are kept up fully as high as in the Pikes Peak region, notwithstanding much lower air temperatures, through the agency of a heavy snow blanket in the Black Hills. Larsen (*13*) shows an August mean of 65° at 1 foot, for the Idaho western yellow pine site, as compared with about 63° at Monument in July. Pearson (*19*) gives May to October values ranging from 53.1° to 66.2° for a number of pine sites in the Southwest.

In the typical western yellow-pine sites the soil temperature at 4 feet does not, for any 10-day period, go so low as 32°. At Station

[7] Five measurements in three Quality I pine sites, between June 24 and July 8, showed an average temperature of 57.7°, 1° lower than Station F–1 for the same period. Thirty observations in 14 Quality II sites, June 22 to July 31, gave a mean temperature of 59.7°, 1.5° higher than the control station. Twenty-two observations in 10 Quality III sites gave a mean of 58.9°, or 1.5° above the control station for the period July 11 to August 3. From this it appears that the moister and better sites are appreciably cooler than yellow-pine sites in the Pikes Peak region. This difference may be due wholly to denser stands in the Black Hills. On the whole, the two localities are more similar than might be expected. The average of all Black Hills observations, June 22 to August 3, was 59.2°, and for the control station 57.9°.

F–4 the soil normally is frozen at the 4-foot depth for 5 or 6 decades. The Nebraska sandhill soil has not, so far, closely approached freezing at the 4-foot depth.

One of the reasons, therefore, for the crowding out of yellow pine by Douglas fir and for the producing of a "succession" in the truest sense, may be the shade of the mother canopy, which induces a prolonged winter drought for the small trees. In the one situation where this is fairly represented (F–4) the condition of the parent trees, as well as the composition of the reproduction seems to show the severity of the strain so produced. However, it should be observed that a heavy canopy at the same time so reduces the exposure of each tree or seedling that the immediate and radical effects of winter drying, commonly described as "winter-killing," are not observed in the fairly dense forest.

(2) It may be well to examine next the limber pine sites, represented by F–6 and F–13. Notwithstanding the fact that the second

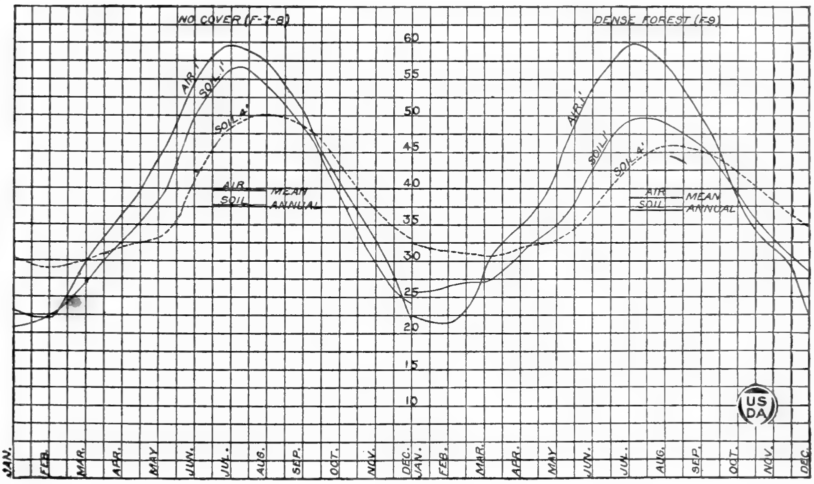

FIG. 8.—Relation of soil and air temperatures with and without forest cover north slopes.

station represents almost the upper limits of the species, its mean temperatures are almost equivalent to those of the lower station, and its growing-season temperatures slightly higher, because of a bare and well-insolated soil. The relatively high values at either station give emphasis to the argument that limber pine seedlings thrive under intense radiation, and that the necessary heat for growth, at elevations where the air temperatures are generally low, is secured on burns and rocky ridges through purely local absorption of heat by the ground. It is probable that the maxima attained in the soil and immediately above it will fall little short of those for yellow-pine sites. Also the winter soil temperatures of these sites are considerably higher than the air temperatures, especially at the higher elevation. In mean soil temperatures the sites correspond closely to the quasi-yellow-pine sites, but in neither of the limber-pine sites is freezing to a depth of 4 feet to be expected. This conclusion for Station F–13 is reached after a consideration of the relative winter temperatures at 1 and 2 feet.

The writer believes, however, that there are situations occupied by limber pine in which the winter soil temperatures go considerably below those characteristic of yellow-pine sites, permitting freezing of the soil for long periods. The ability of limber pine to exist under such circumstances, and with extreme wind exposure, points to a marked difference in adaptation, between this species and yellow pine, which may be quite independent of their apparently similar heat requirements.[8] There has come to the writer's notice what may be called an adaptation of outward form, by which during the winter the needles of limber pine become very closely appressed. This gives the limbs a club-like appearance quite different from the "feathery" one of summer.

It is therefore quite evident that while limber pine has heat requirements similar to those of western yellow pine, which are satisfied by the conditions resulting from the insolation of bare, exposed soils, it has also a faculty for resisting winter-drying, which permits the species to range almost from the lower limits of yellow pine to points practically equivalent to timber line, not reached by the yellow pine. This heat requirement makes it possible for the limber pine to be a forerunner of Douglas fir or spruce on gravel slides too strongly insolated to admit the other species, and on burns and cut-over areas, but excludes it from a prominent place in the ultimate forest.

That limber pine is nowhere more abundant nor more widely distributed than in the Pikes Peak region is, perhaps, due to the presence of a young, denuded soil and to other soil properties which will be discussed in the section on soil moisture.

(3) The conditions brought out by the Douglas fir sites are amply illustrative of the soil-temperature variations which are possible in different localities. These conditions give the impression that both winter and summer soil temperatures may have a bearing on forest composition, but that at times the conditions are not fully expressed by the soil temperatures alone—that atmospheric conditions also must be taken into account.

The data for Douglas fir, considered in connection with the quasi-yellow-pine sites, on the one hand, and the conditions in Douglas fir sites which seem to encourage spruce reproduction, on the other, may be summarized as follows:

(*a*) Sites on which Douglas fir reproduction will about maintain the predominant position of this species (F–14, 15) are characterized by an annual mean soil temperature of about 37° F., a growing-season mean of 51°, and a winter mean of 26°, with the soil at 1 foot frozen for about 140 days.

(*b*) Greater insolation and radiation, secured on a similar site (F–7–8), by complete removal of the cover, create summer soil temperatures about 3° higher, and winter temperatures 2° lower, the freezing period being somewhat earlier. The summer conditions undoubtedly encourage more germination of western yellow and limber pines, but the winter conditions will probably keep the pines to a very subordinate position in the ultimate composition of the stands.

(*c*) Sites in the Pikes Peak region (F–4 and 12) better insolated than the last, but having their summer extremes modified by fairly heavy cover, favor western yellow and limber pines with the fir, but appear to be progressing steadily toward pure fir stands.

(*d*) A site (W–A2) having much more insolation than the last because of a south exposure and a scant cover, scarcely warmer than the "normal Douglas fir" sites in summer, but 4° warmer in winter, and not freezing to a depth of

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[8] An exception was noted early in July, 1917, when with air and soil unusually dry, limber pines in an open stand on a southeast slope showed foliage injury exactly corresponding to winter-killing, while yellow pines on the same site escaped without apparent injury.

4 feet, is very discouraging to any kind of reproduction, but permits some bristlecone pine as well as fir. The entrance of bristlecone rather than yellow pine under these conditions may, perhaps, be taken as evidence of dissimilar soil preferences of the two pines.

(*e*) Additional density of cover on a north slope (F–9) reduces the extremes of soil temperature 1° or 2° without appreciably affecting the period of soil freezing. This change of temperature extremes, which would be much more apparent if absolute maxima and minima nearer the surface could be considered, is conducive to better germination of both spruce and fir, but results in an undergrowth controlled by spruce.

(*f*) A site not unlike the last in its air-temperature conditions (W–A1) may show much lower soil temperatures at all seasons (4° to 6°) without appreciably changing the character of the reproduction. The two sites are most similar during the growing season, both in absolute soil temperature and in having soil temperatures much (8° to 10°) below the air temperatures. They vary widely in the severity of their soil freezing; but, when atmospheric conditions in this period are considered, they are found to be not so unlike. (See Table 30.)

(4) The soil temperatures of the four spruce sites here considered cover a wide range, the mean annual temperatures for the 4-foot depth varying from about 38° on the two sites at 9,000 feet elevation to 33° at or near timberline. The timberline station at Fremont and the north-slope station at nearly the same elevation at Wagon Wheel Gap show essentially the same mean temperatures; but temperatures for the timberline station go to much greater extremes, owing to the lack of forest cover at the observation point, and the lack of a snow blanket in winter.

When the canyon spruce sites (F–3 and F–5) are compared with the north-slope fir site of the same locality in which spruce reproduction is encouraged (F–9), it is found that the former have equal or higher soil temperatures during the growing season and warmer and less deeply frozen soils during the winter. Of all sites, these canyon bottoms would be the last on which fir would be found. The spruce may also control the lower and, perhaps, the coldest portion of the fir slope. It is then evidently not the soil temperature conditions which exclude fir and permit excellent reproduction and development of the spruce. The character of the soil at the foot of the slope and in the canyon bottom is suggestive, as something in common for these two sites, and after soil-moisture conditions are considered, it must be admitted that soil quality and moisture and not soil temperature seem to be the controlling factors in this situation.

The timberline station on Pikes Peak (F–16), where the soil receives full insolation, attains to summer soil temperatures almost equal to those at the lower (canyon) limit of spruce. In view of this fact, as well as the great intensity of sunlight at the high elevation, it is evident that the heat conditions for a reasonable growth each season are fully satisfied. By comparison with a similar elevation at Wagon Wheel Gap, however, the effect of the canopy in modifying temperature extremes is plainly seen and it becomes evident that near timberline the forest may have a tendency to choke itself by creating soil conditions not conducive to vigorous reproduction. In other words, at a certain point the temperature will not permit a permanently dense stand. The result is that in thinner stands each individual tree during the long winter is subjected to an exposure which can not be tolerated beyond a certain point. The temperature conditions at different seasons are thus all interrelated in limiting the upward extension of the forest and in permitting the initiation of single specimens only in sheltered nooks, where there is no room for a self-protecting group or stand and where there is indeed insufficient protection for the individual when it reaches above the level of rocks or of the usual snow blanket.

A mean annual air and soil temperature of 32° may be approximately limiting to growth on fully exposed sites, although there is little question that some excellent spruce forests exist and produce very satisfactory wood increments where this temperature is closely approached. Low temperatures may directly preclude normal development of stands during the growing season, and they may react, through the long period of soil freezing, to create a very great winter exposure; but it becomes evident that it is the winter exposure which directly creates a "timberline."

(5) The single lodgepole pine station shows mean soil temperatures similar to those of the spruce type, but its winter temperatures are more nearly those of the western yellow pine type.

(6) To summarize: Soil temperatures are more responsive to the local effects of insolation than air temperatures are, and even the soil temperatures at a depth of 1 foot are probably more representative of those conditions at the surface of the ground that affect germination and the young seedling than are air temperatures as they are usually and conveniently measured. Consequently, soil temperatures bring out more closely than air temperatures the growing-season contrasts between north and south slopes, between forested and open sites, and between the heat of bare or rocky soils and older or better-protected soils. Every soil-temperature difference in a single locality such as the Pikes Peak region is accompanied by a change in the character of the forest reproduction, although in some cases it is doubtful if the soil temperature is the controlling condition. Yellow pine, limber pine, and bristlecone pine all appear to enjoy warm soils and to reproduce on sites where very high temperatures are to be expected, at least for short periods. Douglas fir, on the other hand, reproduces well only with sufficient shade to greatly modify these high temperatures. This is true in the Pikes Peak region even on northerly slopes where the sun's rays strike obliquely. The distinction between Douglas fir and Englemann spruce does not seem to be so much a matter of temperatures which might injure young seedlings, as of soil or light conditions which in the dense forest gradually starve the fir. This distinction may be more logically discussed after considering the soil moisture data.

Evaporation during the period of soil freezing.—In accordance with what has been shown in Table 29 as to the variation in the extent of soil freezing in the different types, and with the suggestion that this period should be measured, not in days, but in terms of the inducement to evaporation, an effort is made to show, in Table 30, the total probable evaporation for each such period.

TABLE 30.—*Probable total evaporation during the period in which the mean soil temperature, for decades, at a depth of 1 foot, is below 32° F.*

[The letter F in decade spaces indicates periods when soil is commonly frozen.]

Station No.	Type.	Decade.	Cubic centimeters per 100 square centimeters. Jan.	Feb.	Mar.	Apr.	May–Sept.	Oct.	Nov.	Dec.	Total for frozen period.
F-1	Control	1	F.	F.	......	......	......	......	......	......	......
		2	F.	F.	......	......	......	......	......	F.	......
		3	F.	......	......	......	......	......	......	F.	......
		Month.	139.8	78.3	......	......	......	......	......	99.6	317.7
H-2	Sand hills	1	......	F.	F.	......	......	......	......	......	......
		2	F.	F.	......	......	......	......	......	......	......
		3	F.	F.	......	......	......	......	......	......	......
		Month.	25.3	78.6	40.4	......	......	......	......	......	144.3
M-1	Western yellow pine.	1	......	F.	......	......	......	......	......	......	......
		2	F.	......	......	......	......	......	......	......	......
		3	F.	......	......	......	......	......	......	......	......
		Month.	103.2	45.4	......				......	......	148.6
F-2	do	1	F.	......	......	......	......	......	......	......	......
		2	F.	......	......	......	......	......	......	......	......
		3	......	......	......	......	......	......	......	......	......
		Month.	63.8	......	......	......	......	......	......	......	63.8
F-12	do	1	F.	F.	F.	......	......	......	......	......	......
		2	F.	F.	F.	......	......	......	......	F.	......
		3	F.	F.	......	......	......	......	......	F.	......
		Month.	81.2	110.3	98.5	......	......	......	......	53.7	343.7
F-4	Pine-fir	1	F.	F.	F.	......	......	......	......	F.	......
		2	F.	F.	F.	......	......	......	......	F.	......
		3	F.	F.	......	......	......	......	......	F.	......
		Month.	43.4	57.9	66.1	......	......	......	......	50.0	217.4
W-A2	Douglas fir, south	1	F.	F.	F.	......	......	......	......	......	......
		2	F.	F.	......	......	......	......	......	......	......
		3	F.	F.	......	......	......	......	......	......	......
		Month.	49.0	71.8	32.7	......	......	......	......	......	153.5
F-7-8	Douglas fir, north, open.	1	F.	F.	F.	......	......	......	......	F.	......
		2	F.	F.	F.	......	......	......	F.	F.	......
		3	F.	F.	F.	......	......	......	F.	F.	......
		Month.	57.3	55.2	104.2	......	......	......	39.2	41.2	297.1
F-9	Douglas fir, north	1	F.	F.	F.	F.	......	......	......	F.	......
		2	F.	F.	F.	......	......	......	......	F.	......
		3	F.	F.	F.	......	......	......	......	F.	......
		Month.	19.6	23.4	28.1	15.4	......	......	......	30.9	117.4
W-A1	do	1	F.	F.	F.	F.	......	......	F.	F.	......
		2	F.	F.	F.	F.	......	......	F.	F.	......
		3	F.	F.	F.	......	......	......	F.	F.	......
		Month.	11.2	19.3	66.2	65.6	......	......	25.2	7.4	194.9
F-11	Lodgepole	1	F.	F.	F.	F.	......	......	......	F.	......
		2	F.	F.	F.	......	......	......	......	F.	......
		3	F.	F.	F.	......	......	......	......	F.	......
		Month.	22.4	15.2	46.2	41.0	......	......	......	45.6	170.4
F-6	Limber pine, northwest slope.	1	F.	F.	F.	......	......	......	......	F.	......
		2	F.	F.	F.	......	......	......	......	F.	......
		3	F.	F.	F.	......	......	......	......	F.	......
		Month.	69.9	67.6	92.3	......	......	......	......	82.6	312.4
F-13	Limber pine, high ridge.	1	F.	F.	F.	......	......	......	......	F.	......
		2	F.	F.	......	......	......	......	F.	F.	......
		3	F.	F.	F.	......	......	......	F.	F.	......
		Month.	271.5	[1] 206.9	[1] 72.1	......	......	......	112.3	133.9	796.7

[1] Relative evaporation for these months estimated at 150 per cent and 130 per cent, respectively, of that at the control station, as no record is available.

TABLE 30.—*Probable total evaporation during the period in which the mean soil temperature, for decades, at a depth of 1 foot, is below 32° F.*—Continued.

Station No.	Type.	Decade.	Cubic centimeters, per 100 square centimeters.								Total for frozen period.
			Jan.	Feb.	Mar.	Apr.	May-Sept.	Oct.	Nov.	Dec.	
F-3	Canyon spruce	1	F.	F.	F.	...	...	...	...	F.	...
		2	F.	F.	F.	...	...	...	...	F.	...
		3	F.	F.	F.	...	...	...	F.	F.	...
		Month.	9.8	5.5	30.1	...	...	...	7.2	7.4	60.0
F-5	do	1	F.	F.	F.	F.	...	...	...	F.	...
		2	F.	F.	F.	...	...	...	...	F.	...
		3	F.	F.	F.	...	...	...	...	F.	...
		Month.	36.4	41.4	56.2	14.4	...	...	...	25.0	173.4
W-D	High spruce, burn.	1	F.	F.	F.	F.	...	...	...	F.	...
		2	F.	F.	F.	F.	...	...	...	F.	...
		3	F.	F.	F.	...	...	...	F.	F.	...
		Month.	64.4	102.0	104.2	49.5	...	...	23.5	60.4	404.0
F-16	Pikes Peak, timberline.	1	F.	F.	F.	F.	...	...	F.	F.	...
		2	F.	F.	F.	F.	...	...	F.	F.	...
		3	F.	F.	F.	F.	...	F.	F.	F.	...
		Month.	23.8	13.8	40.1	62.6	...	90.6	141.5	44.2	416.6

These data are based on (1) the period, by decades, in which the mean soil temperature is below 32°, the recorded temperature being corrected by one-half the amount indicated in Table 24, and each such decade being shown in Table 30 by a letter F; (2) the relative evaporation by months, for the particular station, as shown by Table 23; (3) the average evaporation for any decade or month at the control station, as shown by Table 22. The result, of course, is the merest approximation to the probable evaporation stresses of the average season, and does not indicate at all the extreme conditions that might be met. In a consideration of these data the fact should be borne in mind that at most of the local stations evaporation has been recorded 7 to 12 inches above the ground surface, but at others the height of instruments has been 5 to 20 feet. (See Table 23.)

Table 30 is based on so many assumptions that it can not be taken as conclusive, yet in a broad way its indications are felt to be important and valuable. The general effect of using the mean soil temperatures for several years is probably to make the period of soil freezing appear longer than it actually is in the average individual year. This is shown by using the actual data for the season of 1919–20, when a good many evaporimeters were in operation. At a well insolated station like the control the soil temperatures in a single season are found to consist of several depressions well below the freezing point, with intervals in which the soil moisture is very evidently available. The maximum continuous stress, therefore, is here only one-third as great as indicated by Table 30, and probably in the most severe of winters it would not be more than one-half as great. On the other hand, even a small amount of shade seems to be sufficient to prevent the thawing of the soil on warm days. The use of the mean soil temperatures, rather than maxima, of course introduces another chance of prolonging the freezing period beyond its actual limits.

Both the possibility of occasional thawing on well-insolated sites (that is, maxima above 32°) to a depth of 1 foot, and the probability that on such sites moisture nearer to the surface will be frequently available, are seen by considering even a few original observations. For example, in a yellow pine site at Fremont, which has a very slight tilt to the south, and averages 1° to 2° cooler than the control station because of shading, while the soil temperature, as recorded at 8 a. m., was continuously below 32° from November 28, 1920, to February 27, 1921, a period of 91 days, there was during this period only one decade in December and one in February in which no surface temperatures above 32° were recorded at 8 a. m. Nor does this by any means speak for the highest temperatures of the day; and even the two exceptional decades showed maximum air temperatures above 40°.

The conclusion is inevitable, therefore, that the evaporation stress during periods in which soil moisture is completely nonavailable is far less for well-insolated sites than is indicated by Table 30. On the other hand, a continuously frozen soil, not only for the average, but in each individual year, is a practical certainty on every north slope and even in the canyon bottoms, which might be reached by the sun, but where the summer moisture supply is adequate to develop very dense stands. Table 30 may possibly exaggerate the evaporation stress by prolonging the period a little after the time when snow melting is rapid enough to provide the surface roots with water, but this very melting greatly retards the warming of the deeper soil. This difference between insolated sites which generally produce open stands and cooler sites which encourage denser stands must be further accentuated when it is considered that the evaporation measurements have nearly all been taken close to the ground. On a warm site the evaporation is likely to be little, if any, higher at a considerable elevation than near the ground. This is true not only because the open forest permits very good air circulation at all levels, but also because, in the winter period, radiation close to the ground may frequently cause thawing which would not otherwise be possible, and this will be an important element in the total evaporation. On the contrary, it is self-evident that in a close stand, the higher the elevation in the midst of the crowns, the greater will be both the insolation and the wind movement. The evaporation at the ground, therefore, is no measure at all of the stresses to which the more exposed crowns are subjected.

With the quantities shown by Table 30 as a guide, then, but with the factors which influence the relative values taken into consideration, the following observations may be safely made:

(1) The evaporation stresses to which seedlings may be subjected in a dense forest, even in a region of high winter-sunshine percentages, are appreciable for the total period of soil freezing, but undoubtedly become wholly insignificant with a snow blanket. On the other hand, the dense forest, as it commonly is on a slope facing the north, creates for its larger and more exposed trees a winter drought of long duration coupled with considerable evaporation stress. It is believed that the capacity for resisting the consequent drying out is, perhaps, a better measure of drought resistance than any ability which has, in the course of this study, been shown during warmer periods, because no severe summer drought has been encountered. The winter drought, as it affects the older trees in a dense stand, not only is of yearly occurrence, but seems to be almost independent of precipitation, except as the presence of a general snow blanket may increase the atmospheric humidity.

The trees which tolerate or in fact thrive under such conditions in this region are spruce and Douglas fir—the so-called "shade-tolerant" species. It is too early to draw a clear line between the two, although it is believed that the spruce is the more resistant of the two. To these conditions yellow pine is plainly unadapted, but limber pine fits in moderately well.

Thus, for the first few years in the life of the trees on the sites which produce the very dense forest, the conditions may give almost equal encouragement to several species. Although dense shade is more favorable to the tolerant spruce, Douglas fir and even the pines may become established because of deeper rooting and more ready adaptability to surface drought. On the other hand, when the trees begin to be exposed above the snow blanket, and the moisture supply is no longer controlled by depth of root, the struggle becomes almost altogether one of resistance to long-continued drying. The evidence presented in the paper on "Physiological Requirements of Rocky Mountain Trees," (*6*) which tends to show the greater photosynthetic activity of spruce, and which suggests that a high osmotic pressure is more normal in that species and, hence, less likely to be injurious, is applicable in this connection. The species which carries a dense sap, especially in a limited light, not only begins to resist evaporation earlier, but is least liable to injury should drying with all species be carried to the same point.

It is therefore believed that the struggle which determines the composition of the forest may continue long after the seedling stage is passed. The evidence, which has already been used more or less, indicates that on north slopes at middle elevations the original forest may be largely of Douglas fir, with considerable pine; but that in the second generation, from the sapling stage upward, spruce predominates, and must therefore form the climax.

(2) That the spruce forest is subjected to, or that spruce may tolerate, winter evaporation stresses of great magnitude is shown by the high spruce burn (W-D) and timberline stations. In neither place can there be much question that the soil freezing is severe and continuous, with no chance for even surface melting. The quantities indicated—around 400 grams of evaporation—are probably more nearly correct than any others that can be given, and must represent the approximate limit of resistance in plant growth. It must, however, be conceded that, after a certain amount of drying of the leaves has occurred, the process is halted until the atmospheric conditions become more severe (warmer or dryer, or both), so that beyond a certain time mere continuance of the stress does not comprise an endurance test.

The fact that both limber pine and bristlecone pine follow spruce nearly to the most exposed of its habitats seems to indicate either that the long exposure, as has just been depicted, is not so severe as it seems, or that these species possess a phenomenal ability to resist transpiration. The sum of the evidence necessitates falling back on the belief that neither of the pines occurs where the long winter drought, which is possible at a high elevation, is entirely unbroken. This is certainly the explanation of the conditions recorded on the high ridge (F-13). Moreover, this record is open to serious question from two angles.

(3) The considerably higher winter evaporation at the Wagon Wheel Gap stations, as compared with similarly situated ones at

Fremont, is not without its significance. (Compare W-A1 with F-9, W-A2 with F-2.) It is due both to a drier atmosphere and to greater prolongation of the soil freezing as a result of lower temperatures at Wagon Wheel Gap. Although the forest conditions at the north-slope stations are not dissimilar in the two localities, it is believed to be true, generally speaking, that both spruce and fir are pushed to somewhat lower levels in the Wagon Wheel Gap locality. On the south exposures, there is at Fremont a yellow pine forest with conditions slightly encouraging Douglas fir, and at Wagon Wheel Gap, a Douglas fir forest with considerable bristlecone pine of all ages. It is believed that the generally lower temperatures at Wagon Wheel Gap would not alone explain the complete absence of yellow pine, but that the greater possibility of destructive winter evaporation does explain it in part.

(4) Examination of the data for yellow pine sites, in the light of what has been shown as to probabilities of relief through frequent thawing, indicates that this species thrives best where the danger of winter drying is least. There is a slight suggestion that the lower limit, as approached at Station M-1, may be reached through an increase in this risk; but there is insufficient data on the plains conditions to justify this statement. It is known that the level plains freeze for considerable periods,[9] and that during such periods the evaporation may be relatively high; but as to the severity of this combination no estimate can as yet be made. It is evident that the Nebraska sandhills are not extraordinarily severe in this respect, and there is no evidence of winter killing in the established yellow pine plantations there. Stations F–12 and F–4 both appear to represent conditions which, as a result largely of the shade cast by the pine trees themselves, are approaching too great severity for the reproduction of that species.

The importance of this factor of winter evaporation with reference to yellow pine is clearly shown by the frequency with which pine forests in various parts of the range are injured by winter killing, which is rarely "killing" except to the foilage, but must detract greatly from the vitality of the trees affected and ultimately decrease their chances for predominance. It has been seen currently that the very lowest evaporation stress occurs on an open, smooth, southerly slope (F-2), and under these conditions the stand is almost pure yellow pine. It is significant that on other parts of this slope and on other similar slopes, which are strewn with boulders, a great deal more injury from winter drying has been noted; and that all such boulder-strewn areas develop a large proportion of Douglas fir, which is less seriously injured than is the western yellow pine.

To sum up: Successively lower temperatures in the types from pine to spruce, particularly well measured by the soil temperatures which show the effects of insolation or its lack, lead to more continuous, more severe, and more certain periods of soil freezing each winter. Consequently, other conditions being at all equal, the fully exposed trees growing on the coldest sites or in the coldest types are most liable to a winter drying so extensive as to be injurious to the trees and probably to affect the composition of the forest. Exactly the reverse is likely to be true with respect to conditions affecting young seedlings small enough to be protected by the snow blanket. Al-

[9] At Laramie, Wyo., the soil temperature at a depth of 3 feet is normally below freezing for 3 months, January to March.

though low temperatures tend to prolong the drought, they are usually conducive to the conservation of moisture in summer, and to the production of dense forests in which the individuals to some extent mutually protect each other from drying. Low air temperatures and high humidity reduce the relative drying power of the atmosphere and limit the extent of drying of the foliage. This may be more decisive than the duration of the drying or the possible amount of drying as indicated by an instrument which does not progressively increase its resistance. The physiological data, however, have indicated that the greatest degree of desiccation occurs in spruce in its coldest habitats.

Because of the many factors complicating the situation, both as to the actuality of complete freezing in the soil, and as to the stress to which the tree is being subjected, only the most direct and thorough measurements of both soil and atmospheric conditions can be entirely convincing. It is believed, however, that the factors have been sufficiently weighed to make it safe to say that spruce in the Rocky Mountains is subjected to winter drying of a degree and duration which would be quickly fatal to yellow pine. The importance of this factor with yellow pine, the writer is convinced, can not be overdrawn. It is only to be hoped that no error has been made in assuming that the other species, which less frequently show winter injury, are nevertheless susceptible in a degree, and that their distribution is affected thereby. As these drought conditions, however, result indirectly from and are so much involved with temperatures, it is still possible that temperatures in their growing-season relations control more definitely the composition of the forest types.

Surface temperatures.—It has been indicated that the soil temperatures at a depth of one foot bring out more fully than do the air temperatures the contrasts between sites which result primarily from differences in insolation and secondarily from differences in the densities of the stands, and the possible consequences of a marked cooling of the soil have just been depicted. There must remain, however, some question as to whether the critical effects of the temperature differences are felt more keenly in the winter than in the summer. It may, perhaps, clarify the situation and at the same time offer an explanation of certain successional changes if the statement is repeated that except in the typical, open and unblanketed yellow pine sites the effect of severe soil freezing can hardly be felt until the seedling has developed considerable height, and is then probably felt increasingly as the tree assumes a more exposed position. Whatever influence may be expected from surface temperatures on the contrary and from certain degrees of surface drying which must accompany them, is the influence exerted upon very young seedlings. The experience of planting shows conclusively that trees 3 or 4 years old are often immune to what are conceived to be the critical surface conditions.

As just suggested, extremely high surface temperatures may be directly fatal, or the extreme dryness resulting from superheating of the soil may tend to desiccate young trees, even though the roots are adequately supplied with moisture. As the direct or indirect influences of high temperatures are necessary concomitants, it is probable that injuries in both ways often occur concurrently. Even in closely controlled experiments, it will always be difficult to determine whether injury to seedlings is the direct result of superheating and coagulation of the protoplasm, or results primarily from an excessive transpiration rate induced by the high temperature.

In "Physiological Requirements of Rocky Mountain Trees" (*6*) the results of a heating experiment are reported, which show that seedlings of Douglas fir and yellow pine, on the one hand, are relatively much more resistant to this form of injury than the seedlings of Engelmann spruce and lodgepole pine. In this test superheating was induced by direct sunlight in a warm greenhouse, and the high temperatures were usually maintained for several hours each day. A temperature of about 130° F, as measured by a blackened thermometer laid on the surface of the soil, appeared to represent the critical point. The form of injury was invariably wilting, first shown by the collapse of the stem of the seedling at the ground-line. In view of the fact that the pans containing the wettest soil showed little injury, the conclusion can hardly be avoided that in this test excessive transpiration and to some extent desiccation of the soil surface and of the stems at this level, were the primary causes of injury. Therefore, yellow pine and Douglas fir seedlings withstood injury because they are stouter and more deeply rooted than spruce and lodgepole pine seedlings of the same age.

Illustrating the complexity of the problem that is encountered when the effects of surface temperatures in the field must be noted, a more recent test may be cited.[10] In this test very high temperatures were secured by placing the pots of seedlings in close proximity to an electric heating coil with its radiation of long wave length. With exposures of about 10 minutes, little or no injury was shown until the pots were brought close enough to the coil so that a temperature of 140° F. was recorded by a thermometer at the level of the cotyledons. Temperatures as high as 130° F. could be endured for much longer periods without marked injury. It therefore appears that a temperature of 140° F. or slightly higher, is directly injurious in a period too short to permit much transpiration loss. Under these conditions the cotyledons of Douglas fir shriveled markedly, and usually with fatal results to the entire seedling; yellow pine seedlings were next in order, but the injury was usually localized in portions of the leaves, and not so likely to be fatal; spruce seedlings shriveled completely, like those of Douglas fir, but much less frequently; within the range of the tests lodgepole pine seedlings were practically immune to this heat injury.

With this view of the problem, and a realization of its intricacy and the need for most careful and complete field records, there can be but one object in introducing the available data on the surface temperatures of sites in the Pikes Peak region, namely to show the magnitude of the variations in surface temperatures, as compared with the variations in the temperatures at a depth of 1 foot. After considering these few data, and the facts which have been stated above relative to the resistance of the several species to direct and indirect heat influences, it will be apparent that while high temperatures bring out a nice distinction between yellow pine and Douglas fir, the line between fir and spruce is probably drawn on a different basis, most probably on the basis of the moisture relations alone.

The determination of the exact temperature of the surface soil, during insolation, is next to impossible. It is practically possible

[10] U. S. Dept. Bul. 1263, Relative Resistance of Tree Seedlings to Excessive Heat.

only to determine the temperature of some object lying on the surface, exposed to the same insolation as the surface and presumably absorbing somewhat the same amount of the radiant energy. In this study the Freiz soil thermograph has been used, the bulb (1 inch in diameter by about 12 inches long) being laid up and down the slope and being about half imbedded in the surface material. Corrections for the thermograph readings have been secured by exposing mercurial thermometers in the same way the thermograph bulbs were exposed. Frequent readings have been made when both thermograph and thermometer would be affected mainly by the soil with which they were in contact. The temperatures, therefore, at correction points, are considerably below the maxima secured in sunlight, and this introduces another possible source of error when the maxima of the thermographs are used. The observations in 1920 extended from May to September, inclusive; but, as the July temperatures were greatly in excess of those for other months, only these need be considered. (Table 31.) It is possible, with the corrections obtained through the 5 months' period, to estimate the maxima from the thermograph traces very closely, except in the record for Station F–5, where the instrument behaved very erratically.

TABLE 31.—*Soil temperatures in July, 1920, in degrees Fahrenheit.*

[Numbers in parenthesis indicate the decade or day of month in which maxima occurred.]

Station No.	Type.	Maximum surface temperatures.		
		Monthly mean.	Highest decade.	Highest day.
F-12	Western yellow pine ridge	112.57	(1) 119.97	(22) 130.6
F-4	Pine-fir east slope	116.68	(1) 124.75	(23) 142.7
F-6	Limber pine northwest slope	94.45	(1) 98.81	(2) 136.5
F-5	Spruce bottom	84.24	(2) 89.71	(2) 110.5

Even though these data do not cover a great variety of conditions, it is possible to make certain generalizations, which at least indicate the importance of the maximum temperatures attained by the soil surface.

(1) The extreme temperatures which may be expected at the surface of the soil vary, as between differently insolated sites, by three to four times as wide a margin as do the corresponding 1-foot soil temperatures. For example, the mean July temperature for Station F–5 (Table 27) is 49.0°, and for Station F–12 is 58.3°, a difference of 9.3°; but the difference in their surface temperatures is 28.3°. It is thus seen that the surface temperatures are needed to give an adequate idea of the possible effects of direct insolation.

(2) In this locality it seems that an east exposure may be liable to greater extremes of temperature than a flat or slightly southerly exposure, simply because of the normal tendency of clouds to accumulate as the day advances. Thus the month in question gave 8,336 minutes of sunshine before noon, and only 3,027 after noon, the hours from 7 to 10 a. m. being about 88 per cent clear. Likewise,

a west exposure is frequently prevented from reaching a high surface temperature; but, if sunshine continues all day, its temperature, as a natural consequence, may be very high after the air has become well warmed.

SUNSHINE.

Since the control station was established in 1910 the duration of sunshine has been measured there by means of the standard Weather Bureau electric-thermometric recorder. At stations in the various forest types it has not been measured long enough to give records of much value. Hence it is believed that, in comparing the types, the indirect evidences of insolation may perhaps be more useful, though it is not desirable to reach any such decision without exhaustive trial. In short, then, the available record is only for the control station, which gives a measure of sunshine values for the general locality at a middle elevation, and for a similar period at Wagon Wheel Gap. These data are valuable in the general study of the climate, and currently in studying such other phenomena as soil temperatures. They may prevent reaching wrong conclusions as to the import of other factors.

Sunshine at the control station.—This record is made up wholly from the graph written by the pen of the triple register, with almost no interpolation, and without the additions which are termed "twilight corrections," and which are sometimes employed to compensate for the lag in the response of the recorder—or, perhaps it might better be said, its lack of response—when the sun is very close to the horizon. The study has not been intensive enough to permit the application of such corrections, although it may be roughly estimated that they would add, on the average, 30 minutes each day to the duration of sunshine, increasing the yearly average by 11,000 minutes or about 5 per cent of the possible. Because of the failure to apply these corrections, the record is not strictly comparable with the Wagon Wheel Gap record or with Weather Bureau records in general.

The possible duration of sunshine at the point where the recorder has been located was determined by observations of sunrise and sunset at that point on almost every clear day during 1910 and 1911. By plotting these hours, the length of each day, decade, and month was computed. The day at this location is considerably shorter than it would be on a plain in the same latitude, as the sun sets at an elevation of nearly 10°, and on the longest days also appears first at a slight elevation.

The basis at Wagon Wheel Gap is the same, namely, short days caused by a high horizon to the west, which on the average shortens the day by more than two hours. Here, however, closer observation has permitted twilight corrections.

In Table 32, the actual sunshine for each decade of record is shown, together with the mean for each decade and the percentage relation of this mean to the possible. It is desirable to call attention to the fact that the records of the last two years have very materially altered the averages, especially for May and June.

TABLE 32.—*Total minutes of sunshine at the control station (F-1).*

[Height of instrument above ground, 22 feet.]

Year.	Decade.	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Total annual.	Total growing season.
1910	1		3,377	5,020	4,718	4,314	6,255	5,747	3,402	5,856	4,790	2,434	2,248		
	2		3,383	4,756	4,424	4,190	6,615	4,741	4,419	3,271	3,370	593	3,215		
	3		3,567	6,261	4,992	5,379	5,841	5,447	5,239	4,391	4,356	2,823	4,479		
	Month		10,327	16,037	14,134	13,883	18,711	15,935	13,060	13,518	12,516	5,850	9,942	[1] 157,451	53,562
1911	1	4,436	4,739	5,358	5,825	5,944	7,132	5,922	4,845	3,663	3,955	2,864	4,307		
	2	4,654	4,263	4,907	6,173	6,160	5,726	6,655	2,831	3,913	3,857	2,947	3,026		
	3	4,448	3,998	6,051	4,992	6,318	7,043	5,585	3,083	3,007	2,674	3,746	4,406		
	Month	13,538	13,000	16,316	16,990	18,422	19,901	18,162	10,759	10,583	10,486	9,557	11,739	169,453	52,485
1912	1	4,722	4,401	5,371	6,256	5,686	5,509	6,611	5,551	5,565	3,795	3,734	3,768		
	2	4,506	4,399	5,478	5,636	5,387	4,634	4,977	4,469	3,065	5,037	4,087	3,871		
	3	5,363	4,225	6,227	6,261	7,602	6,119	5,192	6,082	3,753	3,904	3,353	3,586		
	Month	14,591	13,025	17,076	18,153	18,675	16,262	16,780	16,102	12,383	12,736	11,174	11,225	178,182	54,709
1913	1	2,654	3,354	4,409	2,842	3,178	2,145	5,004	4,569	3,219	2,704	4,048	[2] 3,150		
	2	3,627	3,223	3,286	4,773	3,985	3,686	3,812	3,357	3,294	1,629	3,350	[2] 3,300		
	3	3,753	2,762	4,150	3,572	5,442	5,134	4,844	3,787	1,568	3,330	2,927	3,673		
	Month	10,034	9,339	11,845	11,187	12,605	10,965	13,660	11,713	8,081	7,663	10,325	10,123	127,540	39,557
1914	1	3,095			2,436	4,404	4,959	[2] 3,767	2,506	3,636	5,417	5,359	3,212		
	2	3,417			4,115	2,113	4,422	2,947	3,860	3,599	5,125	4,585			
	3				2,604	5,311	6,166	2,905	2,822	3,837	4,997	4,503			
	Month				9,155	11,828	15,547	9,619	9,188	11,072	15,539	14,447			37,990
1915	1			2,753	3,499	3,687	3,978	5,144	3,646	4,020	4,794	3,491	3,448		
	2			3,132	2,404	4,360	5,651	4,437	4,062	4,764	3,136	3,717	3,514		
	3			3,435	3,362	4,548	3,884	4,203	4,712	3,961	5,363	3,825	3,020		
	Month			9,320	9,265	12,595	13,513	13,784	12,420	12,745	13,293	11,033	9,982		43,737
1916	1	3,802	4,232	4,140	3,937	5,611	4,358	5,273	4,474	4,560	3,690	4,460	3,625		
	2	2,405	4,828	5,088	4,012	3,425	4,936	4,311	3,286	3,537	2,132	3,528	2,992		
	3	3,190	4,121	4,454	2,509	6,752	6,039	3,756	3,629	3,777	5,018	4,269	4,170		
	Month	9,397	13,181	13,682	10,458	15,788	15,333	13,340	11,389	11,874	10,840	12,257	10,787	148,326	44,622

1917	1	4,196	4,353	4,162	4,900	2,745	5,159	3,983	3,888	3,321	4,253	4,552	3,177		
	2	3,480	3,417	4,975	3,754	4,026	5,279	4,229	2,647	3,212	3,725	3,349	3,903		
	3	4,601	2,841	5,419	3,692	1,851	5,369	4,720	3,964	3,909	2,613	3,431	4,144		
	Month	12,277	10,611	14,556	12,346	8,622	15,807	12,932	10,499	10,442	10,591	11,332	11,224	141,239	42,559
1918	1	3,175	4,568	5,067	2,611	3,912	2,897	2,660	3,109	1,866					
	2	2,759	4,605	5,366	2,768	4,655	3,730	2,820	3,730	3,218					
	3	3,747	3,153	4,840	4,402	2,478	3,673	4,510	4,182						
	Month	9,681	12,326	15,273	9,781	11,045	10,300	9,990	11,021						33,177
1919	1					2,596	1,611	4,578	3,881	3,635	3,339	3,449	3,363		
	2					3,368	3,797	3,770	5,401	2,860	3,357	4,020	4,063		
	3					4,215	4,689	4,818	4,735	4,558	4,418	3,121	4,586		
	Month					10,179	10,097	13,166	14,017	10,853	11,114	10,590	12,012		40,915
1920	1	2,991	3,573	3,585	4,663	3,181	2,821	3,671	3,648	2,888	3,783	2,238	2,945		
	2	3,923	4,598	5,024	3,549	2,331	3,112	3,678	3,325	4,227	3,783	2,409	2,596		
	3	4,475	3,341	5,299	4,002	4,086	2,970	4,014	4,731	4,580	2,876	3,094	2,577		
	Month	11,389	11,512	13,908	12,214	9,598	8,903	11,363	11,704	11,695	10,442	7,741	8,118	128,587	34,858
1921	1	3,163	3,147	3,412	4,201	4,655	2,744	5,274							
	2	3,401	4,096	4,069	3,947	3,471	4,171	5,490							
	3	3,944	3,925	4,457	4,691	5,395	4,448	6,933							
	Month	10,508	11,168	11,938	12,839	13,521	11,363	17,697							
Average to July 31, 1921	1	3,582	3,972	4,328	4,172	4,159	4,131	4,803	3,956	3,839	4,052	3,663	3,324		
	2	3,575	4,090	4,608	4,141	3,956	4,647	4,322	3,762	3,542	3,515	3,258	3,387		
	3	4,190	3,548	5,059	4,098	4,948	5,115	4,744	4,270	3,734	3,955	3,509	3,849		
	Month	11,347	11,610	13,995	12,411	13,063	13,893	13,869	11,988	11,115	11,522	10,430	10,560	145,803	43,589
Mean per cent of possible.[3]	1	69	71	71	62	58	55	65	55	57	66	66	64		
	2	68	71	74	60	55	62	58	54	54	59	60	66		
	3	70	72	71	58	61	68	59	56	60	62	66	68		
	Month	69	71	72	60	58	62	61	55	57	62	64	66	62.6	59.0

[1] Twelve months to January, 1911.
[2] Decade value obtained by proportion, two to four days' record missing.
[3] Algebraic means derived from average figures above, for decades, months, growing-season, and year

TABLE 33.—*Distribution, by hours, of sunshine in representative decades at Station F-1.*

[Average, 1910–1918, inclusive.]

Period.	Sunshine duration in minutes.													
	For hour ending (a. m.)—							For hour ending (p. m.)—						
	6	7	8	9	10	11	12 noon.	1	2	3	4	5	6	7
First decade, March	.....	2.5	28.9	46.7	53.7	53.8	53.3	54.8	51.4	47.7	43.7	18.9	.....	.....
Last, June	1.6	42.7	52.1	52.5	52.9	51.8	51	48.6	42.5	38.8	37.8	35.4	30.3	6.6
Middle, August	.....	18.9	44.6	51.8	49.5	41.9	33.7	28.6	26.6	21.9	17.1	16.8	11.6	.3
Third decade, April	.....	19	37.6	39	42.3	44	42.3	40.5	40.4	36	27.1	22.7	13.2	.2

To show more clearly the immediate causes for high and low sunshine percentages, there are given in Table 33 and Figure 9 the distribution of sunlight by hours for representative decades.

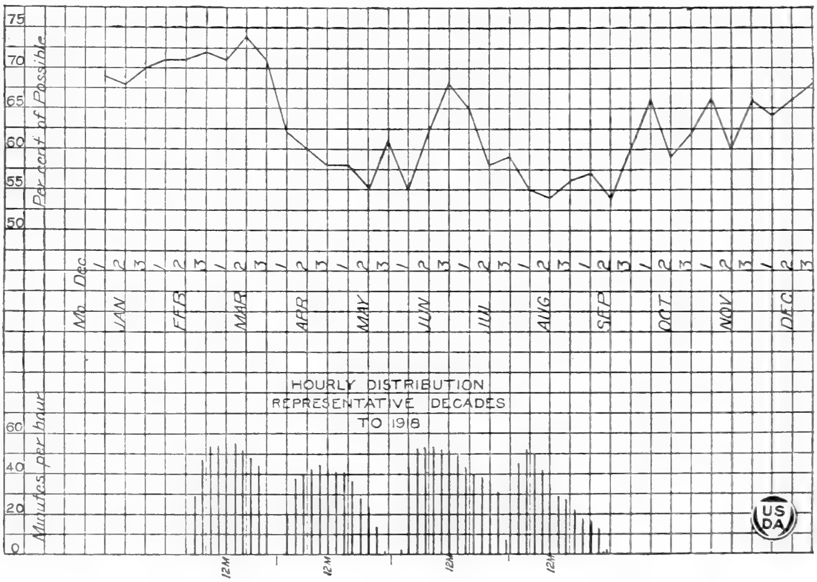

FIG. 9.—Normal sunshine distribution at control to July, 1921.

The first three months of the year, when anticyclonic winds prevail, are characterized by high percentages of sunshine, which reach a climax at the middle of March. After this, as storm centers move eastward in a more northerly path, the humidity of the air is greatly increased, and this makes itself felt in a great deal of foggy weather in April or May, accompanied by much snow or rain. In general, a tendency is noted for the fog to be dissipated in the middle of the day. The control station is at such an elevation as to be frequently engulfed by the clouds which hang over the plains country, while above this elevation it may be clear. Or, again, it may be clear over the plains, but the rising air currents during the day induce the formation of clouds over the mountains.

As the storm centers move farther north, this locality is characterized again by dry weather, which reaches a culmination at the end of June, after which time the summer rains begin. Although the air movements at midsummer are influenced by the position of the continental low-pressure area, the phenomenon of clouds is really a local one, and those that form about Pikes Peak are the result of daily convectional currents. Soon after noon precipitation is likely to occur, and this so cools the ground that convection ceases; the rest of the day is often but not regularly clear. This phenomenon is of interest in that an easterly slope during this period may receive almost as much insolation as a south slope. The autumn is characterized by gradually decreasing cloudiness, but this is interrupted by storm periods about the middle of each fall month. This apparent regularity of the storm periods would probably disappear with a longer record, although the mid-September storm is considered typical of the whole region and usually brings the first snow.

Comparative sunshine in central and southern Colorado.—In Table 34 the mean sunshine percentages are shown for the Fremont and Wagon Wheel Gap stations. The record for the latter is brought up to October, 1920.

TABLE 34.—*Sunshine at Fremont and Wagon Wheel Gap stations.*

Station.	Elevation.	Percentages of the possible, by months.												Year.	Growing season.
		January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.		
	Feet.														
Fremont (F-1)	8,856	69	71	72	60	58	62	61	55	57	62	64	66	63	59
Wagon Wheel Gap (W-C)	9,237	57	59	58	52	55	56	44	48	52	59	61	57	55	50

The sunshine percentage at Wagon Wheel Gap approaches that at Fremont only in May, when the humidity is very low, and from September to November, when clear weather is characteristic of the Rocky Mountain region. The winter at Wagon Wheel Gap is characterized by much less sunshine and more precipitation. The depression is very great in July also, when the rainy season reaches its height, which is about a month earlier than at Fremont.

The general comparison indicates that the vicinity of Pikes Peak is one of high sunshine percentages, a condition which is of especial importance in the winter in facilitating evaporation. As we have seen, this influence on south exposures may be just about counterbalanced by the action of the sunlight in thawing the soil; but where the sunlight does not reach the ground its influence must be solely to increase transpiration.

PRECIPITATION.

Precipitation at the control station, by seasons.—The precipitation record for the control station is complete for the entire period of operation of the station, beginning with January, 1910, and ending with July 31, 1921. Although this record has been obtained as carefully as possible with the 8-inch standard gauge, supplemented by the tipping-bucket gauge during the open season of each year, it is considered to be, like all other precipitation records, only an approximate statement of conditions. Because of this general weakness, it has not been thought necessary to check up minor discrepancies which may exist in the original tabulations of the data. A further reason for not attempting any high degree of precision in the record is the realization that the total precipitation can show only in the most general way the amount of water available for plant growth, as this amount will depend perhaps as much on soil properties as on water received.

TABLE 35.—*Monthly and annual precipitation at the control station, in inches.*

Year.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Total annual	Total growing season[1]
1910	0.01	0.44	0.51.	1.18	2.56	1.89	4.47	3.27	1.01	0.86	0.53	0.61	17.34	9.97
1911	.06	1.56	1.67	2.20	.93	1.21	5.42	2.01	1.44	1.45	.61	1.13	19.69	9.12
1912	.06	1.12	.60	1.56	2.67	4.04	4.62	1.82	1.17	1.59	.17	.22	19.64	10.87
1913	.95	.99	1.04	2.06	1.76	3.91	2.18	3.92	3.32	1.06	.32	5.01	26.52	11.12
1914	[2] .35	......	......	4.01	2.40	4.05	6.76	2.06	.23	1.98	.10	......	......	12.95
1915	......	......	1.66	3.53	3.43	3.09	2.12	4.78	2.18	.70	.37	.40	......	10.74
1916	.40	.03	.97	4.54	1.99	1.83	4.72	3.11	.48	.54	.63	.40	19.64	9.82
1917	.25	1.08	1.83	1.77	3.77	.79	1.50	3.87	1.66	.26	.25	.18	17.21	6.71
1918	.96	.94	1.32	2.68	.52	3.70	3.13	3.32	......	......	......	......	......	[3] 11.42
1919	......	......	......	......	.49	.87	4.16	1.46	1.82	.75	.94	.24	......	6.83
1920	.74	1.12	.59	1.86	2.23	1.88	2.63	6.39	1.17	1.87	.27	.73	21.28	11.74
1921	1.27	.32	1.20	7.22	1.07	8.17	4.70	......	......	......	......	......	......	......
Mean	.50	.84	1.12	2.96	1.98	2.95	3.87	3.27	1.45	1.11	.42	.99	21.46	10.57

[1] Prior to 1918 growing-season totals are obtained by using one-third the total for September; thereafter the actual amount September 1–10 is used.
[2] Based on 0.23 inch, January 1–20.
[3] Based on actual fall of 1.27 inches, September 1–10.

The complete record for the control station, by months, is shown in Table 35. In this, as in all the succeeding records, the total for the growing season has been obtained by adding to the amounts for June, July, and August one-third the total for September. In fact, the greater part of the September precipitation, or at least considerably more than one-third, belongs to the second decade; hence this computation is only an approximation to the truth.

Perhaps the most important thing shown by this table is that normally almost one-half of the total precipitation occurs during the growing season. In nine years the least amount in this 102-day period has been approximately 7 and the greatest 13 inches. To the 7 inches falling in 1917 there may be added, for all practical purposes, the 3.77 inches in May, which left the ground in a soaked condition up to June 5, and which materially assisted in tiding over the marked drought which followed that date. Notwithstanding this, however, the soil moisture at the end of the growing season reached a lower point than has been recorded in previous years, and it may safely be said that with less than this amount in the growing season there would be danger of drought conditions which might affect the composition of established stands. Unfortunately there were no soil-moisture measurements made in the dry summer of 1919.

In brief, then, the summer precipitation is ordinarily quite adequate to maintain the soil of the most exposed sites at this elevation in very good condition. The winter precipitation is very inadequate, either to protect the soil from severe freezing or to store up moisture for late spring use, except on north slopes and under dense stands. Probably there is about as much water here, in the form of snow to be melted in the spring, as the soil will hold within reach of the roots.

Although the individual years do not vary in precipitation much more widely than in other conditions, the months do. Thus a long record seems necessary to establish even an approximate "normal" precipitation for a given month. The addition of the 1918 record to the record for the eight preceding years created two new extremes, namely, a new high for January and a new low for May, and the growing-season total was the highest of record except for 1914. Again, the year 1921, through July, created three new monthly maxima, and the last 12 months of record show a total of 34.38 inches.

Comparative precipitation.—No serious effort has been made to compare the precipitation in the several forest types in the vicinity of the Fremont Station, for it has been assumed that, so far as topography might influence the actual fall, differences would be compensating over any long period. It is perfectly evident that one spot may at one time receive from summer rains much more moisture than another only a few hundred feet away, and such a variation may not be compensated for a long time. However, where the difference is marked, the excess at a given point is likely to be largely wasted in surface run-off.

From March, 1910, to February, 1912, at three stations within a radius of a few hundred feet gages were maintained on towers so situated that there was almost no interference by branches of trees, but with varying degrees of protection from wind. Table 36 gives the mean annual catches that were recorded.

TABLE 36.—*Precipitation catches at three stations, 1910–1912.*

Station No.	Type.	Mean annual precipitation.
		Inches.
F-1A	Control, open	19.25
F-2A	South-slope western yellow pine	18.95
F-3A	Canyon spruce	20.12

For the period April, 1916, to February, 1917, a gage on the ground at Station F–9, under dense cover of fir and spruce and less than half a mile from the control station, gave a catch of 22.73 inches as compared with 19.32 inches at the control station. The excess under canopy was very great from certain rains on account of some spruce branches, but with snow a deficit was generally created by these same branches. A very different result would doubtless have been obtained 2 feet farther from the tree whose branches most directly influenced the path of falling rain or snow.

If the amounts of snow on the ground in the different types are compared for the late spring period when such snow may represent an asset for the coming growing season, the greatest contrasts may be obtained. It is not the purpose of the writer to discuss this feature here. Moreover, because of lack of adequate data, it is not possible to give any numerical weight to the retained precipitation of the various forest types here studied. However, the data given in Table 37, reproduced from the preliminary report on this project, indicate the importance which must be attached to this subject in considering precipitation data.

TABLE 37.—*Snow on the ground under various conditions of exposure, winter 1910–11.*

[Mean snow depth, inches.]

Station No.	Type.	November.	December.	January.	February.	March.	April.	May.
F-1	Control, open ridge	0.2	0.6	0.1	3.5	1.1	0.6	0.0
F-2	South-slope western yellow pine	.2	.5	.1	3.5	1.6	.6	.0
F-3	Canyon spruce [1]	.5	1.5	.6	3.0	6.2	1.7	.0
W-C	Open east slope	4.1	10.4	20.0	20.3	26.1	9.2	.0
W-A1	North-slope Douglas fir	13.4	17.1	23.5	21.2	36.4	28.4	3.4
W-A2	South-slope Douglas fir	.6	4.2	5.0	.9	8.8	.1	.0
W-D	Higher spruce bench	11.8	16.9	24.6	24.5	44.5	36.3	13.8

[1] The ground is the lower edge of a northeasterly slope.

The precipitation in various forest types within the range of this study may now be considered, as shown in Table 38. For the control station the complete record to the end of 1917 is used. For other stations having an unbroken record from 1910 to 1917 the same months are eliminated as are missing from the record of the control station. When the compared record is considerably broken, all that is available is used.

In the Pikes Peak series (C–1, M–1, F–1, L–1) the seasonal variations are very similar to those at the control station. The total amount of precipitation for the year or any shorter period increases fairly regularly with increased elevation, except that in the step from the Plains type to the yellow pine type the increase is generally larger than elsewhere. This, it is thought, may be due to the exposure of the Plains station, which is nearly always subject to north and east winds during precipitation. These winds make it more difficult to secure a complete catch. The yellow pine type for almost the entire winter period, moreover, shows more precipitation than the much higher control station. No adequate explanation of this can be offered.

The yellow pine types of the Black Hills and of southern Colorado (D–1 and P–1, respectively), which support yellow pine stands of far better development than those of the Pikes Peak region, have the benefit of a much greater total precipitation; but this excess is almost wholly outside the growing season. It may be said that the heavier winter snows are of direct benefit to seedlings, and that they protect the older trees by preventing the freezing of the soil. If, however, the low rainfall in southern Colorado during April, May, and June is considered, it is readily seen, as has been pointed out by Pearson (*18*), that the moisture of winter snows may not hold over till summer and hence can not directly affect the rate of growth. In the Black Hills it probably does not hold over, but melts early at that low elevation, but the spring precipitation is itself abundant and undoubtedly is an important supplement to that of the growing season. Nevertheless, in the search for conditions which may influence the growth of all species probably none has been found which is more important than the winter deficit of precipitation in the Pikes Peak region, when considered in connection with high winds and atmospheric dryness.

One hundred miles farther north, in a similar topographic position (Station F–17), this winter deficit is far less apparent, though the high precipitation for this station may possibly be due to purely local conditions which encourage a transport of snow from the high hills round about.

TABLE 38.—*Precipitation, in inches, in various localities and forest types.*

[For the period of record at the control station between 1910 and 1917.]

Station No.	Type.	Locality.	Elevation.	Period.	Record by months. Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Total annual.	Total growing season.[1]
			Feet.															
C-1	Plains	Pikes Peak	6,098	Same as F-1	0.16	0.80	0.56	2.30	1.90	1.93	2.83	1.88	0.79	0.46	0.17	0.56	[2] 14.34	6.90
M-1	Western yellow pine.	do	7,200	1911-1917, 3 months missing.	.47	.92	.96	2.72	2.84	1.80	3.49	2.59	1.18	1.15	.53	1.24	19.89	8.27
D-1	do	Black Hills	4,535	Same as F-1[3]	1.04	1.22	2.99	3.50	3.56	2.97	2.60	2.72	2.21	2.31	1.00	1.38	27.50	9.03
P-1	do	Southern Colorado.	7,108	Jan., 1907, to Mar., 1917, 5 months missing.	2.72	1.94	1.80	1.90	1.08	1.12	3.20	2.61	1.83	3.36	1.08	1.74	24.38	7.54
F-1	Control	Pikes Peak	8,836	1910-1917[4]	.30	.87	1.18	2.61	2.44	2.60	3.97	3.10	1.44	1.06	.37	1.14	21.08	10.15
F-17	Douglas fir	Northern Colorado.	9,300	1910-1917, 4 months missing.	1.39	1.69	1.74	2.79	2.80	2.02	3.61	2.29	2.35	2.20	.91	2.44	26.23	8.70
W-A1	do	Rio Grande	[5] 10,000	Nov., 1910, to Dec., 1917.	1.57	1.33	1.47	2.13	1.14	1.37	3.69	2.37	1.76	2.13	.94	1.40	21.30	8.02
L-1	Spruce	Pikes Peak	10,265	Same as F-1	.56	.96	1.49	2.95	2.64	2.72	4.67	3.79	1.37	1.50	.46	1.53	[6] 24.64	11.64
W-F	do	Rio Grande	11,500	Nov., 1913, to Dec., 1917.	3.06	1.57	1.77	3.98	1.91	.73	4.00	2.37	1.88	2.42	1.61	2.69	27.99	7.73
L-2	Spruce-lodgepole	Continental Divide.	10,248	Same as F-1	1.66	1.13	1.09	1.43	1.32	1.27	1.33	1.56	1.22	1.40	.66	1.29	15.36	4.57
F-18	Lodgepole pine	Northern Colorado.	8,560	do	1.72	1.47	1.58	1.70	1.60	1.01	2.48	1.30	1.85	1.39	.85	2.05	19.00	5.41
N-1	do	Western slope	8,800	do	2.00	1.39	1.31	1.39	1.39	1.15	2.29	1.24	1.50	1.27	1.00	1.09	17.02	5.18
F-11	do	Southern Wyoming.	9,015	1910-1917, 16 months missing.	1.11	1.80	1.25	1.60	1.36	.98	1.47	1.21	1.62	.90	1.01	1.23	15.54	4.20

[1] Growing-season totals obtained by taking one-third the September amount.
[2] December, 1914, substituted for December, 1910.
[3] Normal to 1916, 14.59 inches.
[4] Except February, March, December, 1914, and January, February, 1915.
[5] Mean precipitation determined by gages at 9,600 and 10,900, the difference between the two averaging less than 1 inch per year.
[6] Normal, 22 years to 1916, 24.98 inches.

Somewhat similar conditions are noted at the middle elevation at Wagon Wheel Gap (Station W-A1). Here, however, as farther south, the marked deficit is in May and June. Although the winter precipitation as a whole is adequate, the amount in November and December is hardly sufficient, in connection with the sudden drop in air temperatures, to prevent deep freezing of the soil.

The spruce type in the Wagon Wheel Gap locality, the only one which we may compare with Station L-1 in the Pikes Peak series, does not show much more precipitation than the local station except during the winter, and is much more liable to drought during the summer. The Wagon Wheel Gap site produces a superior spruce forest, but its conditions are not more conducive to abundant reproduction.

The lodgepole types are all inferior to the control station in total precipitation, and only half as favorable in growing-season precipitation. All, however, secure a better snow blanket in the winter, not only because of larger snowfall, but because the snow is protected by low air temperatures. Frequently in lodgepole sites the ground is not exposed after the first heavy snow in September. It is seen, then, that lodgepole receives and thrives with less precipitation during the growing season than even yellow pine, but that, like yellow pine, it is surrounded by conditions conducive to the maintenance of an unfrozen or only slightly frozen soil during the winter.

SOIL MOISTURE.

When it is observed that losses by evaporation may be two or three times as great from one site as from another receiving the same precipitation, it is at once apparent that the record of precipitation is almost without value in indicating the moisture conditions under which the several species develop. If it is at all true that the amount of moisture available, or its degree of availability, appreciably influences the character of the plant formation, then an attempt should be made to measure the soil moisture as directly as possible. This should be done notwithstanding the fact that precipitation and evaporation rates, when considered together, constitute a valuable basis for comparing the moisture conditions of broad regions and the general types of their flora.

That the proper use of soil moisture data in a comparison of sites is by no means a simple matter becomes more apparent as the behavior of the soil solution is more exactly studied. In the "Research Methods in the Study of Forest Environment," (*24*) a serious effort has been made to depict the soil-moisture problem as it actually exists. In order that the viewpoint and treatment in that publication may be understood, it is sufficient to say that the soil solution is regarded as having osmotic properties similar to those of the plant solution, and that the osmotic pressure of the soil solution is always opposed to that pressure within the plant which gives rise to absorption by the plant (root) cells. If the plant pressure is increased by ordinary water loss through transpiration, or if the soil solution is diluted, the rate of absorption must increase. If the plant pressure is decreased or the soil pressure increased, the flow into the plant must be decreased, stopped, or even reversed.

At least a suggestion of this osmotic relation is contained in a statement by Livingston (*14*) as early as 1902, and a much clearer treatment of the subject has gradually evolved in numerous other papers. Livingston says:

> A strong solution will extract water from the organism, a weak one will allow it to be absorbed. * * * Change in the water content of the protoplasm may be directly effective by causing a change in its physical properties. For instance, if water is extracted, the viscosity of the protoplasm must be increased. The change in water content may result in a change in the chemical activity of the protoplasmic solution, since chemical activity, in general, depends upon the concentration of the solution involved. How it comes about is not known, but a review of the literature of experiments upon animals and plants shows that growth is very much retarded by an external solution which extracts water. Especially is the elongation of cells retarded.

Clements (*9*) describes this relation in discussing the plant (par. 60) but ignores it in the method of treating soil moisture control (par. 9).

The investigations of Bouyoucos (*8*) and Hoagland (*12*), especially, in more recent years, have created the conception of the soil solution as one exerting a definite osmotic pressure. This conception has been attained through the study of freezing points, and their correlation with concentration of the soil extract. In the "Research Methods in the Study of Forest Environment" evidence was introduced to show that the soil water exerts a definite vapor pressure.

With this light on the subject, it must be evident that the total quantity of water present in the soil has very little bearing on either growth or survival. The ability of the plant to obtain water in sufficient quantity to maintain life, or in sufficient quantity to maintain conditions favorable for metabolism and growth, must at all times depend primarily on the differential between the osmotic pressure exerted by the cell contents, and that which, for the sake of distinction, we may term the "antiosmotic pressure" of the soil water.

It is of course to be kept in mind that the osmotic pressure of the plant cells is not stable. If atmospheric conditions create a heavy loss by transpiration, and thereby create a great need for water in the plant, it follows that the ability of the plant to extract the water from the soil is automatically increased, by reason of increased osmotic pressure in the cells. It does not follow that this increase in pressure will immediately insure all that is needed. Hence, if the demand is very great or arises too suddenly, there may be wilting; and, if it is too long continued, there may be permanent injury.

Unfortunately the treatment of the soil solution as one exhibiting or following the laws of osmosis is not entirely simple, because, although its properties are primarily determined by the solutes present, they are also affected at all stages by the solid particles and colloidal masses of the soil, whose affinity for liquid water has the same effect on the activity of the water molecules as has the affinity of solids in solution. The critical point, however, is this, that while there is still some water in the soil—sometimes 10 per cent or more—it may be so completely and effectively held in thin films or small aggregates by the soil solids, that the water entirely loses its properties as a liquid. The amount of water so held, which is completely nonavailable for plants, is very important, for, at least broadly, this amount is indicative of the aggregate of forces which may withhold the water from plants when the amount is larger.

There are, then, several ways in which the availability of soil moisture may be more or less precisely determined. The most precise method is undoubtedly to determine the actual osmotic pressure shown by the soil water when it is present in various amounts or percentages. This of course implies somewhat exhaustive study of each soil whose moisture condition in the field is a matter of interest. In the present study a single approximate determination of osmotic pressure is available for each of only about half the individual soils which are of interest. This determination was made by the vapor-transfer method under conditions far from ideal.

Another method is that of comparing the current moisture percentage for each soil with that percentage which represents the completely nonavailable moisture. This, of course, must have been determined by a wilting test in connection with each soil, or approximately through some such physical measurement as the moisture-equivalent or capillarity determination. As fully explained in "Research Methods in the Study of Forest Environment," the "availability" is expressed by the ratio of the available moisture to the whole. This gives a quantity always less than unity, which has a certain logical value, as—

$$A=\frac{M-WC}{M}$$

in which M represents current moisture and WC the wilting coefficient.

Or, finally, granting that within a single soil type there may be a fairly constant relation between the water-holding properties as determined mechanically and the water-withholding properties in the osmotic sense, the current moisture may be related to the moisture equivalent of each soil, and a purely arbitrary ratio may be obtained for purposes of comparison. This method is almost certain to be misleading if radically different types of soil are involved in the comparison.

Method of securing soil-moisture data.—During 1910 and 1911, when only three forest sites were being studied at the Fremont Experiment Station, the attempt was made to secure samples of the native soil at frequent intervals in the usual manner, namely, by means of a tubular soil borer. These samples were usually taken in triplicate at points near the centers of the respective stations, and, like all other samples considered in this study, were dried in a water-bath oven at the temperature of boiling water, which at the Fremont Forest Experiment Station is approximately 92° C. Until 1915, drying for 8 hours was considered adequate, in view of the small size, coarseness, and mineral character of the samples; but later this period was extended to 24 hours, and the water in the bath was kept boiling for at least the last 5 or 6 hours of the period. No allowance was made for varying vapor pressures, which, being generally low, probably made the drying as complete as though brought about by a higher temperature in a more humid locality.

This plan for sampling the native soil at the several stations was not satisfactory, because, as has been said, the soil of the Pikes Peak region in most situations and except for a few inches at the surface, is disintegrated granite in situ, and is not only very unyielding to penetration but almost entirely lacking in cohesive properties when once loosened. Hence it required, in the first place, great labor to sink the soil borer, and, in the second place, great ingenuity to withdraw the desired sample. When the soil was very dry the obtaining of samples at a depth of 2 feet was practically impossible, and samples taken at a depth of 18 inches were substituted.

Even a depth of 2 feet does not seem adequate when one has noted the deep penetration of occasional roots in this soil. Therefore, when in 1914 this study was extended to a greater number of stations both near Fremont and in other localities, a plan was adopted which had been in use at Wagon Wheel Gap since 1911, made necessary there by large rock fragments all through the soil. This was the plan of "soil wells."

The preparation of a "soil well" consists in making an excavation from 18 to 24 inches in diameter and 3½ to 4 feet deep, the space being then filled with the same material as has been taken out, with the exception of the rocks or coarse gravel which interfere with soil sampling. As material must be borrowed from some other place to make up for the coarse material sifted out, the resultant soil in the "well" is, of course, very different from that which previously filled the space.

The following objections may legitimately be raised against soil sampling under these conditions:

(1) The "well" soil, weight for weight or volume for volume, will possess a higher water-holding capacity than the native soil, on account of the absence of the rock fragments, which are of relatively little importance in water storage.

(2) The well soil will at the outset be of the same composition from surface to bottom, whereas the native soil may vary greatly with change in depth.

(3) The well soil, not being protected and held by humus accumulations at the surface, will tend, through leaching and transport of fine material, to become coarser at the surface and of finer texture at greater depths; hence the water-holding properties will then vary with depth and in a direction opposite to the variation of the native soil.

(4) Roots are removed in excavating the well, and constant sampling within such a small radius tends to cut off new roots which may penetrate this special soil zone.

Whatever the objections to the method, it is the only method so far found practicable for repeated sampling of rocky, mountain soils. Considerable encouragement may be taken from the assumption, well founded on experimental fact, that when two soils, both moderately moist, are placed in contact, there is a strong tendency for water to move from one to the other until the capillary forces are in equilibrium. If, then, it may be assumed that the moisture equivalents of the native soil and well soil (ME and ME′) represent points at which the two would be in capillary equilibrium, then the probable moisture of the native soil (M) may be computed at any given time, from that determined for the well soil (M′), by the formula—$M=\frac{M' \times ME}{ME'}$.

But also, if it is desired to relate the current moisture of the soil to the moisture equivalent, on the assumption that this ratio expresses in some degree the availability of the water, then it is just as satisfactory to use $\frac{M'}{ME'}$ as $\frac{M}{ME}$, because it has been assumed above that the two are equal.

In considering soil-moisture quantities that approach the wilting coefficient and that present conditions under which capillary movement may almost wholly cease, it is preferable to assume that an osmotic equilibrium is being approached by vapor transfers between the well soil and native soil. In this event, *OE*, the osmotic equivalent, might be substituted for *ME* above. Unfortunately, there are neither sufficient osmotic equivalents for well soils and native soils, nor sufficient wilting coefficients for well soils, to make this desirable method of computation possible in the present study.

Comparative moisture of native soils, local stations.—In Table 39 are shown the results of sampling the native soils at three points near the Fremont station, under the conditions already described. These are essentially the data published in the preliminary report on this project (*3*), referring to the three stations which were operated comparatively from March, 1910, to February, 1912.

TABLE 39.—*Comparative moisture data from samples of native soil, July, 1910, to October, 1911.*

Depth.	Station No.	Percentages of dry-soil weight.							Mean annual.[1]	Mean growing season.[2]
		April.	May.	June.	July.	August.	September	October.		
1 foot	F-1, control	8.75	6.87	5.09	4.98	5.64	4.65	4.40	5.77	5.18
	F-2, pine	7.72	4.96	4.30	5.16	5.78	4.46	3.34	5.10	5.02
	F-3, spruce	....	16.35	9.92	12.31	9.98	10.07	7.55	11.02	10.67
2 feet	F-1, control	6.01	5.31	2.15	4.28	5.32	5.56	4.15	4.68	4.08
	F-2, pine	4.66	4.19	3.60	4.10	4.34	4.08	3.68	4.09	4.02
	F-3, spruce	....	8.46	4.99	4.86	9.04	6.68	2.83	6.14	6.34
Average of depths	F-1, control	7.38	6.09	3.62	4.63	5.48	5.10	4.28	5.23	4.63
	F-2, pine	6.19	4.58	3.95	4.63	5.06	4.27	3.51	4.60	4.52
	F-3, spruce	....	12.40	7.46	8.58	9.51	8.38	5.19	8.58	8.50

[1] Arithmetic means of the months.
[2] Growing-season means obtained by giving September quantities one-third the value of June, July, and August quantities.

It is to be noted that the south-slope pine site (F–2) shows scarcely less moisture than the control station, the latter being subject to no depletion of moisture through use by trees. The spruce site (F–3) at the foot of a north slope shows considerably more moisture than the other stations, except at a depth of 2 feet at the end of the season. This exception would be very significant if the result were based on more data: but, as the measurements covered only October, 1910, they can not be given much weight.

Periodic moisture at the control station.—As the data for native soils are meager and can be compared only on their face value, in the absence of physical data on the soils themselves, an examination may be made of the more extensive data secured by taking samples from the "wells."

In Table 40 are given the monthly mean moisture figures for the control station for the greater part of five seasons. Each mean figure is based on four or five determinations, at intervals of a week, except where otherwise indicated by a number in parentheses, which denotes the number of determinations. Only the data for 1914, 1915, and 1917 are used in computing the averages, as this is the basis at other local stations.

TABLE 40.—*Mean soil moisture at control station as shown by samples from "well."*

Year.	Depth.	Percentages of dry-soil weight.										Mean annual.[1]	Mean growing season.[2]
		Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.		
	Feet.												
1914	1	......	......	......	......	9.13	8.77	6.84	7.34	7.16	4.82	7.85	8.65
	2	......	......	......	......	8.71	9.40	7.62	8.38	9.15	7.01	8.65	8.85
	3	......	......	......	......	8.38	9.82	8.94	8.56	10.00	8.16	9.14	9.08
1915	1	......	(3) 9.01	8.10	7.50	6.84	8.78	7.91	8.00	7.04	......	7.90	7.73
	2	......	10.78	8.84	8.31	8.42	9.14	8.72	8.68	8.31	......	8.90	8.63
	3	......	11.29	10.11	10.67	9.41	9.80	9.86	9.28	8.16	......	9.82	9.95
1916	1	(1) 4.24	7.88	7.34	6.68	8.08	8.82	6.34	6.33	......	......	7.35	7.71
	2	6.19	8.14	9.10	7.14	7.52	9.10	7.65	7.32	......	......	7.99	7.89
	3	6.06	9.84	10.06	8.50	8.48	10.09	8.32	8.55	......	......	9.12	8.95
1917	S.	......	(3)	9.49	6.05	5.48	5.78	5.29	2.78	3.61	......	5.50	5.72
	1	......	7.96	8.48	7.24	6.14	6.81	7.21	6.09	5.91	......	6.98	6.78
	2	......	8.78	8.75	8.05	7.05	6.69	7.54	6.87	6.44	......	7.52	7.29
	3	......	9.38	9.75	9.82	7.93	7.24	7.39	7.15	7.42	......	8.26	8.24
1918	S.	......	......	(2) 5.54	(3) 4.22	(1) 4.26	(1) 4.07	......	......	......	......	4.52	4.18
	1	......	......	7.40	8.18	6.94	7.62	......	......	......	......	7.54	7.58
	2	......	......	8.16	9.00	7.83	8.15	......	......	......	......	8.28	8.33
	3	......	......	9.35	9.77	9.14	9.14	......	......	......	......	9.35	9.35
Averages 1914–1915 1917	S.	......	......	9.49	6.05	5.48	5.78	5.29	2.78	3.61	......	5.50	5.72
	1	......	8.48	8.29	7.37	7.37	8.12	7.32	7.14	6.70	......	7.60	7.59
	2	......	9.78	8.80	8.18	8.06	8.41	7.96	7.98	7.97	......	8.39	8.19
	3	......	10.34	9.93	10.24	8.57	8.95	8.73	8.33	8.53	......	9.20	9.20

[1] Omit December, 1914, and March, 1916, in computing yearly averages.
[2] The values for June, July, and August are added to one-third of the September value and the sum divided by 10/3.

(1) The moisture at 1, 2, or 3 feet is remarkably uniform in different years if the growing-season means be considered. This may be due in part to the lack of tree growth near the "well" and the inability of grasses and herbs to reach the deeper moisture.

(2) The moisture is less during July and late summer than in the spring and early summer, but is well maintained by precipitation after July.

(3) The year 1917 was the driest of record, the precipitation and especially that for the growing season being below normal.

(4) The mean figures for the soil well, for depths of 1 and 2 feet, when reduced to terms of native soil by use of the moisture-equivalent ratios, are of lower value than the actual figures for native soil obtained during 1910–11. As the early sampling of the native soil covered a considerable area, and as the soil is by no means uniform over large areas, the lack of correlation may mean nothing more than a difference in the conditions surrounding the measurements during the two phases of the study.

Comparative moisture in wells, all types.—In Table 41 is given a summary of the well-moisture data for all stations in the study where data have been obtained. For all local stations except F–12, F–14, and F–15, the data are for 1914, 1915, and 1917, beginning with July, 1914. For Monument the period is 1915 to 1918, inclusive. For Foxpark it is August, 1916, to August, 1918. For Wagon Wheel Gap it is (A1 and A2), August, 1913, to August, 1918; (D) August, 1913, to October, 1917; and (F) July, 1915, to October, 1917. As the unusually dry year 1917 is included in each average, it is not thought the variations in period will introduce any serious discrepancy.

TABLE 41.—*Mean soil moisture in "wells."*

Station No.	Type.	Depth.	Percentages of dry-soil weight.									Mean annual.	Mean growing season.[1]
			Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.		
		Feet.											
F-1	Control	S.	......	......	9.49	6.05	5.48	5.78	5.29	2.78	3.61	5.50	5.72
		1	......	8.48	8.29	7.37	7.37	8.12	7.32	7.14	6.70	7.60	7.59
		2	......	9.78	8.80	8.18	8.06	8.41	7.96	7.98	7.97	8.39	8.19
		3	......	10.34	9.93	10.24	8.57	8.95	8.73	8.33	8.53	9.20	9.20
F-2	South-slope yellow pine	S.	......	......	7.64	2.52	5.44	4.54	5.11	3.57	2.42	4.46	4.26
		1	......	11.84	10.29	8.50	8.62	9.90	8.56	8.19	7.95	9.23	8.96
		2	......	12.93	10.86	10.05	10.97	10.30	9.94	9.73	9.56	10.54	10.39
		3	......	14.98	12.79	12.59	11.70	10.47	10.51	10.28	11.15	11.81	11.48
M-1	Monument yellow pine	S.	0.64	12.92	8.89	4.35	3.03	5.72	5.82	7.74	6.84	6.22	4.51
		1	7.21	10.30	10.57	8.90	5.91	5.96	4.96	7.04	6.10	7.44	6.73
		2	9.42	10.85	11.99	10.82	7.55	6.00	5.03	6.75	6.94	8.37	7.81
		3	14.10	12.20	12.48	11.96	9.98	7.86	5.90	9.03	8.74	10.25	9.53
F-4	Yellow pine-fir	S.	......	......	9.33	4.18	5.38	5.82	6.52	3.64	4.74	5.66	5.27
		1	......	......	10.08	8.75	8.47	9.11	7.72	6.53	7.52	8.31	8.67
		2	......	......	11.70	10.75	10.60	10.86	10.57	8.92	9.49	10.41	10.72
		3	......	......	12.65	12.64	10.62	11.31	10.64	10.60	10.86	11.33	11.44
F-12	Ridge yellow pine	S.	......	......	10.80	5.13	6.64	6.81	8.93	4.91	8.76	7.43	6.47
		1	......	......	11.44	10.62	9.76	11.38	11.04	11.66	10.28	10.88	10.63
		2	......	......	12.97	12.22	10.96	11.64	12 00	12.11	12.38	12.04	11.65
		3	......	......	13.26	12.42	11.41	12.21	13.14	13.10	13.23	12.68	12.13
W-A2	South slope Douglas fir	1	......	......	14.67	11.34	9.92	11.40	9.54	12.68	......	11.59	10.75
		2	......	......	17.60	12.68	12.38	11.73	10.88	12.36	......	12.94	12.12
		3	......	......	16.43	14.42	14.30	12.65	11.12	13.04	......	13.66	13.52
F-9	Fir, north, uncut	S.	......	......	24.02	10.64	9.62	11.97	8.56	4.39	6.76	10.85	10.53
		1	......	......	18.89	13.52	12.23	14.01	12.92	11.50	12.68	13.68	13.22
		2	......	......	19.26	16.61	13.89	15.02	14.33	13.66	13.28	15.15	15.09
		3	......	......	17.34	17.91	13.66	14.38	14.62	13.62	12.42	14.85	15.25
F-14	Fir, north, half cut	S.	......	......	13.18	6.13	11.81	10.50	11.06	7.16	3.90	9.11	9.64
		1	......	......	14.54	12.82	12.94	13.94	13.32	12.10	9.93	12.80	13.24
		2	......	......	15.15	12.70	13.68	14.59	14.40	14.25	12.61	13.91	13.73
		3	......	......	17.83	13.56	14.36	15.21	14.89	14.61	14.49	14.99	14.43
F-15	do	S.	......	21.72	11.77	6.64	9.24	9.89	10.51	6.86	4.66	8.51	8.78
		1	......	......	13.80	12.85	12.18	14.64	13.30	11.41	9.06	12.46	13.23
		2	......	......	14.62	13.57	12.86	14.84	14.20	13.12	12.40	13.66	13.80
		3	......	......	16.56	14.25	14.24	15.50	14.52	13.88	14.15	14.73	14.65
F-8	Fir, north, clear cut	S.	......	16.10	14.27	9.33	5.93	8.76	8.61	6.21	8.21	8.76	8.06
		1	......	......	14.44	12.69	10.81	12.28	12.13	11.50	13.26	12.44	11.95
		2	......	......	13.48	14.66	18.38	12.58	13.13	12.89	13.74	14.12	15.00
		3	......	......	16.84	15.47	13.18	13.16	13.70	13.73	14.47	14.36	13.91
F-7	do	S.	......	......	12.02	5.94	5.26	6.22	6.98	5.27	5.03	6.67	5.92
		1	......	......	13.60	12.31	11.30	11.87	11.57	11.78	10.91	11.91	11.80
		2	......	......	14.61	13.34	11.59	12.34	12.15	12.65	12.65	12.76	12.40
		3	......	......	14.82	13.01	11.00	11.99	11.79	12.36	11.97	12.42	11.98
W-A1	North slope Douglas fir	S.	......	......	......	......	......	......	......	......	......	......	......
		1	......	......	23.60	20.48	18.46	18.58	18.62	18.80	......	19.76	19.12
		2	......	......	25.60	22.24	20.98	20.58	21.66	20.66	......	21.95	21.31
		3	......	......	24.63	25.10	25.10	25.92	24.46	23.52	......	24.79	25.28
F-11	Lodgepole, Wyoming	S.	......	......	......	14.84	7.38	5.29	5.86	5.16	11.51	8.34	8.84
		1	......	......	......	15.30	9.62	7.93	6.75	6.67	6.33	8.77	10.53
		2	......	......	......	16.55	13.00	9.91	7.05	7.36	7.28	10.19	12.54
		3	......	......	......	17.16	17.66	13.00	8.16	9.44	10.51	12.66	15.16
F-3	Canyon spruce	S.	......	......	16.43	10.53	7.59	10.31	13.16	5.81	3.85	9.67	9.85
		1	......	......	15.88	12.15	11.57	12.19	10.88	10.78	10.69	12.02	11.86
		2	......	......	15.90	12.44	12.46	12.68	12.06	11.48	11.61	12.66	12.48
		3	......	......	13.43	13.84	12.88	13.23	12.86	12.91	12.73	13.13	13.27
F-5	do	S.	......	......	23.82	12.29	7.51	11.69	10.72	4.12	3.82	10.57	10.52
		1	......	......	14.34	13.44	12.86	13.50	11.94	11.77	11.36	12.74	13.13
		2	......	......	14.74	14.28	14.12	14.42	12.28	12.73	12.83	13.63	14.07
		3	......	......	15.89	17.90	17.59	16.49	16.86	16.11	15.69	16.65	17.28
W-D	High spruce, burn	1	......	......	30.20	24.08	22.42	23.38	23.58	22.24	......	24.48	23.32
		2	......	......	35.20	28.28	25.00	26.92	27.54	25.40	......	28.06	26.81
		3	......	......	27.80	28.20	23.62	24.64	24.84	23.48	......	25.43	25.42
W-F	High spruce, forest	1	......	......	......	27.90	22.30	20.77	20.23	19.63	......	22.17	23.31
		2	......	......	......	32.20	27.37	21.40	20.50	20.73	......	24.44	26.34
		3	......	......	......	42.30	28.17	22.00	20.37	20.60	......	26.69	29.78
F-6	West slope limber pine	S.	......	......	12.08	7.35	7.88	9.47	11.46	3.84	3.29	7.91	8.56
		1	......	......	15.24	11.52	10.76	13.00	12.13	10.65	10.62	11.99	11.80
		2	......	......	15.78	12.42	11.51	12.82	11.74	11.68	11.65	12.51	12.20
		3	......	......	15.39	13.09	12.21	13.71	13.20	13.32	13.05	13.42	13.02

[1] Growing-season means obtained by giving September quantities one-third the value of June, July, and August quantities.

Surface moisture in the wells was measured for local stations only in 1917, and at Wagon Wheel Gap not at all.

As the large mass of figures in Table 41 is difficult to grasp, the averages by species groups are presented in Table 42.

TABLE 42.—*Average "well" moisture for growing season.*

Group.	Depth.			
	Surface.[1]	1 foot.	2 feet.	3 feet.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*
Control station	5.72	7.59	8.19	9.20
Four western yellow pine sites	5.13	8.75	10.14	11.14
Seven Douglas fir sites	8.59	13.33	14.78	15.57
Four spruce sites	10.18	17.90	19.92	21.44
One lodgepole pine site	8.84	10.53	12.54	15.16
One limber pine site	8.56	11.80	12.20	13.02

[1] Local stations only and season of 1917 only.

On the face of these data it is very evident that the yellow pine sites possess less moisture during the growing season than do the Douglas fir sites, which, with one exception, are northerly aspects—and likewise that the spruce soils have a still larger supply. It is unsafe to estimate the positions of the limber pine and lodgepole pine sites without some correction for the type of soil involved, as there is here no opportunity for compensating peculiarities.

In considering the high average values for the spruce sites, however, it is worth while to mention that the group of four was made up of two local stations and also of two at Wagon Wheel Gap whose soils have much better water-holding properties. Thus, for example, the mean 1-foot moisture for the local sites is only 12.5 per cent, or almost the same as for the local Douglas fit sites, but the corresponding figure for the heavier Wagon Wheel Gap soils is 23.32 per cent. It will be shown later, when wilting coefficients are considered, that this apparent difference is unreal, so far as availability of the water is concerned.

In the yellow pine group, the relatively high moisture contents at Stations F–4 and F–12 are worthy of note, as both of these sites are fairly favorable for Douglas fir. Of the two, Station F–12 has the more favorable conditions if allowance is made for the quality of the soil.

As data are available for every site for the season of 1917, which has previously been mentioned as the driest year in which extensive records have been made, it is desirable to give consideration to minimum moisture conditions, which are far more likely to give something significant with respect to the survival of the species. In using the 1917 data, the individual and successive moisture determinations are found to be so variable that it seems unsafe to base any conclusions on single observations. The most meager basis would appear to be the average for a month, made up from four or five weekly determinations. The lowest monthly average for each station and depth has, therefore, been accepted. In Table 43 the results are grouped according to the plan of Table 42.

TABLE 43.—*Minimum (month) "well" moisture during season of 1917 and percentage ratio to mean growing-season moisture (in parentheses).*

Group.	Depth.			
	Surface.	1 foot.	2 feet.	3 feet.
Control station	(49) 2.78	(78) 5.91	(79) 6.44	(78) 7.15
Four yellow pine sites	(66) 3.37	(65) 5.72	(63) 6.40	(65) 7.28
Seven Douglas fir sites	(66) 5.67	(76) 10.18	(75) 11.08	(79) 12.31
Four spruce sites	(38) 3.84	(71) 12.66	(73) 14.53	(73) 15.66
One lodgepole pine site	(35) 3.08	(63) 6.66	(62) 7.72	(53) 8.11
One limber pine site	(38) 3.29	(72) 8.46	(78) 9.49	(83) 10.87

The data in Table 43 do not appear essentially unlike those of Table 42 in fixing the relative positions of the species, yet the parenthetical figures showing the relation between these minima and the approximately normal growing-season condition are full of significance. It is to be noted that the degree of exhaustion as indicated by these percentages is nearly the same for the 1, 2, and 3 foot depths with perhaps a slight tendency toward greater exhaustion at a depth of 2 feet than elsewhere. On the other hand, although the yellow pine sites do not show greater exhaustion at the surface than in the deeper soil and the north-slope fir sites show only slightly greater drying of the surface, the spruce sites, as well as the limber pine and lodgepole pine sites, show very marked drying out. In the spruce sites this can not be ascribed to insolation; it must be charged in part to the loose duff which forms the surface layer and in part to the prevalence of roots near the surface. As the soil wells can not possibly show either of these factors fully, it is evident that the natural surface soil in a dense spruce forest must represent a very great degree of drought. That is, perhaps, the most striking point that has been brought out by all of the soil-moisture determinations, especially when one considers the importance already attached to surface temperatures. Calculations as to the availability of the moisture, made on the basis of moisture equivalents, indicate that one of the two spruce sites for which the surface data are available becomes physiologically drier than any of the others, and the second is drier than any except the warmest yellow pine sites and the wind-exposed limber pine site.

The attempt to reduce the data of Table 42, first, to terms of moisture percentages for the native soil and then to terms of availability, does not materially alter the evidence of Tables 42 and 43, namely, that the yellow pine sites are the most arid and that the spruce situations are only slightly moister than the north slopes which bear Douglas fir. On the other hand, these calculations do show that, owing to a very sandy soil used in the soil well, the lodgepole site is considerably more favorable than the original moisture data would indicate. The approaches, through osmotic equivalents, through the direct ratio of moisture contents to moisture equivalents or through consideration of the wilting coefficients, all produce, as between the forest types, essentially the same relations. All tend to show that the differences between sites in availability of the moisture are less than are indicated by the bare moisture contents.

Rather for the purpose of illustration than because of the value of the data, calculations of the probable natural soil moisture and of the availability of this moisture are presented in Table 44. These calculations can not be extended to the surface-moisture values, because the native surface soils have not been physically examined. Moreover, such calculations would be of little value, because the surface soils of the wells are so directly influenced by atmospheric conditions.

Probably the most valuable feature of Table 44 is the clear way in which it shows that the high moisture percentages obtained with the heavy soil at Station D, Wagon Wheel Gap, are really on a level with those for the local spruce stations. The slightly higher availability at Station D is easily explained by the almost complete absence of forest. Similarly, although the calculations can not be carried out for the two Douglas fir stations, the high wilting coefficients indicate that Station W–A1 (north exposure) must be just about on a par with similar local stations, but that the strongly exposed Station W–A2 is certainly much more arid.

As has been pointed out, these calculations show the lodgepole pine site to be very moist. This may be due in part to the fact that only a few trees surrounded the soil well, but is probably the result of low evaporation stresses. The limber-pine site is seen to be in a class with the average yellow-pine site. Among the local stations subject to practically the same atmospheric conditions it is evident that direct insolation tends to keep the more insolated pine sites in a drier state than the others; but the very slight difference between fir slopes and spruce bottoms after a prolonged period of drying indicates that each soil, through direct drying and the drying accomplished by the trees, tends to come into vapor-pressure equilibrium with the atmosphere. The probabilities are, therefore, that in the event of more prolonged drought, sufficient to permit an equilibrium to be reached, equally insolated soils will attain the same status quite regardless of the character and amount of vegetation thereon. This is of the utmost importance, indicating, in the present case, that the moisture supply is effective only in controlling the number of individuals and can not differentiate between species, at least as between spruce and fir sites.

It is fairly evident, then, that soil moisture below the surface layer is only an incidental factor in the distribution of the several species. Strongly insolated sites and those exposed to the higher temperatures and to the greater atmospheric stresses of low elevations, as might be expected, are always the driest, but their most important feature, owing to the close connection between insolation, surface temperatures, and surface moisture, is doubtless the very rapid drying of the surface layer after every rain, rather than any decided lack of moisture at greater depths.

73045°—24——9

TABLE 44.—*Calculated minimum moisture in soils during 1917 and relative availability.*

Station No.	Type.	Depth.	"Well" moisture, lowest month (M').	Ratio ME/ME'.	Calculated moisture of native soil (M).	Nonavailable moisture by test (WC).	Availability $\frac{M-WC}{M}$
		Feet.	*Per cent.*		*Per cent.*	*Per cent.*	
M-1	Western yellow pine	1	3.59	0.853	3.06	2.36	0.229
		2	3.90	.632	2.46	1.53	.378
		3	3.47	.647	2.25	1.68	.253
F-2	do	1	4.93	.582	2.87	1.16	.596
		2	5.96	.636	3.79	2.63	.306
		3	6.89	.631	4.35	2.67	.386
F-12	do	1	9.35	.630	5.89	1.99	.662
		2	10.14	.600	6.08		
		3	11.16	.495	5.52	1.97	.643
F-4	do	1	5.02	.526	2.64	1.79	.322
		2	5.61	.475	2.66	1.28	.519
		3	7.61	.375	2.85	1.43	.498
Average	do	1	5.72				.452
		2	6.40				.401
		3	7.28				.445
F-7	Douglas fir	1	9.03	.463	4.18	1.26	.699
		2	10.02	.478	4.79	1.85	.614
		3	10.09	.486	4.90	1.24	.747
F-8	do	1	7.38	.387	2.86	1.76	.385
		2	9.99	.325	3.25	1.64	.495
		3	10.80	.263	2.84	1.18	.585
F-14	do	1	12.38	.481	5.95	1.79	.700
		2	12.42	.536	6.66	2.06	.691
		3	13.23	.371	4.91		
F-15	do	1	10.81	.483	5.22	2.25	.569
		2	11.77	.589	6.93		
		3	13.13	.622	8.17		
F-9	do	1	7.46	.393	2.93	1.62	.447
		2	9.67	.393	3.80	.96	.747
		3	9.69	.435	4.22	1.62	.616
W-A1	do	1	16.20			5.76	
		2	16.20				
		3	20.60			6.63	
W-A2	do	1	8.00			5.04	
		2	7.50				
		3	8.60			5.70	
Average	do	1	10.18				.560
		2	11.08				.638
		3	12.31				.649
F-3	Engelmann spruce	1	6.68	.645	4.31	1.54	.643
		2	9.40	.535	5.03	1.51	.700
		3	11.16	.327	3.65	1.45	.603
F-5	do	1	7.57	.408	3.09	2.12	.314
		2	10.03	.462	4.63	2.64	.430
		3	11.56	.405	4.68	1.98	.577
W-D	do	1	17.50	1.033	18.08	7.56	.582
		2	19.00	.876	16.64	3.59	.784
		3	20.60	.893	18.40	4.14	.775
W-F	do	1	18.90				
		2	19.70				
		3	19.30				
Average	do	1	12.66				.516
		2	14.53				.638
		3	15.66				.652
F-11	Lodgepole pine	1	6.66	2.017	13.43	4.72	.649
		2	7.72	2.437	18.81	3.65	.806
		3	8.11	1.743	14.14	2.99	.789
F-6	Limber pine	1	8.46	.494	4.18	2.44	.416
		2	9.49	.385	3.65	2.65	.274
		3	10.87	.329	3.58	1.85	.483
F-1	Control station	1	5.91	.520	3.07	2.31	.248
		2	6.44	.436	2.81	.93	.669
		3	7.15	.526	3.76	.76	.798

At the other extreme stand the canyon and lower-slope spruce sites, whose soil is mainly transported. This soil is of finer quality than that of the slopes, is rich in humus, which may blow into the low places as well as wash in, and consequently is of the greatest water-holding capacity. This great capacity and the usually high level of the moisture content encourage dense stands. Only spruce can grow in the densest stands; other species are excluded not by lack of moisture, or by too much moisture, but by lack of insolation. It seems possible that these very sites may, after unusually prolonged drought, prove to be the driest. The difficulty which is often experienced in starting plantations in gulches which encourage heavy vegetation is testimony to the extreme desiccation of such soils when rain is withheld. In 1909, the writer definitely found the bottom situations to be the driest of all the sites in late summer in the Nebraska sand hills.

The Douglas fir sites on north slopes are almost as moist as the lower spruce sites, and probably do not dry out to so great a degree. The surface conditions, especially, remain fairly favorable because of the lack of drying insolation. On the other hand, the evidence of the south-slope fir site at Wagon Wheel Gap, and the occurrence of fir seedlings almost on the roots of yellow pine on south slopes, shows convincingly that the need of this species is not for great moisture, but rather for moderate temperature conditions.

RECAPITULATION.

GENERAL CHARACTER OF THE CLIMATE.

The mountain climatic conditions, which have been portrayed mainly through the relatively long-term records at the Fremont Forest Experiment Station, at an elevation of 8,836 feet on the eastern slope of Pikes Peak, may be characterized as follows, in terms which apply generally to the forest types (fig. 10).

(1) The summer or growing-season conditions are not unfavorable to the growth of vegetation that has very moderate heat requirements. The mean growing-season temperature is about 55°, with the period from June 10 to September 10 free from freezing temperatures. Almost 50 per cent of the total precipitation occurs during the growing season (June 1 to September 10, as here considered) following a brief drought in May or early June; hence the moisture of the deeper soil stands throughout the season at a favorable point, rarely if ever approaching the nonavailable content. This period is never characterized by high winds, and great atmospheric dryness occurs only when the drought period extends well into June.

(2) With the cessation of daily showers, which rapidly decrease in number and volume after August 15, a period of clear, dry weather occurs which rapidly depletes the moisture of the surface soil and which may, by the end of October, cause the death of a large proportion of the new seedlings of the season, most of which will not have germinated before July, and will therefore be very immature and poorly rooted. In this wholesale elimination, which doubtless makes some distinction between species, the early frosts may have some influence, but do not appear to be so important as drought.

(3) The winter temperatures at middle and lower elevations in the Pikes Peak region are rarely very low; relatively warm, strong winds occur frequently from January to March; and evaporation stresses are very telling, except at high elevations where the air temperature rarely goes higher than 32° F. The precipitation also during the winter months is very low. Clear weather and the lack of material for evaporation result in great dryness of the atmosphere. Another effect of the lack of snow is seen in the early and deep freezing of the soil, except on well-insolated exposures. In the main, then, trees are subjected to conditions which induce rapid transpiration, and at the same time are cut off from their moisture supply by the freezing of the moisture in the soil. Obviously, these conditions are not a less severe strain upon the well-established tree than

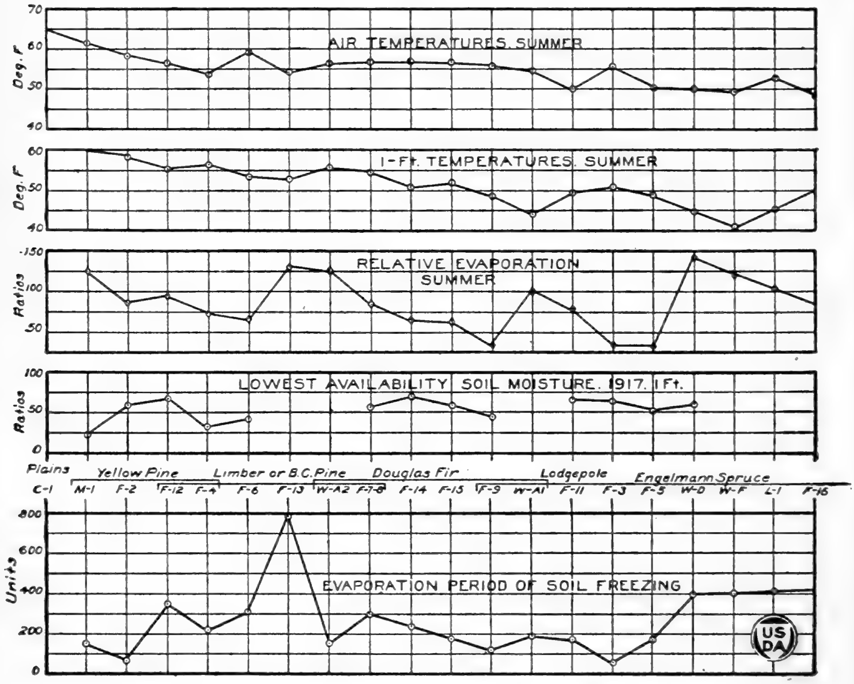

FIG. 10.—Summary of the several conditions in the various forest types.

upon the seedling which may secure protection through shading or through a temporary snow blanket.

It is believed that these winter conditions, rather than the poor quality of the soil, delimit the growth of all forest trees in the locality, and produce a scrubby stand which on some sites has apparently reached its limit at a height of 40 feet or less.

(4) The extension of observations to other localities both north and south of the Pikes Peak region indicates a less complete development of most of the unfavorable features of climate. To the south, to be sure, the spring drought is more pronounced and may possibly destroy seedlings of the preceding season. The summer rainfall is no more abundant, but the fall drought is of less duration; a snow

cover is secured earlier; and the low winter air temperatures are much less conducive to evaporation. To the north, in the lodgepole pine type, precipitation is insufficient to balance losses from May to August, and a pronounced drought develops toward the end of summer. However, as early snows are heavy, there is no acute problem of soil moisture, nor are there menacing evaporation stresses in winter. No doubt the evaporation problem is present at low elevations in Wyoming, South Dakota, and Montana; but in the Black Hills, where yellow pine develops excellently both as to reproduction and growth rate, it is safe to say that both soil and atmospheric dryness are considerably modified by an abundance of snow and by low air temperatures.

TEMPERATURES AND TEMPERATURE GRADIENTS.

The study in the Pikes Peak region has shown that a fairly regular change in air temperatures occurs with change in elevation, amounting to 2.8° F. per 1,000 feet for the year as a whole, 2.9° for the growing season, and 3.3° at its maximum in April. This applies to what may be called "neutral" sites at all elevations except the highest one. Early study showed the air temperatures 20 feet above the ground to be not essentially different for opposing slopes at the same elevation; but near the ground southerly exposures have been shown to be warmer than the mean for the elevation, and northerly exposures cooler, to an extent compatible with the types which they respectively encourage. These contrasts are more clearly seen in the soil temperatures.

The Wagon Wheel Gap locality in southern Colorado shows a temperature gradient of about 2.3° F. per 1,000 feet for the growing season. During the winter months this temperature gradient is not infrequently inverted, and in exceptionally cold weather there may be an inverted gradient of 4° per 1,000 feet, the lowest station here being in a valley affected by cold-air drainage. At a middle elevation this locality is always colder than the Pikes Peak region.

The relation of soil temperatures to air temperatures is by no means constant for the different forest types. During the growing season such differences as exist between air and soil temperatures are largely the results of local insolation, which does not affect local air temperatures so markedly as it does the temperature of the ground near its surface. If the year is taken as a whole, soil temperatures may not reflect the air temperatures of different localities, because of the marked influence on the former of a light or heavy snow blanket.

Because summer soil temperatures agree more closely with the type differences produced by different exposures, no less important than those produced by differences in elevation; because soil temperatures may be seen to have a more direct influence on type compostition at the time of initiation of seedlings; and because winter soil temperatures appear to be indirectly related to survival, through soil moisture, as fully as are air temperatures through evaporation, the detailed consideration of soil temperatures has proved more valuable in the present study than the consideration of air temperatures, even though surface temperatures of the soil, which should by all means be recorded, are largely lacking.

Response of the species to temperatures.—There is every reason to believe that insolation exercises a direct control over the distribution of the species; but in the total absence of direct measurements of insolation, temperature data must be relied on to carry out this idea. It is, of course, difficult to distinguish between the direct effects of insolation and such indirect effects as soil drying; but the total evidence points to the direct and the temperature effects as influencing most strongly the selection of the species for each site, except possibly with spruce, which is more susceptible to drying than to heat injury.

The range of either air or soil temperatures measured in any one type of forest is, however, so small as to indicate that temperatures during the growing season can not vary widely without causing the elimination of the given species, or at least its domination by some other species. It is true that on the lower margin of the mountain forest yellow pine seems to thrive under a wide range of temperatures in different localities. This apparently greater adapatability of yellow pine may be due partly to the fact that, wherever it may extend downward into warmer zones it finds no important competitors, and therefore may exist even if its rate of growth becomes negligible. More important, however, is the consideration that air or soil temperatures as recorded probably mean almost nothing. The temperatures which the young plant experiences will be most intimately bound up with the temperature of the surface of the soil. As may be readily proven, relative to other temperatures the surface maxima, which are probably most important, will vary widely according to the amount of rain and the moistness of the soil during the critical summer months.

A mean growing-season soil temperature of about 58° to 62° F., at a depth of 1 foot, permits the establishment of western yellow pine. At 55° or 56° Douglas fir will appear with the pine. At 52° or 53° fir will probably predominate, but there may still be some reproduction of yellow, limber, or bristlecone pines, the species depending apparently on winter evaporation stresses. At 50° we may expect almost pure Douglas fir if moisture is favorable. At 44° to 48° and perhaps higher, Engelmann spruce reproduction will come in under fir and doubtless ultimately replace it. Spruce may hold complete sway where the soil temperatures are from 40° to 50°, but probably does not reproduce at all where this lowest temperature prevails; the stand must be thinned out before it is rejuvenated.

Lodgepole pine, probably has temperature requirements, for satisfactory reproduction, between those of yellow pine and fir. The single site studied shows soil temperatures a little lower than those for fir, and air temperatures no higher than for good spruce sites. However, the well-known proclivity of lodgepole reproduction for denuded sites, where the radiation is intense, and some few measurements on such sites not conducted long enough to establish averages, show the reason for the usual failure of lodgepole to reproduce under its own canopy and indicate the higher heat requirement of this species. Measurements by Notestein [11] at midsummer in 1912 showed the soil temperatures at 6 inches to be at least 4° higher in an area from which the pine had been cut and the brush burned than in the virgin forest. In each place measurements were taken at about 12 points.

[11] Notestein, F. B., forest examiner, Forest Service, "Progress Report, Exp. R—11," 1923.

Limber pine sites even at high elevations show summer temperatures higher than those for Douglas fir, and undoubtedly reaching almost as great extremes as yellow pine soils.

It is not necessary for a proper explanation of the selective process of insolation to assume, as the present writer once did (*4*) that the temperature of the environment appreciably influences the chemical effectiveness of sunlight; but it is necessary to recognize that a high temperature may contribute to the superheating of the plant tissues, and that a dry atmosphere and wind decrease the liability by facilitating the cooling process of evaporation.

The idea that protection arises from the cooling caused by transpiration is by no means new. In 1902, Barnes (*2*) wrote:

34. Under the present organization of plants exposure of wet cell walls to the atmosphere is indispensable for the solution of necessary gases, oxygen and carbon dioxide, the plant being debarred from waterproofing the cell wall so long as gas absorption is necessary. Transpiration is, therefore, considered as unavoidable, though in itself a constant menace to life and activity. Advantage has doubtless been taken of the xylem bundles to facilitate the movement of solutes, but there is no reason to think this essential. Transpiration also has become a protective factor with sun plants, whose temperature is thereby kept within reasonable bounds. (Since reading the paper the author has ascertained that in certain points his view of transpiration coincides with those expressed by Dr. C. E. Bessey in a paper on the function of stomata, published in Science N. S. 7:13–16, 1898.)

Each species may have, then, functional limits expressed in a minimum amount of light and a certain maximum temperature. It is evident also that the several species may exhibit differences not only in "shade tolerance" but in light tolerance as well, which will be especially marked when the seedling is very young and is subjected to the reflected light from the ground surface and to the attendant temperatures which may prevail there. This limited light tolerance is probably due to the direct effect of heat upon protoplasm. The experiments reported have not, it is true, shown the species to be sensitive to excessive heat in proportion to their shade tolerance. Apparently Engelmann spruce is adapted to a much wider range of light conditions than the other species, while Douglas fir is most clearly sensitive to the heating effects of strong light, and with both spruce and lodgepole pine, the injury to young seedlings evidently arises from loss of water rather than, or commonly earlier than, from superheating.

WIND, HUMIDITY, AND EVAPORATION.

Wind velocities vary widely in different situations and localities of the mountains, recorded velocities depending largely on the immediate conditions of exposure. In general, wind velocities are much higher in winter than in summer, and much higher at high elevations than at low, exposures being equal, because of the fact that the higher atmosphere is more turbulent. Beyond this, comparisons of the sites studied are unsafe. It is entirely in agreement with the physiological qualities of the species to find spruce tolerating much greater exposure to wind, than does yellow pine.

Humidity, as measured by saturation deficits, varies more widely locally, on account of differences in air temperature and not so much by reason of changes in vapor pressure. A wind in descending the slope of Pikes Peak may actually gain some moisture, but its temperature increases so much more rapidly that it gains very quickly in saturation deficit and evaporating power.

Broadly speaking, evaporation rates are almost as high at the highest as at the lowest elevations in summer, temperature and wind movement being almost compensating. In the winter, however, evaporation is almost nullified by very low temperatures in the higher forest types (spruce and lodgepole) where the vapor deficit becomes very small, and high wind is, therefore, noneffective. In the middle and lower portions of the Pikes Peak region winter evaporation is an important factor because of the frequent combination of high temperatures with strong winds. In the Wagon Wheel Gap locality the evaporation is relatively high for corresponding sites except in winter when the temperatures are very much lower than at Fremont.

If measured near the ground the evaporation in the various forest types during the growing season is found to be much more closely controlled by local insolation and temperatures than by the moisture or movement of the atmosphere, and in consequence it can be said that the well-insolated sites are much more conducive to transpiration losses than are the cooler ones. The soil temperatures in this period give a fair indication of the evaporation stresses, which are particularly important in dissipating the soil moisture. Ecologists have generally considered that a high evaporation rate during the growing season constituted a barrier to the success on the site of the more moisture-demanding species. This may be true in the extreme case in which the rate of transpiration is likely to put a serious tax upon the ability of the plant to secure moisture. In the present study it has not been found that the moisture reservoir was seriously depleted on any site. It has been seen that the species of greatest moisture demands according to the results of this study succeeds on the site which produces the greatest evaporation stresses currently during the growing season and in the aggregate. The conclusion is inevitable that, so long as the moisture supply is fairly good, high evaporation can not be considered deleterious in the usual sense and that it can not be a selective factor as between species. Rather it is merely evidence of heat conditions which encourage the species that is most likely to transpire freely, and which are injurious only to the species that for physiological reasons does not transpire so readily.

On the other hand, during the winter the moisture supply may not be available; it is obviously less available at high elevations than at low because of the much lower air temperatures; it is less available on northerly than on southerly exposures because of the poorer insolation of the former; it is less available where the ground is bare than where it is covered by a snow blanket laid on early enough to prevent freezing of the soil. In view of the last-named fact the Pikes Peak region presents a unique situation, a situation in which the very existence of established stands of evergreen trees is threatened almost yearly by drought of the soil and air during the period of vegetative dormancy.

WINTER SOIL TEMPERATURES.

It has been stated that soil temperatures during the growing season supplement or may be substituted for air temperatures as measures of the growing conditions for seedlings. Perhaps the temperature of the soil near its surface is the best measure of the heat, and especially of the maximum temperature, to which the seedling is subjected at a critical age, and no doubt this measurement should receive more consideration than it has in the present study.

Soil freezing.—The fact about soil temperatures which stands out preeminently is that the soil which has a low mean temperature or a low summer maximum is likely to be frozen for a much longer period than the soil which, either because of its low elevation or on account of direct insolation, attains higher mean and maximum temperatures. The period and extent of soil freezing may, however, be considerably modified by a blanket of snow. Everyone knows that an early fall of snow may completely protect the soil from freezing, though Warming, (*22*) considering only one phase of the matter, says: "Only where there is a covering of snow is the temperature of this (the soil's) surface, also its daily mean temperature, lower than that of the air." Evidence might be introduced to show that under a deep snow covering the soil temperature may remain stationary for weeks at, say 32°, while the air temperatures go to 0° or lower. Bouyoucos (*7*) has convincing data on this subject.

The data available show that the mean temperatures of soils at a depth of 1 foot in pure yellow pine types are likely to be below 32° for two or three decades;[12] that the continuance of this temperature for 11 decades does not prove fatal to pine but does tend toward its replacement; that in Douglas fir sites it varies from 7 to 17 decades; and that a period of 15 to 19 decades may be somewhat characteristic of the higher spruce types, where the mean soil temperature for the year is 32° or less. Thus there are marked variations for any one species, but it should be borne in mind that within certain limits the conditions which produce soil freezing are likely to be concomitant with conditions which reduce transpiration.

The gradation from spruce to pine sites in the severity of soil freezing is really more marked than the average soil temperatures indicate. The liability to freezing which will permit injury of the aerial portions of the tree is better measured by the products of periods and greatest depressions, which, as roughly computed, vary from 3,600 at timber line to 30 in the yellow pine type. Where the mean temperature for any decade is never very much below freezing the continuity of the freeze is likely to be broken on any warm day and the possibilities of such relief decrease just about as the amount of depression below 32° increases. At the highest stations there can be found no source of relief until almost the close of the freezing period, when snow water may penetrate the surface soil in advance of thawing at 1 foot.

Evaporation during soil freezing.—In a measure, the longer period of soil freezing at higher elevations and on poorly insolated slopes should be compensated by the decreased opportunities for water loss by evaporation. It is evident that the important thing is not the period of soil freezing, nor the temperature reached, but the fate of the water stored in the stem and foliage of the tree, which must be held during this period.

The best computations which it has been possible to make indicate that the higher forest types are subject to the greatest total loss by evaporation, notwithstanding the much lower daily or monthly losses. A large part of this total loss is likely to come near the end of the period of soil freezing, when air temperatures rise much more rapidly than soil temperatures.

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[12] It is assumed that at a recorded temperature of 32° F. soils will never be frozen because of the depression of the freezing point by solutes and surface tensions.

These computations show a maximum evaporation of about 100 units in the thrifty yellow pine forest, during the mean period of frozen soil. Yellow pine barely exists, in mixture with limber pine and Douglas fir, where the evaporation may be 350 units. Nearly 300 units are possible in an opening of the north-slope Douglas fir forest, but within the forest the total stresses are less than one-third as great. The same type at Wagon Wheel Gap shows the possibility of about 300 units, but only half as much on a well-insolated south slope. The spruce sites show from 60 units (low canyon type) to 400 units at timberline. The greatest loss noted occurs on a high, windswept ridge, where limber pine is now the only claimant of the ground. The lodgepole pine type in southern Wyoming, although soil temperatures are slightly below freezing for five months, has evaporation stresses barely exceeding those of the yellow pine type. Possibly the rapidly increasing exposure to wind at high elevations and the increasing length of the period of soil freezing would set a limit to the upward extension of spruce, though the limit of ability to resist the mechanical effect of wind and snow may be reached first. Regarding drought in alpine situations and the degree of xerophytism which it develops, the following citation from Cowles (*11*) is of interest:

> The distribution of alpine plants, however, is apparently due in large degree to edaphic conditions. The timberline in general may probably be referred to atmospheric conditions, but the marked gaps and oscillations which usually occur are due in a large measure to soil relations. While xerophytes increase in the alpine parts of mountains, it is to be observed that edaphic as well as climatic factors become more xerophytic upwards. While changes occur as one traces one type of edaphic formation upwards, these changes are far less marked than are those observed in passing from one edaphic formation to another.

Although soil freezing does not appear to be a generally critical factor in relegating the species of the central Rocky Mountains to their respective sites, it would seem to have a marked influence on the distribution of yellow pine in view of the sensitiveness of the species to winter drying. "Winter killing" rarely does more than defoliate the established tree, and a few trees of this species have become established where the exposure must be very severe. However, the heavy loss of seedlings of yellow pine during the winter, in both plantations and natural stands, suggests that on sites which do not hold a snow blanket the fatal effects are most likely to be felt by very young trees, both because there is less opportunity for storage of moisture in the tree itself, and on account of the nearness of the foliage to a reflecting surface which would greatly augment transpiration.

PRECIPITATION AND SOIL MOISTURE.

The annual precipitation at the control station is about 22 inches, of which nearly one-half occurs during the growing season. In the Pikes Peak region this annual amount decreases to 14 inches at the base of the mountains, and increases to nearly 25 inches in the spruce zone. There is, then, an increase of about 2.4 inches per 1,000 feet increase in elevation. In the Rio Grande region the precipitation seems to be somewhat less at a middle elevation, but is fully as much at high elevations. In southern Wyoming the lodgepole pine type, slightly higher than the control station, has only 15.5 annually, and only one-fourth of this amount occurs during the growing season.

Precipitation measurements are obviously unsatisfactory for the close analysis of contiguous forest types, since these may receive equal amounts and yet be radically at variance in their moisture conditions. With the precipitation known, measurements of evaporation near the ground should give a very good idea of the extent to which the moisture supply is dissipated, or conserved for the uses of vegetation. It has been shown that the higher forest types have somewhat less evaporation than those at low elevations, for the year as a whole, and that northerly exposures are much less rapidly dried out by insolation, than those which receive the sun's rays more directly.

The measure of the moisture of the soil gives most directly a knowledge of the supply available for the trees of any forest type. It has been shown, with the limited number of stations at which this measure has been taken, that the absolute amounts of moisture in the soil, during either the average growing season, or the driest part of an unusually dry season, are commonly greatest in the spruce sites and the north-slope Douglas fir sites. The yellow pine, limber pine, and lodgepole pine sites have considerably less. Only on strong southerly exposures, however, and near the lower limit of the yellow pine type, where good precipitation is experienced during the growing season, is the depletion of the supply very considerable, and even in these situations the wilting coefficients of the respective soils have not been closely approached at any time during the period of observations. In fact, the higher moisture percentages of the spruce and fir soils do not indicate much more favorable conditions for growth than the lower percentages in the pine types, because the soils of the latter class are always more sandy and hence such moisture as they retain is relatively more available for plants.

Nevertheless, the differences between the types in soil moisture content have a significant bearing. The fact that the minima reached in the various types are so similar in physiological value is in itself evidence that the density of the stand or number of individuals per unit area tends always to adjust itself to the average amount of moisture present, or perhaps even more closely to the absolute minimum amount reached during a long period of years. Therefore, even if the several species showed no differences in their moisture requirements or absolute drought resistance, the moisture content of the soil would strongly influence the character of each forest type by limiting the density of the stand, and thereby affecting the insolation, the evaporation, the soil temperature, and all other contions of the forest floor, which in turn influence the character of the reproduction. This only shows how closely interrelated are the several conditions of the environment. The amount of insolation falling upon a site affects the conservation of the precipitation. The conserved water, by determining the density of the stand in turn, affects the amount of insolation, and so on, ad infinitum.

The important difference between the moisture conditions of the spruce sites at one extreme and the pine sites at the other is not so much in their absolute water contents, considering the entire soil reservoir of each as in the fluctuations of their surface conditions. The well-shaded spruce soil may become very dry at the surface when the atmosphere has been dry for a long time, but it does not dry out severely between the rather frequent summer showers.

Hence spruce seeds have ample time for germinating and are in no haste to extend their roots deeply, often only penetrating the humus layer and establishing contact with the mineral soil by the end of the first summer. The rapid drying of a well-insolated soil, on the other hand, demands prompt germination and rooting of the seedling. Yellow-pine seeds do not germinate more promptly than those of the other Rocky Mountain species, but the seeds are large, the seedlings large and strong, and the root is often extended 3 or 4 inches into the soil before the cotyledons appear above ground. Quite often the roots of yellow-pine seedlings must extend to a depth of a foot and below most of the grass and weed roots before a stable supply of moisture is assured.

In all probability moisture becomes an important factor in limiting the downward extension of the yellow-pine forest, though here we have no proof that excessive temperatures may not as often be the immediate cause of the death of seedlings. Moisture is probably controlling where other vegetation is already established; heat is probably controlling on denuded sites.

CONCLUSIONS.

Each site in the various forest types of a mountain region such as has been studied and reported in this bulletin by means of the several stations presents a unique complex of all the conditions which comprise the atmospheric and soil habitat. Two sites may not vary in a single one of the many conditions which are enumerated as wind, humidity, temperature, soil moisture, etc., without having some effect on the vegetation. In fact when the reproduction of a small forest area is studied in detail most surprising and often unaccountable differences in the number, size, and species of the seedlings growing thereon may be noted in different parts of the area, even though it be only a few yards in extent. It seems, therefore, almost hopeless to attempt to define every factor which is accountable for vegetation of a given type. The best that can be hoped for is that the maxima or minima, or, in other words, the extreme conditions of any nature which a given species will tolerate, may be depicted by a study of the present kind, or by a series of such studies properly correlated. To a limited extent this has been accomplished in the discussion of each factor and in the recapitulation. Since it is a common human desire to have complex matters made to appear simple a single generalization may be indulged in, as a kind of summary, after which the exceptions may be noted and the specific problems of each species may be defined as they are seen at this stage.

A review of the facts that have been presented leaves little doubt that the several tree species of the central Rocky Mountains are controlled in their distribution almost wholly by the degree of insolation of the site, the resultant temperatures, and the closely related surface moisture conditions.

In a general way the forest zones correspond with air-temperature zones, and the considerable differences between the air temperatures of north and south exposures at the same elevation might explain the corresponding differences in the forest types. However, even when air temperatures are measured close to the ground, the critical differences between sites are not brought out. Air moves so freely from one point to another that there can not be a great difference, for example, between a sheltered and an exposed spot on the same slope separated, say, by a distance of 50 feet. Yet it is obvious that the insolation received on the one spot must have the greatest possible influence on the critical conditions for the regeneration of forest trees. Therefore, although air temperatures do generally outline the types fairly well, one must conclude from certain important exceptions that they reflect rather than define the controlling conditions.

The study has shown not only that soil temperatures at a depth of 1 foot bring out more clearly the differences in aspect, which for denuded sites are fully as great as the differences resulting from elevation, but also that the correlation between soil temperatures and the reproduction of the several species is closer than that between air temperatures and species. The meager data on surface-soil temperatures that are so far available indicate that the differences between sites which encourage different species are far greater than might be thought possible—at least three or four times as great as the differences between temperatures at a depth of 1 foot. To use again the example taken above, the spot on a north slope which receives full insolation for two or three hours in the middle of the day may have surface maxima 20° to 25° higher than the nearby sheltered spot, and a similarly exposed south slope may attain surface temperatures 30° to 40° higher still. The surface temperatures on south slopes, moreover, occasionally attain to 150° F., a temperature which, it is believed, is likely to be fatal to any young plant, independent of its drying effect on either plant or soil.

The influence of direct insolation in drying the surface of the soil is hardly less potent than its temperature effect in demanding special adaptations of the plant. Again, direct insolation plays an important part in keeping moisture available to both young and old trees during the winter season, when it is likely to be completely withdrawn through the freezing in the soil.

A frank consideration of the weak as well as the strong points in the evidence which has been adduced in "Physiological Requirements of Rocky Mountain Trees" (*6*) and in the present bulletin, compels the making of somewhat tentative conclusions as follows:

(1) Western yellow pine is not a conservative user of water, nor is it efficient in photosynthesis. It is deduced from this inefficiency that it may thrive best in full sunlight and a warm atmosphere. There is certainly nothing in the evidence to suggest that it prefers a dry to a moist soil. However, its seedlings have the habit of rooting promptly and deeply, a habit which has doubtless been developed because of the need of the species for a warm situation whose surface soil dries out quickly. It may, then, be said unequivocally that yellow pine seeks the warmest sites at middle and low elevations, because of their warmth. With yellow pine at least, the evidence is convincing that warmth of the soil in winter, and availablity of moisture, is a necessity throughout the life of the tree.

At its lower limit yellow pine may come into competition with piñon, or with grasses and other low plants whose life cycle is completed in the short period of most favorable moisture. Little is known regarding piñon, but it is the writer's belief that this pine subsists on a smaller water supply than yellow pine, and also that it is much less sensitive than yellow pine to the high salt concentrations which are encountered in the poorly-watered and largely unleached soils of the foothills.

(2) Douglas fir is often in close competition with yellow pine through much of the altitudinal range of the latter. Douglas fir is undoubtedly more "tolerant" of shade than the pine, is more effective in photosynthesis, and uses less water. Douglas fir seedlings root almost as deeply as those of yellow pine in the first few weeks of life; but fir seedlings are quite evidently more subject to directly injurious effects from high temperatures, than are yellow pine seedlings of equal age. Therefore, it is apparent that Douglas fir can tolerate almost the same condition as yellow pine, and on a soil containing sufficient moisture to support a moderately dense stand, Douglas fir may be the better tree because of its greater photosynthetic capacity, and may eventually dominate the pine. But there is no point in the field evidence clearer than the fact that Douglas fir seedlings will not tolerate full sunlight on a slope where its heating effect is greatest. Therefore, the fir can be a pioneer only on northerly aspects or in the shade of such objects as boulders.

It would appear to be misleading to assume, in any instance, that fir replaces pine as a direct result of favorable moisture conditions. Conditions may be conceived in which great moisture would so modify the surface temperatures as to make possible fir reproduction in full and direct sunlight, but under the conditions of the present study the moisture factor is effective only through the production of canopies and shade.

(3) Engelmann spruce is even more effective in photosynthesis than Douglas fir and uses its water more economically. The seedlings of spruce, however, are very slow in placing their roots at a depth, seeming to prefer the surface layer of the soil and to branch considerably in this layer. This is puzzling in view of the extreme dryness which is sometimes attained by a surface layer composed almost wholly of only partly decomposed litter. It is possible, however, that the roots do penetrate to the top of the mineral soil, with its more certain moisture, and that the seedlings are satisfied with the small supply of moisture insured by this. Another puzzling fact is that spruce seedlings appear to be less easily injured by excessive temperatures than seedlings of Douglas fir, although when drying becomes a factor, the reverse is true.

From the present evidence the conclusion is plain that Engelmann spruce occupies its cold sites and high elevations purely because of a superior ability to grow with less direct light and with lower temperature than are required by any of the other species. Again it is misleading to speak of the direct effects of moisture as a determinant, except in the sense that spruce seedlings are evidently not adapted to situations in which the surface soil dries quickly. There is, however, another soil factor which the writer believes to be very important, and concerning which, it is hoped, convincing evidence may be presented within a short time. This is the factor of chemical composition of the types of soil commonly claimed so exclusively by spruce or perhaps, to use a more familiar term, the factor of soil acidity, although it is the present belief that spruce is equally tolerant of high acidity and strong alkalinity. Without doubt, in some instances, it is the chemical conditions of the soil, rather than moisture contents or light conditions, which draw a sharp line between spruce and Douglas fir forests.

(4) Lodgepole pine is little, if any, more efficient in sunlight than yellow pine, but appears to be more conservative of its water supply. The seedlings are as frail and shallow rooted as those of spruce, so that they do not tolerate drying conditions. On the other hand, the direct effect of heating seems to be less injurious with lodgepole pine seedlings than with those of yellow pine, Douglas fir or spruce. An additional factor in the life of lodgepole is the very sluggish germination of its seed except when stimulated by frequent and wide ranges of temperature, as, for example, a daily range of 30° or more. This characteristic appears to be the outgrowth of repeated regenerations on open ground, where the temperatures are not modified by cover of any sort, or perhaps are augmented by such an absorbent as charcoal. In fact, every quality of lodgepole associates the tree with pioneering in completely denuded ground. Even the slow rooting of the seedlings may be seen to be adapted to a soil in which there is no competing vegetation, and whose moisture has been made more accessible by the destruction of the surface humus. But obviously this slow rooting would be a very unfavorable characteristic in an open situation where the surface moisture was not frequently replenished by showers, or where it was very effectively dissipated by insolation, as in typical yellow pine sites.

Clements (*10*) has rendered a distinct service to students of forestry by picturing vegetation as being constantly in a state of development or flux as the result of changes in the site conditions and because of the competition between species with different qualifications. In somewhat the same vein, it may be best, since it has been shown that the composition of any forest type is very much a matter of competing elements, to consider now the typical situations which have been studied at one or more stations, each in its ensemble, with the hope of destroying any narrow or incomplete view which has been created by considering the physical factors singly. This should be done with the fact clearly in mind that the important differences between sites arise almost wholly from differences in insolation. Otherwise a very poor conception of causes will be obtained.

(1) *A steep south slope at middle elevation.*—The gradient is such that at midsummer the sun's rays fall almost normally on the surface. The insolation may be rated as unity. As the resultant surface temperatures are very high, frequently reaching 140°, and occasionally 150° or more, young succulent vegetation on the surface of the ground might be almost instantly killed. There is an almost complete lack of annual herbs. The rate of evaporation is very high. This rate may be expressed as unity. The soil is almost lacking in humus. The surface dries quickly after showers, but owing to the unbroken mineral soil, capillary action ordinarily keeps a reasonable amount of moisture near the surface. The soil has poor holding capacity because of the lack of humus and also is lacking in nutrient salts. Consequently, it can never support heavy vegetation. At the outset only the sturdiest of seedlings can survive. If they start after midsummer, they must develop rapidly both as to root and lignification, in order to be prepared for the critical conditions of the next season. A freely transpiring species is required, for transpiration may protect the tender leaves from superheating as perspiration protects the bodies of some animals. The ground will not freeze permanently if at all; hence the seedling need not be inherently drought resistant,

that is, of high sap density. Yet deep rooting is essential in order that any adequate supply of water may be had, and later extensive rooting must be developed in order to insure the supply of water from a soil of such meager capacity.

Either yellow pine or limber pine fits these conditions. The large seed of either species is a fairly good guarantee of the vigorous initial growth that is essential. Later, when the pines make shade, an occasional Douglas fir may become established in the most shaded spots. Limber pine will disappear if the stand becomes at all close, because it can not compete with yellow pine in growth rate or ultimate stature. Any species, with the possible exception of spruce, could be planted here if sturdy young trees were used, for the only really dangerous factor is excessive heat.

(2) *A flat ridge.*—The insolation is about 0.80 or 0.85. The highest surface temperatures reach 120° to 130°, but they are not prohibitive to tree establishment except as they induce rapid transpiration and soil-drying. The wind exposure is greater than on the south slope, and the evaporation is almost as high. Greater difficulty is experienced in forming any soil; all the humus is moved away and there is little chance for any to be deposited. The same is true of the finer particles of soil as the rocks break down; consequently there is practically no soil over the rock. Very little water can be retained. The forest must always be very open. The difficulties of initiation, however, are not so great as on the south slope. Limber and yellow pines predominate, but the yellow pines are lacking in vigor, being evidently exposed to some desiccating force they can not cope with. This is probably the winter wind. The insolation is not enough to keep the soil from freezing deeply, and the wind exposure is worse than on any other site except a westerly slope. Some Douglas fir seedlings appear, with a little protection, and they do not suffer from the winter conditions.

(3) *The middle of a north slope.*—In heating effect the insolation can not be rated over 0.50 at midsummer, and may dwindle almost to zero in winter. Hence the striking characteristics of the slope are ability to retain moisture and a long unbroken period of freezing during the winter. As measured just above the surface on a denuded site, the insolation and evaporation may at times be nearly of unit weight; but of course the evaporation may become negligible when the sun is very low. The conditions for soil building are almost ideal. On this kind of a site there is adequate heat and moisture for the early development of any species. The retention of a snow blanket in winter practically eliminates exposure and further encourages a mixture of all the species. Only spruce may at first be prohibited, and until other vegetation shades the ground and modifies the superficial drying of the soil.

The large quantity of moisture present encourages a heavy vegetation of all sorts and quickly changes the denuded site to a thicket. The later conditions are radically different from those which initiate the succession. Direct light, while not entirely wanting during the growing season, is at a premium. Only the species which are more effective in photosynthesis can develop properly. At first Douglas fir will predominate, simply because spruce was handicapped at the outset. In another generation without disturbance, the spruce will be equally or more abundant. The disappearance of the yellow pine and limber pine which at the outset found the conditions favorable is a slow and almost pathetic process. They do not, except in infrequent years, suffer for lack of moisture; and as their crowns rarely appear among the dominants they do not even suffer the most severe winter drying, which is very rigorous for the tallest trees on this site. Unlike the suppression which is so common in crowded stands on less moist sites, which takes the form of complete stunting, the strictly shade suppression here results in putting all of the energy of the tree into height growth, the side branches being quickly eliminated, and no food being left for the proper strengthening of the stem. The result is a long, slender, supple pole, with only a tuft of green at the top, which is invariably a little lower than the tops of the surrounding firs. Limber pines and yellow pines which reach this stage are usually destroyed by snow breakage.

(4) *The foot of the north slope.*—The steepest portion of a slope is very commonly just below the middle. Further down, deposition of material from the upper slope may more than keep abreast of erosion. Hence the ground tends to flatten out, and frequently a bench is formed somewhat above the stream bed. For a considerable part of the year the site may be shaded by the steeper ground to the south. It receives by transport the best of the soil formed on the entire slope; very commonly it receives also the run-off from heavy rains and, with some rock formations, the seepage. There is, then, a greater water supply than elsewhere, a deep, spongy, retentive soil and little insolation to dissipate it.

Probably because such a site is a catch-all for seeds as well as for soil-building material, it can not long remain denuded. Rank herbs appear almost immediately, and tree seedlings rarely start except with the keenest competition for light. Year after year the herbs grow up about the seedlings, and there is at no time opportunity for any but the most shade-tolerant trees. Even these have a very long struggle before they eventually find "their place in the sun." The conditions, of course, do not change materially after a forest is established. There will always be a dearth of light. If the stand is very dense, in a protracted drought there may be a fairly complete exhaustion of the moisture as deeply as the roots penetrate. The most prohibitive condition, however, probably arises from the undisturbed accumulation of litter on the forest floor. After the snow has melted in the spring, and this loose, jack-straw mass has slowly dried out, it will in all probability not become wetted again until the next snow falls. Certain greenhouse tests made by the writer have indicated that the refusal of resinous needle litter to imbibe water creates a serious problem in connection with the germination of seeds. In consequence, a large part of the floor under spruce may be as barren as the desert, and it is especially with such conditions that the marked results of any soil disturbance, such as occurs through the skidding of logs, are to be noted in succeeding reproduction.

The description here given refers in a degree to the lower portions of all north slopes, and commonly to that portion of the stream bench contiguous thereto. It is, of course, evident, that in so far as the slope itself is short or moderate in gradient, it may fail to produce the depicted conditions at its foot, and under certain circumstances there may be no area in this position that would be prohibitive to

Douglas fir or even to yellow pine. The Black Hills in general, being "hilly" rather than mountainous, encourage yellow pine on all sites; but in the more mountainous portion, and where the erosion of sedimentary formations has resulted in long and steep slopes, the Black Hills spruce is found, as might be expected from this description.

In order to complete the picture of a valley cross-section, it is only necessary to add that, except in narrow canyons whose walls shade a great area, the creek bottom facing the south is likely to be of a very different character. That area which is not shaded when the sun is highest will immediately take on the character of the south slope, as described in paragraph 1, with this important exception, that the soil deposition, seepage, and run-off which this area may receive, may encourage a denser stand than characterizes the upper slope, and in this denser stand it is not uncommon to find stragglers of the more tolerant Douglas fir, and even of spruce.

(5) *The east slope at middle elevations.*—As has been clearly shown, the east slope in the Pikes Peak region receives a large proportion of the direct insolation, for the simple reason that the mornings in summer are generally cloudless. This means that surface temperatures may be attained almost, if not quite, as high as on south exposures, it being understood that the maximum effects of insolation are approached very quickly. This direct insolation is, however, of less duration than on south slopes, and its drying powers are proportionately less. The evaporation may be rated between 0.70 and 0.80. The result is of course a better conservation of moisture. This is without doubt augmented by a fairly good soil, built up by the wind deposits of material from west exposures.

The existence of direct insolation, creating excessive temperatures in the morning if only for a short time, means that the pioneer trees must be largely yellow pines. The conservation of moisture however, permits heavier stands than can be supported on south slopes. The result is that on easterly exposures the succession of pine by Douglas fir is more prompt and more certain than on south exposures.

Under certain conditions there may even be no pine stage. A good illustration is that of an extensive east slope below a middle elevation, which after being denuded by fire produced directly a heavy stand in which fir is much more prominent than yellow pine. This entire slope, however, is boulder-strewn, and these boulders perform the same function as pine trees; that is, they supply the necessary shaded spots for fir seedlings. The boulders are much to be preferred to pines as nurses, because they use no water. This phenomenon may occasionally be noted even on south exposures.

(6) *The west slope.*—The winter winds make this aspect by far the most difficult of any at middle elevations to cover with vegetation of any sort. A west slope does not in the aggregate receive so much insolation as an east slope, yet on exceptionally clear summer days it may easily become very warm, and is with certainty fitted only for the limber pine and yellow pine. In summer the evaporation rate is moderate, and the moisture conservation would be good were there any soil to retain it. In winter the evaporation rate is nearly as great as on a south exposure. Probably a more severe strain is presented here because the soil is thawed much less frequently. Along with the desiccating effects of the west wind, which is a factor only in

winter, must of course be mentioned its ability to remove the soil-building materials.

The physiological studies have indicated that limber pine is as low as yellow pine in photosynthetic capacity, and perhaps lower; yet a more important factor in its distribution is the probable fact that it never exposes itself to rapid water losses through the stomata. Lacking the vital qualities which make our forest trees what they are, this weed is apparently satisfied to "close up shop" whenever the conditions are in the least unfavorable, and thereafter it is practically immune to desiccation by wind. It is for this reason that limber pine becomes established on west slopes where yellow pine can not. Although it is a valuable pioneer, it is intrinsically so worthless that its tenure might well be temporary. Unfortunately, a cover of limber pine on a westerly slope is usually scant, and neither the wind exposure nor the insolation is very much modified thereby. So far as the writer's observation goes, only spruce may be expected to supplant the limber pine, and this probably so slowly that centuries may be consumed in the succession.

(7) *Lower elevations.*—The general relationships among the six sites described above, must of course prevail at any elevation. The fact of the matter is, however, that even when, topographically speaking, these sites are duplicated near the foot of the mountains, the conditions are found to be very different. At the foot of the mountains there is less precipitation; higher temperatures prevail the year round, tending further to dissipate this precipitation; the atmosphere is relatively drier at the eastern foot; and perhaps most important, the higher air temperatures further augment insolation in producing unbearable conditions at the surface of the ground. To a certain extent these higher temperatures must be counterbalanced by weakened light intensity.

The effect of less precipitation and its more rapid dissipation must of course be to make impossible on any site such dense stands as prevail at higher elevations. When to the greater openness of stands is added the greater heating opportunity per unit of area, it is readily seen why there should be, first, the entire elimination of the heat-sensitive Englemann spruce, with Douglas fir occupying the most sheltered sites, then the confinement of the forest to northerly aspects, and finally its disappearance where the mountains merge into the plains.

It is not necessary or relevant to do more than mention blue spruce (*Picea parryana*), white fir (*Abies concolor*), or piñon pine (*Pinus edulis*), which are evidently more heat-tolerant than their mountain counterparts and succeed in slightly extending the group ranges. These trees have little place in the economy of the forest and have been given no careful study.

There is not much question in the writer's mind that soil quality is an important factor in the sudden termination of the forest at low elevations. Not only in the Pikes Peak region but generally throughout the Rockies, the mountains proper are composed of igneous rocks and the foothills of sedimentaries. The former produce open, more or less gravelly, well-drained soils, the drainage being further insured by the strong relief. The sedimentaries produce fine, compact soils; and as the foothills are almost invariably devoid of springs and permanent streams it is evident that their soils are rarely subjected to leaching. Such soils are much more fertile than the mountain soils; but if they were equally moist at all times they would still present a more arid condition in the physiological sense. There are still two other aspects to the matter. The fine, compact soils, when rain is withheld, dry out more completely and more deeply than mountain or sandy soils; consequently they may be not only more arid but more liable to super-heating. Again, when the plain is reached the stability of such soils precludes any denudation and permits the firm establishment of perennial grasses; consequently competition alone would preclude the establishment of tree seedlings.

When, therefore, the question is raised whether it is lack of precipitation or heat which excludes the coniferous forests from the plains, the answer may be given unequivocally that it is both, and that it is also alkalinity of soils and competition. It is nature's unanimous verdict. Yet it is to be noted that with the possible exception of alkalinity, none of these conditions need absolutely inhibit tree growth. For this reason, wherever there is a reasonable amount of relief and nature has had extreme difficulty in establishing tree seedlings, planting may still be conducted with a high degree of success.

(8) *Higher elevations.*—On the several sites at higher elevations there is greater light intensity, modified in its effects by lower air temperatures and increased precipitation and conservation. It would seem, therefore, that the conditions were exactly the opposite of those at low elevations. However, there is an important exception in the fact that wind movement in the higher atmosphere is much freer than near the general surface of the earth, and there is no site at high elevations which is entirely free from this added wind effect. This tends to make the evaporation rate relatively high.

Because the coolness of the air is largely, if not fully, compensated by greater intensity of the sunlight, it is not surprising to find that our light-demanding pines invade denuded areas, yellow pine to an elevation of 10,000 feet and limber pine up to timberline. About where yellow pine fails bristlecone pine may be expected to take its place.

Quite different, however, is the behavior of Douglas fir, which in the Pikes Peak region is not seen much above 9,300 feet elevation. Apparently there is no place for this species where conditions are so readily made suitable for spruce by a minimum amount of shade. It is not the intention to say that in an early stage of succession there is no favorable place for Douglas fir but rather that in the final stage there is no place, and having been crowded out of the last climax forest it has been unable to retrieve its position since the fire that occurred about 60 years ago.

At the higher elevations the completely denuded areas are invaded by yellow pine, limber pine, and bristlecone pines; but, with the possible exception of a few rocky ridges incapable of supporting many trees, every site whose elevation is more than about 10,000 feet must eventually be conquered by spruce. On much of the area no other conifer is found. A quick growth of aspen sprouts after a fire is possible on almost any site, and these form abundantly heavy shade for spruce seedlings.

(9) About lodgepole pine sites, which do not exist in the Pikes Peak region, it is necessary to say a word because of the close relation of lodgepole pine in many localities to the more valuable species.

This species, like the other pines discussed, is evidently light-demanding; but, unlike the other pines which through long ages have adapted themselves to the surface drying which results from direct insolation, the germination of lodgepole seeds is slow, and the development of root in the young seedling is feeble. For this reason lodgepole commonly reproduces on fully insolated sites only where there has been complete denudation, as by fire, and where its moisture supply is made as certain as possible by the destruction of its competitors. More frequently than not, mature lodgepole stands are so open as to give plenty of light for germination; but as the open stand results from limited moisture it follows that the seedlings may develop only very slowly and may be wiped out in drought years. The greater the moisture and the denser the lodgepole stands, the more certain it is that spruce seedlings rather than lodgepole will predominate in the reproduction, and that the ground can be regained for this more valuable tree. On the other hand, on drier ground which probably once belonged to Douglas fir, there may be much less opportunity for the fir to take possession primarily because of its very inferior seeding capacity. For this reason much of the ground in this region which is capable of supporting high-quality fir stands will be very slow in returning to that species.

That lodgepole pine is almost completely absent from the immediate territory of this study appears to be due to a dry atmosphere, a loose, rapid-drying surface soil, and hence less favorable conditions for germination than it demands. On sites where the conditions for germination might be favorable, it is possible that soil freezing may be prohibitive. The growth of lodgepole trees planted on yellow-pine sites in the Pikes Peak region has been excellent, but establishment by direct seeding has been accomplished only in a few favored, though warm, spots.

APPLICATIONS.

The value of a more exact knowledge of the forest trees with which we are dealing in the National Forests of the central Rocky Mountains should be evident to anyone at all familiar with the problems of forestry. To what extent knowledge of any fact may affect human plans and activities can never safely be prognosticated. Yet it is safe to point out some of the benefits that may be had immediately as a result of facts brought out by this study or previously discovered and, perhaps, confirmed by the large amount of data here presented. It is necessary, of course, to refrain from generalizing; yet it must be apparent to foresters in other regions that in each forest region there are counterparts of the species here discussed. It may, therefore, be helpful to understand the relations between species as they have here been depicted.

Neither the physiological investigations nor the field data secured in the present study indicate any marked difference between the species in actual drought resistance; and by this is meant ability to extract water from the soil when the condition of physiological dryness is being approached. If there is any such difference, it is theoretically in favor of the species which are commonly thought of as demanding moist sites, but which in reality demand cool sites, namely, spruce and fir. On the other hand, a species like spruce which is accustomed to moist, rich soils and develops a compact root system, may be able to drain the moisture of the soil more completely, because from the outset its roots are more finely divided, and they more completely reach all of the moisture. The tree accustomed to a dry soil insures its moisture supply by reaching into an extensive area.

There has been shown to be, however, a very great difference between the species in photosynthetic efficiency, in ability to utilize whatever of light may be available, in sensitivity to high temperatures and drying which may result from direct insolation, and, finally, in the efficiency with which water is used. The relations of the several species to light are important silviculturally. The fact that one species may utilize 10 per cent of the energy of incident sunlight in the production of carbohydrates, and 90 per cent in the wasteful evaporation of water, while another utilizes only 5 per cent of the energy of incident sunlight, is of the vary greatest importance economically. The species which nature has developed to serve as the climax of any forest succession is the most highly developed plant organism of that association, and in all probability is the species which may most fully serve human needs, at least in the sense of quantity production. For a great many regions, as well as for the one here discussed, this species will probably prove to be spruce.

The most obvious application of the results of this study is that in the reforestation of denuded areas or the afforestation of such areas as our sand-dunes, it is possible to advance nature's process by at least one successional stage. For example, a denuded, strongly insolated site, which is known to have borne in the past a stand of Douglas fir, but which, from direct or indirect knowledge it is known will first be stocked with pine, is under no necessity whatever to go through the pine stage. The area may be immediately stocked with fir, with very great assurance of success, because the 3-year-old trees which may be planted are not susceptible to the heat and drought of the site which would be fatal to young seedlings. To a certain extent, on the same basis, a given species may be planted on a somewhat lower, warmer, and drier site than would naturally, at the same stage, reproduce that species.

Not only are these things possible in reforestation, but they are obligatory upon foresters, in order that the land may be put to the highest use, and the moisture, almost always limited in quantity, may be utilized by the most efficient of the organisms capable of existing under the given conditions. Exception must of course be made where a certain species is most desirable for its technical value.

In the management of forests for continuous production, which always implies the securing of natural reproduction, the realization that the nature of the reproduction secured will depend almost entirely on the conditions of insolation must be very helpful in determining the weight and character of the cutting. It should be kept in mind that, while the cutting of undesirable species may reduce the number of seedlings of that species which will appear, it is no guarantee whatever as to the identity of the seedlings that shall survive. That will be determined by the light and heat conditions which result from the cutting in the aggregate. In general, all cutting in climax forests must tend to encourage the species of the successional order next below the climax, and in clear cutting the result may be a reversion of two or three stages. The maintenance of the climax forest may be anticipated only by very light cutting, except of course in the upper spruce zone where there are no subclimatic trees.

In the lower part of the spruce zone, too heavy selection cutting is almost certain to encourage Douglas fir seedlings where that is the species next in order, and lodgepole in the region where this tree has invaded the Douglas fir and lower spruce zones.

Much of the lodgepole forest would be replaced by spruce, and other portions by Douglas fir, if the lodgepole were left uncut or were thinned very lightly. The heavier the cutting, the more certain it is that lodgepole pine will continue to hold the ground.

Nearly all of the Douglas fir forest of the central Rockies, if cut too heavily, is subject to invasion by western yellow pine or the worthless limber pine. However, on northerly exposures, there is much less danger of this, and a heavy cutting under the shelter-wood plan appears most likely to give prompt and desirable results.

As the less severe yellow-pine sites will in the natural sequence of events go over to Douglas fir, there is no very evident reason why Douglas fir seedlings should not continue to come in with the protection of their parents only, if it should seem desirable to remove the yellow pines, provided only the stand is not too greatly opened. A much more serious problem is presented in the lower portion of the yellow-pine type, where the stands are always so open as to permit the formation of sod, and where any new opening may be quickly occupied by the perennial grasses. Silvicultural caution demands that cutting be done only when there is a seed crop. A favorable year following can of course never be guaranteed. Evidence in the Southwest to the contrary notwithstanding, the writer is firmly convinced that the perpetuation of the mountainous yellow-pine forest in this region can best be insured by the burning of the brush in piles, a measure which, as everyone knows, eliminates the grasses for a period of several years and gives the pine seedlings at least an equal opportunity with other vegetation.

On the general subject of brush disposal this study appears to have offered only one other suggestion. It is believed that, where spruce forests grow on moderately steep to very steep slopes, both the nature of the ground and the relative openness of the stand prevent excessively heavy accumulations of needle litter, which, an attempt has been made to show, may afford a very unfriendly seedbed. On such slopes there is likely to be advanced reproduction, and burning of the brush is neither called for nor desirable. On the contrary, on flats which usually produce the most superb spruce forests, very serious delay of reproduction is likely to result, even after heavy cutting, unless some spots are laid bare. Furthermore, the accumulation of litter should by no means be added to. Here the burning of brush is distinctly called for. There is some evidence that this may also reduce the percentage of alpine fir (*Abies lasiocarpa*) seedlings, which are more vigorous than spruce seedlings and establish more certainly in deep litter.

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