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II

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By G. W. GOLDSMITH

INTRODUCTION

Physiology and ecology depend for their constructive development largely upon the applications of physico-chemical concepts to living organisms and their environment, to their life processes, reactions, and interrelations. A concept is valuable biologically in so far as it can be applied and used as a tool for better understanding of the phenomena related to life. Ecology, as the study of the relations between organisms and their environment and of the interrelations of organisms, depends primarily upon the findings of physiology (Clements, 1905). But to apply physico-chemical concepts and hence make them of value to the physiologist or ecologist commonly requires practicable instrumental methods, and the lack of these often causes a valuable concept to remain sterile, so far as the physiologist or ecologist is concerned, for years after it might have been profitably applied. It is but recently that physiologists and ecologists have made full use of electrolytic dissociation of acids in their field of work although the essential facts were clearly set forth by Arrhenius in 1887 and 8, the recent activity of biologists in this field having followed the development not of the concept but of suitable colorimetric and electrometric methods. Physiology and ecology, as well as the applied branches of biology such as agriculture and forestry, seem fated to lag far behind their physico-chemical opportunities.

Experimental physiology and ecology, as distinguished from descriptive, are at present in great need of improved methods and instruments. Recent developments in physical, colloidal, and organic chemistry have left the biologist far behind. Even a branch of phyto-chemistry so well developed as the chemistry of pigments has still to receive its full physiological and ecological application. A method, an instrument or other tool capable of use by the biologist is always a prerequisite to the application of a concept; physiological-ecological investigation still depends upon the development of simple practicable methods and instruments. But with the growing detail of biology, chemistry, and physics the accuracy and often the complexity of methods and instruments must be increased. The time has passed when an investigator needs only the training and skill of a tinker. Many of our methods are crude in the extreme and further progress must await refinements both of methods and instruments. The man who successfully essays physiological-ecological experimentation must have a reserve of physico-chemical training and skill as well as a biological background; a glance through any of our periodicals will, however, reveal how little this is appreciated.

Field experimentation in biology is the most backward phase of the subject. It may be easy and even recreational to make collections, descriptions, and observations in the field; it takes one out of doors and into interesting places and there is seldom need to go during inclement weather, but field experimentation is quite a different matter; circumstances are hard, apparatus is ill-suited to field work, and conditions are so variable and can be controlled so imperfectly that conclusions must be carefully tested from every possible angle. The increasing accuracy, delicacy, and complexity of modern biological work impose more and more difficult conditions upon the field experimenter who must have apparatus not only accurate enough to meet the requirements of the case but strong enough to withstand the severe use to which field conditions subject it and simple enough to be usable in the field where many facilities common to laboratories are unobtainable. Field experimentation in physiology and ecology is retarded because of the lack of suitable instruments which are accurate, simple, and sturdy. The very difficulties of the field have, however, produced attractive opportunities, for not only are there truths to be found which have entirely escaped the laboratory worker but many experimentally-established facts still await the fuller confirmation and understanding that only field work can give.

The instruments described below are accurate if properly employed, simple, compact, strong, and inexpensive; the methods of use require only supplies which may readily be carried into the field. It is hoped that by their use field workers may be provided with a new means of progress.

IMPORTANCE AND FIELD MEASUREMENTS OF HUMIDITY

The amount of water vapor in the atmosphere has long been recognized as an important environmental factor. There is a growing and voluminous literature relating to the physiological and pathological importance of water vapor to mammals, particularly to man and domestic animals. Recently Huntington (1915), and Huntington and Cushing (1922) have traced the effects of atmospheric humidity upon human energy as measured by the output of factory workers and upon development and health and conclude that optimum humidity conditions are about 80 per cent relative humidity (a somewhat lower value was given in 1915) at temperatures between 65 and 75 degrees Fahrenheit. It appears that not only does very dry or very moist atmosphere reduce the capacity for work, but the inclination to work at temperatures ordinarily experienced within doors. This relation, however, is not a simple one and is not only intimately connected with temperature but also with rate and frequency of change. Hill (1920) points out that a moderately dry cool atmosphere possibly produces the invigorating effects noticeable in mountain resorts because of the more rapid arterial circulation and the increased circulation and secretion of lymph bathing the respiratory epithelium. Thompson (1914) has shown that in England a decrease in relative humidity from 90 per cent to 70 per cent increases the rate of metabolism as measured by the carbon-dioxide production of the body. Lee (1916) finds that the rate of heart beat and the blood pressure are increased by high temperatures together with high relative humidities. Novakovsky (1922), applying the results of Huntington to the climatic conditions of East Russia, shows that unfavorable humidity conditions there are partly the cause of low human efficiency.

The effects of humidity cannot easily be distinguished from those of temperature since the two phenomena are closely related both physically and physiologically. Thus changes in temperature produce alterations in the vapor pressure of water and in the density of the air and hence in the amount of water vapor which a given volume of atmosphere will hold when in equilibrium with water, i. e. when saturated. The reduction in the percentage saturation of the atmosphere with water vapor increases the evaporation from the body surface and thereby reduces the temperature of the organism from which the evaporation occurs since the vaporization of a gram of water requires 596 calories of heat. The physiological effects of atmospheric humidity appear to influence the animal body through two channels: 1. Evaporation effects upon body temperature. 2. Changes in water content of the organism. In both cases it is plain that the important biological effect of humidity is through evaporation.

Numerous investigations on the pathological effects of humidity have appeared, but two of which will be mentioned here. Huntington (1920) pointed out the effects of humidity upon pneumonia and influenza. So general is the feeling among physicians that regions of low relative humidity are helpful in combating pulmonary diseases that patients suffering from such disorders are regularly advised to seek such a climate. Dublin (1922), using statistical methods, has recently concluded that heart disease is most prevalent among workers whose occupations take them on or near the water.

The reactions of animals to evaporation have been carefully studied by Shelford and his students. Shelford (1913, 1913a, 1913b, 1914), working with various vertebrates and invertebrates found that animals are highly sensitive to evaporation, that they react positively to evaporation conditions similar to those of their environment, that they respond to excessive evaporation first by heightened irritability, and that the body integument may afford considerable protection against excessive water loss. Chenoweth (1917), following Shelford's methods, found the white-footed mouse very sensitive to evaporation. Weese (1917) found the horned lizard to be influenced by evaporation in a way comparable to forms studied by Shelford. Shaw (1921) noted the effects of low humidity and high temperature upon the Townsend ground squirrel of Washington. Shelford (1913, page 112), after reviewing the physiological effects of water vapor, says: "From the literature cited and from the literature included in the bibliography it is evident that in the case of mammals temperature data have little significance unless the humidity is known."

Humidity and evaporation effects upon the behavior, structure, and development of animals have been the subject of numerous investigations but a few of which can be mentioned here. Cook (1920) found that the humidity at 7 p. m. was a more important factor governing the nocturnal flight of moths than either air temperature or barometric pressure, 54 per cent relative humidity being the optimum condition for flight. Sanders and Shelford (1922) noted the daily migration of insects corresponding to changes in evaporation and temperature. Ackert and Wadley (1921) point out the great reduction in death among crickets when high atmospheric humidity is maintained in the cages. Shelford (1920) found that at optimum temperature varying the humidity produced differences in the length of pupal life of the insects studied altering both the length and number of instars. The development of insects was found to be closely connected with moisture conditions. Pierce (1916) found that the development of insects is not limited by temperature or any other single factor but by a relation between the habitat factors. For the cotton boll weevil the optimum is about 83 degrees Fahrenheit and 65 per cent humidity. It seems safe to conclude, in the light of the above mentioned work and of other investigations not discussed, that the relations of atmospheric humidity are of great importance to terrestrial animals and that no physiological or ecological investigation can safely omit the consideration of such factors.

If the atmospheric moisture conditions are important to land animals they are of even greater moment to terrestrial plants. In both groups of organisms some water must be retained for carrying on vital activities, and respirational loss, however restricted, cannot be totally eliminated. But with higher land plants extreme environmental conditions must be met without the possibility of moving to new locations, where evaporation is more moderate, and growth is limited by the amount of carbon dioxide secured from the air for photosynthesis. Plants, like animals, developed internal protected respiratory surfaces early in their evolutionary progress, securing thereby reduced evaporational loss, the mechanical protection necessary for delicate thin-walled tissue, and an increased and more efficient surface for respiratory exchange. But while the higher animals have increased the efficiency of the respiratory epithelium by a more or less rapid muscularly-controlled circulation both of air and the body fluids, plants have evolved with an imperfectly controlled and less efficient means of circulating the gases and liquids concerned, and in order to secure adequate gas exchange have developed huge respiratory surfaces thus insuring sufficient oxygen and carbon dioxide absorption from the atmosphere without the expenditure of energy in movement, but rendering themselves especially vulnerable to excessive evaporational water loss.

Protective modifications against excessive water-loss are among the most conspicuous morphological and physiological characters of land plants, developed early in their evolutionary history as a necessary prerequisite to extensive land distribution, and have taken almost every conceivable form, especially among Spermatophytes, such as special epidermal developments and leaf-forms and positions, details concerning which may be found in Bower (1908), Strasburger (1916), Clements (1907), Coulter, Barnes, and Cowles (1910) or any textbook of general botany or ecology, but the development of an extensive internal respiratory surface protected more or less perfectly by stomatal openings is conspicuous among plants from the liverworts to the Angiosperms (Haberlandt, 1914). Extreme humidity conditions call forth, of course, the most conspicuous adjustments on the part of the plant. Plants growing under arid conditions show strikingly modified forms while plants adapted to wet humid habitats show less striking but quite as distinct structural characters (Warming, 1909; Clements, 1907; Coulter, Barnes, and Cowles, 1910-11). Xerophytes, mesophytes, and hydrophytes are structurally and physiologically modified by the total complex of factors comprising their habitat conditions, humidity being but one of the factors concerned. "Sorauer, Mer, Vesque and Viet, Lothélier, and others have found that the effects of moist air are like those of weak illumination. Plants become more elongated, long-jointed, thinner, paler; their leaves are smaller and thinner, more transparent, and have their dorsiventral anatomy obliterated because of the absence or feeble development of palisade tissue; the vascular bundles become weaker, the intercellular spaces larger, and the mechanical tissue weaker or even suppressed" (Warming, p. 30). Jost (1907) enumerates similar structural modifications accompanying changes to moist or dry atmospheres, and cites the work of Kohl, Lothélier, Goebel, and Brenner on the subject. Although in temperate regions high humidities are not often studied in the field yet they are a striking feature of many tropical habitats (Schimper, 1903; McLean, 1919; Shelford, 1917; Henderson, 1913; and Shreve, 1914) and are more commonly present in restricted areas in temperate latitudes than is usually supposed. Under decaying bark, under dung, and in forest soil saturation of the atmosphere is of common occurrence even under climatic conditions as arid as those of central Colorado so that seedlings and many smaller plant forms are frequently under conditions of saturation. In tropical rain forests high humidities produce conspicuous morphological modifications (Schimper, 1903; McLean, 1919; Shreve, 1914) and are recognized as an important though imperfectly investigated habitat factor. With plants from humid habitats, as with xerophytes, humidity relations, while admittedly important in the environmental complex, are not easily distinguished from concomitant factors.

Though in final analysis morphological features are based on physiological changes, the latter are much less easily observed and it is not surprising therefore that comparatively little experimental data are available upon the physiological effects of humidity upon plants. Since the effects of variations in humidity are largely manifest through the alterations in transpiration which it occasions, physiological, like morphological, investigations are largely grouped about this latter subject. Unfortunately many physiological researches have been carried on with no reference whatever to humidity conditions on the assumption that the observed effects have been due to other factors such as temperature.

That xerophytes often tend to become succulent and store water in some plant organ has frequently been described. This tendency toward succulence has been carefully studied by MacDougal (1916, 1916a), MacDougal and Spoehr (1917, 1917a, 1918, 1920), Spoehr (1919), and by MacDougal, Richards, and Spoehr (1919) and shown to be accompanied by the production of comparatively large amounts of pentosans, thus increasing the imbibitional power of the tissue. Just what part the factor of humidity plays in xerophytism is not known. Haberlandt (loc. cit., p. 108) mentions the variations in wax production of certain plants corresponding to fluctuations in the humidity of the air of their habitats. Schlosing (1869) found a correlation between the amount of water absorbed by the tobacco plant and the amount of salt absorbed so that plants grown in moist atmosphere showed a smaller ash content than plants grown under dry atmospheric conditions. Hasselbring (1914), however, obtained quite the opposite results. So the whole matter is in doubt except that there is an undoubted physiological effect of humidity. (See also Palladin and Livingston, 1923, pages 148 and 271). Under conditions of high humidity plants often respond by guttation presumably maintaining thereby the transpiration current and thus obtaining necessary salts (Stahl, 1919). Caldwell (1913) has shown that atmospheric humidity conditions have a profound effect upon water equilibrium between the soil and various plants at the time of wilting. Sprecher (1921) found that the osmotic pressure of the sap of Tropaeolum varied with the relative humidity rather than with light or temperature.

Movements of plants or their parts in response to alterations in humidity have been a perennial subject for description and illustration by plant physiologists. Various awns and other distributional parts of fruits or seeds are well known to be hygroscopic. Flowers of *Anagallis coerulea, Gentiana amarella,* and *Stellaria media* remain closed under conditions of high humidity (Pfeffer, 1906). Newcombe (1922) describes movements of stigmas occasioned by atmospheric humidity conditions. Imbibitional effects due to water vapor produce the breaking of fern sporangia, opening of phanerogam anthers, and alterations in the osmotic pressure of certain fungi resulting in the discharge of spores (Jost, loc. cit.). Movements and structures alike may be but the external expression of changes in neutrality, permeability, and colloidal state occasioned by transpirational variations, but here we have little information.

High transpirational water loss accompanying low atmospheric humidity may be met not only by the protective structures characteristic of xerophytes but by increased absorption. We may thus expect arid conditions to be reflected in root modifications as well as in the characters of the aerial parts of the plant. Weaver (1919 and 1920) has described at length root systems typical of various habitats and has shown that habitat conditions are as capable of producing modifications in the under-ground parts of plants as in the aerial portions. Cannon (1911, 1912) has also described root systems developed under special habitat conditions but thus far little attempt has been made to study the action of the separate environmental factors. Cerighelli (1920) found that the respiration of roots was higher in humid air than in dry air although changes in the humidity produced no alterations in the respiratory ratio. Atmospheric humidity is undoubtedly one of the important factors the sum of which modify root systems as well as aerial parts. Indeed it is not improbable in view of our slender knowledge of the humidity conditions of the soil atmosphere that the phenomenon of hydrotropism is a response to the water vapor in the soil air. Here again the chief characteristic of our knowledge is its paucity.

The humidity relations of various fungi have been investigated. Zeller (1920) has shown that the germination of the spores of *Lenzites saepiaria* is conditioned by humidity relations. Weiss (1918) finds that dry periods check the spread of plant diseases. Lauritzen (1919) has shown that atmospheric moisture conditions are of great importance in the infection of buckwheat with *Ascochyta fagopyrum.* Kopeloff and Morse (1921) have found that lowering the water vapor pressure inhibits the growth of colonies of *Bacillus coli, B. subtilis, Staphylococcus aureus,* and *Streptococcus hemolyticus.* The results of the investigations cited make it evident that humidity conditions cannot be safely neglected in the study of the relation of plant and habitat and that the action of other factors such as temperature cannot be interpreted without accurate information concerning the humidity conditions and the relations of the plant under consideration to such conditions.

While there is a growing feeling among physiologists and ecologists that atmospheric humidity is an environmental factor of great importance there is a great diversity of opinion as to the methods of measurement. Since variations in humidity affect the organism largely through changes in the rate of water loss, numerous methods of measurement of evaporation have been devised, the simplest and most reliable being the free water surface which is employed, under standard conditions, by most meteorological stations (Kadel, 1915). Bigelow (1909) has shown that many factors, such as volume of water exposed and depth of water below the rim of the vessel, are important so that standard apparatus for meteorologists is far too bulky for field use and, moreover, must be corrected for rain and protected from thirsty birds and mammals, while results obtained from vessels of different sizes are not comparable. Free water surface evaporimeters are thus little used in the field by ecologists who usually prefer some form of instrument more easily operated out-of-doors. The porous-cup atmometer has come into rather general use among ecologists since it has been improved and placed upon the market in standardized form (Livingston, 1910, 1910a; Shive, 1915). Another type of evaporimeter designed to simulate more closely plant transpiration is described by Bates (1919, 1922). Various investigators who have tried out evaporation against transpiration have found atmometer evaporation records less satisfactory as a measure of atmospheric moisture factors affecting the plant than the measurement of relative humidity (Briggs, 1917; Loftfield, 1921). Many plant ecologists have come to feel that, with the evident lack of correlation between the results obtained from the various types of evaporimeters and the transpiration of the plant, and with the additional impossibility of comparing results obtained from the various types of instruments, relative humidity, or the saturation deficit computed from humidity determinations, is a more satisfactory measure of the water vapor in the habitat than is an evaporation record obtained from instruments as now employed.

Water vapor in the atmosphere may be measured in four different ways: 1. By determining the weight of water vapor in a known volume of air. 2. By determining the dew point. 3. By determining the fall in temperature of a wet bulb thermometer. 4. By measuring hygroscopic effects. The accuracy of these methods decreases in the order listed. Numbers 1 and 2 are, however, difficult to use in the field at present because of more or less cumbersome or delicate apparatus and are rarely employed in such capacity. Practically all field methods of determining atmospheric humidity make use of methods 3 or 4 in some form.

Determinations based on the rate of evaporation of water from the moistened bulb of a thermometer depend upon the facts that the rate of evaporation varies inversely with the amount of water vapor in the atmosphere, conditions of temperature and pressure remaining constant, and that since the vaporization of water requires heat (596 calories per gram) any difference in the evaporation rate will be shown by the increased or decreased depression of the column of the thermometer from the bulb of which the vaporization is taking place. The chief error in this method of determining the water vapor is due to the radiation factor for which a correction is not possible under ordinary conditions because of the changing physical states and configurations. To reduce this radiation factor to a negligible minimum air currents must be maintained over the wet bulb at a rate of 3 or more meters per second (Paine, 1922).

The instrument in most general use for determining the humidity by means of the depression of the wet bulb thermometer is the sling psychrometer which is standard for meteorological stations and is employed by many field workers in ecology. This instrument is illustrated and described by Marvin (1915) and consists of two thermometers attached to a handle in such a way that the two may be rotated by swinging the forearm and wrist. One of the two thermometers gives the air temperature and the other, the bulb of which is covered with muslin thoroughly moistened, gives the lowered temperature due to evaporation from the bulb. Tables for obtaining the percentage relative humidity, the pressure of the water vapor in the atmosphere tested, and the temperature of dew point are given by Marvin (loc. cit.), calculated from the formula of Ferrel with the constants corrected for use with the sling psychrometer with an air velocity of not less than 15 feet per second. Unfortunately English units are employed in the formula and in the tables made on the Fahrenheit scale, making necessary the transformation of centigrade readings into Fahrenheit if the operator makes use of the usual centigrade instrument.

The sling psychrometer is fragile and cumbersome as a field instrument and it is necessary to have considerable space in order to swing it safely. To avoid these difficulties the cog or eggbeater type of psychrometer has been developed and is frequently employed by field workers (Clements, 1905). This instrument is capable of operating in a comparatively small space, is much more compact than the sling type and is less easily broken. It is, however, an awkward piece of apparatus to pack safely for a field trip unless placed in an individual carrying case and then occupies as much space as the sling type. Moreover the size of the apparatus is reduced at the expense of accuracy by making the thermometers with very short stems. Both of the above psychrometers depend upon the movement of the thermometers through the air to be tested. This requires stopping the circulation operations at frequent intervals in order to make temperature readings to ascertain the minimum reading of the wet bulb instrument. Under such conditions one can never be sure that the lowest reading made is really the minimum reading possible, for the wet bulb temperature can only be observed at intervals, and hence to reduce the chance of error the operation should be repeated until two or more readings check.

The instrument described below is stout, much more compact than either of the types described above, will make readings in a space much more limited than that required by the cog psychrometer, and may be used with a fair degree of accuracy in rain, snow or sun. It requires no special thermometers but only such as are ordinarily carried in the field for temperature observations. It holds the thermometers motionless during the operation so that the minimum reading may be accurately noted without stopping the air circulation over the wet bulb and thereby allowing radiation errors.

The psychrometer consists of a metal tube 1½ inches in diameter and three inches in length, in one end of which is a fan operated by a crank and gearing placed on the outside of the tube and inclosed by a metal cover. A hollow wooden handle of convenient size is attached to the tube at the end opposite the fan and extends downward at an angle of about 35 degrees, forming a grip like that of a pistol. This handle is of wood or other material of low thermal conductivity so as to prevent the hand from affecting the temperature of the metal parts; it is hollow and capped at the lower end and carries a vial of distilled water within, making a compact and at the same time safe carrying compartment for this necessary adjunct to field psychrometer determinations. In the top of the metal tube two centimeters behind the fan are two openings for receiving the thermometers which are held in position by No. 0 split rubber stoppers which not only hold the thermometers in place but act as thermal insulators between the metal of the apparatus and the glass stems. Between the fan and the thermometer bulbs is placed a metal funnel so that all the air current produced by the fan is driven directly over the wet and dry bulbs projecting into the chamber. Figure 1 shows the working drawing of both side and top aspects of the instrument drawn to scale. Figure 2 shows the apparatus ready for a determination.

In operation the dry bulb thermometer is placed in the first opening with the bulb about opposite the funnel aperture. The proper position can be quickly attained by previously marking the stem of the thermometer to show the proper position of the top of the stopper. The wet bulb thermometer is then dipped in distilled water and when thoroughly wet the excess water is gently shaken off and the thermometer placed in the rear opening. The fan is then driven at a high rate of speed by turning the crank at the rate of one revolution or more per second. A rapid current of air is drawn into the muzzle and forced over the thermometers discharging out through the rear of the tube. Both thermometers are clearly visible throughout the operation and the minimum wet bulb reading may be made with certainty and precision. In making determinations in the open it is best to face the wind; in still air a current of

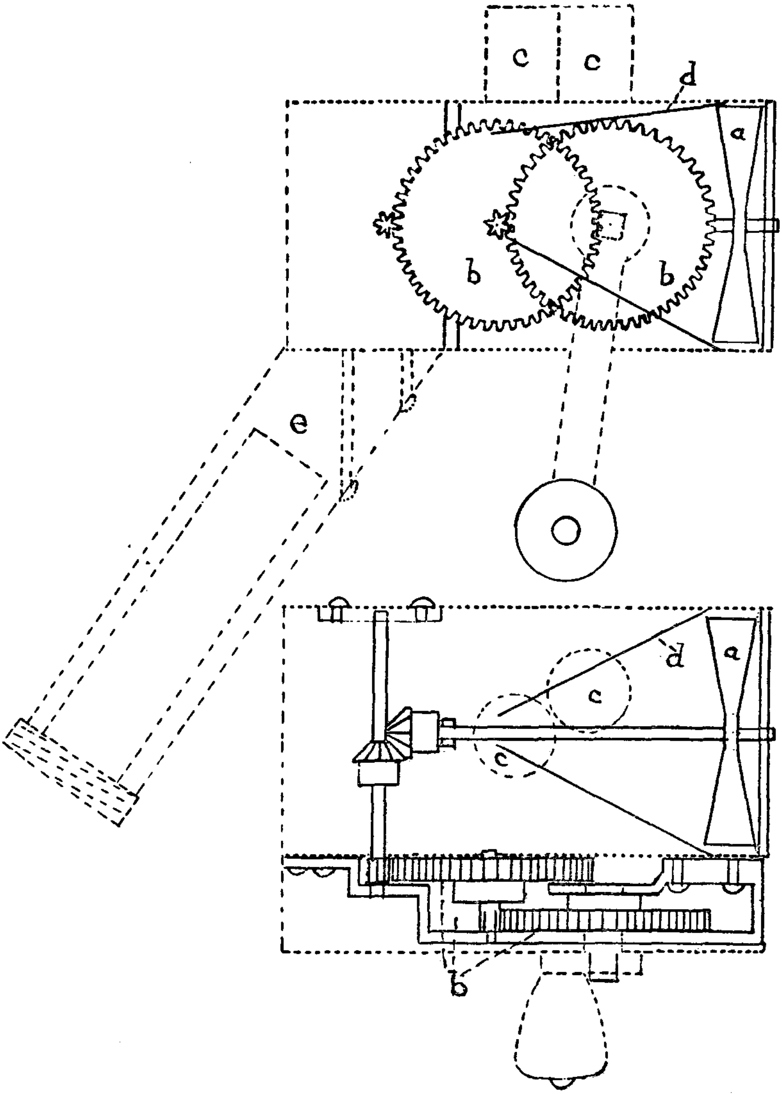

Figure 1.—Psychrometer, x 1. Side and top view; a fan, b driving gears, c thermometer openings, d air current funnel, e handle.

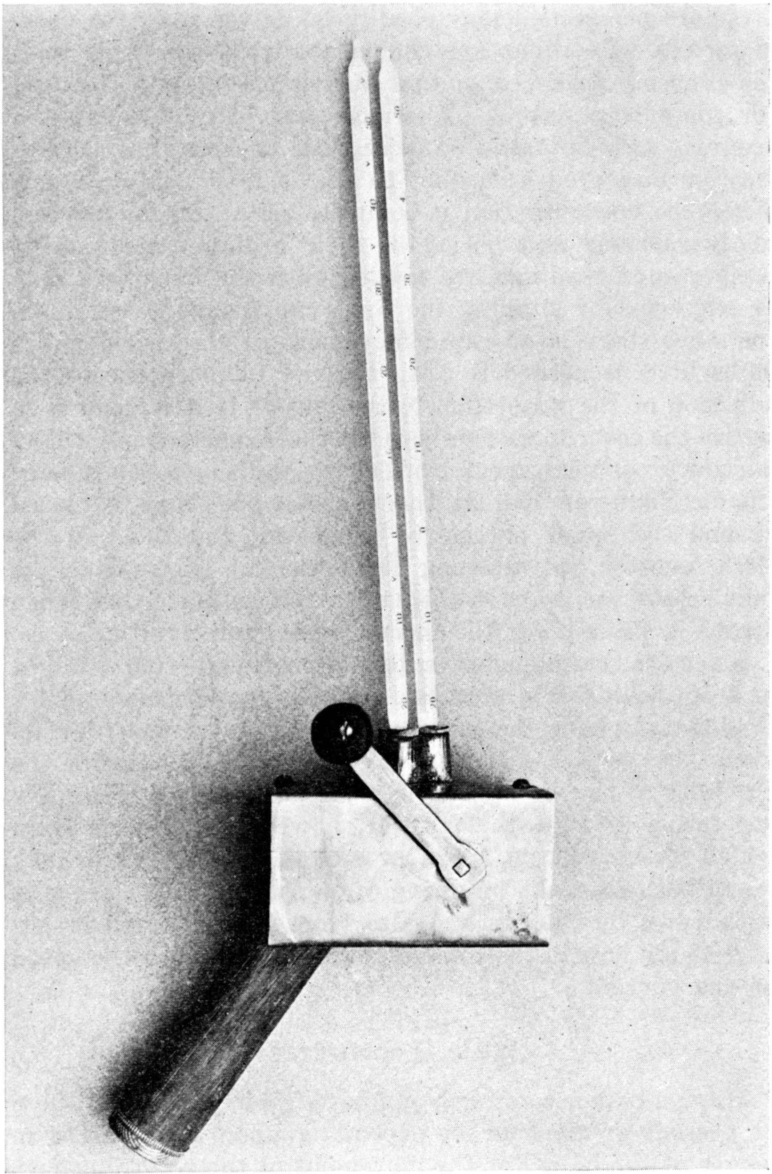

Figure 2.—Psychrometer as employed in field work.

4 meters per second may readily be driven over the thermometers. Readings are comparable to those made with the sling psychrometer so that Marvin's tables may be used for computing results. Thermometers of any length and accuracy may be used and centigrade or Fahrenheit scales may be employed according to the taste of the operator. When the determination is complete the thermometers are easily removed and placed in their ordinary cases or if temperature readings are needed both thermometers may be employed by slipping the linen cap from the wet bulb, for since there is no rapid movement of the thermometer bulbs little is needed to keep the cap in place except the adhesion of the water film to the glass. If it is desired to secure the cover more firmly to the thermometer bulb a very narrow cross section cut from a thin-walled rubber tube of smaller diameter than the thermometer used may be placed around the upper portion of the cover, thus holding the cloth securely but allowing easy removal. Care must be taken, however, to have the cloth cover so made that when drawn in place it fits the thermometer bulb tightly.

Since the thermometer bulbs are protected from sunlight or from falling rain or snow, readings may be made under conditions where the exposed-bulb types of instruments would be useless. It is also possible to determine the humidity of the air in confined locations such as under low vegetation or beneath logs. If, however, the space from which the air current is drawn is closely limited, error may result both from the inflowing of outside air to replace that withdrawn by the fan and also from the increased resistance to air flow in the limited space cutting down the speed of the current.

WOOD HYGROMETER

Human hair is commonly employed in hygrometers, those at present on the market depending upon the changes in length of the hairs for the movement of the recording pen.

So far as simplicity goes they leave little to be desired but in field use they are too inaccurate to be of much service and are being used less frequently in ecological work (Bates, 1922). The writer has found that if checked daily the readings give the humidity curve with a fair degree of accuracy but when subjected to great and sudden fluctuations in humidity, such as are occasioned by showers, errors of 25 per cent are not uncommon even with daily corrections. Hygrometers have the advantage of simplicity of operation and where great accuracy is not required results obtained by their use are of value.

The main error in hygrometers seems to be that the expansion and contraction of the hygroscopic material does not occur in a linear ratio to changes in humidity throughout the range of variation commonly met in the field. Wood is well known to be hygroscopic though little exact work seems to have been done upon the matter. Tiemann (1907) found certain woods very hygroscopic, absorbing from 8 per cent to 16 per cent of their dry weight of water according to the humidity of the air to which they were exposed. The swelling of the wood of long-leaf pine, red spruce, and chestnut plotted against the water content gave a straight line up to the fiber saturation point. The greatest swelling occurs tangentally and the amount of expansion depends to some extent upon the way in which the water is absorbed and the amount of moisture already present in the wood (Betts, 1917). This is true because only the water absorbed by the cell walls is effective in producing swelling, that contained in the cell cavities being without effect. If wood absorbs water only as vapor from the atmosphere little or none will occur in the cell cavities. The point of saturation of the cell walls is the "fiber saturation point" (Tiemann, 1906; Betts, loc. cit.).

The amount of shrinkage with drying from a green to an oven-dry condition has been determined for a large number of our native woods (Betts, loc. cit.; Newlin and

Wilson, 1917) and varies not only with the species of wood but with the locality from which the sample was obtained and with the part of the tree from which the wood was taken. Sap wood usually shows less shrinkage than heart wood but is more porous and hence dries out faster; hard woods shrink more than soft woods and are less porous. (Tiemann, loc. cit.; private communication from Forest Products Laboratory). Zeller (1920) working with long-leaf and short-leaf pine determined the water content of heart-wood and sap-wood in equilibrium with air of various humidities and found the presence of resin to reduce the hygroscopicity of the wood. Basswood *(Tilia americana)* is a light porous wood and shows rather high shrinkage value when dried and hence was chosen for a series of experiments reported in the following pages.

The wood was obtained at Lincoln, Nebraska, but the previous history of the sample is not known other than that the block was in an air dry condition. Sections of various sizes were cut from this block tangentially and employed in the following determinations.

Humidities of 0%, 25%, 50%, 75%, and 100% were maintained at will in a glass chamber by drawing air through a series of four wash bottles containing sulphuric acid and water mixtures according to the method of Wilson (1921). Each series of bottles was connected to the chamber in such a way that air of the desired humidity could be drawn through the chamber containing the wood blocks. The whole apparatus was placed in a thermostat of 25° C. Trap bottles prevented any liquid from being drawn over from the wash bottles and glass wool moistened with the acid mixture was placed in the wash bottles to insure the attainment of equilibrium between the water vapor of the passing air and the solution.

No exact determination of rate of gas flow was made but the number of bubbles escaping per minute from the delivery tubes of the wash bottles was determined for the rate of flow of 25 c.c. per minute and this rate was maintained approximately constant by placing a mercury trap on the line from the aspirator and maintaining an approximately constant negative pressure.

The length of the wood blocks was measured by means of an adapted paper gage. This gage is of the pocket type manufactured by B. F. Perkins and Son and measures accurately and automatically in thousandths of an inch. Readings can easily be made in ten thousandths (.00245 mm.) by estimating the divisions on the dial. Using blocks 50 mm. long, changes in length of .005% can thus be read if that degree of accuracy is desirable. Since this paper gage as placed on the market will take objects only up to about .3 inch in length it is necessary to add an extension to the instrument. The length of this extension can be accurately measured when in place by means of an inside caliper when the dial of the gage registers zero and the value thus obtained added to that registered on the gage dial, when measuring wood blocks, for the total length of the block used. It is best to set the dial, which can be done by turning the crystal of the gage, so that when reading zero there shall be a little pressure on the wood block both to hold it in position and also to insure that all the readings shall be made under similar compression conditions. Since the attainment of equilibrium will be hastened by using blocks of as small cross-section as possible, the extension of the gage should be provided with rests to prevent the bending of the block under the force of the caliper spring. Figure 3 shows the gage with wood blocks in position for measuring.

In measuring, the block was not removed from the glass chamber but the dimensions recorded by the gage read through the window of the thermostat. Of a number of blocks approximately 1 mm. square in cross section tested by this method, the results obtained from but one will be discussed here as the duplicates agree closely.

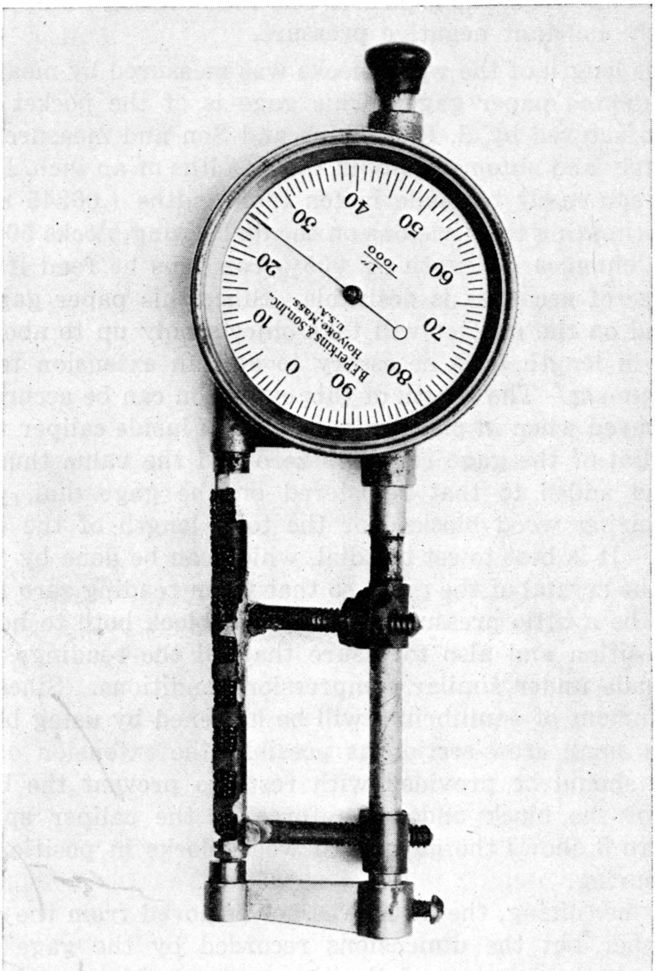

Figure 3.—Gage as used for measuring hygroscopic expansion of wood.

Block No. 62 measured when dried to constant length at 25° C. in air passed at the rate of 25 c.c. per minute through four wash bottles of concentrated sulphuric acid 2.009 inches. When air in equilibrium with water at 25° was passed through the chamber the following values were obtained:

Time (minutes)	35	65	95	195	245	305	365	425	1440	2880	3600
Length (inches)	2.957	2.968	2.973	2.975	2.079	2.083	2.087	2.090	2.096	2.104	2.104
Percentage increase based on dry length	2.38	2.93	3.20	3.31	3.43	3.68	3.88	4.03	4.33	4.72	4.72

Results obtained in the same way as explained above showed the percentage increase, based on dry length when the blocks showed no further change in dimensions, to be as follows under the different humidity values given. The results are averages of values for five blocks:

Percentage Humidity	25	50	75	100
Percentage increase in length based on dry length.	0.25	0.59	1.51	4.62

These values are plotted in Figure 4.

From the above results three points are evident. 1. The total expansion of the wood employed is considerably below the shrinkage obtained by Betts and by Newlin and Wilson (loc. cit.) from a green to an oven-dry condition. 2. Apparent equilibrium is reached between the small blocks of wood employed and the atmosphere of the chamber within 24 hours. 3. The relation of the tangential expansion to percentage humidity is not a linear one for the wood used but is more like the relation found by Zeller (loc. cit.) for long-leaf and short-leaf pine wood, the expansion-humidity curve given in Figure 4 being not unlike the humidity-water content obtained by Zeller.

That the total expansion shown is considerably less than the shrinkage from green to oven-dry condition is not surprising. The colloids of the cell walls possibly never reach a

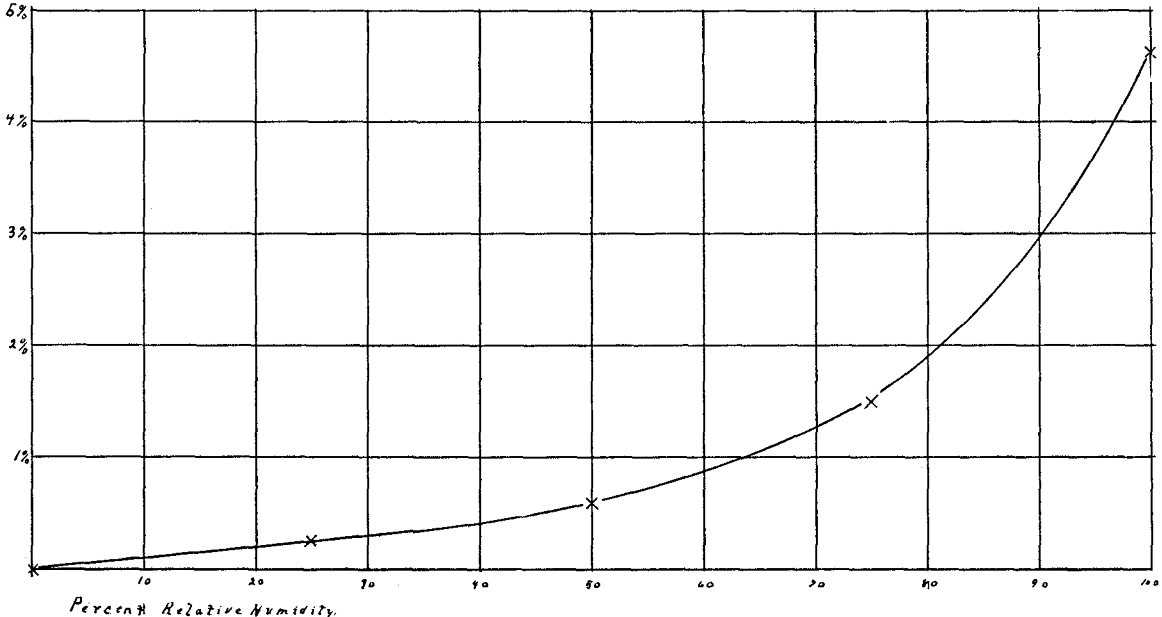

Figure 4.—The humidity-expansion curve of the basswood blocks employed in hygrometric determination.

state of hydration when exposed to air saturated with water vapor comparable to that found in the green wood, and there is doubtless a considerable moisture residue in the wood when no further shrinkage is shown in dry air at 25°. That equilibrium between the wood and the water vapor of the air may be reached within 24 hours under favorable conditions is more surprising. Sachs (1879) working with various conifer woods and with the wood of *Prunus domestica* found that as much as 48 days were required to bring wood shavings and sawdust into moisture equilibrium with air when diffusion currents were relied upon for the distribution of the water vapor in the chamber. The general similarity between the humidity-water-content curves obtained by Zeller and the humidity-expansion curve of Figure 4 suggest that the expansion of the blocks parallels the water content at least in a general way.

Since the object of this work was the use of wood in a hygrometer which could be employed where other methods of humidity measurement are not practicable, further work was carried out under room temperature conditions more nearly similar to those encountered in the field than are offered by a thermostat chamber. In order to eliminate so far as possible the error of differential thermal expansion of the gage extension bar and the wood block, several metals were checked against the wood by placing the gage in a glass chamber, bringing to equilibrium in dry air, and then altering the temperature by means of a water jacket. If the thermal expansion of the wood block and the extension bar are very different this will show in an altered reading on the gage dial corresponding with changes in temperature. Brass, invar, steel, aluminum, and zinc were thus checked, the last two, showing high thermal expansion coefficients, proving the best. The thermal expansion of wood seems to have received very little attention and no figures upon the coefficients for wood similar to basswood are available. Such figures as are given in the Smithsonian Tables indicate a high thermal expansion coefficient for tangential sections of wood, considerably above that of aluminum or zinc, so that it is probable that with a greater temperature range or a more delicate method of measurement than was here employed errors would appear.

Aluminum was selected as best suited for the extension bar. The total expansion from a dry condition to the maximum expansion in air saturated with water vapor was determined for each block of wood, the dry and moist air being aspirated through clean wash bottles containing the blocks which were removed occasionally for measurement and immediately returned until no further change in length occurred. If intermediate points on the humidity-expansion curve are desired vapor pressure corrections must be made for the sulphuric acid dilutions if these are not kept at constant temperature in a thermostat. For accurate work several points on the humidity-expansion curve should be determined for each block used and since the same block may be used repeatedly this is not difficult for but a small number of blocks are required for most purposes.

For field work a number of blocks are placed individually in small rolls of brass screening and these are placed in a soil can with a close-fitting cover which has been lined with moist blotting paper, the paper being retained in position by brass screen and moistened only moderately so that no water will drip out and so that the air in the can will approach a condition of saturation. This is desirable because the atmosphere of most situations is considerably above the point of dryness, and the time required for blocks to come into moisture equilibrium with the air is reduced by maintaining a moisture content approximating that expected. If situations of very low humidity are being studied the blocks may be carried in a soil can the bottom of which contains a layer of phosphoric anhydride held in place by a layer of cotton wool and a brass screen.

Field determinations of humidity can then be made in very limited situations such as spaces between bark and decaying logs, insect burrows, or the air in the interior of a mass of small vegetation by merely placing a block, protected from direct contact with moist objects by the cylinder of screen, in the situation to be studied and measuring when a state of equilibrium is reached. Percentage increase obtained from such measurements may be placed on the humidity-expansion curve of the block employed and the humidity value read directly; or the two end points of the curve, corresponding to 0 and 100 per cent humidity, for the block may be laid off and the humidity-expansion curve of Figure 4, drawn on transparent paper, superimposed and adjusted to pass through them when the humidity value corresponding to the value of the expansion found can be read off as from the individual curve. For example, block No. 74 placed in forest leaf-mold where fungus hyphae were abundant showed a constant length 1.979, being 2.74 per cent increase over 1.926, the dry length. When the two end points of the curve for No. 74, viz: 0 and 3.32 (see table below), are located on plotting paper and adjusted to the curve of Figure 4 the humidity will be seen to be 95.5 per cent.

Simultaneous measurements in the open by means of wood blocks and psychrometer determinations have shown the above method accurate to within 3 per cent. For results of greater accuracy the humidity-expansion curve should be determined for each block and corrections made for changes in barometric pressure. This fortunately is not necessary for most ecological work as the variation between apparently similar habitats is greater than the error of the determination made in the ordinary way described above. In case of great temperature variations the gage should be placed near the wood block for a few minutes prior to the measurement so that the wood and the extension bar of the gage shall be at the same temperature.

The length of time required for attaining equilibrium will vary with conditions and can only be determined by repeated measurements of the block. It has, however, been found that when blocks are in equqilibrium with the air approaching that of the locality tested they will often come to constant dimensions in a surprisingly short time, a half hour frequently sufficing. The best method in the field is to carry a block for each determination required on a field trip and to place them in the locations from which information is desired returning several hours later to make measurements.

By the above method it was determined that the air in the mass of debris at the base of a *Yucca glauca* plant where hibernating insects were found January 12, showed a relative humidity of 62 per cent when the air immediately above was 21 per cent. Under the same conditions air under dung was found to be 86 per cent saturated and fungus mycelia developing actively. In a mass of pine duff March 6, air was at 40 per cent relative humidity, the air above being at 34 per cent. Surface soil under Douglas fir and Engelmann spruce forest where earthworms were abundant and where many seeds were germinating showed air 94 per cent saturated, the air above the soil being 43 per cent saturated. This method, if carefully applied, should yield valuable habitat data on humidity conditions occurring in limited locations in the field where many fundamentally important phenomena occur but where little data upon humidity relations have heretofore been obtained.

Total expansion of some of the basswood blocks used in hygrometric determinations from dry to saturated atmosphere:

Block Number	Length (inches) 0% Humidity	Length (inches) 100% Humidity	Percentage Increase Over Dry Length
73.	1.929	1.991	3.21
74.	1.926	1.990	3.32
75.	2.016	2.078	3.12
79.	2.026	2.087	3.01
82.	2.009	2.104	4.23
84.	2.030	2.080	2.46
85.	1.957	2.030	3.73
86.	1.958	2.032	3.78
87.	1.957	2.034	3.94
88.	1.944	2.025	4.16
89.	1.957	2.031	3.72

SOIL AEROMETER

Since the appearance of an excellent summary and review of extensive literature relating to soil aeration (Clements, 1921) makes it unnecessary to go into the historical features of this subject, only such work will be mentioned in this paper as has a direct and detailed bearing on the present investigation. An extensive bibliography is given by Clements.

The general conclusions, to which the investigations discussed by Clements lead, are: 1. The normal respiration of roots as well as of other plant parts requires free oxygen. 2. Free oxygen is normally necessary for processes such as the germination of seeds, root growth, the development of root hairs, and absorption by roots. 3. Under normal conditions roots secrete carbon dioxide and in some cases other substances; under anaerobic conditions secretions may vary widely often consisting in part of organic acids and acid salts. 4. The oxygen requirements of plants vary widely, swamp plants in general consuming less oxygen than land plants. 5. Carbon dioxide when accumulated in the soil is toxic to many plants, the sensitivity of the plants tested varying widely. 6. Aerotropic root responses are present, in some plants at least, and are suppressed by lack of oxygen. 7. Soil atmosphere contains in general more carbon dioxide and less oxygen than atmospheric air, the percentage of carbon dioxide usually increasing with depth and oxygen varying reciprocally. 8. Compactness, organic matter, plant cover, and cultivation tend to increase the amount of carbon dioxide in the soil air and to decrease the oxygen. 9. The oxygen and carbon dioxide content of the soil air shows a seasonal variation, the oxygen being less during the warmer months and greater during the winter period while the carbon dioxide varies reciprocally. 10. Under conditions of reduced oxygen pressure respiration may still go on but it is of a different type, anaerobic, the oxygen for which is secured intramolecularly at the expense of food materials. 11. The ecological importance of aeration especially of maintaining the oxygen supply but also of preventing the accumulation of carbon dioxide is undoubted particularly in irrigated areas, bogs, etc. 12. Since the anaerobic respiration of plant roots, bacteria, molds, protozoa, etc., gives rise to organic acids, alcohol, and other toxic substances aeration is fundamentally connected with the production of soil toxins which are probably largely carbon dioxide.

The wide and interesting recognition of the importance of the soil atmosphere and the practical absence of quantitative work upon it is a conspicuous feature of modern ecological literature. The favorite method employed in the study of soil atmosphere has been the analysis of the gases removed by aspiration. This has been, for instance, the method employed in the important researches of Pettenkoffer (1871), Wollny (1886) and Russel and Appleyard (1915). Indeed practically all our knowledge of the composition of the soil atmosphere has been gained through this means. The method consists of sinking a metal pipe to the depth in the soil at which observations are desired and then pumping air out for analysis. Much dependable information has been obtained by this procedure, the special advantage being the large volumes of gas obtainable for analysis.

This method has, however, several serious disadvantages. First of all the sinking of soil tubes when accomplished by digging down to the required depth and filling in when the pipes are in place disturbs the composition and physical state of the soil and normal conditions cannot be expected to reestablish themselves for a period measured by months at least. King (1914) has shown that the water content and the size and arrangement of the soil particles affect markedly the passage of gases through the soil and these factors are temporarily or permanently altered by the removal and replacement of soil. Nevertheless Pettenkoffer (1871, 1873) and others have secured valuable results by following this procedure. Driving the aspirating tube to the required depth is doubtless the better plan and has been the method of many investigators. But aspiration is not a practicable field method for general use in the study of the soil atmosphere and when employed is limited to fixed stations leaving variations within the habitat and errors due to the presence of the pipes and the altered state of soil consolidation resulting from driving them in place unchecked.

Secondly, removal of gas by aspiration is not suited to the study of the atmosphere of water-logged soils or of soils which are nearly at the saturation point, because reduced pressure results in the removal of water rather than air from the soil and also because the high water content of the soil retards or prevents the flow of the soil atmosphere to the aspiration tube, making it difficult to prevent atmospheric air passing down the sides of the pipe. Aspiration can thus furnish us little information regarding conditions in wet natural habitats or irrigated fields, but Clements (loc. cit.) has shown that it is in bogs and water-logged soils that the most extreme aeration conditions occur and study of such habitats should bring rich returns.

A third disadvantage with the aspiration method for study of the atmosphere of the soil is the fact that particular and definite areas cannot be investigated because of the uncertainty of the extent of the region about the end of the aspirating tube from which the gas is drawn. It is reasonable to suppose that the area from which the gas is drawn will depend, in practice, largely upon the resistance to gas flow in the soil. This will vary not only with the mechanical composition of the soil, being less in coarse gravel and greater in fine clay soils, but also with the water content and the degree of compacting. King (loc. cit.) found that the number of seconds required for 5 liters of air under a constant pressure to flow through a given volume of dry soil varied from 37 for gravel to 2,903,000 for finest clay and also that moisture may entirely prevent air flow under the pressure tried. If soils show greater compacting with depth, as in the case of those investigated by King, or if the water content varies with depth, as is commonly the case, or if the various layers are cemented by colloidal materials into different states of aggregation the resistance to gas flow, and consequently the areas drained of gas in any given time of aspiration, will vary. In soils which are not homogeneous air drawn from a tube ending at a given depth may be largely coming from a region either above or below the level expected, particularly if sandy strata are present or if earthworm burrows occur. Errors in obtaining soil gases by aspiration are increasingly great as the areas of investigation approach the soil surface so that determinations near the surface are of little value, the general assumption being that surface air will approach the composition of the free atmosphere.

Finally the method of aspiration furnishes no data as to the quantity of oxygen or carbon dioxide present in a given volume of soil unless porosity determinations are made simultaneously and in the same soil stratum from which the gas is removed. Moreover this lack of data upon the quantity of gas available for soil organisms and roots at various depths, in various soils and at different water contents is a serious omission in our knowledge for the real effects of aeration are to be measured not by the percentage composition of the soil atmosphere but by the quantities of these gases available. Upon this point our knowledge is of a most general sort. In view of these unsatisfactory conditions work was undertaken to develop a simple, inexpensive, portable apparatus which would give the porosity of the soil and the percentage composition of the gas contained in that soil. Since there are many excellent methods of determining the composition of air, and since several of these gas analysis methods require but a small volume of gas for analysis, Hemple (1911), Dennis (1918), Haldane (1920), and particularly since research on soil acidity has shown that important variations may occur in small areas such as the region immediately around roots, it is desirable to use but a small quantity of soil, making possible determinations at various depths and also in the vicinity of active roots, earthworm burrows, etc.

Displacement of soil air by means of water has been frequently employed for porosity determinations, Hilgard (1907), King (loc. cit.), Warington (1900), but the difficulty of displacing all air bubbles is great. To obviate this Wollny and others have made use of ammonia gas. Various liquids because of their viscosity and of the solubility of gases in them are not practicable because, even if the pressure at which the fluid is forced into the soil is known, corrections are not possible. Carbon dioxide is particularly difficult to determine by means of liquid displacement because of the high solubility of the gas in water and many other liquids.

The writer first labored under the misapprehension, which apparently is rather general, that paraffin oils dissolve little atmospheric gas and hence began by determining the coefficient of solubility of various oils for atmospheric gases, data for which are surprisingly scarce in physical literature. The results obtained were as follows:

Physical properties of liquids considered for displactment of soil air.

Liquid	Boiling Pt. (607mm)	Coefficient of Absorption at 20° C. 605 mm pressure		
		Nitrogen	**Oxygen**	**Carbon Dioxide**
Kerosene	207.5	.0110	.0143	.854
"Finoil"	356.6	.0124	.0199	.736
White Neutral Oil	331.3	.0092	.0199	1.104
Paraffin Oil	340.7	.0130	.0205	.727
Mineral Oil	383.5	.0020	.0183	1.110
G. S.	107.3	.0139	.0191	.132
Saturated Salt Sol.				.246

Although facilities for accurate temperature and pressure control were not available for the above determinations, it is felt that the values given are approximately correct and sufficiently accurate for comparative purposes here. Mineral oil was of the kind purified for medicinal use and marketed under various trade names. G. S. is the mixture of Schmidt-Jensen (1920) viz. 50 per cent glycerol and 50 per cent saturated salt solution. Since the object of these determinations was to ascertain what alterations to expect in the composition of soil atmosphere after displacement by any of the liquids tried, and not to establish physical constants no attempt was made to obtain the materials free from dissolved atmospheric gases, and since the handling previous to the time of coming into the possession of the author is unknown the various liquids may or may not have been saturated with the gases of the air at atmospheric partial pressures. Saturation with atmospheric gases would greatly reduce the absorption coefficients for nitrogen and oxygen but would produce but little change in that for carbon dioxide due to the low partial pressure of this gas in atmospheric air.

It is evident that air could be displaced from soil with none of these liquids and be suitable for analysis as representative of the soil atmosphere because of the differential absorption of the various constituents of the air. For example, suppose a 50 c.c. sample of soil of 40 per cent porosity to contain an atmosphere composed of 78 per cent nitrogen, 20 per cent oxygen, and 2 per cent carbon dioxide, and suppose further that this atmosphere is displaced by paraffin oil at atmospheric pressure (610) plus 50 mm. and that the gases in the soil are soluble in proportion to the pressure. Then: $.013\times.78\times 20\times 660/760=.176$ or the total number of c.c. of nitrogen which could be dissolved in the displacement oil at 20°. But the total volume of nitrogen in the soil sample is $.78\times 20.=15.6$ c.c. at 610 mm. pressure or 12.5 c.c. at standard and we have $.176/12.5=.014$ or 1.0 per cent of the total nitrogen present. In the same way $.0205\times 20\times 660/760= .0712$ or the total number of c.c. of oxygen which could dissolve in the displacement oil under the conditions. $.20\times 20 =4.$ the total number c.c. of oxygen present measured at 610. mm. or 3.47 c.c. at standard pressure. $.0712/3.47= .0205$ or 2.05 per cent of the total oxygen present. $.727\times.02 \times 20\times 660/760=.2525$ the total number of c.c. of carbon dioxide which could dissolve in the displacement oil. $.02\times 20 =.4$ total number of c.c. carbon dioxide present measured at 610 mm. or .347 c.c. at standard pressure. $.2525/.347= .7276$ or 72.76 per cent of the carbon dioxide present. Under the conditions assumed then paraffin oil used as a displacement fluid for soil gases might dissolve 1.4 per cent of the total nitrogen present in the soil atmosphere displaced, 2.05 per cent of the oxygen, and 72.76 per cent of the carbon dioxide. It is evident that soil air displaced by any of the liquids tried would be useless for analysis for, although the displacement oil would not be likely to become saturated, an indefinite amount of the gases would be dissolved and no correction factor could be applied since neither the degree of saturation nor the partial pressure of the various gases present would be known. The G. S. mixture and saturated salt solution while preferable to the various oils tried are not satisfactory since even using the G. S. mixture in the example just given 13.2 per cent of the total carbon dioxide might dissolve. From the boiling points given it is evident that it would be necessary to make vapor pressure corrections for at least the G. S. and saturated salt solution. The vapor pressure curve can be plotted from the boiling point by the method of Hildebrand (1915). For absorption of atmospheric gases see Coste (1917).

Liquid displacement of the soil atmosphere being impracticable combustible gases were considered. Ammonia was considered undesirable because of the chemical activity and probable reaction in the moist soil with such acids as carbonic. Hydrogen seemed best suited to the work and was therefore used. This gas can be determined by the use of a combustion chamber on any standard gas burette and the total volume of the gas displaced from the soil corrected accordingly. Furthermore there is no trouble due to viscosity in displacing all the air from the soil sample and free hydrogen would occur but rarely in the soil atmosphere.

After some preliminary trials a soil sampler was constructed from bar steel. Figure 5 shows the working drawing made to scale. The sampler consists of three parts (1, 2, and 3). The borer (2) is 2.5 cm. deep by 5.1 cm. in diameter inside measurements, is turned to a smooth accurate bore, and has a case hardened cutting edge. The base is provided with a heavy thread (B) and with a tapered hole (C) to fit a No. 0 rubber stopper and carries two heavy machine screws (D) 4 cm. apart for engaging with the wrench (1) when obtaining a soil sample. The cap (3) is provided with threads (F) to engage with those of the borer (B) and is 3.6 cm. deep so that a rubber gasket may be placed in the bottom and the borer quickly and tightly screwed against it. This cap is also provided with a tapered hole (G) to fit a No. 0 stopper and with two holes of small size (H) about 3 mm. from the floor of the cap to allow the escape of air during clamping operations. The

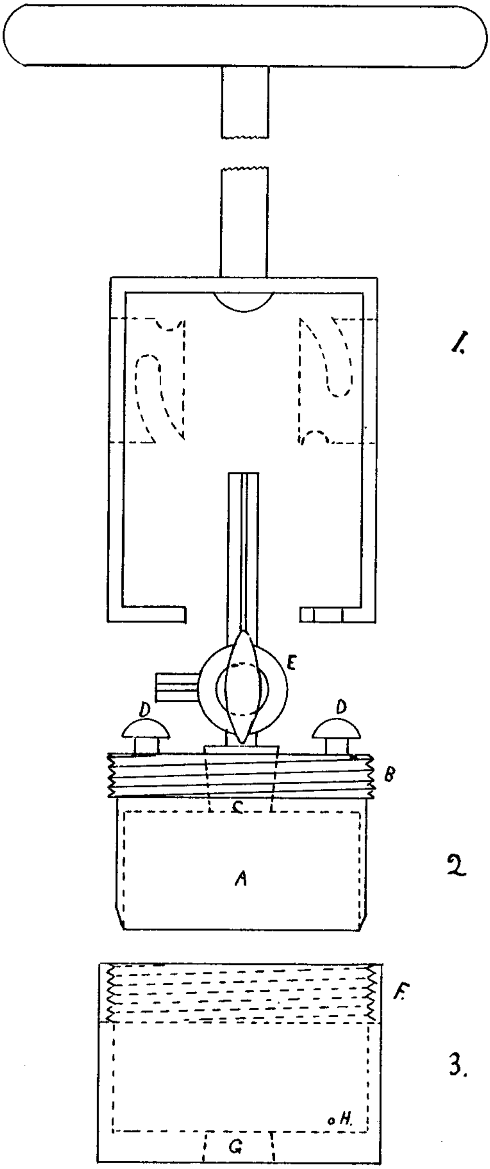

Figure 5.—Aerometer Soil Sampler. Natrual Size.

1. Wrench. The inserted broken-line drawing shows the method of cutting so that turning to the right grips the screws of the soil borer.
2. Soil borer. A barrel, B threads, C rubber stopper, D machine screws for engaging wrench, E three-way stopcock.
3. Cap. F threads for engaging B, G opening for rubber stopper, H hole for escape of air displaced during clamping.

borer (2) carries a three way stopcock (E) of 1 mm. bore.

The total volume of this borer including the bore of the stopcock from the chamber of the borer to the key of the stopcock was determined by careful measurements to be 51.07 c.c. It was found, however, that when tightly clamped in the cap the volume, as determined by the weight of mercury contained, was 49.9 c.c. 57.07—49.9=1.17. Using the measurements of the borer given above R^2=20.428254. Then if x equals the altitude of a cone of radius 2.55 cm. (corresponding to the borer chamber) we have 20.428254x =1.17 or x=.055 which is the decrease in centimeters in the depth of the borer chamber upon clamping. In other words the clamping forced the edge into the rubber gasket 0.55 mm. Numerous determinations made with different rubbers indicated that this value must be determined for the kind of rubber used but that if the same type of rubber is employed for making gaskets the value remains very constant until considerable use has produced a groove in the gasket under the edge of the soil borer. Ordinary gasket rubber manufactured for the use of plumbers was found satisfactory, the variation in hardness between sheets being small. Lead was found unsatisfactory for gaskets because a soil particle remaining under the edge of the borer as it is clamped down would produce a leak.

In obtaining a soil sample the borer is held in the wrench by turning slightly to the right since the slots are arcs of a circle of the same diameter as the distance between the screws in the base of the borer (see broken line drawing in Fig. 5, No. 1.) The stopcock (E) is turned so as to connect the barrel of the borer with the outside air and the sample is made by steadily forcing the borer through the soil, giving it the while a turning movement to the right. If surface soil is wanted this operation can be performed in any desired place. If, however, samples at any depth below the surface are wanted, a pit must be dug to the required depth and the sample immediately taken as described above. If the sample is to be taken at more than a foot from the surface it is best to dig a pit to the necessary depth or a little more and then to extend the excavation laterally for several decimeters as quickly as possible and make a determination, thus avoiding danger of error due to the mixing of the atmospheric air with that of the soil.

As soon as the borer is fully forced into the soil the stopcock, which has been turned as directed above so as to allow the escape of the atmospheric air from the bore as the soil core enters, is turned so as to close the borer chamber from the atmosphere, the soil is quickly removed at one side of the borer, and a smooth iron sheet is forced close under the cutting edge and held firmly while the borer is removed and inverted. The iron plate is then slipped off and the borer immediately screwed into the cap which is connected in an inverted position with the hydrogen supply and is receiving a slow current of pure hydrogen to prevent the entrance of air into the opening in the cap.

Figure 6 shows the apparatus as connected. Hydrogen is supplied to the soil sampler (1) through the connection (2). As soon as the soil sample has been sealed as described above the hydrogen current is turned through (3) by means of stopcock (4). After a few seconds, when the hydrogen has swept all air from the bore of the tubing, rubber tube (5) is connected to the lower arm of stopcock (6), and the tubes swept clean of air by filling the burette barrel (7), stopcocks (6), and (8) being turned as shown and pressure adjustments being made by lowering the leveling tube (9). The burette is filled two or three times, the gases being exhausted through the free arm of stopcock (8), and left filled with pure hydrogen. Connections are then made as shown in Figure 6 and the hydrogen contained in the burette is driven out through the barrel of the testing device, stopcock (10) having been turned so as to allow this passage.

A current of hydrogen is then directed through the soil sampler and into the burette by properly adjusting stopcocks (4), (6), and (8) and slowly lowering the leveling tube (9). The atmosphere contained in the soil sample in (1) is displaced and carried through into the burette where it is measured under known temperature and pressure conditions and forced into a gas collecting tube for later analysis. The amount of hydrogen which is necessary to drive through a soil for complete displacement of the atmosphere contained therein depends largely upon the care with which the current of gas is forced through. A steady current of about 10 c.c. per minute will usually displace over 90 per cent of the soil air in the first volume of gas equal to that contained in the soil. The residual soil atmosphere is not displaced so readily and requires somewhat more hydrogen and is therefore not analyzed with as great accuracy as air containing less combustible material because to determine a large amount of hydrogen it is necessary to dilute the sample with air in order to provide oxygen sufficient for complete combustion.

The first 25 to 30 c.c. of gas displaced are forced into a 30 c.c. gas collecting tube and later used for analysis. About 100 c.c. of gas is then driven through the soil and 20 per cent (10 c.c. from each 50 c.c. burette full) placed in a second gas collecting tube. A stream of pure hydrogen is then turned through the testing device, which is connected as shown in Figure 6, from stopcock (4), through tube (5), sweeping out any residual air present. A small drop of indicator solution is run through tube (11) and allowed to drop into chamber (12), the current of hydrogen carrying it out through the capillary bore (13) below. A small drop of indicator solution is allowed to remain suspended on the tip of the tube (11) which is drawn to a small caliber and turned down at the tip where it extends into chamber (12). This can be accurately adjusted by means of stopcock (14). Stopcocks (4), (6), and (10) are then turned so as to pass the hydrogen carrying any atmosphere displaced from the soil sample through chamber (12). The indicator solution shows by a change of color whether or not oxygen is present. If the color of the indicator shows the presence of oxygen another 50 c.c. of gas is passed through the soil and into the burette and 20 per cent retained in the collecting tube. The testing and displacement is repeated until the indicator shows no oxygen present in the gas flowing through chamber (12). No case has been found in which more than 150 c.c. were required.

The testing device is shown in Figure 6. It consists of a three-way stopcock (10) of about 2 mm. bore to one tube of which is blown a chamber (12) large enough to take a No. 0 rubber stopper and opening into the bore of the arm of the stopcock. This arm is drawn out to a small caliber below the chamber. A 30 c.c. separatory funnel (15) contains the indicator solution. The stem of this funnel is bent at right angles and drawn to a small caliber by a sharp taper at the point. The tip of this taper is given a short downward turn so that when in place in the rubber stopper this downward-curved tip occupies the center of the bore of chamber (12) but does not touch the sides at any point. The mouth of the separatory funnel is closed by a three-way stopcock (16), one arm of which is left free while the other is connected to a series of three wash bottles (17) made from one inch vials and filled with glass wool saturated with alkaline pyrogallic acid solution. If the vials are partially filled with solution there will be too much resistance to air flow through them so that the indicator solution will not flow through the stem (11) of the separatory funnel; the saturated glass wool furnishes adequate protection from oxygen and at the same time interposes little resistance to air flow. It is not necessary to use as many as three vials but since there is little pyrogallol present it has been found safer for with three absorbers even the complete exhaustion of the first vial will leave the indicator solution completely protected.

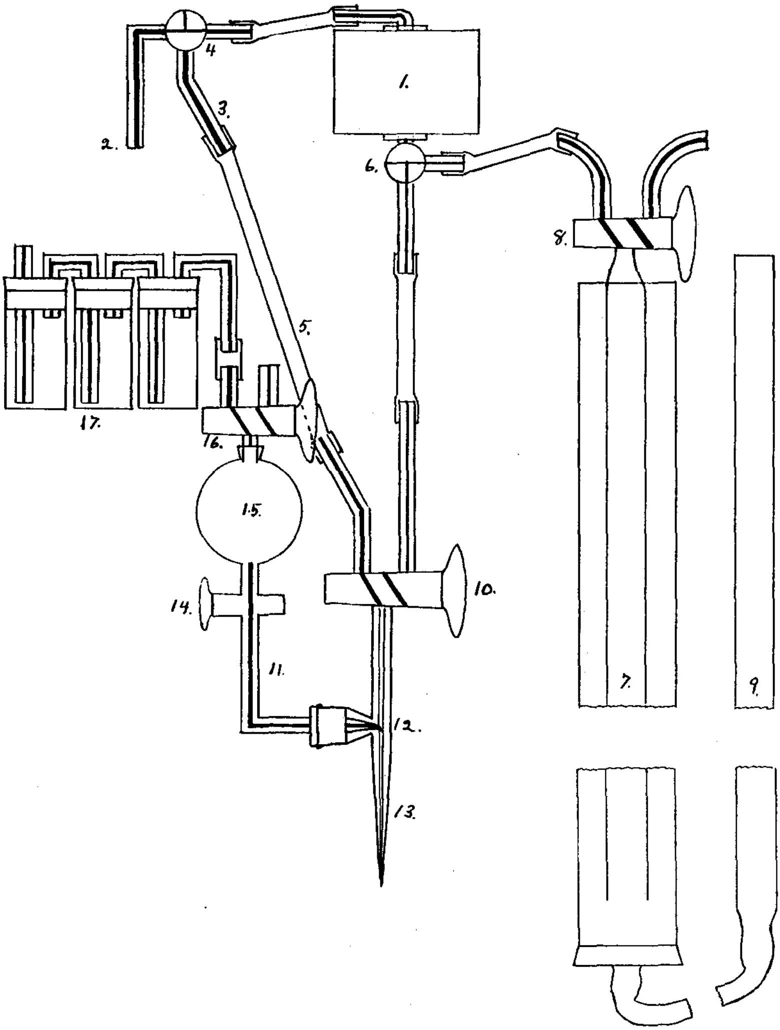

Figure 6.—Displacement aerometer. One-half natural size. 1, soil sampler; 2, connection for hydrogen supply; 3 and 5, connections for carrying hydrogen to the testing device; 4, 6, 8, 10, 14, and 16, stopcocks; 7, gas burette of 50 c.c. capacity enclosed in a water jacket; 9, leveling tube; 15, separatory funnel with stem 11, opening by a capillary point into the testing chamber 12, the bore of which is drawn to a small caliber at 13; 17, wash bottles filled with glass wool saturated with alkaline pyrogallol solution.

Alkaline pyrogallic acid solution was used as an indicator. Phillips (1894) found it the most sensitive indicator for oxygen and while comparative tests were not carried out in the present work it was found that 0.1 per cent oxygen could be detected without difficulty in the apparatus described. In charging the testing apparatus stopcock (16) is removed, funnel (15) thoroughly cleaned and dried and pure dry pyrogallic acid and potassium hydrate introduced. A few c.c. of air is driven through the wash bottles (17) by blowing gently on the open tube in the first bottle to be sure that the tubing is filled with air which has come in contact with the pyrogallol. A stopcock (16) carrying the battery of wash bottles is then fitted tightly into the mouth of the separatory funnel by means of the rubber stopper and turned so that connection is made through the arm of the stopcock. This free arm of stopcock (16) is connected with the hydrogen generator and hydrogen allowed to flow slowly through for 30 minutes or more. Stopcocks (16) and (14) are then closed. About 100 c.c. of distilled water is placed in a beaker and boiled vigorously for 15 minutes or more, a rubber tube is fitted over the free arm of stopcock (16), and the boiling water drawn into the funnel (15) through stem (11) by applying the mouth to the rubber tube mentioned. Stopcock (14) is closed and connection made through (16) between the funnel (15) and the wash bottles (17).

If the apparatus is well made and the stopcocks properly lubricated with heavy grease or a special preparation such as that recommended by Dennis (1918) pyrogallol made according to the above directions will be a colorless solution and will remain such indefinitely. Drops exposed to oxygen will rapidly darken becoming black in a short time. A slight color in the indicator pyrogallol does not interfere greatly with the usefulness of the solution as an indicator for the darkening can still be clearly seen. When not in use stopcock (14) is closed but (16) is left so that there is connection between the separatory funnel chamber (15) and the wash bottles (17). This avoids danger of pressure changes due to cooling causing a sucking back of the fluid in the stem (11) and the consequent entrance of air when stopcock (14) is opened.

For analysis of the gas sample the author prefers the portable Haldane gas burette (Haldane, 1920) because the compact sturdy build permits use in the field or at field laboratories. There is, however, no reason why any type of gas burette may not be employed and more accurate results obtained because of the use of larger samples, for after the soil air has been measured and placed in collecting tubes analysis may be carried out in the laboratory. In any case a careful analysis is made of the gas in the first tube displaced from the soil sample. Using a 30 c.c. collecting tube and the portable Haldane burette this may be done in duplicate. The results of this analysis furnish accurate data for calculating the percentage composition of the soil air. It is only necessary thereafter to determine the amount of oxygen present in the gas of the second displacements to compute the total amount of air originally present in the soil.

For example, air was displaced from a sample of soil by the above described method. A sample from the first 18 c.c. displaced was taken into the Haldane burette and measured 9.950 c.c. After passage through the sodium hydrate absorption pipette the reading was 9.866 c.c. Passage through the combustion pipette reduced the volume to 9.228 c.c. which showed no further reduction by passage through the sodium hydrate indicating the presence of no combustible gas other than hydrogen. Absorption by pyrogallol reduced the volume to 7.527 c.c.

Calculations are:

9.950	Sample.
9.866	Volume after NaOH absorption.
.084	Volume of CO_2 present.
9.228	Volume after combustion of hydrogen.
.638	Reduction in volume (⅓ oxygen, ⅔ hydrogen).
.425	Hydrogen present.
9.950	
.425	
9.525	Volume of soil air present in original sample.
9.228	
7.527	
1.701	Volume absorbed by pyrogallol.
.212	
1.913	Total volume of oxygen present in original sample of soil air.

Computing percentages on 9.525 the volume of soil air originally present we have CO_2 0.88%, O_2 20.08%, and N_2 79.04%.

Analysis for the oxygen and carbon dioxide showed the gas contained in the second collecting tube to be .12 per cent oxygen and no appreciable carbon dioxide. This tube contained samples from 184.5 c.c. of gas displaced through the soil sample. Hence .12% of 184.5=0.2214, volume of oxygen present in second displacement. 100/20.08×0.2214 =1.1, volume of air present in second displacement. 9.525/9.950×18.=17.229, volume of air present in first displacement. 18.329 (total air displaced from sample) is 36.73 per cent of 49.9 the volume of the borer. Thus our soil shows a porosity of 36.73 per cent and a soil air composition of oxygen 20.08 per cent, carbon dioxide 0.88 per cent and nitrogen 79.04 per cent. Or in 100 c.c. of soil there are 7.4 c.c. of oxygen available for plant life and something over 0.3 c.c. of carbon dioxide present.

Temperature corrections for volume have not been included in the above to avoid making the explanation too complicated for clarity. It is necessary to record the temperature of the water jacket of the analysis burette and to correct the volumes determined back to the temperature of the soil at the time the sample was made. This is, of course, simply a matter of applying the gas laws. Barometric pressure should be recorded and corrections made accordingly if necessary.

Since studies on the air content of soils as determined by the aerometer are to appear in a future publication only a few results will be given here to show the application of the apparatus.

Examination of the soils in the mixed prairie to the east of Colorado Springs, Colorado, have been carried out. The vegetation has been described by Shantz (1911) and the soil characteristics may be judged by the analyses given below.

Mechanical Analyses of Soils at Colorado Springs

Depth (dm.)	Coarse Gravel %	Fine Gravel %	Coarse Sand %	Med. Sand %	Fine Sand %	Very Fine Sand %	Silt %	Clay %	Hygros. Coef. %	Ignition Loss %
Surface	1.05	4.51	12.58	13.29	23.56	27.60	12.50	2.90	3.5	4.1
1.	0	0.74	8.11	10.83	19.57	27.70	20.45	10.60	5.4	4.4
2.	0	3.38	9.86	8.98	17.37	28.68	21.10	7.60	5.4	2.6
3.	3.90	16.48	12.33	9.74	15.58	18.90	15.60	6.50	4.2	2.5
6.	0	1.70	12.28	16.05	25.00	20.02	17.01	7.50	3.3	2.6
9.	0	4.70	18.00	16.10	21.81	17.28	14.80	6.40	3.8	2.8
12.	0	2.33	12.38	14.88	24.00	18.44	18.90	8.90	3.9	2.8

On October 26, 1922, after a prolonged dry period aerometer determinations gave the following results:

Depth (dm)	Temperature	Soil Moisture %	Porosity %	Soil Atmosphere Oxygen %	Carbon Dioxide %	Nitrogen %
Surface	14.0	3.1	35.57	20.18	0.34	79.48
1.	11.5	7.7	33.40	18.74	0.60	80 66
2.	12.4	6.6	32.00	18.98	0.99	80.03
3.	12.4	5.1	31.57	18 27	0.90	80.83
6.	14.6	5.2	30 31	19.66	0.78	79.56
9.	15.0	5.1	30.07	20.60	0.36	79.04
12.	15.8	8.1	26.84	20.36	0.54	79.10

The moisture content of the surface was below the hygroscopic coefficient and the deeper layers were moderately dry. Porosity decreases with the depth as was found true by King (loc. cit.) for Wisconsin soils. The 12 decimeter samples were taken in a white hardpan soil cemented together by colloidal material and shows a rather sharp reduction in

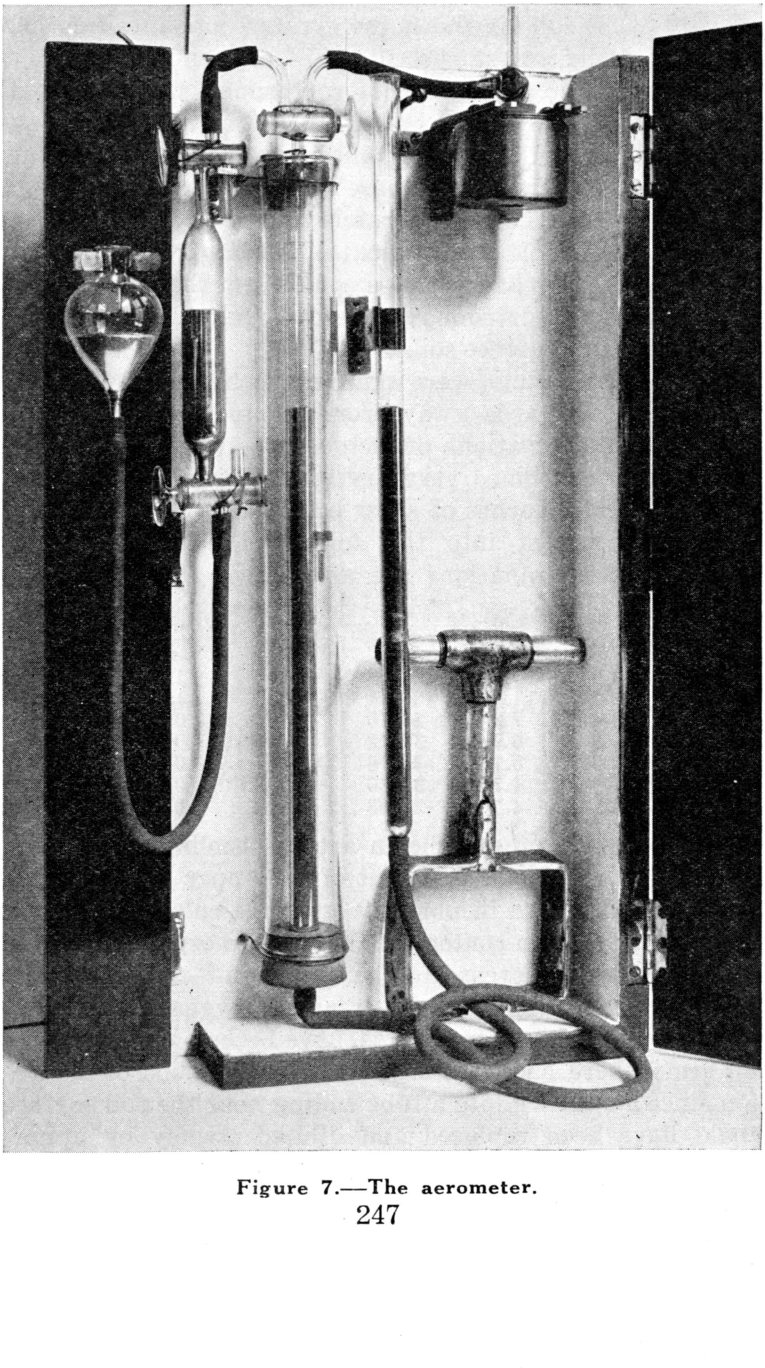

Figure 7.—The aerometer.

porosity. The soil air shows the greatest amount of carbon dioxide and the lowest percentage of oxygen in the 1 to 3 decimeter levels; this does not correspond with the total water content, the water content above the hygroscopic coefficient, or the ignition loss. Since the soil is cooling at this season the temperatures increase with soil depth. Although the weather had been moderately windy the surface soil showed considerable carbon dioxide as compared to the free atmosphere. This had perhaps come from the lower layers and was prevented from rapid escape into the air by the layer of fine dry surface soil.

Aerometer readings were again made November 29, at a spot but a few yards away from the filled pit excavated when the determinations of October 26, were made. The weather had continued very dry until November 27, when a fall of about 4 inches of snow occurred. This melted off slowly and settled into the soil on the twenty-eighth. Aerometer determinations are as follows:

				Soil Atmosphere		
Depth (dm)	Temperature	Soil Moisture %	Porosity %	Oxygen %	Carbon Dioxide %	Nitrogen %
Surface	0.5	15.3	17.23	8.00	1.80	90.20
1.	2.2	11.6	29.11	8.03	1.56	90.41
2.	3.4	7.2	29.85	17.02	0.48	82.50
3.	4.8	6.9	32.72	19.10	0.48	80.42
6.	6.6	5.7	30.78	19.77	0.63	79.60
9.	7.8	4.7	31.86	20.08	0.54	79.38
12.	8.8	4.5	27.88	20.22	0.45	79.35

The striking changes shown are the cooling of the soil, the rise in the moisture content of the upper layers with a consequent decrease in porosity and particularly the great reduction in oxygen content of the soil atmosphere near the surface with an increase in the amount of carbon dioxide but not in proportion to the decreasing oxygen. Conditions here shown would not, of course, have become evident if the soil atmosphere had been studied by the method of aspiration since air drawn into a tube ending near the soil surface would have been replaced and diluted largely by atmospheric air. Richards (1917) has shown that rain not warmer than 15° is nearly saturated with oxygen so that in this instance the water settling into the soil was doubtless saturated with oxygen and hence dissolved none from the soil atmosphere while much of the carbon dioxide was dissolved and thus does not appear in the gas displaced from the samples. This condition appears in the table above as a low CO_2 percentage compared to the oxygen present and consequently, since the nitrogen is computed by difference, in a high nitrogen percentage.

Although the frequency of occurrence and the extent of the region where such changes in soil atmosphere may be expected has not been determined, the phenomenon of reduced oxygen concentration in the upper soil layers following prolonged drouth and sudden precipitation is not so surprising when one realizes that, though contrary to the results of other investigations, practically all field research upon soil atmosphere conditions has been carried out by a method ill suited to work near the soil surface and has been pursued in comparatively humid regions where moisture is rarely a factor limiting the activity of soil organisms. Since these determinations were made at a season when root activity is slight the great consumption of oxygen and the high production of carbon dioxide is doubtless due to microorganisms. Numerous investigations have demonstrated the high rate of activity of microorganism in the soil following partial sterilization and this possibly accounts for the great activity following a long period of drouth broken by a period of comparative humidity. Stoklasa and Ernest (1905) have shown that the respiratory activity of soil organisms is very great, 100 grams of *Bacterium hartlebi* giving off 2.5 grams of CO_2 per hour at 20° and other soil organisms giving but slightly lower values. Wollny (1889) showed that the amount of CO_2 in the soil air is in proportion to the decomposition processes going on therein and also that the rate of this activity is dependent upon that vital factor, temperature or water, which is present in imiting quantities (1881, 1886, and 1896). Stoklasa and Ernest (loc. cit.) found that in the soils which they studied, bacterial activity was greatest at 20 to 30 centimeters below the surface and that below one meter the soil was practically sterile. This agrees with the constantly high oxygen and low carbon dioxide values obtained for the atmosphere from the lower soil levels; the composition of the soil atmosphere here is determined by root respiration alone and the upper layers contain not only more roots but also very active microorganisms. It appears then that when prolonged dry periods are followed by precipitation the activity of soil organisms may be very great, reducing the oxygen and increasing the carbon dioxide in the soil atmosphere in proportion to available moisture even in the surface layers and despite temperatures which approach freezing.

The high moisture content of the surface layers probably retards the exchange of gases between the soil and the atmospheric air and thus aids in maintaining the difference in composition. The aerometer determinations here recorded were made in the early morning so that soil temperatures near the surface rose considerably later in the day.

It will be seen that during this investigation the atmosphere of the lower layers remained fairly constant and did not differ in composition greatly from atmospheric air. Weaver (1919) has shown that plants of this region are typically deep rooted and this might be expected from the favorable atmosphere which the roots encounter in the deeper layers of the soil especially in view of the work of Noyes, Trost, and Yoder (1918) showing that most plants tried, respond to increased CO_2 in the soil atmosphere by developing spreading shallow root systems. From the work of Caldwell (1913), Livingston and Free (1916) and others, as well as from unpublished results obtained by the author it is evident that rate of root-growth, root-hair development, root absorption, and wilting point are intimately related to the oxygen supply of the soil atmosphere. It is not improbable then that an adequate oxygen supply in the subsoil may account not only for the root growth into that region of the soil but also for the fact that the deeper subsoil is kept continually dry by root absorption (Alway, McDole, and Trumbull, 1919). The form of the root system may be affected by the oxygen and carbon dioxide supply (Noyes, Trost, and Yoder, loc. cit.; Noyes and Weghorst, 1920; Cannon and Free, 1921) and also the mineral nutrition of the plant (Davis, Hoagland, and Lipman, 1923).

These facts will, of course, apply to root systems in the upper layers of the soil. If regions, the climate of which is characterized by extreme dryness of the soil and short periods of abundant surface water following a rain, are inhabited by plants with characteristic root systems, as the work of Cannon and of Weaver shows, this may be in some measure due to the secondary effects of soil moisture upon root form and activity by modifications produced in the soil content. With the great variation in response to oxygen and carbon dioxide in the soil atmosphere shown by the work of Noyes, Trost, and Yoder (loc. cit.) and of Cannon (1921 and 1922) it is not improbable that plants dominant in regions characterized by long drouth and sudden rains are those which do not require a high oxygen pressure in the soil atmosphere for maintaining root absorption and growth. Full and immediate root activity after a rain might well be as vital a characteristic for a dominant as an extensive root system or a reduced transpiring area.

To indicate the possibilities of aerometer readings in other soils the following determinations may be given. The soils in the flood plains of the streams in the Colorado Springs region are, of course, quite different from those of the plains. The following mechanical analyses were made of soil from the flood plain of Monument Creek:

Mechanical Analyses of Flood Plain Soil, Colorado Springs

Depth (dm.)	Rock %	Coarse Gravel %	Fine Gravel %	Coarse Sand %	Med. Sand %	Fine Sand %	Very Fine Sand %	Silt %	Clay %	Hygros. Coef. %	Ign. Loss %
Surface	15.51	20.12	16.70	7.19	6.35	9.43	13.67	9.10	1.80	3 8	6.2
1.	13.15	10.73	10.93	10.20	6.53	9.11	14.16	18.70	3.60	4.9	4,5
4.	1.35	1.69	3.79	6.70	5.48	8.71	16.30	36.60	8.10	7.1	7.2
8.	40.89	19.92	18.01	10.35	3.77	2.54	1.41	0.40	0.60	1.5	0.5

At 2 P. M. of November 10, aerometer readings gave the following results:

Depth (dm.)	Temperature	Soil Moisture %	Porosity %	Oxygen %	Carbon Dioxide %	Nitrogen %
Surface	11.0	8.7	34.8	19.97	0.38	79.65
1.	9.0	11.9	20.5	20.60	0.29	79.11
4.	8.6	21.1	24.1	19.36	0.49	80.15
8.	8.5	2.4	26.2	20.00	0.90	79.10

Another markedly different soil occurring in the Pike's Peak region is found in the mountains. The granite rocks here have weathered forming a coarse gravel soil which slopes at angles up to 45 degrees on the walls of the canons. In this soil the southern slopes are bare or covered with a sparse growth of scrub oak and yellow pine but the northern aspects are forested with Douglas fir and Engelmann spruce. Bates (1923) has shown that this condition is, to a large degree, the result of temperature and moisture relations. Mechanical analyses of the soils from the two opposing slopes of Engelmann Canon at 8300 feet elevation follow:

Mechanical Analyses of Soil from Engelmann Canon

South Slope-exposure (north side of canon).

Depth (dm)	Rock %	Coarse Gravel %	Fine Gravel %	Coarse Sand %	Med. Sand %	Fine Sand %	Very Fine Sand %	Silt %	Clay %	Hygros. Coef. %	Ign. Loss %
Surface	52.97	17.66	14.63	5.72	1.97	2.23	2.36	2.00	0.30	1.2	0.5
1.	32.75	34.86	15.19	2.78	2.80	2.91	2.39	5.00	0.60	3.3	1.8
2.	58.40	12.08	6.86	4.26	2.28	3.78	4.77	6.80	0.70	4.3	0.2
North Slope-exposure (south side of canon).											
Surface	0	25.56	14.88	5.52	16.12	2.52	16.20	16.00	3.20	7.6	89 66
1.	40.38	17.01	11.08	5.79	3.38	3.20	5.77	11.50	1.10	3.0	1.3
2.	21.80	21.28	18.80	11.35	6.02	6.12	5.76	7.90	0.80	1.8	0.9
3.	33.51	16.30	16.97	9.74	5.02	5.43	5.79	5.70	0.80	1.2	1.4
5.5	32.33	16.58	18.32	9.39	4.04	4.00	4.62	8.70	1.20	4.3	2.3

Plant materials in the soil of the northern aspect bring up the ignition value and also retain fine material which would be carried down the slopes of the southern aspect by water. This appears in the table in the increased percentages of the finer soil constituents and the consequent apparent reduction in the values for the coarse materials. The sieve analysis of the surface layer on the northern slope is not of much value since it is misleading. This layer is composed almost entirely of dead plant material with an occasional rock which has rolled from some exposed place on the slopes above. This is shown in the ignition loss. Upon sieve analysis much of this plant material remains upon the coarse screen and is thus recorded above as gravel while other plant-parts in various stages of decay and disintegration pass through some of the coarser sieves and lodge on the finer, appearing above as gravel or sand. This gravel soil is often shallow and closely underlaid with rock or with gravel which has but partially disintegrated so that the depth to which a soil borer can be driven is often small; the above determinations were made only to the depth to which it was found possible to force the soil borer of the aerometer.

Aerometer Readings South Slope-exposure of Englemann Canon, October 24, 1922.

Depth (dm.)	Temperature	Soil Moisture %	Porosity %	Oxygen %	Carbon Dioxide %	Nitrogen %
Surface	15.5	1.4	43.17	20.74	0.17	79.09
1.	8.4	3.9	40.73	20.82	0.10	79.18
2.	9.7	3.2	30.18	20.90	0.05	79.05
	North Slope-exposure, November 2, 1922					
Surface	0.8	67.8	56.9	20.45	0.42	79.13
1.	1.4	3.3	34.8	20.61	0.23	79.16
2.	2.8	1.8	38.1	20.70	0.20	79.10
3.	3.2	2.0	33.3	20.81	0.12	79 07
5.5	3.9	4.4	34.4	20.53	0.27	79.20

Aerometer readings can thus be made upon soils as different as those of the flood plains of streams with a porosity as low as 20 per cent and of the coarse rock soils of the mountain slopes the soil of which shows a porosity of about 40 per cent. Even the duff under conifers can be studied and shows a porosity in the neighborhood of 60 per cent. It is not assumed, however, that determinations made either in vegetable matter, which is easily compressible, or in coarse gravel, which is difficult to enclose in the borer, without allowing the escape of the contained air show the same degree of accuracy as readings made in the finer more uniform soils. But the accuracy even under these adverse conditions is sufficient to show the varying porosity and gas content of fine and coarse soils, rich or poor in organic matter, and it is felt that the careful use of the aerometer should throw much light on the little known phenomena of soil aeration.

To reduce errors due to mechanical disturbances caused by forcing so small a borer through the soil as the one used for the above described work a borer was constructed 10.35 cm. in diameter and 31 mm. deep. This large sampler is shown in Figure 7. It is used in the same way as described for the 50 c.c. sampler, being carried in the same wrench to which the smaller size attaches. The volume when clamped against a gasket of plumber's rubber is 256.7 cc. This sampler can be used in the same way and with the same equipment as the small size. In using this sampler it is more difficult to displace the soil air completely, both because of the greatly increased surface for the diffusion and mixing of the hydrogen and the soil air and also because when using the 50 cc. gas burette it is necessary to make a number of measurements of the displaced gas to obtain the complete soil atmosphere, thus increasing the time during which diffusion may occur. For this reason as well as because of the nuisance of generating hydrogen in the field the aerometer is now used without the displacement gas, somewhat in the way that Robinson (1920) has made use of the Van Slyke apparatus for getting the carbonate present in soils except, of course, that no acid is added to the sample. The method follows:

The soil sample is taken in the same way as described for the displacement method. The sheet of metal, which is used to cut off the core of soil and prevent the dilution of the soil atmosphere during the transfer of the sampler and its contents to the burette stand, is provided with a cutting edge made by turning back the metal at a sharp angle so as to form a spring clamp for the edge of the rubber gasket. The opposite side of the gasket touches a low shoulder which runs across the plate parallel with the cutting edge and distant from it slightly more than the diameter of the gasket to be used. Soldered to the upper side of the plate near the shoulder are two stops so adjusted that, when the plate, carrying the rubber gasket, is forced through the soil immediately below the sampler until the stops are in contact with the sides, the gasket exactly covers the bore, preventing the dilution or escape of the contained atmosphere as the sampler is withdrawn and freed from any particles adhering to the outside. The metal is easily slipped free from the rubber gasket by a movement to the side, i. e. at right angles to the direction of shoving into the soil. The cap is then screwed into place, clamping the gasket without exposing the soil contained in the sampler to contact with the air.

The sampler is held in the stand in the reverse position from that used in the displacement method, stopcock (6) Figure 6 being above the barrel (1) of the sampler. Stopcock (6) is turned so as to leave a free passage from the burette to the air and the leveling tube (9) is raised until all air is displaced from the burette connecting tubing and stopcock bore. Stopcock (6) is then turned so as to connect with the bore of the sampler and the leveling tube lowered until the mercury levels show a negative pressure of 100 to 200 mm. The volume is then read on the gas burette and the temperature of the water jacket recorded, the water having been circulated by blowing air through it. Barometric pressure is determined by means of an aneroid barometer. The sample of gas is then stored in a collecting tube for later analysis.

Since the total volume of gas must be used the capacity of the tubing and stopcock bore between the burette and the soil sample must be determined. This volume can easily be measured by weighing the mercury required to fill the tubing, care being taken to redetermine this value if alterations in the tubing are made. Short rubber connections should be made from ⅛ inch heavy tubing so as to reduce errors arising from the decrease in caliber of the rubber tubing under negative pressure. If the burette is kept out of the direct sunlight the temperature of the water jacket will be so nearly that of the air that this reading may be taken as the temperature of the parts outside of the water and the volume of the tubing merely added to the burette reading. Before use in the field the sampler should be tested for leaks by closing and forcing air into the chamber until a positive pressure is created which is greater than the negative pressure to be employed. If the sampler is then submerged in water any leaks will make themselves apparent. A special stopcock lubricant such as that recommended by Dennis (loc. cit.) should be employed.

The negative pressure is read directly from the mercury levels in the burette and leveling tube by attaching a millimeter scale to the side of the water jacket and reading on this the difference in level of the two surfaces.

Calculations are made as follows: A sample of soil taken in the large sampler showed a temperature of 16.3°, the barometric pressure at the time being 610 mm. The pressure in the sampler was reduced 200 mm. and the volume in the burette and tubing was 41.39 c.c. at 22.2° or 40.57 at 16.3°, the soil temperature. If v_1 is the volume of air in the soil sample in c.c., v_2 the volume in the burette and connections in c.c., and p_1 and p_2 the pressures under which the volumes v_1 and v_2 were read respectively, then $v_1 = \frac{p_2 v_2}{p_1 - p_2}$ and we have by substituting the values obtained $v_1 =$

$\frac{410\times 40.57}{200} = 83.16$ which is the original volume of air contained in the soil sample of 256.7 c.c. volume. This corresponds to a porosity of 32.4 per cent.

The great advantage of this method of using the aerometer is the reduction in field equipment, no hydrogen generator or testing device is used, and the simplification in gas analysis, the soil atmosphere is not diluted by hydrogen so that but one tube of gas is required for analysis and all the gases present are from the soil atmosphere.

The following tables give the results of analyses made on opposing slopes of Engelmann Canon of 8300–8800 feet. Mechanical analyses are similar to those already recorded for these soils:

South Slope-exposure of Englemann Canon, May 11, 1923.

Depth (dm.)	Temperature	Soil Moisture %	Porosity %	Oxygen %	Carbon Dioxide %	Nitrogen %
Surface	32.4	1.3	42.40	20.72	0.20	79.08
1.	15.6	4.2	38.65	20.75	0.17	79.08
2.	12.2	3.7	31.02	20.63	0.33	79.04
3.	9.8	3.8	30.52	20.69	0.24	79.07

North Slope-exposure, May 12, 1923.

Surface	11.1	69.4	54.21	20.43	0.47	79.10
1.	10.4	4.9	32.70	20.59	0.30	79.11
2.	9.2	3.8	36.43	20.68	0.21	79.11
3.	7.0	4.0	33.27	20.74	0.18	79.08
4.	6.8	4.1	33.01	20.71	0.20	79.09

South Slope-exposure, July 25, 1923.

Surface	46.8	1.4	44.30	20.90	0.07	79.03
1.	40.4	2.8	39.00	20.78	0.12	79.10
2.	32.1	3.4	33.61	20.78	0.12	79.10
3.	28.0	3.7	27.77	20.67	0.18	79.15

North Slope-exposure, July 27, 1923.

Surface	21.3	47.2	61.30	20.72	0.19	79.09
1.	18.5	4.1	34.62	20.71	0.21	79.08
2.	15.2	4.0	35.27	20.70	0.23	79.07
4.5	10.8	4.1	30.00	20.71	0.25	79.04

South Slope-exposure of Engelmann Canon. September 6, 1923.

Depth (dm.)	Temperature	Soil Moisture %	Porosity %	Oxygen %	Carbon Dioxide %	Nitrogen %
Surface	18.8	2.0	43.71	20.83	0.11	79.06
1.	20.2	4.1	40.02	20.84	0.12	79.04
2.	17.5	3.9	35.00	20.85	0.13	79.02
3.	13.1	3.7	30.41	20.83	0.13	79.04

North Slope-exposure. September 6, 1923.

Surface	9.3	58.3	55.70	20.57	0.37	79.06
1.	9.1	4.4	34.12	20.71	0.26	79.03
2.	8.7	4.1	35.68	20.72	0.23	79.05
3.	7.5	4.2	30.27	20.75	0.20	79.05
4.	7.2	4.4	28.93	20.73	0.24	79.03

These results show, as do those already given for 1922, the great effect of the plant cover on the north slope-exposure of the canon. The organic matter in the surface layers is indicated by high soil moisture and porosity percentages. At a depth of one decimeter or more porosity values for the soils of the two slopes are similar. The plant cover on the north exposure tends to increase the soil moisture by checking run-off. The minimum water content occurred in July.

Carbon dioxide varies with the water content for each slope, the minimum occurring in July. The surface layers of the soil of the north exposure, which were rich in organic matter, show a carbon dioxide content markedly higher than that occurring in the soil of the south exposure. When the surface soil is rich in organic matter the carbon dioxide content may be comparatively high if temperature and moisture conditions are favorable.

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