The Rural Text-Book Series

EDITED BY L. H. BAILEY

THE PRINCIPLES OF SOIL MANAGEMENT

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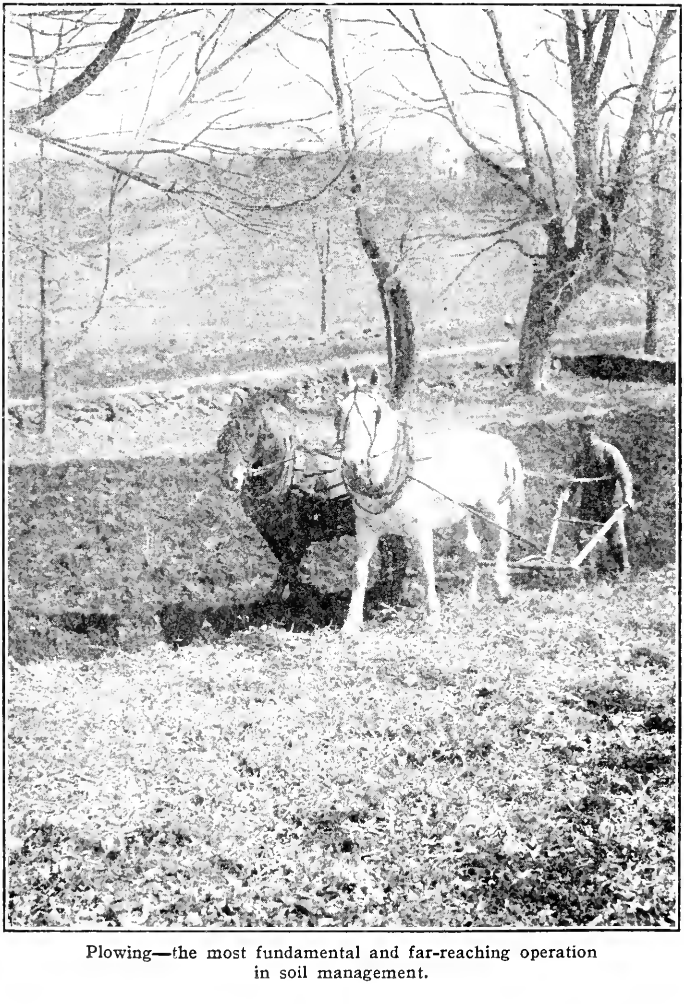

Plowing—the most fundamental and far-reaching operation in soil management.

THE PRINCIPLES
OF
SOIL MANAGEMENT

BY

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PREFACE TO THE RURAL TEXT-BOOK SERIES

In 1895 the preface was written for the Rural Science Series. It set forth the purpose of the Series to be the desire to place in readable form the best results of scientific thought and discovery relating to agriculture and country life, in order that the general public might be made aware of the progress, and that farmers might be led more effectively to apply the information in their daily work. It was the hope that the Series, under the present writer's direction or another's, might gradually extend itself to the whole range of agricultural scientific literature. The books now included in The Rural Science Series are about two dozen, making nearly two volumes, on the average, for each year. The number of writers on agricultural topics is increasing, the knowledge on all subjects is rapidly accumulating, and the reading-public is gradually enlarging; there is every reason to expect, therefore, that the Series will extend itself still more rapidly in the years to come.

It was considered to be an auspicious circumstance that the Rural Science Series began with a book on the soil, for this grounded the enterprise. The scientific and literary character of this first volume also won a good hearing for the undertaking.

The time has come when special texts on agricultural and rural subjects are needed in educational institutions; and I now, therefore, project another line of rural books, to be known as The Rural Text-Book Series. This Series is to be coördinate with the other Series, the former designed primarily for popular reading and for general use, this one for class-room work and for special use in consultation and reference. It is planned that the Rural Text-Book Series shall cover the entire range of public-school and college texts.

I consider it to be significant that I am able to begin this new Series, also, with a book on the soil. These two soil books well illustrate the two methods of treatment of a subject; and this later one impels us anew not to forget, in all our new discussions, and especially amid the social and economic speculations on which we are now entering, that a well-maintained soil is the first essential, not only to agricultural progress but to human prosperity. The soil is the greatest natural resource. We must never, in our philosophy, get away from the land.

Attention is called to the analysis of the subject-matter of this volume as outlined in the table of contents and expanded in the text. The educational value of any subject or volume lies not so much in the information that is presented as in the organization of the information into a systematic treatment, whereby a philosophy of the subject is developed. A college text should be a unity, rounding up the subject so completely as to give the student a grasp of the material as one problem, and at the same time expounding the reasons on which the treatment rests. When the student has completed any text, he should have a clear mental topography of the subject that it treats. So may the agricultural subjects be made the agencies in developing clear thinking, sound argument, constructive imagination, and effective application to the needs of life.

L. H. BAILEY.

Ithaca, N. Y.
October 1, 1909

AUTHORS' PREFACE

In teaching introductory courses in soil technology to agricultural students, the authors feel that the use of a text book enables the student to get a more thorough mental discipline and a better grasp of the details of the subject than can result from a course of lectures. The present book is the outgrowth of their experience in teaching soil technology through a period of several years. It has been their endeavor to present the application of science to soil problems from the standpoint of crop-production rather than that of any one of the underlying sciences of geology, chemistry, physics or bacteriology. This has necessitated drawing from a wide range of literature, and arranging the material in a form which it is thought adequately represents all phases of the subject. The sources of such data have been freely drawn upon, and the authors take this opportunity to express their obligations for the aid they have received from a very large number of papers and books dealing with soils, and which it has not been found practicable to credit specifically in the text, as has been done in many instances.

It may happen that some teachers will not wish to follow the entire text, in which event we think it will be found possible to omit certain sections and yet have a connected treatment of the subject. On the other hand, very little attempt has been made to supply illustrations of the principles which are explained. Such illustrations and amplifications are left to be added by the teacher as local conditions and interests may dictate.

The book, as its title implies, deals largely with the Principles of Soil Technology, and applications of these to local practice should constitute a part of the instruction.

Attention is called to the outline of contents, which shows the method of treatment and the relation of the several parts of the subject. As an elementary treatise, it has been the aim to properly balance the discussion of all phases of the subject, which may be followed in greater detail in advanced courses.

In the illustrations, endeavor has been made to include cuts of all of the more common types of soil-working implements. We are indebted to the United States Bureau of Soils for several illustrations, and to Pfeffer's 'Pflangenphysiology' for three cuts which, by mistake, were not credited in the text.

THE AUTHORS

Cornell University,
Ithaca, N. Y.
October 18, 1909.

OUTLINE AND TABLE OF CONTENTS

*Number in parenthesis refers to section

CLASSIFIED LIST OF ILLUSTRATIONS

INTRODUCTION

By L. H. BAILEY

The exposed surface of the crust of the earth tends always to pass into a loose and disintegrated layer. In this layer many organisms live, and out of it many of them derive an essential part of their nourishment. The organisms die and their remains return to the place whence they came. In every successive epoch of the earth's history, this layer has tended to become more differentiated and complex in each epoch supporting a higher type of plant, and in each succeeding age maintaining a more advanced kind of activity. Thus the soil has been formed, and the evolution of it and of the plant tribes that grow out of it have been reciprocal, one contributing to the other. If the soil is essential to the growing of plants, so have the plants been essential to the formation of soil.

This marvelously thin layer of a few inches or a very few feet that the farmer knows as "the soil," supports all plants and all men, and makes it possible for the globe to sustain a highly developed life. Beyond all calculation and all comprehension are the powers and the mysteries of this soft outer covering of the earth. We do not know that any vital forces pulsate from the great interior bulk of the earth. For all we know, the stupendous mass of materials of which the planet is composed is wholly dead; and only on the veriest surface does any nerve of life quicken it into a living sphere. And yet, from this attenuated layer have come numberless generations of giants of forests and of beasts, perhaps greater in their combined bulk than all the soil from which they have come; and back into this soil they go, until the great life principle catches up their disorganized units and builds them again into beings as complex as themselves.

The general evolution of this soil is toward greater powers; and yet, so nicely balanced are these powers that within his lifetime a man may ruin any part of it that society allows him to hold; and in despair he throws it back to nature to reinvigorate and to heal. We are accustomed to think of the power of man in gaining dominion over the forces of nature,—he bends to his use the expansive powers of steam, the energy of electric currents, and he ranges through space in the light that he concentrates in his telescope; but while he is doing all this he sets at naught the powers in the soil beneath his feet, wastes them, and deprives himself of vast sources of energy. Man will never gain dominion until he learns from nature how to maintain the augmenting powers of the disintegrating crust of the earth.

There are three great kinds of natural resources,—

the earth itself, the atmosphere that envelopes it and which may be considered an outer layer of it, and the sunshine. From these three, and all the materials and forces that are in them contained, we derive the conditions of our existence and express our outlook to destiny. We can do little to control or modify the atmosphere or the sunlight; but the surface of the earth is ours to do with it much as we will. It is the one great resource over which we have dominion. Within this crust are great stores of minerals and of metals and of other materials that we can use for our comfort; these materials we can save and we may use them with economy, but we cannot cause them to increase. But the soil may be made better as well as worse, more as well as less; and to save the producing powers of it is far and away the most important consideration in the conservation of natural resources.

The man who owns and tills the soil, therefore, owes an obligation to his fellowmen for the use that he makes of his land; and his fellowmen owe an equal obligation to him to see that his lot in society is such that he will not be obliged to rob the earth in order to maintain his life. The natural resources of the earth are the heritage and the property of every one and all of us. We shall reach the time when we shall not allow a man to till the earth unless he is able to leave it at least as fertile as he found it. A man has no moral right to skin the earth, unless he is forced to do it in sheer self-defence and to enable him to live in some epoch of an unequally developed society; and if there are or have been such social epochs, then is society itself directly responsible for the waste of the common heritage.

On every side, therefore, it is important that we study the soil. Beyond all mere technical agricultural practice, the principles of soil management must be comprehended and taught. There is no good sociology that does not recognize this fact.

We tend always to discuss great subjects from one point of view. So has the soil usually been treated from the chemical point of view, from the geological, from the agricultural. In this book, the authors have attempted to discuss the soil in all its relations to plant production, developing the inter-dependence of geological, chemical, bacteriological, physical and industrial relationships in such a way as to give the student a grasp, albeit a brief one, of the entire subject in its many bearings. In its treatment, the book considers, first, the soil as a medium for root development; second, as a reservoir for water; third, as a source of nutrients; fourth, as a realm of organisms; fifth, in its relation to air; sixth, its relation to heat; and the relation of man to the soil follows as a consequence and conclusion.

The past few years constitute a period of great activity in the study of the soil, so much so that many of our most established opinions have been challenged. Perhaps it is yet too early to rationalize all the new discussions into a clear course of practice, but we are surely getting nearer to the fundamental problems, and we shall evolve a better system of agricultural procedure. The stimulation of inquiry and imagination cannot fail to produce great results.

So am I glad of every new effort that puts men rationally on their feet on the soil. It will be a great thing when the soil is known in schools. I wait for good politics and good institutions to grow out of the soil. I wait for the time, also, when we shall have good poetry and good artistic literature developing from subjects associated with the soil; for we want good literature to appeal to all men.

THE PRINCIPLES OF SOIL MANAGEMENT

A. THE SOIL AS A MEDIUM FOR ROOT DEVELOPMENT

The soil is a medium for the development of plants. In the main, the plants which are of agricultural importance are differentiated into root and top, and the former penetrates the soil in order to obtain food and moisture, and to afford a firm support for the aërial portion. Every plant has definite requirements for its best development. The character of the mature plant is the result of two sets of forces. The first of these is the inherent capacity of the seed to develop and produce a normal individual of its kind. The second set of forces constitute the environment in which the plant grows, and of which the soil is one part, the other component being climate. Every plant is an expression of the combination and interaction of these three groups of forces—the seed, the climate, and the soil.

The external factors in plant growth may be further differentiated into the following: (1) Food, (2) moisture, (3) heat, (4) light, (5) air, (6) mechanical support, and (7) freedom from biological enemies, such as fungous disease and animal attack. With the exception of light, every one of these factors is partially or wholly determined by the character and condition of the soil. It is the source of the majority of the nutritive elements, it contains the water necessary for the plant and in which is carried its food, it holds air in its pores, and it absorbs and transmits the necessary heat. Enemies of one plant may or may not be present; but, if present, they may exercise a controlling influence. All the parts of the soil mechanism—for such it must be considered—are closely related to each of these essential factors, and it is from this point of view of the growing plant that the following treatment is developed.

The characteristics of the soil may be viewed from both the origin of the material and its properties. The first of these may be termed "The Rock and Its Product," and, second,—in so far as they pertain to physical properties,—"The Soil Mass."

1. THE ROCK AND ITS PRODUCTS

Since all soil material forms a part of the structure of the earth, its origin and derivation constitute a part of the field of geology. The following discussion of the rock and its products deals primarily with these facts and processes. But the discussion is not taken up because of its geological interest, great as that is, but because of the fundamental connection these have to the physical, chemical and biological properties of the soil which determine its ability to grow plants. The kinds of minerals and rocks in which the essential elements of plant-food originally occur, and the changes which they may have undergone in their transition to the present combinations in the soil, as well as the fact that the physical properties of the soil are primarily determined by its derivation, render their study of fundamental concern in order to understand the soil as a medium for plant-growth. The classification and detailed study of the soil is inseparably linked with its derivation, because determined by it. On one side, it supplies certain elements of food whose relative abundance is determined by their distribution in the original rocks and their concentration or dissipation through geological changes, and, on the other side, it affords the physical medium for the development of the plant.

I. THE ELEMENTS OF PLANT-FOOD

The plant must have certain food elements for its growth and development. These elements are affected by the changes to which the rock is subjected, and in the end will reflect the character of these changes.

1. Elements essential to plant-growth.—The essential elements of plant-food are ten in number, to which may be added three others which seem to be useful under certain conditions. The essential elements may be divided into two groups, on the basis of their origin: (1) The elements derived entirely and only from the solid portion of the soil. These are calcium, magnesium, potassium, phosphorus, iron and sulfur. (2) The elements derived either directly or indirectly from air and water. These are carbon, hydrogen, oxygen and nitrogen.

2. General abundance of the plant-food elements.—Having now in mind the essential food elements it is of interest to know their general abundance in the earth's crust. The following table is given by Clark:

Oxygen	47.02
Silicon	28.06
Aluminum	8.16
Iron	4.64
Calcium	3.50
Magnesium	2.62
Sodium	2.63
Potassium	2.32
Titanium	.41
Hydrogen	.17
Carbon	.12
Phosphorus	0.09
Manganese	.07
Sulfur	.07
Barium	.05
Strontium	.02
Chromium	.01
Nickel	.01
Lithium	.01
Chlorin	.01
Fluorine	.01
	100.00

The first eight elements form 98.8 per cent of the earth's crust. In this list are found all of the food elements except nitrogen, which forms four-fifths of the atmosphere. All of the food elements except nitrogen appear among the first thirteen, and in amounts of not less than .07 per cent. This gives assurance that none of the food elements are rare. It will appear later that they are all very generally distributed. The ultimate source of the elements of the first or so-called incombustible groups is the minerals of the earth's crust.

II. IMPORTANT SOIL-FORMING MINERALS

Minerals are the units of which soils and rocks are primarily composed. A mineral is a compound occurring in nature having approximately a definite chemical composition, usually a distinct crystalline form and definite physical properties. A very large number of species of minerals which differ greatly from each other in composition and physical properties have been recognized. It is these differences which renders necessary a study of those important species which are found in the soil, in order to gain a thorough knowledge of the relations which they bear to plant nutrition and the physical and chemical characteristics of the soil mass. By their chemical and physical weakness or resistance, they modify the supply of food elements and determine the physical make-up of the soil, with all the attendant physical conditions of heat, moisture, air, etc., which this limits.

While the number of minerals known is very great, only a comparatively small number occur in the soil in important amounts; but these are thoroughly representative. All minerals may be divided into two groups: (1) The original or primary constituents which were formed at the first consolidation. (2) The secondary constituents which result from changes in the minerals subsequent to their first consolidation, and which are due in large part to the chemical action of percolating water.

3. Soil-forming minerals; their composition and properties.—The soil is composed of a great variety of minerals and probably almost every recognized species could be found in some soil. But the number of minerals which make up the bulk of soil is relatively small. The following table includes the most important soil-forming minerals and their leading properties:

TABLE I.—COMMON SOIL-FORMING MINERALS AND THEIR PROPERTIES

Name of mineral	Character of compound	Elements present	Hardness	Specific gravity	Color	Solubility in p. p. m.	
						In pure water	In carbonated water
1. Quartz	SiO_2	Si, O	7.0	2.7	Colorless-yellow-black	1	3
2. Orthoclase Feldspar ..	K_2O, Al_2O_3, $6SiO_2$	K, Al, Si, O	6.0	2.6	Flesh	20	45
3. Plageoclase Feldspar...	(Na, Ca) O, Al_2O_3, $6SiO_2$	Na, Ca, Al, Si, O	6.0	2.7	White	....	....
4. Leucite.....	$KAl(SiO_3)_4$	K, Al, Si, O	6.0	2.4	Gray	....	....
5. Nephelite...	$(K, Na)_2Al_2Si_2O_3$	K, Na, Al, Si, O	6.0	2.6	White-red	....	....
6. Amphiboles.	Poly-silicates	Ca, Mg, Fe, Mn, Al, Si,O	5.7	3.2	Dark-black	....	....
7. Pyroxines...	Poly-silicates	Mg, Ca, Fe, Al, Si, O	5.5	3.4	Green-black	....	....
8. Micas.......	Poly-silicates	K, Na, Fe, Mg, Al, Si, O	2.5	3.0	Gray and black	5	18
9. Olivine	$(MgFe)_2SiO_4$	Mg, Fe, Si, O	7.0	3.4	Green-yellow	....	....
10. Epidote	$HCa_2Al_3Si_3O_{13}$	Ca, O, H, Al, Si	6.5	3.4	Green-red	....	....
11. Calcite and Aragonite..	$CaCO_3$	Ca, C, O	3.0	2.7	White	34	980
12. Dolomite ...	$(Ca, Mg)(CO_3)_2$	Ca, Mg, C, O	4.0	2.9	White	25	325
13. Apatite.....	$Ca_3(PO_4)_2Fl, Cl$	Ca, P, O, Cl, Fl	5.0	3.2	All colors	3	10

TABLE I.—COMMON SOIL-FORMING MINERALS AND THEIR PROPERTIES, continued

Name of mineral	Character of compound	Elements present	Hardness	Specific gravity	Color	Solubility in p. p. m.	
						In pure water	In carbonated water
14. Gypsum ...	$CaSO_4 + 2H_2O$	Ca, S, O, H	2.0	2.3	White-reddish	2390	4600
15. Garnet	$(CaMgFeMn)_3Al_2Si_3O_{12}$	Ca, Mg, Fe, Mn, Al, Si, O	7.0	3.2-4.3	Red and all colors but blue	....	....
16. Sodalite	$Na_4ClAl_3Si_3O_{12}$	Na, Al, Cl, Si, O	5.5	2.3	Blue-gray	....	....
17. Hematite ..	Fe_2O_3	Fe, O	6.5	5.2	Red-black	2	15
18. Magnetite...	$FeO + Fe_2O_3$	Fe, O	6.0	5.1	Black	....	....
19. Limonite ...	$FeO3H_2O + Fe_2O_3$	Fe, H, O	5.5	3.6-4.0	Brown-yellow	....	....
20. Halite......	$NaCl$	Na, Cl	2.5	2.2	White-red	360000	....
21. Serpentine .	$3MgO, 2SiO_2, 2H_2O$	Mg, Si, O, H	2.5	2.6	Yellow-green	....	....
22. Pyrite and Marcasite..	FeS_2	Fe, S	6.0	4.9	Brass yellow	....	....
23. Chlorite	$2MgO, Al_2O_3, SiO_2, 2H_2O$	Mg, Al, O, Si, H	2.5	2.2	Green	....	....
24. Talc........	$3Mgo, 4SiO_2H_2O$	Mg, Si, O, H	1.0	2.7	White-green	....	....
25. Zeolites.....	Poly-silicates $+ H_2O$	K, Na, Ca, Al, Si, O, H	..	..	......	....	....
26. Kaolinite ...	$2H_2O, Al_2O_3, 2SiO_2$	H, O, Al, Si	1.0	2.5	White-yellow	....	....
27. Glauconite .	Poly-silicate $Fe + H_2O$	K, Ca, Mg, Na, Fe, Al, Si, O	2.0	1–2	Green	....	....

4. Relative abundance of the common minerals.—Hall quotes D'Orbigny as saying that in the earth's crust the chief minerals are present in the following proportions:

Feldspars	48
Quartz	35
Micas	8
Talc	5
Carbonate of lime and magnesium	1
Hornblend, augite, etc.	1
All other minerals and weathered products	2
	100

These general relations agree with the statements of Chamberlin and Salisbury, who give the following summary of the salient facts relating to the composition of minerals: "(1) Out of the seventy-odd chemical elements in the earth, eight form the chief part of it. (2) One of these elements uniting with the rest forms nine leading oxides. (3) One of these oxides acts as an acid, and the rest as bases. (4) By their combination they form a series

FIG. 1. Section of granite, magnified. The crystals are orthoclase, microline, plagioclase, quartz, black mica or biotite, white mica or muscovite. (Merrill.)

of silicates, of which a few are easily chief. (5) These silicates crystallize into a multitude of minerals, of which again a few are chief. (6) These minerals are aggregated in various ways to form rocks."

Hundreds of analyses of rocks have been made in this country and abroad and from these Clark finds the mineralogical composition of igneous rocks of the earth's crust to be as follows:

Feldspars	59.5
Hornblend and pyroxine	16.8
Quartz	12.0
Biotite mica	3.8
Titanium minerals	1.5
Apatite	0.6
	94.2

This leaves 5.8 per cent to be distributed among the more rare minerals.

III. IMPORTANT SOIL-FORMING ROCKS; THEIR PROPERTIES AND OCCURRENCE

A rock is an aggregate of minerals. Moreover, it usually exhibits a considerable degree of consolidation, and forms an essential portion of the earth's structure. Very few minerals occur in nature in large pure masses. They are usually grouped together in different combinations, and, while it is essential to trace the changes of each mineral, it is also necessary to give attention to the groups of minerals—rocks—since the association of minerals determines very largely the processes by which rocks are transformed into soil and the characteristics of the resulting soil.

These aggregates of minerals, or rocks, are essentially without order or arrangement. The minerals are in irregular crystals or fragments of greatly differing sizes closely packed together. The great variety of minerals, as well as the different physical forms of the same mineral, is productive of an infinite variety of rocks. While individuals may differ greatly, there is an easy and gradual transition from one form to another which renders it impossible to draw hard and well-defined lines separating each species of rock from every other species. They blend one into the other, not only in structure and crystalline form but also in chemical composition.

FIG. 2. Photomicrograph of diorite rock. Compare with Figs. 3, 5, and 6, which have a different mineral composition, crystalline form and structure. These differences determine the type and rate of their weathering. (Lord.)

The classification of rocks is based upon these facts, and they are grouped broadly under four main heads, the distinctions being their origin and structure. Each of the main divisions is again divided into groups and families, the distinctions being those of mineral and chemical composition, structure and mode of occurrence.

The main divisions are: Igneous rocks—sometimes called eruptive—which have been brought up from below in a molten condition from which they have cooled and solidified. They usually have two or more essential minerals, and are massive, crystalline, glassy, or, in certain altered forms, colloidal in structure. Aqueous rocks have been formed mainly through the agency of water, as (*a*) chemical precipitates, or as (*b*) sedimentary deposits. They are usually fragmental, but may be crystalline or colloidal, but never glassy. They have a laminated or bedded structure, and usually have many constituent minerals. Æolian rocks are formed from wind-drifted material. They are fragmental in character and irregularly bedded in structure. Metamorphic rocks embrace those of any of the foregoing divisions which have been changed from their original condition through the agencies of dynamic and chemical forces so that they exhibit new properties. They may have one or many constituent minerals, and in structure they are usually crystalline and bedded or foliated.

Fig. 3. Photomicrograph of basalt (trap) rock. (Lord.)

5. Igneous, aqueous, aeolean and metamorphic rocks.—The igneous rocks are parent to all the other forms. They may be arranged according to the amount of silica they contain, those that are rich in that compound being termed acid, and those that are lean, basic. In this order, some of the most abundant rock types are granite, quartz, syenites, diorites, gabbro, diabase and basalts.

FIG. 4. Photomicrograph of fossiliferous limestone. (Lord.)

Of the aqueous rocks the chemical precipitates are relatively of small importance. They seldom form extensive rock masses and are usually intimately mingled with other types of rock, especially those of the sedimentary group. The most important ones agriculturally are the sulfates, represented by gypsum beds. Certain phosphatic deposits and some chlorides also belong in this group.

The aqueous sedimentary rocks are the most important agriculturally of any of the groups of rock and especially of the aqueous rocks, because of their large surface distribution and their physiography. They are composed of the fragments derived from the degeneration of all the older rocks and from the inorganic remains of plant and animal life. These comprise clay and shale (argillaceous), sandstone, conglomerate and breccia (arenaceous); limestone and dolomite (calcareous), together with minor rocks of volcanic, phosphatic and carbonaceous character.

The sandstones, shales, limestone and dolomite are easily the most prominent of this group, and, in fact, of all the types of rock, in their present agricultural importance. They compose immense strata of rock, and

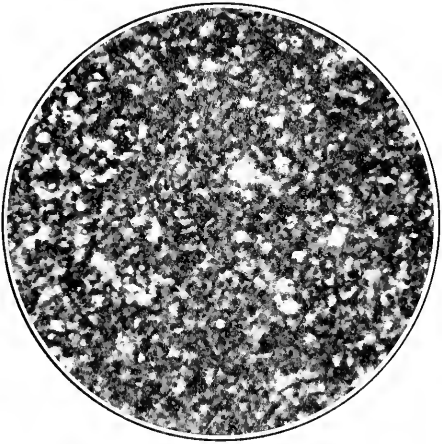

FIG. 5. Photomicrograph of chert. (Lord.)

FIG. 6. Photomicrograph of sandstone. (Lord.)

are usually arranged in alternating layers of variable thickness and extent, and have given rise to important areas of soil.

Æolian rocks are relatively insignificant, and are generally of a sandy or clayey character.

Metamorphic rocks are correlated with all the other types of rock, and have resulted from pronounced alterations in other rocks. Their individual properties are therefore similar to the rock from which they were formed. Often their resistance to decay is increased by the process, as in quartzite and slate.

IV. CHEMICAL AND PHYSICAL AGENCIES OF ROCK-DECAY

There are five chief agencies of rock-decay. They are, (*a*) the atmosphere, (*b*) heat and cold, (*c*) water, (*d*) ice, and (*e*) plants and animals. The operations of each of these agencies are of two sorts: (1) chemical; (2) mechanical. The products of these two types of force are distinctly different in their relaiton to the plant. The chemical action of the various agencies results in a changed composition of the minerals. It results in the breaking down of the mineral compounds, with the possible removal of the elements, as when feldspar is changed to kaolinite. Here the base—potash, soda or lime—is replaced by the elements of water, and may be carried entirely away. The hydrated residue loses some of its silica, and kaolinite is the result. In other cases the change may be effected by the addition of material, as when pyrite is oxidized by the

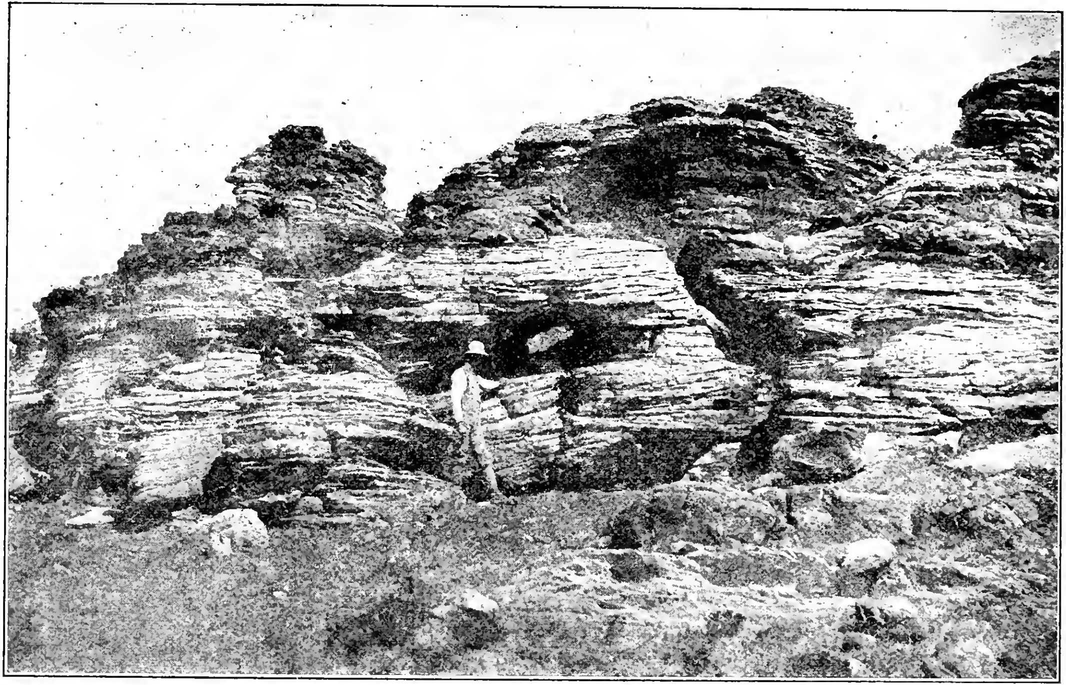

FIG. 7. Typical erosion form of sandstone. The material removed in the decay of these rock masses is deposited in some other position where it may ultimately serve as soil. The material constituting these cliffs may have served as soil for the growth of plants at some earlier time. Thus the process of change from the condition of soil material to rock and back again is continually in operation. Soil has been defined as "rock in transition from one form to another."

atmosphere to the sulfate by the direct union of oxygen with the compound. Whether the process be an addition or subtraction of material, it usually changes the stability of the mineral, and perhaps the stability of the mass of which the mineral is a part. The chemical action of one agency often opens the way for the chemical and mechanical action of other agencies, so that the decay processes are hastened. This chemical breaking down of minerals, and thereby of rock masses, is termed decomposition. The mechanical breaking up of rocks whereby only the state of division of the material is changed is termed disintegration. The breaking up of rocks due to expanison of heat, the freezing of water, flowing of water, the grinding of glacial ice, and the expansion of plant roots, are types of disintegration by which the rock is simply reduced to a finer state of division. The general tendency is for finer material to result from decomposition than from simple disintegration.

6. Atmosphere.—The atmosphere is composed of a mixture of the gases nitrogen and oxygen, in the proportion of four parts of the former to one part of the latter, together with very minute quantities of carbon dioxide, nitric oxide, ammonia, and, in even less amounts, other volatile compounds, and a variable, but usually very considerable amount of water-vapor, evidenced by clouds, rain, snow, dew, etc. These gases, dissolved in the atmospheric moisture, come in contact with rock masses and change certain of its minerals into compounds more or less soluble than they were originally. The iron compounds are perhaps the most affected, and the change of the mineral pyrite is typical of the process.

$$2\mathrm{Fe\,S_2} + 7\mathrm{O_2} + 2\mathrm{H_2O} = 2\mathrm{Fe\,SO_4} + 2\mathrm{H_2SO_4}$$
$$\mathrm{Fe\,SO_4} + 2\mathrm{H_2O} = \mathrm{Fe(OH)_2} + \mathrm{H_2SO_4}$$

All of these changes of iron compounds under the action of moist atmosphere are imperfectly understood, but it is agreed that the above products may result from the process. Since the sulfate is much more soluble than the sulfid, the mineral is in this way easily removed.

The purely chemical action of the atmosphere is less pronounced in its effects than its mechanical action. As wind, it exerts some pressure upon projecting masses tending to push them over, but its great work is accomblished when the wind carries solid particles of dust and sand and when it acts on vegetation as a lever. In arid and semi-arid regions, particularly, the amount of solid material carried in the atmosphere is very large at some seasons. There frequently occur dust storms, when the atmosphere is so filled with wind-driven particles as to obscure the sun and all objects, at even a short distance away. In the region of western Nebraska and Kansas these dust storms are well known, and on certain soils it is unwise to plow in the fall, because by spring the soil will have been blown away to the depth of the furrow, and indeed this sometimes results from plowing at any other season of the year. Further west in the mountain region this wind-blown material is most effective, where the particles may be driven against the bare rock faces. It then becomes a titanic sand blast to drill away the rock. It eats into the rock surface with remarkable rapidity, carving fantastic forms, as a result of the varying hardness of the rock and the uneven distribution of the particles. The abraded particles are born along by the wind and become new tools of destruction.

In humid regions this form of disintegration is less prominent, but in sandy regions it performs some effective work. As an example of this effectiveness, Merrill describes a large sheet of plate-glass, once a window, in a lighthouse on Cape Cod,—well known for its sand-dunes. During a severe storm, of not above forty-eight hours' duration, this became on its exposed surface so ground by the impact of grains of sand blown against it as to be no longer transparent, and to necessitate its removal. He reports that window-panes in dwelling-houses in the vicinity are frequently drilled quite through by the same means.

Material blown about by wind is very much rounded and smoothed by the impacts to which it has heen subject, a characteristic very much less in evidence in water-moved material of the same fineness.

Winds also act in conjunction with plants where the roots have penetrated into a crevice or joint, using the tops as a lever to push off or further fracture masses of rock. This process is most effective in rough mountainous regions where the larger vegetation is just getting a foothold. In passing, attention may be called to this process of overturning plants as one of nature's cultural methods, whereby the soil is subjected to very thorough, if long-drawn-out, tillage.

7. Heat and cold.—In general, heat accelerates all chemical processes. It greatly increases the solvent power of water for many substances, and renders it a more destructive agent generally. This action can not be discussed separately, but must be kept in mind in the consideration of those other agencies of decomposition. Especially important are alterations of temperature, by which compounds whose rates of solution are differently affected by temperature may be successively acted upon.

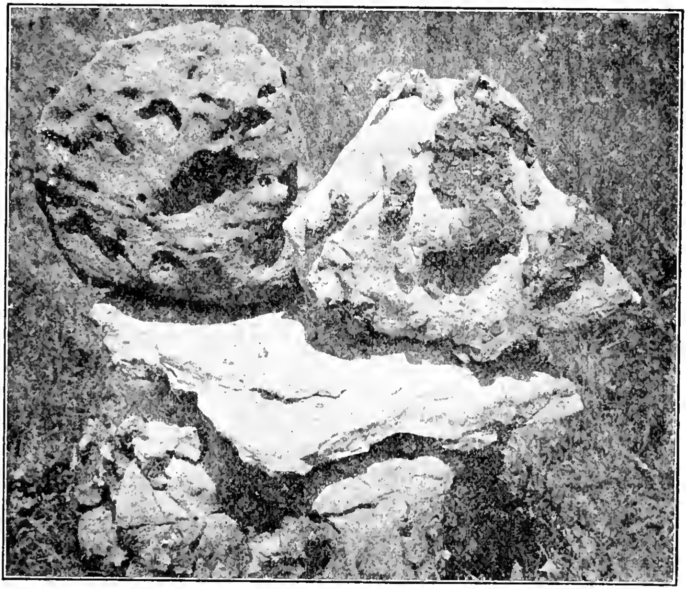

FIG. 8. Two types of rock disintegration. The forms reflect the different hardness and composition of the rocks

Heat acts mechanically in two ways to break up rocks: (1) Through expanison and contraction due to changes in temperature. All substances change volume with changes in temperature. Different minerals expand at different rates, and the same mineral may have different rates of expansion along different axes. So that, when a rock made up of several minerals has its temperature changed, it expands unequally, and a strain is set up all through the mass, which, if severe enough, and repeated often enough, will break it into small fragments. Further, even if a rock did expand uniformly in all its parts with changes of temperature, these changes of temperature are far from uniform. Heat is conducted slowly into a rock. Since the rock may have very different temperatures at points a short distance apart, as a result of this slight conductivity a great strain may result from expansion due to temperature differences. Merrill quotes Bartlett to the effect that granite expands .000004852 inch per foot for each degree of Fahr., marble .000005668 inch, and sandstone .000009532 inch. While these movements appear exceedingly small, they are multiplied through many feet of rock and through many degrees of temperature. The differences in temperature between day and night on rock surfaces exposed to the sun is extreme, although it varies with the color of the rock. (2) When water is carried below its freezing-point, it may be exceedingly destructive. In freezing, water expands about one-eleventh of its volume. It has been determined that water at a temperature of—1°C. exerts an expansive force of 150 tons per square foot, and that to keep it from becoming ice would require the weight of a column of granite 1,800 feet high. All rocks are somewhat porous. Soils have a porosity anywhere from 30 to 75 per cent of their volume. Sandstone may have as much as 25, limestone from .1 to .01. marble .008, and granite .01 per cent. If this spore space is filled with water, as is generally the case in nature, and the rock is cooled below the freezing-point, it is evident that it will be shattered. As the process is repeated, the fractures become larger and more numerous.

8. Water.—The chemical and mechanical action of water in rock-decay may be discussed separately.

(1) The chemical action may be divided into: (*a*) The changes due to pure water. (*b*) Changes due to material in solution in the water. Owing to the porosity of rocks, water is distributed through all the earth's crust to a depth of many thousand feet.

The first direct result of the presence of water is the assumption of its elements by many of the minerals. This is hydration. It may be the direct imbition of water, as when calcium sulfate in crystallizing takes into its constitution several molecules of water; or it may be the substitution of the elements of water for some elements already in the mineral. The alterations in the mineral orthoclase feldspar may be taken as the type of this kind of changes as follows:

$$K_2O, Al_2O_3, 6SiO_2 + 6\ H_2O = 2KOH + H_2O, Al_2O_3, 6SiO_2, 4H_2O$$

Since water is so widely diffused, this process of hydration is an especially important one. The significant chemical effect of hydration is that it alters the solubility of the mineral, and particularly of the elements composing the mineral.

The second direct chemical action of water, and perhaps the most important of all the chemical changes involved in soil formation, is that of solution. It is worth while to remember that no mineral is completely insoluble. They differ greatly in solubility, ranging from the readily soluble common salt to the exceedingly insoluble silica or quartz. But all are amenable to the action of pure water. In the above instance of hydration of feldspar, we have a type of a large number of changes in minerals which alter their solubility. And by altering the solubility of one mineral the other minerals present

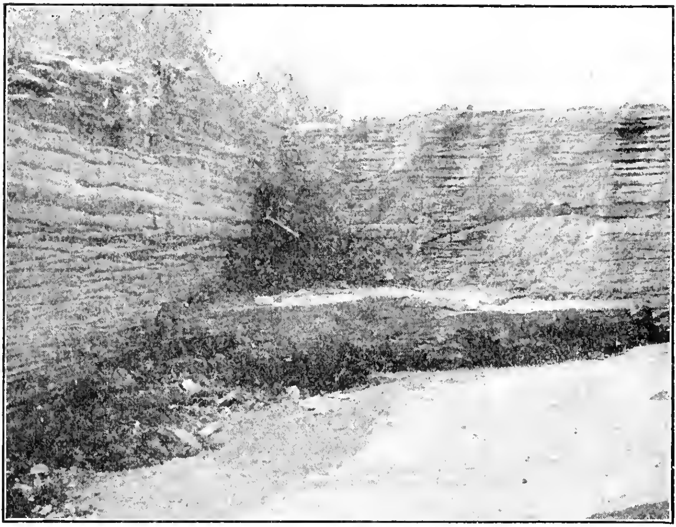

Fig. 9. Traces of residual soil in a limestone quarry. Note the joints and partings. Soil of a dark red, silty character

are opened to attack by any one of many agencies, both mechanical and chemical. In feldspar, which is very slightly soluble, hydration and hydrolysis develops potassium hydrate, a very soluble compound and therefore readily removed. Its removal may develop a cavity, and thus weaken the rock. Agriculturally, the removal of the base is also significant. It is the basic element, and therefore largely plant-food elements, or those which condition soil-productiveness, such as potash, lime and soda, which are removed by this process.

It is because of the unequal solubility of minerals that soil results from the process of solution. If all the minerals of a rock were equally soluble, the rock might be removed bodily from the exposed surface inward. Solubility, operating differently for different minerals in a rock mass, removes one, and leaves the others in a less coherent mass, which we term soil. It therefore happens that residual soils comprise the less soluble portions of the rock from which they were formed.

Materials in solution in water greatly affect its capacity to dissolve minerals. Carbon dioxid is present in the air in the pores of rocks and soils in much larger proportion than in the air above the earth's surface. It is particularly abundant in the surface layers, where it is derived from organic decay. It is taken up by the water as it passes along and becomes a means of solution. The most striking example of this is in the case of lime carbonate or limestone. In pure water this mineral is soluble only to the extent of about one part in twenty-five thousand, but in carbonated water its solubility is about one part in one thousand, or twenty-five times as soluble. It is this solvent action of carbonated water which has formed the extensive caverns and passages in every fairly pure limestone formation, and thereby has given rise to such features as the Mammoth Cave and the great sinks of Southern Missouri, Kentucky, Tennessee, Georgia, Florida and many other regions underlain by limestone.

In the superficial layers of soil, organic acids also add to the solvent power of the water.

Since water is an universal solvent, in the earth it contains a large variety of mineral compounds, all of which affect its solvent power, usually increasing it.

The destructive action of solution is indicated by the considerable amount of dissolved substances in all natural waters. The Mississippi river carries in solution annually sufficient material to cover a square mile of land ninety feet deep; the Danube, sufficient material for a depth of eighteen feet; and the Nile, sufficient material for a depth of thirteen feet.

(2) The mechanical action of water.—The destructive action of running water transcends all other agencies of rock degradation in its extent. It has been the most potent force in carving the earth's surface into its present form. It is continually at work reducing elevations and filling depressions.

This destructive action is due largely to the power of running water to carry material. This transported material becomes the tool of the water in wearing away its channel.

The transporting power of water varies as the sixth power of its velocity of flow. That is to say, if the

Fig. 10. "Pot holes" formed in shale rock. The boulders and pebbles in the "pot" are set in motion by flowing water and thereby the rock is broken down with the formation of soil material.

velocity of a stream is doubled, its carrying power will be increased sixty-four times. But the volume, and therefore the weight, of a body varies as the cube of its diameter. Therefore the diameter of the material carried does not vary directly as the velocity of the current. but at a less rate.

This power of flowing water to carry rock material is exemplified in every stream of whatever size. Where the flow is checked and thereby the carrying power reduced, some of the coarsest material is deposited. Where the flow is increased, instead of deposition, coarser material is picked up. Changing an obstruction causes extensive regrading of the channel by the current. Bends in the stream which require a greater velocity on one side of the channel than on the other cause the same sort of rearrangement, and this is nicely illustrated in the meandering of streams. They wind over their course always cutting away the material on the outer side of the curves, and depositing it on the inner side of the curves lower down. Thus the stream is continually changing its course. It meanders from one side of its flood-plane to the other. It cuts off large curves and proceeds to form new ones. All these processes may be observed in any rivulet, yet they are the exact counterpart of the things which are taking place in every large river valley. Careful determinations reported by Bobb, show that the large rivers of the world remove annually in suspension the following amounts of material:

	Height in feet of column of sediment with base 1 mile square.	Thickness of sediment, in inches if spread over drainage area.
Mississippi river	241.4	.00223
Potomac	4.0	.00433
Rio Grande	2.8	.00116
Uruguay	10.6	.00085
Rhone	31.1	.1075
Po	59.0	.01139
Danube	93.2	.00354
Nile	38.8	.00042
Mean	76.65	.00614

In addition to the material carried in suspension, a large amount is rolled along the bottom of the channel.

Because of the unequal carrying power of streams of different velocity, the load of debris is sorted into groups of somewhat uniform size. In this way have been formed great areas of clay, silt, sand and gravel found in all farming sections, and which owe their peculiar crop-producing properties most largely to this sorting action of water.

9. Ice—glaciers.—Masses of ice have exerted a tremendous influence in the reduction of rocks to soil material. Their action is chiefly mechanical, but is intimately associated, as a rule, with the action of water. The chief agency of ice is in the form of glaciers, which issue from regions of high latitude, or of great elevation, and in times past have pushed down over much larger areas of country than they now occupy. A large part of all of the continents have been overrun by such masses, which, through their great weight and almost resistless movement, ground even the hardest rocks to fine powder and mixed the materials from many sources. Fragments of rock imbedded in the bottom of the ice became its tools to scratch and crush the floor upon which it rested. In this way has come about the scouring and pulverization of rocks, analogous to the action of water. The ice appears to have attained a depth of thousands of feet in some places, and consequently was able to override even mountainous areas, sweeping away and grinding to fragments the smaller eminences and irregularities. Since the access of water was limited, there was little opportunity for pronounced chemical change, or the removal of constituents, which fact is shown in the tables of soil-composition on pages 32-57. Their influence on surface topography is profound, and of great importance to the pursuit of agriculture because of the leveling which results.

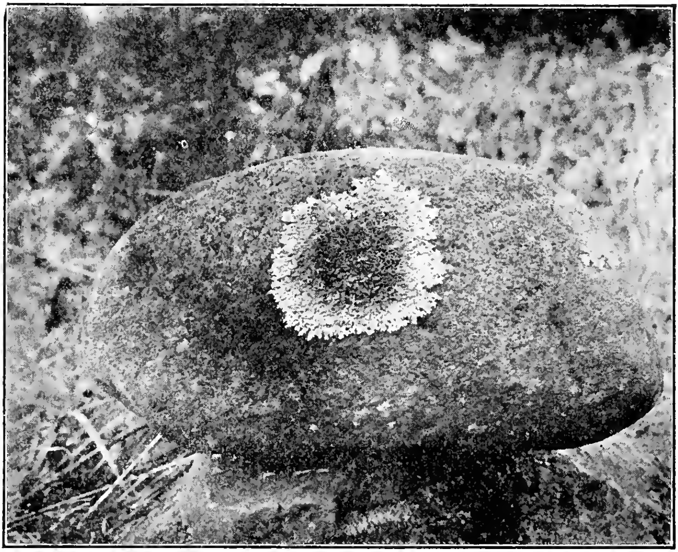

FIG. 11. Lichen growing on a granite boulder. These low forms of plants disintegrate the rock and assist in the decomposition of its constituent minerals.

10. Plants and animals.—Plants and animals unite with the other agencies mentioned to effect the breaking down of minerals and rocks. Like the other processes, they have both their mechanical and their chemical side. The development of plant roots in crevices of rock created by other agencies, exerts sufficient pressure to force them further apart and extend the fractures. Occasional striking examples of the forcing apart of rock-masses by plant-growth may be observed. The process is well

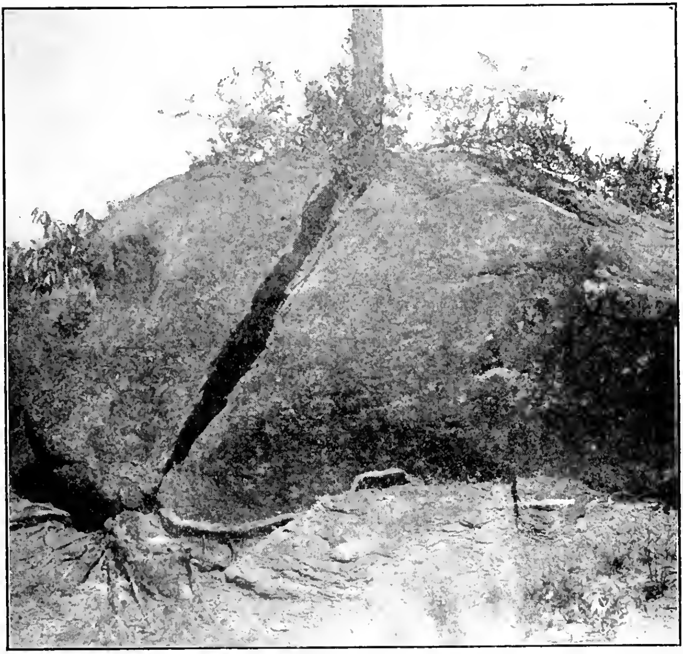

FIG. 12. Growing roots of the tree have broken apart and otherwise disintegrated the granite boulder, thereby assisting in the formation of soil

illustrated by the lifting of sidewalks and the tipping over of stone fences, due to the development of trees near by and even such soft tissues as those of mushrooms have been observed pushing up through cement and brick sidewalks. In mountainous regions where vegetation has gained a foothold in the crevices, the tops serve the wind as a lever to pry rocks apart. The overturning of trees is a familiar example of the process.

Animal life also has a part in the mechanical breaking down of rocks. Burrowing animals are most active. The gopher, the prairie dog, the badger, the rabbit, moles, etc., all burrow in the ground and, in the aggregate, move large masses of material. Cray-fish and earth-worms are even more widespread, and the latter by their large numbers have a capacity which is likely to be underrated because it is largely out of sight. Ants are another very active form of animal life in effecting soil formation. They burrow into crevices of rocks and into soil formations, and deposit the material from the passages at the surface mixed with their acid saliva. Like the earth-worms, they handle immense amounts of material.

V. GEOLOGICAL CLASSIFICATION AND CHEMICAL COMPOSITION OF SOILS

All soil material may be divided into two groups, depending upon the extent to which it has been moved in the process of formation. Those materials which have not been subject to any appreciable transportation are termed (*a*) Sedentary. Those which have been carried to their present position—that is, have been appreciably moved—are termed (*b*) Transported. There are several agencies of transportation, such as gravity, water, ice and wind. These give rise to subdivisions.

11. Sedentary soils.—Sedentary soils are of two kinds: (1) Residual, or soils consisting of the residue left behind in rock decomposition. (2) Cumulose, or soils resulting from the slow accumulation and decay of plant remains.

12. Residual soils.—There may be as many kinds of residual soil as there are rocks. Because of similarity between the species in a group of rocks, a few of these groups may be considered as types. The most prominent groups are the igneous rocks, the calcareous rocks, shale or slate and sandstone. Attention will be directed as far as possible to the relation of the soil composition to the composition of the original rock and to the character of the material lost in the transition.

In calculating the relative loss of the different elements in the transition process, some one element—usually iron or aluminum, and, in the case of limestone, silicon—is assumed to have suffered no loss. This method, adopted from Merrill, is, of course, not strictly accurate, since every element is subject to losses; but it serves as a fair comparative basis for the study of the loss of plant-food elements.

The important areas of residual soil in North America occur south of the limit of glaciation, which extends roughly from New York to Cincinnati, thence to St. Louis and up the Missouri river to the Dakotas, and west to the Sound region of Washington, where it again loops well to the south. The residual soils are further hemmed in by coastal deposits, which have their greatest extent in the South Atlantic and Gulf Coast region, where they reach a width of more than a hundred miles.

TABLE II. — COMPLETE CHEMICAL COMPOSITION OF ROCKS AND RESIDUAL SOILS.

	Granite. District of Columbia		Gneiss. Albemarle Co., Va.		Diabase. Spanish Guiana		Basalt. Crouzet Haute Loire, France	
	I Fresh Rock	II Residual Sand	III Fresh Rock	IV Residual Clay	V Fresh Rock	VI Residual Clay	VII Fresh Rock	VIII Residual Soil
1. Silica (SiO_2) . .	69.33	65.69	60.69	45.31	49.35	43.38	48.29	37.09
2. Alumina (Al_2O_3)	14.33	15.23	16.89	26.55	15.30	18.36	13.25	30.75
3. Ferric iron (Fe_2O_3)	4.00	4.39	9.06	12.18	14.25	20.39	17.12	4.31
4. Ferrous iron (FeO)	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .
5. Sulfur trioxid (SO_3)	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .
6. Phosphoric acid (P_2O_5).	0.10	0.06	0.25	0.47	. . . .	. . . .	. . . .	. . . .
7. Lime (CaO) . .	3.21	2.63	4.44	*t*	9.60	2.37	7.37	8.97
8. Carbon Dioxid (CO_2)	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .
9. Magnesia (MgO)	2.44	2.64	1.06	0.40	7.38	3.45	7.03	0.61
10. Soda (Na_2O).	2.70	2.12	2.82	0.22	1.98	0.14	2.71	1.01
11. Potash (K_2O).	2.67	2.00	4.25	1.10	0.85	0.59	1.81	0.71
12. Ignition [water (H_2O)]...	1.22	4.70	0.62	13.75	3.25	11.34	4.92	16.55
	99.60	99.77						

In addition to these large areas, many small areas occur scattered through areas of other kinds of soil.

The most nearly original soil is that formed from igneous rocks. That is to say, the composition of such a soil might be expected to approach most nearly to that of the original rock. The relative composition of several igneous rocks and the soils derived from them,

TABLE II.—COMPLETE CHEMICAL COMPOSITION OF ROCK AND RESIDUAL SOILS, continued.

	Soapstone		Igneous Rock	Sandstones	Shales	Limestone		
	Albemarle County, Va.		Average of about 700 samples	Composite analyses 253 samples	Composite analyses 78 samples	Composite analyses 345 samples	Carboniferous, Arkansas	
	IX Fresh Rock	X Residual Soil	XI	XII	XIII	XIV	XV Fresh Rock	XVI Residual Clay
1. Silica (SiO_2)..	38.85	38.82	59.87	78.66	58.38	5.19	4.13	33.69
2. Alumina (Al_2O_3) ...	12.77	22.61	15.02	4.78	15.47	0.81	4.19	30.30
3. Ferric iron (Fe_2O_3)....	12.86	13.33	2.58	1.08	4.03	0.54	2.35	1.99
4. Ferrous iron (FeO).....	....	....	3.40	0.30	2.46	....	....	....
5. Sulfur trioxid (SO_3)......	....	....	0.28	0.07	0.65	0.05	....	....
6. Phosphoric acid (P_2O_5).	....	....	0.26	0.08	0.17	0.04	3.04	2.54
7. Lime (CaO)..	6.12	6.13	4.79	5.52	3.12	42.61	44.79	3.91
8. Carbon dioxid (CO_2)	....	....	0.52	5.04	2.64	41.58	34.10	....
9. Magnesia (MgO).....	22.58	9.52	4.06	1.17	2.45	7.90	0.30	0.26
10. Soda (Na_2O) .	0.11	0.20	3.39	0.45	1.31	0.05	0.16	0.61
11. Potash (K_2O).	0.19	0.18	2.93	1.32	3.25	0.33	0.35	0.96
12. Ignition [water (H_2O)] .	6.52	9.21	1.86	1.64	5.02	0.77	2.26	10.76
					MnO	0.05	4.33	14.98

as given by Merrill, is shown in Table II, numbers I to VIII. Numbers I and II represent a gray foliated granite from the District of Columbia, the soil of which is very sandy. By reference to Column II of Table III,

TABLE III.—PERCENTAGE OF LOSS IN TRANSITION OF ROCKS FROM ONE FORM TO ANOTHER AND TO SOIL MATERIAL. COMPLETE ANALYSES

	Residual sand from granite. District of Columbia		Residual clay from gneiss. Albemarle Co., Va.		Residual clay from diabase. Venezuela		Residual soil from Basalt. France		Residual soil from soapstone. Albemarle Co., Va.	
	I	II	III	IV	V	VI	VII	VIII	IX	X
	Per cent loss of each constituent	Per cent loss for entire rock	Per cent loss of each constituent	Per cent loss for entire rock	Per cent loss of each constituent	Per cent loss for entire rock	Per cent loss of each constituent	Per cent loss for entire rock	Per cent loss of each constituent	Per cent loss for entire rock
1. Silica (SiO_2)	14.89	10.50	52.45	31.90	42.40	20.92	65.56	30.34	43.58	16.92
2. Alumina (Al_2O_3)	3.23	0.46	....	....	21.30	3.27	....	....	....	....
3. Ferric iron (Fe_2O_3)	....	....	14.35	1.30	....	....	88.84	16.64	41.48	5.33
4. Ferrous iron (FeO)	....	....	....	....	....	....	....	....	....	....
5. Sulfur trioxid (SO_3)	....	....	....	....	....	....	....	....	....	....
6. Phosphoric acid (P_2O_5)	40.00	0.04	gain	gain	....	....	....	....	....	....
7. Lime (CaO)	25.21	0.81	100.00	4.44	83.23	8.05	47.24	3.46	44.45	2.66
8. Carbon dioxid (CO_2)	....	....	....	....	....	....	....	....	....	....
9. Magnesia (MgO.)	1.49	0.36	74.70	0.80	61.37	5.12	96.38	6.77	76.19	17.20
10. Soda (Na_2O)	28.62	0.77	95.03	2.68	95.37	1.82	74.41	1.40	....	....
11. Potash (K_2O)	31.98	0.85	83.52	3.55	45.88	0.33	83.24	1.51	47.05	9.03
12. Ignition [water (H_2O)]	*	*2.16	*	*	*	*	*	*	20.26	1.32
Total loss		13.47		44.67		39.51		60.12		52.46

* Gain.

TABLE III, continued.—PERCENTAGE OF LOSS IN TRANSITION OF ROCKS FROM ONE FORM TO ANOTHER AND TO SOIL MATERIAL. COMPLETE ANALYSES

	Residual soil from limestone. Arkansas		Residual soil from slate. Maryland		Average loss in transition from igenous rocks to shales, based on composite analyses		Average loss in transition from igneous rocks to sandstone, based on composite analyses	
	XI	XII	XIII	XIV	XV	XVI	XVII	XVIII
	Per cent loss of each constituent	Per cent loss for entire rock	Per cent loss of each constituent	Per cent loss for entire rock	Per cent of loss each constituent	Per cent loss for entire rock	Per cent loss of each constituent	Per cent loss for entire rock
1. Silica (SiO_2)	....	....	57.57	25.34	37.56	22.49	....	....
2. Alumina (Al_2O_3)	11.35	0.35	....	....	34.09	5.12	75.80	11.38
3. Ferric iron (Fe_2O_3)	89.56	2.13	8.78	1.23	....	....	68.20	1.76
4. Ferrous iron (FeO)	....	....	....	....	53.83	1.83	67.65	3.17
5. Sulfur trioxid ($S\ O_3$)	....	....	....	....	1.50*	0.13*	96.43	0.27
6. Phosphoric acid (P_2O_5)	89.76	2.73	....	....	61.58	0.16	76.54	0.199
7. Lime (CaO)	98.93	44.32	100.00	0.48	58.25	2.79	12.11	0.58
8. Carbon dioxid (CO_2)	100.00	34.10	....	....	225.00*	1.17*	636.15*	3.31*
9. Magnesia ($Mg.O$)	89.38	6.25	28.16	0.08	61.34	2.49	80.00	3.25
10. Soda (Na_2O)	53.26	0.085	99.64	0.33	75.22	2.55	90.00	3.05
11. Potash (K_2O)	66.37	0.23	77.95	3.39	29.30	0.86	65.87	1.93
12. Ignition [water (H_2O)]	41.63	0.95	....	....	72.60*	1.35*	32.26	0.60
13. Manganese dioxid (MnO_2)	57.59	2.49	....	....	....	....	....	....
Total loss		97.64		40.83		35.94		22.89

* Gain.

it will be seen that the total loss from the rock is 13.47 per cent. Column III of Table III represents a gneiss from Albemarle county, Virginia, under almost the same climatic conditions as the granite. But the soil is a red clay of the Cecil series, and represents a loss in transition from the rock of 44.67 per cent, or three and one-half times as much as from the granite. The composition of the two rocks is not greatly different. The differences in the two soils illustrate the two types of rock-decay. The granite soil, which is very sandy, probably does not represent the same advanced stage of decay as the gneiss soil, and apparently has been subjected most largely to disintegration, or physical breakdown. On the other hand, the gneiss soil represents both the disintegration and an advanced stage of chemical change or decomposition.

In general, the productiveness of a soil depends even more on its physical characteristics than on its chemical composition. The physical characteristics of a residual soil depend quite as much on the stage and type of decay to which it has been subject as to its chemical composition. Mechanical processes, such as abrasion and fracture due to impact, temperature changes and frost, never produce the same fine texture which may result from chemical processes, and therefore such material is usually very sandy. A sand composed of aluminum silicate minerals in large proportion is increasingly subject to chemical decay, which will reduce it to a gritty clay of progressive coarseness from the surface downward. These principles may be summed up in the statement that the characteristics of a soil are determined by two factors: (1) The original chemical and physical composition of the rock. (2) The relative prominence of physical and chemical processes in its formation. These facts make possible the existence of a full series of soil from any group of rocks.

The composition of other rocks and soils than those mentioned above are shown in Columns V to X of Table II. For comparative purposes, Column XI is also of great interest, as showing the average composition of over 700 bulk analyses of igneous rocks as given by Clark. This gives some idea of the relative abundance of the several plant-food constituents in the rocks. It will be noted that the least abundant elements, sulfur and phosphorus, are present in amounts of several thousand pounds per acre foot.

Columns XII, XIII and XIV give the analysis of a composite of many samples of sandstone, shales and limestones. The first two may be considered as ancient soils, and their average composition of the mineral elements should be much the same as modern soils of the same origin.

Columns XIV to XVI give the composition of limestones, and of a residual soil from such a rock in Arkansas. From a comparison of the first two columns, it will be found that the rock from which the soil is derived is far from the average, especially in the amounts of manganese and phosphorus it carries. A study of the soil analysis also shows that, while it is derived from a lime rock, it is not rich in lime, a condition not uncommon.

Turning now to Table III, there is given the proportion of loss of the different elements calculated to the amount of the element originally present, and to the proportion the loss bears to the original rock. This exhibits some of the reasons for the difference between many soils and the rocks from which they were derived. Assuming that there is any element which is constant in amount, these figures show that the total loss suffered by different rocks ranges from 97.64 per cent for the limestone to 13.47 for the granite. In other words, a limestone soil represents the supplementary materials in the original rock, the main constituent having been

FIG. 13. Residual soil from limestone. Showing relation to underlying rock

removed. In this particular sample, 100 feet of rock would produce only 2.34 feet of soil. It is not uncommon in limestone soil regions, as Kentucky, Tennessee and the Ozark region, to find soils forty and more feet in depth, and, since the average limestone contains nearly 90 per cent of carbonate, these deep layers of soil must represent some hundreds of feet of rock. This is the result almost entirely of solution by carbonated waters, which gradually develop crevices and caverns in the rock.

Other types of rock, however, do not suffer such a large amount of loss. The loss, of course, varies with the character of the processes which are at work, as has been pointed out in the case of granite and gneiss. In Columns V and VI, a clay from diabase rock suffered a loss of 39.51 per cent, and a basalt soil in France represented a loss of over 60 per cent. The latter are much more basic than the granite or gneiss, and would therefore be more amenable to chemical decay. The soapstone, which results from the alteration of pyroxinite rock, undergoes a loss of 52 per cent in the transition to soil. In Columns XV to XVIII are given the calculated loss in changing from the average analysis of igneous rocks to shale and sandstone respectively. As was stated above, these latter are ancient soil material, or potential soil material, and the figures given represent an attempt to determine the average change which takes place in the derivation of a shale or sandstone (corresponding to clay or sand soil) from igneous rocks. These calculations are, of course, less accurate than the previous figures on such loss, because these rocks have been subject to mechanical sorting by wind and water, in addition to the fact that no single element has come through without loss.

The figures in the first column of each pair show the proportionate loss of each constituent. The second column shows what would be expected, viz., that the elements present in largest amount would be subject to the largest total loss. But the first column shows that certain elements are more weak chemically than others. These elements are lime, magnesium and the alkalies. While the figures are limited, still phosphoric acid appears to be subject to a large loss. There is almost invariably the assumption of water, and frequently of carbon dioxid, indicating alterations in chemical combinations which, while freeing some elements, may render others more resistant.

The striking change in the physical properties of a residual soil from the parent rock depends in part upon this unequal loss of elements. As a rule, unweathered residual soils are highly colored, usually red or yellow. This results from the accumulation and alteration of the iron. Hence, a gray limestone will produce a dark red clay. Other properties, as the texture, result in the same way. Any very refractory material, as chert in limestone or quartz in igneous or secondary rocks, is likely to persist and remain scattered through the soil. The cherty hills of Tennessee and the Ozarks are examples of the former, and the topography of the country is largely determined by the accumulation of this material. Some of the stony soils of the Piedmont regions are examples of the second type of soils. The occurrences of these refractory materials in layers may exercise a very unfavorable effect on the agricultural value of such land.

Further, residual soils are seldom uniform in texture. The clays are usually gritty, especially when derived from igneous rocks. It has been suggested that this is due to the accumulation of silica set free from the silicic minerals in their loss of alkaline materials. In this state much of it passes into solution and is removed, which probably explains some of the large losses of this element. But, where the decay is rapid, not all of the silica can be so removed, and it combines with oxygen, to form quartz particles.

All of these considerations should be kept in mind in the study of residual soils, as they assist in understanding their characteristics.

13. Cumulose soils. — Cumulose soils consist of years and even centuries of accumulations of plant remains. They occur in every section of the country in areas of from a fraction of an acre to thousands of acres, known as peat bogs and muck swamps. The one condition which always accompanies these deposits, and is most largely responsible for their existence, is poor drainage. Such a condition may result from a variety of circumstances. In the North Central states of the glacial section, scattered over the undulating country, are numerous small depressions where water accumulates during much of the year, together with a small amount of sediment from the surrounding hills. These conditions favor the large growth of vegetation which, upon its death, is slowly

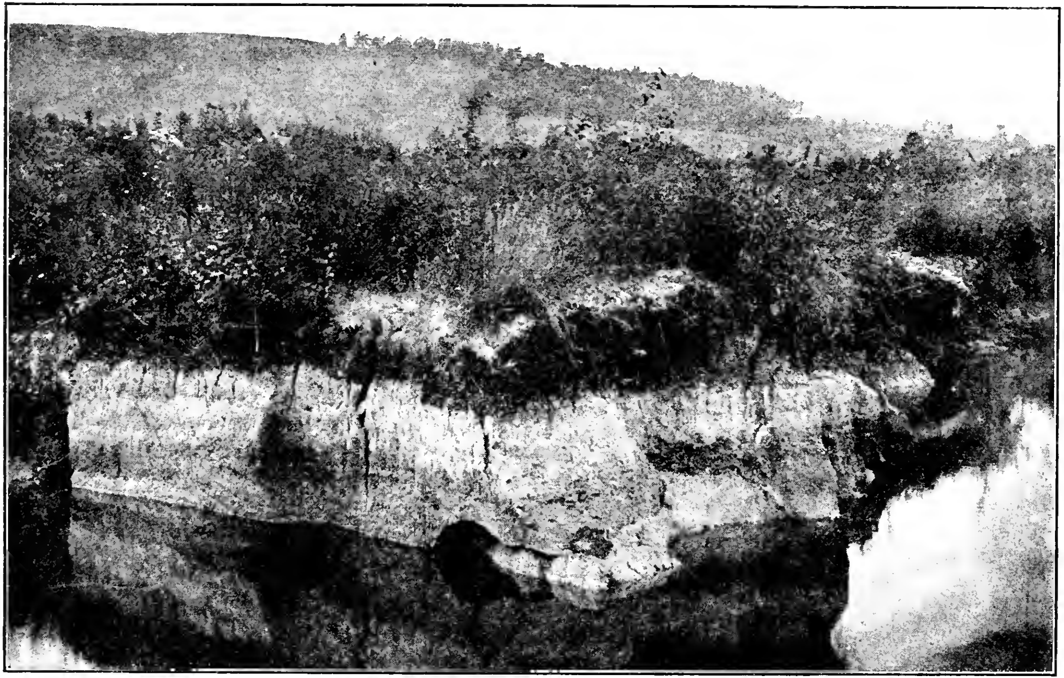

FIG. 14. Deposit of marl ($CaCO_3$) under muck. The dark surface layer consists of muck soil. The marl beneath is six feet in depth. These deposits vary greatly in thickness and purity. Those containing 70 per cent or more of lime carbonate may be used for agricultural purposes.

accumulated on the bottom of the depression. The dead remains are kept saturated with water, which excludes the air and keeps down the temperature, and otherwise hinders decay, so that the annual additions exceed the annual loss by decay. Hence, an accumulation of vegetable remains is inevitable. This is the genesis of hundreds of the mucky marshes throughout the country. Old abandoned stream channels are a common beginning of such accumulations. Very similar in origin are muck and peat beds, which were formerly deep lakes. A peculiarity of fresh water deposits of this sort are beds of marl, or impure lime carbonate, beneath the vegetable matter.

A slightly different type of these deposits are the seacoast swamps from Massachusetts to Texas, many of which are of large extent. These have formed in brackish water

The chemical composition typical of many of the cumulose deposits is shown in the accompanying table. The physical and chemical properties of such soil will be more fully discussed under the head of physical properties of organic soils.

Cumulose deposits are characterized chemically by their large percentage of carbonaceous matter. If the vegetation suffered no decay and received no mineral matter, it would be simply a mass of plant tissue; but, as has been stated, there is every degree of "wash" mixed with the dead plants. These also have accumulated to all depths from almost nothing to many feet in thickness. Many areas of soil, such as Miami black clay and the Clyde soils of the northern states, and the

TABLE IV

CHEMICAL COMPOSITION OF CUMULOSE DEPOSITS

	I	II	III	IV	V	VI	VII
	Snyder Bulletin 40, Minn.	Florida Bulletin 14, Average 8 samples	Merrill, p. 315. Swamp North River Carteret Co., N. Carolina		Illinois Bulletin 123		
			Margin oak fringe	Center of swamp	Deep peat 0–7 in.	Peat 7–20 in.	Deep peat 7–40 in.
1. Moisture	....	49.00	2.50	9.60	....	....	....
2. Volatile matter	71.80	....	....	....	84.72	86.70	78.52
3. Organic matter	....	30.00	7.70	87.25	42.36	43.35	39.62
4. Insoluble matter	18.47	17.00	....	....	....	....	....
5. Soluble silica (SiO_2)	....	....	3.70	....	....	....	....
6. Insoluble silica (SiO_2.	....	....	80.84	1.52	....	....	....
7. Ash	....	20.00	....	....	....	....	....
8. Iron oxide (Fe_2O_3)	2.60	....	1.18	0.15	....	....	....
9. Alumnia (Al_2O_3)	1.38	....	2.69	0.39	....	....	....
10. Lime (CaO)	0.51	....	0.44	0.36	....	....	....
11. Carbon dioxid (CO_2)	1.77	....	....	....	....	....	....
12. Magnesia (MgO)	0.10	....	0.22	0.14	....	....	....
13. Soda (Na_2O)	0.20	....	0.02	0.13	....	....	....
14. Potash (K_2O)	0.32	0.14	0.07	0.06	0.318	0.36	0.366
15. Phosphoric acid P_2O_5	0.32	0.10	0.08	0.06	0.196	0.15	0.12
16. Nitrogen (N)	0.62	1.11	....	....	3.48	3.36	3.14
17. Sulphuric acid (SO_3)	1.06	....	0.06	....	....	....	....

Portsmouth and other soils of the southern states, represent the very first stages in the formulation of such cumulose deposits. That is, they are simply mineral soils with a high content of organic matter.

14. Transported soils.—The four great agencies of soil-transportation are (1) water, (2) ice, (3) wind, and

(4) gravity. It will be remembered that each of these agencies was mentioned as active in soil-formation through the physical and chemical forces brought to bear on rocks. The material is moved from its original position and laid down under new conditions which develop properties entirely different from those possessed by sedentary soils.

Of the four groups, those soils transported by water are easily the most extensive, and next to these in area stand those moved by glacial action. Wind-moved soils are of much importance in some sections, but gravity-moved soils are of small extent.

15. Gravity or colluvial soils.—In mountainous or hilly regions, soil material of all dimensions is moved down the slope under the pull of gravity. In those sections of the country where stone fences are common, the accumulation of soil on the uphill side of the fence, due to gravity movement, not infrequently reach the top of the wall. Because of its associations with a hill (Collis meaning hill), such material is termed colluvial. The first footings of soil in the niches and at the base of a rocky ledge are usually of this sort, and in mountain regions the accumulation of such material is sometimes large.

16. Water.—It has been shown how water is able to transport sand and even boulders several times heavier than itself, if it be flowing with a sufficient velocity. (See page 24.) This large transporting power may be observed in any creek or rivulet, and in every hilly region it is brought forcibly to the farmer's notice in the gullies formed by heavy rains. The bed of every stream is strewn with material which has been dropped by the water. If the bed of the stream is steep, it is paved almost entirely with large stones and boulders. If the bed is very flat and the flow slow, the bottom is formed by sand or silt. These variations are well illustrated by the ripples and quiet pools of almost any stream, the former being stony, the latter more fine-textured. This principle of the varying carrying power of flowing water is of great agricultural importance. It results in sorting the material which comes into the water, and the particles of one size are deposited together. In this way is accumulated a fine pure clay in one place, a sand at another place, and gravel at still another. These formations are strikingly different in their relations to plant-growth because of their different physical and chemical properties, as will be shown in the further discussion of these matters.

The character of such soil depends upon two factors: (1) The character of the rocks from which it is derived. (2) The conditions under which it is deposited.

The soils of this group are by far the most important, agriculturally, of any which will be discussed, on account of both their relative area and crop relations. In a general way, they may be divided into three sub-groups; but it is impossible to draw any sharp line of distinction between these groups. These are: (1) Marine soils. (2) Lake and pond deposits, or lacustrine soils. (3) Stream-laid, or alluvial soils.

17. Marine soils.—The marine soils occupy large areas in the United States and many other countries. They consist of stratified gravels, sands, silts and clays deposited in shallow off-shore water, and subsequently raised above sea-level, where they have been subject to erosion by the present drainage channels, so that they are furrowed by a ramifying system of shallow, steep-sided gorges. These channels reveal the different sorts of material from coarse to fine, and have exposed each of them over considerable areas. The material has not been deposited long enough or buried deep enough to be much consolidated, although there are very soft shales and limestones in the Gulf states which are only partially consolidated.

18. Lacustrine soils.—Closely related to the marine soils are soils deposited in lakes, such as those fringing the Great Lakes. These lacustrine soils differ from the former in the different source of their material and somewhat different conditions of deposition. Most of them are fresh-water bodies, but in some instances, as Great Salt Lake, they are brackish. It is impossible to draw any definite line of distinction between these two sub-groups of soils further than in the extent and character of the waters in which they were deposited, and for a specific understanding of their characteristics the respective types must be studied in detail.

19. Alluvial soils.—Along every stream course is a ribbon of material formed by the deposition from the water of that stream at either normal or flood time. Along the steep-bedded streams it is very narrow and usually coarse, often with a base of stone covered by a veneer of fine material. As the course becomes less steep, it widens and is more meandering. The stream swings from side to side of its valley in large sweeping curves, which become actually tortuous in very flat bottoms. Such a crooked channel is much reduced in capacity over a straight channel, and therefore in flood season the water is piled up over the bank and overflows the adjacent land. When the water passes from the deep channel, its velocity is checked, and some of the material—the coarsest—is deposited on the bank. The finer material is carried further out. If there is a general movement over the whole bottom the very finest material may not be deposited, and con-

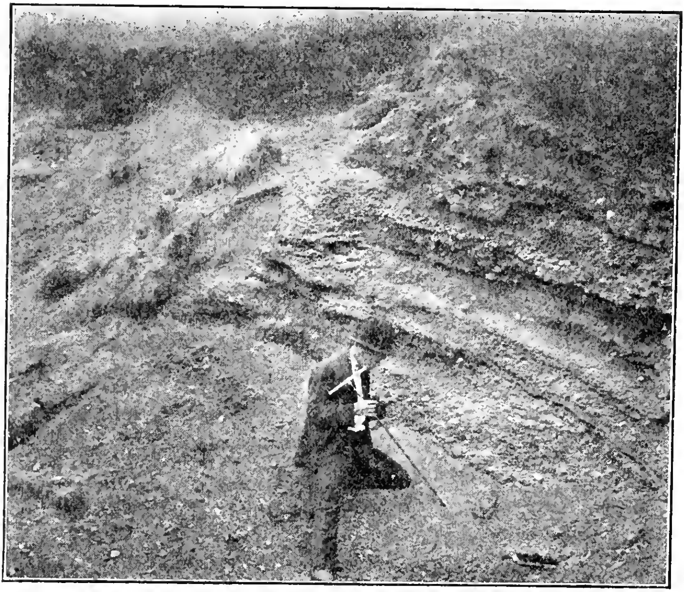

Fig. 15. Shows the stratified arrangement of a gravelly soil

TABLE V

CHEMICAL COMPOSITION OF SOILS DEPOSITED BY WATER. COMPLETE ANALYSES

COASTAL PLAIN SOILS OF MARYLAND

	I	II	III	IV	V
	Light sandy loam. Truck soil. Columbia formation. Maryland. Average of five samples.	Heavy, fine sandy loam. Tobacco soil. Chesapeake formation. Maryland. Average of four samples.	Clay loam. Corn and wheat soil. Columbia formation. Maryland. Average of three samples.	Clay. Very low productivity. Potomac formation. Maryland. Average of three samples.	Sand, "Pine Barrens." Lafayette formation. Maryland.
1. Insoluble	....	....	....	....	....
2. Silica (SiO_2)	92.30	83.86	80.55	64.26	94.32
3. Alumina (Al_2O_3)	3.20	6.10	8.82	19.92	2.66
4. Ferric iron (Fe_2O_3)	0.91	2.63	2.67	5.74	1.25
5. Ferrous iron (FeO)	....	....	....	....	....
6. Sulfur trioxid (SO_3)	0.08	0.12	0.07	0.09	....
7. Phosphoric acid (P_2O_5)	0.05	0.23	0.42	0.16	0.02
8. Lime (CaO)	0.41	0.50	0.47	0.44	0.04
9. Carbon dioxid (CO_2)	0.08	0.06	0.05	0.15	....
10. Magnesia (MgO)	0.35	0.45	0.29	0.59	0.07
11. Soda (Na_2O)	0.50	0.56	0.49	0.58	0.11
12. Potash (K_2O)	0.70	0.92	1.22	1.50	0.12
13. Water	0.23	1.30	1.28	0.75	....
14. Organic matter	....	....	....	....	....
15. Volatile matter	1.13	3.00	3.26	6.58	1.21

sequently the accumulated soil is a fine, friable loam rather than a clay. Heavy alluvial clay is seldom found outside the larger river bottoms and generally in depressions remote from the channel.

Another source of heavy soil is ponds formed by the cutting off of bends in the channel. These "ox-bow

TABLE V, continued

CHEMICAL COMPOSITION OF SOILS DEPOSITED BY WATER. COMPLETE ANALYSES

BRICK CLAYS OF SOUTHERN PLAIN

	VI	VII	VIII	IX	X	XI
	Brick clay. Columbia formation. North Carolina	Brick clay. Pleistocene formation. North Carolina	Sandy brick clay. Pleistocene formation Taylor Co., Texas.	Brick clay. Pleistocene formation. Harris Co., Texas.	Sandy loam, pine woods, Mississippi	Sandy loam. First-class pine. Florida
1. Insoluble	....	....	....	+ silica	93.23	94.46
2. Silica (SiO_2)	53.75	70.45	90.00	44.40	sol.	1.67
3. Alumina (Al_2O_3)	24.91	17.34	4.60	17.90	2.36	0.92
4. Ferric iron (Fe_2O_3)	7.99	3.16	1.44	4.50	1.25	0.32
5. Ferrous iron (FeO)	....	....	....	....	....	....
6. Sulfur trioxid (SO_3)	....	....	....	....	....	0.09
7. Phosphoric acid (P_2O_5)	....	....	....	....	0.03	0.11
8. Lime (CaO)	0.70	0.25	0.10	9.50	0.12	0.07
9. Carbon dioxid CO_2	....	....	....	9.55	0.02	....
10. Magnesia (MgO)	1.12	0.22	0.10	1.88	0.18	0.04
11. Soda (Na_2O)	2.94	0.70	t	....	0.07	0.04
12. Potash (K_2O)			t	t	0.26	0.19
13. Water	1.03	0.98	3.04	4.58	....	....
14. Organic matter	....	....	....	....	....	....
15. Volatile matter	....	6.63	....	....	2.33	1.88

bends," "cut-offs," or "bayous," as they are variously termed, become in succession lakes, ponds and marshes, where the clay-laden water is gradually evaporated or filtered away, leaving behind only the very fine material that may be carried in suspension almost indefinitely. As a result of these processes much of the

TABLE V, continued

CHEMICAL COMPOSITION OF SOILS DEPOSITED BY WATER.
COMPLETE ANALYSES

GLACIAL AND WESTERN SOILS

	XII	XIII	XIV	XV	XVI
	Lacustrine clay, Albany, New York	Adobe, Santa Fe, New Mexico	Adobe, Salt Lake City, Utah	Leda Clay, Lake material, St. Lawrence Valley	Clay. Lake material, Shore Lake Michigan, Milwaukee, Wisconsin.
1. Insoluble	....	....	....	....	....
2. Silica (SiO_2)	55.60	66.69	19.24	56.17	40.22
3. Alumina (Al_2O_3)	14.80	14.16	3.26	24.25	8.47
4. Ferric iron (Fe_2O_3)	5.80	4.38	1.09	....	2.83
5. Ferrous iron (FeO)	....	....	....	3.54	0.48
6. Sulfur trioxid (SO_3)	....	41	0.53	....	0.13
7. Phosphoric acid (P_2O_5)	0.15	0.29	0.23	....	0.05
8. Lime (CaO)	5.70	2.49	38.94	2.09	15.65
9. Carbon dioxid (CO_2)	4.94	0.77	29.57	....	18.76
10. Magnesia (MgO)	2.48	1.28	2.75	2.57	7.80
11. Soda (Na_2O)	1.07	0.67	*t*	2.25	0.84
12. Potash (K_2O)	3.23	1.21	*t*	4.06	2.36
13. Water	5.18	4.84	1.67	4.69	1.95
14. Organic matter	....	2.00	2.96	....	0.32
15. Volatile matter	....	....	....	....	....

soil formed in stream bottoms is friable and easily tilled, but they also give rise to some of the heaviest and most intractable clay soil known. Soils of this sub-group may be either very uniform or exceedingly variable in fineness. It is evident from what has been said that, the smaller the stream, the more variable the soil is likely to

TABLE V, continued

CHEMICAL COMPOSITION OF SOILS DEPOSITED BY WATER.

STRONG HYDROCHLORIC ACID ANALYSES.

	XVII	XVIII	XIX	XX	XXI	XXII	XXIII
	Silt loam, Brazos river, Texas	Black wax clay, Bell Co., Texas	Sandy loam, Bell Co., Texas	Sandy loam, Rush valley, Texas	Virgin. First bottom. Oklahoma	First bottom. Subsoil of XXI. Oklahoma	Second bottom. Station farm. Oklahoma
1. Insoluble	70.92	44.23	77.05	83.22	84.97	81.77	79.99
2. Silica (SiO_2)	....	....	....	....	*5.65	7.68	7.76
3. Alumina (Al_2O_3)	5.58	1.58	4.91	2.11	1.42	3.33	2.78
4. Ferric iron (Fe_2O_3)	3.62		2.66	5.82	2.71	3.07	3.40
5. Ferrous iron (FeO)	....	....	....	....	....	....	....
6. Sulfur trioxid (SO_3)	0.29	0.15	0.02	....	....	....	0.15
7. Phosphoric acid (P_2O_5	0.34	0.12	0.18	0.243	0.04	0.05	0.06
8. Lime (CaO)	5.66	23.98	1.03	0.56	0.44	0.32	0.95
9. Carbon dioxid (CO_2)	4.00	18.00	0.81	0.44	....	....	....
10. Magnesia (MgO)	1.85	0.94	0.93	1.13	0.16	0.18	0.21
11. Soda (Na_2O)	0.23	0.25	0.96	0.40	0.48	0.39	0.31
12. Potash (K_2O)	0.88	0.22	1.45	0.48	0.80	1.21	0.44
13. Water	3.26	2.42	3.56	1.32	3.69	2.18	4.10
14. Organic matter	....	....	....	....	0.62	1.54	0.51
15. Volatile matter	2.69	7.34	6.52	4.60	....	....	....

* Soluble.

be. It embraces large areas of the most productive soils. Properly drained, bottom lands are generally regarded with favor for several of the staple crops. Corn is probably the most grown. Wheat is important on the heaviest soils. They are generally rich in organic matter to an unusual depth because they represent largely the wash

Table V, continued

Chemical Composition of Soils Deposited by Water. Strong Hydrochloric Acid Analyses

	XXIV	XXV	XXVI	XXVII	XXVIII	XXIX
	Clay loam, Marshall Co., Minnesota. Red River Valley	Lake Clay. Red River Valley, Crookston, Minnesota	Gumbo clay. Red River Valley, Crookston, Minnesota.	Loam. Red River Valley. Moorehead, Minnesota	Buckshot, Clay. Yazoo bottoms, Mississippi	Silt loam, Colorado river, San Diego Co., California
1. Insoluble	41.21	39.17	60.21	45.06	51.06	58.57
2. Silica (SiO_2)	8.37	15.09	9.00	16.43	20.70	5.33
3. Alumina (Al_2O_3)	10.72	13.61	9.15	10.20	10.54	8.40
4. Ferric iron (Fe_2O_3)	3.48	3.98	3.94	4.22	5.82	4.14
5. Ferrous iron (FeO)	....	....	....	....	....	....
6. Sulfur trioxid (SO_3)	0.10	0.06	0.11	0.09	0.02	0.15
7. Phosphoric acid (P_2O_5)	0.19	0.28	0.16	0.27	0.30	0.13
8. Lime (CaO)	7.45	8.10	1.07	8.84	1.35	8.67
9. Carbon dioxid (CO_2)	14.26	13.27	0.13	7.22	....	7.82
10. Magnesia (MgO)	4.48	2.04	0.84	3.02	1.67	2.97
11. Soda (Na_2O)	0.48	0.40	0.61	0.27	0.33	0.16
12. Potash (K_2O)	0.25	0.60	0.90	0.81	1.10	1.18
13. Water	....	....	....	....	....	....
14. Organic matter	0.89	0.81	5.16	....	....	....
15. Volatile matter	6.22	3.20	14.29	2.61	7.37	3.34

from the surface layer of the upland soils, and they are not old enough to have lost this supply of organic matter by decay. Frequently, the supply is replenished by annual additions.

Table V illustrates the variations in the proportion of the different elements in water deposits of different physical properties, from different parts of the United States. Many of these analyses are less complete with reference to some of the plant-food constituents than is desirable for the purpose here intended. So far as possible, analyses of the entire soil have been used, but, where these could not be obtained, analyses of the strong hydrochloric acid extract are given.

20. Ice—glacial soils.—In many parts of the world there exist soils which have been formed under the influence of large bodies of ice.

In earlier times, masses of ice extended far to the southward over the country now devoted to agricultural purposes. Around the world this mass of ice appears to have extended down from the north and south poles to a zig-zag limit. It reached into Asia, Central Europe and the American Continent as far south as New York City, Cincinnati, St. Louis, Kansas City and Omaha, and farther west in the Puget Sound region it extended south across the Columbia river. All the country north of this line with the exception of one or two small areas was covered by an immense sheet of ice which moved slowly down from the northward. In the southern hemispheres are similar—though more limited—traces of the same condition.

The depth of the ice was so great that it flowed over such elevations as Mount Washington in New Hampshire and over the Adirondacks in New York. Its general movement in the northern hemisphere was southward. Its flow was modified by the original topography of the country, but its depth was so great it was able to disregard and override many of the land forms. It advanced first through the valleys, and at the bottom of the mass appears to have been guided in its flow by these channels. The advance probably consumed a long period of years, or even centuries, and the retreat was similarly slow. Along the margin, as in modern glaciers, there were annual fluctuations in the position of the ice front which are indicated by the greater or less accumulation of rock debris, as undulating piles of earth or terminal moraines. This ice picked up immense amounts of material along its way. Most of the original soil overlying the rocks was swept away. Prominences were torn away or planed down, and depressions were filled up. Masses of rock were ground to powder, and boulders were transported to entirely new surroundings. The advance of the ice over the country largely disregarded the rock formations, as it did topographic forms, so that the rocks and soil materials from many sources were mixed and ground together. In this way, the granite boulders strewn over the surface near the southern margin of the ice extension in the United States were derived from points hundreds of miles to the northward, even into northern Canada. The movement was not straight south, but deflected by broad obstructions in the land, so that the source of the soil in any region is determined by the direction of movement in that section. This movement may often be traced by the kind of rocks which have been left, and may lead back to the ledges from which they were derived.

The relation of glacial soils to the underlying rock depends entirely on the conditions which prevailed in that region when it was formed. In central Michigan, the soil bears scarcely any relation to the underlying rock of the region; but, in Southern New York and Northern Pennsylvania, the very shaley character of the soil may be traced to the broad area of shale rock which underlies all that section of country, and which was the main source of the glacial debris. As one passes northward through the finger-lake region of New York, the proportion of limestone and other foreign material resting on the gray shale increases until the exposures of ledge limestone are met at Syracuse and Rochester, portions of which rock had been raked far southward by the ice-movement. This shifting and mingling of material must always be kept in mind in examining glacial soils.

Purely glacial deposits differ in chemical and physical properties from soils derived from the same formations by other means. There is a large element of mechanical grinding without any large amount of chemical change or solution. The particles have not been subjected to long-continued leaching, which characterizes residual or marine soils. Such material is chiefly rock-flour, that is, pulverized rock. The readily soluble minerals and elements are therefore present in proportionately larger amounts than in soil formed by other means. While a residual soil from limestone may be very poor in lime carbonate, a glacial soil formed from lime-rock is often rich in lime, sometimes containing 50 per cent of that constituent, as has been found in some Dakota soils. As appears from the tables of analyses, such soils are generally rich in all of the basic elements.

TABLE VI

CHEMICAL COMPOSITION OF GLACIAL SOILS
HYDROCHLORIC ACID ANALYSES

	I	II	III	IV	V	VI
	Silt loam, Wooster, Ohio	Clay loam, Strongville, Ohio	Loam, Columbus, Ohio	Clay loam, Germantown, Ohio	Loam subsoil, Prairie, Western Minn.	Loam subsoil, Prairie, Southeastern Minn.
1. Insoluble	87.85	83.80	83.87	89.20	73.95	74.05
2. Silica (SiO_2)	....	....	....	....	6.85	8.46
3. Alumnia (Al_2O_3)	3.46	4.11	4.26	3.69	4.63	3.27
4. Ferric iron (Fe_2O_3)	3.30	4.72	3.63	2.26	3.05	5.44
5. Ferrous iron (FeO)	....	....	....	....	....	....
6. Sulfur trioxide (SO_3)	0.04	0.03	0.10	0.03	0.04	0.12
7. Phosphoric acid (P_2O_5)	0.11	0.09	0.15	0.12	0.26	0.16
8. Lime (CaO)	0.25	0.18	0.69	0.13	0.70	0.51
9. Carbon dioxid (CO_2)	....	....	....	....	0.36	0.09
10. Magnesia (MgO)	0.39	0.45	0.62	0.37	0.36	0.22
11. Soda (Na_2O)	0.34	0.29	0.78	0.23	0.42	0.16
12. Potash (K_2O)	0.25	0.22	0.56	0.21	0.40	0.22
13. Water	....	....	....	....	....	....
14. Organic matter	....	....	....	....	....	....
15. Volatile matter	4.09	5.92	5.64	3.86	9.12	7.29

The physical properties of glacial soils are also distinctive. Excepting subsequent modifications due to water, such deposits show little or no stratification or sorting. They are heterogeneous in material and arrangement. Much of such material is termed boulder clay, from the mixture of coarse and fine particles. It is also to be noted that such soils contain, relatively, a larger proportion of silt particles, and a smaller amount

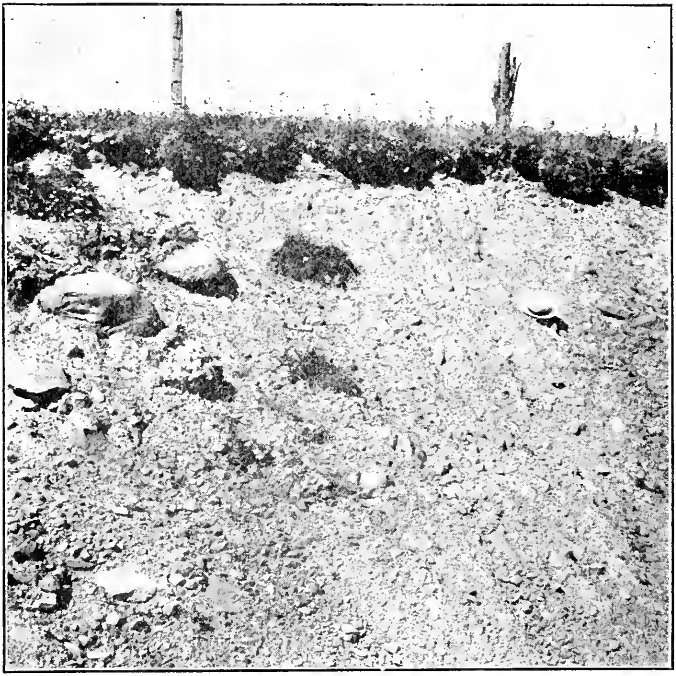

FIG 16. Section of glacial soil, showing its uneven texture and dense structure. When unmodified by water action, it usually shows no stratification

of clay, than soil formed by purely chemical process from the same rock.

Associated with the results of pure ice-action is much modified glacial till, due to the influence of great volumes of water. Naturally, the melting of the ice results in immense volumes of water, which drain away over, under, or along the ice margin. Temporary streams of large size and great violence existed and there were also ponds and lakes, some of the latter of very large extent. This water further assisted in moving the ice debris. Such deposits are called modified drift, or aqueo-glacial deposits. For this reason, they have in part been included with glacial soils. The streams, ponds and lakes associated with the ice have given rise to much stratified material, and these deposits are intimately related in many ways to the purely ice deposits. Beds of gravel, sand and clay are frequently found, and so intimate is their relation to the purely ice deposits that they are sometimes, though incorrectly, classed with them. These deposits of modified till generally rest upon the distinctly ice deposits, and are of large extent. Around the Great Lakes and in the large valleys of New York and New England, in the valley of the Red River of the North, and in many other places in the Central States, are large areas of such stratified glacial material, ranging in fineness from heavy clay to coarse gravel. These materials constitute some of the most valuable agricultural lands of the country. The Great Lakes region is notably productive, and the Red River Valley of the North is celebrated for its production of small grains.

The thickness of glacial deposits varies greatly. Pre-glacial valleys may be filled in, and the evidence of their presence completely obliterated. In general, the topographic effect of glacial action is to level the surface. However, in the New England states, where the country is very mountainous, the rocks very hard and the preglacial soil blanket meager, the present soil covering is generally thin and very stony.

Further west, where the country is less rugged and the rocks less refractory, the soil covering is of greater depth and generally less stony. In the states of the Mississippi valley, the broad, level areas of excellent agricultural soil are very largely the result of these glacial influences.

21. Wind or æolian soils.—Attention has been directed to the transporting power of wind. It is continually picking up particles, which are deposited in accord with the same general laws which govern water deposits. The material thus carried, often to great heights, is again brought to the surface by gravity. These particles are frequently accelerated in their fall by rain and snow. Every particle of fog, of rain and of snow has for its nucleus a particle of dust around which condensation began, and for this reason the atmosphere is always most clear after precipitation. Large amounts of material are, in the course of time, brought to earth in this way.

This continual deposition from the atmosphere is illustrated by the layer of dust that quickly accumulates in any unoccupied building, however tightly it may be closed.

Besides this general filtering of dust particles from the atmosphere, there is the definite drifting of soil by wind, of which sand-dunes are the most common illustration. These occur in many parts of the world. They are likely to be developed wherever dry sand is exposed to the wind.

Related to these modern wind deposits are immense areas of soil of great agricultural value, the origin of which is not clearly understood, but which appears to owe its existence, at least in part, to wind deposition. This is the so-called loess, a fine, silty soil of remarkable uniformity in physical and mineralogical composition. It covers thousands of square miles of country throughout the Mississippi valley and its tributaries, from Cincinnati to western Nebraska, and from west-central Wisconsin to southern Mississippi. It lies uncomformably over formations of many ages, as a mantle of soft earth of varying thickness. It does not extend over the whole of the region mentioned, but alternates with other formations, especially drift. It imparts to the regions on which it rests a soil character greatly different from what would exist were it absent.

Neither is it limited to the United States, for it occurs extensively in central Europe, where it extends from northern France across Belgium, and up the Rhine, Oder and Vistula valleys in Germany; and into central and southern Russia, where it is the basis of the famous "black earth," or tschernosem. In northern China, von Richtofen has described it as covering a large part of the region drained by the Hoang-Ho, where it reaches a thickness of 1,000 feet.

In thickness it varies greatly. Over much of the United States it is only a few feet in thickness, generally thinning toward the outer margin. In the central areas it may be 150 to 200 feet in thickness, and, similarly, in other countries it is of variable thickness, reaching the great depth mentioned above for China.

A striking physical character of the loess is its ability to stand for a long time in vertical cliffs, although so soft it may be easily carved with a shovel. Another character common to much of the formation is the presence of nodules and tubes formed by cementation by lime carbonate.

The loess is associated in occurrence with the margin of the glacial deposits, especially in America and Europe, and possibly in China. Just what this relation is is not known, but much of the loess seems to be a fine rock-flour of glacial origin, which has been drifted by the wind and deposited on both purely glacial deposits and on residual and water deposits, for it extends from Illinois southward over the limestone region on to the coastal plain in Mississippi.

The adobe soils of the arid regions are thought by some to be related to the loess in mode of formation. Adobe also has peculiar physical properties, later to be mentioned, but it exhibits a closer relation to water deposits with which it has been classed.

In parts of Kansas, Nebraska and other western states, are soils formed of dust from volcanic vents and deposited from the atmosphere. Such dust may be so fine as to be carried long distances and remain in suspension for a long period. Dust from the eruption of Krokatoa, in the island of Java, was wafted around the world, and gave a red glow to the sunset for a year after its discharge.

Table VII shows the chemical composition of the wind deposits, chiefly loess. Columns I and X are analyses of the hydrochloric acid solution. All others are complete analyses. Agriculturally, sand-dunes are of small value, largely because of their unfavorable

TABLE VII

CHEMICAL COMPOSITION OF LOESS SOIL. HYDROCHLORIC ACID SOLUTION

	I	II	III	IV	V	VI	VII	VIII	IX	X
	Silty fine sand, dust soils. Arid regions, Northwestern states. Average 3 samples.	Silt Loess. Vicksburg, Mississippi	Silt Loess. Dubuque, Iowa	Silt Loess. Galena, Illinois	Silt Loess. Kansas City, Missouri	Silt Loess. Denver, Colorado	Silt Loess. Cheyenne, Wyoming	Silt Loess Rhine Valley	Silt Loess. Neubod, Switzerland	Silt Loess. Lincoln, Nebraska
1. Insoluble	79.60	....	....	....	....	....	....	....	....	77.75
2. Silica (SiO_2)	....	60.69	76.68	64.61	71.46	69.27	67.10	58.97	71.09	57.97
3. Alumnia (Al_2O_3)	6.68	7.95	12.03	10.64	12.26	13.51	10.26	9.97	16.78	7 .96
4. Ferric iron (Fe_2O_3)	6.21	2.61	3.53	2.61	3.25	3.74	2.52	4.25		4.51
5. Ferrous iron (FeO)	....	0.67	0.96	0.51	0.12	1.02	0.31	....	....	....
6. Sulfur trioxid (SO_3)	0.02	0.12	0.51	0.11	0.06	....	....	....	....	trace
7. Phosphoric acid (P_2O_5)	0.16	0.13	0.23	0.06	0.09	0.45	0.11	....	0.11	0.09
8. Lime (CaO)	1.82	8.96	1.59	5.41	1.69	2.29	5.88	9.88	1.81	0.58
9. Carbon dioxid (CO_2)	....	9.63	0.39	6.31	0.49	*t*	3.67	9.33	0.80	....
10. Magnesia (MgO)	1.30	4.56	1.11	3.69	1.12	1.09	1.24	1.65	....	0.78
11. Soda (Na_2O)	0.21	1.17	1.68	1.35	1.43	1.70	1.42	1.75	1.23	0.29
12. Potash (K_2O)	0.89	1.08	2.13	2.06	1.83	3.14	2.68		1.30	1.06
13. Water	....	1.14	2.50	2.05	2.70	4.19	3.09	....	1.96	....
14. Organic matter	....	....	....	....	....	....	....	....	2.87	....
15. Volatile matter	2.60	....	....	....	....	....	....	2.31	....	6.91

physical properties. They are also likely to be highly silicious. But the loess formations are of great agricultural importance, and in this country they constitute some of the most important soil types. In some sections its value has been greatly reduced by erosion. Some of the bluff areas along the Mississippi river are thus modified, and some of the loess of China is also deeply eroded.

But the physical properties, as well as the chemical properties of loess, combine to give it in general a high agricultural value.

VI. HUMID AND ARID SOILS

In discussing the process by which soil is derived from rock, attention was directed to the fact that physical disintegration results in material having different properties from those derived through chemical decomposition, and that the relative prominence of these two processes is dependent largely on climate. Aridity is one of those phases of climate which markedly alters the balance between these two processes, giving the larger ascendancy to the physical. Soils formed under arid conditions are less fine in texture than those formed from the same rock in humid regions. A study of soils in the two regions reveals a much greater prevalence of the coarser soils—the sandy and loamy soils—in the arid region.

But chemical processes are not absent, for in every arid region there is some precipitation which is able to bring about changes in the minerals, although the products of these chemical changes are likely to accumulate in the soil because of the absence of sufficient moisture to leach them away. (See page 307.) Their presence is evidenced by incrustations on the particles either at the surface or in the mass of the soil. For this reason, the unfavorable conditions which would tend to result from the coarser grade of the material is more than offset by the large amounts of readily soluble elements present. These differences are well illustrated by the following table, compiled by Hilgard from the results of many acid analyses in the two regions. All soils derived from limestone are excluded.

TABLE VIII

CHEMICAL COMPOSITION OF ARID AND HUMID SOILS
STRONG HYDROCHLORIC ACID ANALYSES

	I	II	III
	Humid regions. Average of 696 samples	Semi-arid regions. Average of 178 samples	Arid regions. Average of 573 samples
1. Insoluble residue	84.17	75.04	69.16
2. Soluble silica (SiO_2)	4.04	8.46	6.71
3. Alumnia (Al_2O_3)	3.66	4.57	7.21
4. Ferric iron (Fe_2O_3)	3.88	2.08	5.48
5. Sulfur trioxid (SO_3)	0.05	0.02	0.06
6. Manganese (MnO_2)	0.13	....	0.11
7. Phosphoric acid (P_2O_5)	0.12	0.21	0.16
8. Lime (CaO)	0.13	0.70	1.43
9. Magnesia (MgO)	0.29	0.47	1.27
10. Soda (Na_2O)	0.14	0.32	0.35
11. Potash (K_2O)	0.21	0.33	0.67
12. Humus	1.22	3.24	1.13
13. Water and organic matter	4.40	8.55	5.15

From this table it appears that, in spite of the finer texture, the humid soils contain 15 per cent less soluble material and, as compared with the semi-arid region, 9 per cent less soluble material.

VII. RÉSUMÉ OF SCHEME OF CLASSIFICATION AND GENERAL CHARACTERISTICS OF THE GROUPS

From the foregoing discussion it appears that each group of materials may have properties which are fairly characteristic. Physically, the sedentary materials differ from the transported material chiefly in arrangement. In the transported soils those laid down by wind and water are distinctly stratified—that is, arranged in layers. This is the result of settling or sedimentation from a fluid, and such soils are frequently spoken of as sedimentary. Wind and water are the only two media in which sedimentation occurs in nature, and therefore this arrangement indicates their influence. Thereby the extent and variation of such deposits may be largely interpreted.

Upon the basis of these formative differences, it is possible not only to identify the different soil materials but to represent their extent upon maps. The broadest separations represented by sedentary and transported soils may be termed divisions. Within these divisions are sub-divisions, according to the agency or material involved. These are termed provinces, that is, meaning the region or province where a certain set of conditions prevailed. For example, in the sedentary division are residual soils from igneous rocks and from limestone rocks. These latter constitute soil groups, and, similarly, in the transported division there is the sub-division or province of soils deposited in water, and these are further sub-divided into those formed in the ocean, marine; in lakes, lacustrine, and by streams alluvial, each constituting a soil group. Within the soil group the first division is the soil series, based upon the fineness of the material, color, drainage and other properties, and each series is made up of soil types, the material in each one being practically identical in all respects. The series and type distinctions will be better understood after a consideration of the physical properties of soil. Maps of soils based upon such a classification are constructed by several countries and institutions, the most extensive being the United States department of Agriculture. These maps are constructed upon different scales, but one inch to one mile is the most common. The maps are accompanied by legends and reports, for the proper explanation of the conditions in the area reported upon.

Chemically, there is also a wide variation among soil materials in the total amount of the elements present. It might be expected that the repeated and long-continued mixing of materials from many kinds of rock would result in a very great uniformity in all soils. This is true of the number of elements present, for no important element is absent from any soil. But the amount may differ greatly. Aside from organic soils (cumulose), the most striking differences occur in sand soils. While the average analyses of many sandstones and sand soils reveals a fair amount of all elements, there are materials composed almost entirely of the refractory mineral quartz. Such, for example, is the barren LaFayette sand of Maryland, which contains 94.4 per cent of silica, and a sandstone occurring in Utah contains 96.6 per cent of silica. Doubtless, dune sands as rich in quartz might be found. Not all silica is in the form of quartz, but it is an indication of the latter.

Fine-textured soils also exhibit much variation, but do not go nearly to the extreme in silica content shown by sand soils.

It is the very exceptional soil of any grade of fineness which does not contain, in its ultimate analysis, a fair amount of all of the essential mineral plant-food elements. Other conditions must also be taken into account in determining the crop value of such soil—its physical properties, the climate, the crop, the introduction of new materials by wind, the movements of water and the action of plants and animals.

2. THE SOIL MASS. PHYSICAL PROPERTIES OF THE SOIL AND THEIR MODIFICATION

The term soil is used to designate that superficial portion of the earth's surface in which plant roots distribute themselves. This includes sand, gravel and boulders, containing practically no available plant-food material, as well as rich garden soil.

22. Soil and subsoil.—A common and natural distinction is made of (*a*) the top soil, which is called "soil," and which usually extends to the depth of the furrow slice or a little deeper. It is characterized by being darker in color, and more friable and porous than (*b*) the subsoil, which constitutes the material beneath the soil in which plant roots are found. (See Fig. 13.) A distinction is sometimes made between the upper and the lower subsoil, the former being the layer of subsoil lying between the top soil and a depth of twenty-four inches from the surface, the remainder of the section being the lower subsoil.

In humid regions the subsoil is usually less productive than in arid regions, owing to the greater amount of leaching, and to deficient aëration consequent on the movement of large quantities of water through the subsoil. Plowing up the subsoil in the humid region frequently results in a decreased productiveness, while in an arid region the soil and subsoil may be freely mixed without injury, and good crops may be grown even where the top soil has been entirely removed, as is sometimes done in preparing land for irrigation.

The soil substance may be conveniently divided into two groups of constituents which exhibit quite different properties. These are the inorganic and the organic.

I. INORGANIC CONSTITUENTS

The inorganic constituents of the soil are more or less modified particles of rock, varying in size from boulders and coarse sand to the finest dust. Each particle may consist of several minerals, but in those smaller than coarse sand it is unusual to find them composed of more than one mineral.

23. Texture.—The size of the individual particles in a soil is a large determining factor in all of its properties. The term texture is used to refer to the size of the individual particles of which a soil is composed.

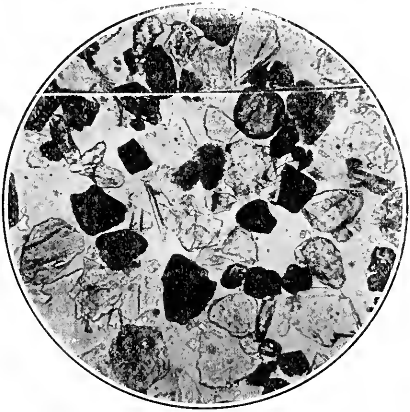

FIG. 17. Fine sand, photomicrograph. Magnified about 110 diameters. Differences in color indicate differences in mineral composition. Each particle composed of one mineral.

In shape the particles are very irregular. Being minerals or mineral aggregates, they tend to have the characteristic lines and faces of their species. Ordinarily, however, the numerous forces that have been at work in the formation of the soil have rounded or broken the mineral into angular, jagged or partially smoothed fragments. The relative number of particles of corresponding sizes varies greatly in different soils, some being composed largely of coarse particles while others are made up largely of fine ones. The relative proportion of these various-sized particles influences greatly the physical properties of the soil.

24. Textural classification.—When a soil is divided into groups of particles of approximately one size, the process constitutes a mechanical analysis and each group is a soil separate. The limit in size of each of these groups is arbitrarily arranged, and is determined by the relative value of the different sizes in determining the properties of the soil and its crop-producing power. It is found that the fine groups exert relatively much more influence, weight for weight, than the coarse ones. Therefore there are more divisions made among the fine than among the coarse particles.

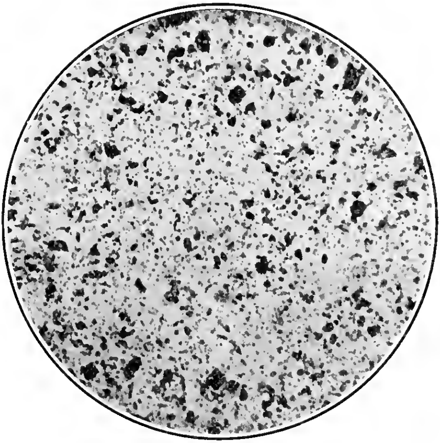

FIG. 18. Silt soil, photomicrograph. Magnified about 110 diameters. Stained so that differences in mineral composition are not so distinguishable as in Fig. 17. The particles have the same characteristics as those of fine sand. Some of the smallest particles are of the size of clay.

25. Textural groups. — A number of systems of grouping have been devised. The limits of these groups have been determined by the method of analysis used by the investigator and by his judgment of the relative agricultural importance of each group. A further element which limits the number of groups is the practicability of recognizing distinctions in the field based upon them. The following table, from Bulletin 24 of the United States Bureau of Soils, exhibits the most generally known of these systems of grouping employed in mechanical analysis. Some of these multiply groups in the small particles, while others give prominence to the sand particles.

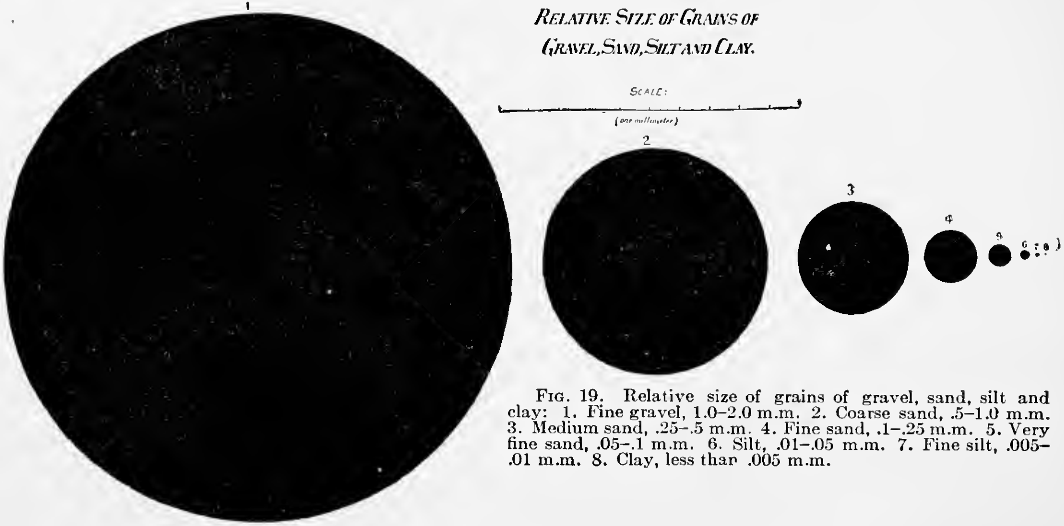

Fig. 19. Relative size of grains of gravel, sand, silt and clay: 1. Fine gravel, 1.0–2.0 m.m. 2. Coarse sand, .5–1.0 m.m. 3. Medium sand, .25–.5 m.m. 4. Fine sand, .1–.25 m.m. 5. Very fine sand, .05–.1 m.m. 6. Silt, .01–.05 m.m. 7. Fine silt, .005–.01 m.m. 8. Clay, less than .005 m.m.

Table VIII *a*

Number of group	Hilgard m.m.	Osborne m.m.	U. S. Bureau of Soils m.m.	Hopkins m.m.
1	3.000	3.00	2.000	1.0000
2.	1.000	1.00	1.000	0.3200
3.	0.500	0.50	0.500	0.1000
4.	0.300	0.25	0.250	0.0320
5.	0.160	0.05	0.100	0.0100
6.	0.120	0.01	0.050	0.0032
7.	0.720	....	0.005	0.0010
8.	0.047	....	....	....
9.	0.036	....	....	....
10.	0.025	....	....	....
11.	0.016	....	....	....
12.	0.010	....	....	....
13.	....	....	....	....

Of these systems, that of the Bureau of Soils has been applied to the largest number of samples and is most widely known. The names which it applies to its different groups or separates are as follows:

1. Fine gravel	2.000–1.000 m.m.
2. Coarse sand	1.000–0.500 m.m.
3. Medium sand	0.500–0.250 m.m.
4. Fine sand	0.250–0.100 m.m.
5. Very fine sand	0.100–0.050 m.m.
6. Silt	0.050–0.005 m.m.
7. Clay	0.005–0.000 m.m.

All that material above two millimeters in diameter is classed as gravel and stone, and in any complete examination must also be taken into account. The material resulting from the above analysis is sometimes termed the fine earth, in distinction from the gravel, etc. That there are distinctions which should be made between the grades of gravel is obvious, for small pebbles constitute a very different condition from large boulders in all phases of tillage.

The relative dimensions of the particles in the groups may be illustrated graphically by the following diagram.

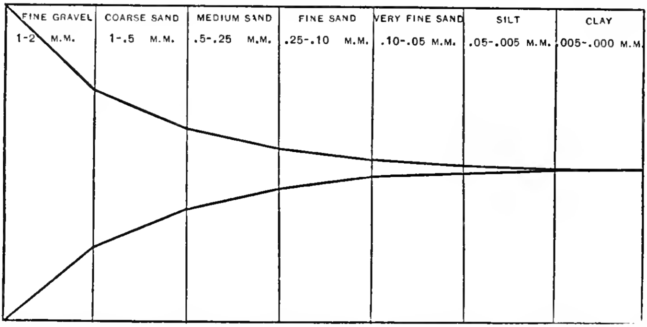

FIG. 20. Diagram illustrating the relative size of the groups of particles, made in mechanical analysis by the Bureau of Soils Classification

26. Agricultural classes based on texture. — Obviously, no natural soil is composed entirely of material like any one of these groups, but a soil may contain a large proportion of material of any one size. Thus, a sandy soil is one containing a large proportion of sand particles, and the coarser the sand or the larger its proportion the more sandy the soil appears. A clay soil is one containing a large proportion, but not necessarily a larger quantity of clay than of material of any other size. A given amount of fine particles has a larger effect on the properties of the soil than the same amount of coarse particles. The presence of silt particles in addition to clay serves to make a soil more heavy than if the same quantity of sand were substituted for the silt.

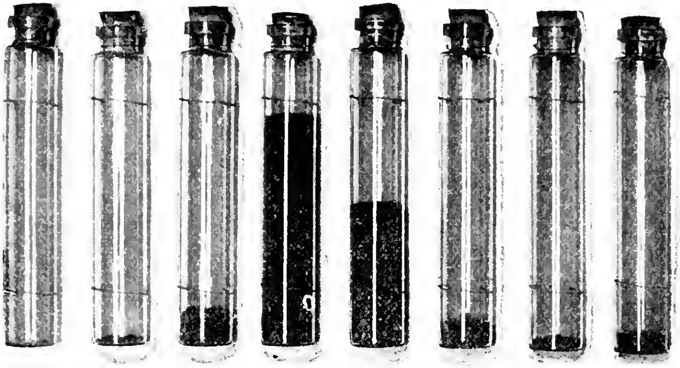

Fig. 21. Fine sand soil, showing the mechanical composition. Each vial contains the proportion of particles of given size found in the samples. Clay on the right; fine gravel on the left. For key to sizes, see Fig. 19 and page 73.

Fig. 22. Silt loam, showing the mechanical composition. For explanation, see Fig. 21

A mixture of all the groups without the preponderance of the properties of any one group constitutes a loam soil.

For purposes of a soil survey, a classification is made that permits of finer distinctions. The textures which have been recognized are given in the table opposite, together with the limits in mechanical composition which they represent. It is of course, impossible to fix all of the limits in such a classification, and therefore only certain groups are specified. This scheme has been devised by the United States Bureau of Soils in its soil-survey work.

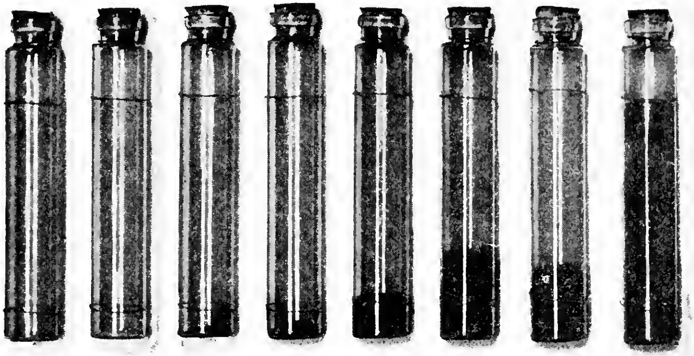

Fig. 23. Heavy clay, showing the mechanical composition. For explanation, see Fig. 21. Compare with Figs. 21, 22.

All those soils having the same general texture, although they may have been derived in a very different way, constitute a soil class. Thus there is the sandy loam class, the silt class, the clay class, etc. The following curves exhibit the average composition of several

TABLE IX

	1 Fine Gravel 2.–1. m.m.	2 Coarse Sand 1.–.5 m.m.	3 Medium Sand .5–.25 m.m.	4 Fine Sand .25 -.10 m.m.	5 Very Fine Sand .10 -.05 m.m.	6 Silt .05–.005 m.m.	7 Clay .005–0 m.m.
Coarse sand	More than 25 % (1+2)					0–15	0–10
	More than 50% (1+2+3)					Less than 20% (6+7)	
Medium sand	Less than 20% (1+2)					0–15	0–10
	More than 20% (1+2+3)					Less than 20% (6+7)	
Fine sand	Less than 20% (1+2+3)					0–15	0–10
						Less than 20% (6+7)	
Sandy loam	More than 20% (1+2+3)					10–35	5–15
						More than 20% and less than 50% (6+7)	
Fine sandy loam	Less than 20% (1+2+3)					10–35	5–15
						More than 20% and less than 50% (6+7)	
Loam							15–25
						Less than 55% (6)	
						More than 50% (6+7)	
Silt loam						More than 55% (6)	Less than 25% (7)
Clay loam						25–55	25–35
						More than 60% (6+7)	
Sandy clay						Less than 25% (6)	More than 20% (7)
						Less than 60% (6+7)	
Silt clay						More than 55% (6)	25%–35% (7)
Clay							More than 35% (7)
						More than 60% (6+7)	

classes, as they are found in the field. The field classification may not be strictly in accord with the mechanical analysis, for the reason that the same essential conditions may result from more than one mixture of groups. By experience much facility in judgment may be attained.

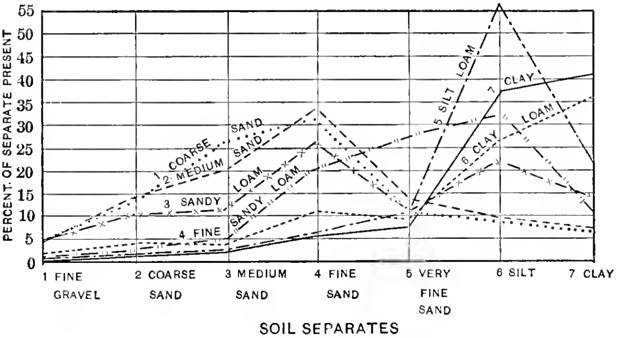

Fig. 24. Curves representing the average analysis of seven common field classes of soil

Taking the soils formed in the same general way, alluvial for example, they are found, to exhibit all gradations of fineness from clay up to the coarsest gravel and stony loams. All these classes constitute a soil series. In the same way, there may be a glacial series or even several of them, lacustrum series, residual series, etc. The river-bottom soils of the Central states are chiefly classified by the Bureau of Soils into the Wabash and Waverly series. Some of the glacial soils into Miami, Volusia, etc.; coastal plain soils into Norfolk (yellow), Orangeburg (red), etc., through all the divisions, provinces and groups.

This means that, while sandy loams or silt loams as a class are similar in texture, they may differ in many other properties of importance in plant production. A complete series is one in which all the possible classes are represented.

Some idea of the relation of these classes of soil to crops is given by the following curves. These soils are especially suited to the production of the crops with which they are associated.

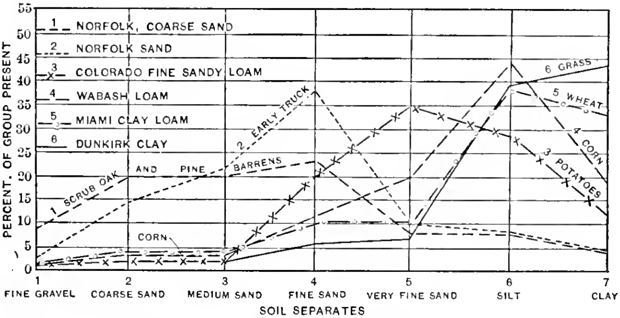

FIG. 25. Curves showing the relation of soil texture to crop adaptation

27. Some physical properties of arid and humid soils.—In discussing the formation of soils, attention was directed to the effect of climate upon the process, and it was noted that under arid conditions physical disintegration is likely to predominate over chemical decomposition, which results in an average coarser texture of the soil. This appears especially in the greater proportion of soils of the sandy and loam classes to those of the silt and clay classes.

Climate also exercises a modifying effect as between the soil and the subsoil. In humid regions, the large rainfall and consequent seepage through the soil is associated with a greater degree of fineness in the subsoil than in the soil. On the other hand, in arid regions where there is not this large rainfall, and consequent leaching, the subsoil is not finer than the soil, and, in fact, is inclined to be more coarse.

28. Some properties of soil separates and classes.—As has been indicated, the justification for a study of individual soil particles from an agricultural standpoint is in their fundamental relation to the management of the soil. Every farmer is well acquainted with the striking difference in crop relations and tillage properties of sand and clay. He well knows that they must be managed differently and are suited to different crops. He knows sand to be better suited to early maturing crops, like truck, than to late crops and the grasses. He knows that one does not withstand dry weather, while the other will carry a crop through a long period of drought. The cause traces back to the size and consequent properties of the soil units. This will appear more clearly in the discussion of soil moisture.

29. Number of particles.—Since soil particles run to very small diameters, the number in any given mass or volume is very great. This is shown in the following table, which gives the number of particles in 1 gram (1 lb. equals 453.6 gr.) of each of the fine earth separates, considering the particles to be spheres of mean diameter and of specific gravity 2.65.

If the particles of a soil are assumed to be spheres of uniform diameter and weight, the number in a given mass of soil may be calculated from the following formula:

$$N = \frac{W}{\frac{4}{3}\pi R^3 \times 2.65} = \frac{W}{\frac{\pi D^3 \times 2.65}{6}}$$

Where N = Number of particles.
W = Weight of soil used.
R = Mean radius in centimeters.
D = Mean diameter in centimeters.
$\frac{4}{3}\pi R^3$ = Volume of sphere.

For example, the mean diameter of the medium sand class is .0375 centimeters, and in 3.5 grams of this material there would be

$$N = \frac{3.5}{\frac{\pi .0375^3 \times 2.65}{6}} = \frac{3.5}{.0000737} = 47{,}500 \text{ particles}$$

From the mechanical analysis which gives the weight of each class of particles in a given amount of soil, the number of particles of each size may be calculated by use of the above formula, and the sum of the particles in each class gives the total number in the sample.

TABLE X.—NUMBER OF PARTICLES IN ONE GRAM OF PURE SOIL SEPARATE, SUPPOSING THAT ALL PARTICLES ARE SPHERICAL

	Diameter in m.m.	Number of particles in one gram
Fine gravel	2.000–1.000	252
Coarse sand	1.000–0.500	1,723
Medium sand	0.500–0.250	13,500
Fine sand	0.250–0.100	132,600
Very fine sand	0.100–0.050	1,687,000
Silt	0.050–0.005	65,100,000
Clay	0.005–0.000	45,500,000,000

Since normal field soils are mixtures in different proportions of these groups, the number of particles in unit weight of any class will be different from those shown above, and will not reach the extreme upper limits.

The number of particles in one gram of the classes of soil whose analyses are shown by the curves on page 78 is approximately as follows:

TABLE XI.—APPROXIMATE NUMBER OF PARTICLES IN ONE GRAM OF SOIL

Coarse sand	3,276,000,000
Medium sand	3,956,000,000
Sandy loam	6,485,000,000
Fine sandy loam	4,902,000,000
Silt loam	9,639,000,000
Clay loam	16,371,000,000
Clay	19,525,000,000

30. Surface area of soil particles.—The significance of these large numbers of soil particles in any mass of soil lies in their relation to the surface area of the particles. These surfaces of the particles hold on to the moisture the more, the greater their area. This large surface also increases the rate of chemical solution, by which the food constitutes contained in the mineral particles become available for the plant's use. Another important property of this immense surface area of soils is to retain food materials in a semi-available form, as will be explained in discussing the absorptive power of soils. (See page 299.)

The surface area of a fine-textured soil is greater than the first thought might indicate. This immense area exposed by soils is shown by the following table, which gives: (1) The area in square feet of one gram of the soils represented by the curves on page 78. (2) The surface area per pound of the same soil. (3) The approximate weight per cubic foot of the material in the field. (4) The approximate area of surface in one cubic foot of these soils as they occur in the field.

The surface area of the particles in a given weight of soil may be calculated from the formula.

$$S = \pi D^2 N.$$

Where S = Surface area in square centimeters.
D = Mean diameter in centimeters.
N = Number of particles in the class or separate.

Thus in the calculation on page 81 there were found to be approximately 47,500 particles in 3.5 grams of medium sand. Their surface area, provided the particles were spherical, would be:

$$S = \pi .0375^2 \times 47{,}500 = 212 \text{ sq. cm.} = 32.8 \text{ sq. in.}$$

TABLE XII.—INTERNAL SURFACE AREA OF FIELD SOILS IN SQUARE FEET (Analysis of first seven represented by curves on page 78)

	I Area per gram. Sq. ft.	II Area per pound. Sq. ft.	III Approximate weight per cubic foot. Pounds	IV Surface area per cubic foot Sq. ft.
1. Coarse sand.....	0.8900	405.0	100	40,500
2. Medium sand ...	1.0440	473.0	96	44,500
3. Sandy loam.....	1.8000	816.0	83	66,600
4. Fine sandy loam.	1.6600	756.0	82	62,000
5. Silt loam	2.9600	1,340.0	77	104,000
6. Clay loam	4.0250	1,825.0	75	136,500
7. Clay	4.4130	2,000.0	71	142,000
8. Sand hill	0.0708	32.2	110	3,540
9. Hobart clay	7.2820	3,316.0	60	200,000
	24.15			

From this table it appears that one pound of the average agricultural soil may have from about 400 square feet, in the case of coarse sand, to 2,000 square feet internal surface area, in the case of the average clay. A more reasonable basis of comparison, because of differences in volume weight, is that of one cubic foot of the material, as shown by the fourth column, from which it appears that these soils have from one to three acres of surface area. These are striking differences, particularly those between soils 8 and 9, which represent extremes in light and heavy soils, respectively. Number eight is the sand-hill soil of the Carolinas, and is of exceedingly low agricultural value. Number nine, Hobart clay, occurs in eastern North Dakota, and is derived from shale rock. The range in surface area per cubic foot of these soils is from one-twelfth of an acre, for the sand, to almost five acres for the clay. The latter contains 76 per cent of clay in the subsoil, the former 2 per cent.

31. Chemical composition of the soil separates.—There is some relation between the soil classes or separates and their chemical composition. Quartz, for example, in the original rock resists decay and comes through largely as sand particles, while the silicate minerals undergo much more decay which results in a larger proportion of clay particles, and this partial difference in derivation is reflected in the composition of the separates. The distribution of plant-food constituents and the general chemical composition of the classes of a soil is shown by the following table of results of acid analysis, obtained by Loughridge as reported by Merrill.

TABLE XIII

Conventional name	Clay	Finest silt	Fine silt	Medium silt	Coarsest silt
Per cent present in soil	21.64	23.56	12.54	13.67	13.11
Diameter of particles	.011–.000 m.m.	.005–.011 m.m.	.013–.016 m.m.	.022–.027 m.m.	.033–.038 m.m.
Constituents	Per cent	Per cent	Per cent	Per cent	Per cent
1. Insoluble residue...	15.96	73.17	87.96	94.13	96.52
2. Soluble silica (SiO_2)	33.10	9.95	4.27	2.35	....
3. Aluminum (Al_2O_3).	18.19	4.32	2.64	1.21	....
4. Ferric iron (Fe_2O_3).	18.76	4.76	2.34	1.03	....
5. Phosphoric anhydrid (P_2O_5)	0.18	0.11	0.03	0.02	....
6. Sulfur trioxid (SO_3)..........	0.06	0.02	0.03	0.03	....
7. Lime (CaO)	0.09	0.13	0.18	0.09	....
8. Magnesia (MgO) ..	1.33	0.46	0.26	0.10	....
9. Soda (Na_2O)	....	0.24	0.28	0.21	....
10. Potash (K_2O)	1.47	0.53	0.29	0.12	....
11. Volatile matter ...	9.00	5.61	1.72	0.92	....
Totals	99.84	99.30	100.00	100.21	....
Total soluble constituents	75.18	20.52	10.32	5.16	....

This table illustrates, (1) The much greater solubility of the fine particles in strong hydrochloric acid. (2) That the absolute amount of food elements dissolved is greater in the fine-textured class than in the coarse-textured class. (3) That the ratio of food elements dissolved to the aluminum and other refractory constituents dissolved is narrower in the coarse than in the fine-textured class.

Failyer's results are summarized in the following table.

Table XIV.—Partial Chemical Composition of Soil Separates. Average of a Large Number of American Soils

Number and kind of samples	I Phosphoric acid (P_2O_5)			II Lime (CaO)			III Magnesia (MgO)			IV Potash (K_2O)		
	Sand %	Silt %	Clay %	Sand %	Silt %	Clay %	Sand %	Silt %	Clay %	Sand %	Silt %	Clay %
3. Heavy residual soil, crystalline and metamorphic rocks. Eastern states....	.07	.22	.70	.50	.82	.94	.48	.86	1.33	1.60	2.37	2.86
3. Heavy residual soils, limestone. Central states............	.28	.23	.37	12.26	10.96	9.92	.61	.68	1.84	1.46	1.83	2.62
7. Medium marine soils, Coastal Plain	.03	.10	.34	.07	.19	.55	.09	.14	.61	.37	1.33	1.62
10. Glacial and loessial soils	.15	.23	.86	1.28	1.30	2.69	.54	.88	1.80	1.72	2.30	3.07
2. Arid, sandy, alluvial soils	.19	.24	.45	4.09	9.22	8.03	1.49	2.97	5.33	3.05	4.15	5.06

These figures, and those published by a number of other experimenters, clearly show the larger portion of the phosphorus, calcium, magnesium and potassium in the fine-textured classes in all kinds of soil. The absolute amount of the food elements is also greatest in the fine separates. It is shown that those soils which have undergone the greatest weathering—the coastal plain soils—are much the lowest in the food elements throughout the different classes. On the other hand, glacial soils are relatively rich in these food elements. There is also much less difference in composition between the clay and the sand particles in glacial soils, presumably because these soils have been formed largely by mechanical processes, without much weathering or leaching. The arid soils presented are not fully representative, but they illustrate the high percentages of the food elements in all the classes of particles, although the same concentration in the fine particles is apparent.

It is, therefore, concluded that clay particles are relatively richer in food elements than sand particles. But in glacial and arid soils, and to a degree in residual soils, the sand particles are much richer in food elements than they are in soils of water-deposition, such as the coastal plain.

32. Modification of soil texture.—The only feasible method of changing the texture of a soil is by adding to it material of a different texture. Thus, the greenhouse man considers the requirements of his crops, and by mixture of fine and coarse material obtains the texture which is necessary for their best development. This is entirely practicable where only a small volume of soil is involved, but under field conditions modifications of texture artificially are not practicable, because of the expense involved. The farmer must generally accept the texture of the soil as he finds it, and make the best of his conditions by suitable selection of crops adapted to his soil, and by such modifications of the structure of the soil as its texture will permit.

33. Structure.—Soil structure deals with the arrangement of the soil particles independently of their size.

34. Some aspects of soil structure.—The arrangement of the soil particles may be viewed in many different ways. Upon this arrangement depend several very important physical properties, which in turn have a fundamental bearing on chemical and biological properties.

35. Ideal arrangements.—Taking the simplest case first, that of spherical particles of one size, these may be arranged in general forms: (1) In columnar order, with each particle touching its neighbors at only four points. (2) In oblique order, with each particle touching its neighbors at six points. (3) These spheres may be gathered into larger spheres which rest together in the second order. In the first the unoccupied or pore space is 47.64 per cent of the total volume occupied by the spheres. In the second it is 25.95 per cent. In the third case, however, where there are spheres within spheres, the pore space is greatly increased—to 74.05 per cent. (4) On the other hand, if there are spheres of several sizes so that the small ones may rest in the spaces between the large ones, the total pore space will be reduced below 25.95 per cent, and the spaces may continue to be filled in by smaller spheres until the mass is practically solid, without pores. (See Fig. 26.) It is of course recognized that under field conditions these ideal arrangements do not pertain, but these figures illustrate the underlying factors which determine differences in pore space, and, also, differences in other physical properties. Soil particles are irregular in shape and uneven in size. When brought very close together, as occurs in mixing in a wet condition, their molecular attraction is brought into operation and, especially when dry, they are held together very securely. In this way the normal molecular attraction of the soil particles is increased by the deposition around them of the material in solution.

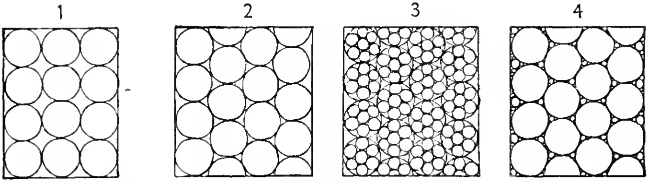

Fig. 26. Ideal arrangements of spherical soil particles: (1) Columnar order, 47.64 per cent of pore space. (2) Oblique order, 25.95 per cent of pore space. (3) Compound spheres in oblique order, 74.05 per cent of pore space. (4) Three sizes of spheres with closest packing, about 5 per cent of pore space.

Applying these principles to the soil, it is observed that there may be two general arrangements of the particles. (1) Each particle may be separate and free from its neighbors. This is a separate-grain structure. That is, each particle of soil functions separately. When by proper manipulation the particles are so packed together that the small particles quite completely fill in the spaces between the large ones, so that a very dense mass is formed (Fig. 26, No. 4), the structure is termed puddled. The term puddled, in this connection, is related to the fact that such an arrangement can be obtained only in fine-textured soils when they are mixed (puddled) in a very wet condition, so that the fine particles will move into the large spaces.

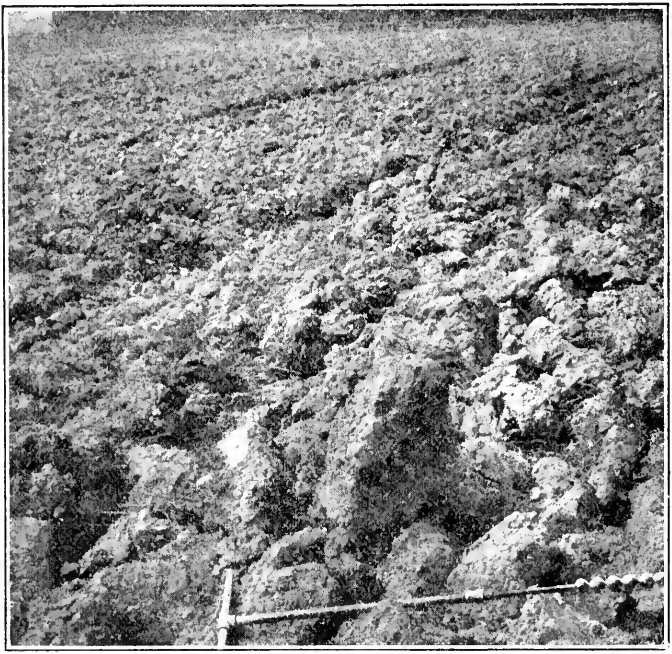

FIG. 27. An example of undesirable structure. A clay soil which had been puddled by tramping when wet. "Bad tilth." Compare with Fig. 28, showing "ideal tilth." Note also a type of auger used in examining soils. A common one and one-half inch wood auger welded to a one-half-inch shank, giving a total length of about three feet.

On the other hand, the small particles may adhere to the large ones, or a number of small particles may adhere together as a group or granule. When a number of united particles function together as a single larger particle or granule, the structure is termed granular.

FIG. 28. Ideal tilth of a soil

This arrangement is also termed the crumb structure. According as these groups are prominent or inconspicuous, the soil is said to be well or poorly granulated.

But when the granules reach large size, so that they interfere with the best functioning of the soil, they are termed clods. That is, a clod is an unsizable granule.

It is well known that a box of baseballs, or a pile of boulders, or even a box of sand, does not adhere together to any appreciable extent. That is, in all the coarser-textured classes, certainly down to the size of very fine sand, there is very little tendency to granulate. But in the silt, to a small extent, and in the clay, to a very great extent, granulation is strong.

36. Porosity.—In a mass of particles there is some unoccupied or pore space. If the particles are fine, then the intervening spaces are correspondingly small; if large, the spaces are large. In the discussion of ideal particles above, it was shown that the pore space is theoretically independent of the size of the particles, with any given arrangement. There would be as much pore space in a cubic foot of buckshot as in one of marbles. But in the soil this is not true. For, the finer the particles, the larger the proportion of pore space is found to be.

A clay has much more total pore space than a sand, although the individual spaces or openings between the particles are much smaller in the clay. The approximate per cent of pore space in a soil may be calculated by use of the following formula.

$$P = \frac{Vs - \frac{Vw}{2.65}}{Vs} \times 100 = \frac{Vp}{Vs} \times 100$$

Where P = Per cent of pore space.
Vs = Volume in c.c. occupied by the soil.
Vw = Weight of water equal to weight of soil in grams.
Vp = Volume in c.c. of pore space in soil.
2.65 = Specific gravity of soil particles.

Another and more simple formula which may be used in the calculation of the pore space is as follows:

$$P = 100 - \frac{\text{Ap. sp. gr.}}{\text{Ab. sp. gr.}} \times 100$$

Where P = Per cent of pore space.
Ap. Sp. = Apparent specific gravity or volume weight.
Ab. Sp. = Absolute specific gravity of soil material.
100% = Total space occupied by soil mass.

This relation between texture and pore space is exhibited by the following table of figures for soils in field condition.

		Per cent by volume
1.	Clean sand	33.50
2.	Coarse sand	40.00
3.	Medium sand	41.80
4.	Fine sand	44.10
5.	Sandy loam	51.00
6.	Fine sandy loam	50.00
7.	Silt loam	53.00
8.	Clay loam	54.00
9.	Clay	56.00
10.	"Gumbo" clay (Wedgefield)	58.46
11.	Heavy clay (Potomac puddled)	47.19
12.	Very heavy clay (pipe clay)	65.12

The reason for the greater porosity of the finer soils appears to be, that the smallest particles are so light that they do not settle so closely together in proportion to their size as do the sand particles, because of the greater friction between their surfaces. When this is overcome by mixing in water, such material becomes dense. Treatment greatly affects the structure and therefore the porosity of the soil. This is well shown by figures from the Rothamsted fields. The porosity of the surface nine inches of soil in an old pasture was 56.8 per cent, while in the same depth of a cultivated field it was 45.5 per cent. Extensive areas of loam soils in the North Central states have a porosity of from 45 per cent to 49.6 per cent. In many of the heavier soils it much exceeds 50 per cent, and in well-granulated clays it may reach 70 per cent, or in light sand it may be less than 40 per cent. In general, it may be said that about one-half of the volume of ordinary cultivated soils of intermediate texture is pore space.

The diameter of the individual pore spaces is of importance, as well as the total volume of pore space, since these determine the capacity of the soil to retain and move water and to permit the circulation of gases in the soil mass, as well as to facilitate the extension of the plant-roots.

37. Weight.—The weight of soil is the result of two factors. These are, first, the absolute weight of the individual particles, or *absolute specific gravity,* and second, the *volume of pore space* in the mass.

By reference to the table of minerals on page 6, it will be seen that the minerals entering into the soil vary greatly in specific gravity—that is, their weight as compared with an equal volume of water. They range from about 2.5 to 6 or 8, but the minerals which make up the great bulk of the soil—quartz, feldspars, micas, calcite, etc.,—all have a specific gravity of from 2.6 to 2.8. (See Table I, pages 6 and 7.) Many determinations of this property have been made. Fineness does not appear to have any material effect upon it.

Whitney has obtained the following specific gravities of composite soil separates.

TABLE XV

Conventional name	Diameter (m.m.)	Specific gravity
Fine gravel	2–1	2.647
Coarse sand	1–.5	2.655
Medium sand	.5–.25	2.648
Fine sand	.25–.10	2.659
Very fine sand	.1–.05	2.680
Silt	.050–.005	2.698
Clay	.005–.000	2.837

There is a very small increase in the specific gravity of the clay group, probably due to the greater concentration of the iron compounds here as a result of chemical processes; but it is not sufficient to materially change the result. The average specific gravity of soil material is, therefore, usually taken as 2.65, and this figure is used in all calculations here given.

Since the pore space enters into the calculation of the weight of any volume of field soil, this figure is much more variable for different soils than the one just given. It is directly related to pore space, and the larger the volume of pore space, the smaller the unit weight.

Combining the figures for pore space given above with that for average specific gravity, the figures in the following table are obtained.

The weight of a given volume of soil may be determined from the pore space and specific gravity of the material, by use of the following formula.

$$Ws = Ww \times (2.65 \times (100 - P).$$

Where Ws = Weight of given volume of soil.
Ww = Weight of volume of water equal to volume of soil.
P = Per cent of pore space.
$(100 - P)$ = Per cent of volume occupied by soil.

Or the following formula may be used, and is often more convenient.

$$Ws = \text{Ap. Sp.} \times Ww.$$

Where Ws = Weight of soil.
Ap. Sp. = Apparent specific gravity.
Ww = Weight of volume of water equal to that occupied by the soil.

TABLE XVI

	Volume weight or apparent specific gravity	Weight per cubic foot		Weight per acre foot
		Kilograms	Lbs.	Lbs.
1. Clean sand	1.76	50.0	110.0	4,800,000
2. Coarse sand	1.60	45.5	100.0	4,356,000
3. Medium sand	1.54	43.5	96.0	4,200,000
4. Fine sand	1.48	42.0	93.0	4,080,000
5. Sandy loam	1.30	36.8	81.0	3,550,000
6. Fine sandy loam	1.32	37.4	82.5	3,590,000
7. Silt loam	1.24	35.2	77.5	3,400,000
8. Clay loam	1.22	34.5	76.0	3,330,000
9. Clay	1.17	33.1	72.6	3,180,000
10. "Gumbo" clay	1.10	31.2	68.5	3,000,000
11. Puddled heavy clay (Potomac)	1.39	39.6	87.2	3,820,000
12. Heavy pipe clay	0.93	26.3	58.0	2,540,000
13. Old pasture clay loam (Rothamsted)	1.14	32.3	71.0	3,100,000
14. Cultivated soil, clay loam (Rothamsted)	1.43	40.5	89.0	3,900,000
15. Hagerstown loam	1.44	41.0	90.0	3,940,000
16. Janesville loam	1.33	37.8	83.0	3,640,000

One kilogram = 2.2 pounds.

This table shows that the finer the soil the lighter its absolute weight. Clay soils may range from 60 to 90 pounds in weight, according to their fineness and state of granulation. Sand soils weigh from 90 to 110 pounds. In practice, soils are spoken of as "light" and "heavy," but this use of these terms does not apply to the weight of the soil. The term light is applied to sandy soil because the particles move freely. On the other hand, a clay is termed heavy because of its cohesiveness.

38. Plasticity.—The property of stickiness of soils, when mixed with water, is termed plasticity. Soils exhibit it in very different degrees. In general, it may be said that the finer the soil the greater the plasticity, and therefore the finest-textured clays generally exhibit the greatest degree of plasticity. On the other hand, plasticity is not absolutely lacking in sandy soil, for, when moist, this material adheres together and may support a considerable weight. But, when the water is removed by drying, the sand will fall apart readily, and therefore the cohesiveness exhibited was largely due to the surface tension of the water between the particles. However, when the clay is dried out, it becomes a hard mass, and it has a superior adhesive and cohesive property when dried from the wet puddled state.

But while plasticity and great tensile strength appear to be very closely associated with fine texture, the fineness does not appear to be entirely responsible for the property, as is shown by the results of numerous studies reviewed by Ries. Writers in the past have dwelt much on the effect of colloidal clay in this connection. The real significance of colloidal material is somewhat doubtful, and, further, the amount present in even the most plastic clays is so small as hardly to be given credit for the effects noted. It seems probable that plasticity and cohesiveness of the material is due to several uniting causes, but for all practical purposes of the farmer it may be identified with fineness of texture. Associated with plasticity is a certain amount of shrinkage upon drying, and expansion upon wetting. The checking of the clay soil is an example of this. As the water dries out of the soil, the surface film draws continually closer about the particles, and, if these are small enough, may move them closer together. Then, if the whole mass is not drawn together as one unit, there will be cracks developed as a result of the shrinkage. The cracks occur where there is a weakness, from whatever cause, in the structure of the soil. Warington reports the results of Schübler, which show that a very pure clay, when dried from a thoroughly puddled condition, contracted 18.3 per cent of its original volume; a sandy clay contracted 6 per cent, and a sample of humus, 20 per cent of its volume. Gallagher found a shrinkage of over 30 per cent in drying out a sample of muck. These figures illustrate the general fact that the finer the texture the greater the shrinkage. Conversely, on wetting, there is a similar though smaller degree of expansion.

The checking of soil resulting from this shrinkage may be very injurious to crops. Where large checks or cracks are formed, the roots of plants may be injured or broken. And, further, these cracks greatly hasten

FIG. 29. Excessive checking of a heavy clay soil as a result of drying. Illustrates the process of soil granulation.

the drying out of clay soil to a much greater depth than is possible through surface evaporation. They also interfere greatly with the advance of roots.

39. Cementing material.—The cohesion of a soil when dry is due to several causes, one of which is much the most prominent. This is cementing materials. A cementing material is any material which binds surfaces together. In a gravel or sand pit, masses of the material are sometimes found united into a conglomerate rock. After a protracted dry spell, moist surfaces show a white incrustation in the surface layer, which is due to the deposition of the salts in solution when the moisture evaporated, and this acts as a binding material. This is one of the main reasons why a fully dried soil is usually so much harder than one slightly moist. The salts of many kinds which were in solution in the moisture have been deposited.

This composite of dissolved salts is the first of *four common cementing materials* which occur in the soil. It is generally a weak binding material. The second material is lime. Some soils are very rich in this compound. Particularly is this true of most glacial soils, and in North Dakota and other sections of the country extended areas of gravel beds occur, in which the upper two or three feet are completely bound together by the deposition of lime between and around the particles. It has been leached out of the soil above as bicarbonate, under the influence of carbonated water formed by the decaying organic matter, but here, in the loose gravel, by the escape of some of the carbon dioxid it was deposited. This is the usual history of the process. Cementation by lime carbonate is a very common and very general process. The third cementing material is the various forms of iron—usually oxides—in various stages of hydration. They have come into solution by the assistance of various organic acids, and are again deposited where there is some change in physical conditions. This form is most common in the unglaciated section of the country in the older deposits. Some of the red soils of the coastal plain region exhibit a strong tendency to "case-harden,"—that is, become quite hard at the surface upon drying, largely due to iron compounds. The fourth cementing material is silica, and is less prominent in soil practice than the other three cementing materials mentioned. It is the binding material in most sandstones and quartzite rock, as an advanced stage of silica infiltration.

All these cementing materials except the iron compounds, which are red, yellow or brown, are light-colored.

40. Color.—A great variety of colors are exhibited by soils. These are not usually the result of the color of the individual particles which make up the bulk of the material. Rather, it is usually the result of material which adheres to the particles.

There are two chief coloring materials in soil. These are iron compounds and organic matter. The first gives rise to red, yellow, blue and gray colors. The latter gives rise to some shade of black or brown color. When these are combined, various intermediate tints are obtained. For example, when a red soil is rich in decayed organic matter—humus—it becomes of a rich brown color.

The color of soils, especially as regards iron compounds, is not fully understood, but it is safe to say that much color is the result of different forms of iron in the soil. In the boulder clay of the glaciated sections a bluish color is common, which seems to be due to the presence of protoxid of iron (FeO), resulting from the great deficiency of oxygen. Where this comes in contact with carbonated water, it may be changed to the carbonate of iron, which is gray, and consequently along the line of roots and in the bottom of ponds this gray color may be found.

Where there is an abundant supply of oxygen, the iron takes on the sesquioxid (Fe_2O_3) form, which has a deep red color, typified by iron rust. Where the red soil stands much in contact with water, it may become yellow by the hydration of the iron ($Fe_2O_3 + H_2O$). In many regions a dark-colored soil is looked upon as a fertile soil. This relation has developed because of the association of a dark color with the presence of organic matter, with all its beneficial effects, while the light color indicates its absence. This relation does not hold universally, but it is quite a reliable guide.

The only instances where the color of the particles themselves give color to the soil is in some of the clean quartz sands, where the white color of the dominant mineral gives color to the mass. In some dark shaley sands this same principle obtains.

To the experienced person, the color of the soil is a valuable guide to its condition and productiveness. Mottled and uneven color, for example, indicates poor aëration, frequently the result of deficient drainage.

41. Physical absorption.—The soil particles attract and hold materials upon their surfaces. This physical absorption, or adsorption, as it is sometimes called, is different from chemical absorption, later to be mentioned, with which it is closely associated. As a result of this property, gases and materials in solution in the soil moisture are attracted to and, loosely held by the surface of the soil particles. It varies with the extent of surface exposed, and is consequently greatest in fine-textured soil. In clay soil, which has a relatively large surface area, it is very large, and is an important factor in the retention of fertilizers.

42. Conditions affecting structure.—The arrangement of the particles in a soil may be modified in many ways. Some conditions tend to produce the compact separate-grain structure, while others favor the granular or crumb structure.

It has been suggested by Whitney, King and others, that much of the formation of granules in the soil is due·to the contraction of the moisture film around the particles, when, for any reason, the moisture content is reduced. It is known that the soil particles tend to be drawn together by this reduction in the soil moisture. Add to this some influence to determine the size of the granules and a binding material to permanently hold the granules together, and the essential conditions for the granular conditions of soil are realized. Several natural conditions, and the various tillage operations, probably exert their influence on granulation in this way. Warington attributes granulation to unequal expansion and contraction of the soil mass, due to the unequal imbibition and loss of water. In such a soil, the cohesive force being different in different parts, and the internal strains and pressures unequal, a tendency arises for the mass to divide along the lines of weakness into groups of particles, as the soil moisture is much reduced below a certain optimum condition. Tillage operations, development of roots, burrowing of animals and insects, the presence of humus, and the development of frost crystals, may assist in further developing these lines of weakness in the soil mass, upon which the tension of the moisture films around the soil particles is brought to bear. The flocculation of soil particles may also develop lines of cleavage by the aggregation of particles around certain centers. The movement of the soil particles is, in every case, facilitated by the presence of a moderate amount of moisture.

On the other hand, conditions opposite from the above, including tillage at inopportune times, the operation of some natural agencies, as the beating of rain, erosion, and bad drainage, may not only destroy the tendency to the granular condition, which is always strongest in the finest soil, but may induce the opposite or separate grain structure.

43. Means of modifying structure.—It is apparent that some of the means of modifying the soil structure are natural, others are within the control of man. The following are among the better-known of these factors: (1) Variation in the water content. (2) Development of frost crystals. (3) Tillage. (4) Growth of plant roots. (5) Organic matter. (6) Certain soluble salts. (7) Earth-worms and other forms of animal life. (8) Heavy rain storms. Whether a desirable or an undesirable soil structure will result depends upon the combination of factors in operation. These structural modifications have to do primarily with the finer-textured soils—the loams, silts and clays,—rather than with the sandy soils. The structure of the latter can not be greatly changed.

44. Variation in moisture content.—The alternate wetting and drying of a clay or a loam soil tends to produce a granulated structure. It has been suggested by Whitney that this is due to the contraction of the moisture film around the particles, as it is reduced in drying. The very considerable pressure of the moisture film and the reduced friction due to the presence of moisture in the mass causes the particles to be drawn together in small masses. This process is well illustrated by Fig. 30, which was made from a micro-slide in which was mounted a suspension of fine clay in water. The water slowly evaporated from under the cover, and at last disappeared along the dark lines which are formed by the concentration of the particles by

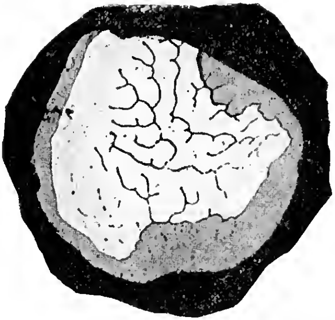

Fig. 30. Photo-micrograph, showing the distribution of soil particles by a water film. A small quantity of clay was suspended in water on a micro-slide and sealed in with balsam. Evaporation was permitted to take place very slowly through a small opening. The retreat of the water to the dark border line assembled the soil particles so that they were left to form the dark lines when their mass became too great to be moved by the surface tension of the liquid. This illustrates the granulating influence of a contracting water film, which is the primary force in operation during the drying-out of a wet soil. Note also the uniform curvature of the film, as indicated by the arrangement of the soil particles.

the moisture film as it contracted. The small particles are moved into the spaces between the large ones, thereby reducing the volume, as is shown by the checks. The checks which result from shrinkage are due to the unequal contraction. There comes a time when the general film around the whole mass must rupture. It breaks, along the line of least resistance, through a large pore space independently of how this space may have been formed. If the soil mass is very uniform, there will be few breaks, and the shrinkage will be, as a whole or at most, around a relatively few centers. This process produces clods or overgrown granules. But, if there are numerous lines of weakness, there will be many centers of contraction, and consequently a larger number of small clods or granules will be formed. This is the desirable condition, and constitutes good tilth,—that is, the most favorable physical condition for plant growth.

While once drying produces some checks,—a few large ones and many small ones, — such a structure does not constitute good tilth. The process must be continued further. When the soil is remoistened, it expands, but usually not to its original wet volume. Therefore the checks remain as lines of weakness, and, upon a redrying, are effective in further reducing the size of the granules. When this process is repeated a number of times, as occurs under field conditions, it results in a small and very desirable size of soil granule. Further, the drying out of the water in the granule deposits the salts in solution, which binds the particles together in a somewhat permanent and stable aggregate. The following figures represent the relative force required to sink a knife-edge into a puddled clay soil, different samples of which were subject to drying and rewetting a different number of times.

1. Soil dried once	100.00
2. Soil dried twenty times	31.44
3. Soil dried twenty times	30.60
4. Soil dried twenty times	32.05
Average	31.40

From this table it appears that the effect of twenty times drying is to reduce the force necessary to penetrate the soil a given uniform distance to one-third of that for the untreated sample. This is certainly a large change.

This fact has many practical applications. It should be observed that the change in structure is not associated with continual wetness, nor is it any more identified with a continued dry state. In neither case is the force necessary to change the structure brought to bear on the particles. This is exerted in the *drying process.* It is a well-known fact that soils which are continually wet are usually in bad physical condition. In the drainage of wet land, it is found that the soil is at first very refractory; but, when good drainage is established, there is a gradual amelioration of the physical condition which is primarily a change in structure. On the other hand, in a soil continually in a dry state there is no change in granulation. The improvement of soil structure, as a result of changes in the moisture content, is dependent largely on lines of weakness in the soil mass. Some of these are produced in the process of drying and others in ways already noted.

45. Formation of ice crystals.—As will be seen in the consideration of soil moisture, the water is distributed in the fine pores in the soil. When it freezes, it crystallizes in long needle-like crystals. The crystallizing force seems to be considerable. In freezing, the crystals gradually grow first in the larger spaces. There is a marked withdrawal of moisture from the smallest spaces to build up the ice crystals in the large spaces. The soil mass is separated by the crystal, and the result of a single hard freeze of a wet soil is to shatter it into pieces. And the repetition of this process by subsequent freezing further breaks up the soil, that is, it creates new lines of weakness. This weakness is shown by the following

Fig. 31. Ice crystals formed on the surface of a heavy clay soil. These crystals are very effective in breaking up the soil and promote the process of granulation.

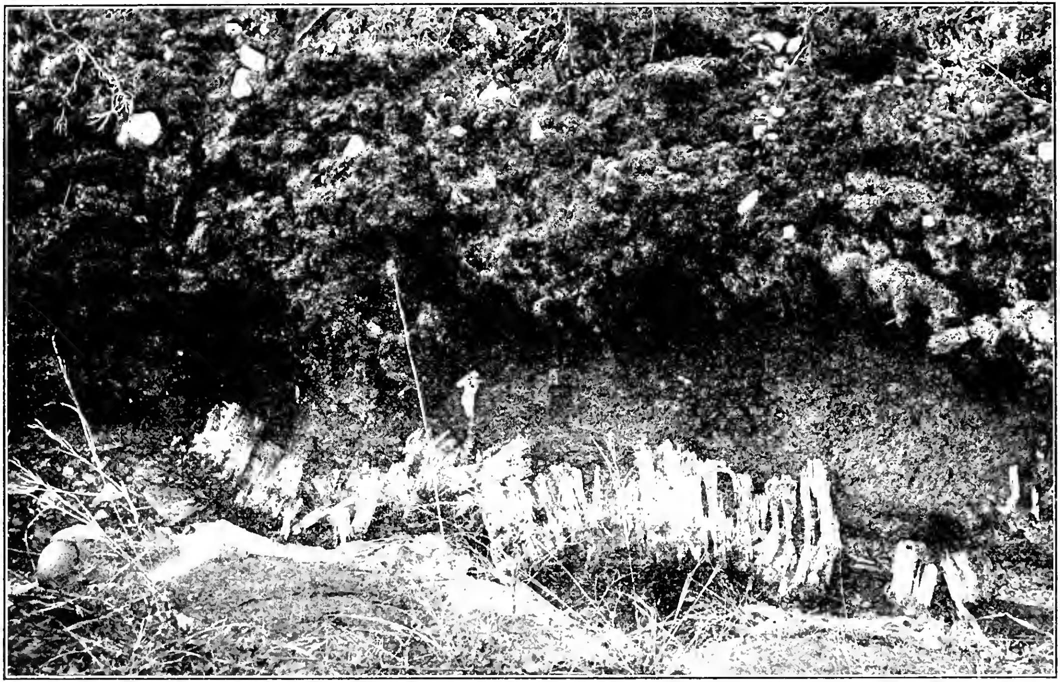

Fig. 32. "Honey-comb" ice crystals, formed in very wet soil. These assist in the process of soil granulation.

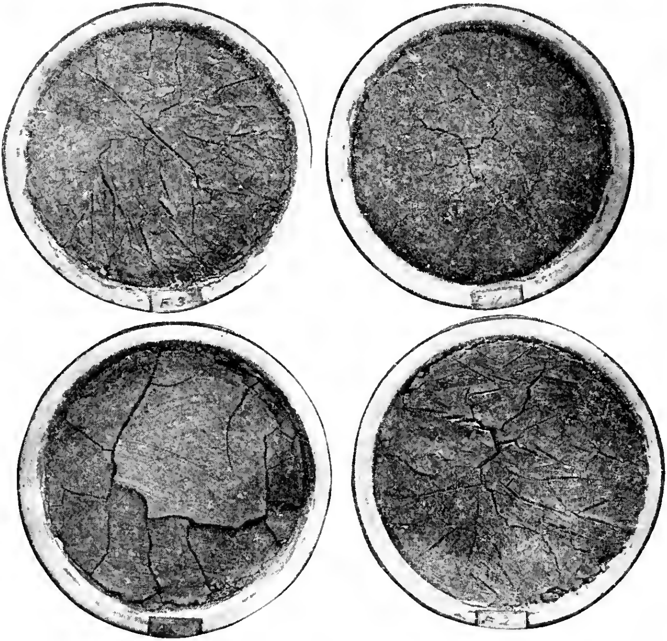

FIG. 33. Effect of freezing on the granulation of clay soil. The lower pan of soil on the left was not frozen. That on the right was frozen and thawed once. The upper pan of soil on the left was frozen and thawed three times, the one on the right five times. Notice the increased number of checks on the more frequently frozen soil.

table, which represents the effect of repeated freezing of a uniform sample of wet puddled clay, after which all were permitted to dry out. The figures are for the weight necessary to force a knife-edge a uniform distance into the soil, in each case reduced to basis of 100.

1. Check, unfrozen	100.00
2. Frozen once	30.31
3. Frozen three times	27.33
4. Frozen five times	21.88

This process has several interesting illustrations. In concrete work, the freezing of the material in the wet state, before it has an opportunity to harden, is recognized as decidedly injurious to the strength of the wall. The development and action of the ice crystals may be readily observed in the freezing of any thoroughly wet soil in winter. Such examples are shown in Figs. 31, 32 and 33.

To a much less extent, expansion and contraction of the soil mass caused by variations in temperature may contribute to the formation of granules. Any movement of the particles will tend to produce changes in the cohesive forces, and when the particles can move easily they are drawn together by this attraction.

46. Tillage.—The effect of tillage upon soil structure is to produce lines of cleavage, and these, when produced by plowing, are multitudinous, and quite uniformly distributed. As pointed out by King, plowing when the moisture content is suitable tends to break the soil into thin layers, which move one over the other,

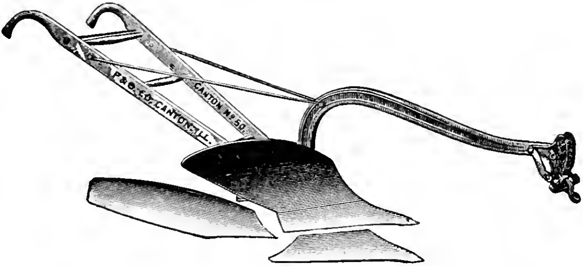

FIG. 34. Plow with interchangeable moldboard and share, which adapts it to different kinds of plowing The plow tends to shear the soil into thin layers which are very thoroughly broken up.

like the leaves of a book, when the pages are bent. This disturbance of the existing arrangement of particles starts in motion two forces: (1) The surface tension of the water films, which must now readapt themselves to the new arrangement, and which, by opening larger spaces, may lose some moisture by evaporation into the larger interstitial spaces. (2) The cohesive forces between particles, some of which have been forced closer together and some farther apart. The strength of cohesion between small particles, like clay, can be

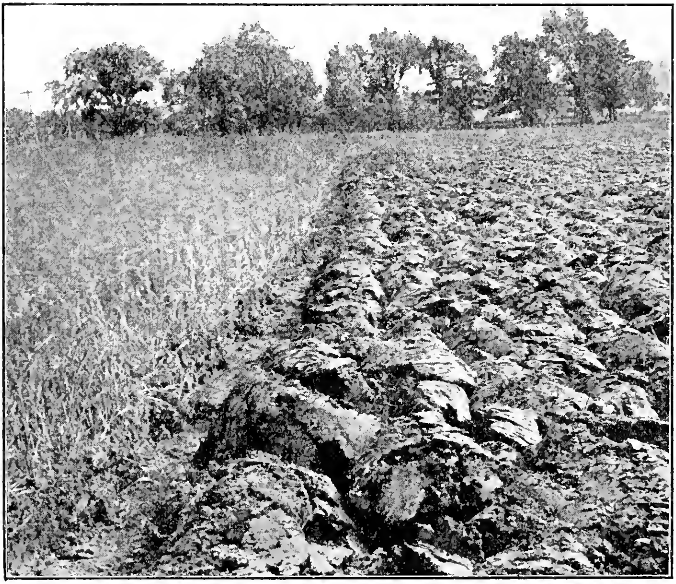

Fig. 35. Clay soil plowed when very wet. Condition indicated by the slickened soil surfaces and coarse, dense structure

realized when one considers the tenacity with which these particles are held together in brick. This cohesive attraction is inversely proportional to the square of the distance between the centers of the attracting bodies. Particles that can be brought so closely together as can clay particles are thus held with great firmness. The effect of tillage, when an excess of water is present, is to force the particles into large masses, which become clods when dry. These masses are too large to form granules, and leave the soil in a compact condition, poorly adapted to plant growth. When the soil is very dry when worked, the particles are not brought close enough together to cohere, but are powdered, forming the separate-grain structure, which forms clods when wet. Tillage may thus produce a granular structure when the moisture is neither excessive nor deficient, and the separate-grain structure when either of these conditions exists.

47. Growth of plant roots.—The growth of plant-roots changes the soil structure by forcing the particles apart at each growing root point, and possibly by some action yet to be explained. Crops differ greatly in their effect upon soil structure. Grass, millet, wheat and other plants with fine roots are more beneficial to tilth than coarse or tap-rooted plants as corn, oats and beets. Grass also affects structure by protecting the surface of the ground. (See page 119.) It is advisable to practice a rotation on clay soil, which requires relatively infrequent plowing, and gives long periods in fine-rooted grass and grain crops.

48. Organic matter.—Soils rich in humus or decomposed organic matter are generally in better physical condition than soils low in organic content. The marked effect of the absence of this material in many long cultivated soils is well known. For example, in much of southern New York the hill soils are now recognized to have a much different relation to crop growth than they had for a few years after they were cleared. Their color has changed, and with the decay of the humus has come a decided physical change in the soil, which is largely corrected by the restoration of the humus content. In certain prairie soils the effect of humus depletion on structure is even more marked. The actions of humus are many, as will be noted in the more complete discussion of that topic yet to follow; but one of those actions is on the granular nature of the soil. (1) As will appear, humus is somewhat plastic, and tends to hold the soil in a more loose condition than

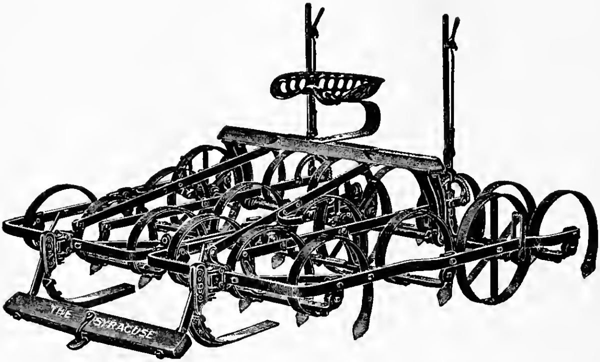

FIG. 36. The spring-toothed harrow. A type of cultivator adapted to all classes of soil and more efficient than any other in rough and stony ground.

would otherwise occur, and the large spaces thus produced constitute lines of weakness. (2) It is a property of humus to undergo great change in volume when dried out. This is another factor akin to the fineness of the soil, and produces larger shrinkage crack. This is noticeable in many black clay soils, which check excessively. (3) The great capacity of humus for moisture permits a wide range in moisture content, which produces corresponding physical alteration. (4) The color of the humus affects the color of the soil, and thereby increases the rate of change from wet to the dry state by increased evaporation of moisture. The relative effects of crude muck, and the ammonia extract from the same muck, upon the cohesion of the soil, as indicated by the force required for a uniform penetration of a knife-edge reduced to a basis of 100, is shown in the following table. Samples dried and rewetted twenty times.

CRUDE MUCK

1. Check	100.00
2. Muck, 5 per cent	82.00
3. Muck, 15 per cent	73.50
4. Muck, 25 per cent	58.48
5. Muck, 50 per cent	50.25

AMMONIA EXTRACT OF CRUDE MUCK

1. Check	100.00
2. Muck extract, 1 per cent	85.30
3. Muck extract, 2 per cent	76.40
4. Muck extract, 4 per cent	69.00

This table indicates that the material represented by the muck extract is the constituent of the muck which most influences the structure of the soil. All these processes promote the development of lines of weakness upon which the water may act. In this way organic matter promotes granulation.

49. Soluble salts.—In the action of certain salts, a different process from the previous ones is introduced. When lime is mixed with water containing fine particles in suspension, there is almost immediately a change in the arrangement of the particles. They appear first to draw together in light fluffy groups or floccules, which then rapidly settle to the bottom, so that the supernatant liquid is left clear or nearly so. This phenomenon is termed flocculation, because of the groups of particles. It is not an action limited to lime, but in greater or less degree results from the use of many substances. Lime is about the most active flocculating agent, and a very small amount is required. Acids, especially the mineral acids, are strong flocculating agents. Many of the common fertilizing materials have a flocculating power. Some substances, however, prevent or break up flocculation. Such, for example, is the effect of carbonates of the alkalies. From an agricultural point of view, the various forms of lime are the most important in this connection because their use on the soil is practical for the farmer. When introduced into the soil, this flocculating action occurs whereby granules are formed, the stability of which may be further increased by other favoring conditions.

The effect of lime on this process and the relative rapidity of the action for different forms, as shown by its influence on the cohesion of a puddled soil, is shown by the following table. The force required for a uniform depth of penetration of the knife-edge is reduced to the basis of 100 for the check.

1. Check	100.0
2. Calcium carbonate, 5 per cent	98.5
3. Calcium oxid equivalent to CaO in 2	56.5
4. Calcium carbonate, 10 per cent	111.0
5. Calcium oxid equivalent to CaO in 4	43.5
6. Calcium carbonate, 25 per cent	95.0
7. Calcium oxid equivalent to CaO in 6	33.6

This table indicates that the oxide of lime, or the hydrate as it would be in the wet soil, is more efficient in granulating the soil than is the carbonate. It is possible that this difference is the result of the short time of contact of the lime with the soil, which was only a few weeks. In the soil the hydrate will in time change to the carbonate, owing to the presence of carbon dioxid in the soil, so that in the end the form of the lime would be the same. These figures emphasize a fact recognized in practice, viz., that a considerable time is necessary for lime to have its full effect on the soil, and therefore it should be applied some months or even a season or two in advance of the crop it is to benefit.

Warington reports the statement of an English farmer to the effect that by the use of large amounts of lime on their heavy clay soil they were enabled to plow with two horses instead of three. It is generally true that soils rich in lime are well granulated, and maintain a much better physical condition than soils of the same texture which are poor in lime.

Carbonates of the alkalies, which are present in many alkali soils, tend to produce a compact soil structure. The remedy lies in a conversion of the carbonate into some other form, or in the removal of the alkali. (See page 314.) Hall has shown that the continued and extensive use of nitrate of soda on the land may, even in humid regions, deflocculate the soil.

FIG. 37. A portion of a Meeker harrow, showing its effect on lumpy, clay soil. (See page 481.)

50. Animal life.—Many forms of animal life affect the soil structure. Earth-worms, in passing soil through their bodies, leave it in a granulated condition in the "casts" which they deposit. Their action is frequently quite important. (See page 28.) Insects, especially ants and other burrowing creatures, aid in this and other ways.

51. Rainfall.—Rain storms compact the surface soil by washing the fine particles into the interstitial spaces, and by the actual pressure of the rain-drops. The result is to form a surface layer having the separate-grain structure, and which when dry, forms a crust, sometimes capable of preventing germinating plants from reaching the surface of the ground, and which is conducive to the loss of moisture by evaporation. Some clay soils are very susceptible to a change of structure in this way. A heavy thunder-storm may entirely change the structure of a clay soil to the depth of several inches, in a short time. This is due both to the impact of the rain-drops and the saturated condition of the surface layer.

Surface covering—mulches, sod or any kind of covering during the summer season—serves to protect the surface soil from the compacting effect of rain. The volume weight of a mulched soil will generally be found to be less, at the end of the growing season, than that of a well-cultivated one. The benefit to be derived from sod has already been mentioned.

II. ORGANIC CONSTITUENTS OF THE SOIL

Examination of almost any soil shows it to contain not only mineral particles but also plant and animal remains. The forest soil contains in the surface layer a large amount of partially decayed leaves and stems, sometimes termed leaf-mold. Sod land is filled with fine roots, which have served their period of usefulness to the plant and are being returned to their native elements. The low swamp areas of soil contain a large proportion of dark or black material, which, when the soil is dry, may be burned away, and leaves the residue a much lighter color. And in all soils there is some of this same volatile material derived from the growth and partial decay of plants and animals, and commonly termed organic—organized matter.

Organic matter may be found in the soil in all stages of decay, from the fresh tissues to the last oxidation products of its components. These products of the various stages in the decay process, comprehended by the term organic matter, constitute probably the most important body of material which enters into normal soil.

52. Sources, derivation and forms.—The organic matter in the soil is derived from both plants and animals: plants are the chief source. These materials undergo decay through the action of bacteria and fungi, in addition to purely chemical changes. The character of the intermediate material depends largely on the relative prominence of the different agencies concerned in its decomposition. This great variety in the material, together with the differences in processes of decay, gives rise to a number of forms of organic material which are recognized in the soil. These materials do not represent any definite composition. They represent, rather, stages in the general process of decay. Leaf-mold is the partially decomposed layer of leaves, twigs, etc., found on the surface of the ground, usually in well-drained forest areas. Decomposition is very incomplete. Humus is the black or brown pulverent material resulting from a considerably more advanced stage of decay than is represented by leaf-mold. When wet, it forms a very fine, gelatinous mass of a colloidal nature. Peat represents large and usually deep accumulations of plant remains in the early stages of decay. Disintegration has usually been stopped by the saturation of the mass. The products of bacterial and fungicidal action have accumulated, until the organisms are killed, and any further growth is prevented until the water is removed and more thorough aëration is introduced. Plant tissues are plainly evident. When the peat results from a particular kind of plant, the name of the latter may be affixed as moss peat. Peat is generally unproductive as a soil. Muck represents a much more advanced stage in the decay of peat. It has a black or brown color, more closely resembling humus, due to the large proportion of the latter which it contains. Plant tissues are much less apparent. It is generally productive, or will very quickly become so under drainage and cultivation.

53. Chemical composition.—There is no definite chemical composition of the organic matter in the soil. It is as variable as the materials from which it is derived and the conditions under which it is formed. It is composed of a great variety of carbon compounds, into which enter nitrogen and all of the mineral elements which are necessary to plant and animal growth.

These original compounds are broken down in the process of decay into other successively simpler compounds. The end of the process is always essentially the same—the reduction of the elements to their simplest and most stable forms, the carbon to carbon dioxid, the nitrogen to nitrates, ammonia or even free nitrogen; and the mineral elements to their simple salts. The soil constituents which are termed humus, mold, peat, muck, etc., simply represent stages in the transition process from the fresh materials to the native elements. There is no single compound or group of compounds which imparts definite characteristics. These are the result of the mixture; and this fact of an infinitely complex mixture is exceedingly important to keep in mind, in considering the effects of the organic matter of the soil. Many of them are acids. Some—as ammonia and marsh gas—function as bases. They react with each other in many ways, and, what is more important, they react with the mineral elements of the soil to form organic salts. It is by this union that organic matter has not only a direct effect as a food, but also an indirect effect in releasing food elements from their less soluble mineral combinations. Aside from the production of many complex organic acids, the two most significant facts of their composition are the per cent of nitrogen present and the chemical form of part of the carbon. Nitrogen, which is not a constituent of rocks, is made available to all higher forms of plants through this organic decay process, and these various compounds constitute the soil store-house of the element from which it gradually changes over into the available forms. The percentage of nitrogen present varies greatly—viz, from less than 2 per cent in the humus of some humid soils to more than 22 per cent in the humus of some arid soils, as reported by Hilgard. His results show that under arid and semi-arid conditions the humus is much more rich in nitrogen than in humid regions, and he attributes to this fact the large capacity of the former soils to produce crops with so little organic matter. His figures on this point are exhibited in the following table.

PER CENT OF NITROGEN IN HUMUS OF SOIL FROM DIFFERENT REGIONS

Humid soils, average of sixteen samples	4.58
Sub-irrigated arid soils, average of fifteen samples	8.38
Arid upland soils, average of forty-two samples	15.23

The nitrogen is changed under good soil conditions to forms available to plants.

There is a similar relative increase in the proportion of carbon in humus over that in the original material. The coals are metamorphosed muck and peat deposits, and their value for fuel lies in their carbon content. Hilgard has shown by a series of analyses that there is a gradual increase in the carbon content during the decay process, at least up to the humus stage, which is shown physically by the darkening of the material. This darkening, which appears in peat and muck may be the result of the separation of free carbon which, in the amorphous form, is black. Its practical significance in a soil way is its large effect on the color of the soil, which alters its heat relations. Crops always start first on black soils, other things equal, and, as has been stated, this dark color is generally due to humus.

54. Amounts present.—The amount of organic matter present varies greatly with different soils. Peat and muck deposits are very largely organic material, the per cent depending on the state of decomposition. Some porous, well-drained soils are almost lacking in this constituent. But nearly all soils have a moderate per cent. The accumulation is larger in the soil than in the subsoil, and generally decreases with depth. In 237 types of soil, representing thousands of samples from all parts of the United States, the soil was found to contain 2.06 per cent, and the subsoil .83 per cent. This latter refers to the upper subsoil, and at greater depths the organic content is very much less. But in those soils recently formed by stream action the organic content in the third, fourth and fifth foot may be very considerable, as is indicated by the color.

In general, arid soils contain less organic matter than soils of humid regions; those of cold climates more than those of warm climates. The soils of the northern states and Canada are very generally quite dark colored, while those of the southern states under similar treatment are much lighter colored, due to difference in organic content. Wet soils contain more than dry soils, and clay soils contain more than sandy soils.

These facts are illustrated by the following figures, showing the amount of organic matter in different soils, which in the first six lines are the average of ten samples representing several soil types of approximately the same natural drainage.

TABLE XVII

	Sandy soils		Loam and clay loam soils	
	Soil Per cent organic matter	Subsoil Per cent organic matter	Soil Per cent organic matter	Subsoil Per cent organic matter
Northeastern states	1.66	0.60	3.73	1.35
Southeastern states	0.93	0.41	1.53	0.73
North Central states	1.84	0.76	3.06	1.07
South Central States	1.16	0.55	1.80	0.65
Semi-arid states	0.99	0.62	2.64	1.11
Arid states	0.89	0.64	1.05	0.62

	Soil 0–7 inches Per cent organic matter	Subsoil 7–40 inches Per cent organic matter
Illinois deep peat and muck	84.6	55.80
Miami black clay loam, average twelve samples	5.9	2.50
Portsmouth sandy loam, average nine samples	4.1	0.92
Wabash silt loam, average eleven samples	3.3	1.30

The Miami black clay loam is a famous corn soil of the North Central states, and comprises areas of glacial clay loam, which were originally very wet and swampy, but have been reclaimed by drainage. The Portsmouth sandy loam occurs in the coastal plain of the southern states, and represents a mild form of swamp soil, but in which the accumulation of organic matter is not sufficient to permit its classification as muck. When well-drained, this soil is a first-class truck soil. The

Wabash silt loam is the much-prized deep, dark silt loam of the stream bottoms in the North Central states. It is a close competitor of the Miami black clay in the production of corn and grass.

FIG. 38. A soil of loamy texture in good tilth.

The proportion of organic matter is the chief distinction between soils and subsoils. It will be noted from the table that in all of the humid sections this difference is very marked, and agrees well with the color differences generally observed. But in the arid regions this distinction between soil and subsoil is not so obvious. The difference in organic content is even less marked than the figures indicate, for the reason that several of those for the soil extend to a depth of two feet or more and those of the subsoil extend often to six feet.

55. Some physical properties.—The physical properties of the organic constituents of the soil are different in value from those of the mineral constituents. Though usually present in small amounts their properties are such as to have a large influence on its productiveness.

56. Solubility.—The organic matter may be divided into two general classes of materials: (*a*) If an ordinary soil or peat or muck be leached with water, particularly if the water contain a little ammonia, a dark brown or black color will be imparted to the extract. This is due to a mixture of organic compounds which have a colloidal or gelatinous consistency. It is the material —to which the specific term humus is applied—which gives the brown color to the drainage water from swamps and to the leachings from the manure heap. This color is an indication of the loss of the humus constituent, and should remind one of the necessity for precautions against the loss, as far as possible. When the humus is united with salts like lime to form humates, this loss is very much reduced. It follows from this that the loss of humus, by leaching from soils rich in lime, is very much less than in those soils poor in lime. Many of the soils in the southern states are very low in lime, and the streams are generally bordered by swampy areas. As a result, the drainage water is usually of a brown coffee-color. On the other hand, in those northern states where the soils are rich in lime, this brown color is much less pronounced and is usually absent. If lime or some other flocculating agent be added to this brown liquid, the humus separates out in fluffy masses, which settle to the bottom, leaving the liquid above almost colorless. This is, in part, what takes place in the soil when these flocculating materials are present.

(*b*) The remainder of the organic material, after extraction, is composed of the fresh and partially decomposed fragments of plant and animal remains more or less stained. It is a light chaffy material, which by decay may be changed to humus, but in this condition is not subject to direct loss.

57. Weight.—The organic material is the lightest constituent in the soil. Warington gives the specific gravity of humus as 1.2 to 1.5, as compared with 2.68 for the mineral constituents, and Hilgard reports its volume weight when dry as .33, as compared with about 1.1 for clay and 1.5 for sand. Therefore, in proportion as a soil contains humus, it is lighter in weight. On the basis of the above figures, a cubic foot of humus would weigh about twenty-one pounds. Muck and peat, however, contain mineral matter washed in with the organic material and their volume weight is higher. It ranges from twenty to forty-five pounds per cubic foot, according to the stage of decay when dry.

58. Absorption properties.—In the form of humus, organic matter has a very large absorptive power for gases and salts in solution, similar to that shown by powdered charcoal. It is much greater than that of even clay soils, and for this reason its addition to soil increases this important property.

59. Volume changes.—Like clay soil, when humus is dried, it shrinks very greatly, and conversely, when it is moistened it expands. In humus this property is much more pronounced than in even the heaviest clay. Warington reports the shrinkage of a very pure clay, in drying from a saturated state, to be 18 per cent of the original volume, and that of humus to be 20 per cent; while others report the shrinkage of muck samples to be more than twice this amount.

60. Plasticity.—The crude organic matter exhibits no striking peculiarities, but the humus substance has many. One of these is its plasticity. Although very fine, its plasticity is not great as compared with clay. But it is sufficient to act as a weak cementing material in soil, which is very important in binding together light sandy soils, and in lightening up and holding apart the aggregates or crumbs in clay soil. Thereby it greatly promotes the granulation of clay soils which are properly drained.

61. Effects of organic matter.—The effects of organic matter on the soil, and thereby upon plant growth, are so numerous and so far-reaching and generally so beneficial, and further, its maintenance is so important a part of good soil management that, at the risk of anticipating some of the subsequent discussions, its effects are here briefly summarized. They are of two sorts, (1) Physical, and (2) Chemical.

62. Physical effects.—(*a*) Physically, it affects both tilth and granulation. Owing to its weak plasticity and its great contraction when dried, it is a very potent factor in hastening the granulation process of clay soils in the way that has been explained above. And on light sandy soils which are loose and inclined to be drifted by the wind or eroded by rains, it has the effect of binding them together and imparts a much more loamy character.

(*b*) By its beneficial effect on the structure of the soil, it very greatly increases its moisture-holding capacity, which is further increased by the great capacity of humus itself to retain water, which amounts to 200 or 300 per cent of its dry weight, as compared with 10 or 15 per cent for sandy loam and 25 to 35 per cent for clay soils. It therefore improves the drought resistance of soils by increasing their reservoir for available water.

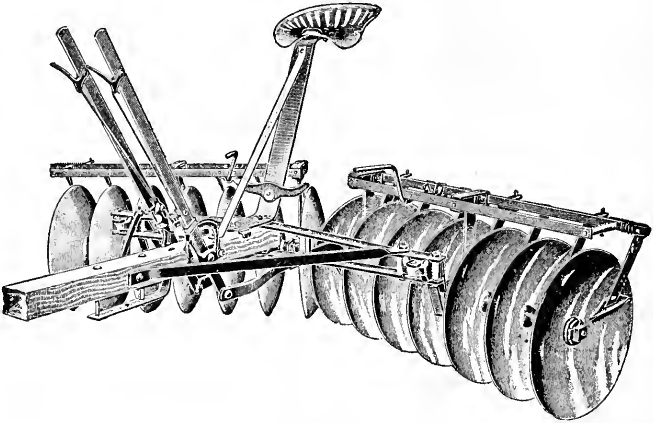

FIG. 39. The solid disc harrow. Most efficient on medium heavy soil free from stone and rubbish.

(*c*) The dark color which humus imparts to soils permits them to absorb the heat of the sun's rays very much more than when the humus is absent, and thereby their average temperature is decidedly raised. It is for this reason that the corn first appears in the spring in the low areas of dark-colored soil, which difference in time may amount to several days.

63. Chemical effects.—The chemical effects are of two sorts: (*a*) Vegetable and animal remains contain all of the essential elements of plant food, and by their decay these are given back to the soil in a form readily available as food for other plants. It is therefore a direct source of food elements.

(*b*) The products of the decay of organic matter are many forms of organic acids, the simplest and most abundant of which is carbon dioxid. In the soil moisture these act powerfully upon the mineral soil particles to bring their elements—particularly the bases—into solution. Because of their presence, the soil water must be regarded as a weak solution of all of these products and by their presence its dissolving power is greatly increased.

64. Maintenance of organic matter.—Two conditions are necessary to maintain an adequate amount of organic matter in the soil. These are, first, an adequate supply, and second, avoidance of a too-rapid loss, together with the maintenance of those soil conditions which promote the proper form of decay.

The organic matter derived from the higher plants is supplemented by that from bacteria and fungi, which are generally abundant in the soil. Much may be accomplished by good soil management to favor the development of the lower forms, so that they may be a very important source of humus. In fact, it has been suggested that they may sometimes be the chief source of supply.

Any plant may be used as a green manure, to furnish organic matter to the soil. Plants which have been much used for this purpose are the clovers, vetch, field-peas, cowpeas, soy beans, rye, and buckwheat. When any of these crops are planted in the late summer to conserve plant food, they are termed "catch crops," and when used to cover the ground and protect it from erosion, they are termed "cover crops." Many forms of organic manures and waste materials are applied as a source of humus.

Good tillage and the proper rotation of crops greatly assist the accumulation of organic matter in the soil, and to these may sometimes be added amendments such as lime. Some of the conditions which favor the accumulation of organic matter in the soil are: (1) The presence of an excess of water. (2) Low temperature. (3) Limited aëration. (4) Deficiency of basic elements. (5) Absence of decay organisms. (6) Application of organic manures. (7) Accumulation of plant residues in the soil. (8) Proper rotation of crops. (9) Absence of tillage.

Some of the conditions which favor the rapid disappearance of humus from the soil are: (1) The presence of a moderate amount of water. (2) Thorough aëration. (3) High temperature,—from 75° to 110° Fahr. (4) Abundance of available basic elements. (5) Abundance of decay organisms. (6) Failure to maintain the supply of organic matter. (7) Complete removal of all crops. (8) Improper crop rotation. (9) Excessive tillage.

Good management seeks to adjust these two sets of conditions, so that large crops are produced without imparing the humus supply in the soil.

B. THE SOIL AS A RESERVOIR FOR WATER

I. FUNCTIONS IN PLANT GROWTH

When plants grow, they use water. It circulates through their vessels, is built into their tissues, and is evaporated by the leaves. In these capacities it performs three important and vital functions for the plant. It is (*a*) a direct food of the plant, and becomes a part of its tissues either directly as water, or it is broken up and its elements are used in new compounds. (*b*) It is a carrier of food to the plant, and serves as the medium of transfer for the mineral elements from the soil and the gaseous elements from the air to their appropriate points of assimilation and use in the growth of the plant mechanism. (*c*) In addition to the last two functions, water serves as a regulator of the physical condition of the plant. It equalizes the temperature of the plant and modifies its stability.

From 60 to more than 95 per cent of the green weight of the staple crops is due to water.

In the ordinary processes of growth, the amount of water transpired is many times greater than that used directly as food. Investigations in different parts of the world have shown that for the production of each pound of dry matter ordinary crops transpire from 200 to 500 pounds of water.

Warington has compiled the following figures, showing the amount of water used by different crops in the production of organic matter.

TABLE XVIII.—WATER EVAPORATED BY GROWING PLANTS FOR ONE PART OF DRY MATTER PRODUCED

Lawes and Gilbert England		Hellriegel Germany		Wollny Germany		King Wisconsin	
Beans	214	Beans	262	Maize	233	Maize	272
Wheat	225	Wheat	359	Millet	416	Potatoes	423
Peas	235	Peas	292	Peas	479	Peas	447
Red clover	249	Red clover	330	Rape	912	Red clover	453
Barley	262	Barley	310	Barley	774	Barley	393
		Oats	402	Oats	665	Oats	557
		Buckwheat	371	Buckwheat	664		
		Lupine	373	Mustard	843		
		Rye	377	Sunflower	490		

The variation exhibited by the figures for the crop, as well as for different crops, illustrates the influence of climate and soil upon transpiration. Other things equal, more water will be required in an arid region than in one of humid climate; more in a warm region than in a cold region; more on a clay soil than on a sandy soil; more in a windy section than in a region of still atmosphere; more with a high soil moisture content; more on a poor soil; and, finally, more water is used per pound of dry matter produced in a small crop than is required in a large crop. All of these figures agree in indicating the large amount of water used in the production of crops. Not only is the total seasonal requirement to be considered, but the maximum demands of the crop at any period of its growth must be met. King observed that a single corn plant during the first week of August, when it was coming into tassel and the ear was forming, used water at the rate of 1,320 grams (one and one-half quarts) per day. Hunt observed in Illinois that in one week in July the growth of corn amounted to 1,300 pounds of dry matter per acre. Assuming the requirement observed in Wisconsin,—272 pounds per pound of dry matter,—this is equivalent to 1.55 inches of water.

Assuming the average production of dry matter to be two tons per acre, the amount of water required to produce such a yield of the staple crops, under the best conditions of management, would amount, according to the above figures, to from 427 tons to 1,820 tons of water per acre, which is equivalent to a rainfall of 3.7 and 15 inches, respectively.

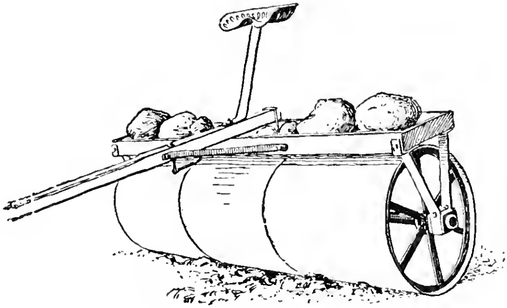

FIG. 40. Solid, metal roller. The prevailing type of compacter.

II. AMOUNT OF WATER IN THE SOIL

Soils exhibit great differences in moisture content and in their ability to meet the needs of the plants for water. In some of the southeastern states, where the rainfall is from fifty to sixty inches, crops suffer more from a lack of moisture than they do in some of the states of the northern Mississippi valley, with only a third of the rainfall. The light truck soils of the Atlantic coast suffer much more from a lack of water than do the interior soils of heavy texture which are under the same rainfall and general temperature conditions. Plants in a dry greenhouse use more water than in the more moist outside air. These illustrations serve to emphasize the three factors which determine the amount of moisture a soil contains. These are (*a*) the available supply of water; (*b*) the retentive capacity of the soil for water; (*c*) the rate and amount of loss of water from the soil. Each of these factors depends on many conditions.

65. The supply.—The supply of water is obviously controlled by conditions external to the soil. These are the precipitation in the forms of rain and snow, underground seepage, and irrigation.

66. Retentive capacity of the soil.—The retentive capacity of the soil varies greatly according to its physical properties, As soils ordinarily occur in the field, they show the presence of moisture. This moisture is held quite intimately. Two soils may appear equally moist, yet have very different capacities to maintain crops. Plants suffer much more quickly from dry weather on sand soil than on clay soil, even when the soils appear equally wet at the outset.

67. Statement of water content.—Five different methods are commonly used in stating the moisture content of soils. These are: (1) In terms of per cent

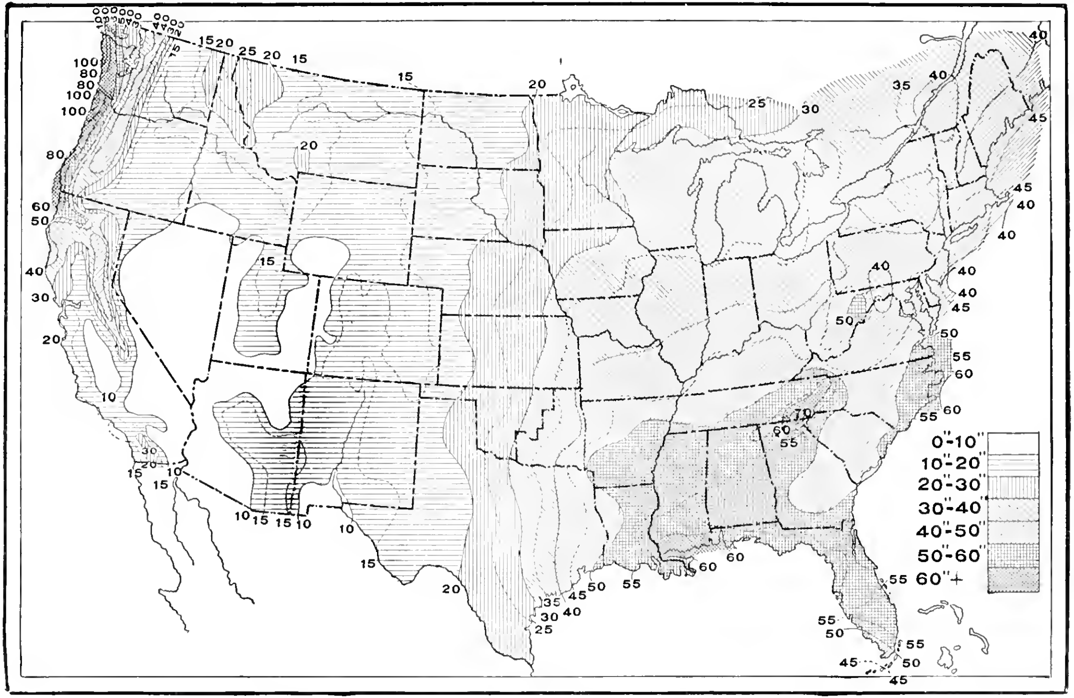

FIG. 41. Normal annual precipitation in the United States.

based on the dry weight of the soil. (2) In terms of per cent based on the wet weight of the soil. (3) In terms of the per cent of volume based on the total volume occupied by the soil. (4) In cubic inches per cubic foot, or in cubic centimeters per liter or per cubic meter. (5) In inches in depth of water over the surface of the soil.

Of these methods the first is most largely used, because it gives the most definite and constant basis from which to derive any other quantities. The dry weight of a soil remains constant, and percentages referred to that base are always comparable. But it has several disadvantages which lead to inconsistent results in practical work. For example, 10 per cent of water in a cubic foot of clay soil represents a very different quantity of water from the same percentage in a sand or a muck soil, because of the very different volume weights of these materials. In the clay it would mean about 7 pounds, or 3.5 liters; in the sand soil 10 pounds or 4.5 liters; and in the muck soil 3.5 pounds, or 1.6 liters,—manifestly very different quantities of water. Or, to state the matter in a different way, 30 per cent of water in a clay, 12 per cent in sand, and 150 per cent in muck, do not represent as different volumes of water as is indicated by the figures, because of the relative weights of the soils. But, because almost any other figure can be readily derived from the moisture percentage expressed in terms of dry weight of soil, it has been very generally used, especially in laboratory studies. In field practice, a volume method is more convenient.

The second method—that based on the wet weight of the soil—is unsatisfactory, because it is not only open to the objections made to the first method, but also because figures on moisture content of the same sample of soil are not comparable. They do not represent the same degree of wetness indicated by the percentages. For example, 100 grams of wet clay containing 10 per cent of water would consist of 10 grams of water in 90 grams of soil, and 100 grams of wet clay containing 20 per cent would consist of 20 grams of water in 80 grams of soil. In the first case, the ratio of water to soil is as 1 to 9; while, in the second, case the ratio is 1 to 4, instead of 1 to 4.5, as the percentage comparison would indicate. The difficulty in deriving other figures from percentages based on wet weight makes its use undesirable.

The third method, statement of percentage of water by volume, is the most rational of the first three. It gives a direct practical basis of comparison for all soils. It shows the volume of water held by the soil, which is really the important consideration from the point of view of the plant. For purposes of comparing the moisture content of different soils in the field, it is probably the most satisfactory method. Derivation of these quantities involves considerable calculation, and often the determination of some quantities not readily obtainable.

The fourth method of statement is really a variation in detail from the third method by which specific quantitive statements are made. One hundred seventy-two and eight-tenths cubic inches of water in one cubic foot of soil, is a cumbersome method of saying the soil contains 10 per cent of water by volume.

The fifth method is most generally used in field practice in stating quantities of water. In irrigation practice, water is often measured in inches in depth per acre of area. In stating the quantity of water held within root range by different soils, this method is also direct and convenient. For example, a sand soil of a certain texture will hold in the four feet surface 9 acre-inches of water; clay soil, 16; and a muck soil, 40 inches; which figures are directly comparable for purposes of crop-production.

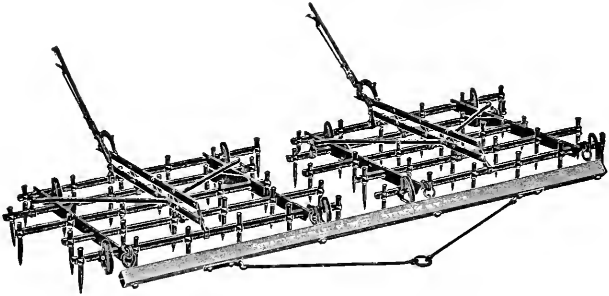

Fig. 42. A common type of spike-tooth, iron-framed harrow. It operates as a shallow cultivator, and may often be very effective in mulching the soil and conserving moisture.

The method used in stating the moisture content of a soil will therefore depend upon the line of investigation and the application of the results to be made. Both the percentage of dry weight and the percentage of volume will be used in this book, according to the point of view of the discussion.

68. Forms and availability.—There are three forms in which water may exist in soils: (1) Gravitational water, or that which is free to move through the soil under the influence of gravity. (2) Capillary or film water, or that which is held against gravity by the surface tension of the films of water surrounding the soil particles. (3) Hygroscopic moisture, or that which condenses from the atmosphere on the surface of the soil particles, when the soil is allowed to become air dry.

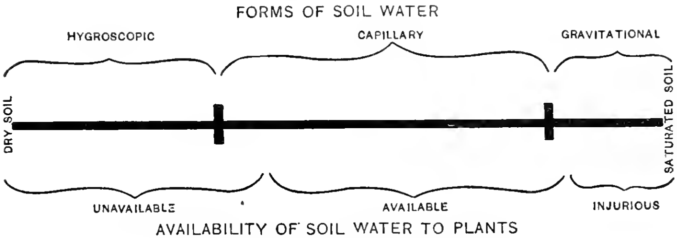

Fig. 43. Diagram illustrating the forms, proportions and availibility of soil water.

There is no sharp change in the moisture condition of the soil in passing from one form to the other. Still, it is true that there are certain marked changes in some of the physical properties of the soil, such as volume, weight and resistance to penetration, which are in a general way associated with these transition points.

Not all of the water in the soil is available to use of plants. It is a matter of general experience that for most farm crops the saturated condition of the soil is unfavorable to the best development. There are, of course, many plants which are adapted to such conditions, as for example the swamp type of vegetation. About the only cultivated crops of this sort are rice and cranberries. Practically all of the common cultivated crops, from vegetables to fruit trees, are adapted to growing in soil from which the gravitational moisture has been removed. The gravitational water is directly injurious to the growth of these plants, and its practical removal from the soil constitutes the practice of agricultural drainage, later to be considered as a phase of soil management. It may therefore be stated that gravitational water in the root zone is injurious to most farm crops, and consequently it is in a sense unavailable. It is the film or capillary moisture which supports plants. The roots of ordinary crops are adapted to take the moisture needed by threading their way between the soil particles, where they may come in intimate contact with these moisture films and absorb the needed supply of water, without being excluded from the air supply which promotes their growth. For, in the capillarily moist soil, the water is retained chiefly in the very small spaces, and the large spaces are occupied by air.

While capillary moisture is practically the only form upon which plants depend, it is not possible for them to use all of this form of moisture in the soil. They take their supply most readily when the films are relatively thick, and when the globules between the particles are large. But, as the thickness of the films is reduced by the use of the plant and by evaporation, it becomes increasingly difficult for the plant roots to take their needed supply. Before all of the capillary moisture has been removed, this difficulty becomes so great that it practically amounts to the prohibition of further extraction by the plant. At this stage, if evaporation from the leaves continues, the plants wilt, because they are not supplied with moisture by the roots as rapidly as it is being lost.

Since plants cannot utilize all of the capillary moisture it is manifestly impossible for them to derive any benefit from the hygroscopic moisture, which is held much more intimately by the soil particles than is the capillary moisture. In other words, the hygroscopic moisture capacity of a soil represents that much water unavailable to plants, to which must be added the proportion of the capillary moisture which is also unavailable.

69. Amounts of each form.—The relative amount of each form of water varies with the soil, and is determined by its physical properties. The forms of water merge one into the other.

70. Hygroscopic water.—The amount of each of the three forms of soil water depends on the physical properties of the soil. These are best explained by first considering the hygroscopic capacity. This depends on the texture of the particles and the content of organic matter. Since hygroscopic moisture is a function of the surface exposed, it results that the larger the surface area exposed by the soil particles, the greater the hygroscopic capacity of the soil. Reference to the table on page 83 shows fine-textured or clay soils to have the greatest surface area, and these hold the most hygroscopic moisture. Sand soils, with a relatively small surface area, hold a small amount of this form of water. This fact is illustrated by the following table.

	Per cent of hygroscopic water at 21° C.
Very fine sand	1.8
Silt	7.3
Clay	16.5
Muck	48.0

The above soils were pure separates derived by mechanical analysis. These figures serve to show the direct relation between the (1) surface area exhibited by soil particles and the hygroscopic moisture retained. The hygroscopic moisture content of a soil depends also on the (2) temperature, and the (3) humidity of the atmosphere. The hygroscopic moisture decreases with increase in temperature. It varies directly as the relative humidity of the atmosphere with which the soil is in contact. Consequently, in the air-dried condition, while a soil always retains some moisture, it seldom exhibits its maximum hygroscopic capacity. Under average conditions of humidity, a light sand may retain from .5 to 1 per cent, a silt loam from 2 to 4 per cent and a clay from 8 to 12 per cent. This is, of course, unavailable for the use of plants.

71. Capillary water.—The capillary water capacity is much larger than the hygroscopic capacity. Its amount is determined by three things: (1) Texture, (2) structure; (3) content of organic matter.

72. Texture.—Texture is well known to be the greatest determining factor in the water-holding capacity of soils, due to its control of the internal surface, and this is particularly true with reference to the capillary form. The following table illustrates this effect of texture.

TABLE XIX

Class	Per cent of clay	Per cent of moisture retained against force 2,940 times that of gravity
1. Coarse sand	4.8	4.6
2. Medium sandy loam	7.3	7.0
3. Fine sandy loam	12.6	11.8
4. Silt	10.6	12.9
5. Silt loam	17.7	26.9
6. Clay loam	26.6	32.4
7. Clay	59.8	46.5

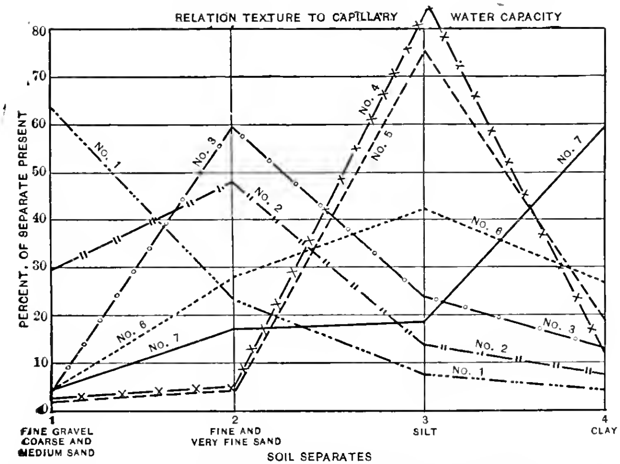

FIG. 44. Showing the mechanical composition of the soils whose relative capillary water capacity is given in Table XIX.

No. 1. Coarse Sand.	No. 5. Silt Loam.
No. 2. Medium Sandy Loam.	No. 6. Clay Loam.
No. 3. Fine Sandy Loam.	No. 7. Clay
No. 4. Silt.	

It must be remembered that the hygroscopic capacity of these soils also increases with their fineness, and that the strictly capillary moisture is represented by the difference between the total moisture content given above and the hygroscopic moisture.

The above figures are the most exact available which show the influence of texture upon moisture retention. But, while they show the relative effect of texture, they do not indicate the amount of water retained by field soils; because these samples have been subject to a force almost 3,000 times that of gravity. When under the influence of gravity alone, these same soils will retain much more water than is indicated by the figures. However, this influence of gravity introduces a modification in the moisture content of the soil which must be constantly kept in mind. Moisture is retained in the soil as a result of two sets of forces. These are, first, the attraction of the soil for water, or adhesion. For example, if a marble is dipped into water and withdrawn, it carries with it a film of water over its entire surface. This shows that for a certain small distance from its surface, the marble exerts a stronger pull on the water than the water exerts for itself. If the marble were dipped into mercury instead of water, it would come out with a dry surface, because in this case the attraction of the mercury for its own substance is greater than the attraction of the marble for the mercury. Quinke estimates the appreciable range of this attraction to be approximately .002 millimeter, which, it will be remembered, is equivalent to the diameter of a medium-sized clay particle. Its tendency is to arrange upon the surface of the soil particles a film of water molecules equivalent to this thickness.

But, because of the second set of forces the film is always thicker than this range of molecular attraction of the solid. This is due to the attraction of the water particles for each other, or cohesion. The water molecules hang together. This cohesion of the water molecules is exhibited in surface tension which will permit a clean steel needle to be suspended upon the surface of water, or makes possible the common trick of putting a handful of nails into a goblet already level full of water. This surface tension acts like a stretched elastic membrane, and permits the water to be piled up. This is what happens in the soil when capillarity comes into play. As a result of these two sets of attraction, the water hangs on the particles in thick films; and it drops away only when the weight of the water becomes greater than the surface tension of the liquid.

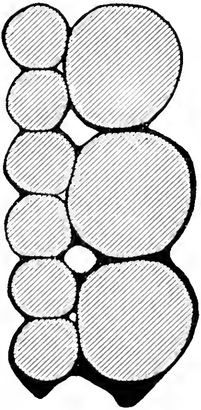

FIG. 45. Showing the distribution of water on columns of spherical particles of different texture. Note the accumulation of water in the lower part, also, the approximately equal curvature of water surfaces at each level.

It is clear that soil forms a column of considerable height, and further, that the closer the water film is drawn around the soil particles, the thinner it will be, and consequently the less water it will contain. To illustrate: Suppose a cylinder to have flexible rubber diaphragms stretched across at frequent intervals from the top to the bottom. If now a heavy ball is dropped upon the upper membrane, it will be weighed down upon the next membrane below, and this in turn will be depressed, until the ball has brought enough of the membranes in contact to support its weight. Under these conditions, the upper membrane will be stretched most severely, and will therefore be thin, while the lower membrane will be very slightly stretched. If, now, we calculate the actual amount of rubber in each section of the cylinder it will be found smallest at the top and largest at the bottom.

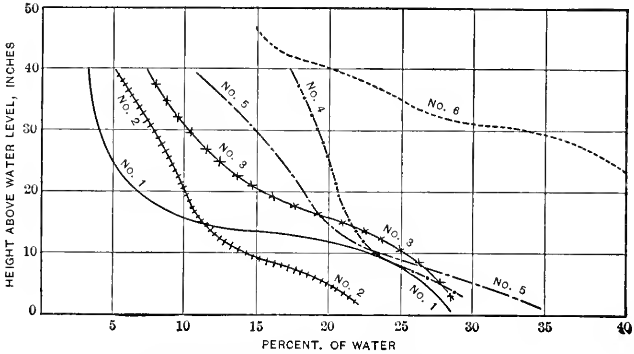

FIG. 46. Curves showing the distribution of water in columns of soil capillarily saturated, as given in Table XX.

In the same way, gravity affects the distribution of water in the soil. It forms thick, bulging films in the lower part of the column, and thin, closely drawn films at the top of the column. Consequently, the surface of a soil of uniform texture is normally less moist than the subsoil.

As a result of this fact, it is not practicable to say that any soil contains a definite uniform per cent of capillary moisture. The content varies with the height of the column and the plane in the column at which the determination may be made. This important principle in the distribution and amount of moisture in the soil is well illustrated by the following tables and curves, for soils of different texture, as obtained by Buckingham:

TABLE XX

	Per cent of water at different distances from bottom of column in inches					
	2	10	20	30	40	50
1. Clean dune sand	27.0	23	7	3.5	3	
2. Coarse sand	23.0	14	10	7.5	5	
3. Fine sandy loam	28.5	25	16	9.5	7	
4. Light silt loam	29.0	23	21	19.0	17	
5. Clay	35.0	23	18	15.0	11	
6. Heavy loam, rich in humus	64.0	55	47	36.0	20	

The above moisture curves illustrate very clearly the accumulation of the water in the lower part of the soil column. These columns were permitted to stand in contact with water for many days, so that, with the possible exception of the finest textured soils, they had come to equilibrium. It will be noted that the difference in moisture content is much greater at the top of the columns than at the bottom, and decidedly greater than at a height of about ten inches above the water.

When two soils of different texture are placed in contact with moisture free to move from one to the other, they come into moisture equilibrium after a time, and each holds a certain proportion of the water. The curvature of the water surfaces between the particles of the two soils is the same. But since in a given volume of soil the fine texture has so many more of these individual drops of water, its total content is greater than that of the coarse-textured soil. This matter of the curvature of the water surfaces in the soil will come up

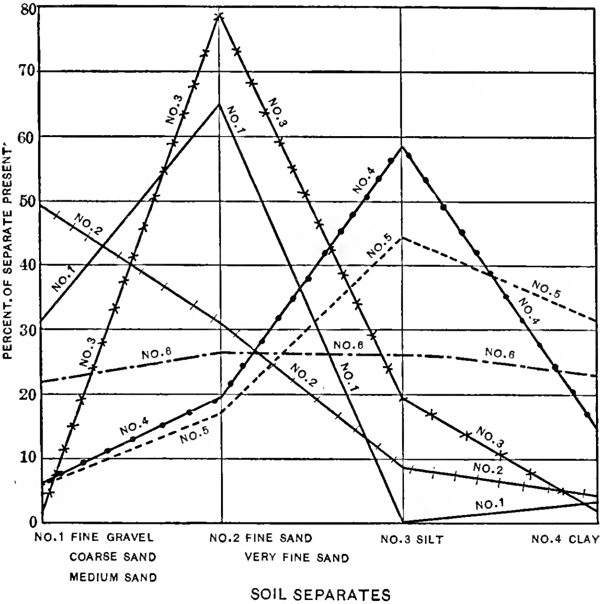

FIG. 47. Curves showing the mechanical composition of the soils whose capillary moisture capacity is shown in Table XX and Fig. 46.

prominently in considering the capillary movement of moisture. The relative adjustment and distribution of the moisture between small and large particles in contact is illustrated in Fig. 45. When in capillary equilibrium, two soils should appear equally moist.

73. Structure.—Structure is the second factor which determines the moisture capacity of a soil. If the statements in reference to the effect of texture have been fully understood, the influence of structure will be readily grasped. The effect of structure is to alter the effective size of the soil units or granules, and also of the spaces which they form. In a coarse sand soil, the general effect of rendering the structure of the soil more loose is to proportionately reduce its water-holding capacity, because the spaces are already so large as to hold a relatively small amount of water, and that to a very limited height. Change in structure further decreases that already deficient capacity. On the other hand, in a fine clay soil the spaces are all very small, and all have a capillary efficiency to a great height. This height is much more than is ordinarily needed to bring the moisture from the deep subsoil to the root zone. In such a soil a more loose and open structure has the effect of increasing the effective moisture capacity, so long as the spaces are still able to hold water at the surface of the column. But when this maximum size of space is exceeded, as in a coarsely clodded soil, the moisture capacity drops low, as in the case of sand or gravel, when growth may be seriously interrupted. Ordinarily, then, it may be said, that loosening the structure of a coarse sand or gravel soil lowers its moisture-holding capacity while a reasonable granulation of a clay soil increases its moisture-retaining capacity.

This effect of structure on the moisture capacity of two soils is illustrated by the following curves, based upon the results of Buckingham. The mechanical analysis of these soils may be found in curves already given. (See page 150.) The sandy loam is No. 3, and the clay is No. 5.

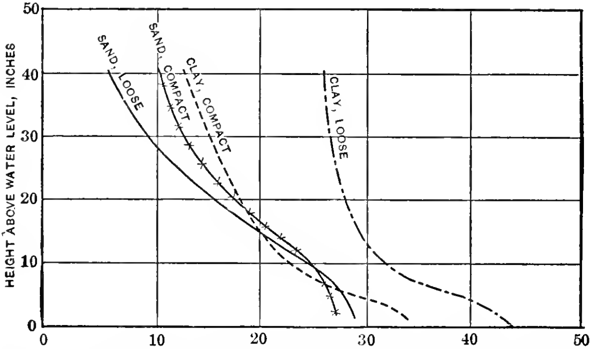

FIG. 48. Curves showing the distribution of water in columns of sand and clay when loose and compact and capillarily saturated. Figures given in Table XXI.

TABLE XXI.—PER CENT OF WATER IN SAND AND CLAY, LOOSE AND COMPACT

Soil	Structure	Dry porosity per cent	Per cent of moisture at different heights above water level				
			2 in.	10 in.	20 in.	30 in.	40 in.
Sandy loam..	Loose	50	28.0	25	16.0	9.0	6
	Compact ..	35	27.0	25	17.5	12.5	10
Clay	Loose......	59	42.5	32	28.0	27.0	26
	Compact ..	52	34.0	23	18.0	15.0	12

74. Content of organic matter.—Organic matter, especially in the form of humus, has a larger capacity for moisture than has the mineral portion of the soil. Aside from the fact that such material has a large inherent moisture capacity, and that in proportion to its amount in the soil it increases the water capacity, no exact figures can be given. The moisture content of such material varies with the stage of decay, as well as the general physical properties of the material. The following figures compiled by Storer illustrate this capacity.

	Per cent of water retained
1. Humic acid extract from peat	1,200
2. Non-acid humus prepared from peat	645
3. Ordinary vegetable mold	190
4. Peat	201–309
5. Garden loam, 54 per cent clay, 7 per cent humus	96
6. Dark Illinois prairie soil	57
7. Mucky soil (weighing 30 pounds per cubic foot)	75

Besides its inherent capacity, organic matter affects the moisture capacity through its influence on soil structure. In clay it produces a desirable condition of granulation and therefore increases the absolute moisture capacity. And its addition to sand has a similar, though smaller effect. This is illustrated by the following figures, obtained by Detmer, as quoted by Storer, which resulted from the mixture of sand and muck. It will be noted that in proportion as muck is substituted for an equal weight of sand, the water capacity of the mixture is increased, as is well shown by the ratio in the last column.

TABLE XXII

Per cent of sand	Per cent of muck	Grams of water absorbed	Ratio of absorption of water in sand and in mixture
100	....	12.2	1 : 1
80	20	24.0	1 : 2
60	40	42.0	1 : 3.5
40	60	71.7	1 : 6.0
20	80	99.1	1 : 8.0
....	100	114.4	1 : 9.3

75. Volume of water held by different soils.—The columns of soil from which the figures presented on page 148, with the accompanying curves, were obtained, were forty-five inches in height, with their lower ends dipping in water. As they were run for several months, their moisture content represents the maximum capacity for each soil. Under these conditions, the mean moisture content was as follows:

TABLE XXIII

	I Dry porosity. Per cent	II Final mean water content Per cent	III Approximate per cent of moisture at which crops will wilt	IV Per cent of available moisture
1. Dune sand......	52	10.7	3	7.7
2. Coarse sand.....	51	10.6	3	7.6
3. Fine sandy loam.	50	18.0	5	13.0
4. Light silt loam ..	50	20.9	10	10.9
5. Clay	59	30.4	17	13.4
6. Muck soil	80*	250.0	80	170.0

*Estimated.

TABLE XXIII, continued

	V Weight of dry soil per cubic foot	VI Volume of available water per cubic foot		VII Inches of available water to depth of four feet
	Lbs.	cu. in.	c.c.	
1. Dune sand	80	166	2,720	4.60
2. Coarse sand	81	170	2,790	5.20
3. Fine sandy loam	83	300	4,900	8.50
4. Light silt loam	83	250	4,100	6.90
5. Clay	68	252	4,140	7.03
6. Muck soil	15	740	11,550	20.50

But all of this moisture is not available to crops. The third column gives the per cent of water in these soils which would be unavailable, or the point at which plants would ordinarily wilt. This per cent, or amount of water at which plants are just able to survive, is termed the minimum or *critical moisture content*, while the highest per cent at which the plant will survive is termed the *maximum moisture content*. The intermediate point at which any crop makes its best growth is termed the *optimum moisture content*.

Each of these points, or moisture conditions, is very definite for each soil and for each crop. The minimum for different crops on the same soil is not the same as the results of a number of investigators have shown. Storer reports that, on a calcareous soil having a hygroscopic capacity of 5.2 per cent, the minimum for grasses was 9.85 per cent, and for legumes 10.95 per cent; while, on peat (muck) with a hygroscopicity of 42.3 per cent, the grasses suffered at 50.87 per cent of moisture, legumes at 52.87 per cent of moisture. Warington concludes, from the results of Hellriegel and Wollny, that "when the soil contains 80 per cent of the water required to saturate it, the proportion was too high; and that when the water amounted to only 30 per cent of saturation. the proportion was too low for the production of a maximum crop. The largest crops were obtained when the proportion of water lay between 40 and 60 per cent of that required for full saturation."

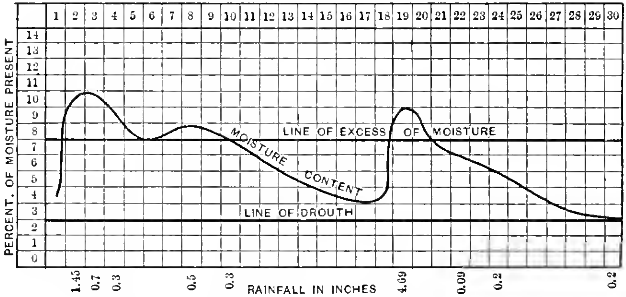

FIG. 49. Curve showing moisture content of a light sandy loam—early-truck soil, Union Springs, Alabama, June, 1896.

Cameron and Gallagher have shown that the maximum and minimum points are marked by distinct changes in: (1) The cohesion of the soil. (2) Its volume weight. (3) The freedom with which the soil gives up moisture. The first of these facts is of especial importance in the tillage of soil. Between the maximum and the minimum points the soil "works" at its best. It does not puddle, and it is sufficiently moist to give that desirable state of granulation which is expressed by good tilth. The clods of the clay soil are not hard, and therefore pulverizing operations attain their maximum efficiency with the minimum of work. (See page 103.) A soil always tilled in this condition should never get into bad tilth.

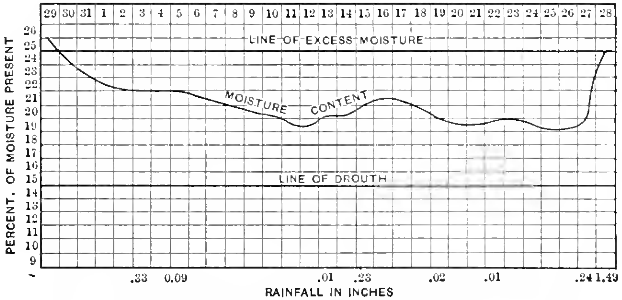

FIG. 50. Curve showing moisture content of silt loam—blue-grass soil, Lexington, Kentucky, September, 1896.

76. Available water in some field soils.—The actual moisture content and fluctuations through a part of the growing season for different soils is always of prime concern to the farmer. The following curves, (Figs. 49, 50 and 51) based upon the results of Whitney and Hosmer, illustrate these fluctuations.

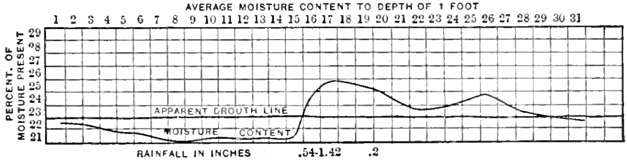

FIG. 51. Curve showing moisture content of clay soil—black cretaceous prairie—Macon, Mississippi, July, 1896.

If we assume for the above soils a porosity of 47, 52, and 65 per cent, respectively, their weights per cubic foot would be 88, 79 and 58 pounds each. Using the maximum and minimum moisture contents indicated by the above curves, the available moisture retained by each of the soils is as follows:

TABLE XXIV

	Water capacity		Amount of available water		
	Minimum Per cent	Maximum Per cent	Per cent	Cu. in. per cu. ft.	In. per acre, 4 ft.
Light sandy loam	3	8	5	122	3.4
Silt loam	15	25	10	218	6.0
Clay	23	40*	17	274	7.6

It is possible that the maximum assumed for the clay is too high, in which event the available moisture in the fifth column for this soil is also too high; but field experience indicates that it is reasonable.

By reference to page 134, giving the amount of water required to produce a crop, it will be observed that the surface four feet of the sand soil will not retain enough water for the medium crop yield, and that the clay soil contains less than half enough water for a large yield of many crops under the best management. This necessitates the replenishment of the supply by rainfall, irrigation, or movement up from the subsoil, after the best tillage practice has been employed to prevent unnecessary loss by evaporation.

77. Relation of surface tension to capillarity.—In addition to the three factors mentioned as controlling

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*Assumed.

the capillary moisture capacity of a soil, one other is to be considered. The surface tension, or cohesiveness, of the moisture was described as one of the forces which acts in conjunction with the texture, structure and organic content, to retain water. The surface tension of any liquid is not a constant quantity, and the soil water is no exception to this rule. Anything which increases surface tension increases moisture retention, and likewise anything which decreases surface tension decreases the moisture retention. Soil moisture is subject to considerable variation in surface tension. Two things are most active to change this tension, or cohesiveness. These are: (1) Materials in solution in the water. Lime and many other salts increase the tension, some substances decrease it below the normal for pure water. (2) Changes in temperature alter the surface tension.

Whitney and others have determined the surface tension of a number of salt and soil solutions, some of which are given in the table on the following page. The concentrations are not uniform.

The figures show that many salts increase the surface tension of the soil moisture above that for pure water, and that certain other substances decrease the surface tension. Among the latter are some of the most common constituents of manures which greatly decrease surface tension. All oily or fatty substances reduce the tension, and, since both these latter are present in nearly all soils, the average surface tension of the soil moisture is less than that of pure water. Consequently, the tendency is to retain less of such a solution than of pure

TABLE XXV

Solution	Specific gravity	Surface tension dynes per sq. cm.
Water	1.0000	73.9
Common salt ($NaCl$)	1.1000	77.6
Muriate potash (KCl)	1.1000	77.5
Ammonium sulfate ($(NH_4)_2SO_4$)	1.1000	76.8
Sodium sulfate (Na_2SO_4)	1.1000	75.8
Sodium nitrate ($NaNO_3$)	1.1000	75.8
Potassium hydrate (KOH)	1.1000	75.1
Potassium sulfate (K_2SO_4)	1.0830	75.1
Wood ashes	1.0038	75.2
Thomas slag	1.0012	77.4
Marl	1.0013	77.0
Lime	1.0020	75.5
Ammonia (NH_4OH)	0.9600	67.5
Urine	1.0260	64.9
Stable manure	1.0013	73.2
Kentucky Blue Grass soil	1.0000	71.0
Wheat soil	1.0000	69.6
Garden soil	1.0000	69.4

water. Various salts in solution as fertilizers or otherwise, tend to overcome this weakness, and therefore to increase the moisture capacity.

Increase in temperature decreases the surface tension, until near the boiling point it is almost nil. Briggs reports that at 0°C. the tension of pure water is 75.6 dynes per square centimeter, and at 25°C. it is 72.1. At the lower temperature more water is held in the soil, and this is one reason why soils appear more moist in cool seasons. (See also page 183.)

78. Gravitational water.—By reference to the original illustration (page 141), it will be noted that the gravitational water was defined as that portion in excess of the hygroscopic and capillary capacity of a soil. It is not retained by the same forces, and is, therefore, free to move under the influence of gravity, in so far as the condition and character of the soil will permit. The amount of gravitational water depends on the total pore space of the soil on the one hand, and on the total hygroscopic and capillary capacities on the other hand. It is the difference between the total capacity of the soil for water and that held in the other two forms. It is measured by that amount which will flow from a soil having all of its pores filled with water.

The *maximum water capacity* of a soil refers to the total amount of water which can be put in a given volume of soil. It is therefore determined directly by the total pore space of the soil. The pore space may range from 35 per cent in a clean sand to 60 or 70 per cent in a well-granulated clay, and to 80 or 90 per cent in a muck soil. If we assume the weight per cubic foot for these materials given on page 155, the maximum per cent of water is as follows:

Table XXVI

	I Weight per cu. ft. Pounds	II Per cent pore space	III Pounds of water per cu. ft.	IV Per cent of water in soil at saturation
1. Dune sand	80	52	32.5	40.5
2. Coarse sand	81	51	32.0	39.5
3. Fine sandy loam	83	50	31.5	38.0
4. Light silt loam	83	50	31.5	38.0
5. Clay	68	59	37.0	54.5
6. Humus	15	80	50.0	333.0

One effect of moisture on porosity is to be noted here. When a dry soil imbibes water it expands, so that, when the porosity is determined in a wet soil, it is always found to be larger than in the same soil when dry. This expansion is greatest in the fine-textured soil, and in muck it is at the maximum. There are several factors which enter into this result, one of which is the tendency of the soil moisture to float the particles, so that they rest together with less force than when the soil is dry. Gallagher has shown that a sample of muck soil having a hygroscopic capacity of above 40 per cent lost 29.2 per cent of its original volume in drying from a moisture content of 210 per cent to one of about 80 per cent.

In Table XXIII on page 154 is given the maximum capacity and approximate wilting point of the soils

TABLE XXVII

	I	II	III	IV	V	VI
	Weight per cubic foot, in pounds	Maximum capillary capacity	Maximum water capacity	Gravitational moisture	Gravitational moisture in pounds per cubic foot	Ratio of capillary moisture to total water capacity
		Per cent	Per cent	Per cent		
1. Dune sand	80	10.7	40.5	29.8	23.8	1 : 3.8
2. Coarse sand	81	10.6	39.5	28.9	23.4	1 : 3.7
3. Fine sandy loam	83	18.0	38.0	20.0	16.6	1 : 2.1
4. Silt loam	83	20.9	38.0	18.9	15.7	1 : 1.8
5. Clay	68	30.4	54.5	13.9	9.5	1 : 1.8
6. Muck soil	15	250.0	333.0	83.0	12.5	1 : 1.3

recorded in the last table. If this per cent be subtracted from the per cent given in Column IV of the last table, the per cent of actual gravitational water in those soils may be determined. This is shown by the preceding table.

The amount in Column V represents the pounds of water per cubic foot which would be lost by drainage from each of the soils if their pores were all completely filled with water. Such a soil is said to be saturated. That plane in the soil to which level all of the pores are filled with water—saturated—is known as the water-table. This region of saturation is sometimes known as the "ground water."

It is possible to have such a structure in a fine clay soil that all of its spaces are practically filled with water held capillarily. It will be noted from the table that the proportion of the total water capacity which is permanently retained increases with the fineness of the soil, and consequently with the decrease in the size of the individual pores, as is shown in Column VI. The clay in the above tables appears to be very thoroughly granulated, which is responsible for the similarity in the ratios for the silt and clay.

Gravitational water is directly injurious to upland crops, but when it exists at a depth of from four to six feet below the surface, it may serve as a reservoir from which moisture is withdrawn by capillarity, to offset losses by evaporation. Water may be removed by capillarity from the saturated zone to the point where the loss is taking place, and under these conditions the ground water—which then becomes capillary water—

is directly beneficial, and the process constitutes a form of natural sub-irrigation.

The figures presented above illustrate the effect of texture on the total water capacity of a soil, and upon the proportion of gravitational water. Anything which increases the pore space increases the total water capacity. When there is not a corresponding increase in the capillary capacity, as happens in a sandy soil, the total amount of gravitational water is thereby increased. That is, in such a soil, there is a larger amount of water which may be lost by percolation. In so far as organic matter alters the structure of the soil, it modifies the gravitational water content of a soil in the manner just outlined.

79. Amount and rate of loss.—Near the outset of the discussion of soil moisture, it was stated that the amount of water in a soil depends upon the extent and rate of loss of water, as well as upon the factors which have just been explained. For example, fifteen inches of water is far more efficient in crop production when applied to a loam soil in a humid region, like the New England states, than when applied to the sand of the Imperial Desert, California. In the latter case, the loss by percolation and evaporation is so great and so rapid that the amount of moisture available to crops is very small. The two forms of loss which affect the moisture in the soil are: (1) Percolation. (2) Evaporation.

Percolation is the gravitational flow of water through the pores of a soil. Percolation concerns the gravitational water. The total loss in any given soil will depend upon the distribution of the rainfall or the irrigation supply.

Evaporation takes place at the surface, and from the plants growing in the soil. The rate of such loss depends on the climatic conditions. In those regions where the rainfall comes in frequent small showers, which wet the soil to a depth of only a few inches, a very large proportion of this water is immediately returned to the surface by capillarity, and lost by evaporation. On the other hand, if the rainfall occurs at long intervals and in large amounts, so that it percolates deeply into the subsoil. it may be held there by appropriate surface tillage.

III. MOVEMENT OF SOIL WATER

Soil moisture is subject to movement in three ways. This movement may be injurious if it facilitates the loss of moisture, which should be retained for the crop; it may be beneficial when it serves to replenish the moisture supply upon which the plant is dependent. In the discussion of the moisture content and capacity of soils, it was pointed out that no soil retains within the surface four feet enough water to meet the needs of a full-crop yield under average field conditions. This indicates the necessity for the movement into the root zone of moisture, to take the place of that removed by the plant and lost in other ways. The movement of moisture from adjacent supply in the soil,—as the deep subsoil—is just as useful as the direct addition of water to the soil by rainfall. The three types of movement of soil moisture are (*a*) gravitational, (*b*) capillary and (*c*) thermal.

80. Gravitational movement.—Gravitational movement is the result of the gravity pull upon the soil water. The slower the downward movement of water, the longer the water will be in the root zone of the crop, and therefore the greater use will the plant be able to make of that particular supply of moisture. This gravitational movement concerns primarily the gravitational water, and is not effective to move either the hygroscopic or the capillary forms of water, although these are subject to the same gravity pull. The reason is, so far as these forms of moisture are concerned, that the gravity pull upon them is overbalanced by other forces. It will be noticed, in fact, that gravitational water is defined as that part of the soil water which is free to move under the influence of gravity, Such movement constitutes percolation.

The rate of percolation depends upon two primary conditions. These are: (1) The texture of the soil. (2) The structure of the soil. The rate of movement depends directly upon the diameter of the individual soil spaces. The larger the size of spaces, the more freely will the water descend. King has observed the following movement of water through sands of different texture in twenty-four hours:

Table XXVIII

Sands				Clay loam	Black marsh
Mean diameter in m.m.					
.50	.35	.27	.25	......	......
Inches	Inches	Inches	Inches	Inches	Inches
301	160	73.2	39.7	1.6	0.7

The columns were one-tenth of a foot in cross-section and fourteen inches high, and a head of two inches of water was maintained above the top of the soil. These figures show very clearly the reduction in the flow of water as the texture becomes finer.

Under field conditions, the percolation of water through the soil is much facilitated by the presence of numerous cracks, root passages, and worm and insect burrows, because of their relatively large diameter.

Several other factors affect the percolation of water. The entrance of rain or irrigation water into the dry soil where it is applied in a sheet over the surface is hindered by the presence of the air in the pores in the soil. If the subsoil is dense, or is filled with water, this intermediate band of air-filled soil serves to hold back the surface water, except as the air may escape in bubbles through the upper layer. For this reason, in part, a heavy shower of rain sinks into the soil to a very small depth, and is relatively ineffective. Entrance of the water may be greatly facilitated by a loose condition of the soil, which affords quite large as well as small spaces. The large spaces are less likely to be entirely filled with water, and hence afford means for the escape of air, while the water passes in through the smaller pores. There is another hint here in the conservation of rainfall. If the soil is in a very loose condition to a depth of eight or ten inches, the water will percolate into this layer, and its movement will be so much retarded that a larger part will find its way into the deep subsoil and be permanently retained than if the surface soil is uniformly fine.

Changes of temperature affect the flow of water through soils in several ways. It affects the gravitational water directly by changing its viscosity. Warm water is more limpid and flows more freely than cold water, just as oil is thinned by heating. Consequently soils drain more readily in summer than in winter. (See also page 183.)

Changes in temperature also affect percolation indirectly through their effect on the free air in the soil, and the air in the water in the soil. Air, in common with all gases, expands very greatly with a small increase in temperature, and it thus exerts a pressure which may force water out of the soil into the larger drainage channels. Conversely, a lowering of the temperature contracts the air, and causes water to be sucked into the soil.

In the same way, barometric changes affect the drainage of soils. Alternate periods of low and high pressure sweep over the country at intervals of a few days apart, and the changes in volume of the outer air are transmitted to the air in the soil, which expands or contracts and tends to draw water into the soil, or forces it out as the pressure is decreased or increased. The suctional effect of winds may have a similar effect. Strong winds considerably modify the air pressure, and where this is brought to bear on the soil through a tile drain or other underground channel it increases the flow of water.

Water does not necessarily percolate vertically into the soil. It may flow off nearly horizontally, depending on the character of the soil and its conditions. A hard subsoil will deflect its movement. Entrapped air will do the same thing, and this has been found to be a potent source of contamination of open wells with shallow curbing. This is particularly true in heavy soils, where the escape of entrapped air is especially difficult. One of the beneficial effects of under drains is that they facilitate the entrance and movement of rain-water in the soil by affording a channel for the escape of entrapped air. (See page 241.)

81. Capillary, or film movement.—Capillary water has been described (see page 141) as occurring in the soil in a thin film overspreading the particles, and thickened into a waist-like form at their points of contact. Toward the bottom of any soil column the film is always thicker than at the top, owing to the less weight which the surface tension must bear. This form of distribution has given rise to the term film water, from which is derived the idea of film movement, to describe this type of capillary movement.

Film movement expresses very accurately the actual condition of affairs, for if there is any translocation of water at this stage it must be through this film.

82. Principles governing capillary movement.—It will be remembered (page 147) that, when equilibrium is established in any mass of wet soil short of saturation, the water surfaces are comparable to a stretched elastic membrane. The more closely this film is drawn about the particles, the more surface there is exposed, and the greater pull the surface tension exerts. Consequently the greater the amount of water which will be retained.

In a soil capillarily saturated with water there is no movement. For the pull at any one point is balanced by the pulls from every other point, due to the surface curvature of the film and to the weight of the liquid. In the bottom of the column, where the weight of the water acts in conjunction with the curvature of the film, the curvature is less than at the top of the column, where the only effective pull is due to the curvature of the water surfaces. This may be illustrated by the following diagram. (Fig. 52.)

P represents soil particles carrying their maximum film of water, and therefore in equilibrium at every point, so that no movement may take place. The force or pull exerted by the film at the different points is represented by the arrows at A, B, C, D, E, etc., the length of the arrow being proportional to the pull exerted by the film, and in the same direction, or toward the center of curvature of the surface. The difference in the pull, and therefore the length of the arrows at the top and bottom, is compensated by the weight of the water at the bottom. If water is now taken from the film into the rootlet at R, the curvature of the film at that point will be increased. Therefore it will exert a greater pull than the curvatures in the other spaces, and water will be moved to R along the lines U, to replace that taken in by the root. So that the new adjustment would be represented by the dotted lines which show the new curvature assumed at each point, when equilibrium is reëstablished, and the water comes to rest. If water continues to be lost to the root, or by evaporation from the soil at R, the movement of water to that point will be continuous as long as movement is

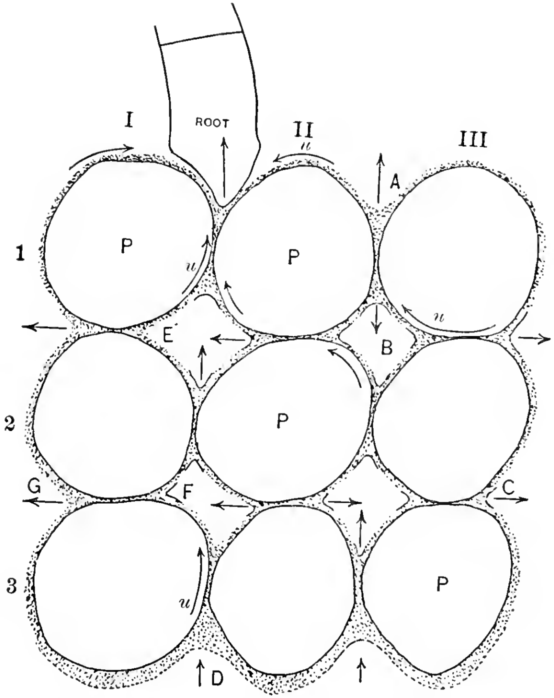

FIG. 52. Showing the distribution of water around a group of soil particles, and the distribution of forces and direction of movement in the re-establishment of equilibrium after the removal of water by a rootlet. For further explanation see text.

possible; the curvatures meanwhile increasing, and the films become thinner and thinner.

It will be noted that the curvature at every point in the plane 1 is the same, and that a similar uniformity prevails for planes 2 and 3. Likewise, in the columns I, II and III the relative curvatures are the same.

Theoretically, therefore, there is no limit to which this adjustment might take place in the horizontal plane. Water might be moved in from a distance of one inch or one rod. Vertically, however, there would be a limit to the height to which water could be lifted, because of the limit to the pull of the surfaces in plane 1.

The larger the number of curves, the greater the total pull per unit area, and consequently the higher could water be lifted—just as there is a definite limit to which water will rise in glass tubes of different sizes. It is therefore possible to keep trimming off the upper end of a column of soil, whose lower end dips in water, until the maximum height through which water may be lifted and lost by evaporation, or otherwise, is determined. This is the *maximum capillary efficiency* of the soil, or the maximum height to which it could deliver water.

According to the above propositions, the movement of water would go on freely and uniformly until the minimum thinness of film was reached. This free movement is modified, however, by another condition. Water, in moving from any point, as C to R, must pass through the thin part of the film between the points of contact, and where it comes in close contact with the soil substance. In this, friction is developed, and the thinner the film, and the closer it is drawn about the particle, the greater does this friction become until it all but stops movement.

For a period, when the film is thick, the movement is relatively free; but, after the water comes within the range of great attraction of the particle, the friction increases rapidly, and therefore the movement of water is correspondingly cut down. This factor of friction greatly limits the effective capillary capacity of a soil both vertically and horizontally. If the coefficient of friction is great, it will soon overcome the pull due to curvature, and water will be quickly moved in from only a short distance. In proportion as the friction coefficient is reduced, the range of movement is extended. It should be noted that friction retards movement rather than stops it. The greater the surface over which a given volume of water is spread, the slower therefore will be its movement. (See page 183.)

In the above discussion it was assumed that the water is uniform in all its properties, and therefore that corresponding curvatures were the same. If, however, anything modifies the surface tension of the liquid at one point—as change of temperature, solution, etc.,—this would be expected to disturb the balance, and result in film movement. Such is the case, as later examples will show. (See page 183.) It is probable that, in the soil, equilibrium is never established, because of these disturbing variations all through the soil mass. Further, the last end of the process of adjustment is exceedingly slow, and probably never actually takes place; because the force producing the motion is successively reduced as equilibrium is attained, and because the difference in curvature of the films is so slight.

83. Extent, rate and importance of capillary movement.—Capillary movement of water is of great consequence to growing plants. Since it concerns the capillary water, it affects that form of soil water upon which ordinary crops are directly dependent. The withdrawal of water at any point by a rootlet is made up by movement of water from the adjacent soil zones. But the plant is not dependent entirely on the movement of water to its roots. The roots are themselves constantly pushing into fresh soil zones, where the moisture, and perhaps also the food, have not been so thoroughly withdrawn. The roots go to meet the capillary advance of the soil water. This advance of the fine rootlets is rapid, and of great consequence in the nourishment of the plant. It also enables the roots to come into more intimate contact with the soil; for, as the water is extracted, it is lost first and most readily from the large pores. The latter amount of water is found in the smaller spaces, and consequently the roots are

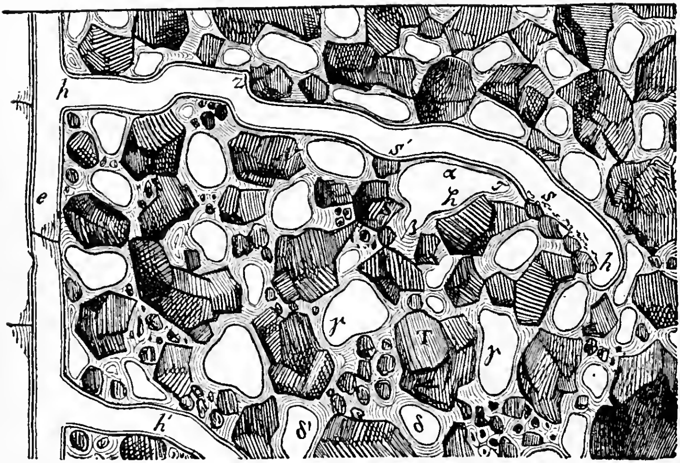

FIG. 53. Penetration of root-hairs through the soil. (*h*, *h'*) root-hairs; (*T*) soil particles; (*s*, *j*) air-spaces. Water is indicated by concentric lines.

led toward these small pores by their attraction for water.

Three primary soil factors govern the capillary movement of water. These are: (*a*) Texture, (*b*) structure, (*c*) dampness of the soil. In addition to these, the movement is affected by (*d*) the surface tension of the soil water, and (*e*) by the condition of the surfaces of the soil particles.

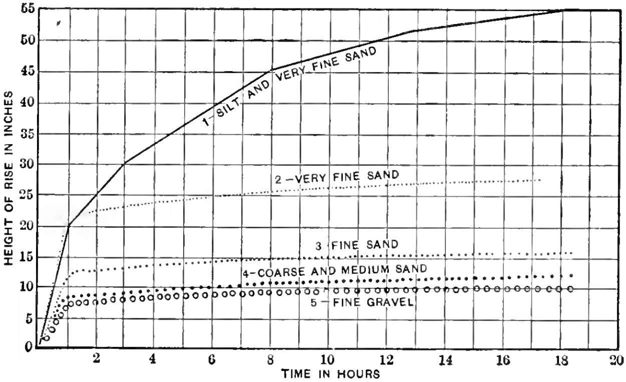

FIG. 54. Curves showing the height and rate of rise of water in dry soils of different texture as given in Table XXIX.

84. Texture.—The influence of texture was explained in the principles outlined above. The finer the soil, the more surface it will expose, the more points of contact there will be between the particles, and therefore the greater total curvature the water surfaces will have. For this reason, a clay containing 20 per cent may draw water from a sand containing 10 per cent of water.

The capillary capacity of a soil may be measured in two ways: (1) By the height to which water will be raised in soils of different texture. (2) By the total amount of water raised through a given height in a definite time. The time element enters into both sorts of measurements, and is an especially important consideration in clay soil where the movement is generally very slow.

TABLE XXIX

SHOWING HEIGHT OF RISE OF WATER IN DRY SOILS OF DIFFERENT TEXTURE, AS SHOWN IN THE ABOVE CURVES

	Time							
	Min.	Hours		Days				
	15	1	2	1	3	8	13	19
	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches
1. Silt and very fine sand . . .	2.7	4.7	7.0	20.0	30	45.0	52.0	56.0
2. Very fine sand	7.6	10.0	12.4	21.0	23	26.0	27.5	28.5
3. Fine sand.	9.0	9.5	10.0	11.6	13	14.3	15.2	16.0
4. Coarse and medium sand . .	5.8	6.0	6.3	7.5	9	10.0	11.5	12.5
5. Fine gravel . . .	4.0	5.0	5.3	6.4	8	9.0	10.0	10.8

These materials were sifted to fairly uniform sizes, according to the scale given above (page 73). The silt was a natural material, containing a large amount of very fine sand, together with some clay. It might be termed a light silt loam. It will be particularly noted that the smaller classes of particles—silt and clay—have a relatively large influence on capillary movement. Above the class of fine sand, there is not much variation in the height of rise for different textures, the total height attained being slight.

Loughridge has made very careful determinations of the capillary power of four dry soils of known physical composition over a period ranging from 6 to 195 days. These soils range in texture from light sandy loam to heavy clay adobe of the following mechanical composition.

TABLE XXX

	Per cent of each separate present			
	Clay less than	Fine silt	Coarse silt	Sand
	Limits used in diameter of particles			
	.01 mm.	.01–.025 mm.	.025–.047 mm.	.047–.5 mm.
1. Sand soil	2.82	3.03	3.49	89.25
2. Light sandy loam	3.21	5.53	15.42	72.05
3. Silty loam	15.02	15.24	25.84	45.41
4. Clay soil	44.27	25.35	13.47	13.37

The composition of these soils is also shown in the following curves:

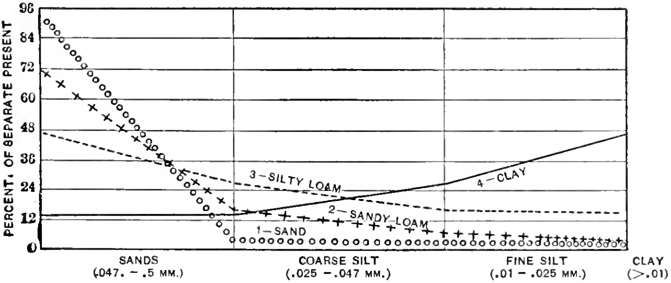

FIG. 55. Curves showing the mechanical composition of the soils whose analysis is given in Table XXX, and whose capillary water capacity is given in Table XXXI and Figs. 56 and 57.

The capillary rise of water in these soils was as follows:

TABLE XXXI.—TIME IN HOURS

	Min.	Hours			
	30	1	2	6	12
	Height of rise in inches				
1. Sand	. .	8.0	10.0	12.0	13
2. Light sandy loam	6.3	9.0	12.7	19.0	24
3. Silty loam	. .	2.7	4.8	8.8	11
4. Clay	0.8	1.4	2.5	5.0	8

TABLE XXXI, continued.—TIME IN DAYS

	Days								
	1	2	6	12	26	48	90	160	195
	Height of rise in inches								
1. Sand	14.0	15.5	17.0						
2. Light sandy loam	28.2	30.5	35.0	38	41	44	46.5		
3. Silty loam	13.0	17.0	20.5	25	31.5	35	40.0	45	50
4. Clay	10.0	14.0	20.0	23	26.5	. .	. .	. .	46

As is always the case, the rise is most rapid immediately after the soil is placed in contact with the water and the rate of rise decreases progressively as the limit is reached. The more coarse the texture of the material, the more quickly is the limit of rise attained.

These figures are shown in the following curves: (1) For the first twelve hours; (2) for the full period.

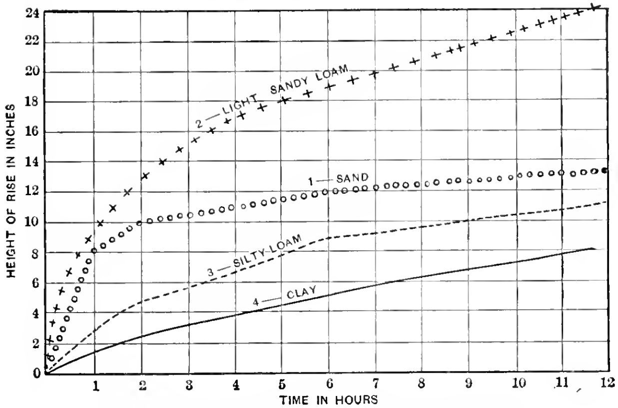

Fig. 56. Curves showing the capillary rise of water in twelve hours in dry soils of different texture as given in Table XXXI.

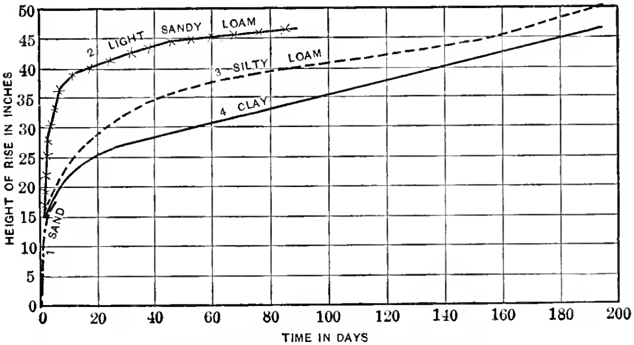

Fig. 57. Curves showing the capillary rise of water in 195 days in dry soils of different texture as given in Table XXXI.

It is evident, from a very simple laboratory experiment, that the rate of capillary movement in dry soil is inversely proportional to the fineness of texture, while the total height of rise is directly related to the texture. Up to a height of three feet, the sandy loam moves water most quickly. But when it is necessary to move water to a greater height, a finer soil is required. The maximum height traversed by capillary water in the above soils is fifty-six inches in the silt loam, and in two instances this appeared to be near the limit of capillary efficiency in dry soil of that texture. In clay the movement goes on very slowly, and an excessively long period is required for the limit to be reached. A crop might perish of drought before water would move up to meet its needs. That is, in fine-textured soil, although its capillary capacity is very great, the surface area of the particles is so large, and therefore the friction in the movement of water so great, that the actual capillary movement is very inefficient.

The same fact appears here that appeared in the discussion of the water capacity of soils, namely, that it is the soil of intermediate texture—the silt and fine sandy loam—which most readily meets the needs of crops for water.

85. Dampness of soil particles.—The capillary movement in dry soil, as given above, does not represent the true capillary capacity. When a soil is dry, it has been shown that it resists wetting, and therefore resists the capillary rise of water. Natural field soils always contain some oily substances, which are deposited on the surface of the soil particles when the soil is dried. This oily matter retards greatly the wetting of the particles, which takes place only after this material has been again dissolved, so that a clean surface is exposed to the solution. Therefore, in a soil which already contains a small amount of water, it is to be expected that the total capillary rise, and the rate of movement of water, would be most rapid. That is, a slight dampness of the soil is conducive to the most rapid capillary movement. Briggs found the limit of capillary movement in dry Sea Island soil—light, fine, sandy loam—to be about 36 centimeters, or 15 inches, in 14 days; while, in the same soil in a moist condition, water was raised through a column 165 centimeters, or 66 inches, in height—4.5 as great a height as in the dry soil. Stewart found the following limits for three sands of slightly different texture when dry and wet.

TABLE XXXII

	Dry	Wet
	Inches	Inches
Soil No. 1	31.8	112.5
Soil No. 2	58.1	141.8
Soil No. 3	86.8	174.1

These results are in accord with field experience. The figures for the moist soil most nearly represent the heights to which soils raise water, and further, under field conditions, the soil, with the exception of the immediiate surface, seldom becomes air dry in the humid regions. Consequently, capillary movement concerns chiefly moist soils.

There are two factors operative to prevent capillary distribution from moist to dry soil. One of them is resistence to wetting. The other is the very slow movement of water in thin capillary films,—that is, when it is reduced to near the minimum capillary content, or wilting point. At this stage the movement is exceedingly slow, because of the excessive friction. This fundamental principle is made use of in soil mulches and determines their usefulness, and should direct their management. (See page 203.)

86. Structure.—Structure affects capillary movement. It has been shown how capillary movement is largely due to the size of the individual spaces in the soil. The size of the spaces is due, (1) To the size of the particles. (2) To their arrangement. (See page 203.) The smaller the particles, and therefore the smaller the pores, the greater the capillary power and the slower the movement. In so far as the arrangement of the particles or structure effects a change in the effective size of the pores, it affects the capillary movement. In a puddled structure the movement is much more slow than in a soil having a granular or crumb structure. Any tillage operation which alters the structure, in either one direction or the other, thereby alters the capillary power and the rate of movement. Compacting a soil is well known as a process which seems to draw moisture into the compacted zone; while cultivation, or loosening the soil structure, has the opposite effect. Upon this fact are based many important tillage operations, such as rolling after seeding small grains.

87. Surface tension.—Surface tension affects capillary movement in the same way that it affects the capillary retention of water. It represents the cohesive properties of the liquid, and corresponds to an elastic membrane.

The stronger such a membrane, the larger the pull it can exert under a given strain. Consequently, in a soil of uniform texture, and in moisture equilibrium, anything which changes the surface tension may set up motion of the soil water. The introduction of fertilizers may set up such a movement, and this addition to a soil may enable it to draw and permanently retain more water than the adjacent soil of same texture. Applications of magnesium chloride, salt and muriate of potash, are observed to keep the soil more moist in dry weather, and a similar effect of some alkali salts has been noted. These materials all raise the surface tension. High temperature reduces the surface tension, and therefore, in a soil in moisture equilibrium, if one part, as the surface, is heated, the water will be drawn away from that region to the cooler zone, where the tension is higher.

88. Condition of surfaces of particles.—The condition of the surface of the soil particles affects the tenacity with which water adheres to them. The application of oil to a soil tends to destroy its capillary capacity; and any substance in the soil which will bring about such a condition reduces the capillary efficiency of the soil.

The action of capillarity is not limited to any one direction. It may take place in any direction. It has usually been measured vertically upward. But it operates vertically downward, as well, and it moves water horizontally. The vertical upward movement of capillary water is modified by the influence of gravity, as is capillary retention. (See page 149.)

The following curves show the capillary transfer of water in two soils through eight feet horizontally.

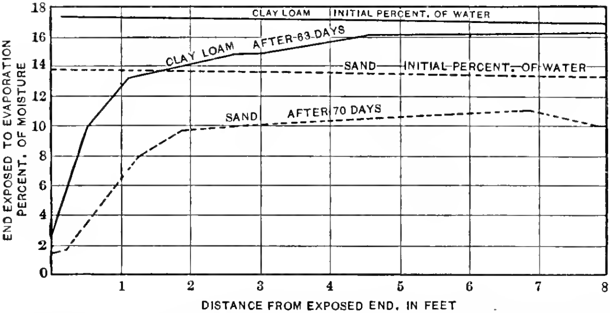

FIG. 58. Curves showing the initial moisture content of horizontal columns of sand and clay loam soil and the distribution of moisture after free evaporation from one end of each column, for a period of days. Note the general movement of water throughout the columns.

It is evident that plants may make use of supplies of moisture to one side, as well as below their roots even, in some soils, to a distance of several feet, through the agency of capillarity. On the other hand, irrigation farmers have repeatedly noted the very limited lateral influence upon crops of the application of water in irrigation. The limit of the application of water is in some soils marked almost to the row. In this instance, it should be remembered that water is added only after the soil has become relatively dry, at which stage the moisture films move with great difficulty due to friction, and probably also to cracks, which of course very effectively break up capillarity. King has concluded from studies on vertical columns that an adjustment of water through ten feet of soil may readily take place.

89. Examples of the amount of water moved.—In crop production, the crucial test of the capillary capacity of the soil is the amount of water it is able to move. It must not only be able to move water a long distance, or to a great height, but it must be able to move a relatively large amount of water, and to move it quickly if the movement shall be effective. The important consideration is the amount of water moved a given distance in a given time. A soil may be able to quickly move large volumes of water to a height of a foot, and be utterly ineffective to a height of five feet. On the other hand, a soil may be so fine as to be able to lift water to a height of forty feet, and yet the movement be so slow and the amount of water moved be so small that the result is negligible,—that is the soil is capillarily ineffective. It therefore appears that, for any given distance within reason and for any normal moisture demand of a crop, there is a texture and structure of soil which will most readily meet those demands. If the water-table is three feet below the surface, a very coarse soil may suffice. If the water-table is ten feet below the surface, a much finer soil will be necessary. On the other hand, to supply a full-sized pumpkin vine, having a large evaporation, from a water supply five feet away, will require a finer soil than is required to supply a Jersey pine having a small evaporation. In other words, we need to know the effective capillary capacity of each soil to different heights and distances, up to their limits.

Very little data of this sort is available. None is available for horizontal movement, and the figures on vertical movement are very incomplete and inadequate. King made such a study of sifted quartz sand having a mean diameter of .47 mm., by means of a column with an expanded top, and found that the sand was able to raise water to a height of 6.75 inches at the rate of 44 inches of water per day, equivalent to 1,340 feet per year. But this same sand failed to lift any appreciable amount of water to a height of 11.75 inches. King has also found the following movement to take place to different heights in columns of soil one square foot in cross section, where the loss was measured by evaporation from the surface.

Table XXXIII

	Height in feet							
	1 foot		2 feet		3 feet		4 feet	
	Pounds per day per sq. ft.	Inches per year	Pounds per day per sq. ft.	Inches per year	Pounds per day per sq. ft.	Inches per year	Pounds per day per sq. ft.	Inches per year
1. Fine quartz sand	2.37	166	2.07	146	1.23	86	.91	64
2. Clay loam	2.05	144	1.62	113	1.00	70	.90	63

As remarked by Professor King, these figures probably do not represent the maximum capacity of these soils to the heights stated. The shorter the column, the less accurate are the figures. For in the short columns the evaporation was correspondingly less than the movement. From the results, it appears that the clay soil was in a very well-granulated condition, which brings its rate very near that of the sand. It also appears from this data, as was shown in the data on height and time of capillary rise, that, up to three or four feet, the fine sand is as efficient as the soil of much finer texture.

In studies on the capillary rise of water in moist Sea Island cotton soil—a fine sandy loam,—Briggs found the movement to be at the rate of 1.3 pounds per square foot per day, or 91 inches per year, through a height of 85 centimeters (34 inches). But when the column of the sand soil was 165 centimeters long, water was raised at the rate of .32 of a pound per square foot per day, or 21.4 inches per year,—a decreased efficiency from doubling the height of the column of 75.4 per cent, When the column was 185 centimeters in height, no appreciable loss took place,—indicating that this sand

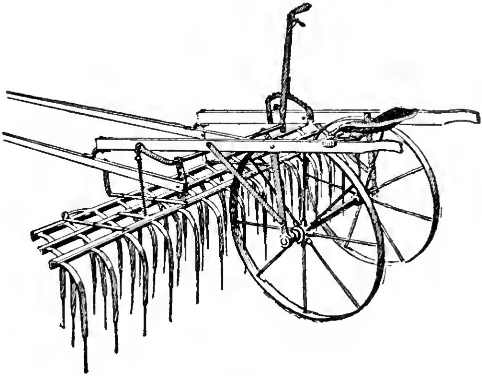

FIG. 59. The weeder, with riding attachment. For very shallow cultivation in mellow soil free from stone and rubbish.

was not able to raise water to the height, even when moist.

Buckingham obtained the following results, which show a very considerable vertical movement in fine sandy loam soils to a height of nearly four feet.

TABLE XXXIV

	I Height of column. Inches	II Dry porosity	III Pounds of water per day per sq. ft.	IV Inches of water per year
1. Takoma lawn......	46	48	.73	51.6
2. Podunk fine sandy loam	46	35	.56	39.4

It must be kept in mind, in examining these figures, that the evaporation conditions in the different experiments were not uniform, and therefore, that the results are not strictly comparable. They do, however, show the movement of a very large amount of water in this way through distances of several feet. The amount so moved in these sandy soils per year is several times the total amount required to produce normal crops. (See page 134.) There is also indication that in the short period of a day the amount of water moved is sufficient to meet the needs of a considerable mass of growing plants. It is regrettable that no figures are available for silt and clay soils, and to greater heights and horizontal distances, in order that a more complete idea of the availibility of water supplies at a distance of six, eight and ten feet, or even more, may be had. This is an important body of information yet to be gained.

90. Thermal movement.—Water moves through the soil in the form of vapor. If a glass vessel or tube filled with moist soil be set on a hot surface, the bottom of the column will be seen to become lighter in color, indicating a loss of moisture. If the whole column is not heated and the moisture is determined in successive sections, beginning at the top, or coldest portion, the moisture content will be found greatest a short distance above the heated layer at the bottom.

When the moist soil is heated, steam is formed, which develops a pressure that forces the vapor rapidly through the soil. But, at ordinary temperatures, this vapor movement is the result of simple diffusion, and it obeys the same laws. Buckingham has shown that the diffusion of air through the pores of the soil is exceedingly slow, and therefore that this phase of soil aëration is of small effect. (See page 439.) He has also shown that the diffusion of water vapor through the fine pores of the soil is very slow. (See table below.)

It is well known that water does not necessarily evaporate at the surface of the soil. It may evaporate in the deep pores in the soil if the air at that point is sufficiently dry. Atmosphere in a moist soil is very near saturation. In a mulched soil (see page 199) evaporation may take place at the top of the moist layer. The loss of water will therefore depend very largely upon the loss of moisture by diffusion through the mulch. Buckingham obtained the interesting results given in Table XXXV bearing on this point:

TABLE XXXV.—LOSS OF WATER BY EVAPORATION FROM BELOW COLUMNS OF DIFFERENT AIR-DRIED SOILS

Soil	Depth of soil layer	Initial porosity	Rate of loss of water per year
	Inches	Per cent	Inches
Coarse sand	2	45	4.30
Fine sandy loam	1	48	2.52
Fine sandy loam	2	46	1.59
Fine sandy loam	4	41	0.93
Fine sandy loam	6	46	0.67
Silt loam	1	54	2.71
Silt loam	2	51	1.60
Silt loam	4	49	0.95
Silt loam	6	51	0.69
Clay	2	46	0.60

It appears from these figures that the thermal movement of water by simple diffusion is determined: (1) By the size of the individual pores. (2) By the total amount of pore space in the soil. (3) Upon the thickness of the soil layer. When equally dry the fine-textured soil retains moisture as vapor more effectively than does coarse-textured soil. In so far as the structure of the soil modifies either the size of the pores or their total volume, it may modify the loss of water. A coarsely cloddy mulch would therefore be ineffective. Particularly striking is the small depth of soil which is effective to prevent the loss of water. Even the one-inch mulch has a wonderfully high efficiency.

IV. CONTROL OF SOIL WATER

In the control of soil moisture it is desired to accomplish one of two things: (*a*) The average *water content* *of the soil* is increased or, (*b*) the average *water content of the soil* is decreased. If the crop is likely to suffer from a deficiency of water, or from conditions associated with a deficiency of water—as food,—we aim to increase the moisture supply by conserving the rainfall, or by direct additions of water. On the other hand, in soils saturated with water, or which are too cold, or too poorly aërated because of an excess of water, it is desired to remove this excess either by drainage or appropriate tillage methods.

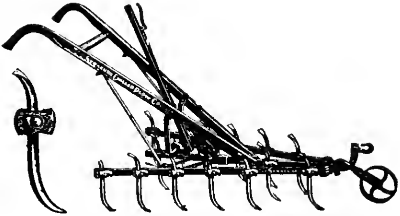

FIG. 60. One-row toothed cultivator. Adapted to shallow tillage and the maintenance of a mulch.

91. Means of increasing the water content of the soil.—The average water content of the soil may be increased in three ways: (1) By decreasing the losses from (*a*) percolation and (*b*) evaporation. (2) By increasing the capacity of the soil for water (*a*) by modifications of texture and structure, and (*b*) by increasing the humus content. (3) By the direct addition of water to the soil, which is irrigation.

92. Decreasing loss.—The water which comes on the soil is subject to two forms of loss. (*a*) It may percolate through the soil and beyond the reach of plant roots. (*b*) It may evaporate.

93. Percolation.—The amount of loss in this way is very great. (See page 192.) Water percolates most rapidly in large spaces, and whether these large spaces are the result of coarse texture or of a loose, cloddy structure, the final result is the loss of water. The following table shows the average results of the Rothamsted drain gages for thirty-four years, by months from 1871 to 1904, on a rather heavy loam or clay loam soil, and twenty, forty and sixty inches in depth. These gages have an area of one thousandth of an acre each, and are kept free from vegetation.

TABLE XXXVI

	Rainfall	Drainage through soil			Proportion of rainfall drained through soil		
		20	40	60	20	40	60
	Depth in inches				Per cent		
January	2.32	1.82	2.05	1.96	78.5	88.4	84.5
February	1.97	1.42	1.57	1.48	72.2	80.0	75.2
March...........	1.83	0.87	1.02	0.95	47.6	55.6	52.0
April............	1.89	0.50	0.57	0.53	26.5	30.0	28.0
May.............	2.11	0.49	0.55	0.50	23.2	26.1	23.6
June	2.36	0.63	0.65	0.62	24.0	27.6	26.3
July	2.73	0.69	0.70	0.65	25.3	25.6	23.8
August	2.67	0.62	0.62	0.58	23.2	23.2	21.7
September	2.52	0.88	0.83	0.76	35.0	32.8	30.0
October	3.20	1.85	1.84	1.68	57.8	57.5	52.5
November	2.86	2.11	2.18	2.04	76.7	76.3	72.4
December........	2.52	2.02	2.15	2.04	80.3	85.4	81.0
Mean total per year...........	28.98	13.90	14.73	13.79	48.2	51.0	48.0
	Results for maximum and minimum rainfall						
Maximum........	38.70	23.50	23.60	24.30	60.7	61.0	63.0
Minimum........	20.50	7.32	7.90	7.70	35.7	38.5	37.6

The rainfall and relative loss through gages of different depths is shown in the following curves, based upon the above figures.

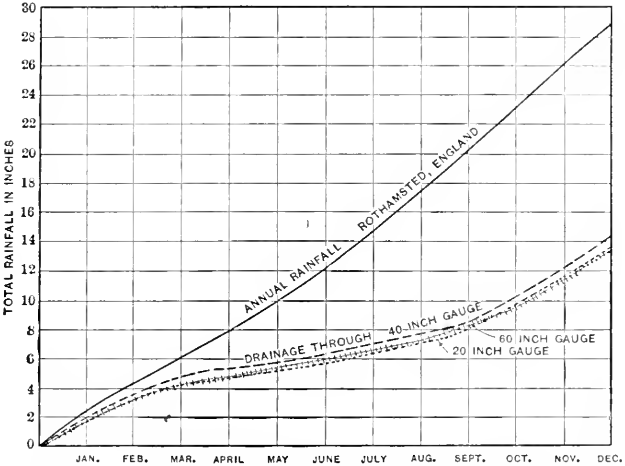

FIG. 61. Curves representing the annual rainfall and percolation through 20, 40 and 60 inches of soil by months. Rothamsted, England. Average of 34 years.

It appears from these figures and curves that about 50 per cent of the rainfall is lost by percolation, under the climate of England. It also appears that the loss is slightly less from the sixty-inch than from the twenty-inch gage. Under a climate less humid, this difference is greater. This is illustrated in two ways: (1) In the above table it is clear that the proportion of water lost by drainiage is much less in summer than in winter. (See page 195.) The saving is somewhat larger in the deep than in the shallow gage, as the proportionate capacity of the soil for water is somewhat greater in this case. (2) It has been estimated that the annual run-off of the streams in the eastern half of the United States amounts to about 50 per cent of the rainfall; but in the basin of the Missouri river the run-off is not over 20 per cent of the rainfall, and in the Great Basin it is practically nil.

These figures give some idea of the total amount of water lost by percolation through the soil, and represent a supply which it is the aim of good soil management to lessen or eliminate, according to the needs of the crop. Loss from percolation may be reduced in two ways, which depend upon the fact that the rapidity of such loss is directly proportional to the size and volume of the pore spaces in the soil. These are (*a*) by modifications of texture, (*b*) by modifications of the structure of the soil. The primary method is, or course, that modification of structure which breaks down the granular arrangement and permits a greater compactness. When rain falls on the soil, its fall is not stopped. It continues to fall through the soil at a reduced rate as gravitational water. And, as the movement of this gravitational water is directly determined by the fineness of the soil spaces, it is possible to very greatly reduce this type of movement by compacting the soil structures. The greater compactness of the soil lengthens out the period during which the soil contains hydrostatic water, and, if the roots of growing plants are distributed through the soil, they are able to make a larger use of this free water than would be possible if the wave of saturation, as a result of rainfall or irrigation, quickly passed beyond their reach. Therefore, on soils subject to excessive leaching, water may be conserved by use of the roller or other compacting implement, and by such management as permits the deep subsoil to become more dense.

94. Evaporation.—The second form of soil-moisture loss is by surface evaporation. It has been shown that, in the process of growth, a large volume of water is evaporated directly from the tissues of the plants. In this process it performs useful functions. But a large amount of water is also lost by direct evaporation from the surface of the soil. If the plants which evaporate the soil water are those of the desired crop, the loss is proper and not to be avoided. But it frequently happens that, either before the regular crop is on the land or mixed with it, are large numbers of worthless plants through which this same moisture loss occurs. This is of course a waste of moisture, and is to be avoided by preventing their growth. It may happen in the spring that the late plowing of land bearing a heavy growth of vegetation permits so great a loss in this way that, unless the subsequent season is one of abundant rainfall, the regular crop may suffer from the lack of moisture which was stored in the soil, and by timely plowing and preparation could have readily been utilized. In this connection, it should be kept in mind that green manure crops may be directly injurious the first season if they are permitted to grow so late before being turned under as to unduly deplete the soil moisture. In the management of green manure crops, that optimum point when the excess of water due to heavy spring rain and winter snow has been removed, but the capillary supply not impaired, should be selected. In semi-arid regions, where dry farming—farming without irrigation where it is usually required—is practiced, it is sometimes advisable to grow but one crop in two years, because the annual rainfall is not sufficient to produce a profitable crop each season. This practice, of course, implies those conservation practices which safeguard the rainfall as it collects, by appropriate tillage methods.

The loss of water by direct evaporation from the soil may be excessive, and result in direct reduction of the crop yield. This type of loss is so familiar that examples hardly need be cited. In the results with the Rothamsted rain gages, about 50 per cent of the annual rainfall was regained in the drainage water. Since the gages bore no crop, the remaining 50 per cent must have been lost by evaporation. And it will be noted that in the summer months under warm temperature this loss was greatest, amounting to 75 per cent of the rainfall. Correspondingly, in the semi-arid and arid sections of the country, where there is little or no drainage, the rainfall is all lost by evaporation. Investigations indicate that about 70 per cent of the precipitation on the land surface is derived from evaporation from the land surface. Even in the humid sections, where the annual rainfall is ample for maximum crop production, the crops are frequently reduced even below the profit point by prolonged periods of dry weather in the growing season, during which the loss from the plants, coupled with the loss from the soil, exhausts the soil supply. If we refer to page 135, we note that the water absolutely needed for crop production, and including the necessary losses from the soil, is only a small proportion of the annual rainfall of most of the cultivated sections. These losses are therefore preventable; and that this is true is exemplified by the large difference in average crop yield on those lands where the best conservation practices are in vogue over those where they are neglected. It should be remembered that over the vastly larger proportion of cultivated land area the crop yields are controlled more directly by the lack of water than by the excess of water. It is a common observation that soils which ordinarily give a low yield in seasons of normal or low rainfall give good yields in wet season, indicating how large a dominating factor is the moisture supply. For the moisture concerns not only its direct use as a food and carrier for the plant, but by its influence on solution, and other essential conditions of plant growth, its is a chief dominating factor in growth.

Soil evaporation occurs almost entirely at the surface. Exception may be made where evaporation occurs into large, deep cracks in heavy clay soil, which is the primary source of subsoil loss in such cases. If this be prevented, as it may be, the loss will be very small. Since evaporation is chiefly at the surface, the nearer the available store of moisture is held to the surface, the larger proportionate loss will occur. This principle has its application in the amount and distribution of the rainfall or irrigation. Frequent small rainfalls are much less effective than less frequent rains in larger amounts. For if the rainfall or irrigation produces only shallow percolation before the water assumes capillary forms, it may be quickly returned to the surface, and lost.

Also there is a certain inherent loss in the most careful field practices, which are proportionately greater with small applications of water than with large ones. It has been shown (page 182) that as the capillary films are reduced in thickness the movement becomes increasingly difficult and slow. Therefore in a fine-textured or dense soil, where evaporation occurs only at the surface, the top layer may become so dry in warm, clear weather that capillary movement practically ceases. Therefore, loss is also stopped. If now there comes a light rainfall,—sufficient to replenish the superficial moisture films, but not enough to produce deep percolation,—the result may be the renewal of capillary movement, which will ultimate in a few days in a greater total loss than would have occurred had there been no rainfall. These results have frequently been observed in practice, and were definitely shown in field moisture studies made by Stewart. In moisture studies of the soil in the open, and under a muslin shade used in growing wrapper tobacco in the Connecticut valley, it was observed that a small rainfall had a much larger effect on the soil-moisture content outside than inside the tent. A rainfall of less than half an inch increased the water in the surface nine inches of the soil outside the tent to a larger extent than could be accounted for by the rainfall. Careful calculations and observations indicated that the difference represented movement up from the subsoil, due to the renewal of film movement. King has obtained similar results in field studies which he has checked experimentally. This emphasizes the desirability of storing water as deeply in the soil as is practicable, and of giving a few relatively large applications rather than many small ones, in the artificial addition of water.

Surface evaporation may be reduced in two ways: (1) By the application of some protective covering to the moist soil. (2) By such surface treatment as will reduce the tendency to evaporation.

95. Mulches.—The protective covering constitutes a mulch. That is, a mulch is any material applied to the surface primarily for the purpose of preventing evaporation. It may at the same time fulfil other useful functions, as keeping down weeds and maintaining a more uniform soil temperature, but its primary use is to prevent evaporation. Of course, in so far as the growth of weeds is prevented, moisture loss from that source is eliminated, and at the same time plant food is conserved for the regular crop.

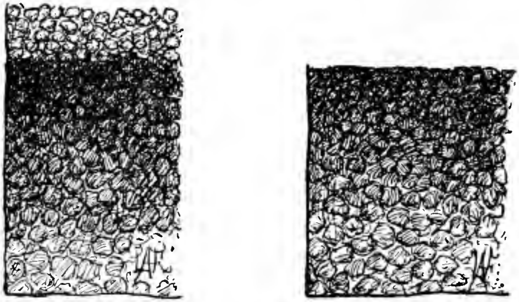

FIG. 62. Two types of soil structure. On the right, compact soil, due to the use of the roller. On the left, the same soil, loosened at the surface to form a mulch.

Mulches are of two sorts: (1) Foreign material applied to the surface of the soil. (2) Those composed of the natural soil modified by appropriate tillage.

The action of both sorts of material depends on the facts shown on pages 180 and 189; namely, that capillary action may be changed or broken by sufficient change in the texture or structural properties of the material, and, second, that the diffusion of water vapor, even after evaporation has taken place, is exceedingly slow through small irregular pore spaces, such as exist in all materials effective as mulch. Any material is effective as a mulch in proportion as it fulfils these conditions; and their practical application, therefore, becomes chiefly a matter of selecting that material which meets these requirements, and may be readily applied.

Many kinds of material are used as a mulch. Straw, chaff, dead weeds, stubble, leaves, sawdust, manure, boards, canvas, stone, coarse sand—all of these are used, and many other waste materials which may be available. They act as a cover to the moist soil, so that water which is held in the surface of the soil, or is brought up by capillarity, must evaporate into this stagnant and therefore soon-saturated atmosphere; under which conditions the loss must be much less than where the vapor is freely removed, and dry air brought in contact with the moist soil. All of these materials are very efficient as a mulch, their efficiency depending upon their thickness and porosity. Straw and leaves, when fresh and dry, will reduce evaporation below 10 per cent of the normal, when in a layer three or four inches thick. As they decay and become water-soaked from successive rains, their efficiency decreases; but they retain an efficiency of at least 50 per cent for a long period, or until they are so decayed that they acquire decided capillary capacity. A practice based upon this effect is that of growing potatoes under straw. The potatoes are laid upon the surface of the ground, and covered deeply with straw, which keeps the surface soil so moist that the potatoes sprout and will grow a reasonable crop to maturity, when the straw has simply to be raked back and the tubers, clean and smooth, are found on or very near the surface. Leaves, including pine needles,

Fig. 63. A very stony soil. Boulders and gravel serve as a mulch, promote drainage, and increase the warmth of the soil.

and sawdust, are very effective as a mulch, but some precautions should be observed in their application. For example, the oak is rich in tannic acid, which may be washed out of the mulch into the soil and cause injury to its producing power, by its effect on the growing plant. In some European countries, as well as in a few places in America, stone has been drawn on the soil, particularly in orchard and vineyard culture, to serve as a mulch, and with markedly beneficial effects. Particularly is this true on those lands too steep to permit cultivation. And, as a corollary to this practice, it has been observed in the fruit-growing section of the Ozark Mountains, and doubtless in other regions, that the removal of stone from the land not only permits the soil to become more hard, but also reduces crop yield by increasing the loss of moisture. It is therefore for the farmer to decide whether the inconvenience to tillage or other operations due to the presence of the stone may not be more than offset by their beneficial effects. A layer of two or three inches of coarse sand or fine gravel is a very effective mulch, and is frequently used in greenhouse practice.

The above-mentioned mulch materials are all strictly artificial, and their application is greatly limited, due to the lack of material and the expense involved. They are therefore used only under special conditions. But the second type of mulch is almost universal in its practical availability.

Almost any soil may be converted into an effective mulch by proper treatment. This treatment will differ with the character and condition of the soil and the climate. Mulches formed from the natural soil are commonly termed "dust mulches," or more expressively "dust blankets." A dust mulch is simply an air-dry layer of the natural soil covering the moist soil below. It may be in a compact condition, but ordinarily it is loose and friable. Its creation is dependent on the principles explained on pages 172 and 189 concerning capillary movement and diffusion of water-vapor. Under arid conditions where the atmosphere is dry and hot, and in free circulation, the surface soil is quickly dried out after an application of water. This drying takes place so rapidly that the capillary films quickly become so thin that movement is stopped, and no more water is brought to the surface. The soil may be ever so hard and compact, but so long as it is kept dry it very effectively preserves the moisture below. The more rapid the loss, the more quickly will the mulch condition be created, and therefore the less the total loss of water is likely to be. This has been demonstrated by Buckingham in some experiments in which arid climate conditions were created at the surface of a capillary column forty-six inches in height. The soil was a fine sandy loam, the equilibrium distribution of water in which is shown in the curve on page 148. At first, the loss under the arid conditions was very rapid and exceeded the humid conditions, but the rate of loss soon dropped considerably below the humid column, and continued to fall behind during the twenty days of the experiment. This experiment was conducted under the most difficult conditions for creating a mulch, since the soil used was of intermediate fineness and had a large effective capillary capacity, and, further, it had a full supply of water at the bottom of the column,—conditions seldom found in practice, and certainly not common under arid-climate conditions. The curves of water loss, showing the mulching effect of rapid drying, appear below:

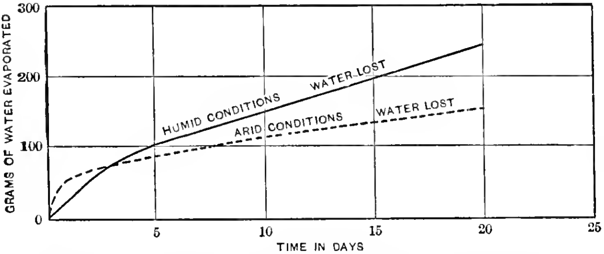

FIG. 64. Curves showing the relative evaporation of water from two columns of the same soil. One was kept in a dry atmosphere at the immediate surface. The other was maintained under normal humid climate conditions of moisture and temperature.

For the reasons presented, the moisture supply in arid regions appears to be naturally more effectively conserved than in humid regions,—certainly a wise provision. This fact is to be connected with the further one that capillary movement into the deep subsoil is very slow.

The mulching effect described above gives further emphasis to the unwisdom of frequent small applications of water to the soil.

In humid regions the natural mulching effect is much less marked than in arid regions. If the farmer would produce a soil mulch, he must do it by creating as far as possible the arid conditions. That is, he must bring about such a rapid drying of the surface soil as to convert it into a mulch which will retain the moisture below. Since in humid regions drying is usually slow and capillary movement strong, the process is hastened by loosening the top soil by frequently stirring, in order (1) to hasten the drying of that surface portion to the point where capillarity is stopped, and (2) to reduce its capillary conductivity,—both of which hasten the formation of the mulch. It is for these reasons that a mulch is generally a loose layer of soil.

The management of the mulch is evident from the principles involved. It must be kept dry in order to break up capillarity. In humid regions, where frequent rains occur, the mulch may be destroyed. After such a rain, when the soil has reached the proper dryness, it should be again stirred, to renew the mulch. On heavy clay soil in fine tilth, a mulch may be destroyed by very moist foggy weather, or by a number of days of very humid atmosphere, which, by condensation of moisture on the clay, hastens the reëstablishment of capillarity with the subsoil, by which moisture may be pumped up and lost. This is to be overcome by occasional stirring, as conditions may require. Another important effect of the mulch on clay is to keep the shrinkage cracks filled up, and thereby prevent the deep drying-out of such soil.

When perfectly dry, a coarse sand and a pulverized clay are of almost the same practical efficiency. (See page 190.) It is only when the structure becomes that of coarse clods or stone that the efficiency is greatly reduced. A cloddy surface soil is worse than a smooth surface with no mulch, for the clods are free to evaporate water, and offer small protection to the subsoil. On the other hand, the pulverized clay has so great hygroscopic and capillary power that its efficiency as a mulch may be readily destroyed by natural climate and soil conditions of common occurrence. It is therefore more difficult to maintain a dust mulch of clay than of sand. The strong natural mulching tendency of sand may be seen on sand-dunes, where, although the surface is dry and hot, moisture may be exposed by the toe of one's boot at any season.

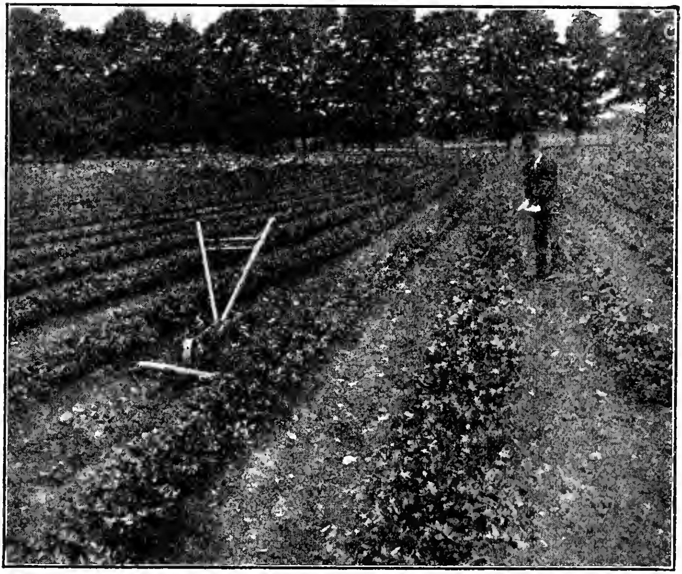

FIG. 65. An example of clean, thorough tillage, and the maintenance of an effective "dust mulch."

A perfectly dry dust mulch need not be very deep, to be effective. One inch of sand will permit loss by diffusion of less than three inches of water per year, under the most favorable conditions. In practice, however, it is found that two or three inches are usually most effective because of capillary action. And Fortier has concluded from experiments on irrigated soil in California that a ten-inch mulch conserves more moisture than one of less depth. But the efficiency of the ten-inch mulch as compared with the four-inch is very much less in proportion to depth, and the latter conserves 75 per cent of the water lost where no mulch was used. Sand mulches may be thinner than clay mulches. King found in Wisconsin that, for corn, cultivation with a small toothed cultivator to a depth of three inches saved more moisture in fifteen cases out of twenty than did more shallow tillage, but that increase in depth resulted in no corresponding increase in efficiency. The sweep or blade type of cultivator (Fig. 137) may be used more shallow than an implement producing ridges. The mulch should be no deeper than is necessary to prevent loss of water, since this top layer is usually most rich in available plant-food, particularly nitrates, and the roots are excluded from it by tillage. Unnecessary depth reduces the root range. Some results from an experiment conducted at Cornell University serve to illustrate the relation of mulches and weeds to soil moisture and crop production in a humid region in a season of good rainfall. The crop grown was maize. Every third plot was a check, and was given normal treatment. The figures show the increase or decrease in yield as compared with the nearest check plots. Moisture determinations were made on portions of the plots bearing no crop, but otherwise receiving the same treatment as the remainder of the plot. The table thus shows the moisture conserved or lost by treatment, entirely aside from that transpired by the crop.

TABLE XXXVII

	Increased (+) or decreased (—) yield	Yields calculated to basis of 100 on check plots	Soil moisture during August	Comparison soil moisture basis of 100 on check plots
	Pounds		Per cent	
Check plot	......	100	21.1	100
Weeds removed, but not cultivated	—157	96	18.2	90
Mulched with straw	+873	121	25.0	130
Check plot	......	100	18.2	100
No cultivation; weeds allowed to grow	—2,888	31	9.8	54
One cultivation; weeds allowed to grow	—109	98	17.0	95
Check plot	......	100	17.7	100

The application of the dust mulch is not confined to inter-tilled crops like maize, potatoes, vineyards, fallow, etc. Under some conditions, it may be applied to grain fields with good results. In those sections of the country where "dry farming" is practiced, it is not uncommon to drag the grain field with a sharp-toothed harrow, the teeth pointing very slightly backward. This is begun when the plants are small, and may be kept up until they attain a considerable size or until they sufficiently shade the ground to greatly reduce surface evaporation. The surface soil between the plants is broken up and converted into a mulch. Similar to this is the use of the harrow in the early stage of growth of cultivated crops, by which the weeds are kept down and a mulch created. If the practice is begun when the plants are very young—even before they appear above the ground—so that the formation of roots very near the surface is prevented, it may be kept up to very a advanced stage of growth without serious injury.

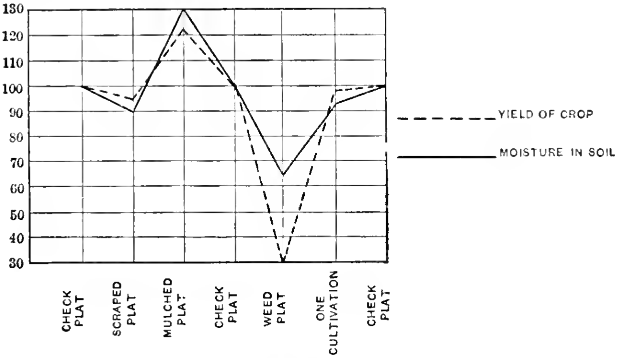

Fig. 66. Curves representing relative yield of dry matter and moisture content of soil on field plots given different cultural treatments. (See Table XXXVII.)

But dragging only after the plants are good-sized may cause serious loss.

96. Mulching plow land.—It frequently happens, especially on heavy soil, that it is impracticable to complete plowing before the soil, if left in its natural condition, becomes too dry for the best results. In such cases it is frequently practicable to quickly form something of a mulch by use of the disk or toothed harrow. Further, this treatment creates numerous lines of weakness which, although drying may progress further than is desired, will cause the soil to break up into a much better condition than if the surface had not been treated. The width of the disk or harrow makes it possible to cover a large area in a short time, and thereby considerably lengthen the period during which plowing can be satisfactorily done, as well as conserving moisture for the succeeding crops.

To summarize briefly the cardinal points in mulch control: (1) They are more effective and more easily maintained in an arid than in a humid climate. (2) Their efficiency depends directly on their dryness and fineness. (3) Sandy soil is more easily maintained as mulch than clay soil. (4) From two to three inches is ordinarily the most effective depth. (5) After heavy rain, the soil mulch must be renewed by tillage, and this is much more urgent on clay than on sand soil. Even without rain, a clay mulch may become inefficient. (6) Tillage for mulch purposes must ordinarily be more frequent in the spring, or humid season, than at other times of the year. (7) The use of foreign materials as mulch may be justified under special circumstances.

97. Fall and spring plowing.—Fall and early spring plowing owe much of their efficiency to the conservation of moisture effected through the creation of a mulch over the surface. Fall plowing may be practiced for a number of reasons, but in regions of deficient rainfall, particularly in the winter, the conservation of the moisture in the soil at the close of the growing season is an important consideration. This practice is well adapted to those soils in the semi-arid section that do not blow too badly when fall-plowed, and where the winter rain is not sufficient to saturate the soil. If the soil is left in the bare, hard condition resulting from the removal of a crop of maize, wheat or barley, a large amount of water may be lost by evaporation during the fall months.

For the average farmer in humid regions where the winter rainfall is sufficient to saturate the soil, early spring plowing, coupled with tillage, is much more important. Not only may moisture be conserved, but the soil is worked at the stage when it yields most readily to pulverization. Fallow land, and bare stubble land of fine-textured soil, are most benefited, since they become compact to the very surface as a result of the winter rain and snow, and are therefore in condition for the most rapid loss of water. They should be plowed as early as practicable without injury to their structure. At the Wisconsin station, two adjacent pieces of land very uniform in character were plowed seven days apart. At the time the second plot was plowed, it was found to have lost 1.75 inches of water from the surface four feet in the previous seven days; while the earlier plowed piece had actually gained, doubtless by increased capillarity, a slight amount of water over that it contained when plowed. There was a gain of nearly two inches of water in the root zone as a result of plowing one week earlier, enough to produce 1,500 pounds of dry matter in maize per acre, if properly conserved.

In arid and semi-arid regions, and in other sections where heavy soil is plowed in the late summer, and especially where a large crop of green manure or a large application of coarse strawy manure is plowed under at any season, it is essential that the lower part of the furrow slice be brought into close contact with the subsoil as soon as possible, in order, (1) that the best possible capillary contact with the subsoil may be established; (2) that there may be sufficient moisture to promote the rapid decay of the organic matter; (3) to increase the moisture capacity and cut down loss by percolation and evaporation. This may be accomplished

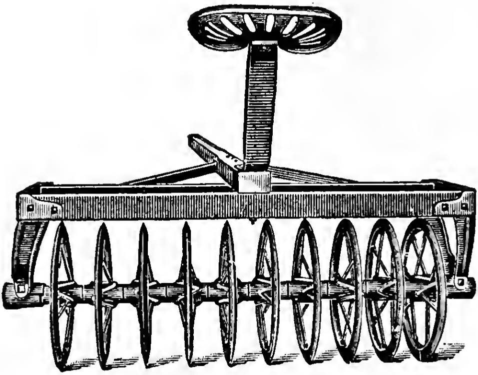

FIG. 67. The Campbell subsurface packer

by rolling the plowed land, but in particularly dry regions the practice of *sub-surface packing* is advantageous. The aim of sub-surface packing is to pack the soil and still leave a loose mulch on the surface. The subsurface packing may very well be applied to land subsoiled in the spring. Land subsoiled in the fall will not, as a rule, require this treatment,—certainly not in the humid sections of the country. To accomplish subsurface packing, a special group of implements have been devised, one of which consists of small wheels placed five inches apart on an axle. The rim is much thickened and is triangular in shape, with the thin edge outward, so that the effect is to give a decided downward and sidewise pressure, while enough fine earth is left at the immediate surface to serve as a mulch.

98. Other surface treatments.—Other surface treatments aim to decrease the tendency to evaporation. When evaporation takes place into a quiet atmosphere, the layer next to the soil soon becomes so nearly saturated with moisture that the rate of evaporation is greatly reduced. But if the atmosphere is in free circulation,—that is if there is wind,—the saturated air is removed, and more dry air is brought over the soil into which evaporation is continuous. The drying effect of wind is very generally recognized. Warm winds in spring and early summer are recognized as particularly drying, and in the semi-arid section just east of the Rocky mountains so-called hot winds sometimes do great damage to growing crops by the rapid evaporation they produce. Obviously anything which reduces the free circulation of the air—"breaks the wind"—will reduce evaporation. In practice, this takes the form of wind-breaks of various types. Strips of timber are commonly grown or retained for this purpose. Wooden fences and walls of one sort or another have a similar effect. Wind-breaks composed of growing plants have the disadvantage that for a considerable distance beyond the spread of their branches their roots penetrate the soil and use the moisture, which is one reason for the smaller growth of crops near trees. But artificial shelters do not have this advantage. Bearing on the efficiency of wind-breaks, results by King show that when the rate of evaporation at 20, 40 and 60 feet to the leeward of a black oak grove 15 to 20 feet high was 11.5 cc., 11.6 cc., and 11.9 cc., respectively from a wet surface of 27 square inches the evaporation was 14.5, 14.2 and 14.7 cc., at 280, 300 and 320 feet distant,—or 24 per cent greater at the outer stations than at the inner ones. A scanty hedge-row reduced evaporation 30 per cent at 20 feet, and 7 per cent at 150 feet, below the evaporation at 300 feet from the hedge.

On sandy soil, wind-breaks prevent the blowing of the dry surface soil, which would expose a fresh surface of wet soil from which evaporation would be increased.

The glass house reduces evaporation by preventing winds. Some crops are grown only in the shade of other crops, where they are not only protected from the sun but from evaporation by the stagnating effect of the surrounding vegetation on the atmosphere. Grass protects the surface of the soil from evaporation, acting like a mulch. The largest application of this principle is in the tents used in growing wrapper tobacco in Florida and the Connecticut valley, and, to a less extent, for other special crops in various parts of the country. The most common form of the tent is a frame eight or nine feet high, over which is spread a loosely woven cloth—cheese-cloth. Investigations by Stewart in Connecticut showed: (1) That the tent greatly reduced the velocity of the wind. This reduction amounted to 93 per cent when the outside velocity was seven miles per hour, and 85 per cent when the outside velocity was twenty miles per hour, there being a small regular decrease in relative efficiency with increased velocity of the wind. (2) The relative humidity under the tent was higher than outside, and during a good part of the time attained a difference of 10 per cent. The effect of this was to reduce evaporation, by from 53 to 63 per cent on different days in July, in spite of a higher temperature inside the tent. (3) The direct effect of these was to increase the moisture content in the soil in spite of a larger crop growth under the tent. These differences are shown by the following curves, which represent the per cent of water in the soil to a depth of nine inches from June 13 to August 1.

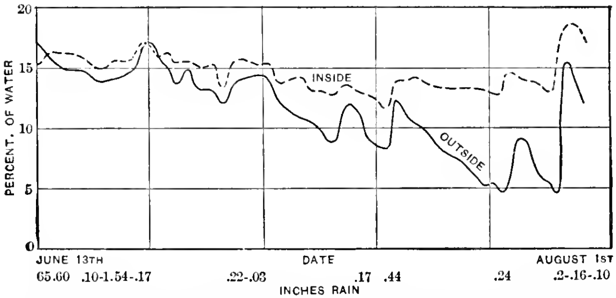

FIG. 68. Curves representing the per cent of moisture in a sandy soil to a depth of nine inches inside and outside of a loosely woven cloth tent, July 13 to August 1, Western Connecticut.

Not only was the effect of the tent to prevent evaporation and thereby increase the average moisture content of the soil, but the soil was able to maintain a more uniform content, due to the more free movement and adjustment of the capillary water under the tent—conditions most conducive to rapid crop growth. (See page 172.)

The velocity of the wind next to the ground may be checked by ridging the soil. It is doubtful if this practice conserves moisture, because more surface is exposed over which evaporation may take place. On the other hand, wide experience, as well as investigation, indicates that for the conservation of water level culture is better than ridged culture. This principle has led to the gradual abandonment of the practice of "laying by" corn and potatoes with a high ridge. In all regions of deficient rainfall, the best practice prescribes level tillage and a fine, dry mulch, both of which are attained by the frequent use of shallow-running small-toothed cultivators. Many experiments have demonstrated the larger crop yields to be obtained from this practice, on the average.

The removal of weeds has been mentioned as a means of conserving moisture. The plants serve to expand evaporating surface in the same way as ridged culture. (See page 195.)

99. Increasing the water capacity.—Increasing the water capacity of the soil may be effective in conserving soil moisture by holding more of the water which falls. The first aim should be to get the rainfall or irrigation water into the soil. It is well known that after a long dry period when the soil—particularly a fine-textured soil—has become dry and hard, the first rainfall may be largely lost by running away over the surface. Sudden showers are almost entirely lost in this way, because not only is the water repelled, but the small amount which is absorbed is held so near the surface that it is quickly lost. Gentle rains are usually much more effective than sudden showers in soaking up the soil. On the other hand, if the soil is loose and porous, all the water which is applied sinks into the soil and may percolate deeply. It is this condition which should be maintained. Correlated with the loose surface soil is the rough surface maintained in level sections of strong winds, where a considerable part of the precipitation falls as snow. A rough surface holds the snow against blowing, and upon melting in the spring it enters the soil.

The moisture taken up by the soil should be retained and conserved by appropriate cultivation. It will be apparent from the principles which have been outlined that all soils may not be managed in the same way, to increase their moisture capacity. In some the end is accomplished by loosening the structure, and in others by compacting the structure. Cultivation, the roller, the subsoil plow, or fall plowing, are to be adopted in so far as they accomplish the desired result on the particular soil in hand. The opposite effect of the same treatment on different soils is shown by the following figures.

TABLE XXXVIII

Soil	Condition	Amount of water taken up	Per cent of water taken up
Clay loam	Loose	178	43.6
	Compact	85	23.8
Silt loam	Loose	182	44.1
	Compact	99	15.3
Medium sand	Loose	158	26.8
	Compact	147	23.2

The proportionate increase in the water capacity of the sand and decrease of the clay loam is here well shown, and doubtless, if the column had been longer, the compact sand would have had a greater absolute capacity than when loose.

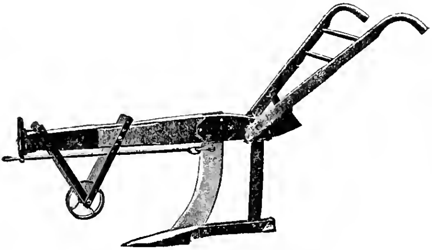
FIG. 69. Subsoiler that loosens the subsoil by raising and breaking it.

Deep plowing is greatly to be recommended as a practice to increase the moisture capacity of the soil, particularly where organic matter is well supplied. It creates a deep soil, and should establish the best conditions for the storage of moisture, as well as food for the plant. If organic matter is not supplied, deep plowing is not advisable on light sandy soil; but on clay soil it is beneficial because of the loosening or granulating effect.

The practice of subsoiling aims to loosen up the structure of the deep subsoil without turning the material to the surface. It increases the ease of root penetration, the rate and depth of percolation, and on clay soil it increases the water capacity. Subsoiling is unnecessary and may even be injurious on sandy soil, and on clay soils must be used with discretion. It is difficult to secure the proper moisture condition of clay subsoils for plowing in the spring in time for spring planting. The soil may be in good working condition, or even dry, while the subsoil is wet enough to puddle. On the other hand, if the subsoil gets dry enough to break up, it may remain so loose and lumpy during the remainder of the season that capillarity is largely destroyed, and crops suffer from shallow rooting and lack of moisture. Decrease in crop yields as a result of subsoiling in spring are frequently reported. On the other hand, subsoiling in the fall, although usually more difficult to accomplish, is more likely to result in benefit. The cloddy condition which may be developed is largely broken down in regions of heavy winter rain by the saturated condition. Still the structure does not become nearly so compact as before the treatment, and good results.

King presents figures which show that, as a result of the application of 1.34 inches of water, the soil which had been subsoiled to a depth of twenty-one inches retained, after a period of four days, 65.6 per cent more water in the surface four feet than the adjacent land not subsoiled.

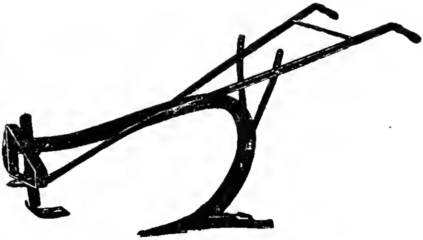

FIG. 70. Subsoiler that loosens the subsoil by breaking through.

Not only is subsoiling effective to increase the absolute water capacity, but it may strengthen the capillary or film movement to such an extent that an important amount of water is drawn up from the deeper subsoil or from adjacent zones not so treated. A "hardpan" layer below the plow depth may seriously interfere with the upward movement of water and the penetration of roots. This condition may be largely corrected by subsoiling.

Coupled with deep plowing and subsoiling, subsurface packing is often very beneficial. Particularly is this true in early fall and late spring plowing, where the soil is likely to be cloddy and to make poor capillary contact with the subsoil. Spring crops may be greatly injured by this condition. The subsurface packer crushes the clods, presses the furrow slice down more firmly on the subsoil without compacting the surface soil. It leaves a light mulch on the top to hold moisture. Not only is it useful in improving the soil structure under the conditions just mentioned, but it promotes the decay of organic manures and assists plant roots in penetrating into the subsoil below, where they may have a larger moisture and food supply.

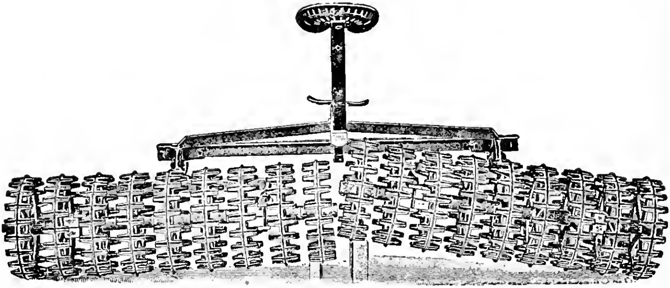

Fig. 71. "Clod crusher" and sub-surface packer.

Increase in the humus content stands next to modification in texture and structure as a means of increasing the water capacity of the soil in accordance with the principles explained on pages 144 and 153. It accomplishes this not only through its own large water capacity, but by its favorable influence on the structure of the soil. It should be worked deeply into the soil, in order that its many beneficial effects may be brought to bear on as large a volume as possible. It is especially favored as the adjunct of deep plowing and the use of lime for improving soil condition, particularly clay soil.

The means for increasing the organic content of the soil have been discussed. (See page 131.) They include the application of animal manures and other refuse, and the growth of crops for green manure, together with that crop rotation which promotes the accumulation of crop remains, and that type of farming which removes the smallest proportion of the crop from the farm and returns the largest proportion to the soil.

100. Irrigation.—Irrigation is the third method by which the soil moisture may be increased. It is the practice of directly adding water to the soil, to supplement the natural rainfall. It is chiefly identified with the arid and semi-arid sections of the country, where the annual rainfall is small. It is customary to consider a region as having a semi-arid climate when the rainfall is between ten and twenty inches, and arid when it is less than ten inches. These limits are arbitrary and necessarily elastic, because the actual aridity of a region depends on other factors than the total annual rainfall. It depends on the distribution of the rainfall, the climate, particularly temperature, and the character of the soil.

While irrigation has been chiefly identified with arid and semi-arid sections (see map, page 137), it is not limited to those regions, and is applicable under any condition where the natural rainfall is deficient at any period of the growing season. Consequently, irrigation is practised even under the very humid climate of Florida, with sixty inches of rainfall, around New York City and Boston, with forty inches of rainfall, and at many other places in the United States and Europe, where a so-called humid climate prevails. In these latter places it is identified with special crops of high value which will justify the expense involved. In France, Germany and other European countries, there are extensive areas of grass land which are artificially watered, often with sewage, which adds the element of food supply as well as water. Of course, all greenhouse management involves the practice of irrigation.

Many engineering problems are involved in the practice of irrigation, and have to do with the collection, storage and application of water to the land. But the principles which govern the application—the method, time and amounts of water—suitable for each crop and soil are purely agricultural considerations, to be handled in each case as the local conditions may indicate.

The amount of water necessary to be added to produce a full crop constitutes the "duty," or efficiency, of water. It is the least amount of water which will produce a given yield under a given set of conditions. The "duty of water" depends upon a great many factors; in fact, is limited by as many things as affect the moisture supply of soils in humid regions. The discussion of irrigation which follows presupposes an adequate supply of water, a condition often not fulfilled. For example, the area of the Western States containing public lands is 973 million acres, of which Newell estimates that about 70,000,000 is of a desert character. At the present time, irrigation is practiced on less than 1 per cent of this area, and the total water supply is estimated to be sufficient for less than 10 per cent of the total area.

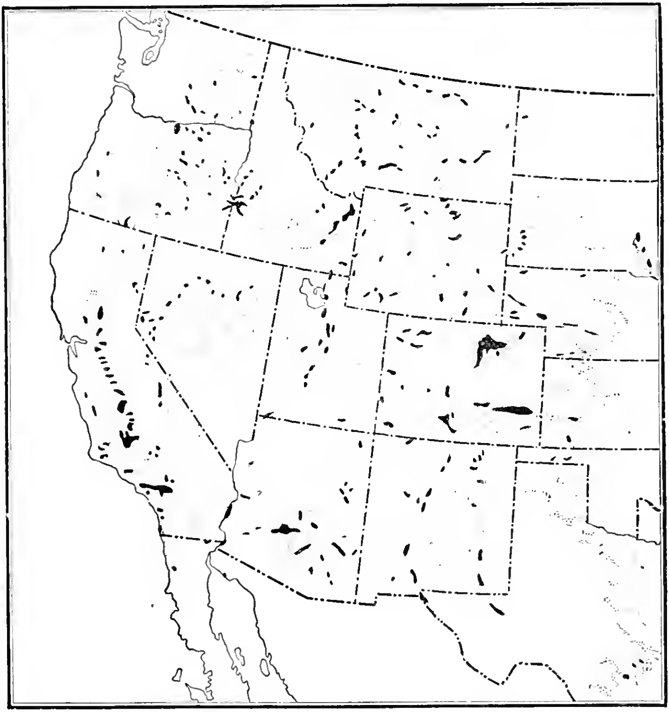

FIG. 72. Map of the western portion of the United States, showing in black the irrigated land, and in dots the area which may be irrigated if all the available water supply is utilized.

101. Factors affecting the duty of water.—Eleven factors, as follows, affect the duty of water in irrigation:

(1) The peculiarities of the crop (see page 134). Some crops require much more water than others for their growth and maturity. Even certain varieties may require much more water than others of the same species.

(2) The physical character of the soil. If the application of water is such that leaching may take place, more water will be lost through sand than through clay. The character of the soil also determines the effectiveness of the mulch, which may be maintained.

(3) The character of the subsoil.

(4) The frequency of irrigation.

(5) Amount and distribution of the rainfall. These last two factors are closely related in their effect on the duty of irrigation water. Their frequency determines the proportion of the water which will be lost by surface evaporation. (See page 198.)

(6) The amount and time of applying water. Water applied in the evening will be more efficient than when applied in the morning, because during the cool night it will have opportunity to diffuse deeply into the soil, where the hot sun of the following day will have less effect upon it than if the water were applied in the morning.

(7) The climate. Other things being equal, more water will be required in a warm, windy climate than in one of a cool, quiet atmosphere. This factor, of course, largely determines the rate of evaporation.

(8) Method of applying water. The furrow system is usually more economical of water than the flooding system, because less opportunity is given for evaporation.

(9) The fertility of the land, as distinguished from its physical properties, determines the duty of water through its influence on the size of crop which may be produced. A large crop is more economical of water than a small one, but a large crop will require a larger total amount of water.

(10) The closeness of planting affects the loss of water in much the same way as a large or a small crop: (*a*) By determining the total amount of water which must be used directly by the plants; and (*b*) by shading the ground and cutting down temperature and wind movement more or less, it decreases the loss of water directly from the soil.

(11) The tillage practice affects the efficiency of water under irrigation as it does the efficiency of rainfall in humid regions. If lax conservation methods are used, much more water will be needed than where the best tillage processes are applied.

For these reasons, it is not possible to specify any definite amount of water which should be used in the practice of irrigation. It varies widely for different sections of the world and, since it is very common to measure the total amount of water supplied at the head of the intake canal, it is largely determined by seepage from the canals and ditches. (See page 134.) The amounts of water which are applied in different irrigation sections are given by different authorities as follows:

TABLE XXXIX

	Acres irrigated per second-foot of water used	Equivalent to inches per ten days
Northern India	60–150	3.96–1.580
Italy	65– 70	3.66–3.400
Idaho	60– 80	3.97–2.980
Utah	60–120	3.97–1.980
San Joaquin Valley, California	100–150	2.38–1.580
Santa Clara Valley, California	150–300	1.58– .798

In Sefi, on the lower Nile canals in Egypt, one second-foot is said to be sufficient for 350 acres, as managed. In the humid regions much less water need be added by irrigation, and is necessary only to supplement the rainfall in the drought periods—to fill in the gaps. Ordinarily only a few inches per season are needed, usually toward the latter part. Dr. Voorhees has compiled the following figures, which show the percentage of years in which there was a deficiency of one inch or more per month in the rainfall, as compared with the average.

TABLE XL

	One month	Two months	Three months
	Per cent	Per cent	Per cent
New York, 1836–1895	75	42	21
Philadelphia, 1868–1895	88	56	30

In this region, the deficiency is most likely to occur in the summer season. The records show that during one-fourth of the term there is a deficiency of rainfall covering three months. Considering the monthly rainfall to be from two to three inches, a deficiency of one inch amounts to from one-half to one-third of the total, which must be a serious hindrance to crop growth, without the most careful soil management.

On light, sandy soils, and with careless tillage in general, the above figures indicate that there may frequently be occasion for irrigation. The annual rainfall is ample for full crop production, if it could all be utilized.

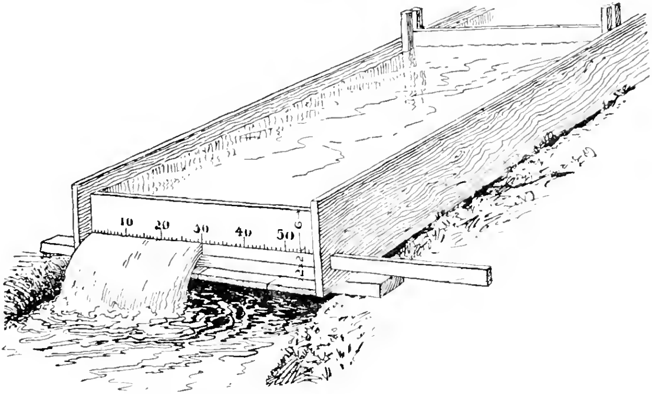

FIG. 73. Flume for measuring miner's inches.

Many units are used in the measurement of water for irrigation. The two most common methods of stating the quantity of water used are: (1) In depth of water over the area, as acre-inches or acre-feet. (2) A given-sized stream flowing through the growing season. The two most common units under the latter system are the second-foot and the miner's inch. It is frequently estimated that a flow of a second-foot of water—one cubic foot per second—through a growing season of ninety days, is sufficient to irrigate one hundred acres. This is sufficient to cover the area 21.3 inches deep, and is equivalent to a little over seven inches per month. (See pages 135 and 137.)

The miner's inch varies in value in different sections. It is most commonly defined as the amount of water which will flow from an opening one inch square under a pressure-head of six inches above the top of the orifice, during a year, and is considered sufficient to irrigate from 5 to 10 acres. It is equivalent to about 1.5 cubic feet per minute, or 21.6 inches over 10 acres in a season, which, it will be observed, is practically the same application as one second-foot, as stated above.

102. Methods of applying water.—In his book on Irrigation and Drainage, King makes the following cogent statement with reference to the application of water in irrigation practice. "When water has been provided for irrigation, and brought to the field, where it is to be applied, the steps which still remain to be taken are far the most important in the whole enterprise,—not excepting those of engineering, however great,—which may have been necessary in providing a water-supply that shall be constant, ample and moderate in cost; for failure in the application of water to the crop means utter ruin for all that has gone before."

"To handle water on a given field so that it shall be applied at the right time, in the right amount, without injuring the crop, requires an intimate acquaintance with the conditions, good judgment, close observation, skillful manipulation, and patience after the field has been put into excellent shape; and just here is where a thorough understanding of the principles governing the wetting, puddling and washing of soils, and possible injury to the crop as a result of irrigation, becomes a matter of the greatest moment." (See page 103 *et seq.*)

Mead reports that there are over thirty methods of distributing water in use in the United States. Each of these has its special adaptations as to soil, crop, water supply, climate and land contour. All of these methods may be grouped under four general heads, the further differences being in detail of application and not in essential principles.

These are: (1) Flooding. (2) Furrow distribution. (3) Overhead sprays. (4) Sub-irrigation.

103. Flooding.—Flooding is practiced in several ways, and is applied to a much larger area than any other system. There are two fundamentally different types of flooding: (1) One covers the surface of the soil with a thin sheet of flowing water, maintained until the desired degree of saturation has been reached. (2) The other covers the surface with a sheet of standing water, which is allowed to remain until the soil is sufficiently saturated, when any balance is drawn off, or may be dissipated by percolation through the soil, as is frequently though unwisely done.

The former system corresponds closely with what is termed wild flooding, where the water is distributed by a minute dendric system of ditches, and the remnant gathered by a reversed dendric system of ditches, or by a head ditch at the foot of the slope. The essential point is to keep a thin sheet of water moving over the land until the soil is saturated. The second system agrees with check flooding, in which the water is turned on a nearly level area to a considerable depth. The check, or block, may be a small area—a few square rods on a decided shape, or a large area is possible on very level land. These may be so arranged that the water flows successively from one to the other, perhaps at successively lower levels. The relative advantages of the two types depend on the character and slope of the soil. On gently sloping land of moderately porous character, and not easily washed or puddled, so that the water may be controlled, wild flooding is the most convenient method. Grain fields especially lend themselves to the method. On the other hand, on very level or very steep land the block type must be used. The water is more definitely under control, washing is largely prevented by levees, and puddling is reduced by the almost entire elimination of current.

The flooding system is best adapted to certain classes of crops, as follows: (1) Grain fields. (2) Meadows and hay fields. (3) The soaking of land preliminary to planting other crops, sometimes termed winter irrigation, where the water-supply is available only in the winter season, and is stored in the soil until crop-growing time. The above crops are adapted to occasional or intermittent flooding; but some crops succeed best under a continual flood of water, as in: (4) Rice culture and (5) Cranberry culture. A phase of the flooding system is the basin system sometimes used in orchard irrigation.

The advantages of the system are: (1) Ease in handling water. (2) Economy in irrigation works. (3)

Avoids necessity of tearing up the crop to form large irrigation furrows.

The objections to its use are: (1) The large amount of water required. (2) The danger of over-irrigation, with the possible consequent injury from seepage, and the appearance of alkali salts. (3) The impossibility of conserving water by appropriate cultivation. (4) On heavy soils possible injury from the crusting and checking of the surface soil as a result of the lack of tillage. (5) Direct injury from flooding some crops, as the potato.

104. Furrows.—Furrow distribution, by which, as the name implies, the water is not applied to the whole surface but is distributed in furrows. The length, size and arrangement of these depends directly on the soil, chiefly its texture. This includes the subsoil as well as the soil. In soils which are porous or easily eroded, the furrows must be shorter than where the opposite conditions prevail, in order that the water may reach the further end of the field before over-wetting the portion near the head ditch. That is, in loose, porous soil, head or feeder ditches must be nearer together than on dense, impervious soil.

The furrow system is adapted to all intertilled crops. Next to the flooding system, it is used on the largest area, and is adapted to all intensively cultivated crops. Its advantages are that: (1) It conserves water. (2) It is especially adapted to inter-tilled crops. (3) It permits the conservation of water by appropriate cultural practices. (4) It avoids injury to crops sensitive to an excess of water. Water should not come in contact with the trunk of trees, or, in general, with the stem of any plant not well shaded. A bright, warm sun in conjunction with the excess of water is usually injurious. (5) It is the more convenient method to apply to the class of crops to which it is adapted. (6) It more readily permits the avoidance of the injuries due to seepage by avoiding the losses to which that is due. (7) It assists in the control of alkali soils by permitting tillage.

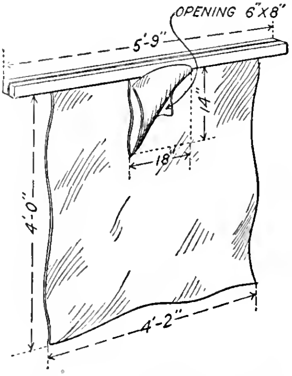

Fig. 74. Canvas dam with opening to divide the water in an irrigating furrow.

The supply of soil moisture by capillarity is most satisfactory to the majority of cultivated crops, and by promoting this the furrow system generally gives better results than flooding.

The flooding system has some disadvantages: (1) It is not so economical of water as is to be desired. (2) Much attention must be given to forming the furrows, to the construction of head or supply ditches, to the collection of the overflow water at the end of the furrows, and in the general supervision of the flow of the water over the land to repair broken levees, etc. (3) The water is not applied uniformly. The head of the furrow invariably becomes more wet than the lower end. (4) Erosion and puddling occur very readily in cultivated furrows.

105. Overhead sprays.—Overhead spray is used only on very limited areas, and almost entirely in humid sections. It has been applied in the growth of Sumatra wrapper tobacco in Florida, and of truck crops near New York, Boston and other large cities. It is therefore used as a very limited supplement to the regular rainfall. It is accomplished by the use of a very thorough piping system with spray nozzles at sufficiently frequent intervals to cover the area. These are connected with a relatively large pressure-head of water—at least five pounds is necessary.

The advantages of the system: (1) Economy in the direct application of water to shallow rooted crops. (2) Convenience in applying water at the desired point. (3) Absence of injury from erosion or puddling the soil. (4) No land wasted in irrigation ditches. (5) Natural climatic conditions developed by such irrigation.

The disadvantages of the system are great: (1) The large initial cost of the plant. (2) The high operating expenses ordinarily necessitated to develop the pressure necessary to distribute water from the nozzles, and to maintain the system. (3) The limited capacity of the system. (4) The large evaporation from the spray in the atmosphere, and from the soil and surface of the plants.

The spray system is practicable only with special crops under peculiar conditions.

106. Sub-irrigation.—Sub-irrigation often occurs naturally. It is the application of water beneath the surface of the soil. The structure of the land is such that on many low benches and in river bottoms the percolation of water through the soil and fissures of the rock brings it near the surface at these lower levels, where it maintains a fairly constant supply of water to those crops which may be growing on the surface. The ground water is so near the surface in some stream bottoms, lake shores, etc., that this condition prevails. Soils ordinarily poor in their moisture relations become highly satisfactory in such cases. Sandy land is almost ideal in its crop relations, so far as moisture goes, under such conditions.

In a limited way it has been attempted to irrigate the soil from beneath the surface by forming underground channels of porous pipe, properly graded, into which irrigation water may be turned, which should diffuse through the soil by percolation and capillarity.

In some situations, as lawns, truck and fruit gardens, it may be possible to install a drainage system of tile, which may also serve as a means of irrigation.

The system has a number of advantages, which in ordinary practice are more than offset by its disadvantages. Its advantages may be summarized as follows: (1) It is very economical of water. (2) In alkali soil it greatly reduces the surface accumulation of alkali. (3) It insures deep rooting of the crop. (4) It avoids waste land. (5) It avoids injury to the physical condition of the soil. (6) Involves very little supervision in the application of water. (7) Possibility of the use of the system for drainage purposes.

Its disadvantages are: (1) The strong tendency of roots to enter and clog the pipes. (2) The slow diffusion of water by capillarity in dry soil. (3) The expense involved in the installation of a system of pipes adequate to irrigate most soils.

Plant roots seek the most moist soil which is short of saturation, and therefore they are drawn toward and tend to concentrate around and in the lines of tile, just as roots are found to do where drain tiles carry living water through dry soil. This is the greatest disadvantage of the system. Especially is this true in orchard work. It is more adapted to shallow-rooted annual crops, and to soils of strong rapid capillary power, such as fine sand and coarse silt loam or loam soil.

The amount of water to be added at one time must be determined chiefly by the texture and structure of the soil,—or more specifically its water capacity,—and the supply of water available. Under arid conditions, it is generally advisable to apply as much water as can be held within the root zone by capillarity without loss from percolation. Frequent small applications should be avoided, because of the large proportionate loss from surface evaporation. (See page 197.) Also, there is a stronger tendency to the accumulation of alkali salts at the surface, because of the larger evaporation. On the other hand, less frequent large applications of water, particularly under any but the flooding system, where a crop occupies the land, permits the creation and maintenance of a mulch to conserve moisture; besides which, the deep distribution of the water insures a deep distribution of the roots, where they are not only in contact with a larger moisture reservoir, but also with a larger food-supply than is available to shallow-rooted plants. It is a fact of common experience that in arid regions crops generally root deeper than in humid regions.

A common accompaniment of irrigation, certainly in semi-arid and arid regions, is the excessive accumulation of soluble salts—"alkali salts"—in the soil. They may become so concentrated as to injure crops or prevent their growth. (See page 307.) In the original condition of such soils they are usually distributed in relatively small amounts through a deep section of soil. But by excessive irrigation, which produces seepage and a general rise in the water-table, aided by those careless tillage methods which permit free evaporation at the surface, these soluble salts become concentrated in the root zone, and at the surface as an alkali crust. It has frequently happened that land not originally in a seriously "alkaline" condition has become so by careless management. It is obvious that to avoid this injury there must be (*a*) conservative irrigation, and (*b*) the most thorough tillage methods which shall avoid surface evaporation. Where an excess of akali salts exists, they are most successfully removed by means of a deep thorough drainage system, coupled with heavy irrigation which shall wash out of the soil the excess of salts.

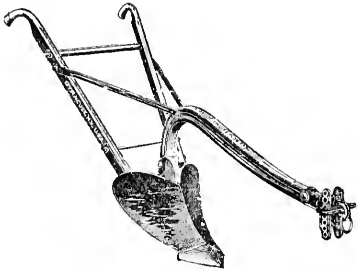

FIG. 75. Middle breaker plow. Sometimes used in constructing irrigation and drainage ditches.

It is a safe and wise rule to cultivate the soil as soon after applying water as its moisture condition will permit without injury, and this should be kept up at frequent intervals until an effective dust mulch has been reated. It has been noted (page 204) that in arid egions soil mulches are relatively more efficient and more easily managed than in humid regions.

Soils of intermediate fineness lend themselves most eadily to the practice of irrigation. Excessively heavy lay is generally to be avoided, because of (*a*) the slow iffusion of water, by both capillarity and percolation, nd (*b*) the danger from puddling after an irrigation, nless cultivation is delayed so long that a large amount f water is lost. On the other hand, very light sand should e avoided because of its leachy character, and the great oss of water by percolation or surface evaporation, he former, if a large amount of water is added at once; he latter, if it is added very frequently.

But in humid regions it is wise to practice irrigation or crops easily injured by an excess of water except on hose light and porous soils which have thorough rainage, because of the possibility of a rainfall following losely upon the application of water, thereby rendering he soil over-wet, to the injury of the crop. On the porous oil the excess quickly drains away. In the Sumatra obacco region of Florida, for example, where there is a arge rainfall, irrigation has been found successful only pon the lighter sandy loam and sand soils. This crop s particularly sensitive to an unfavorable soil condition. hen too, the heavy soil, the clay loam, or clay, has a arge water capacity, which makes possible the storage f a large amount of water against the needs of the crop-rowing season. Consequently it is on these latter that ry farming of grains is most generally practiced in the Western states.

As the demand for produce of high value increases, the maintenance of the moisture supply of the soil by irrigation may well be extended on large areas of soil in so-called humid regions, as well as in arid sections.

The highest type of soil-management must seek to utilize the available water-supply for crops in the three ways outlined above, that is, by increasing the water capacity of the soil, by eliminating as far as possible the losses by percolation and evaporation and, lastly, by supplying any deficiency which may still exist by wise irrigation.

Fig. 76. An example of poor drainage on level clay soil.

107. Means of decreasing the water content of the soil.—The removal of water from the soil may be accomplished in two general ways. These depend upon facilitating the two types of loss, by percolation and evaporation, described on page 191. They are: (1) Drainage. (2) Surface culture, to hasten evaporation.

108. Drainage by ditches.—Drainage consists essentially in the direct removal of the gravitational water from the root zone of the soil by affording free passages for its percolation and flow. In general, the soil conditions requiring drainage may be divided into two groups, which are fairly distinct in the problems which they present. These are: (1) Those lands which are saturated with water throughout the year. (2) Those lands which are saturated with water for only brief periods. Into the first group are placed all those lands of an acknowledged swamp character, which not only retain a large part of the water which falls upon their own surface, but may receive the water which flows from other lands. Into the second group is put all those wet lands which are saturated for a sufficient period to interfere with the best condition of the soil, or the proper development of the crop. It represents a very mild or incipient stage of the conditions included in the first group.

In the manipulation of soil for the staple upland crops, the establishment of effective drainage is at the foundation of all the other practices which must be employed. If it does not exist, the other farm practices, such as tillage, fertilization etc., can not be applied effectively.

An excess of water in the soil has many and far-reaching effects upon the soil as a medium for plant growth, especially if this condition is intermittent. The management of the latter condition is even more crucial than the former.

109. Effects of drainage.—Twelve of the most important effects of drainage are as follows: (1) Firms the soil. (2) Improves the granulation. (3) Increases the available moisture capacity. (4) Improves the aëration of the soil. (5) Raises the average temperature. (6) Promotes the growth of desirable organisms. (7) Increases the available food supply. (8) Enlarges the root zone of the soil. (9) Reduces "heaving." (10) Removes injurious salts from "alkali soils." (11) Reduces erosion. (12) Increases crop yields, and improves sanitary conditions of the region.

110. Firms the soil.—In a saturated soil the particles are held apart and are partially floated by the water, with the result that they afford a poor support for plants, and are largely unable to bear the weight of travel incident to cultural operations. Heavy objects sink into the surface, and become mired as a result of the easy movement of the soil particles from beneath their weight. This movement is greatly facilitated by the lubrication afforded by the water between the particles. It is because of this freedom of movement that a wet soil may readily be "puddled," that is, the small particles moved into the spaces between the large ones, producing a more dense mass, a change not possible in dry or even moderately moist soils.

111. Improves the structure.—Drainage improves the granular structure of fine-textured soil. One of the most important factors in soil granulation is alternate wetting and drying. (See page 105.) In a wet soil, this drying and drawing together does not take place. On the other hand, if a granular soil be kept saturated, the crumb structure will be broken down and a bad physical condition results. This is well illustrated by the fact that nearly all swamp soils are in a puddled, or otherwise bad physical condition, when first drained. Drainage brings to bear upon the soil all those natural agencies which promote the granular arrangement. In turn, the granular structure, particularly in fine-textured soil, affects the movement and capillary retention of water, the circulation of air, the growth of organisms, the temperature of the soil, and other conditions dependent on these, in a manner highly beneficial to the crops generally grown.

FIG. 77. Section of a 20-year-old tile drain in heavy clay soil. Note the more open structure above the drain.

112. Increases the available water.—Drainage increases the available moisture capacity of fine-textured soil. This is accomplished through the better granulation and larger porosity which results. The possibilities in this direction are indicated by the effect of structure on the moisture capacity of the soil. (See page 151.) Field experience has many times shown this result to follow drainage. Instead of plants suffering from lack of moisture, as a result of drainage, it is found that they are not only free from the excesses, but that in dry periods the soil is likely to contain more moisture than the same kind of soil under poor drainage. This is especially true of those soils which are wet only a part of the season. They are subject to great extremes in moisture content.

113. Improves the aëration.—Drainage improves the aëration of the soil in two ways. (1) It removes the gravitational water from the large pores, thereby permitting the admission of air. (2) Through its effect on granulation it permits the soil to hold a larger volume of air and facilitates its circulation. This also is due to two conditions, especially where the drainage is beneath the surface. The larger pores resulting from granulation greatly aid the process. And the underground passages, formed by tile or other media, afford channels for the escape of soil air following rain or reduction in barometric pressure, and facilitate its readmission when the opposite conditions prevail. The net result is a much larger total change between the outer air and the soil air. This reacts strongly upon the soil organisms and upon the general chemical activity of the soil.

114. Raises the average temperature.—Drainage raises the average temperature of the soil. The specific heat of water is much higher than that of soil, and therefore the larger proportion of water a soil contains the more heat is required to increase its temperature. (See page 461.) Further, in a wet soil the surface evaporation is large, and since the evaporation requires several hundred times as many units of heat as is necessary to raise the same volume of water from the normal temperature to the boiling point, it is clear that the process must consume a large amount of heat. But the heat supplied to any given area of soil is fairly uniform, and consequently, if it is used up in evaporating water, it is not effective to raise the temperature of the soil mass. If the soil contains water which must be removed by evaporation, its temperature will be kept correspondingly low; or, what is the same result, the time required to warm the soil will be correspondingly extended. For this reason a wet soil is a "late soil," while a well-drained soil is much "earlier" in attaining the temperature necessary for the germination and growth of plants. The practical result of this rapid warming of a well-drained soil is to *lengthen the growing season* by permitting its earlier seeding in the spring, and the later growth of crops in the fall. In some sections of the world, this margin in the length of the growing season determines the growth of certain crops, and materially affects all crops. All of the activities of the soil, both chemical and biological, are favorably affected by the higher temperature. In the peat bogs of England, Parkes found that at a depth of seven inches the drained soil was 15° warmer than the undrained soil, and at thirty-one inches it was 1.7° warmer. King reports the frequent observation of a difference of 12° between the temperature at the surface of drained and undrained land.

115. Influences the growth of soil organisms.—Drainage promotes the development of the desirable forms of organisms, and hinders the development of the undesirable forms. As will be shown (page 399), the soil organisms may be divided into two groups, one of which requires free oxygen for their growth, the other does not. These two groups are concerned with different types of chemical change,—the one producing decay the other putrefaction. In proportion as the air is excluded by an excess of water, normal decay is inhibited and putrefaction promoted. The one is beneficial, the other is likely to be injurious. Further, the products of the organisms accumulate in the excess of soil water and sooner or later may kill most of the forms; as is exemplified in peat bogs, which owe their origin chiefly to this fact. Not only is the decomposition of organic matter retarded, but the chemical changes in the mineral portion of the soil resulting from these processes are correspondingly reduced by lack of drainage. And most important of all is the stimulation to the formation of nitrates which results from good drainage. The supply of nitrates is often the controlling factor in plant growth, and consequently, in so far as drainage increases this supply, it is directly beneficial.

116. Increases the food-supply.—Drainage increases the available food-supply of the soil in three direct ways: (1) By holding in the soil a larger proportion of available moisture which favors a larger chemical activity without removing the products from the root zone. (2) Through direct chemical changes which result from good aëration. (3) Through the activity of organisms which not only form nitrates but produce carbonic acid and other materials which increase the availability of the mineral portion of the soil. The thoroughness of these chemical changes is well illustrated by the uniform color of a well-drained and well-aërated soil, in contrast to the usually mottled color of poorly aërated and wet soil. Drainage enables the plant-grower to make better use of the food stored in his soil.

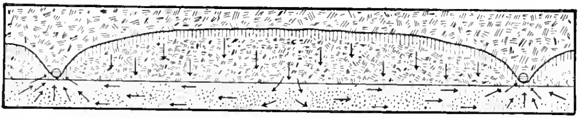

FIG. 78. Cross-section of tile-drained soil, showing the elevation of the water-table between lines of drains.

117. Enlarges the root zone.—Drainage deepens and enlarges the root zone of the soil by the removal of the gravitational water and by the admission of air. Thereby the plant is brought into intimate relation with a much larger volume of soil from which it may draw moisture and food. It is thus enabled to withstand more protracted periods of dry weather; it enjoys a more uniform climate, and has a larger food-supply, all of which are conducive to a rapid growth and a larger yield.

118. Reduces "heaving."—Drainage reduces "heaving," which results from freezing of a wet soil. When water freezes, it expands one-eleventh of its volume. In a saturated soil, this expansion can take place in only one direction—upward—with the result that the soil and consequently the crop is lifted. Shallow-rooted crops are gradually raised out of the ground by repeated freezing when wet, because the soil settled back into place more quickly than the root. Not only is the plant lifted out of the ground, but many of the smaller roots are broken off, all of which greatly reduces the vitality of the plant. It is most serious on clay soil, because this

FIG. 79. Alfalfa roots raised out of the soil ("heaved") by the repeated freezing of a wet clay.

texture holds more water and is most likely to contain an excess of water. Drainage reduces this type of injury in two ways: (1) By reducing the amount of water present to freeze. (2) The larger volume of free pore space, due to the removal of part of the water and to the better granulation, permits the expansion due to freezing to be taken up within the mass of the soil, rather than produce a lifting of the surface. Serious "heaving" is always dependent upon an excess of soil water.

119. Removes injurious salts from alkali soils.—Drainage in conjunction with heavy irrigation is the most effective means of removing "alkali salts" from arid soils. These salts are dissolved in the irrigation water as it passes through the soil, and are then removed in the drainage system beyond any possibility of further injury. By this practice it is possible to reclaim the most pronounced areas of alkali soils to the growth of the most sensitive crops.

120. Reduces erosion.—Drainage reduces erosion due to water. This type of injury results from the flow of water over the surface. Drainage reduces this process: (1) By increasing the absorption of water. (2) By affording channels in which it may be removed without injury, due to a less fall, or in conduits not subject to erosion, such as tile drains.

121. Increases crop yields and improves sanitary conditions.—The direct practical result of all of the above effects is larger and more reliable crop-yields, together with greater ease in all cultural and harvesting operations.

Coupled with the direct economic effect of drainage, is a large improvement in the general sanitary conditions of the region, which was recognized long before the economic advantages of the practice, and has generally been sufficient reason for public interest in the practice. It is only within recent years that the economic benefits of drainage have been recognized as of sufficient public concern to warrant regulative legislation.

122. Principles of drainage.—There are two general types of drains: (1) Open, or "surface drains." (2) Covered, or "under drains." Each of these types has a particular range of usefulness and, while they may be substituted one for the other under some conditions, their respective spheres of usefulness are fairly distinct.

123. Open, or surface drains.—Open or surface drains remove water from both the surface and from the depths of the soil. Their efficiency in removing water from the subsoil depends upon their depth and fall, and upon the level of water in the channel. There are certain conditions to which open surface drains alone are adapted. These are: (1) Where the volume of water to be moved is very large. (2) Where the water table is so near the surface, and the fall so slight, that it is not possible to place a drain below the surface. (3) Where the drainage is designed to be for only a short time.

As open ditches their efficiency depends on the surface flow of water into their channel. They usually tap the low areas where the water accumulates. Sometimes, as in river bottoms, they may be arranged regularly at intervals, and be of such size as to hold the water which may fall upon the surface during any ordinary rain, until such time, after the subsidence of a general overflow as it may be removed. They may serve to remove the water accumulated as the result of an overflow. In every such case their efficiency depends upon taking advantage of the natural inequalities of the surface of the land. One phase of this practice is to plow the land in narrow beds, so that the frequent "dead furrows" serve as surface drains and as temporary storage for the surface water.

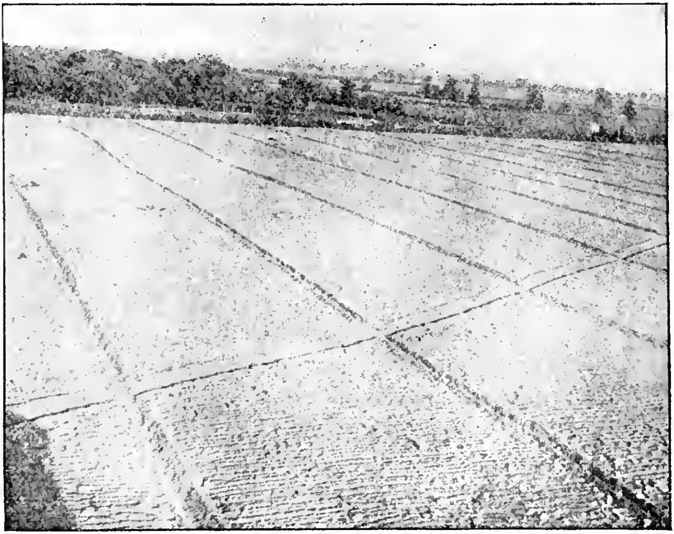

FIG. 80. Surface ditches for drainage in a grain field. Such drains are usually of low efficiency.

As sub-surface drains, their efficiency depends upon their depth being sufficient to permit percolation from the adjacent subsoil. This, in turn, is determined by the texture and structure of the soil, and upon all those other factors which determine the efficiency of closed drains, later to be discussed.

To be efficient, an open drain should be properly graded, should have a smooth bottom and sides, should have sufficiently tenacious walls to resist incidental erosion, and should have a shape approximately that of a semicircle, which is the form giving the greatest carrying capacity per cross-sectional area. Since this exact shape is difficult to maintain, it is common in practice to make the depth and bottom width, respectively, one-half the width of the top, with sloping sides. The form and grade of the ditch must be governed by the character of the soil. The steepness of the sides will be determined by the ability of the soil to form resistant walls. Clay soil will maintain a much steeper bank than sand. The fall must not be so great as to produce serious erosion. A loam or sand soil is much more susceptible to erosion than a clay. The fall should be uniform, in order that there be no undue accumulation of sediment at any point. Sedimentation may be reduced by preventing the growth of vegetation in the bottom.

As deep-soil drains, open surface ditches have a number of disadvantages, some of which are: (1) They are seldom of sufficient depth. (2) As ordinarily constructed, they have a small carrying capacity, due to their uneven grade and rough bottom and sides. (3) They are expensive to maintain. (4) They waste much land. (5) They greatly interfere with cultural operations. (6) They may be subject to serious erosion.

124. Covered or under-drains.—Covered or under-drains are any underground channels constructed for the removal of water. Many kinds of material have been used for this purpose. Some of the earlier materials used were brush, stone, poles, boards, and brick. In recent years these have been almost entirely supplanted by pipes made of clay or cement because of the greater permanency and efficiency of the latter.

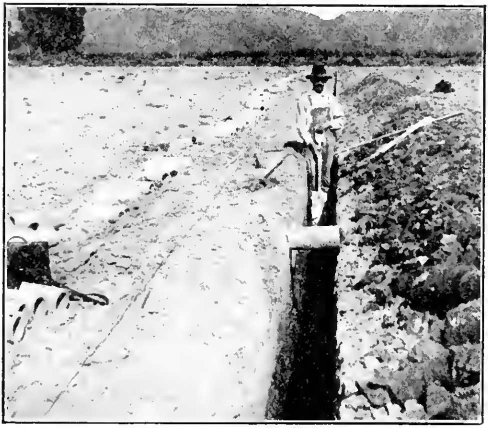

Fig. 81. Construction of a ditch for tile drains.

The depth, frequency and size of drains depends on the character of the soil and subsoil, the amount and distribution of the rainfall, the topography of the surface, the crop to be grown, the prevalence of underground seepage, and the level of the ground water. The system should always be arranged with reference to these conditions.

FIG. 82. Laying tile in the bottom of ditch by use of the tile hook. Shows arrangement of tile preparatory to filling the ditch.

(*a*) Depth.—The depth of the drain must be such that the water can find entrance before it shall have caused serious injury to the crop. Since water percolates through sand and gravel so much more readily than through clay, drains may be placed much deeper in the former than in the latter. In coarse-textured soil, drains attain their full efficiency almost at once; but in clay, owing to its dense character from long wetness, there is a gradual increase in efficiency through several seasons, as the soil becomes better granulated and acquires other favorable structural properties. In sand, water percolates rapidly into the drain, but in clay this general movement is greatly reduced and takes place largely from the sides and top of the drain. In fact, a dense clay soil holds its pores almost full of capillary water, which is not subject to percolation. Under such conditions, a large part of the injury comes from water standing on the surface. Here the under-drains must be placed very near the surface, and function chiefly as surface drains. But, as the excess of water is removed, and the soil structure is improved, they assume more fully the function of deep drains by removing water from the joints, or checks, which extend deeply into the soil. Where deep-rooted crops and trees are to be grown, deeper drainage is necessary than where shallow-rooted crops are grown. In general, it is not desirable to lower the water-table so much in sandy as in clay soils, because of the less capillary capacity of the former. The water-table should be lowered to from three to five feet below the surface, but it is not always necessary to place tile at this depth, to attain sufficiently thorough drainage. Where there is a distinct change from sand to clay, or vice versa, within from two to four feet of the surface, it is usually best

FIG. 83. Laying double-sole drain-tile by hand.

to place the drain on the boundary between the two. If the clay is below, the water will percolate along its surface through the sand and enter the tile. On the other hand, if the clay is underlain by sand, it is easier for the water to percolate downward into the coarse-texture stratum, and through this into the tile, entering from below.

(*b*) Frequency.—There are two general systems of arranging drains: (1) The gridion or regular system. (2) The natural or irregular system. In the first, the drains are arranged at definite regular intervals apart,—this interval depending chiefly on the texture of the soil. This is necessary where the surface is very uniform and the soil very homogenous. It may be applied to a slope as well as to level land. In clay soil the interval must be less than in coarse-textured soil. This is because there is a drainage gradient between the drains. In fine-

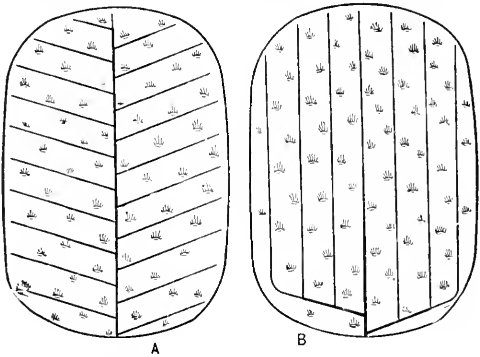

FIG. 84. Two systems of arranging tile drains. Compare the amount of double draining in each system, due to junctions. Note the relative lengths of tile required for the same area under each system.

textured soil the water level rises rapidly away from the drain and reaches the surface at no great distance. On sand soil this gradient is much less. The aim must be to have the water level reduced a definite distance below the surface, after a reasonable interval of time following rainfall, and the drains must be sufficiently frequent to accomplish this. In heavy clay soil this interval may be as small as twenty-five feet, while in coarse-textured soil it may be 200 or 300 feet. Usually, it is best to adopt some minimum interval, and place the first lines of tile at two or more times this interval. If the drainage does not prove sufficiently thorough, additional drains may be installed without affecting the general system.

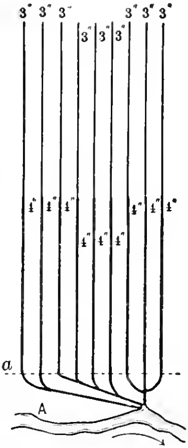

FIG. 85. A more simple system of drains, but one requiring more large tile than in Fig. 86.

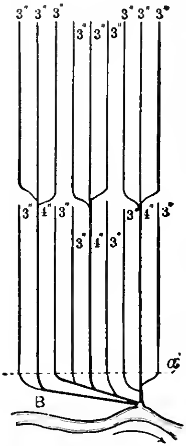

FIG. 86. Drain with minimum number of large tile, but having many turns and branches.

The natural or irregular system is designed primarily to collect water from the surface where it has accumulated, or beneath the surface where it comes within the range of the plant roots. Large areas of land are drained by a single line of tile in the low places. Where land is kept wet by seepage, the drains should tap these as near their source as is practicable.

The size of drains depends on the

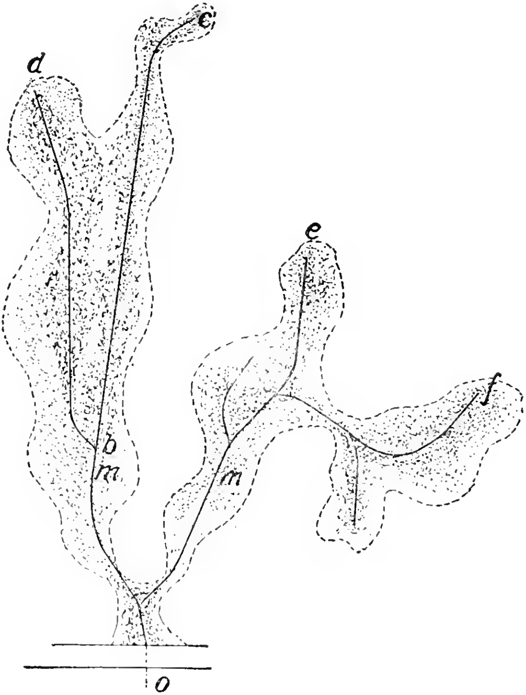

FIG. 87. The so-called natural or irregular system of arranging drains to remove water from local wet spots. Shading indicates degrees of wetness.

volume of water to be handled and on the fall. Where several laterals empty into a main drain, the main must have a capacity equal to their combined flow; but it is not possible to calculate the total or relative sizes with the exactness which is possible in a pressure system of pipes. This is due to the effect of the soil. It acts as a sponge to hold the water, and gives it up gradually. The

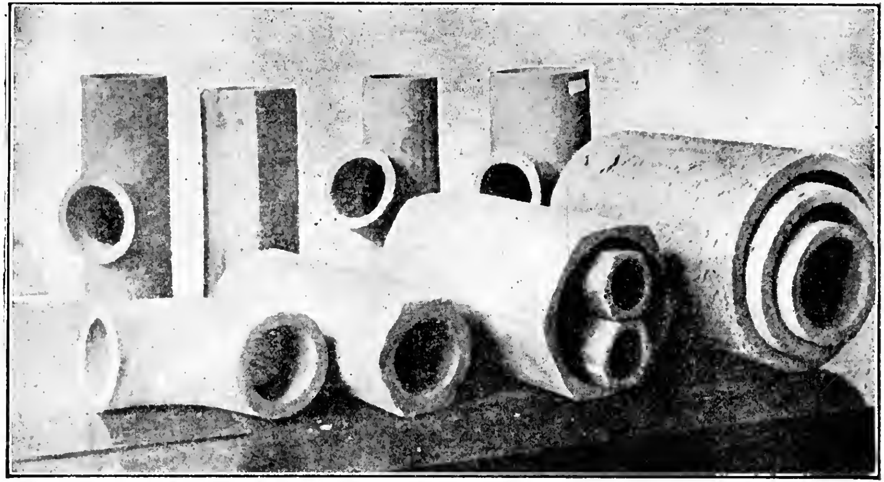

Fig. 88. Some types of drain tile. Round or hexagonal shapes are most convenient to lay. The hexagonal tile in the figure are hard-burned and very impervious; the others are much more porous.

finer the soil the greater this retentive effect, and consequently the less demand there is for drains capable of carrying all of the rainfall in a given short time. Drains run full for only a very small part of the year, and therefore the normal laws of hydraulics are not entirely applicable to them. In a general way, doubling the fall increases the carrying capacity of any given size of tile by one-third. Where the fall is less than 1 per cent, it is unwise to use tile smaller than three inches in diameter, because of their strong tendency to clog.

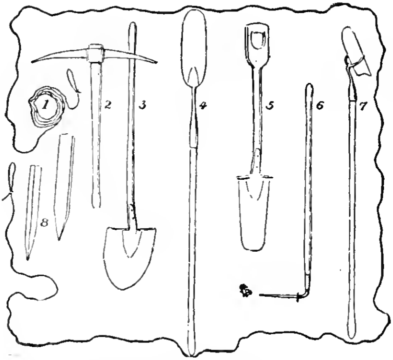

FIG. 89. Hand tools used in tile-drain construction. 1, Grade cord; 2, pick; 3, long-handle, round-point shovel; 4 and 7, types of grading shovel for finishing the bottom of the ditch; 5, spade; 6, tile hook, used in placing tile in ditch from the bank; 8, grade stakes.

Water enters tile almost entirely through the joints between the sections. Short lengths are therefore better than long ones. Through the walls of even soft brick tile very little water is able to percolate. There is, therefore, no appreciable advantage in using soft tile, while there are many disadvantages,—such as their weakness and liability to go to pieces rapidly under alternate wetting and drying, especially if permitted to freeze when saturated with water.

Dense, hard-burned tile are most safe to use under average soil conditions.

"Silting-up" of drains results where the alignment is bad, the joints too open, or a section is broken. The joints should be fairly snug, but it is not now considered necessary to use collars in ordinary soils. The textures of soil which give most trouble by entering the joints and stopping flow are very fine sand and silt. These materials flow readily when saturated with water. Consequently, in laying tile in these materials, precaution must be taken against this. "Silting-up" is most troublesome immediately after laying the tile, and before the soil structure has become settled and readjusted. When this has taken place, the tendency to silting-up is small, even in fine sand and silt. In clay and coarse sand it is negligible. This difficulty can be checked or controlled by using some filtering medium around the joints. Straw, leaves, chaff, etc., are excellent and undergo slow decay, coincident with which a resistent structure of soil is

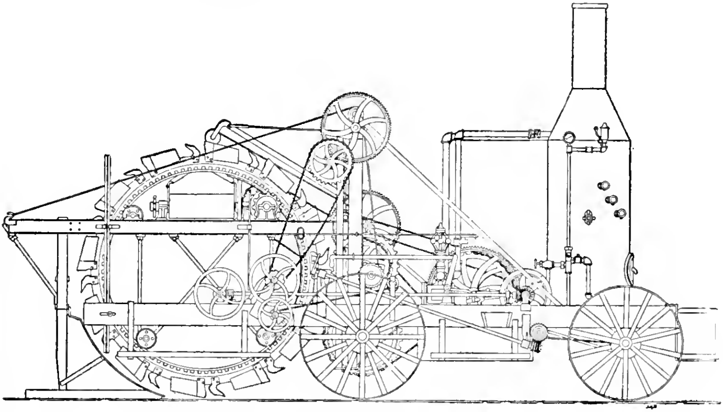

Fig. 90. Traction ditching machine. A modern machine for constructing tile ditches. (See Fig. 91.)

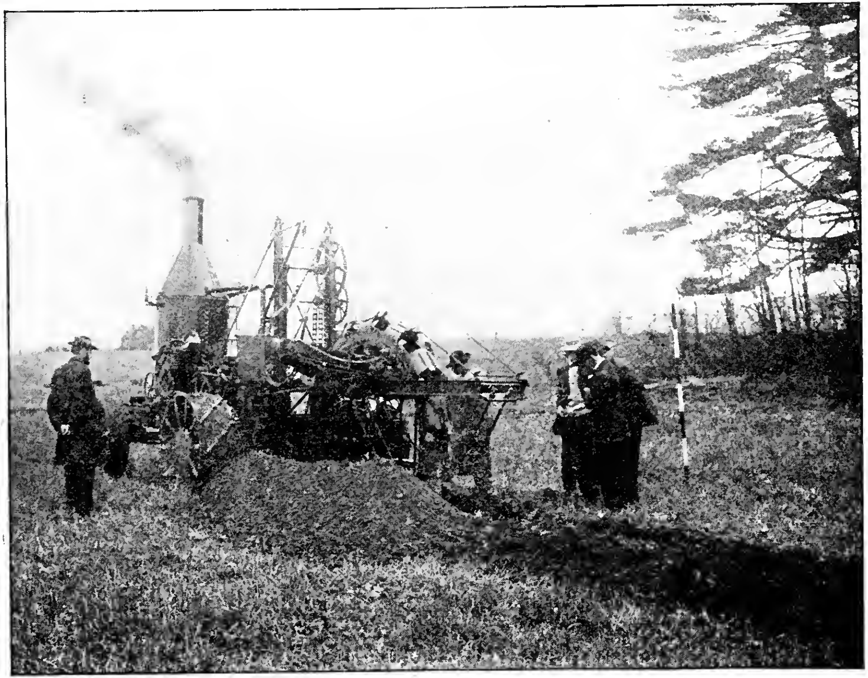

FIG 91. Traction ditching machine in operation

established. Fine gravel or coarse sand is a more permanent filtering medium.

Plant roots sometimes enter the joints of tile drains, and develop so as to stop the flow of water. This occurs most readily where the tile carries "living water," as where a permanent spring is drained. During dry periods and in naturally well-drained soil, water percolates from the joints of the tile into the adjacent soil, which conditions attract roots and may lead them into the tile at the joints. Depth is not a decided protection against this difficulty unless it be excessive.

There are many points about the construction of a tile-drain system about which special precaution should be taken. Some of these are: (1) Uniformity of grade. (2) Avoid leading a lateral into a main with a less fall unless silt basins are used. (3) Protection of outlets against caving and freezing. (4) Protection of the outlet

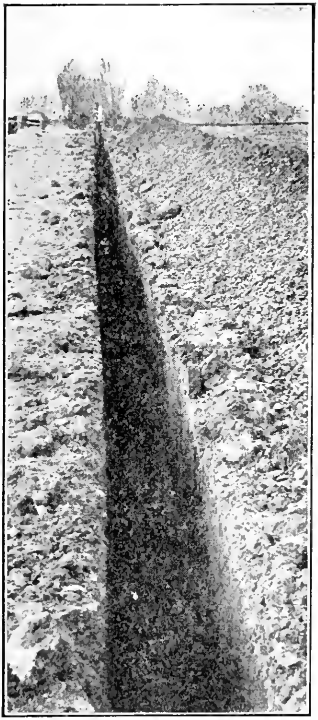

FIG. 92. Ditch cut by the machine shown in Fig. 91. Soil a heavy clay. Depth 4½ feet.

against the entrance of animals. (5) Free flow of water from the outlet. (6) Close joints, which may be more easily attained with round or hexagonal than with U or soft tile. (7) Junctions should be made at an acute rather than at a right angle. (8) On hilly land the drain should run with the slope, as far as possible. (9) In general, the fall should be as great as the surface fea-

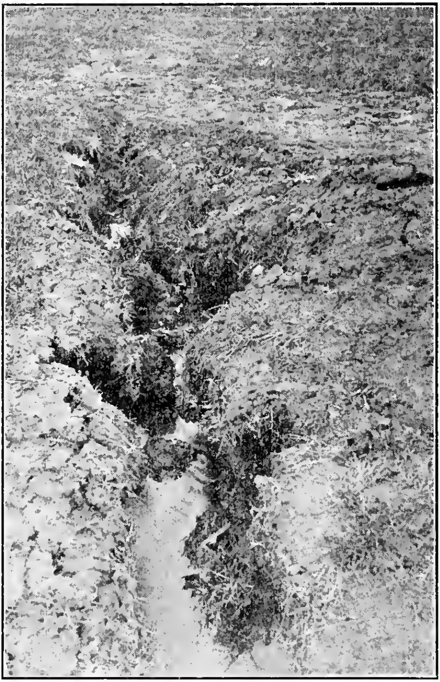

FIG. 93. A poorly constructed outlet for a line of drain tile.

tures will permit. (10) Avoid throwing the tile out of alignment in filling the ditch.

The chief advantages of covered drains, especially when constructed of tile, are: (1) Permanence. A well-constructed system will last for many decades. (2) Greater efficiency where they are suitable. (3) No waste of land. (4) No interference with cultural operations. (5) Require very little care for maintenance. (6) Less cost over a period of years.

125. Other types of drainage.—Drainage may sometimes be accomplished by means of levees. Where land is subject to overflow at either frequent or infrequent intervals, such as river bottoms and tidal marshes, their drainage consists largely in excluding these inundations. Until this is accomplished, any other form of drainage may be useless. Frequently direct drainage may advantageously be combined with some form of levee, and for tidal marshes is useful with the aid of the fresh water derived from rainfall and upland drainage, in removing its saltness.

Wells or filter basins may be used to drain certain sinks or flat areas having no other outlet. This is possible only where a very porous stratum occurs beneath the soil within a reasonable depth. Usually this is practicable where a clay stratum is underlain by sand or gravel, as occurs in many sections of the country. Wells are constructed through the clay to the porous stratum, and this may be filled with stone or brush as a filtering medium, and covered drains may be emptied into these.

126. Surface culture.—Surface culture may be employed to remove a limited excess of water from the soil. Those practices which may be employed for this purpose are the opposite of those applied in the conservation of water. The most applicable ones are: (1) Rolling. (2) Ridged surface. (3) Growth of plants.

Rolling, or any other practice which compacts the soil and strengthens capillary movement of water to the surface, places the moisture in the most favorable position

FIG. 94. Water forced to the surface by the closure of the outlet of a tile drain.

for evaporation. It would be unwise, as a rule, to roll the soil when it is excessively wet, because of the injury to the structure of the soil which would result. But the land may be rolled in anticipation of a wet period, which condition of the soil will facilitate the formation of that compact surface which most favors evaporation. In the spring, in regions of cold winters, bare or fallow land has usually settled into this condition, which, if permitted to continue, will most rapidly dry the soil.

FIG. 95. A well-constructed outlet for a line of drain tile.

Ridging increases evaporation by exposing a larger surface. In some sections of the country where the wetness is most serious in the spring, the crops are planted on ridges which are sufficiently raised above the general surface to be drained; and, by the time the roots are ready to penetrate deeply, the excess of moisture will have been removed by percolation and evaporation.

Crops of any sort, including weeds, green manures and cover-crops, may serve to dry the soil by evaporating water from their leaves. It has been seen (page 134) that the amount of water so used is large because of the functional activity of the plants and the large surface which they expose. Growing crops expand the evaporating surface of the soil and are especially useful in removing a temporary wetness in the spring.

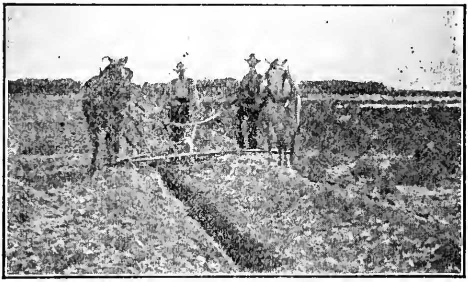

FIG. 96. The nine foot evener used in the final filling of the ditch by the use of the turning plow after laying drain tile. Care should be exercised in placing the first covering of earth over the tile not to disturb their alignment or break any of the sections. This is best accomplished by hand, and the earth should be carefully pressed around the tile.

The application of any of the above methods for the removal of water must be guided by the local conditions of soil, season, climate, crop and system of farming.

C. PLANT NUTRIENTS IN THE SOIL

I. SOLUBILITY OF THE SOIL THROUGH NATURAL PROCESSES

Fortunately for mankind, only an exceedingly small proportion of the soil is at any one time soluble in water or in the aqueous solutions with which it is in contact. It is this great insolubility that gives the soil its permanence, for, otherwise, in humid regions, it would be rapidly carried away in the drainage water. The portion soluble in the various natural solvents with which it comes in contact furnishes the mineral-food materials for plants. The great mass of soil which is relatively insoluble is constantly subjected to natural processes which very slowly bring the constituents into solution. Those agents concerned in the decomposition of rock also act upon the soil to bring about its further disintegration, and thereby render it more soluble, while added to those are the operations of tillage, which contribute to the same end.

The surfaces of the particles alone come into contact with the decomposing agents, and hence it is these portions of the particles that are rendered most soluble. The factors that determine how rapidly solution shall proceed are: (1) The amount of surface exposed, which we have seen varies with the size of the particles. (2) The composition of the particles. (3) The strength of the decomposing and solvent agencies. Were it not for this process, there would soon be no mineral food available to plants, as drainage water and the ash of crops carry off relatively large amounts of these substances each year; but in spite of this loss, the soil is able to provide at least some plant-food material for each crop, when called upon by the plant.

II. SOLUBILITY OF THE SOIL IN VARIOUS SOLVENTS

For purposes of analysis intended to show the amounts of mineral plant-food materials in the soil any one of several different solvents may be used. These solvents differ in strength, and consequently the percentages of the various constituents obtained from samples of the same soil are different for each solvent. A chemical analysis of a soil is a determination of the amounts of the constituents that have been dissolved in the solvent used. Therefore it will readily be seen that the interpretation of a chemical analysis must depend largely upon the nature of the solvent, and, unless the solvent is equivalent in its action to some process or processes in nature, the result must be entirely arbitrary. The solvents used have generally been intended to show some definite relation of the soil to the food requirements of crops. Upon the accuracy with which this is accomplished depends the value of the chemical analysis.

127. Complete solution of the soil.—By the use of hydrofluoric and sulfuric acids, the entire soil mass may be decomposed and all of its inorganic constituents determined. Such an analysis shows the total quantity of the plant-food materials except nitrogen, which is never determined in any of the acid solutions, but by a separate process. A deficiency of any particular substance may be discovered in this way, but nothing can be learned as to the ability of the plant to obtain nutriment from the soil. A rock may show as much mineral plant-food material as a rich soil. Such an analysis is used only to ascertain the ultimate limitations of a soil or its possible deficiency in any essential constituent.

128. Digestion with strong hydrochloric acid.—Analyses made with hydrochloric acid of 1.115 specific gravity are those usually called "chemical soil analyses." They are supposed to show the amount of plant food at the time the analysis is made, which is in a condition to be ultimately used by the plant, and the plant-food materials not dissolved by treatment with hydrochloric acid are assumed to be in a condition in which plants can not use them. It may reasonably be questioned whether these relations hold under field conditions. In fact, it is quite certain that some of them do not hold. In other words, while treatment with hydrochloric acid of a given strength marks a definite point in the solubility of the compounds in the soil, it does not bear a uniform relation to the natural processes by which these compounds become available to the plant.

129. Interpretation of results of analysis of hydrochloric acid solution.—This method of analysis was originally thought to give some indication of both the permanent fertility and the immediate manurial needs of a soil; but for both purposes the accuracy of the deductions are limited by a number of conditions which make it impossible to predict from an analysis how productive a soil may be, or what particular manure may be profitably applied. It is very apparent that the chemical composition of a soil is only one of the many factors affecting its productiveness. Unfortunately, not all of the factors are understood, and consequently these unknown ones cannot be determined either qualitatively or quantitatively. If it ever becomes possible to determine quantitatively all of the factors entering into soil productiveness in the field condition, the problem will be solved.

130. Permanent fertility, and manurial needs.—Permanent fertility can best be judged by the complete analysis of the soil, but, with the exception of potash, the possible deficiency the constituents likely to be required in manures may be judged from the hydrochloric acid solution with a fair degree of accuracy.

Conclusions as to the manurial needs of the soil are confined to ascertaining whether any constituent is present in such small amount as to furnish an inadequate supply for crop production. If, for example, a certain ingredient is found to be present in very small amount, it may be concluded that the addition of a manure containing this substance would be profitable; but there is considerable difference of opinion among analysts as to what this figure is for each of the ingredients. This minimum amount may vary with certain conditions of soil.

131. Relation of texture to solubility.—The relative amounts of sand and clay in the soil and the distribution of the fertilizing materials in these constituents will affect the minimum amounts required. Hilgard has shown that the addition of four or five volumes of quartz sand to one of a heavy but highly productive black clay soil greatly increased the productiveness, while diluting the potash content of the mixture to .12 per cent and the phosphoric acid to .03 per cent. It is evident that in this soil the plant-food materials were in a condition to be easily taken up by the plant when the physical condition of the soil was suitable.

If these small amounts of food elements had been distributed in the sand particles as well as in the original clay, the result would doubtless have been different. Suppose, for example, that 50 per cent of the potash and phosphoric acid had been in the sand particles and the remainder in the clay, the former which expose much the less surface to dissolving liquids would be proportionately less soluble, and as the minimum quantity is approached, as shown by the more dilute soil yielding less than the other, the effect would doubtless have been to decrease the production. (See page 86.) In some soils, particularly those of the arid region, the larger particles may carry much of the mineral nutrients, in which case it is quite evident that a higher percentage of fertility is required than in soils carrying the plant-food material largely in the small particles.

132. Nature of subsoil.—The nature and composition of the subsoil is naturally a factor in determining soil productiveness, and must be considered as well as the soil. An impervious subsoil, or a very loose sandy one, will confine the productive zone largely to the top soil, and hence require a greater proportionate amount of fertility.

133. Calcium carbonate.—A determination of the amount of calcium present as a carbonate is important as an aid to the interpretation of an analysis of the soil. Lime not so combined is generally in the form of a silicate, or possibly phosphate. When there is a large amount of calcium carbonate in a soil, the potash, phosphoric acid and nitrogen are always more readily soluble, and smaller quantities are sufficient for crop growth than where the calcium is not found in this form. The effect of the carbonate of lime upon the nitrogen[1] compounds is to furnish a base for the acids produced in the formation of nitrates and its presence promotes that process. It probably replaces potassium in certain compounds where otherwise it would be secured with more difficulty. It insures the presence of some phosphates of lime, in which form phosphorus is more soluble than when combined with iron. The form of the manures to be used upon the soil will also depend in large measure upon the presence or absence of calcium carbonate. (See page 349.) For instance, where calcium carbonate is deficient, steamed bone or Thomas slag are more profitable than superphosphate, and nitrate of soda than sulphate of ammonium. Finally, the absence of calcium carbonate indicates the need of liming, and, if the analyses show a considerable amount of potash and phosphoric acid, but practice shows them to be somewhat deficient, it is probable that liming will be all that is necessary, and that manures carrying these

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[1] Not determined in the hydrochloric acid extract.

substances may be dispensed with. It must be stated, however, that there are cases for which these deductions do not hold, owing to the intervention of other factors.

134. Estimation of deficiency of ingredients.—In a soil in which the other conditions are normal, one would suppose it possible to prescribe, with some degree of accuracy, the content of certain constituents below which a deficiency exists. The use of a manure containing this constituent should therefore be expected to produce beneficial results. However, opinions differ so widely, depending, apparently, upon the soils with which the respective analysts have had to deal, that it is difficult to decide where to set the limit. It is evident that, as the content of any constituent becomes less, the probable need for its application becomes greater, and it thus suggests a practice without assuring its success.

135. Conclusions.—An analysis of the hydrochloric acid extract, therefore, cannot be taken as a guide to the fertilizer needs of the soil, and of itself should not be relied upon; but in connection with other knowledge, particularly that derived from fertilizer tests, it may be useful.

136. Extraction with dilute organic acids.—Other methods used for dissolving soils for analysis depend upon extraction with some dilute organic acid, as citric, acetic, oxalic or tartaric acid. The assumption upon which these methods are based is that the dilute organic acids correspond to the solvent agents in the soil, and thus take from it the amounts of those materials that the plant could take up if it came in contact with all portions of the soil to the depth represented by the sample analysed.

137. Advantages in showing manurial needs.—The action of each of these dilute acids upon the same soil does not give equal amounts of the various constituents in solution. Citric acid dissolves especially lime, magnesia and phosphoric acid, and is the most satisfactory solvent for purposes of analysis. The organic acids naturally dissolve a much smaller amount of material from the soil than does hydrochloric acid. The former acids permit the detection of smaller amounts of easily soluble phosphoric acid and potash than does the latter, larger quantities of soil being used. For example, a chemical analysis of the hydrochloric acid solution is very likely not to show any increase in the phosphorus or potassium in a soil that may have been abundantly manured with these fertilizers, and its productiveness increased greatly thereby. This is because the amount of plant-food material added is so small in comparison with the weight of the area of soil nine inches deep over which it is spread that the increase in percentage may well come within the limits of analytical error. An acre of soil nine inches deep weighs about 2,500,000 pounds. If to this be added dressings of 2,500 pounds phosphoric acid fertilizer containing 400 pounds phosphoric acid, it would increase the percentage of that constituent in the soil only .016 per cent, which difference could not be detected by the analysis of the hydrochloric acid solution.

138. Usefulness of citric acid.—As shown by Dyer, the use of a 1 per cent solution of citric acid is well adapted to show the amount of easily soluble phosphoric acid and potash in certain soils, but for other soils it has failed to give satisfaction in the hands of a number of analysts. Shorey, for instance, finds that it fails utterly for the highly ferruginous soils of Hawaii. It is, doubtless, better adapted to soils rich in calcium and low in iron and aluminum.

The reason urged by Dyer for the superiority of the citric acid over the hydrochloric acid extraction of the soil is that the former gave, in his hands, several times as great a difference in the amounts of soluble phosphoric acid in soils needing phosphoric manures as compared with those not needing them.

The application of both the hydrochloric and citric acid methods to a soil may, when used to supplement each other, add greatly to a knowledge of the potential and present productiveness of the soil.

There should be present in a soil for cereals and most other crops at least .01 per cent phosphoric acid, soluble in 1 per cent citric acid. A soil containing less than this amount is deficient in phosphoric acid, unless it exists largely in the form of ferric or aluminum phosphate, which is not readily soluble in citric acid, but is fairly available to the plant. Sod land contains organic compounds of phosphorus that are easily soluble in the citric acid, but less readily available to the plant; hence such soil should show by analysis more than .01 per cent phosphoric acid, to indicate sufficiency.

139. Extraction with an aqueous solution of carbon dioxide.—As carbon dioxide is a universal constituent of the water of the soil, and without doubt a potent factor in the decomposition of the mineral matter, it has been proposed to use a solution of carbon dioxide as a solvent in soil analysis. The amounts of soil constituents taken up by this solvent are much less than by any of the others heretofore mentioned, but all mineral substances used by plants are soluble in it to some extent. The amount of phosphorus is so small as to make its detection by the gravimetric method difficult. Like other methods employing very weak solvents, it is open to the objection that the extraction fails to remove a considerable portion of the dissolved matter that is retained by absorption, and, as this will vary with soils of different texture, it makes impossible a fair comparison of such soils by this method.

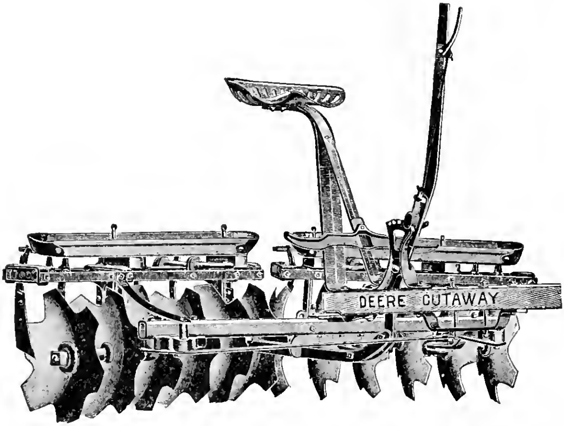

FIG. 97. The cut-out disc harrow, adapted to hard or stony soil.

140. Extraction with pure water.—When soil is digested with distilled water, all of the mineral substances used by plants are dissolved from it, but in very small quantities. It has been proposed to use this extract for soil analysis on the ground that it involves no artificial solvent, the presence or amount of which in the soil is doubtful, but shows those substances which are undoubtedly in a condition to be used by plants. By determining the water content of the soil and using a known quantity of water for the extraction, the percentage of the various constituents in the soil water or in the dry soil may be calculated.

The substances dissolved from the soil by extraction with distilled water are probably only those contained in the soil-water solution, including a part of the solutes held by absorption. The aqueous extract does not contain all of the nutritive salts in solution in the soil water, and hence is not a measure of the fertility held in that form. An undetermined amount of nutrients is retained in the water in the very small spaces and on the surface of the soil particles. It is, however, a fair comparative measure of the content of available nutrients.

141. Influence of absorption.—The quantity of extracted material depends upon the absorptive properties of the soil, and upon the amount of water used in the extraction, or upon the number of extractions. Analyses of the aqueous extract of a clay and of a sandy soil on the Cornell University Farm serve to illustrate the greater retentive power of the former for nitrates. Sodium nitrate was applied to a clay soil, and to a sandy loam soil at the rate of 640 pounds per acre. Analyses of aqueous extract, some ninety days later, showed the following:

TABLE XLI

Kind of soil	Fertilizer	Nitrates in soil. Parts per million
Clay	Sodium nitrate	7.8
Clay	No fertilizer	1.8
Sandy loam	Sodium nitrate	150.0
Sandy loam	No fertilizer	29.7

There was apparently a much greater retention of nitrates by the clay soil, as shown by a comparison of the fertilized and unfertilized plats on both soils.

Schulze extracted a rich soil by slowly leaching 1,000 grams with pure water, so that one liter passed through in twenty-four hours. The extract for each twenty-four hours was analyzed every day for a period of six days. The total amounts dissolved during each period were as follows:

TABLE XLII

Successive extractions	Total matter dissolved	Volatile	Inorganic
First	.535	.340	.195
Second	.120	.057	.063
Third	.261	.101	.160
Fourth	.203	.083	.120
Fifth	.260	.082	.178
Sixth	.200	.077	.123

It will be noticed that the dissolved matter, both organic and inorganic, fell off markedly after the first extraction, which was larger on account of the matter in solution in the soil water. Later extractions were doubtless supplied largely from the substances held by absorption and which gradually diffuse into the water extract, as the tendency to maintain equilibrium of the solution overcomes the absorptive action. With the removal of the adsorbed substances, the equilibrium between the soil particles and the surrounding solution is disturbed, solvent action is increased, and more material gradually passes from the soil into the solution. In this way the uniform and continuous body of extractives is maintained.

142. Other factors.—For purposes of soil analysis, the quantity of water used for extraction must be placed at some arbitrary figure, and the method is open to the objection that it does not represent accurately the soil water solution. Analyses of soils of different types are not comparable, and the water extract cannot be considered to measure the concentration or even the composition of the solution existing between the root hair and the soil particles. However, for studying some of the changes that go on in the soil, and which are detectable in the soil-water solution, the method may be used to advantage.

III. MINERAL SUBSTANCES ABSORBED BY PLANTS

The plant, in its process of growth, withdraws from the soil certain mineral matters that are presented to its roots in a dissolved condition. As the salts in solution are quite numerous, and as the osmotic process by which the absorption is accomplished does not admit of the entire exclusion of any substance capable of diosmosis, there are to be found in the plant most of the mineral constituents of the soil. Some of these are concerned in the vital processes of the plant and are essential to its growth. Others seem to have no specific function, but are generally present.

143. Substances found in ash of plants.—The substances commonly met with in the ash of plants are potassium, sodium, calcium, magnesium, iron, aluminum, phosphorus, sulfur, silicon, and chlorine. In addition to these, nitrogen is absorbed from the soil in the form of soluble salts.

The substances known to be absolutely essential to the mature growth of plants are potassium, calcium, magnesium, iron, phosphorus, sulfur and nitrogen, while the others are probably beneficial to the plant in some way not yet discovered.

Of the substances acting as plant nutrients, each must be present in an amount sufficient to make possible the maximum growth consistent with other conditions, or the yield of the crop will be curtailed by its deficiency. To some extent certain essential substances may be substituted by others, as, for instance, potassium by sodium; but such substitution is probably possible only in some physiological role other than that of an elemental constituent of an organic compound. The substances that are likely to be so deficient in an available form in any soil as to curtail the yield of crops are potassium, phosphorus and nitrogen, while the addition of certain forms of calcium is likely to be beneficial on account of its relation to other constituents and properties of the soil. It is for the purpose of supplying these substances, and to some extent to improve the mechanical condition of the soil, that mineral manures are used.

144. Amounts of plant-food material removed by crops.—The utilization of mineral substances by crops is a source of loss of fertility to agricultural soils. In a state of nature, the loss in this way is comparatively small, as the native vegetation falls upon the ground, and in the process of decomposition the ash is almost entirely returned to the soil. Under natural conditions, soil usually increases in fertility; for, while there is some loss through drainage and other sources, this is more than counterbalanced by the action of the natural agencies of disintegration and decomposition, and the fixation of atmospheric nitrogen affords a constant, although small supply, of that important soil ingredient.

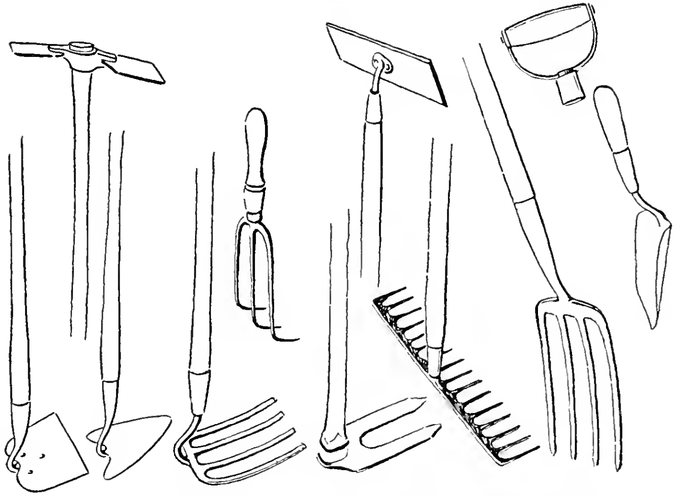

FIG. 98. A collection of hand-tillage implements. From left to right: 1. Field and garden hoe. 2. Mattock. 3. Weeding-hoe. 4. Stone-hooks. 5. Finger-weeder. 6. Grub-hoe. 7. Scuffle-hoe. 8. Garden rake. 9. Spading-fork. 10. Garden trowel.

When land is put under cultivation, a very different condition is presented. Crops are removed from the land, and only partially returned to it in manure or straw. This withdraws annually a certain small proportion of the total quantity of mineral substances, but, what is of more immediate importance, it withdraws all of this in a readily available form.

The following table, computed by Warington, shows the amounts of nitrogen, potassium, phosphorus and lime removed from an acre of soil by some of the common crops. The entire harvested crop is included.

TABLE XLIII

Crop	Yield	Total ash	Nitrogen	Potash	Lime	Phosphoric acid
		Pounds	Pounds	Pounds	Pounds	Pounds
Wheat	30 bus.	172	48	28.8	9.2	21.1
Barley	40 bus.	157	48	35.7	9.2	20.7
Oats	45 bus.	191	55	46.1	11.6	19.4
Maize	30 bus.	121	43	36.3	...	18.0
Meadow hay	1½ tons	203	49	50.9	32.1	12.3
Red clover	2 tons	258	102	83.4	90.1	24.9
Potatoes	6 tons	127	47	76.5	3.4	21.5
Turnips	17 tons	364	192	148.8	74.0	33.1

145. Amounts of plant-food materials contained in soils.—Comparing the figures given above with those showing the total amounts of the fertilizing constituents in certain soils, it is evident that there is a supply in most arable soils that will afford nutriment for average crops for a very long period of time. The following table shows the amount of nutrients contained in the chief divisions of soil as given on page 30.

TABLE XLIV

AMOUNTS OF PLANT-FOOD CONSTITUENTS CONTAINED IN ONE-ACRE-FOOT OF SOIL. IN THOUSAND POUNDS

	Residual soils Table II			Cumulose soils Table IV		Water-deposit soils Table V				
Column where analysis of material is given	Column V Gneiss clay Va.	Column VIII Basalt clay France	Column XVI Limestone clay Ark.	Column I Muck Minn.	Column IV Peat N. C.	Column V Sand, barren Md.	Column II Sandy loam Md.	Column III Clay loam Md.	Column IV Clay barren Md.	Column XIII Adobe clay N. M.
Estimated weight per acre-foot in million pounds	3.3	3.3	3.3	1.6	1.2	4.3	3.7	3.5	3.5	3.5
	M	M	M	M	M	M	M	M	M	M
Phosphoric acid (P_2O_5)	15.5	....	79.0	4.8	0.6	0.9	9.2	14.1	5.6	10.0
Lime (CaO)	0.5	259.0	135.0	7.6	3.6	1.8	20.0	16.1	15.5	85.0
Magnesia (MgO)	13.0	21.5	9.1	1.5	1.4	3.1	18.0	10.0	20.0	45.0
Soda (Na_2O)	6.5	30.0	21.0	3.0	1.3	4.9	22.0	17.0	20.0	23.0
Potash (K_2O)	36.0	25.0	33.0	4.8	0.6	5.5	37.0	42.0	52.0	44.0

TABLE XLIV, continued

AMOUNTS OF PLANT-FOOD CONSTITUENTS CONTAINED IN ONE-ACRE-FOOT OF SOIL. IN THOUSAND POUNDS

	Water-deposit soils Table V		Glacial soils Table VI			Wind-deposit soils Table VII				
Column where analysis of material is given........	Column XII Clay N. Y.	Column XVI Clay Minn.	Column II* Silt loam Ohio	Column III* Loam Ohio	Column V* Loam Prairie Minn.	Column I* Dust Arid region	Column II Loess Miss.	Column III Loess Ia.	Column VI Loess Col.	Column IX Loess Switzerland
Estimated weight per acre-foot in million pounds...	3.3	3.3	3.5	3.5	3.5	3.7	3.5	3.5	3.5	3.5
	M	M	M	M	M	M	M	M	M	M
Phosphoric acid (P_2O_5).	50.0	16.5	3.2	5.3	5.7	6.4	4.5	8.0	15.8	38.0
Lime (CaO)..........	185.0	500.0	6.3	24.0	29.0	73.0	340.0	56.0	80.0	63.0
Magnesia (MgO)......	82.0	250.0	17.5	22.0	12.5	52.0	160.0	39.0	38.0	....
Soda (Na_2O).........	35.0	28.0	10.0	27.0	15.0	8.4	41.0	59.0	60.0	43.0
Potash (K_2O).........	101.0	75.0	7.5	20.0	14.0	35.0	38.0	75.0	110.0	45.5

*Strong hydrochloric acid analysis. All other analyses are of the entire material.

146. Possible exhaustion of mineral nutrients.—On the other hand, when we consider that the soil must be depended upon to furnish food for humanity and domestic animals as long as they shall continue to inhabit the earth, at least so far as we now know, the very apparent possibility of exhausting, even in a period of several hundred years, the supply of plant nutrients becomes a matter of grave concern. The visible sources of supply, to replace or supplement those in the soils now cultivated are, for the mineral substances, the subsoil and the natural deposits of phosphates, potash salts, and limestone, and for nitrogen deposits of nitrates, the by-product of coal distillation and the nitrogen of the atmosphere. The last of these is inexhaustible, and the exhaustion of the nitrogen supply, which a few years ago was thought to be a matter of less than half a century, has now ceased to cause any apprehension. The conservation or extension of the supply of mineral nutrients is now of supreme importance. The utilization of city refuse and the discovery of new mineral deposits are developments well within the range of possibility, but neither of these promises to afford more than partial relief. The utilization of the subsoil through the gradual removal by natural agencies of the top soil will, without doubt, tend to constantly renew the supply. The removal of top soil by wind and erosion is, even on level land, a very considerable factor. The large amount of sediment carried in streams immediately after a rain, especially in summer, gives some idea of the extent of this shifting. This affects chiefly the surface soil and thereby brings the subsoil into the range of root action.

IV. ACQUISITION OF NUTRITIVE SALTS BY AGRICULTURAL PLANTS

All of the salts taken up by the roots of agricultural plants are in solution when absorbed. The movement into the root thus depends upon the presence of moisture, which is the medium of transfer. The root hairs are the great absorbing portions of the plant, and through the cells of their delicate tissues the solutions of the various salts pass by osmotic action. (See Fig. 53.) The nature and quantity of material absorbed is determined by the law of osmosis. From the cells of the root-hairs the dissolved salts are transferred to other portions of the plant, where they undergo the metabolic processes that determine which constituents shall be retained in the tissues of the plant. The unused ions which remain in the plant juices prevent by their presence the further absorption of those particular substances from the soil water. It thus happens that the composition of the ash of a plant may be very different from that of the substances presented to it in solution. For instance, aluminum, although always present in the soil, in a very slightly soluble form, is either absent or present in mere traces in the ash of most plants. On the other hand, iodine, although present in sea-water only in the most minute amounts, is present in large quantities in the ash of certain marine algæ.

147. Selective absorption.—A plant will, in general, take up more of a nutritive substance when presented in large amount, as compared with the other soluble substances in the nutrient solution, than if presented in small amount. Thus, the percentage of nitrogen in maize, oats and wheat may be increased by increasing the ratio of nitrogen to other nutritive substances in the nutrient media. This is also true of potassium and phosphorus, respectively. This fact is accounted for by the maintenance of the osmotic equilibrium at a higher level for a particular ion which is relatively abundant in the nutrient solution, thus preventing the return of the excess from the plant.

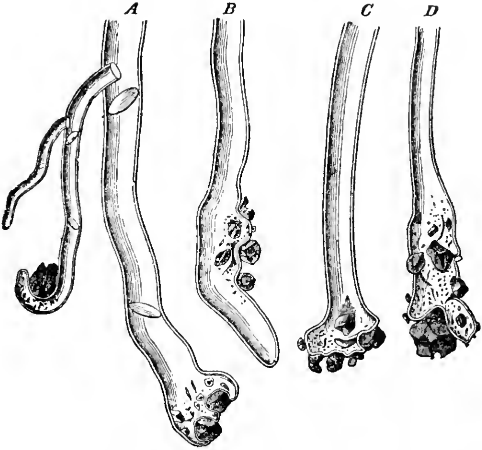

FIG. 99. Showing the intimate relation of root-hairs and soil particles.

148. Relation between root-hairs and soil-particles.— In a rich, moist soil the number of root-hairs is very great, while in a poor or a dry soil there are comparatively few. The connection between the root-hairs and the soil-particles is extremely intimate. When in contact with the particle of soil, the root-hair frequently almost incloses it, and by means of its mucilaginous wall forms a contact so close as to practically make the solution between the particle and the cell-wall distinct from that between the soil-particles.

There has been considerable difference of opinion as to how the plant can obtain its mineral nutrients from a substance so difficultly soluble as the soil. It has, of course, been recognized that the soil-water is aided in its solvent action by a variety of substances that may be normally present in solution, beginning with the gases taken up by the rain in its descent through the atmosphere, and further aided by the carbon dioxide and organic and mineral substance obtained from the soil. It has been held that the plant-roots aid solution of mineral matter by excretion of acids, which act effectively as solvents. The well-known root-tracings on limestone and marble have been taken as proof of the excretion of such acids. Sachs and, later, other investigators grew plants of various kinds in soil and other media in which was placed a slab of polished marble or dolomite or calcium phosphate, covered with a layer of washed sand. After the plants had made sufficient growth, the slabs were removed and on the surfaces were found corroded tracing, corresponding to the lines of contact between the rootlets and the minerals.

In order to test this theory, Czapek repeated the experiments, using plates of gypsum mixed with the ground mineral that he wished to test, and this mixture he spread over a glass plate. Using these plates in the same manner as previously described, Czapek found that, while plates of calcium carbonate and of calcium phosphate were corroded by the roots, plates of aluminum phosphate were not. He concludes that if the tracings are due to acids excreted by the plant-roots, the acids so excreted must be those that have no solvent action on aluminum phosphate. This would limit the excreted acids to carbonic, acetic, propionic and butyric. Czapek also replies to the argument that the acids producing the tracings must be non-volatile ones, because of the definite lines made in the mineral, by stating that the excretion of carbon dioxide alone would be sufficient to account for the observations, as it dissolves in water to form carbonic acid, and that carbonic acid is always present in the cell-walls of the root epidermis, from which it does not readily exude.

Czapek has also shown that liquids having an acid reaction exude from root-hairs, and he attributes the reaction to the presence of acid salts of mineral acids, having found potassium, phosphorus, magnesium, calcium and chlorine in this exudate. He has not proven, however, that the exudations were not from dead root-hairs, or from the dead cells of the root-cap. In either case they would have some solvent action, but whether sufficient to make them of importance it is impossible to say.

Kunze, who followed up this work, discredits the theory of excretion of acid salts of mineral acids, and attributes the corrosive action of roots to organic acids. In his experiments with 200 species, he found that many plants do not excrete enough acid to be detected by litmus. He attributes to fungi much the greater activity in this respect, and considers them more important in disintegrating the soil than are the higher plants.

The present status of experimental evidence on excretion of acids other than carbonic by the roots of plants does not admit of any very satisfactory conclusion as to their relative importance in the acquisition of plant-food materials. There can be no doubt, however, that carbon dioxide, resulting from root exudation, and from decomposition of organic matter in the soil, plays a very prominent part in this operation. The very large quantity of carbon dioxide in the soil, amounting in some cases to from 5 to nearly 10 per cent of the soil air, or several hundred times that of the atmospheric air, must aid greatly in dissolving the soil-particles.

Whatever may be the concentration of the soil-water, it seems probable that the liquid to be found where the root-hair comes in contact with the soil-particle, and which is separated, in part at least, from the remainder of the soil-water, must have a density much greater than that found elsewhere in the soil. The comparatively rich juices of the plant separated from the soil water only by the delicate cell-walls of the root-hair insures a copious transfer of the constituents of these juices into the intervening water, thus bringing into contact with the soil mineral salts, of which some are doubtless acid salts and also mineral salts of organic acids, and, possibly, some free organic acids. That portion of the soil-water immediately in contact with the soil grain is a much stronger solution than the water further from the soil surfaces on account of the absorptive action of the particles. These solutions, coming in contact with the surface of the soil-particles already subjected to the bacterial and other disintegrating agents of the soil, may readily be conceived to start an active transfer of mineral substances into the plant.

Plants grown in solutions of nutritive salts have few or no root-hairs, but absorb through the epidermal tissue of the roots. If the plant depended upon the prepared solution in the soil-water, a similar structure would doubtless suffice. The special modification by which the root-hairs come in intimate contact with the soil-particle, and almost surrounds it, indicates a direct relation between the soil-particles and the plant, and not merely between the soil solution and the plant.

New root-hairs are constantly being formed, and the old ones become inactive and disappear. The contact of a root-hair with a soil-particle is not long-continued. Whether the period of contact is determined by the ability of the root to absorb nutriment from the particle is not known. Certain it is that only a small portion of the particle is removed. It may be true that only the immediate surface which had been previously acted upon by the disintegrating agents of the soil, and thus rendered more easily soluble, is affected by the absorbent action of the root-hairs.

149. Absorptive power of different crops.—As has already been pointed out (page 281), crops of different kinds vary greatly in their ability to draw nourishment from the soil. The difference between the nitrogen, phosphorus and potassium taken up by a corn crop of average size and a wheat crop of average size is very striking. Corn has the longer growing period, but as between oats and wheat, where the growing period is nearly identical, a similar relation exists.

The difference in absorbing power may be due to either one or both of two causes: (1) A larger absorbing system. (2) A more active absorbing system. The former is determined by the extent of the root-hair surfaces; the latter by the intensity of the osmotic action.

150. Extent of absorbing system.—Plants with large root systems may, therefore, be expected to absorb the larger amounts of nutrients from the soil, and such is usually the case, although the extent of the root-system is not necessarily proportional to the total area of the absorbing surfaces of the root-hairs.

151. Osmotic activity.—The osmotic activity of a plant under any given condition of soil and climate depends upon: (1) The rapidity and completeness with which the plant elaborates the substances taken from the soil into plant substance or otherwise removes them from solution. (2) The extent to which the exudations from the root-hairs act upon the soil particles to increase the density of the solution between the root-hair and the soil-particle.

The first of these is a function of the vital energy of the plant and its ability to utilize sunshine and carbon dioxide to produce organic matter. It may be compared to the property which enables one animal to do more work than another animal of the same weight on a similar ration.

The removal from the ascending water current in the plant of substances derived from the soil is accomplished in the leaves. By the dissociation of these, ions are constantly furnished for metabolism into materials that may be built into the tissues of the plant. The remaining ions are kept in the solution. There is a constant tendency to bring the composition and density of the solution into equilibrium, by diffusion and diosmosis, with the solution between the soil-particle and the root-hair. The rapidity with which the metabolic process removes a substance from the solution in the plant, therefore, determines the rate at which it is removed from a solution of given composition and density in the soil. Plants making a rapid growth remove more nutrients in a given time than those making a slower growth, when the nutrient solution is of a given composition and density. A maize plant, for instance, removes more nutriment from a given solution in one day during its stage of most rapid growth than does a wheat plant during a corresponding stage.

Another factor which affects the rate of absorption of salts from the soil is the solvent influence of exudates from the root-hairs. This subject has already been treated (page 287), and it only remains to say that this action apparently varies with different kinds of plants, and probably accounts in no small measure for the difference in the ability of different plants to withdraw salts from the soil.

These several factors, which, when combined, determine the so-called "feeding-power" of the plant, are recognized by the popular terms "weak-feeder" and "strong-feeder,"—applied, on the one hand, to such crops as wheat or onions, which require very careful soil preparation and manuring, and, on the other hand, to maize, oats or cabbage, which demand relatively less care. In manuring and rotating crops, this difference in absorptive power must be considered, not only to secure the maximum effect upon the crop manured, but also to get the greatest residual effect of the manure upon succeeding crops.

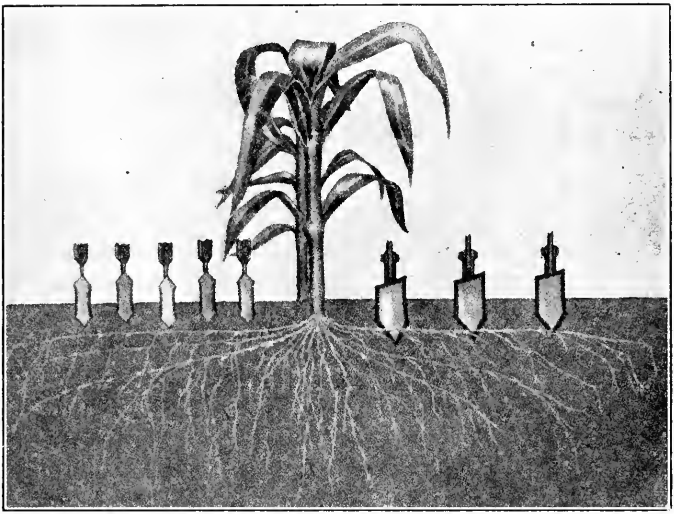

FIG. 100. Deep and shallow cultivation for corn. On the right-hand side of the picture the deep cultivator shovels are destroying the upper roots. On the left-hand side the shallow cultivation does not reach the roots.

152. Cereal crops.—These plants possess the power of utilizing the potassium and phosphorus of the soil to a considerable degree, but generally require fertilization with nitrogen salts. Most of the cereals, like wheat, rye, oats and barley, take up most of their nitrogen early in the season, before the nitrification processes have been sufficiently operative to furnish a large supply of nitrogen, and hence nitrogen is the fertilizer constituent that usually gives best results, and should be added in a soluble form. Wheat, in particular, needs a large amount of soluble nitrogen early in its spring growth. Since it is a delicate feeder, it does best after a cultivated crop or a fallow, by which the nitrogen has been converted into a soluble form. Oats can make better use of the soil fertility and does not require so much manuring. Maize is a very coarse feeder, and, while it removes a very large quantity of plant-food from the soil, it does not require that these be added in a soluble form. Farm manure and other slowly acting manures may well be applied for the maize crop. The long growing period required by the maize plant gives it opportunity to utilize the nitrogen as it becomes available during the summer, when ammonification and nitrification are active. Phosphorus is the substance usually most needed by maize.

153. Grass crops.—Grasses, when in meadow or in pasture, are greatly benefited by manures. They are less vigorous feeders than the cereals, have shorter roots, and, when left down for more than one year, the lack of aëration in the soil causes decomposition to decrease. There is usually a more active fixation of nitrogen in grass lands than in cultivated lands, but this becomes available very slowly.

Different soils and different climatic conditions necessitate different methods of manuring for grass. Farm manures may well be applied to meadows in all situations, while the use of nitrogen is generally profitable.

154. Leguminous crops.—Most of the leguminous crops are deep-rooted and are vigorous feeders. Their ability to acquire nitrogen from the air makes the use of that fertilizer constituent unnecessary except in a few instances, such as young alfalfa on poor soil, where a small application of nitrate of soda is usually beneficial. Lime and potassium are the substances most beneficial to legumes on the majority of soils.

155. Root-crops.—Many of the members of this class of crops will utilize very large amounts of plant-food if it is in a form in which they can use it. Phosphates and nitrogen are the substances generally required, the latter especially by beets and carrots.

156. Vegetables.—In growing vegetables, the object is to produce a rapid growth of leaves and stalks rather than seeds, and often this growth is made very early in the season. As a consequence, a soluble form of nitrogen is very desirable. Farm manure should also have a prominent part of the treatment, as it keeps the soil in a mechanical condition favorable to retention of moisture, which vegetables require in large amounts, and it also supplies needed fertility. The very intensive method of culture employed in the production of vegetables necessitates the use of much greater quantities of manures than are used for field crops, and the great value of the product justifies the practice.

157. Fruits.—In manuring fruits, with the exception of some of the small, rapid-growing ones, it is the aim to maintain a continuous supply of nutrients available to the plant, but not sufficient for stimulation, except during the early life of the tree, when rapid growth of wood is desired. An acre of apple trees in bearing removes as much plant-food from the soil in one season as does an acre of wheat.

Farm manure and a complete fertilizer may be used, of which the constituents should be in a fairly available form, as a constant supply is necessary.

V. ABSORPTION BY THE SOIL OF SUBSTANCES IN SOLUTION

If the brown water extract from manure be filtered through a clay soil not containing soluble alkalies, the filtrate will be nearly colorless. Many solutions of dye stuffs are affected in the same way. Solution of alkali or alkaline earth salts are more or less modified by this operation, the bases being retained by the soil. Thus when a solution of the nitrate, sulfate, or chloride of any one of these bases is filtered through the soil, a part of the base is absorbed by the soil, while the acid comes through in the filtrate. If these bases are in the form of phosphates or silicates, not only the base is absorbed but the acid as well.

158. Substitution of bases.—Associated with the absorption of the base from solution, there is liberation of some other base from the soil, which combines with the acid in the solution and appears in the filtrate as a salt of that acid.

When absorption takes place from solution, the base is never entirely removed, no matter how dilute the solution may be. A dilute solution of potassium chloride filtered through a soil will produce a filtrate containing some calcium chloride or sodium chloride, or both, and some potassium chloride. The more dilute the solution, the larger the proportion retained. Peters treated 100 grams of soil with 250 c.c. of a solution of potassium salts, and found that the potassium of different salts was retained in different proportions, and that the stronger solutions lost relatively less than the weaker.

Table XLV

Strength of solution	$\frac{1}{10}$ normal	$\frac{1}{20}$ normal
	Grams K_2O absorbed	Grams K_2O absorbed
KCL	.3124	.1990
K_2SO_4	.3362	.2098
K_2CO_4	.5747	.3134

The same bases are not always absorbed to the same extent by different soils; one soil may have a greater absorptive power for potassium, while another may retain more ammonia. They seem to be interchangeable, as any absorbed base may be released by another in solution.

159. Time required for absorption.—The amount of absorption depends upon the time of contact between the soil and the solution. While a large part of the dissolved base is taken up in a short time after being in contact with the soil, the maximum absorption is only effected after considerable time. Ammonia, according to Way, reaches its maximum absorption in half an hour, while Henneberg & Stohmann found that phosphorus required twenty-four hours to reach the same degree of absorption.

160. Insolubility of certain absorbed substances.—Although bases once absorbed may be easily displaced by other bases, it is a difficult matter to dissolve them from the soil with pure water. Peters treated 100 grams of soil with 250 c.c. of water containing potassium chloride, of which .2114 grams of K_2O were absorbed. The soil was then leached with distilled water, using 125 c.c. of water daily for ten days. At the end of that time .0875 grams of K_2O had been removed, or at the rate of 28,100 parts of water to one part of K_2O dissolved from the soil. Henneberg and Stohmann found that it required 10,000 parts of water to dissolve one part of absorbed ammonia from the soil.

161. Influence of size of particles.—The surface area of the soil-particles determines to some extent the amount of substance absorbed. For this, and other reasons, a fine-grained soil absorbs a greater quantity of material than a coarse-grained soil. In fact, it was early shown by Way that the absorption phenomenon is largely a function of the silt, clay and humus of the soil.

162. Causes of absorption.—A number of causes have been assigned for the absorption of substances by soils, and there can be no doubt that the phenomenon is not due to any one process. Several distinct causes are now quite generally recognized and, while others that have been suggested may have a part in the result, they cannot all be taken up at this time. The better-known and more important absorption processes are the following:

163. Zeolites.—As stated on a preceding page, Way demonstrated that sand had little absorbing power as compared with clay, and further, that when the zoelitic silicates were removed from clay by digestion with hydrochloric acid, the clay largely lost its power of absorption. Way produced an artificial hydrated silicate of alumina and soda, and Eichorn found natural hydrated silicates or zeolites that removed bases with the substitution of other bases, in the manner of natural soil. A further characteristic of these zeolites is that the replaced base is present in the filtrate in amounts chemically equivalent to the base removed.

It has further been shown that the absorptive power of soils is more or less proportional to the amount of acid soluble silicates it contains. The zeolites being rather easily soluble in strong mineral acids, it is held that the bases so combined are more readily available to plants than in most combinations found in the soil, and yet are not readily leached out of it.

Soluble bases added to the soil in manures are taken up and held by zeolites, instead of being removed in the drainage water. However, nitric acid, important as it is to agriculture, is not absorbed, and, together with the sulfuric and hydrochloric acid, is quickly but not completely removed from the soil by drainage water.

164. Other absorbents.—Humus, ferric and aluminum hydrates, and calcium carbonate, exercise absorbent properties, but to what extent and of what importance it is difficult to say. Soils rich in humus, without doubt, owe much of their fertility to the retention by that constituent of a large supply of readily available plant-food material. Many prairie soils that have been reduced in productiveness under cultivation respond to the application of organic matter in a remarkable manner. Humus in these soils seems to be the chief conserver of readily available plant-food materials.

Ferric and aluminum hydrate aid in the retention of acids, notably phosphoric, by forming highly insoluble compounds.

165. Adsorption.—There is a physical absorption, termed adsorption, due to the concentration of the soil solution in contact with the surface of the particles. The phenomenon is familiarly exemplified in the clarifying effect of the charcoal filter. This process results in the retention of considerable soluble material in fine-grained soils, that would otherwise be washed out. In the case of nitrates, which are not retained by the zeolites, adsorption is an important factor. (See page 325.) If a solution of a known quantity of nitrate of soda be added to a clay soil, and it is then attempted to extract the nitrate from the soil with distilled water, it will be found impossible to recover a very appreciable per cent of the amount added. While adsorption probably does not account for all of the nitrates retained, there can be no doubt that it plays an important part. Nutritive salts held in this way are readily available to the plant whose root-hairs come in contact with the soil particles.

166. Occlusion.—According to Wiley, clay in a colloidal state has the property of dissociating to a certain extent potash salts, and entangling the basic ion in the meshes of the colloid structure. How extensive or important this action is has not been demonstrated.

167. Absorption as related to drainage.—The drainage water from cultivated fields in the humid region, and to a less extent in the semi-arid and arid region, except where irrigation is practiced, carries off very considerable amounts of plant-food material. The loss of this material is due to the operation of the various natural disintegrating agents upon the soil mass, and to the application of fertilizing materials in a soluble form. The various absorptive properties stand between the natural solubility of the soil and the tendency to loss in drainage, and hold these materials that would otherwise be lost, in a condition in which they may readily be used by the plant.

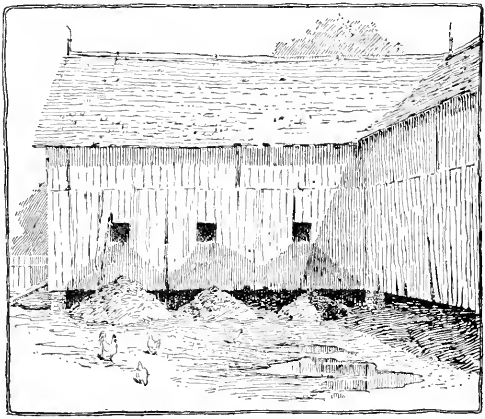

FIG. 101. Wasting manure by leaching.

168. Substances usually carried in drainage water.—However, some material is always lost in drainage water, of which, among the bases of the soil those most likely to be found are soda, magnesia and lime, and of the acids nitric, carbonic, hydrochloric and sulfuric. Nitric acid and lime undergo the most serious losses. The former may be curtailed to a great extent by keeping crops growing on the soil, during all of the time that nitrification is going on, and if the crop does not mature or if, for any other reason, it is not desired to harvest the crop, it should be plowed under, to return the nitrogen in the form of organic matter. A crop used for this purpose is called a "catch crop." Rye is used quite commonly as a catch crop, as it continues growth until late in the fall, and resumes growth early in the spring, conserving nitrates whenever nitrification may occur, and it may then be plowed under to prepare the land for another crop. Rye also has the advantage of small cost for seed.

The loss of calcium cannot well be prevented, and the use of commercial fertilizers always greatly increases such loss. The only remedy is the application of some form of calcium to the soil.

169. Drainage records at Rothamsted.—Drainage water from a series of plats at the Rothamsted Experiment Station, which have been manured in various ways and planted to wheat each year since 1852, have been analysed at certain times, and the results of these analyses, as compiled by Hall, give some idea of the loss of salts from cultivated soils. The drainage water was obtained from the tile drains, one of which extended under each plat from one end to the other, and opened into a ditch, so that the water could be collected when desired. The analyses shown in the accompanying table

TABLE XLVI

COMPOSITION OF DRAINAGE WATER FROM BROADBALK WHEAT PLATS, ROTHAMSTED EXPERIMENT STATION

Manures applied, rate per acre	Parts per million											Average yield of wheat, 1852–1902
	Peroxide of iron	Lime	Magnesia	Potash	Soda	Chlorine	Sulfuric acid	Phosphoric acid	Soluble silica	Nitrogen as ammonia	Nitrogen as nitric acid	
Plat												Bus.
2 Farm manure, 14 tons	2.6	147.4	4.9	5.4	13.7	20.7	106.1	....	35.7	0.16	16.1	35.7
3 and 4 No manure	5.7	98.1	5.1	1.7	6.0	10.7	24.7	0.63	10.9	0.12	3.9	*13.1
5 Minerals only	4.4	124.3	6.4	5.4	11.7	11.1	66.3	0.91	15.4	0.13	5.1	14.9
6 Minerals + 200 lbs. ammonium salts	2.7	143.9	7.9	4.4	10.7	20.7	73.3	1.54	24.7	0.20	8.5	24.0
7 Minerals + 400 lbs. ammonium salts	8.1	181.4	8.3	2.9	10.9	26.1	90.1	0.91	17.0	0.07	14.0	32.9
8 Minerals + 600 lbs. ammonium salts	2.7	197.3	8.9	2.7	10.6	39.4	89.7	0.17	20.9	0.27	16.9	37.1
9 Minerals + 550 lbs. nitrate of soda	5.1	118.1	5.9	4.1	56.1	12.0	41.0	....	10.6	0.24	18.4	
10 400 lbs. ammonium salts alone	4.0	154.1	7.4	1.9	7.1	32.0	44.4	1.44	13.7	0.08	13.9	20.7
11 400 lbs. ammon. salts + superphosphate	3.4	165.6	7.3	1.0	6.6	31.6	54.3	1.66	11.3	0.17	15.3	24.0
12 400 lbs. ammon. salts + superphosphates + sulfate soda	3.6	191.6	6.6	2.7	24.6	30.9	96.7	1.26	17.9	0.30	15.1	30.0
13 400 lbs. ammon. salts + superphosphates + sulfate potash	3.7	201.4	9.3	3.3	6.1	36.6	86.9	1.09	28.3	0.16	17.4	31.5
14 400 lbs. ammon. salts + superphosphates + sulfate magnesia	3.7	226.7	11.6	1.0	5.6	39.4	99.7	1.01	14.0	0.09	19.2	30.1
16 Minerals + 1,100 lbs. nitrate of soda	3.0	117.1	5.3	2.4	5.1	11.4	21.9	0.91	17.0	0.09	7.0	....

*Yield on Plat 3 alone—

were made by Dr. A. Voelcker, and represent the mean of not more than five collections made in December, May and January and April during a period of two years. They can not be regarded as showing accurately the annual removal of salts from the soil but are still significant.

From this table it will be seen that lime is the ingredient lost in largest amount from this soil and that the character of the manure applied influences this loss to some extent. The sulfates of sodium, potassium, and magnesium have notably increased the loss of lime, as have also the ammonium salts. The loss of lime from all of the manured plats was notably greater than from the unmanured.

Potash was not removed in large amount by the drainage water from any of the plats. Ammonium salts with superphosphate and with magnesia occasioned only a slight loss of potash, as did also the absence of manure. The plats receiving mineral manure alone and farm manure lost the greatest quantities of potash.

The quantity of sulfuric acid leached from the soil is quite large and highly variable. It is frequently, but by no means uniformly, large on those plats from which lime is removed in large amounts. The plat receiving farm manure lost the largest quantity of sulfuric acid.

Phosphoric acid was removed in small amounts and, except in the case of the unmanured plat, those plats losing the least phosphoric acid gave the largest yields. The loss of phosphoric acid seems to be a matter of failure on the part of the crop to utilize it, rather than its liberation by any manurial substance.

Ammoniacal nitrogen in the drainage water is very small in amount, but nitrate nitrogen is present in amounts sufficient to make the loss of some concern. The use of sodium nitrate occasioned the greatest loss of nitrogen while ammonium salts and farm manure contributed nearly as much. Forty to fifty pounds of nitrogen per acre may be lost annually in this way, which amount would have a commercial value of from eight to nine dollars.

The most serious losses are those of nitrogen and lime, and both are to an extent unavoidable. Potassium and phosphorus, which must also be purchased in manures, are lost only at the rate of a few pounds per acre but had lime been applied to any of these plats, the loss of potassium would probably have been larger. Nitrogen and phosphorus are best conserved by keeping crops growing on land as much of the time as possible, and the former may also be protected by applying the soluble nitrogen salts only at a time when they can be utilized by crops. The loss of calcium frequently amounts to several hundred pounds per acre annually, and, as the presence of calcium carbonate is essential to a healthy condition, of the soil this loss, particularly from the soil receiving salts like sulfates and chlorides, the bases of which are absorbed by plants in larger amounts than the acids, is likely to result in a very bad condition of the soil. The only method of obviating this is to lime the soil from time to time.

170 Relation of absorptive capacity to productiveness.—The absorptive capacity of a soil is not so much a measure of its immediate as of its permanent productiveness. It is well known that a very sandy soil responds quickly to the application of soluble manures, but that the effect is confined mainly to one season; while a clay soil, although not so quickly responsive to fertilization, shows the effect of the application much more markedly the second or third year than does the sandy soil. Mechanical absorption holds the nutritive material in a very readily available condition, while absorption by zeolitic bodies renders these substances somewhat less readily available. There are also other reasons why the sandy soil is more responsive.

It cannot be said that there is a relation between the absorptive capacity of a soil and its productiveness when manured or when nearly virgin, but soil long-cultivated and unmanured frequently show such a relation. King, in working with eight types of soil in different portions of the United States, found that those soils removing the most potassium from solution gave the largest yield of crop. It would not be permissible, however, to adopt this test as a method for determining productiveness in soils.

VI. ALKALI SOILS

As already explained (page 14), soils are acted upon by a great variety of agencies, which gradually render soluble a portion of the particles. The soluble matter is taken up by the soil water, and in humid regions where a large amount of water percolates through the soil and passes off in the drainage, the soluble matter is found only in small quantity at any time. In arid regions the loss by drainage is slight or entirely wanting, and under such conditions the soluble materials accumulate in the soil, being transposed downward with the percolating water and upward again with the capillary rise of water during the dry period. The lower soil may at one time contain considerably more soluble salt than the upper soil, while at another time the upper soil may contain more of these salts, in which case the solution in contact with plant-roots may, and often does, contain so much soluble matter that vegetation is injured or destroyed. This excess of soluble salts may or may not have a marked alkaline reaction, but in any case produce what are termed alkali soils.

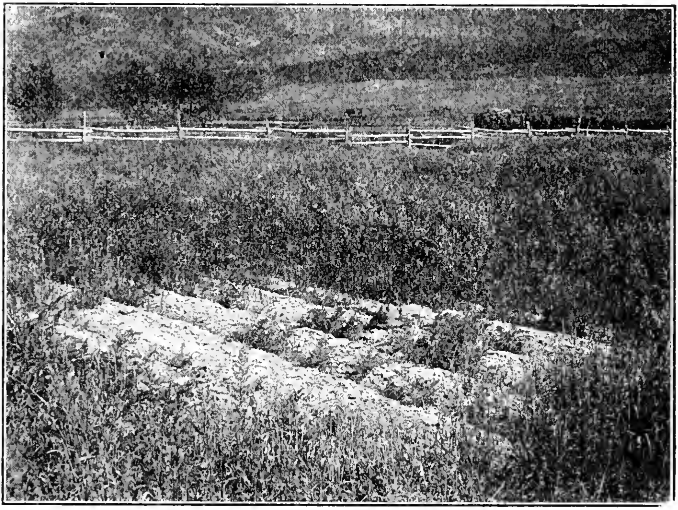

FIG. 102. Bare spot, marking the first appearance of injurious quantities of alkali salts in the surface layer of soil. Utah.

171. Composition of alkali salts.—The materials dissolved in the soil water consist of all of the substances found in the soil, but, as the rates of solubility of these substances vary greatly, there accumulates a much larger quantity of some substances than of others. Carbonates, sulfates and chlorides of sodium, potassium, calcium and magnesium occur in the largest amounts. Sodium may be present as carbonate, sulfate, chloride, phosphate and nitrate. Potassium may be similarly combined. Magnesium is likely to appear as a sulfate or chloride, and calcium as a sulfate, chloride or carbonate. In some soils one salt will predominate, and in other soils other salts will prevail. A base may be present in combination with several different acids. The nature of the prevailing salt influences greatly the effect upon vegetation. Table XLVII gives the composition of the soluble salts from a number of alkali soils.

172. White and black alkali.—Sulfates and chlorides of the alkalies when concentrated on the surface of the soil produce a white incrustation, which is very common in alkali regions during a dry period, as a result of evaporation of moisture. Alkali in which these acids predominate is called white alkali.

Carbonates of the alkalies dissolve organic matter in the soil, thus giving a dark color to the solution and to the incrustation, and for this reason alkali containing large quantities of these salts is called black alkali.

Black alkali is much more destructive to vegetation than is white. A quantity of white alkali that would not seriously interfere with the growth of most crops

Table XLVII.—Percentage Composition of Alkali*

	Yakima Co., Wash. Meadowland			Boise Valley Idaho		Grand Forks, N. Dakota		Billings, Montana		California		
	Surface 12 inches	Second 12 inches	Third 12 inches	Surface 12 inches	Surface deposit	Alkali crust	12–36 inches	Crust 0–1 inch	Surface 10 inches	Tulare Exp. Sta.	Mojave Plateau	Imperial desert
Potassium chloride, KCl..	....	5.61	7.82	8.08	1.84	1.81	5.50	....	....	....	....	1.15
Potassium sulfate, K_2SO_4.	....	....	....	....	....	....	....	1.60	21.41	3.95	.92	....
Potassium carbonate, K_2CO_3	8.74	9.73	8.64	....	....	....	....	....	....	....	....	....
Sodium sulfate, Na_2SO_4..	....	....	....	16.54	67.70	....	....	85.57	35.12	25.28	43.34	....
Sodium nitrate, $NaNO_3$..	....	....	....	....	....	....	....	....	....	19.78	....	8.21
Sodium carbonate, Na_2CO_3	66.94	13.86	6.58	41.55	.10	....	....	trace	7.28	32.58	15.38	.58
Sodium chloride, NaCl...	....	....	....	....	17.56	26.15	....	.55	trace	14.75	39.34	28.83
Sodium phosphate, Na_3HPO_4...............	....	....	....	....	....	....	....	....	....	2.25	1.02	....
Magnesium sulfate, $MgSO_4$.................	....	....	....	.82	6.15	41.49	24.31	8.90	4.06	....	....	....

*Compiled from analyses made by the Bureau of Soils of the United States Department of Agriculture and by the California Experiment Station.

TABLE XLVII.—PERCENTAGE OF COMPOSITION, continued

	Yakima Co., Wash. Meadowland			Boise Valley Idaho		Grand Forks, N. Dakota		Billings, Montana		California		
	Surface 12 inches	Second 12 inches	Third 12 inches	Surface 12 inches	Surface deposit	Alkali crust	12–36 inches	Crust 0–1 inch	Surface 10 inches	Tulare Exp. Sta.	Mojave Pla teau	Imperial desert
Magnesium chloride, $MgCl_2$	13.30	....	....	....	....	9.24	8.80	....	....	....	....	2.81
Calcium chloride, $CaCl_2$	1.90	....	....	....	....	....	....	....	....	....	....	58.42
Sodium bicarbonate, $NaHCO_3$	....	36.72	45.28	31.27	.72	1.49	4.29	.67	22.06	....	....	....
Calcium sulfate, $CaSO_4$	9.12	1.87	6.17	.64	5.93	19.82	57.10	2.71	10.07	....	....	....
Calcium bicarbonate, $Ca(HCO_3)_2$	....	16.48	13.17	....	....	....	....	....	....	....	....	....
Magnesium bicarbonate, $Mg(HCO_3)_2$	....	12.57	12.34	....	....	....	....	....	....	....	....	....
Potassium bicarbonate, $KHCO_3$	....	....	....	1.10	....	....	....	....	....	....	....	....
Ammonium carbonate, $(NH_4)_2CO_3$	....	....	....	....	....	....	....	....	....	1.41	....	....

might completely prevent the growth of useful crops if the alkali were black.

173. Effect of alkali on crops.—The presence of relatively large amounts of salts dissolved in water and brought in contact with a plant cell has been shown by DeVries to cause a shrinking of the protoplasmic lining of the cell, the shrinking increasing with the concentration of the solution. This causes the plant to wilt, cease growth and finally die. The nature of the salt, and the species and even the individuality of the plant, determine the point of concentration at which the plant succumbs.

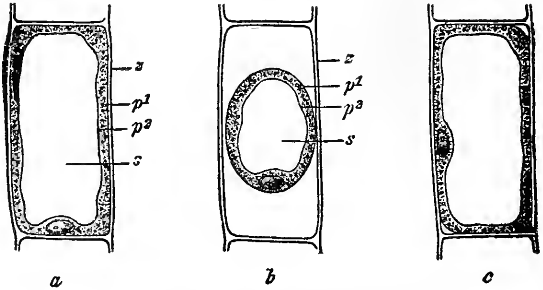

FIG. 103. Showing plasmolysis of plant cells produced by strong solutions of salts. (*a*) Normal cells; (*b*) cell subjected to action of 5 per cent solution of KNO_3, showing (*z*) cell-wall, (p^1, p^2) plasmatic membranes, (*s*) vacuole; (*c*) cell subjected to action of 2.3 per cent solution of KNO_3, causing a slight contraction of the plasmatic membranes.

174. Direct effect.—The directly injurious effect of the chlorides, sulfates, nitrates, etc., of the alkalies and alkali earths is due to this action on the cell contents. The carbonates of the alkalies have, in addition, a corroding effect upon the plant tissues, dissolving the portions of the plant with which they come in contact.

175. Indirect effect.—Indirectly alkali salts may injure plants by their influence upon the soil tilth, soil organisms, and fungous and bacterial diseases.

176. Effect upon different crops.—The factors that determine the tolerance of plants to alkali are: (1) The physiological constitution of the plant. (2) The rooting habit.

The first is not well understood, but resistance varies with species, and even with individuals of the same species. So far as the rooting habit influences tolerance of alkali, the advantage is with the deep-rooted plants like alfalfa and sugar-beets, probably because at least a part of the root is in a less strongly impregnated portion of the soil.

Of the cereals, barley and oats are the most tolerant, being able in some cases to produce a fair crop on soil containing one-tenth per cent of white alkali. Of the forage crops, a number of valuable grasses are able to grow with somewhat more than one-tenth per cent of alkali. Timothy, smooth brome and alfalfa are the cultivated forage plants most tolerant of alkali,—although they do not equal the native grasses in this respect. Cotton will also tolerate a considerable amount of alkali.

177. Other conditions influencing the action of alkali.—The larger the water content of the soil, the less the injury to plants from alkali; but, should the same soil become dry, the previous large quantity of water would, by bringing into solution a larger amount of alkali, render the solution stronger than it would otherwise have been, and thus cause more injury.

The distribution of the alkali at different depths may have an important bearing on its effect upon plants. Young plants and shallow-rooted plants may be entirely destroyed by the concentration of alkali at the surface, when the same quantity evenly distributed through the soil, or carried by moisture to a lower depth, would have caused no difficulty.

A loam soil, by reason of its greater water-holding capacity, will carry more alkali without injury to plants than will a sandy one.

Certain of the alkali salts exert a deflocculating action upon clay soils, and effect an indirect injury in that way.

178. Reclamation of alkali land.—The alkali salts, being readily soluble, are carried by the soil-water where there is any lateral movement, as frequently occurs where land slopes to some one point. Low-lying lands adjacent to such slopes are thus likely to contain considerable alkali, and the "alkali spots" of semi-arid regions and the large accumulations of alkali in many of the valley lands of arid regions are traceable to this cause.

179. Irrigation and alkali.—In irrigated regions, the injurious effect of alkali is frequently discovered only after irrigation has been practised for a few years. This is due to what is known as a "rise of alkali," and comes about through the accumulation, near the surface of the soil, of salts that were formerly distributed throughout a depth of perhaps many feet. Before the land was irrigated, the rainfall penetrated only a slight depth into the soil, and when evaporation took place salts were drawn to the surface from only a small volume of soil. When, however, irrigation water was turned upon the land, the soil became wet for perhaps fifteen or twenty feet in depth. During the portion of the year in which the soil is allowed to dry, large quantities of salts are carried to the upper soil by the upward-moving capillary water. These salts are in part carried down again by the next irrigation, but the upward movement constantly exceeds the downward one. This is because the descending water passes largely through the non-capillary interstitial spaces, while the ascending water passes entirely through the capillary ones. The smaller spaces, therefore, contain quite a quantity of soluble salt after the downward movement ceases and the upward movement commences. In other words, the volume of water carrying downward the salts in the capillary spaces is less than that carrying them upward through these spaces. Surface tension causes the salts to accumulate largely in the capillary spaces, and it is therefore the direction of the principal movement through these that determines the point of accumulation of the alkali.

There are large areas of land in Egypt, India and even in France and Italy, as well as in this country, that have suffered in this way, and not infrequently they have reverted to a desert state.

There are a number of methods that have been used with more or less success to reclaim alkali land.

180. Underdrainage.—Of the various methods for removing an excess of soluble salts the use of tile drains is the most thorough and satisfactory. When this is used in an irrigated region, heavy and repeated applications of water must be made, to leach out the alkali from the soil and drain it off through the tile. When used for the amelioration of alkali spots in a semi-arid region, the natural rainfall will in time effect the removal.

In laying tiles, it is necessary to have them at such a depth that soluble salts in the soil beneath them will not readily rise to the surface. This will depend upon those properties of the soil governing the capillary movement of water. Three or four feet frequently suffices, but the capillary movement should first be determined.

After drains have been placed, the land is flooded with water to a depth of three or four inches. This is allowed to soak into the soil and pass off through the drains, leaching out part of the alkali in the process. Before the soil has time to become very dry the flooding is repeated and the operation kept up until the land is brought into a satisfactory condition.

Crops that will stand flooding may be grown during this treatment, and they will serve to keep the soil from puddling, as it is likely to do if allowed to dry on the surface. If crops are not grown, the soil should be harrowed between floodings.

The operation should not be carried to a point where the soluble salts are reduced below the needs of the crop, or to lose entirely their effect upon the retention of moisture.

181. Correction of black alkali.—The use of gypsum on black-alkali land has sometimes been practiced for the purpose of converting the alkali carbonates into sulfates, thus ameliorating the injurious properties of the alkali without decreasing the amount. The quantity of gypsum required may be calculated from the amount and composition of the alkali. The soil must be kept moist, in order to bring about the reaction, and the gypsum should be harrowed into the surface, and not plowed under.

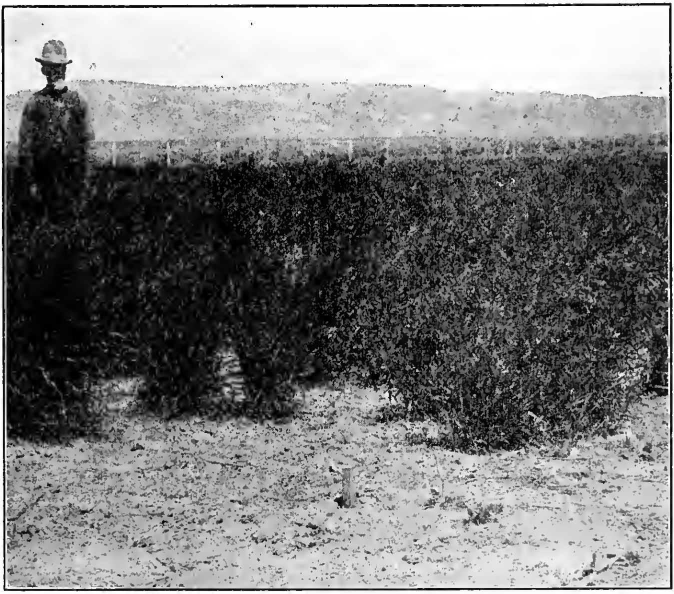

FIG. 104. *Bromus inermis* growing on reclaimed alkali land.

When soil containing black alkali is to be tile-drained, it is recommended that the land first be treated with gypsum, as the substitution of alkali sulfates for carbonates causes the soil to assume a much less compact condition and thus facilitates drainage, as well as preventing the loss of organic matter dissolved by the alkali carbonates, and soluble phosphates, both of which are precipitated by the change.

182. Retarding evaporation.—As evaporation of moisture from the surface of the soil is the cause of rise of alkali, it is important to reduce evaporation to a minimum, either in drained or in undrained land. Especially where irrigation is practiced without drainage, it becomes desirable to use as little water as is necessary to produce good crops, and to conserve this to the utmost by checking evaporation from the surface of the soil.

The methods used for checking evaporation are the maintenance of a soil or other mulch, and of a good tilth. (See page 195.) In handling alkali spots in the semi-arid region, it is very important to reduce evaporation to the smallest amount practicable.

183. Cropping with tolerant plants.—Certain alkali soils that are strongly impregnated with alkali may be gradually improved by cropping with sugar-beets and other crops that are tolerant of alkali, and which remove large amounts of salts. This is more likely to be efficacious where irrigation is not practiced.

184. Other methods.—Numerous other methods of disposing of alkali or ameliorating its effects have been used or proposed. Among these are the following: (1) "Leaching," which consists of flooding the surface of the soil for the purpose of carrying the soluble salts down to a depth of three or four feet, where they will not effect the roots of ordinary crops. If natural drainage exists, this plan is effective and without danger; otherwise evaporation must be reduced to the smallest possible amount. (2) Removal of alkali by scraping the surface when the salts have accumulated there in time of drought. While this may aid in the work of amelioration, it is not a final solution of the difficulty. (3) Washing the alkali from the land by turning on a rapidly moving body of water, when the alkali is encrusted on the surface of the soil, has been tried, but with poor success, as the alkali is largely carried into the soil, instead of being removed by the water passing over the surface of the land.

185. Alkali spots.—In semi-arid regions, small areas of alkali are frequently found, varying from a few square yards to several acres in size. The quantities of alkali in these are usually not sufficient to prevent the growth of crops in years of good rainfall, but in periods of drought the concentration of the salts and the compact condition they tend to produce combine to injure the crop. The methods already mentioned for treating alkali land are of service on these small areas, and, in addition, the plowing under of fresh farm manure has been found to improve their productiveness. This, with surface drainage, deep tillage and good cultivation, to prevent the soil from drying out, will usually remedy the difficulty. Frequently these spots become highly productive under proper treatment.

VII. MANURES

A manure is any solid substance added to the soil to make it more productive. This it may do: (1) By improving the physical condition of the soil, as usually results from the application of lime and the incorporation of organic matter. (2) By favoring the action of useful bacteria, which is one of the most beneficial results of farm manure, and also of lime. (3) By counteracting the effects of toxic substances, as, for instance, the conversion of sodium carbonate into sulfate by gypsum, or the neutralization of acidity, or possibly the removal of toxic organic substances by certain salts. (4) By adding to the soil the nutrient materials absorbed by plants, which results in the case of almost all substances used as manures.

186. Early ideas of the function of manures.—Manures were at one time supposed to pulverize the soil, and the French word *manœuvrer,* from which the word manure comes, means to work with the hand. This idea probably originated through the observation that farm manure, which was the only manure in use at that time, made the soil less cloddy.

It has been argued, notably by Jethro Tull, that as tillage pulverizes the soil it may be used as a substitute for manures. There are, however, conditions aside from tilth that are influenced by manures, and good tilth alone will not suffice to maintain a permanently intensive agriculture. It is true in the United States, as it is in Europe, that a large consumption of manures goes hand-in-hand with a highly developed and intensive system of farming.

187. Development of the idea of nutrient function of manures.—While the use of animal excrement on cultivated soils was practiced as far back as systematic agriculture can be definitely traced, the earliest record of the use of mineral salts for increasing the yield of crops was published, in 1669, by Sir Kenelm Digby. He says, "By the help of plain salt petre, diluted in water, and mingled with some other fit earthly substance, that may familiarize it a little with the corn into which I endeavored to introduce it, I have made the barrenest ground far outgo the richest in giving a prodigiously plentiful harvest." His dissertation does not, however, show any true conception of the reason for the increase in the crop through the use of this fertilizer. In fact, the want of any real knowledge at that time of the composition of the plant would have made this impossible.

In 1804, Theodore de Sausure published his chemical researches upon plants, in which he, for the first time, called attention to the significance of the ash ingredients of plants, and pointed out that without them plant-life is impossible, and further, that only the ash of the plant tissue is derived from the soil.

Justus von Liebig, in his writings published about 1840, emphasized still more strongly the importance of mineral matter in the plant, and its extraction from the soil. He refuted the theory, at that time popular, that plants absorb their carbon from humus, but made the mistake of attaching little importance to the presence of humus in the soil. He showed the importance of potassium and phosphorus in manures, but, in his later expressions, failed to appreciate the value of nitrogenous manures, holding that a sufficient amount is washed from the atmosphere in the form of ammonia.

A true conception of the necessity for a supply of combined nitrogen in the soil was even at that time entertained by Boussingault and by Sir John Lawes, although the elaborate experiments conducted by Lawes, Gilbert and Pugh, in 1857, were required to fully demonstrate the fact. Their care in conducting the experiments resulted in their sterilizing the soil with which they experimented, and hence their failure to discover the utilization of free atmospheric nitrogen by legumes.

Between 1840 and 1850, Sir John Lawes began the manufacture of bone superphosphate, and, about the same time, Peruvian guano and nitrate of soda were introduced into Europe. The commerical fertilizer industry thus dates from this time.

188. Classes of manures.—While manures are very numerous as to kind, and a certain manure may have a number of distinct functions, they may yet be roughly divided into classes. They will accordingly be treated under the following heads: (1) Commercial fertilizers. (2) Farm manures. (3) Green manures. (4) Soil amendments.

189. Commercial fertilizers.—Although the commercial fertilizer industry is little more than half a century old, the sale of fertilizers in this country amounts to about $50,000,000 annually. Animal refuse and phosphate fertilizers are exported, while nitrate of soda and potassium salts are imported.

Of the fertilizers sold in 1899, about 70 per cent was consumed in the North Atlantic and South Atlantic states, in an area lying within 300 miles of the seaboard. Nearly one-half of the remainder was purchased in four states, Ohio, Indiana, Alabama and Louisiana.

190. Function of commercial fertilizers.—Primarily the function of commercial fertilizers is to add plant

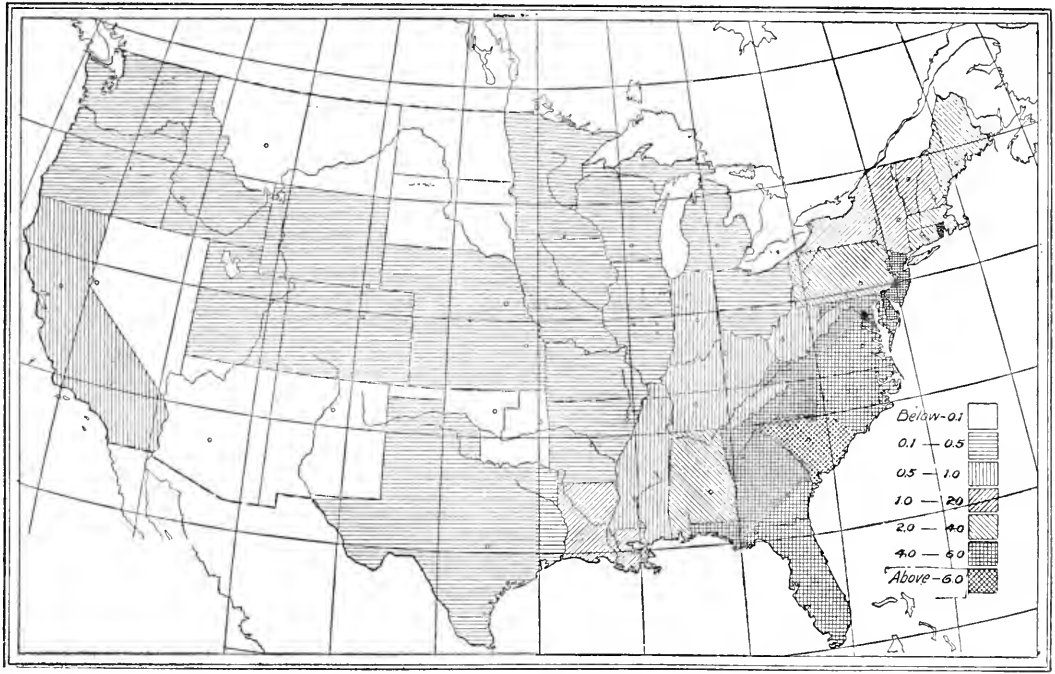

FIG. 105. Expenditures for fertilizers in 1899 by states expressed in per cent of total value of products raised.

nutrients to the soil, usually in a form more readily soluble than those already present in large quantity. While other beneficial effects may be produced by certain fertilizers, they are usually of secondary importance, as compared with the addition of the plant nutrients.

191. Fertilizer constituents.—Prepared fertilizers, as found on the market, are usually composed of a number of ingredients. As these are the carriers of the fertilizing material, and as it is upon their composition and solubility that the value of the fertilizer depends, a knowledge of the properties of these constituents is of interest to every user of fertilizers, and is a valuable aid in their purchase.

192. Fertilizers used for their nitrogen.—Nitrogen is the most expensive constituent of manures, and is of great importance, as it is very likely to be deficient in soils. A commercial fertilizer may have its nitrogen in the form of soluble inorganic salt, or combined as organic material. Upon the form of combination depends to a certain extent the value of the nitrogen, as the soluble inorganic salts are very readily available to the plant, while the organic forms must pass through the various processes leading to nitrification before the plant can use the nitrogen so contained. The inorganic nitrogen fertilizers are sodium nitrate, ammonium sulfate, calcium nitrate and calcium cyanamid.

193. Sodium nitrate.—This fertilizer now constitutes the principal source of inorganic nitrogen in commercial fertilizers. The salt occurs in the crude condition in Northern Chili, and is believed to be due to the action of soil organisms acting through a very long period, and leaving the product finally in the form of sodium nitrate that has crystalized out of solution in which it has sometime been held. The crude salt is purified by crystallization, and, as put upon the market, contains about 96 per cent sodium nitrate, or about 16 per cent of nitrogen, 2 per cent of water, and small amounts of chlorides, sulfates and insoluble matter. The cost of nitrogen in this form is from fifteen to eighteen cents per pound.

On account of its easy availability, sodium nitrate acts quickly in inducing growth. For this reason it is used much by market gardeners, and for other purposes when a rapid growth is desired. It is the most active form of nitrogen. A light dressing on meadow land in the early spring assists greatly in hastening growth by furnishing available nitrogen before the conditions are favorable for the process of nitrification. On small grain it serves a similarly useful purpose where the soil is not rich.

Owing to the fact that it is not absorbed by the soil in large quantities, it is easily lost in the drainage water; for which reason it should only be applied when crops are growing upon the soil, and then only in moderate quantity.

The continued and abundant use of sodium nitrate upon the soil may result, through its deflocculating action, in breaking down aggregates of soil-particles, thus compacting and injuring the structure. This effect is attributed to the accumulation of sodium salts, particularly the carbonate, as the sodium is not utilized by the plant to the same extent as is the nitrogen.

194. Ammonium sulfate.—When coal is distilled, a portion of the nitrogen is liberated as ammonia, and is collected by passing the products of distillation through water in which the ammonia is soluble, forming the ammoniacal liquor. The ammonia thus held is distilled into sulfuric acid with the formation of ammonium sulfate and the removal of impure gases.

Commercial ammonium sulfate contains about 20 per cent of nitrogen. It is the most concentrated form in which nitrogen can be purchased as a fertilizer, having from sixty to eighty pounds more of nitrogen per ton than sodium nitrate. It is, therefore, economical to handle. Its effect upon crops is not so rapid as that of sodium nitrate, but it is not so quickly carried from the soil by drainage water, as the ammonium salts are readily absorbed by the soil. A pound of nitrogen in the form of sulfate has about the same value as the same amount in the form of nitrate.

The long and extensive use of ammonium sulfate on a soil has a tendency to produce an acid condition, through the accumulation of sulfates which are not largely taken up by plants.

Ammonium sulfate, like sodium nitrate, should not be applied in the autumn, as the ammonia is converted into nitrates and leached from the soil in sufficient quantities to entail a very decided loss of nitrogen. There is not likely to be so large a loss of nitrogen from ammonium salts as from nitrates, and, as would naturally be expected, there is greater loss of nitrogen when these salts are used alone than when they are combined with other fertilizing ingredients.

Hall has estimated the loss of nitrogen from certain drained plats, of the Rothamsted Experiment Station. This estimate is based upon the concentration of the drainage from the different plats, of which there was no record of total flow, but for which the measurements of flow from the lysimeter draining 60 inches of soil were taken, and the total loss of nitrates calculated on this basis. Estimated in this way, the effects of several different methods of manuring are shown in the accompanying table.

TABLE XLVIII

POUNDS PER ACRE NITRIC NITROGEN IN DRAINAGE WATER

Treatment	1879–80		1880–81	
	Spring sowing to harvest	Harvest to spring sowing	Spring sowing to harvest	Harvest to spring sowing
Unmanured	1.7	10.8	0.6	17.1
Mineral fertilizers only	1.6	13.3	0.7	17.7
Minerals + 400 pounds ammon. salts	18.3	12.6	4.3	21.4
Minerals + 550 pounds nitrate of soda	45.0	15.6	15.0	41.0
Minerals + 400 pounds ammon. salts applied in autumn	9.6	59.9	3.4	74.9
400 pounds ammon. salts alone	42.9	14.3	7.4	35.2
400 pounds ammon. salts + sulfate of potash	19.0	16.4	3.7	25.3
Estimated drainage in inches	11.1	4.7	1.8	18.8

This table, in addition to confirming the statements already made in regard to the loss of nitrogen in drainage waters, also shows how closely the supply of available nitrogen was used by the crops on those plats, evidently in need of nitrogen fertilization, as these plats lost very little nitrogen during the growing season, while during the remainder of the year they lost nearly as much as did some of the nitrogen manured plats. It also indicates that the loss when nitrate is used is greater than when ammonium salts are applied, as the amount of nitrogen in the 550 pounds of nitrate is really eight pounds per acre more than in the 400 pounds ammonium sulfate, which is not sufficient to account for the difference in the loss. However, half of the nitrate treated plat received no other manure, and produced only a small crop, which would naturally result in a a greater loss by drainage.

195. Calcium cyanamid.—The vast store of atmospheric nitrogen chemically uncombined, but very inert, will furnish an inexhaustible supply of this highly valuable fertilizing element, when it can be, with reasonable economy, combined in some manner that will result in a product commercially transportable, and that will, when placed in the soil, be or become soluble without liberating substances toxic to plants. The importance of the nitrogen supply for agriculture may be appreciated when we consider that nitrates are being carried off in the drainage water of all cultivated soils at the rate of from twenty-five to fifty pounds and even more per acre, annually, and that nearly as much more is removed in crops.

The exhaustion of the supply of nitrogen in most soils may be accomplished within one or two generations of men, unless a renewal of the supply be brought about in some way. Natural processes provide for an annual accretion through the washing down of ammonia and nitrates by rain-water from the atmosphere, and through the fixation of free atmospheric nitrogen by bacteria; but, without the frequent use of leguminous crops, the supply could not be maintained. Farm practice of the present day requires the application of nitrogen in some form of manure, and, as the end of the commercial supply of combined nitrogen is easily in sight, there is urgent need of discovering a new source. This has lately been done by combining calcium with atmospheric nitrogen in the forms of calcium cyanamid and calcium nitrate.

The most successful process for the production of cyanamid consists in passing nitrogen into closed retorts containing powdered calcium carbide heated to a temperature of 1,100° C., the product being calcium cyanamid, and free carbon.

$$CaC_2 + 2\,N = CaCN_2 + C.$$

The free carbon remains distributed in the cyanamid and gives it a black color. A modification of the process provides for the use of lime and coke instead of calcium carbide, but this has not yet been used on a commercial scale. The nitrogen required for the process is obtained either by passing air over heated copper, or by the fractional distillation of liquid air.

The fertilizer, as placed on the market, is a heavy, black powder with a somewhat disagreeable odor. At present it is not manufactured in America and is not obtainable except in small amounts. Plants for its production are being promoted, which will doubtless result in its being placed on the market in the near future.

There are, at present, two calcium cyanamid fertilizers being manufactured. One is called lime-nitrogen, and is made in Italy; the other is called nitrogen-lime, and is made in the province of Saxony,. Germany. The former contains 15 to 23 per cent nitrogen, 40 to 42 per cent calcium, and 17 to 18 per cent carbon dust. The latter is said to contain somewhat less nitrogen, and to have in it some calcium chloride, which is sometimes injurious to plants.

The value of calcium cyanamid as a fertilizer has not yet been definitely and conclusively ascertained. The cyanamid must be decomposed before becoming available to the plant. Under favorable conditions, the nitrogen of the cyanamid is converted into ammonia; but, if the conditions for decomposition are not favorable, the dicyanamid may be formed, which has a poisonous effect upon plants. Another objection which sometimes obtains is that acetylene is produced from the carbide, which remains unchanged in the manufacture of the cyanamid. Acetylene is also injurious to plants.

By incorporating the calcium cyanamid in the soil eight to fourteen days before the seed is planted, this difficulty may be overcome. It is also important that the cyanamid be plowed under, and not left on or near the surface of the soil, as, under these circumstances, decomposition does not go on properly, and the poisonous action above referred to takes place.

Upon heavy soil the value of cyanamid as a fertilizer is not greatly below that of sodium nitrate, but upon sandy soil it ranks much lower. Indeed, it appears to be but poorly suited to use on sandy soils.

196. Calcium nitrate.—The other process for combining atmospheric nitrogen is of even more recent invention than that for the manufacture of calcium cyanamid and, like it, is not conducted on a commercial scale in this country; but, with the vast opportunities for developing electric power which are offered in certain localities, factories for the manufacture of calcium nitrate will soon be established.

The process employs an electric arc to produce nitric oxide by the combustion of atmospheric nitrogen, according to the simple equation:

$$N_2+O_2=2\ NO.$$

A very high power is required for this synthesis, involving a temperature of 2,500° to 3,000° C., and the expense of the operation is determined almost entirely by the cost of the electricity.

The nitric oxide gas is passed through milk of lime, giving calcium nitrate.

The calcium nitrate produced by this process has a yellowish white color, and is easily soluble in water, but deliquesces very rapidly in the air. This last property can be overcome by adding an excess of lime in the manufacture, thus producing a basic calcium nitrate, which contains only 8.9 per cent nitrogen. Another way of avoiding the difficulties involved by the deliquescent property of the nitrate is practiced by the factory at Nottoden, Norway. This consists in first melting the product, then grinding it fine, and packing it in air-tight casks. The fertilizer thus prepared contains 11 to 13 per cent nitrogen.

Calcium nitrate contains its nitrogen in a form directly available to plants. It resembles sodium nitrate in its solubility, availability, and lack of absorption by the soil. It may be spread upon the surface of the ground, as it exerts no poisonous action, and does not tend to form a crust, as does sodium nitrate.

The relative values of the different soluble nitrogen fertilizers vary with a great many conditions and can be accurately judged only by a large number of tests. At present, both the calcium nitrate and the cyanamid are being produced at less cost per pound of nitrogen than is sodium nitrate, when laid down in the neighborhood of the factories in Europe. It seems quite certain that, when the processes have been further improved, the result will be to greatly reduce the cost of the available nitrogen.

197. Organic nitrogen in fertilizers.—The commercial fertilizers containing organic nitrogen include cottonseed-meal, which contains 7 per cent nitrogen, when free from hulls; linseed-meal, with 5.5 per cent nitrogen; castor pomace, having 6 per cent nitrogen; and a number of refuse products from packing-houses, among which there are red-dried blood and black-dried blood, the former having about 13 per cent nitrogen, and the latter 6 to 12 per cent; dried meat and hoof meal, carrying 12 to 13 per cent nitrogen; ground fish containing 8 per cent nitrogen; and tankage, of which the concentrated product has a nitrogen content of 10 to 12 per cent, and the crushed tankage, 4 to 9 per cent; also leather-meal and wool-and-hair waste, which last two, on account of their mechanical condition, are of practically no value.

The meals made from seeds are primarily stock-foods, but are sometimes used as manures. They decompose rather slowly in the soil, owing to their high oil content, and are much more profitably fed to live stock than applied as farm manure. They contain some phosphorus as well as nitrogen.

Guano consists of the excrement and carcasses of sea-fowl. The composition of guano depends upon the climate of the region in which it is found. Guano from an arid region contains nitrogen, phosphorus and potassium, while that from a region where rains occur contains only phosphorus—the nitrogen and potassium having been leached out. In a dry guano the nitrogen occurs as uric acid, urates, and, in small quantities, as ammonium salts. A damp guano contains more ammonia. The phosphorus is present as calcium phosphate, ammonium phosphate, and as the phosphates of other alkalies. A portion of the phosphate is readily soluble in water. All of the plant-food is thus either directly soluble, or becomes so soon after admixture with the soil. The composition is extremely variable. The best Peruvian guano contains from 10 to 12 per cent of nitrogen, 12 to 15 per cent phosphoric acid, and 3 to 4 per cent of potash.

Guano was formerly a very important fertilizing material, but the supply has become so nearly exhausted that it is relatively unimportant at the present time.

Of the abattoir products, dried blood is the most readily decomposed, and therefore has its nitrogen in the most available form. In fact, it produces results more quickly than any other form of organic nitrogen. It requires a condition of soil favorable to decomposition and nitrification, which prevents its exerting a strong action in the early spring. It should be applied to the soil before the crop is planted. The black dried blood contains from 2 to 4 per cent of phosphoric acid.

Dried meat contains a high percentage of nitrogen, but does not decompose so easily, and is not so desirable a form of nitrogen. It can be fed to hogs or poultry to advantage, and the resulting manure is very high in nitrogen.

Hoof-meal, while high in nitrogen, decomposes slowly, being less active than dried blood. It is of use in increasing the store of nitrogen in a depleted soil.

Ground fish is an excellent form of nitrogen, and is as readily available as blood, but has a lower nitrogen content.

Tankage is highly variable in composition, and the concentrated tankage, being more finely ground, undergoes more readily the decomposition necessary for the utilization of the nitrogen. Crushed tankage contains from 3 to 12 per cent of phosphoric acid, in addition to its nitrogen.

Leather-meal and wool-and-hair waste are in such a tough and undecomposable condition that they may remain in the soil for years without losing their structure. They are not to be recommended as manures.

198. Fertilizers used for their phosphorus.—Phosphorus is generally present in combination with lime, iron or alumina. Some of the phosphates also contain organic matter, in which case they generally carry some nitrogen. Phosphates associated with organic matter decompose more quickly in the soil than untreated mineral phosphates.

199. Bone phosphate.—Formerly, bones were used entirely in the raw condition, ground or unground. When ground, they are a more quickly acting fertilizer than when unground. Raw bones contain about 22 per cent phosphoric acid and 4 per cent nitrogen. The phosphorus is in the form of tricalcic phosphate ($Ca_3(PO_4)_2$).

Most of the bone now on the market is first boiled or steamed, which frees it from fat and nitrogenous matter, both of which are used in other ways. Steamed bone is a more valuable fertilizer than raw bone, as the fat in the latter retards decomposition, and also because steamed bone is in a better mechanical condition. The form of the phosphoric acid is the same as in raw bone, and constitutes 28 to 30 per cent of the product, while the nitrogen is reduced to 1½ per cent.

Bone tankage, which has already been spoken of as a nitrogenous fertilizer, contains from 7 to 9 per cent phosphoric acid, largely in the form of tricalcium phosphate. All of these bone phosphates are slow-acting manures, and should be used in a finely ground form, and for the permanent benefit of the soil rather than as an immediate source of nitrogen or phosphorus.

200. Mineral phosphates.—There are many natural deposits of mineral phosphates in different portions of the world, some of the most important of which are in North America. The phosphorus in all of these is in the form of tricalcium phosphate, but the materials associated with it vary greatly.

Apatite is found in large quantities in the provinces of Ontario and Quebec, Canada. It occurs chiefly in crystalline form.

The tricalcium phosphate of which it is composed is in one form associated with calcium fluoride, and in the other with calcium chloride. The Canadian apatite contains about 40 per cent phosphoric acid, being richer than that found elsewhere. Phosphorite is another name for apatite, but is chiefly applied to the impure amorphous form.

Caprolites are concretionary nodules found in the chalk or other deposits in the south of England, and in France. They contain 25 to 30 per cent of phosphoric acid, the other constituents being calcium carbonate and silica.

South Carolina phosphate contains from 26 to 28 per cent of phosphoric acid, and but a very small amount of iron and alumina. As these substances interfere with the manufacture of superphosphate from rock, their presence is very undesirable,—rock containing more than from 3 to 6 per cent being unsuitable for that purpose.

Florida phosphates occur in the form of soft phosphate, pebble phosphate, and boulder phosphate. Soft phosphate contains from 18 to 30 per cent of phosphoric acid, and, on account of its being more easily ground than most of these rocks, is often applied to the land without being first converted into a superphosphate. The other two, pebble phosphate and boulder phosphate, are highly variable in composition, ranging from 20 to 40 per cent phosphoric acid. Tennessee phosphate contains from 30 to 35 per cent of phosphoric acid.

Basic slag, or, as it is also called, phosphate slag or Thomas phosphate, is a by-product in the manufacture of steel from pig-iron rich in phosphorus. The phosphorus present is in the form of tetracalcium phosphate, $(CaO)_4P_2O_5$. It also contains calcium, magnesium, aluminum, iron, manganese silica and sulfur. On account of the presence of iron and aluminum, and because its phosphorus is more readily soluble than the tricalcium phosphate, the ground slag is applied directly to the soil without treatment with acid.

201. Superphosphate fertilizers.—In order to render more readily available to plants the phosphorus contained in bone and mineral phosphates, the raw material, purified by being washed and finely ground, is treated with sulfuric acid. This results in a replacement of phosphoric acid by sulfuric acid, with the formation of monocalcium phosphate and calcium sulfate, and a smaller amount of dicalcium phosphate, according to the reactions:

$$Ca_3\ (PO_4)_2 + 2\ H_2SO_4 = CaH_4\ (PO_4)_2 + 2\ CaSO_4 \text{ and}$$
$$Ca_3\ (PO_4)_2 + H_2SO_4 = Ca_2H_2(PO_4)_2 + CaSO_4.$$

The tricalcium phosphate being in excess of the sulfuric acid used, a part of it remains unchanged.

In the treatment of phosphate rock, part of the sulfuric acid is consumed in acting upon the impurities present, which usually consist of calcium and magnesium carbonates, iron and aluminum phosphates, and calcium chloride or fluoride, converting the bases into sulfates and freeing carbon dioxide, water, hydrochloric acid and hydrofluoric acid. The resulting superphosphate is therefore a mixture of monocalcium phosphate, dicalcium phosphate, tricalcium phosphate, calcium sulfate, and iron and aluminum sulfates.

In the superphosphates made from bone, the iron and aluminum sulfates do not exist in any considerable amounts. However, as long as the phosphorus remains in the form of monocalcium phosphate, the value of a pound of available phosphorus in the two kinds of fertilizer is the same; but the remaining tricalcium phosphate has a greater value in the bone than in the rock superphosphate.

The superphosphates made from animal bone contain about 12 per cent available phosphoric acid, and 3 or 4 per cent of insoluble phosphoric acid. They also contain some nitrogen. Bone-ash and bone-black superphosphates contain practically all of their phosphorus in an available form, but they contain little or no nitrogen. South Carolina rock superphosphate contains from 12 to 14 per cent available phosphoric acid, including from 1 to 3 per cent reverted phosphoric acid. The best Florida rock superphosphates contain from 17 per cent downward of available phosphoric acid, part of which is reverted. The Tennessee superphosphates vary from 14 to 18 per cent available phosphoric acid.

202. Reverted phosphoric acid.—On standing, a change sometimes occurs in superphosphates by which a part of the phosphoric acid becomes less easily soluble, and to that extent the value of the fertilizer is decreased.

This change, known as "reversion," is much more likely to occur in superphosphates made from rock than in those derived from bone. It will also vary in different samples,—a well-made article usually undergoing little change, even after long standing. It is supposed to be caused by the presence of undecomposed tricalcium phosphate, and of iron and aluminum sulfates.

203. Double superphosphates.—In making superphosphates, a material rich in phosphorus must be used, —not less than 60 per cent tricalcium phosphate being necessary for their profitable production. The poorer materials are sometimes used in making what is known as double superphosphates. For this purpose they are treated with an excess of dilute sulfuric acid; the dissolved phosphorus and the excess of sulfuric acid are separated from the mass by filtering and are then used for treating phosphates rich in tricalcium phosphate and forming superphosphates. The superphosphates so formed contain more than twice as much phosphorus as those made in the ordinary way.

204. Relative availability of phosphate fertilizers.—Superphosphates and double superphosphates contain their phosphorus in a form in which it can be taken up by the plant at once. They are therefore best applied at the time when the crop is planted, or shortly before, or they may be applied when the crop is growing. Crude phosphates, on the other hand, become available only through the natural processes in the soil. The presence of decomposing organic matter is a great aid to the decomposition of crude phosphates.

Reverted phosphorus, although not soluble in water, is readily soluble in dilute acids. It is now quite generally believed that it furnishes an available supply of phosphorus to the plant. In a statement of fertilizer analyses it is termed "citrate soluble," and this and the "water soluble" are termed "available."

The degree of fineness to which the material is ground makes a great difference in the availability of the less-soluble phosphate fertilizers, especially in the ground-rock phosphates, and in ground bone. This material should be ground fine enough to pass through a sieve having meshes one-fiftieth of an inch in diameter.

205. Fertilizers used for their potassium.—The production of potassium fertilizers is largely confined to Germany, where there are extensive beds varying from 50 to 150 feet in thickness, lying under a region of country extending from the Harz mountains to the Elbe river, and known as the Stassfurt deposits. Deposits have lately been discovered in other parts of Germany.

206. Stassfurt salts.—The Stassfurt salts contain their potassium either as a chloride or a sulfate. The chloride has the advantage of being more diffusible in the soil, but in most respects the sulfate is preferable. Potassium chloride has an injurious action on certain crops, among which are tobacco, sugar-beets and potatoes. On cereals, legumes and grasses, the muriate appears to have no injurious effect.

The mineral produced in largest quantities by the Stassfurt mines is kainit. Chemically it consists of magnesium and potassium sulfate, and magnesium chloride, or magnesium sulfate and potassium chloride. Kainit has the same action on plants as has potassium chloride. It contains from 12 to 20 per cent of potash, and 25 to 45 per cent of sodium chloride, with some chloride and sulfate of magnesium.

Kainit should be applied to the soil a considerable time before the crop for which it is intended is planted. It should not be drilled in with the seed, as the action of the chlorides in direct contact with the seed may injure its viability. In addition to the potassium added to the soil by kainit, there are also in this fertilizer magnesium and sodium. The magnesium may be objectionable if there is much already present in the soil. (See page 350.) Sodium may to some extent replace potassium in the soil economy, and in that way may be beneficial.

Silvinit contains its potassium both as chloride and as sulfate. It also contains sodium and magnesium chlorides. Potash constitutes about 16 per cent of the material. Owing to the presence of chlorides, it has the same effect on plants as has kainit.

The commerical form of potassium chloride generally contains about 80 per cent potassium chloride, or 50 per cent potash. The impurities are largely sodium chloride and insoluble mineral matter. The possible injury to certain crops from the use of the chloride has already been mentioned. For crops not so affected, potassium chloride is a quick-acting and effective carrier of potassium, and one of the cheapest forms.

High-grade sulfate of potassium contains from 49 to 51 per cent of potash. Unlike the muriate, it is not injurious to crops but is more expensive.

There are a number of other Stassfurt salts, consisting of mixtures of potassium, sodium and magnesium in the form of chlorides and sulfates. They are not so widely used for fertilizers as are those mentioned above.

207. Wood ashes.—For some time after the use of fertilizers became an important farm practice, wood ashes constituted a large portion of the supply of potassium. They also contain a considerable quantity of lime and a small amount of phosphorus. The product known as unleached wood ashes contains 5 to 6 per cent of potash, 2 per cent of phosphoric acid, and 30 per cent of lime. Leached wood ashes contain about one per cent of potash, 1½ per cent of phosphoric acid, and 28 to 29 per cent of lime. They contain the potassium in the form of a carbonate, which is alkaline in its reaction, and may be injurious to seeds when in large amount. They are beneficial to acid soils through the action of both the potassium and calcium salts. The lime is valuable for the other effects it has on the properties of the soil. (See page 348.)

208. Insoluble potassium fertilizers.—Insoluble forms of potassium, occurring in many rocks, usually in the form of a silicate, are not regarded as having any manurial value. Experiments with finely ground feldspar have been conducted by a number of experimenters, but have, in the main, given little encouragement for the successful use of this material. An insoluble form of potassium is not given any value in the rating of a fertilizer, based upon the results of its analysis.

209. Fertilizer practice.—The purchase and use of commercial fertilizers is an art that requires some technical knowledge for its efficient conduct. There are many fertilizing materials put up under numerous brands that must be selected from and applied to a great variety of crops grown on innumerable types of soil. The result is that an economical fertilizer practice is difficult to establish, and the use of fertilizers is usually conducted in an entirely empirical manner.

210. Brands of fertilizers.—Each manufacturer or compounder of commercial fertilizers places on the market a number of brands of fertilizers that have some trade name, frequently implying the usefulness of the fertilizer for some particular crop, but without reference to the character of the soil on which it is to be used. Each brand of fertilizer is usually composed of several of the constituents that have been described. If those substances are used that are difficultly soluble, the fertilizer is not so valuable as if composed of easily soluble substances. The solubility, as well as the percentage of each ingredient of the fertilizer, should be known by the purchaser.

A fertilizer is known in the market as a high-grade or a low-grade product, depending upon the percentage of fertilizing constituents that it contains. Low-grade fertilizers are cheaper than high-grade merely because they contain less plant-food, although the price per pound of plant-food may be no less,—and, in fact, is usually more. The low-grade product is encumbered with a large amount of inert material, that adds to the cost of transportation and handling, without adding to the value of the fertilizer. For these reasons, the high-grade material is almost always the cheaper fertilizer.

A ton of low-grade fertilizer may contain 500 or 600 pounds more inert material than a high-grade fertilizer, upon which freight must be paid, and which must be hauled from the station and spread upon the field.

211. Fertilizer inspection.—Some thirty states have enacted legislation providing for the inspection and control of the sale of commercial fertilizers. Each package of fertilizer must bear a certificate stating the percentage of nitrogen, phosphoric acid and potash, and more or less information in regard to the forms in which these are held and their rates of solubility. This must be guaranteed to be correct by the manufacturer.

The guarantee does not always state the percentage of nitrogen (N), phosphoric acid (P_2O_5), and potash (K_2O), but often uses other terms that imply the presence of these substances, but so combined that the percentage of the carrier is larger,—as, for instance, ammonia, bone phosphate and sulfate of potash. To convert one term into another, factors have been devised which greatly simplify the process.

Per cent ammonia × .8235 = per cent nitrogen (N.)
Per cent nitrate of soda × .1647 = per cent nitrogen (N).
Per cent bone phosphate × .458 = per cent phosphoric acid (P_2O_5).
Per cent muriate of potash × .632 = per cent potash (K_2O).
Per cent sulfate of potash × .54 = per cent potash (K_2O).

212. Trade values of fertilizers.—It has been customary for the authorities charged with fertilizer inspection in the states concerned to adopt each year a schedule of trade values for nitrogen, phosphoric acid and potash, in each of the various forms in which they appear in fertilizers. These values are based on the cost of the unmixed constituents, if purchased in wholesale lots from the manufacturer, and are secured by averaging the wholesale prices per ton of all the various fertilizer supplies for the six months preceding March 1, to which is added about 20 per cent of the price, to cover cost of handling. The trade values for 1907 were as follows:

	Value per pound Cents
Nitrogen, in nitrates	18.5
Nitrogen, in ammonium salts	17.5
Organic nitrogen, in dried and finely ground fish meat and blood, and in mixed fertilizers	20.5
Organic nitrogen, in finely ground bone and tankage	20.5
Organic nitrogen, in coarsely ground bone and tankage	15.0
Phosphoric acid, soluble in water	5.0
Phosphoric acid, soluble in ammonium citrate	4.5
Phosphoric acid, insoluble, in fine bone and tankage	4.0
Phosphoric acid, insoluble, in coarse bone and tankage	3.0
Phosphoric acid, insoluble, in mixed fertilizers	2.0
Phosphoric acid, insoluble, in finely ground fish, cottonseed meal, castor pomace and wood-ashes	4.0
Potash, as muriate	4.5
Potash, as sulfate, and in forms free from muriates	5.0

213. Computation of the commercial value of a fertilizer.—The percentage of each fertilizing constituent of a fertilizer, and its form or rate of solubility being known, it is possible to calculate its commercial value. Suppose a fertilizer costing $48 per ton contains the following:

	Per cent
Nitrogen in sodium nitrate	4
Nitrogen in fine bone	3
Phosphoric acid, available, in rock superphosphate (corresponds to soluble in ammonium citrate)	6
Phosphoric acid, insoluble, in fine bone	22
Potash, water soluble, in muriate of potash	10

The number of pounds of each constituent per ton of fertilizer is then found thus:

Nitrogen as nitrate	4×20 =	80 pounds per ton
Nitrogen in fine bone	3×20 =	60 pounds per ton
Phosphoric acid, available	6×20 =	120 pounds per ton
Phosphoric acid, insoluble	22×20 =	440 pounds per ton
Potash, muriate	10×20 =	200 pounds per ton

The trade values, as published by the fertilizer inspection authorities, are then applied to the several constituents.

Nitrogen, as nitrates	80×.185 =	$14 80
Nitrogen in fine bone	60×.205 =	12 30
Phosphoric acid, available	120×.045 =	5 40
Phosphoric acid, insoluble	40×.040 =	1 60
Potash, muriate	200×.045 =	9 00
		$43 10

The computed value may then be compared with the market price. It must be remembered that this is the commercial value, and not necessarily the agricultural value, which is determined by the profits from its use, and will depend upon many other factors. For instance, a soil markedly deficient in nitrogen will not respond to a phosphate fertilizer alone to an extent which would justify its use.

214. Mixing fertilizers on the farm.—It has been shown by several of the Experiment Stations that the raw materials may be purchased from the manufacturers and mixed on the farm at a considerably lower cost than they can be bought in fertilizer mixtures, and that the results obtained from them are fully as satisfactory.

Other advantages from home-mixing are, that it permits the farmer to use exactly the proportions of the several constituents that he desires, and that it makes unnecessary the handling of a large amount of inert material frequently contained in mixed fertilizers. It is thus possible for him to ascertain by fields test the best proportions of the various fertilizer constituents to use upon his own land for each of the crops he is growing, which knowledge makes it possible to decrease greatly the expenditure for fertilizers.

215. Methods of applying fertilizers.—The distribution of the fertilizer by means of machinery is much more satisfactory than is broadcasting by hand, as the former method gives a much more uniform distribution. Cereals and other crops planted with a drill or planter are now usually provided with an attachment for dropping the fertilizer at the same time that the seed is sown, the fertilizer being by this method placed under the surface of the soil. Broadcasting machines are also used, which leave the fertilizer uniformly distributed on the surface of the ground, thus permitting it to be applied and harrowed-in sufficiently, before the seed is planted, to prevent injury to the seed by the chemical activity of the fertilizing material.

Corn planters with fertilizer attachments deposit the fertilizer beneath the seed, so as not to bring the two in contact. Grain drills do not do this, and, where the amount of fertilizer used exceeds 300 or 400 pounds per acre, it is better to apply it before seeding. Grass seed and other small seeds should be planted only after the fertilizer has been mixed with the soil for several days.

For crops to which large quantities of fertilizers are to be added, it is desirable to drop only a portion of the fertilizer with the seed, the remainder to be broadcasted by machinery and harrowed in earlier, and, as is frequently better for crops requiring very liberal fertilization, a later application may be made.

216. Soil amendments.—Certain substances are sometimes added to soils for the purpose of increasing productiveness through their influence on the physical structure of the soil, and thereby upon the chemical and bacteriological properties. These substances are called soil amendments. It is true that they may add essential plant ingredients to the soil, but that function is of minor importance.

217. Salts of calcium.—Calcium, although essential to plant growth, need seldom be added to the soil to supply the plant directly; but, on account of its effect upon the soil properties, its use is beneficial to a great number of soils.

218. Effect on tilth and bacterial action.—On clay soils, the effect of lime is to bring the fine particles into aggregates which are loosely cemented by the calcium carbonate. The effect of this structure upon tilth has already been explained. (See page 117.) On sandy soils, the carbonate of calcium serves to bind some of the particles together, making the structure somewhat firmer, and increases the water-holding power. It should be used only in small amounts on sandy soils.

There is a tendency for most cultivated soils to become acid, owing to the formation of organic acids in decomposition and to the greater removal of mineral bases than acids by plants, but particularly because of the loss of lime and the alkali salts in the drainage water. Acidity may reach a point where it becomes directly injurious to certain plants, but it becomes indirectly injurious before that point is reached. One way in which this occurs is by curtailing the action of certain bacteria in their processes of rendering plant-food available. A slightly alkaline reaction and an easily available base to combine with the organic acids affords the most favorable condition for the decomposition processes due to bacterial action, and hence the best results cannot be obtained where carbonate of lime is not present. Its action in improving tilth also facilitates desirable forms of bacteriological activity by increasing the permeability of the soil for air.

219. Liberation of plant-food materials.—It has been stated (page 297) that the alkalies and alkaline earths are more or less interchangeable in certain compounds in the soil. The addition of lime may in this way liberate potassium, when otherwise it would be difficult for crops to obtain a sufficient supply from a particular soil. Magnesium, although rarely deficient, may also be made available in this way. The use of calcium salts may also render phosphorus more useful, probably by supplying a base more soluble than iron or alumina with which in soils deficient in calcium the phosphorus might otherwise be combined.

Boussingault, as quoted by Storer, found that the addition of lime to a clover crop increased greatly the calcium, potassium and phosphorus contained in the crop.

TABLE IL

	Kilos per hectare		
	Lime	Potash	Phosphoric acid
Crop not limed (first year)	32.2	26.7	11.0
Crop limed (first year)	79.4	95.6	24.2
Crop not limed (second year)	32.2	28.6	7.0
Crop limed (second year)	102.8	97.2	22.9

Calcium salts may also increase greatly the rate at which nitrogen becomes available by its effect upon bacterial action, as before explained.

220. Effect on toxic substances and plant diseases.—Free acids are toxic to most agricultural plants. Some plants are much more sensitive than others. Clover and alfalfa, for instance, should have a slightly alkaline medium for their best growth, and any acid is very injurious. Calcium salts in neutralizing acidity remove this toxic condition.

Certain toxic substances of an organic nature are also said to be rendered innocuous by the presence of calcium carbonate. Magnesium salts, when present in excess, may exert a toxic action upon plants. The relative proportion of calcium and magnesium, according to Loew, determines whether or not magnesium is toxic. The exact limits of the ratio of magnesium to calcium beyond which the former is toxic depends upon the combinations and solubilities of the two, and also upon the crop grown. An actually greater amount of magnesia, as shown by a strong hydrochloric acid digestion analysis, is not present in very fertile soils of any region, according to Loew. If injury from magnesium is suspected, the obvious means of correction is to increase the proportion of calcium by its addition in some form.

The use of limestone, ground or burned, that contains a large percentage of magnesium may be injurious to some soils, as may also those Stassfurt salts containing magnesium.

The presence of soluble calcium, with its effects upon the soil, retards the development of certain plant diseases, like the "finger and toe" disease of the cruciferæ. On the other hand, it may promote some diseases, as, for instance, the potato "scab."

221. Forms of calcium.—Calcium is used on the soil in the form of calcium oxide, or quicklime (CaO), water-slaked lime ($Ca(OH)_2$), air-slaked lime ($CaCO_3$), ground limestone (also a carbonate), and calcium sulfate, or gypsum ($CaSO_4$, $2H_2O$). The application of any of these is usually called liming the soil, although gypsum does not serve exactly the same purpose as do the other forms. Owing to differences in the molecular weights of these compounds of calcium, it requires more of some forms than of others to furnish the same amount of calcium. Approximately equivalent quantities of some of the common forms when fairly pure are:

Quicklime	56 pounds
Water-slaked lime	74 pounds
Air-slaked lime, marl and ground limestone	100 pounds

Caustic lime, or the hydrate, when added to the soil, eventually assume some of the more insoluble forms of combination or remain as the carbonate, never being present as the oxide. It is always desirable to have present in the soil at least a small amount of calcium carbonate.

222. Caustic lime.—Quicklime and water-slaked lime have a markedly alkaline reaction, and hence neutralize quickly any acidity that may exist in the soil. They act also quickly in liberating plant-food, particularly nitrogen. Some soils respond more rapidly to quick- or water-slaked lime than to carbonate of lime, especially when the carbonate is in the form of marl or ground limestone, in which cases it is never in such a finely pulverized condition. The use of the caustic forms of lime has been said to result in the loss of nitrogen by the decomposition of organic compounds.

Upon clays, the granulating effect of caustic lime is more marked than that of the carbonate, and for this reason the former has a distinct advantage for use on heavy clay. An occasional moderate dressing is, for the same reason, better than a heavy dressing given less frequently.

223. Carbonate of lime.—Air-slaked lime has the advantage of being in a finely divided condition, and does not produce the injurious action upon organic matter attributed to caustic lime. Its effect upon the granulation of clay soils is probably less pronounced than that of caustic lime.

Marl differs from air-slaked lime principally in its property of being in a less finely pulverized condition. It acts less quickly than does caustic lime. Owing to the fact that marl deposits differ greatly in the composition of their products, it is well to know the quality of the material before purchasing it. The carbonate of lime in marl may vary from 5 or 10 to 90 or 95 per cent in different samples.

Ground limestone has been used as a substitute for marl. It is very important that it be finely ground, as upon the comminution of the material much of its efficiency depends. As there was some question as to the value of ground limestone, experiments in which it was compared with caustic lime have been conducted at some of the experiment stations. These have, in the main, given results very favorable to finely ground limestone.

Frear reports tests in which plats treated with slaked lime, at the rate of two tons per acre once in four years, were compared with plats treated with ground limestone, at the rate of two tons per acre every two years. The records, at the end of twenty years, show that in every case the total yields were greater on the plats receiving ground limestone. After the treatment on these plats had been continued for sixteen years, a determination of nitrogen showed the upper nine inches of soil on the limestone-treated plats to contain 2,979 pounds of nitrogen per acre, and the slaked-lime plats to contain 2,604 pounds. It may be inferred from these figures that the slaked lime caused a greater destruction of organic matter than did the limestone.

Patterson also conducted experiments for eleven years with caustic lime produced by burning both stone and shells, and the carbonate of lime in ground shells and shell marl. The average crops of maize, wheat and hay were all larger on the carbonate-of-lime treated plats.

224. Sulfate of lime.—Gypsum, in which form calcium sulfate is usually applied to soils, is effective in liberating potash, and possibly other substances, from the more difficultly soluble combinations. Its action in improving tilth is less marked than that of caustic lime, or of the carbonate. Whether it eventually contributes to the presence of carbonate of lime is a matter regarding which there is still a difference of opinion. It has the disadvantage of introducing into the soil an acid radical, which is removed by plants only in small amounts, and which tends to produce an acid condition of the soil. On the whole, gypsum is not an adequate substitute for, nor so desirable a form of, calcium as the oxide, hydroxide or carbonate.

225. Common salt.—Sodium chloride has a marked effect upon some soils, but wherein its effectiveness lies is not well understood. The addition of sodium and of chlorine as plant constituents is clearly not the reason, as these substances are always present in soils in available form far in excess of their requirements.

The effect of sodium chloride upon clay-bearing soils is to liberate certain plant nutrients, among which are calcium, magnesium, potassium, calcium and phosphorus. This action, although limited in amount, is, in some cases at least, partly responsible for the beneficial action of common salt.

The structure of the soil is improved by the application of sodium chloride, just as it is by lime,—although usually not to the same extent.

Another effect of salt is to conserve and distribute soil moisture. Its conserving action is probably due to an increase in the density of the soil-water solution retarding transpiration. The film movement of water is likewise increased by the presence of salt in the solution, and in this way the upward movement of bottom water is facilitated, and the supply within reach of the roots maintained in time of drought.

It is not all soils, however, that are benefited by salt, its usefulness not being of such wide application as that of lime. Certain crops, as previously mentioned (page 340), are injured by the presence of chlorine.

226. Muck.—The effect of muck is to change the structure of soils; making heavy clay soils lighter and more porous, and binding together the particles of a sandy one. Both classes of soils, but particularly the sandy type, have a greater water-holding capacity after treatment with muck, owing to its great absorptive power, amounting to 70 per cent or more of its own weight. (See page 153.) It is to its content of organic matter that the physical effects of muck are due.

Muck contains 1.0 to 2.0 per cent of organic nitrogen, calculated to dry matter which does not readily undergo ammonification. The addition of farm manure which ferments readily, and of lime, serves to hasten ammonification. Its use as an absorbent in the stable fits it well for use on the land.

Very large applications of muck are necessary when it is used to improve the structure of the soil. From ten to forty or fifty tons per acre are frequently applied.

227. Factors affecting the efficiency of fertilizers.— The potentially available nutrients in a soil, whether natural or added in manures or fertilizers, are only in part utilized by plants, and the extent of their utilization depends upon the operation of certain limiting factors. This is a very important consideration in the manuring of land, for under conditions as they frequently exist the use of fertilizers is wasteful and extravagant.

The factors within the control of man that effect the availability of fertilizing material are the following: (1) Soil moisture content. (2) Soil acidity. (3) Organic matter in the soil. (4) Structure or tilth of the soil.

An undesirable condition of any one or more of these factors is a very common and apparent occurrence, and yet fertilizers are expected to produce profitable returns, in spite of these adverse conditions. It must be remembered that fertilizers are primarily only nutrient materials, and that the supply of nutrients is only one of the conditions that influence plant growth. Furthermore, an economical use of fertilizers requires that they merely supplement the natural supply in the soil, and that the latter should furnish the larger part of the soil material used by the crop. Finally, most fertilizers are rendered more or less difficultly soluble, or in some cases practically insoluble in pure water, by the absorptive properties of the soil, and the release of these substances for plant use depends to a great extent upon the factors mentioned above.

For instance, when a potassium fertilizer, as potassium sulfate or chloride, is placed in the soil, a considerable portion of the potassium is (page 297) fixed by absorption as one of the bases in a poly-silicate, and thus held in a condition very sparingly soluble in pure water. Other reactions take place, and a portion of the potassium in some form is doubtless mechanically held by the soil particles. While this added potassium is more readily obtained by plants than that contained naturally in many soils, it must become available largely by the processes by which the natural supply is rendered soluble. Ammonium sulfate undergoes a somewhat similar process, while the nitrate of soda remains in a soluble form.

It is evident, therefore, that the conditions which contribute to the natural fertility of the soil also apply to that added as fertilizers, with the possible exception of the nitrate.

Phosphate fertilizers may be rendered practically insoluble in pure water, when added to the soil, and in the presence of a large amount of iron and aluminum it forms more or less ferric and aluminum phosphate, which becomes soluble very slowly, even under the action of soil-water and plant-roots. When converted into tricalcium phosphate, the phosphorus becomes soluble more readily; but, in any case, its rate of solubility depends upon those conditions which are most favorable to the solubility of the natural soil phosphates.

It is generally recognized that a sandy soil responds more promptly to the application of fertilizers than does a clay soil. There may be two reasons for this: (1) Absorption may not be so complete both on account of the particles being larger, and because in many sandy soils the particles are largely composed of quartz, which does not have the property of forming combinations with bases as does clay. (2) Drainage and aëration are likely to be better, as are all those conditions that conduce to solubility of plant-food. For these reasons, a sandy soil generally gives larger returns the first year from the application of manures, but shows less effect in subsequent years unless the treatment is repeated. Clay soils are, for these reasons, more likely to involve a wasteful use of fertilizers than are sandy soils, except in respect to loss of nitrogen in drainage, in which the sandy soil is more likely to be at fault, especially if there is no crop on the land.

228. Soil-moisture content.—Soils in a humid region commonly suffer from an excess of water in the spring, and a deficiency in the summer. Cereals and many other crops require the largest quantity of water at the time of heading and blossoming, and the largest production of crop can be secured only where the supply is adequate at that time. It is safe to say that in the great majority of cases crops raised, even in the humid region, suffer at some time from a deficient water-supply. On the other hand, it is well known that crops, almost without exception, suffer either by lateness of planting, or by delayed early growth from an excess of moisture in the spring.

A control of the soil-moisture supply should, therefore, remove the excess of moisture in a time of large rainfall, and conserve it in time of drought.

There are three means that may be employed to bring this about: (1) Drains, especially by means of tile. (2) Use of green manures or other organic matter. (3) Good tillage. (See page 190.)

Viewed purely from the standpoint of soil fertility, tile drainage does much to increase crop production, and to effect economy in the use of fertilizers. The relation of soil drainage to soil fertility may be summarized as follows. (See, also, page 239.)

(1) Aëration provided by the removal of water greatly facilitates nitrification. This relieves the constant necessity for the use of soluble nitrogen fertilizers, and makes it possible to rely largely upon the use of leguminous crops for nitrogen fertilization. Aëration also renders the other fertilizing constituents of the soil more easily soluble.

(2) By quickly removing the excess moisture in the early spring, and thus increasing the length of the growing period, plants secure more nutriment, there is a corresponding increase in the length of time in which nitrification can take place, also in other action brought about by aëration. Available nitrogen thus produced at an early period in the crop growth is more effective than a later supply would be.

(3) By removing an excess of water from the soil, a larger proportion of the available fertility, both natural and that added in manures, is absorbed by the crop. This is because the solution is less dilute, and consequently a larger amount of mineral nutrients pass through the plant by transpiration.

229. Soil acidity.—An acid condition of the soil renders ineffective a large proportion of the fertilizing material that might otherwise be available. A good illustration of this is the comparison of the crops grown on acid soil when treated with lime with a similar soil not so treated. The size of the crop on contiguous plats has been increased several hundred per cent by the use of lime at a number of the Experiment Stations. The amount of the acidity determines the injury it occasions. There is always a great waste of fertilizers when they are added to an acid soil. The acidity should be corrected by the application of lime, in order that manuring shall be most effective.

There are several ways in which an acid condition of the soil operates to render ineffective the natural and applied fertility.

(1) Bacteria which are concerned in the processes of rendering plant-food available do not usually thrive in an acid media, preferring a neutral or slightly alkaline condition. Acidity for this reason checks nitrification, as well as the bacteriological processes by which phosphorus is rendered soluble.

(2) Bacteria concerned in the acquisition of atmospheric nitrogen in symbiosis with legumes are greatly injured by an acid condition of the soil. Nitrogen conservation, one of the most important features of the use of legumes for green manuring, cannot be effectively carried out on an acid soil.

(3) The liberation of potassium from zeolitic combinations is best effected only where there is a basicity that will permit the replacement of one base by another. The presence of at least a small amount of calcium carbonate in the soil is essential for this, as it is for many other desirable processes, and an acid condition of the soil means that no basicity exists.

(4) Lime, when present in large amount, reacts with the very insoluble phosphates of iron and alumina,

and by producing phosphate of lime, renders the phosphoric acid more available for the plant.

230. Organic matter.—The ways in which organic matter contributes to economy in the use of fertilizers are: (1) By improving the soil structure. (2) By conserving moisture. (3) By producing through decomposition carbon dioxide which, dissolved in water, is a weak but continuously acting solvent of the mineral fertilizers; also by forming organic acids that act in a similar way. (4) It furnishes a source of food and energy for bacteria, which aid in rendering soluble the absorbed fertilizing constituents.

It is particularly in rendering available to plants the more difficultly soluble phosphate fertilizers that organic matter directly aids in making fertilizers more effective.

Farm manure is undoubtedly the best all-round fertilizer to be had. In addition to adding organic matter and certain mineral plant-food materials, it introduces into the soil, and furnishes a favorable medium for the growth of large numbers of bacteria that are of great value in rendering available the plant nutrients contained in soils.

The use of raw or untreated phosphates to replace superphosphates in soil manuring has received much attention in Germany and to some extent in this country in recent years. Raw phosphates, being much more difficultly soluble than the superphosphates, do not, under most conditions of the soil, give as marked returns. On the other hand, the raw phosphate has the advantage of being very much cheaper, and of not containing sulfuric acid. The extent to which raw phosphates will become available in the soil depends largely on the extent of decomposition of organic matter. A soil poor in humus, and which has not been treated with farm manure or green manure, is not likely to respond very strongly to an application of raw phosphate. The fact that superphosphate is available under these conditions is likely to lead to its use without any attempt to improve the humus-content of the soil, and thus increase those difficulties that arise from a deficiency of organic matter. It is this condition that makes it necessary to constantly increase the dressings of fertilizer in order to maintain productiveness.

Experiments by Thorne have shown that the use of farm manure in conjunction with raw phosphates serves to increase greatly the availability of the latter. In these experiments stall manure was used at the rate of eight tons per acre, in one case alone, and in another in connection with 320 pounds of rock phosphate. The manures were applied to clover sod, and plowed under for maize in a rotation of corn, wheat and clover. In the following table, average yields from the manured plats and from the unmanured ones are given.

TABLE L

EFFECT OF STALL MANURE ON AVAILABILITY OF ROCK PHOSPHATE

	Average yield eleven crops maize	Average yield ten crops wheat	Average yield seven crops hay
	Bushels	Bushels	Tons
Stall manure, 8 tons per acre	57.7	20.3	1.6
Stall manure, 8 tons per acre and rock phosphate, 320 pounds per acre	64.0	25.6	2.2
No manure	34.6	10.4	1.0

It will be seen from this table that the combination of stall manure and rock phosphate produced larger crops than did the same quantity of stall manure alone; from which it may be fairly concluded that, under these conditions, the raw phosphate becomes available to an extent sufficient to make its use practical. Whether raw phosphate can be used without supplementing them with superphosphate will depend upon the natural fertility of the soil and the amount of decomposing organic matter it contains.

231. Structure or tilth of the soil.—Tillage aids the plant in several ways to obtain nutrients from fertilizers added to the soil: (1) By promoting aëration. (2) By permitting the plant-roots to come in contact with a large area of soil. (3) By conserving moisture in time of drought.

232. Cumulative need for fertilizers.—It is often remarked that on fertilized soils there is a gradually increasing need for greater quantities of fertilizers. This is doubtless the case in many instances, and arises from neglect of other factors affecting soil productiveness. As we have seen, certain fertilizers induce a loss of lime from the soil, which, if allowed to continue, requires an increased amount of fertilizer to maintain the yield of crops. Organic matter is allowed to decrease and this, as well as loss of lime, causes the soil to become compact and poorly aërated, and so, one bad condition leading to another, crops become poorer in spite of increased applications of fertilizer.

233. Farm manures.—The original components of farm manure are the solid excreta from the animal, the urine, usually from the same animal or animals, and the litter used as bedding and also for the purpose of absorbing the liquid manure and to render the whole easier to handle. As these constituents differ greatly in their physical and chemical properties, the proportions in which they exist affect appreciably the properties of the manure.

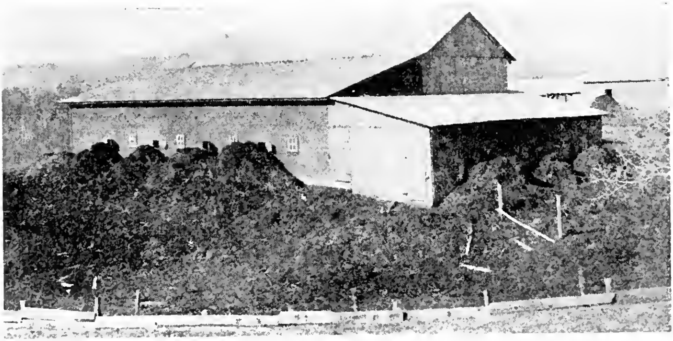

FIG. 106. A striking example of waste of manure. Leaching and fermentation will remove over half of its value in six months.

234. Solid excreta.—The solid excreta furnishes most of the body of the manure, and as it is already in a stage of partial decomposition, and in a condition both physically and chemically to favor the further processes of decomposition, it is largely to this constituent that the fermentative action of manure is due. It is particularly valuable for the effect it has upon the physical condition of the soil and the encouragement it gives to decomposition processes.

Chemically, it is not so valuable as the liquid excreta.

It represents, in part, the food materials that have passed undigested through the alimentary canal, and also the secretions this has received on the way, and these substances are not all held in a soluble form, as are those in the urine.

Stoeckhardt states the composition of the solid excreta of different farm animals to be as follows:

TABLE LI

	Water	Composition of dry matter		
		Nitrogen	Phosphoric acid	Alkalies
	Per cent	Per cent	Per cent	Per cent
Horses (winter food)	76	2.08	1.45	1.25
Cows (winter food)	84	1.87	1.56	0.62
Swine (winter food)	80	3.00	2.25	2.50
Sheep (two pounds hay per day)	58	1.78	1.42	0.71

Calculated to 1,000 pounds of solid excrement, these figures show the following number of pounds of each constituent.

TABLE LII

	Water	Nitrogen	Phosphoric acid	Alkalies
	Pounds	Pounds	Pounds	Pounds
Horse	760	5.0	3.5	3.0
Cow	840	3.0	2.5	1.0
Swine	800	6.0	4.5	5.0
Sheep	580	7.5	6.0	3.0

The smaller percentage of water in the sheep excrement makes it, pound for pound, the richest of any. Next to it stands hog excrement, and cow excrement is the poorest in fertilizing materials.

235. Urine.—The urine represents a portion of the food which has been digested by the animal and excreted as a waste product through the kidneys. The proportion of the nitrogen and mineral matter retained by the tissues depends upon the age of the animal and upon the nature of the food. An animal receiving a large amount of easily digestible nitrogenous food excretes more nitrogen in the urine than a poorly fed animal.

The composition of urine, as given by Stoeckhardt is as follows:

TABLE LIII

	Water	Composition of dry matter		
		Nitrogen	Phosphoric acid	Alkalies
	Per cent	Per cent	Per cent	Per cent
Horse (hay and oats)	89.0	10.9	trace	13.6
Cow (hay and potatoes)	92.0	10.0	trace	17.5
Swine (winter food)	97.5	12.0	5.0	8.0
Sheep (two pounds hay per day)	86.5	10.4	3.7	14.9

These figures show the following number of pounds of each constituent in 1,000 pounds of urine.

TABLE LIV

	Water	Nitrogen	Phosphoric acid	Alkalies
	Pounds	Pounds	Pounds	Pounds
Horse	890	12	....	15
Cow	920	8	....	14
Swine	975	3	1.25	2
Sheep	865	14	0.50	20

The liquid excreta of the sheep contains in a given quantity more fertilizing material than that of any of the other animals.

Comparing the solid and liquid excreta of these animals as a whole, it will be seen that, in general, the urine is richest in nitrogen and alkalies, while the solid excrement is richest in phosphoric acid.

The amount and composition of the urine is more constant than that of the solid excrement. Both are influenced by the character and amount of feed, but the urine much less so than the solid excrement. Experiments conducted at the Rothamsted Experiment Station have shown that from 57 to 79 per cent of the total nitrogen of the food is excreted in the urine, and from 16 to 22 per cent in the solid excrement.

236. Litter.—The use of a bulky absorbent, like straw, sawdust or leaves, is almost universal where live stock are kept in a stable. This is useful in providing a soft bed for the animal, in absorbing the liquid excrement, in lightening the manure, making it easier to handle, less likely to undergo undesirable fermentation, and more effective in improving the physical condition of heavy soils.

Straw is the absorbent usually used, and is, all things considered, the most satisfactory. It decomposes readily in most soils and, in decomposing, adds to the soil considerable fertilizing material. Of the different kinds of straw, oat straw has the greatest fertilizing value. A ton of oat straw contains about 16 pounds nitrogen, 4 pounds phosphoric acid, 26 pounds of potash, and 9 pounds of lime. As this is more nitrogen and potash than is contained in a ton of average manure, the use of this absorbent increases the fertilizing value of the manure. It is, however, undesirable on some soils to have a very large proportion of straw, on account of its effect in retarding decomposition.

Sawdust and shavings are sometimes used, but, while they are good absorbents, they decompose very slowly in the soil, making them objectionable on light soils, and they have practically no plant-food materials. Dry leaves absorb well, and decompose satisfactorily in the soil. They do not add much fertility.

237. Manures produced by different animals.—There is a great difference in the amount and value of manure produced by different kinds of live stock. This is due to a number of causes, among which are the size of the animal, the nature of its food, and the mechanical condition in which the digestive processes leave the solid excrement. The differences affect not only the amount of fertilizing constituents in the manures, but, what is of more importance, they determine the nature and rapidity of the decomposition processes, and hence affect the loss of manurial substances and the value of the manure as a fermentive agent in the soil.

238. Horse manure.—A well-fed, moderately worked horse will produce from 45 to 55 pounds of excrement per day, of which from 12 to 15 pounds consists of urine. The straw used for bedding will amount to from 4 to 6 pounds. Roberts has computed the value of the excrement to be nearly one-half the cost of the food, while from Wolff's tables, based on a large number of determinations in Europe, the combined solid and liquid excreta contains the following average percentages of the organic matter, nitrogen and mineral substances originally present in the food consumed:

	Per cent
Organic matter	33.90
Nitrogen	39.50
Mineral substances	56.25

In Robert's calculations, the value of the manure is based entirely upon its content of nitrogen, phosphoric acid and potash, valued at 15 cents, 7 cents and 4.5 cents, respectively. It is difficult to get a true idea of the value of animal manure, as its content of fertilizing substances is only a part of its manurial value, of which its physical and bacteriological effects upon the soil are extremely important.

Horse manure has the fibrous matter of the food less well broken down than has cow manure, and this, with its lower water content, produces a light, easily fermentable substance that readily loses its nitrogen, which passes off as ammonium carbonate. The dry fermentation, indicated by a whitish appearance of the interior of the manure heap and a slight smoke, is the cause of this loss. The values calculated for the excrement are never realized in practice because of the losses that occur between the stable and the field. To preserve horse manure to the best advantage, it should be mixed with cow manure,—the wet, compact character of which lessens the amount of fermentation by changing the physical condition of the manure.

239. Cow manure.—A mature cow, given good feed, will produce from 60 to 90 pounds of excrement daily.

depending upon the weight of the animal. Of this 20 to 35 pounds is likely to be urine. Even the solid excreta contains a large percentage of water, and, according to Boussingault, only about one-eighth of the total excreta is dry matter.

The very watery nature of cow excreta causes it to require a large amount of litter. In spite of the lightening effect of the litter, it decomposes slowly as compared with other manures. When applied alone to the soil, action is slow, but it is prolonged over a considerable number of years.

The loss of ammonia in the decomposition processes is much less than with horse manure. The admixture of other manures adds much to the rapidity of fermentation and to the ease of handling.

The percentage of organic matter, nitrogen and mineral substances contained in the food of cattle that appear ultimately in the excrements are as follows:

	Per cent
Organic matter	27
Nitrogen	42
Mineral matter	50

This corresponds fairly well with the percentage for horse manure, and would justify the belief that the value of the manure would hold about the same ratio to that of the food as in the case of the horse.

240. Swine manure.—The quantity of excrement voided by swine varies greatly even for mature animals, the amounts per 1,000 pounds live weight varying from less than 50 to more than 100 pounds per day. A more concentrated ration produces less excreta, but causes it to be much richer in fertilizing ingredients. Roberts calculated the value of the manure produced in one year by a 150-pound pig fed on a highly nitrogenous ration to be $3.24, and that of a pig of similar weight fed on a carbonaceous ration to be $1.84 for the same period.

The manure of swine is wet, but not quite so much so as cow manure. According to Boussingault, about one-sixth of the solid excrement is dry matter. It decomposes slowly. As the urine contains by far the larger part of the nitrogen, it should be saved.

241. Sheep manure.—The total amount of excrements voided by mature sheep is from 30 to 40 pounds per 1,000 pounds of live weight, of which about one-fourth is dry matter. Although drier than horse manure and generally richer in nitrogen it is less likely to lose that constituent by fermentation, as the compact nature of the solid excreta is not so favorable to rapid decomposition as is the physical structure of horse manure. It is however, when placed in the soil, a readily acting manure and is frequently used by gardeners for that reason. To obtain the best results, it should be mixed with horse and cow manure.

242. Relative values of animal manures.—Extensive experiments conducted by Roberts, Wing and Cavanaugh at Cornell University Experiment Station, with several different kinds of animals fed on the common American feeds, but perhaps in somewhat heavier rations than the average, and kept under normal conditions, may well be taken to show the relative values of animal manures, although the absolute values may be somewhat above the average. In calculating the values of the manures produced by these animals, nitrogen is reckoned at fifteen cents per pound, phosphoric acid at six cents, and potash at four and one-half cents. The composition, amount and value of the manures without litter are given in the following table.

TABLE LV

COMPOSITION, AMOUNT AND VALUE OF MANURES (WITHOUT LITTER) FROM DIFFERENT ANIMALS

Kinds of live stock	Percentage composition				Pounds ingredients per ton manure			Value per ton	Production per 1,000 pounds live weight	
	Water	Nitrogen	Phosphoric acid	Potash	Nitrogen	Phosphoric acid	Potash		Pounds per day	Value per year
Horses . . .	48.70	0.49	0.26	0.48	9.00	5.20	9.60	$2.21	48.8	$27.74
Cows	75.25	0.43	0.29	0.44	8.60	5.80	8.80	2.02	74.1	29.27
Calves	77.73	0.50	0.17	0.53	10.00	3.40	10.60	2.18	67.8	24.45
Swine.	74.13	0.84	0.39	0.32	16.80	7.80	6.40	3.29	83.6	60.88
Sheep.	59.52	0.77	. . .	0.59	15.40	7.60	11.80	3.30	34.1	26.09

243. Poultry manure.—The droppings of poultry are nearly twice as valuable, pound for pound, as cow manure, when calculated on the value of the nitrogen, phosphoric acid and potash they contain. It is in the former constituent particularly that poultry manure is rich. A thousand pounds live weight of fowls produce from thirty to forty pounds of droppings daily. These contain when fresh between 50 and 60 per cent of water and over 1 per cent of nitrogen. The nitrogen is largely present as ammonium compounds. It quickly undergoes fermentation, with loss of nitrogen. Lime or alkalies decompose the ammonium compounds with liberation and loss of free ammonia. An absorbent, such as land plaster, superphosphate, kainit or dry earth will greatly lessen the loss of nitrogen. Mixing it with other manures is also advisable.

When applied to the soil, poultry manure decomposes rapidly, and is used by market gardeners on account of its rapid action.

244. Factors affecting the values of farm manures.—The value of animal excrements for manurial purposes depends upon a number of factors, among which are: (1) The relative proportions of solid excrement and urine. (2) The species of animal producing the manure. (3) The age of the animal. (4) The character of the food the animal receives. (5) The use to which the animal is being put. In addition to the factors affecting the excrement, the manure may always be modified by the litter or other absorbent added, and by the method of handling. The effects of solid and liquid excreta, and of the species of animal, have already been discussed.

245. Age of animal.—A young and growing animal requires more nitrogen and phosphoric acid to build bone and muscle than does an animal that has completed its growth. This is taken from the food, and not excreted in the urine or other excretory products, and hence does not appear in the manure.

246. Food of the animal.—Since the large part of the nitrogen, phosphorus and potassium contained in the food is contained in either the solid or liquid excrement, it follows that the richer the food in these constituents the more of them the manure will contain. A highly carbonaceous ration produces a poor manure largely because it is low in nitrogen. The manurial value of a food-stuff is generally increased by passing through the animal, provided it can largely be recovered, because the digestion process leaves it in a condition more favorable to decomposition and to thorough mixing with the soil.

247. Use of the animal.—The amounts of the fertilizing constituents recovered in the excrement vary to some extent with the use that is being made of the animal. Animals that are being fattened, or that are producing milk, divert a portion of the fertilizing constituents to their products. Experiments by Laws and Gilbert with different classes of animals used for different purposes show the following disposition of some of the constituents of the food. As the excrements include the perspiration, the small amount of matter passing off in that form is, of course, not recovered in the manure.

TABLE LVI

	Nitrogen		Mineral matter	
	Contained in product	Contained in excrement	Contained in product	Contained in excrement
	Per cent	Per cent	Per cent	Per cent
Horse at rest	None	100.0	None	100.0
Horse at work	None	100.0	None	100.0
Milking cows	24.5	75.0	10.3	89.7
Fattening oxen	3.9	96.1	2.3	97.7
Fattening pigs	14.7	85.3	4.0	96.0
Fattening sheep	4.3	95.7	3.8	96.2

It will be seen from these experiments that milch cows divert more of the fertilizing constituents from the manure than do any other class of animal, that fattening pigs divert much more of the nitrogen than do cattle or sheep similarly employed, and that the work of the horse does not affect the composition of the manure.

248. Deterioration of farm manure.—There is always a loss in the value of farm manure on standing. The two processes most operative in bringing this change about are: (1) Fermentation. (2) Leaching. The first of these is a natural process, common to all farm manure, and not occasioned by any outside agencies; the second is due to the running off of the liquid portion of the manure, and to the exposure of the manure to rain.

249. Fermentations.—The fermentations occurring in heaps of farm manure are produced both by aërobic and anaërobic bacteria, that is, by bacteria requiring oxygen for their activity, and by those that do not. The fermentations of the outside of the heap are constantly different from those on the interior, where air does not readily penetrate; but, as fresh manure is thrown upon the pile from day to day, most of the manure first undergoes aërobic fermentation before the anaërobic bacteria begin their work.

It is through the action of bacteria on the nitrogenous compounds of the manure that loss of value through fermentations occurs. The action of the aërobic bacteria is to convert the nitrogen of the organic matter into ammonia, which, owing to the large formation of carbon dioxid, is partly converted into ammonium carbonate. Both of these substances being volatile, there is danger of their passing off from the heap into the air. The drier the heap, the more apt these substances are to escape.

The production of ammonia is very rapid from some of the compounds in farm manure. Urea, in which form the nitrogen of urine is largely found, undergoes conversion into ammonia very rapidly, and some loss in this way is inevitable even under the best management. Chemically the process is a simple one, which may be represented by the following equation:

$$CON_2H_4 + H_2O = 2\,NH_3 + CO_2.$$
$$2\,NH_3 + CO_2 + H_2O = (NH_4)_2\,CO_3.$$

The use of certain preservatives makes it possible to decrease the loss of ammonia from manure. The preservatives are intended to convert the ammonia into a less volatile compound. For this purpose gypsum, kainit, superphosphates and ground phosphate rock are used. The action of gypsum, for instance, in the manure, is to convert ammonia or ammonium carbonate into the form of ammonium sulfate, which is not volatile. The reaction is as follows:

$$(NH_4)_2\,CO_3 + CaSO_4 = (NH_4)_2SO_4 + CaCO_3.$$

It is customary to sprinkle the preservative in the stall of the animal, where it comes in contact with the excreta as soon as they are voided. Salts of calcium other than the sulfate, cannot be used, on account of their action in decomposing ammonium salts.

The decomposition of proteins forming, among other products, hydrogen sulphide, which becomes oxidized to sulfuric acid, causes a part of the ammonia to naturally take the form of a sulfate, which protects this portion from volatilization.

The other fermentation resulting in the loss of nitrogen is due to the action of certain anaërobic bacteria that convert ammonium salts into free nitrogen. Certain of these organisms are able to reduce nitrates to nitrites, and the latter to ammonia, but the greatest loss is doubtless due to the ammonium salts formed directly from proteins. This process occurs only in the poorly aërated portions of the heap. There does not appear to be as great loss of nitrogen through the action of the anaërobic ferments as through the loss of ammonia, which makes it advisable, in practice, to keep the manure heap as compact as possible, and to prevent the heap from becoming very dry by the application of water in amounts sufficient to keep the heap moderately moist without leaching it. In the arid and semi-arid parts of the country, this is an important precaution to be taken in the preservation of farm manure.

250. Leaching.—When water is allowed to soak through a manure heap and to drain away from it, there is carried off in solution and in suspension a certain quantity of organic and inorganic compounds containing nitrogen as urea, other organic nitrogen in small amounts, ammonium salts and nitrates, some phosphorus and considerable potassium, with other mineral substances of less importance. The amount of loss to the manure in this way may be very great; and, without doubt, in the humid portions of the country leaching is the greatest source of loss. Protection of manure from the rain is therefore very important.

Experiments conducted by Roberts serve to show the rate and extent of deterioration of manure in a region having a rainfall of about twenty-eight inches in the six months from spring until autumn, during which period the tests were made. The loss arising from fermentation and leaching combined was determined in these experiments.

Horse manure was lightly packed in a wooden box, not water-tight, surrounded with manure, and left exposed to the weather from March 30 to September 30. Analyses made at the beginning of and at the end of the experiment showed the following:

TABLE LVII

	April 25	September 30	Loss
	Pounds	Pounds	Per cent
Gross weight	4,000.00	1,730.00	57
Nitrogen	19.60	7.79	60
Phosphoric acid	14.80	7.79	47
Potash	36.00	8.65	76

At the same time, cow manure was similarly treated, except that 300 pounds of gypsum were mixed with it. This, doubtless, protected some of the nitrogen, and the greater body of material would also decrease loss of all constituents.

TABLE LVIII

	April 25	September 30	Loss
	Pounds	Pounds	Per cent
Gross weight	10,000	5,125	49
Nitrogen	47	28	41
Phosphoric acid	32	26	19
Potash	48	44	8

The greater loss suffered by the horse manure was doubtless due in part to the more rapid fermentation accompanied by volatilization of ammonia, and to its less compact nature making it more permeable to the rain water.

Roberts also reports an experiment in which a block of undisturbed manure one foot deep, consisting of both horse and cow excrement mixed with straw and solidly packed by trampling of animals in a covered shed, was exposed from March 31 to September 30 in a galvanized iron pan with perforated bottom. The losses were as follows:

	Loss Per cent
Nitrogen	3.2
Phosphoric acid	4.7
Potash	35.0

This shows a great saving to both kinds of manure when they are mixed and tramped. The enormous difference in the nitrogen lost, without a corresponding difference in the loss of potash, indicates that the volatilization of ammonia, which is greatly reduced by compacting, is responsible for a very large share in the deterioration of manure, even in a humid climate.

251. Methods of handling.—The least opportunity for deterioration of farm manure occurs when it is hauled directly to the field from the stall and spread at once. This is not always possible, and manure must be stored on every farm for longer or shorter periods. In holding manure, the two important conditions are, a sufficient, but not excessive supply of moisture, and a well-compacted mass. Water draining away from a manure heap, and a fermentation producing a white appearance of the manure under the surface of the pile ("fire fanging"), are both sure indications of unnecessary loss in its fertilizing value.

Composting farm manure increases the availability of its fertilizing constituents; but, even when carefully conducted, is accompanied by some loss of nitrogen. The total amount of organic matter is decreased by reason of the decomposition, in which process carbon dioxid and water are formed, part of which escapes, and part remains in the manure. The mineral constituents increase percentagely, due to the loss of organic matter; and the water increases for the same reason, and because it is sometimes added to the compost. The mineral constituents are not materially changed in their solubility, but the organic matter becomes more soluble. The nitrogen, after conversion into ammonium salts, is oxidized finally into nitrates, but only in small amounts, and after considerable time. The beneficial effects of composing are only in small part due to the chemical changes in the manure, but chiefly to the good physical condition of the composted material, and to the fact that the operations preliminary to the formation of nitrates have largely been effected in the compost, and when applied to the soil nitrification is rapid. Composting manure with soil, sod, muck or other absorbent material increases the manurial value of the latter by increasing its decay, and therefore its availability, and by reducing loss by leaching.

The following analyses, by Voelcker, show the composition of fresh and rotted farm manure:

TABLE LIX

	Fresh	Rotted
Water	66.17	75.42
Soluble organic matter	2.48	3.71
Soluble organic nitrogen	0.15	0.30
Soluble inorganic matter	1.54	1.47
Insoluble organic matter	25.76	12.82
Insoluble inorganic matter	4.05	6.58

In applying farm manure to the field, it is customary either to throw it from the wagon into small heaps, from which it is distributed later, or to scatter it as evenly as possible immediately on hauling it to the field. The use of the automatic manure spreader accomplished the latter procedure in an admirable manner. As between these two methods, the advantage, so far as the conservation of the manurial value is concerned, is with the practice of spreading immediately. When piled in small heaps, fermentation goes on under conditions that cannot be controlled, and that may be very unfavorable. The heaps may dry out, and thus lose much of their nitrogen; or they are likely to leave the field unevenly fertilized by leaching into the soil directly under and adjacent to the heap. On the other hand, when spread immediately, little fermentation takes place, as the temperature is generally low and the soluble compounds are leached quite uniformly into the soil. Plowing should follow as closely as possible the spreading of the manure, and, except in winter, at which time deterioration is not likely to be great, this can well be done.

The amounts and frequency with which farm manure should be applied must depend, to some extent, upon the nature of the farming and upon the character of the soil. Farm manure tends to render all soils more porous and light. A naturally light soil may be rendered less productive by the application of heavy dressings of manure; particularly in a dry climate is this the case. In regions where so-called "dry farming" is practiced, the return of organic matter to the soil is a great problem, on account of the difficulty in accomplishing its decay

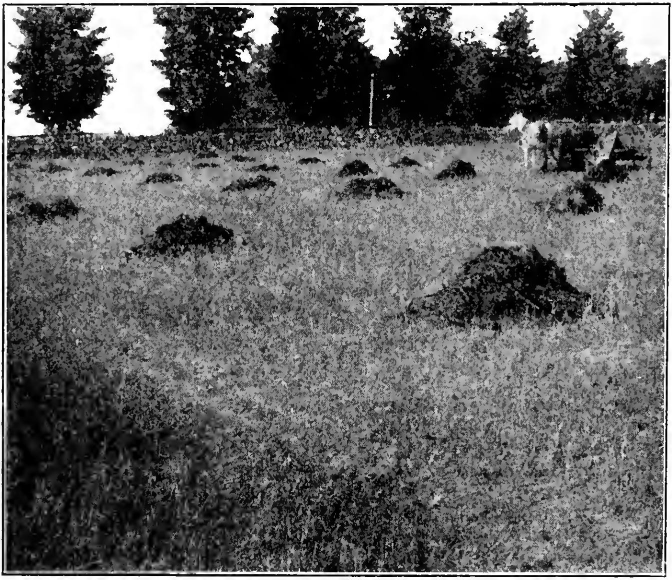

FIG. 107. The wrong way to distribute manure. There is large loss by decay and an uneven growth of crop.

when plowed under. Composting, or plowing under after it has been applied to sod for several months, or incorporating with a green manure, are methods that must be used with "dry farming."

Even on heavy soils in a humid region, there is an advantage in applying small dressings of farm manure frequently, rather than large amounts at long intervals. Organic matter decomposes more rapidly when present in the soil in relatively small amounts, and its influence on the solubility of plant nutrients is therefore greater in proportion to the amount of manure used. There can be no doubt that the bacterial flora introduced into the soil by the incorporation of farm manure is an important factor in its usefulness, and when this occurs at frequent intervals it has a marked effect on productiveness. Applications of ten tons to the acre are better than twenty tons at twice the interval.

252. Place in crop rotation.—When a crop rotation includes grass or clover as one of the courses, the application of farm manure may well be made at that time as a top-dressing. The spreading can be done at times when cultivated land would not be accessible, and the crop of hay will profit greatly. The sod, when plowed, is frequently planted to corn—a crop that is rarely injured by farm manure. On light, dry soils this practice is of advantage, as already explained.

Most cultivated crops, with the exception of tobacco, and occasionally sugar-beets, are much benefited by farm manure. Small grains are usually benefited when grown on poor, heavy soils with plenty of rainfall; but in a dry region farm manure should not be applied for these crops, and on rich soils manure is likely to cause small grain to lodge.

Farm manure, in judicious amounts, may be plowed under in orchards to great advantage.

253. Functions.—The useful function which farm manures perform in the soil are as follows: (1) To improve the physical condition of the soil by the introduction of organic matter, with its favorable influence on the structure and moisture content. (See page 129.) (2) To add a certain quantity of plant-food in a comparatively readily available condition. (3) To introduce a new bacterial flora capable of increasing the rapidity of decomposition of organic matter, and of thereby increasing the amount of available fertility.

254. Green Manures.—Crops that are grown only for the purpose of being plowed under to improve the soil are called green manures. They may benefit the soil in one or all of four ways: (1) By utilizing soluble plant-food that would otherwise escape from the soil. (2) By incorporating vegetable matter with the soil. (3) Leguminous crops, when used, add to the nitrogen content of the soil through the fixation of atmospheric nitrogen. (4) Plant-food from the lower soil may be brought to the surface soil.

A large number of crops may be used for this purpose, but certain ones are more useful than others, while the climate determines to some extent which crops should be used. Leguminous crops have the great advantage of acquiring nitrogen from the air. Crops that can be planted in the fall and grow during the cool weather can be utilized when otherwise the land would frequently lie bare. Deep-rooted crops usually accumulate a large amount of nutriment from the soil, and considerable from the lower depths. They are therefore useful in bringing plant-food to the upper layer of soil. Succulent crops decompose easily, and dry out the soil less, when plowed under, than do woody crops. Crops with extensive root-systems prevent loss of soluble matter more thoroughly than do plants with small roots.

255. Leguminous crops.—A soil that has become less productive under cultivation, and that must be improved before profitable crops can be grown, receives more benefit from the use of leguminous crops than any other. The legume to use is naturally the one best adapted to the region in which the soil is located. Red clover, mammoth clover and field peas on the soils to which they are adapted in the northern states; alsike clover in the wet soils of that region; cowpeas and crimson clover in the South, and alfalfa, clovers, soy beans and cow peas in the West, are the principal leguminous green-manuring crops. More recently a positive effort has been made in certain northern states to grow sweet clover (*Melilotus alba*), which is a vigorous wild legume, as a green manure crop. Marked success has followed its use, but, like alfalfa and the clovers, it requires a soil well stocked with lime.

The legumes have the important property of securing nitrogen from the air, which is added to the soil from the decomposition of the tops and roots when the crop is plowed under. The nitrogen contained in a ton of the green crop, when in a condition to plow under, is as follows:

TABLE LX

	Nitrogen per ton	Probable yield per acre	Nitrogen per acre
	Pounds	Tons	Pounds
Red or mammoth clover	10	6	60
Crimson clover	9	6	54
Alsike clover	10	5	50
Alfalfa	14	8	112
Cowpeas	8	6	48
Soy beans	10	6	60
Field peas	11	5	55

Not all of the nitrogen contained in these crops is taken from the air. On soils rich in nitrogen, a considerable proportion may be obtained from the soil. On poor soils, the proportion derived from the atmosphere is considerably larger. The soils needing the nitrogen most are those that benefit most largely.

As the legumes need other fertilizing material in an available form to produce a good yield, mineral fertilizers or farm manure should be added to the soil. Especially on run-down land this treatment is profitable.

The crops should be plowed under while green and succulent, as they decompose most readily at that stage. On sandy soils and in dry regions, the soil may be rendered so porous by plowing under a crop of dry vegetation that the capillary rise of water is greatly decreased, and the movement of air through the soil causes it to become very dry.

The perennial clovers (red, mammoth and alsike) and alfalfa do not make a rapid growth after seeding, which is a disadvantage when quick results are desired, as on a badly run-down soil. Crimson clover is an annual, and in the central and southern states may be sown in the fall and plowed under in the late spring, thus making use of a period of the year when the soil is most likely to be unoccupied by a crop. Cowpeas, soy-beans and field peas must be grown during the summer months. Vetch promises to be a useful green manure for winter growth in the northern states.

256. Cereal crops.—Where it is desired to keep a crop on the soil during the autumn, winter and spring, for the purpose of utilizing the soluble plant-food, the cereals, especially rye, are useful. Rye has the advantage of being an inexpensive crop to seed, besides being very hardy, and capable of growing on poor soil. It furnishes fall pasture, but should not be pastured in the spring if intended for green manure. It is important that it be plowed under while green.

Buckwheat, on account of its ability to grow on poor soil, is adapted to use as a green manure, but it must be grown in the summer.

D. ORGANISMS IN THE SOIL

A vast number of organisms, animal and vegetable, live in the soil. By far the greater part of these belong to plant life, and these comprise the forms of greatest effect in producing those changes in structure and composition which contribute to soil productiveness. Most of the organisms are so minute as to be seen only by the aid of the microscope, while a much smaller proportion range from these to the size of the larger rodents. They may thus be classed as macro-organisms and micro-organisms.

I. MACRO-ORGANISMS OF THE SOIL

Of the macro-organisms in the soil the animal forms belong chiefly to (1) rodents, (2) worms, (3) insects; and the plant forms to (1) the large fungi and (2) plant roots.

257. Rodents.—The burrowing habits of rodents, of which the ground-squirrel, mole, gopher and prairie-dog are familiar examples, result in the pulverization and transfer of very considerable quantities of soil. While their activities are often not favorable to agriculture, the effect upon the character of the soil is quite beneficial, and analogous to that of good tillage. Their burrows also serve to aërate and drain the soil, and in permanent pastures and meadows are of much value in this way.

258. Worms.—The common earthworm is the most conspicuous example of the benefit that may accrue from this form of life. Darwin, as the result of careful measurements, states that the amount of soil passed through these creatures may, in a favorable soil in a humid climate, amount to ten tons of dry earth per acre annually. The earthworm obtains its nourishment from the organic matter of the soil, but takes into its alimentary canal the inorganic matter as well, expelling the latter in the form of casts after it has passed entirely through the body. The ejected material is to some extent disintegrated, and is in a flocculated condition. The holes left in the soil serve to increase aëration and drainage, and the movements of the worms bring about a notable transportation of lower soil to the surface, which aids still more in effecting aëration. Darwin's studies led him to state that from one-tenth to two-tenths of an inch of soil is brought to the surface of land in which earthworms exist in normal numbers.

Instances are on record of land flooded for a considerable period so that the worms were destroyed, and the productiveness of the soil was seriously impaired until it was restocked with earth-worms.

Wollny conducted experiments with soil, in one case containing earthworms, and in another destitute of them. Although there was much variation in his results, they were in every case in favor of the soil containing the worms, and, in a number of the tests, the yield on rich soil was several times as great as where no worms were present.

Earthworms naturally seek a heavy, compact soil, and it is in soil of this character that they are most needed, on account of the stirring and aëration they effect. Sandy soil and the soils of the arid regions, in which are found few or no earthworms, are not usually in need of their activities.

259. Insects.—There is a less definite, and probably less effective, action of a similar kind produced by insects. Ants, beetles, and the myriads of other burrowing insects and their larvæ effect a considerable movement of soil particles, with a consequent aëration of the soil. At the same time they incorporate in the soil a considerable amount of organic matter.

260. Large fungi.—The larger fungi are chiefly concerned in bringing about the first stages in the decomposition of woody matter, which is disintegrated through the growth in its tissues of the root-mycelia of the fungi. These break down the structure, and thus greatly facilitate the work of the decay bacteria. Action of this kind is largely confined to the forest and is not of much importance in cultivated soil.

Another function of the large fungi is exercised in the intimate and possibly symbiotic relation of the fungal hyphæ to the roots of many forest trees, in soil where nitrification proceeds very slowly, if at all, for nitrates are apparently never present in forest soils. This enveloping system of hyphæ, which may consist of masses in a definite zone of the cortex, with occasional filaments passing outward into the soil, or which may surround the root with a dense mass of interwoven hyphæ, is called *mycorhiza.*

The cereal, cruciferous, leguminous and solanaceous plants are not associated with mycorhiza. Mycotropic plants are usually those that live in a humus soil filled with the mycelia of fungi. It is thought that the mycorhiza aid the higher plants to obtain nutriment that they must strive for in competition with the fungi.

Mycotropic plants are also able to grow with a very small transpiration of moisture, as is well known to be the case with many conifers; and this restricted transpiration would doubtless result in lack of nutriment were it not for the assistance of the mycorhiza.

261. Plant roots.—The roots of plants assist in promoting productiveness of the soil both by contributing organic matter and by leaving, upon their decay, openings which render the soil more permeable to water and which also facilitate drainage and aëration. The dense mass of rootlets, with their minute hairs that are left in the soil after every harvest, furnish a well-distributed supply of organic manure, which is not confined to the furrow slice, as is artificially incorporated manure. The drainage and aëration of the lower soil, due to the openings left by the decomposed roots, are of the greatest importance in heavy soil, and the beneficial effects of clover and other deep-rooted plants are due in no small measure to this function.

II. MICRO-ORGANISMS OF THE SOIL

Of the micro-organisms commonly existing in soils, the great majority belong to plant rather than to animal life. Of the latter, the only organisms of economical importance are the nematodes, whose injurious effect upon plant growth is accomplished through the formation of galls on the roots, in which the young are hatched and live to sexual maturity.

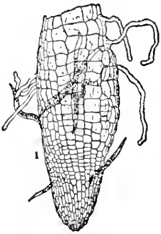

FIG. 108. Nematodes entering a root.

262. Plant micro-organisms.—The microscopic plants of the soil may be classed as slime-molds, bacteria, fungi and algæ.

263. Plant micro-organisms injurious to higher plants.—Injurious plant micro-organisms are confined mostly to fungi and bacteria. They may be entirely parasitic in their habits, or only partially so. They injure plants by attacking the roots. Those attacking other portions of plants may live in the soil during their spore stage, but these are not strictly micro-organisms of the soil. Some of the more common diseases produced by soil organisms are: Wilt of cotton, cowpeas, watermelon, flax, tobacco, tomatoes, etc., damping-off of a large number of plants, root-rot, galls, etc.

These fungi or bacteria may live for long periods, probably indefinitely, in the soil, if the conditions necessary for their growth are maintained. Some of them will die within a few years if their host plants are not grown upon the soil, but others are able to maintain existence on almost any organic substance. Once a soil is infected, it is likely to remain so for a long time, or indeed indefinitely. Infection is easily carried. Soil from infected fields may be carried on implements, plants, rubbish of any kind, in soil used for inoculation of leguminous crops, or even in stable manure containing infected plants, or in the feces resulting from the feeding of infected plants. Flooding of land by which soil is washed from one field to another may be a means of infection.

Prevention is the best defense from diseases produced by these soil organisms. Once disease has procured a foothold, it is practically impossible to eradicate all its organisms. Rotation of crops is effective for some diseases, but entire absence of the host crop is more often necessary. The use of lime is beneficial in the case of certain diseases. Chemicals of various kinds have been tried with little success. Steam-sterilization is a practical method of treating greenhouse soils for a number of diseases. The breeding of plants immune to the disease affecting its particular species has been successfully carried out in the case of the cowpea and cotton plants and can doubtless be accomplished with others.

264. Plant micro-organisms not injurious to higher plants.—The vegetable micro-organisms of the soil all take an active part in removing dead plants and animals from the surface of the soil, and in bringing about the other operations that are necessary for the production of plants. The first step in the preparation for plant growth is to remove the remains of plants and animals that would otherwise accumulate, to the exclusion of other plants. These are decomposed through the action of organisms of various kinds, the intermediate and final products of decomposition assisting plant production by contributing nitrogen and certain mineral compounds that are a directly available source of plant nutriment, and also by the effect of certain of the decomposition products upon the mineral substances of the soil, by which they are rendered soluble and hence available to the plant.

Through these operations the supply of carbon and nitrogen required for the production of organic matter is kept in circulation. The complex organic compounds in the bodies of dead plants or animals, in which condition plants cannot use them, are, under the action of micro-organisms, converted by a number of stages into the very simple compounds used by plants. In the course of this process, a part of the nitrogen is sometimes lost into the air by conversion into free nitrogen, but fortunately this may be recovered and even more nitrogen taken from the air by certain other organisms of the soil.

The slime molds, bacteria, fungi and algæ all play a part in these processes, but none of them so actively during every stage of the process as do the bacteria. Molds and fungi are particularly active in the early stages of decomposition of both nitrogenous and non-nitrogenous organic matter. Molds are also capable of ammonifying proteins, and even reforming the complex protein bodies from the nitrogen of ammonium salts. Certain of the molds and algæ are apparently able to fix atmospheric nitrogen, and contribute a supply of carbohydrates required for the use of the nitrogen-fixing bacteria.

265. Bacteria.—Of the several forms of micro-organisms found in the soil, bacteria are the most important. In fact, the abundant and continued growth of plants upon the soil is absolutely dependent upon the presence of bacteria, as through their action chemical changes are brought about which result in making soluble both organic and inorganic material necessary for the life of higher plants, and which, in part at least, would not otherwise occur.

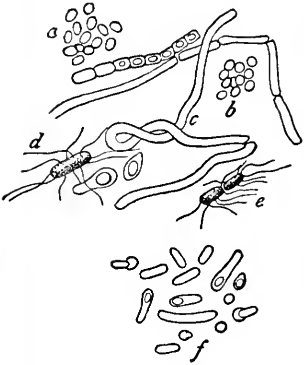

FIG. 109. Some types of soil-bacteria, highly magnified. *a*, Nitrate formers; *b*, nitrite-formers; *c*, *Bacteria graveolens;* *d*, *B. fusiformis;* *e*, *B. nebtilis;* *f*, *Closteridium pasteurianum.*

Bacteria are thus transformers, and not producers, of fertility in the soil, although, as we shall see later, certain kinds of bacteria take nitrogen from the air and leave it in the soil. With this exception, however, they add no plant food to the soil. It is their action in rendering available to the plant material already present in the soil that constitutes their greatest present value in crop-production. It is to their activity in conveying nitrogen from the air to the soil that we are indebted for most of our supply of nitrogen in virgin soils.

It is not usually the entire absence of bacteria from the soil that is to be avoided in practice, for all arable soils contain bacteria, although sometimes not all of the desirable forms; but, as great bacterial activity is required for the large production of crops, the practical problem is to maintain a condition of soil most favorable to such activity.

266. Distribution.—Bacteria are found almost universally in soils, although they are much more numerous in some soils than in others. A number of investigators have stated that in soils from different localities and of different types that they have examined, the numbers of bacteria were proportional to the productiveness of the soils. The number of bacteria present has, in some cases, been shown to be proportional to the amount of humus contained in the soil. It is natural to expect that within certain limits both of these findings will hold. The conditions obtaining in a productive soil are those favorable to the development of certain forms of bacteria, and these kinds constitute a very large proportion of those generally found in soils. However, there is evidence that comparatively unproductive soils may contain a large number of bacteria which are presumably not favorable to plant-growth.

Samples of soil taken from certain productive and relatively unproductive portions of a field on Cornell University farm contained a larger number of bacteria in the poor soil, although the two soils were equally well drained, and the good soil had slightly more organic matter. They had also received practically the same treatment during the preceding few years.

Character of soil	Number of bacteria per gram of dry soil
Good	1,200,000
Poor	1,600,000

After wheat had been growing for two months on these soils in the greenhouse, and maintained at the same moisture content, they were again sampled.

Character of soil	Number of bacteria per gram of dry soil
Good	760,000
Poor	1,120,000

Another reason why this relation between the number of bacteria and soil productiveness does not hold is that those bacteria having the same functions in relation to plant-food do not always have the same physiological efficiency. In other words, they do not have the same virulence, a small number in some cases being able to bring about the same changes that in other cases require a much larger number.

Bacteria are found chiefly in the upper layers of soil, although not at the immediate surface of the ground. The layer between the first and sixth or seventh inches contains, in most soils, the great bulk of the bacteria present. Below that depth they decrease in numbers, and below a depth of six to eight feet there are usually none.

267. Numbers.—The number of bacteria in any soil will naturally vary with the conditions that favor or discourage their growth. In sandy soils, forest soils, desert soils, acid soils, waterlogged soils and soils low in humus, the bacteria are either absent or very few in numbers. In soils very rich in organic matter, especially where animal manure has been applied, or where a carcass has been buried, the number becomes very large, as many as 100,000,000 per gram having been found; while in soil of ordinary fertility and tilth the numbers range from 1,000,000 to 5,000,000 per gram. The extreme rapidity with which reproduction occurs makes it possible for the number to increase enormously when conditions are favorable for their growth. While, therefore, very few bacteria are present in soils of the northern states during the winter, the number increases with great rapidity in the spring. Marshall Ward has shown that in the mild winters in England some soil bacteria at least continue their activity throughout the winter. In the southern states of America the same is doubtless true.

The following table shows the number of bacteria per gram of soil found in different parts of the United States during some portion of the growing season:

TABLE LXI

State	Soil	Crop	Investigator	Number
Delaware . .	. . . . . .	Grass, 12 yrs.	Chester	425,000
Delaware . .	. . . . . .	Grass, 4 yrs.	Chester	425,000
Delaware . .	. . . . . .	Clover, following fallow	Chester	1,880,000
Delaware . .	. . . . . .	Woodland	Chester	70,000
Delaware . .	Rich garden	Vegetables	Chester	1,860,000
Kansas	Loam (humus 2.19%)	. . . . . .	Mayo & Kinsley	33,931,747
Kansas	Loam (humus 3.07%)	. . . . . .	Mayo & Kinsley	53,596,060
Kansas	Thin soil, gumbo subsoil	. . . . . .	Mayo & Kinsley	78,534
Kansas	Loam, low in humus	. . . . . .	Mayo & Kinsley	8,543,006
Kansas	Loam, low in humus	. . . . . .	Mayo & Kinsley	3,192,131

268. Conditions affecting growth.—Many conditions of the soil affect the growth of bacteria. Among the most important of these are the supply of oxygen and moisture, the temperature, the presence of organic matter, and the acidity or basicity of the soil.

269. Oxygen.—All soil bacteria require for their growth a certain quantity of oxygen. Some bacteria, however, can continue their activities with much less oxygen than can others. Those requiring an abundant supply of oxygen have been called aërobic bacteria, while those preferring little or no air are designated anaërobic bacteria. This is an important distinction, because those bacteria which are of the greatest benefit to the soil are, in the main, aërobes, and those bacteria that are injurious in their action are chiefly anaërobes. However, it seems likely that an aërobic bacterium may gradually accommodate itself within certain limits to an environment containing less oxygen, and an anaërobic bacterium may accommodate itself to the presence of a larger amount of oxygen. Thus a bacterium may be most active in the presence of an abundant supply of oxygen; but, when subjected to conditions in which the supply is small, growth continues, but with lessened vigor. The term facultative bacteria has been used to designate those bacteria that are able to adapt themselves to considerable variation in oxygen supply. The structure, tilth and drainage of the soil consequently determine largely whether aërobic or anaërobic bacteria shall be most active.

270. Moisture.—Bacteria require some moisture for their growth. A notable decrease in the moisture content of the soil may temporarily decrease the number of bacteria by limiting their development to the films of moisture surrounding the particles. With a decrease in the moisture content of any soil, there occurs an increase in the oxygen in the interstitial spaces. Those bacteria thriving in the presence of oxygen are thereby favored, and the character of the bacterial flora is correspondingly changed. When the soil remains saturated, or nearly so, for any considerable period, the anaërobic forms assert themselves, and the usually beneficial activities of the aërobic bacteria are temporarily suspended. The most favorable moisture conditions for the activity of the most desirable bacteria is that found in a well-drained soil.

271. Temperature.—Soil bacteria, like other plants, continue life and growth under a considerable range of temperature. Freezing, while rendering bacteria dormant, does not kill them, and growth begins slightly above that point. Warrington has shown that nitrification goes on at temperatures as low as 37° to 39° Fahr. It is not, however, until the temperature is considerably higher that the functions of any of the soil bacteria are pronounced. From 70° to 110° Fahr. their activity is greatest, and it diminishes perceptibly below or above those points. The thermal death points of most forms of bacteria is found at some point between 110° and 160° Fahr., but the spore forms even resist boiling. Only in some desert soils does the natural temperature reach a point sufficiently high to actually destroy bacteria, and there only in the upper surface. In fact, it is seldom that soil temperatures become sufficiently high to curtail bacterial activity.

272. Organic matter.—The presence of a certain quantity of organic matter is essential to the growth of most, but not all, forms of soil bacteria. The organic matter of the soil, consisting as it does of the remains of a large variety of substances, furnishes a suitable food-supply for a very great number of forms of organisms. The action of one set of bacteria upon the cellular matter of plants embodied in the soil produces compounds suited to other forms, and so from one stage of decomposition to another this constantly changing material affords sustenance to a bacterial flora the extent and variety of which it is difficult to conceive. Bacteria not only affect the organic matter of the soil, but, in the case of certain forms, their activities produce changes in the inorganic matter that cause it to become more soluble and more easily available to the plant.

A soil low in organic matter usually has a lower bacterial content than one containing a larger amount, and, under favorable conditions, the beneficial action, to a certain point at least, increases with the content of organic substance; but, as the products of bacterial life are generally injurious to the organisms producing them, such factors as the rate of aëration and the basicity of the soil must determine the effectiveness of the organic matter.

273. Soil acidity.—A soil having an acid reaction makes a poor medium for the growth of bacteria. A neutral or slightly alkaline soil furnishes the most favorable conditions for bacterial growth. The activities of many soil bacteria result in the formation of acids which are injurious to the bacteria themselves, and, unless there is present some basic substance with which these can combine, bacterial development is inhibited by their own products. This is one of the reasons why lime is so often of great benefit when applied to soils, and especially to those on which leguminous crops are growing. For the same reason, the presence of lime hastens decay of organic matter in certain soils, and the conversion of nitrogenous material with a minimum loss into compounds available to the plant. As showing the value of lime in the process of nitrification, it has been pointed out that in the presence of an adequate supply of lime the availability of ammonium salts is almost as high as

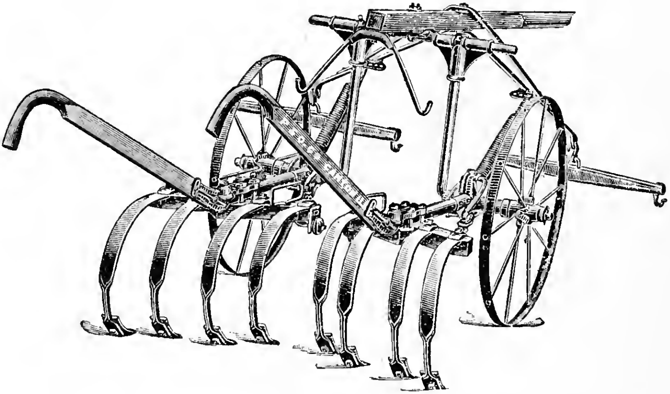

Fig. 110. Spring-toothed walking cultivator. For thorough, shallow tillage.

that of nitrate salts, but where the supply is insufficient the value of ammonium salts is relatively quite low.

274. Functions of soil bacteria.—Bacteria have a part in many of the processes of the soil which greatly affects its productiveness. It has become customary to refer to the changes produced by certain forms of bacteria as their function in contributing to soil-productiveness.

275. Decomposition of mineral matter.—Certain bacteria decompose some of the mineral matter of the soil and render it more easily available to the plant. While the nature of the processes and their extent are not known, there is sufficient evidence to justify the above statement. It is well known that several forms of bacteria are instrumental in decomposing rock, and that sulfur and iron compounds are acted upon by other forms. Again, the much greater efficiency of difficultly soluble phosphate fertilizers, when used in conjunction with a quantity of organic matter, is evidence of the relation of bacterial action to the decomposition of mineral substances. Stocklasa has shown that, when *B. megatherium* and *B. fluorescens* are added to soil fertilized with insoluble phosphates, plants grown thereon take up a larger amount of phosphorus than those on uninoculated soils.

Organic acids and carbon dioxid are constantly produced by soil bacteria. These in soil water are weak but ever-acting solvents, the effect of which must in the end be considerable. It seems likely, however, that there is a more direct effect of certain bacteria upon mineral matter than merely the solvent action of these acids. That rock may be disintegrated through the action of bacteria has been already commented upon. Although it has not yet been demonstrated, bacteria such as are capable of decomposing rock may, in all probability, exist in the soil where their activities result in the "weathering" that always goes on in soils even when no organic matter is present.

It has been suggested that carbon dioxid dissolved in water may act on the very difficultly soluble tri-calcium phosphate, producing di-calcium phosphate, a more soluble form, and calcium bicarbonate, thus:

$$Ca_3(PO_4)_2 + 2CO_2 + 2H_2O = Ca_2H_2(PO_4)_2 + Ca(HCO_3)_2$$

The calcium bicarbonate thus produced, as well as that derived from other sources, may then act on the double silicates of aluminum and one of the alkalies, thus:

$$K_2O.\ Al_2O_3.\ 6\ SiO_2 + Ca(HCO_3)_2 = CaO.\ Al_2O_3.\ 6\ SiO_2 + 2\ KHCO_3$$

There is then another nutrient rendered available to the plant.

It has been shown by Van Delden and by Nadson that several forms (*M. desulfuricans*, *M. æstuarii*, *Proteus vulgaris* and *B. mycoides*) are able to reduce sulfates, while transformations of iron, silicon and calcium are effected by *Proteus vulgaris*.

276. Decomposition of non-nitrogenous organic matter.—The organic matter commonly decomposed in soils contains a large proportion of compounds containing no nitrogen. The non-nitrogenous substances decompose quite rapidly, and the organic nitrogen disappears less rapidly than the carbon, hydrogen and oxygen of organic bodies.

Humus always contains a higher percentage of nitrogen than do the plants from which it is formed (page 123).

The non-nitrogenous substances consist of cellulose and allied compounds forming the cell-walls of plants, and the carbohydrates, organic acids, fats, etc., contained in them. The dissolution of cellulose is brought about by the action of the enzyme cytase secreted by a number of fungi, and is also probably accomplished by the *Bacillus amylobacter*, but whether through the secretion of an enzyme is not known. Other bacteria have been reported to secrete a cytase that acts on certain constituents of the cell-wall. It is probable that numerous organisms capable of fermenting cellulose and allied substances exist in the soil, which decomposition they accomplished through the production of cytase.

The effect of cytase upon cellulose and other fiber is to hydrolyse it with the formation of sugar, as glucose, mannose, zylose, aribinose, etc.

Starch is converted into glucose by a ferment (diastase) either present in the plant itself or possibly secreted by fungi or bacteria. All the sugars are finally converted into organic acids which may combine with mineral bases. Distinct organisms have been isolated that can utilize for their development formates, acetates propionates, butyrates, etc., the final product being carbon dioxid and water. Thus, step by step, the non-nitrogenous matter incorporated in the soil is carried by one and another form of organisms from the most complex to the simplest combinations.

The final product of the decomposition of carbonaceous matter being carbon dioxid, there is a return to the air of the compound from which the carbon of the decomposing substance was originally derived. In the plant, unless it is saprophytic, the carbon of the tissues comes directly from the carbon dioxid of the air, from which more complex carbon-bearing compounds are produced and utilized in its functions or in its tissues. A portion of the carbon is returned to the air by the plant in the form of carbon dioxid, the remainder is retained by the plant, and may be returned by the process of decay, or may be consumed by an animal, and, as the result of its physiological processes, either exhaled as carbon dioxid or deposited in the tissues to be later decomposed and converted into carbon dioxid. The soil is thus the scene of at least a part of the varied transformations through which carbon is continually passing, as it is utilized by higher plants, animals, bacteria and fungi.

The non-nitrogenous organic substances in their various stages furnish food for a large number of bacteria, among which are those concerned in the decomposition of mineral matter and in the processes of nitrification and nitrogen-fixation. There are, therefore, two ways in which these substances are of great importance in soil fertility: (1) As a source of organic acids. (2) As a food-supply for useful soil bacteria.

277. Decomposition of nitrogenous organic matter. —The decomposition of nitrogenous organic matter is accomplished by a series of changes from one compound to another, as we have seen was the case with the non-nitrogenous materials. The final products are carbon dioxid, water, and usually some hydrocarbon gases resulting from the carbon and hydrogen of the organic matter, and also some hydrogen sulfide or other gas containing sulfur or a final oxidation of the sulfur of the proteids into sulfates, while the nitrogen is ultimately converted into nitrates, or into free nitrogen, although a portion of the original nitrogen sometimes escapes into the air in the intermediate stage, ammonia.

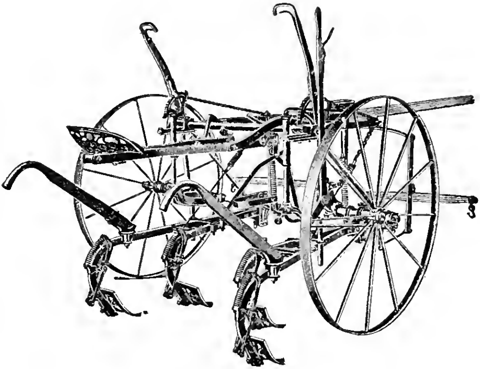

FIG. 111. The large-shovel riding cultivator.

The processes will be discussed under the following heads, which represent certain more or less definite stages in the decomposition: (1) Decay and putrefaction. (2) Ammonification. (3) Nitrification. (4) Denitrification.

278. Decay and putrefaction.—Decomposition of the nitrogenous organic matter of the soil, consisting largely of the proteins, begins with either one of two processes—decay or putrefaction. Decay is produced by aërobic bacteria, and naturally occurs when the conditions are most favorable for their development. When the conditions are otherwise, the growth of these bacteria is checked, and then further decomposition would be extremely slow were it not for the other process—putrefaction. Putrefaction is produced by anaërobic bacteria. In the same body, and consequently in the same soil, decay and putrefaction may be in progress simultaneously, decay taking place on the outside and on the surfaces of other parts exposed to the air, while putrefaction occurs on the interior, where the supply of oxygen is limited. By means of the two processes, decomposition is greatly facilitated.

Decay produces a very rapid and complete decomposition of the substance in which it operates, most of the carbon and hydrogen being quickly converted into carbon dioxid and water, and the nitrogen into ammonia and probably some free nitrogen. The latter is possibly due to the oxidation of ammonia, thus

$$4\ NH_3 + 3\ O_2 = 6\ H_2O + 2\ N_2.$$

The sulfur of the proteins finally appears in the form of sulfates.

What the intermediate products are has not been determined, but in the decay of meat, where there was an abundant supply of oxygen, succinic, palmytic, oleic and phenyl-propionic acids have been found.

Putrefaction results in a large number of complex intermediate compounds and proceeds much more slowly. Many of the substances thus produced are highly poisonous and most of them have a very offensive odor. They may be further broken down by decay when the conditions are suitable, or by a continuation of the process of putrefaction. In either case, the poisonous properties and the odor are removed.

In the process of decomposition of organic matter two classes of substances are produced: (1) Those which have been excreted or secreted by the bacterium, and therefore have passed through the metabolic processes of the organism. (2) Those that have been formed because of the removal of certain atoms by bacteria or enzymes from compounds, thus necessitating a readjustment of the remaining atoms and the consequent formation of a new compound.

Putrefaction is carried on by a large number of forms of bacteria, the resulting product depending upon the substance in process of decomposition, and upon the bacteria involved. Some of the characteristic, although not constant products, formed in the putrefaction of albumin and proteins are albumenoses, peptones, and amino-acids, followed by the formation of cadaverin, putrescin, skatol and indol. Where an abundant supply of oxygen is present, or where a sufficient supply of carbohydrates exist, these substances are not formed. There are many other products of putrefaction, including a number of gases, as carbon dioxid, hydrogen sulfide, marsh gas, phosphine, hydrogen, nitrogen, etc.

It will be noticed that these changes, like those occurring in the non-nitrogenous organic matter, involve a breaking down of the more complex compounds and the formation of simpler ones; that a very large number of bacteria are concerned in the various steps, while even the same substances may be decomposed and the same resulting compounds formed by a number of different species of bacteria.

Present-day knowledge of the subject does not make it possible to present a list of the bacteria concerned in each step, or to name all of the intermediate products formed; but for the student of the soil the principal consideration is a knowledge of the circumstances under which the nitrogen is made available to plants, and the conditions which are likely to result in its loss from the soil.

279. Ammonification.—Decay and putrefaction may be considered as a continuation of ammonification, or the latter process as the beginning of the former. Ammonification, as its name implies, is that stage of the process during which ammonia is formed from the intermediate products.

Like the other processes of decomposition, there are many species of bacteria capable of forming ammonia from nitrogenous organic substances. Different forms display different abilities in converting nitrogen of the same organic material into ammonia, some acting more rapidly or more thoroughly than others. In tests by certain investigators where the same bacteria are used upon different substances, the order of their efficiency is changed with the change of substance. It seems likely, therefore, that certain forms are most efficient when acting on certain organic compounds. That, in other words, each species is best adapted to the decomposition of certain substances, while capable of attacking others, although less effectively.

Among the bacteria producing ammonification are *B. mycoides*, *B. subtilis*, *B. mesentericus vulgatus*, *B. janthinus* and *Proteus vulgaris*. Of these, *B. mycoides* has been very carefully studied, and the findings of Marchal may be taken as representative of the process of ammonification. He found that when this bacterium was seeded on a neutral solution of albumin, ammonia and carbon dioxid were produced, together with small amounts of peptones, leucin, tyrosin, and formic, butyric and proprionic acids. He concludes that in the process, atmospheric oxygen is used, and that the carbon of the albumin is converted into carbon dioxid, the sulfur into sulfuric acid, the hydrogen partly into water, and partly into ammonia by combining with the nitrogen of the organic substance. He suggests that a complete decomposition of the albumin occurs according to the following reaction:

$$C_{72}H_{112}N_{18}SO_{22} + 77O_2 = 29\ H_2O + 72CO_2 + SO_3 + 18NH_3.$$

The greatest activity occurred at a temperature of 86° Fahr., and as low as 68° Fahr. action was quite strong. Access of an increased amount of air, produced by increasing the surface of the liquid, increased the rate of ammonification. A slightly acid reaction in the liquid produced the maximum activity, but in a neutral or even slightly acid medium the process was continued, although much less actively.

He found that *B. mycoides* was also capable of ammonifying casein, fibrin, legumin, glutin, myosin, serin, peptones, creatin, leucin, tyrosin and asparagin, but not urea and ammonium salts.

280. Nitrification.—Some agricultural plants can utilize ammonium salts as a source of nitrogen. This has been determined for maize, oats, barley and potatoes. Other plants, such as beets, show a decided preference for nitrogen in the form of nitrates. Whether any of the common crops can thrive as well on ammonium salts as upon nitrates has not been finally demonstrated. In all arable soils the transformation of nitrogen does not stop with its conversion into ammonia, but proceeds by an oxidation process to the formation of first nitrous and then nitric acids. This may be considered to proceed according to the following equations:

$$2NH_3+3O_2=2HNO_2+2H_2O.$$
$$2HNO_2+O_2=2HNO_3.$$

The acid in either case combines with one of the bases of the soil, usually calcium, so that we have calcium nitrate resulting.

Each of these steps is brought about by a distinct bacterium, but they are closely related. Collectively they are called nitro-bacteria. Nitrosomonas and Nitrosococcus are the bacteria concerned in the conversion of ammonia into nitrous acid or nitrites. The former are supposed to be characteristic of European, and the latter of American soils. They are sometimes referred to as nitrous ferments.

Nitrobacter are those bacteria that convert nitrites into nitrates. They are also designated nitric ferments. There seem to be some differences in bacteria from different soils, but the differences are slight, and the conditions favoring their actions are similar. It is also true that the conditions favoring the action of Nitrosomonas and Nitrobacter are similar, and they are generally found in the same soils, although some experiments show that, in the same soil, nitrites may sometimes accumulate, indicating conditions more favorable to the development of the Nitrosomonas bacteria. The formation of nitrates usually follows closely on the production of nitrites, so that there is rarely more than a trace of the latter to be found in soils. A soil favorable to the process of nitrification is usually well adapted to all of the processes of nitrogen transformation.

Marked differences have been found in the nitrifying power of bacteria from different soils. Highly productive soils have generally been found to contain bacteria having greater nitrifying efficiency than those from less productive soils, but this may not always be the case, as other factors may limit the productiveness.

281. Effect of organic matter on nitrification.—A peculiarity in the artificial culture of nitrifying bacteria is that they cannot be grown in artificial medium containing organic matter. This property for a long time prevented the isolation and identification of these organisms, as it was hardly conceivable that organisms living in the dark, where energy cannot be obtained from sunlight, could exist without using the energy stored by organic matter. It has been suggested, in explanation of this, that the energy produced by the oxidation involved in the process of nitrification makes possible the growth of the organisms under these, apparently impossible, conditions. Some experimenters report having grown nitrobacteria in organic media, but it is generally believed, at present, that this is not possible, and that there has been some error in their work.

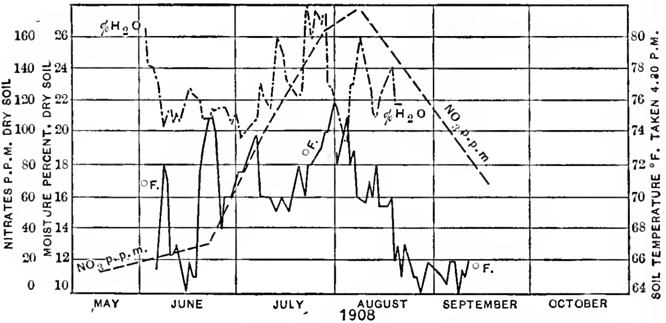

FIG. 112. Curves showing the relation of the moisture and temperature of the soil to the formation of nitrates which are given in parts per million of dry soil. Depth of sampling, eight inches. These curves bring out clearly the fact that the warmer soil temperature, combined with a moderately high soil moisture content favors the formation of nitrates.

The presence of peptone in the proportion of 500 parts per million completely prevents the development of nitrobacteria and one half that quantity checks it, while 150 parts of ammonia per million has a similar effect. In a normal soil, the quantity of soluble ammonium salts is well below this amount, as must also be that of soluble organic matter. In confirmation of the inhibiting effect of organic matter on the nitrobacteria, cases have been reported of soils very rich in organic matter in which no bacteria of this type occur.

It has also been stated that very heavy manuring with organic manures results in decreased nitrification in the soil. While this may be true where farm manure is used in the quantities sometimes applied in gardening operations, it is not likely to occur in soils on which ordinary field crops are grown. The principle is well illustrated by the dry-earth closet. Manure mixed with earth in relatively small proportions and kept aërated by occasional mixing undergoes a very thorough decomposition of the manure but without any corresponding increase in nitrates. On the other hand, under field conditions, manure used in relatively small amounts does not undergo this serious loss.

The application of twenty tons of farm manure per acre to sod on a clay loam soil for three consecutive years, at Cornell University, resulted in a larger production of nitrates on the manured soil than upon a contiguous plat of similar soil left unmanured. This was true during the third year of the applications, when the land was in sod, and also the fourth year when no manure was applied to either plat, and when both were planted to corn, as may be seen from the following table:

TABLE LXII.—NITRATES PRODUCED ON HEAVILY MANURED AND ON UNMANURED SOIL

	NO_3 in parts per million, dry soil	
	Unmanured soil	Twenty tons manure per acre for three years
Land in timothy—		
April 23	8.2	21.0
May 3	4.1	4.6
May 14	3.3	4.5
May 30	2.0	4.0
June 1	2.4	2.0
June 13	0.8	1.1
June 20	1.3	3.0
July 24	2.2	2.8
August 14	1.8	3.0
Land in maize—		
May 19	17.5	20.1
June 22	42.8	79.3
July 6	50.0	105.0
July 28	195.0	304.0
August 10	151.0	184.0

282. Effect of soil aëration on nitrification.—Probably the most potent factor governing nitrification in the soil is the supply of air. In clay and even in loam soils, the tendency to compactness is such as to exclude air sufficient to enable nitrification to proceed as rapidly as desirable unless the soil be well tilled. Columns of soil eight inches in diameter and of the same depth were removed from a field of clay loam on Cornell University farm, and carried to the greenhouse without disturbing the structure of the soil as it existed in the field. At the same time, similar-sized vessels were filled with soil dug up from a spot nearby. These may be termed unaërated and aërated soils. Both were kept at the same temperature and moisture content in the greenhouse, but no plants were grown upon them. The production of nitrates was as follows:

TABLE LXIII

Date of analysis	Nitrates in dry soil, parts per million	
	Unaërated soil	Aërated soil
When taken from field	3.2	3.2
After standing one month	4.2	17.6
After standing two months	9.0	45.6

283. Effect of sod on nitrification.—Nitrification proceeds slowly on sod land, especially if the soil is heavy. On the same type of soil as that used in the experiment last described, the average quantities of nitrates for each month of the growing season in the surface eight inches of sod land as compared with maize land under the same manuring were as follows:

TABLE LXIV

Month	Nitrates in dry soil, parts per million	
	Sod land	Maize land
April	8.9	....
May	3.0	17.1
June	2.4	40.3
July	4.0	194.0
August	5.4	186.7

The amount of nitrogen removed by the maize crop was greater than that removed by the timothy, consequently the greater amount in the former soil can not be due to the effect of the crop.

So far as the conservation of nitrogen is concerned, sod is an ideal crop, for nitrates are formed very little faster than they are used, and are not carried off in large amounts by the drainage water.

In the corn land as much as 500 pounds of nitrates were present in the first twelve inches of one acre, or fully five times as much as was used by the crop.

284. Depth at which nitrification takes place.—Warington concluded from his experiments that nitrification takes place only in the surface six feet of soil. Hall has pointed to the fact that no more nitrates were leached from the 60-inch lysimeter at Rothamsted than from the one 20 inches deep; which is very good evidence that in that particular soil nitrification does not take place below 20 inches from the surface. In more porous soils, however, nitrification probably extends deeper, especially in the rich and porous subsoils of the arid and semi-arid regions.

In all probability, nitrification is largely confined to the furrow slice, where the opening up of the soil by tillage has provided the necessary air, and where the temperature rises to a point more favorable to the action of nitrifying bacteria. The results from the aërated and unaërated soils cited above represent the differences that doubtless exist between the furrow slice and the subsoil so far as nitrification is concerned.

285. Loss of nitrates from the soil.—Nitrogen having been converted into the form of nitric acid, it immediately combines with available bases in the soil forming salts, all of which are very easily soluble, and which are carried in solution by the soil water. In a region of large rainfall, the removal of nitrates in the drainage water is very rapid. Hall states that nitrates formed during the summer or autumn of one year are practically all removed from the soil of the Rothamsted fields before the crops of the following year have advanced sufficiently to utilize them. It was formerly customary to fertilize with ammonium salts in the autumn, but the drainage water showed on analysis such a large quantity of nitrates during the months intervening between the time of fertilizing and the opening of the growing season that the practice was discontinued.

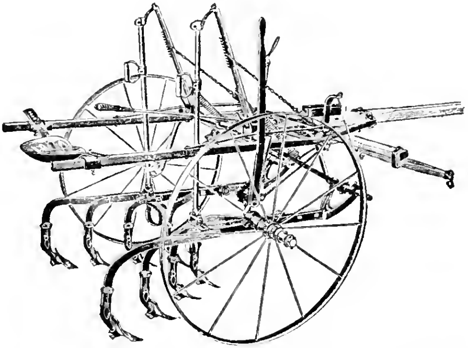

FIG. 113. The modern, small, eight-shovel riding cultivator.

In regions of less rainfall or of greater surface evaporation, the loss in this way is less, reaching a minimum in an arid region when irrigation is not practiced. Under such conditions, there is a return of nitrates to the upper soil, as capillary water moves upward to replace evaporated water. In fact, wherever evaporation takes place to any considerable extent, there is some movement of this kind. The need for catch crops to take up and preserve nitrogen is therefore greater in a humid region than in an arid or semi-arid one. An arrangement of crops that allows the land to stand idle for some time, or a crop that requires intertillage, as does maize, fails to utilize all of the nitrates produced, and promotes the loss of nitrogen in drainage water.

286. Denitrification.—The nitrogen transforming bacteria thus far studied have been those that cause the oxidation of nitrogen as the result of their activities. We may now consider a number of forms of bacteria that accomplish a reverse action. The several processes involved are commonly designated by the term denitrification, and comprise the following: (1) Reduction of nitrates to nitrites and ammonia. (2) Reduction of nitrates to nitrites, and these to elementary nitrogen.

The number of organisms that possess the ability to accomplish one or more of these processes is very large,—in fact greater than the number involved in the oxidation processes,—but, in spite of their numbers, permanent loss of nitrogen in ordinary arable soils is unimportant in amount, although in heaps of barnyard manure it may be a very serious cause of loss.

Some of the specific bacteria reported to bring about denitrification are: *B. ramosus* and *B. pestifer*, which reduce nitrates to nitrites; *B. mycoides*, *B. subtilis*, *B. mesentericus vulgatus* and many other ammonification bacteria which are capable of converting nitrates into ammonia.

Bacterium denitrificans alpha and *Bacterium denitrificans beta* reduce nitrates with the evolution of gaseous nitrogen.

In addition to these nitrate-destroying bacteria, there are other bacteria which also utilize nitrates; but, like higher plants, they convert the nitrogen into organic nitrogenous substances. However, as they operate in the dark and cannot obtain energy from sunlight, they must have organic acids or carbohydrates as a source of energy. While these bacteria cannot be considered to be denitrifiers, they help to deplete the supply of nitrates when conditions are favorable for their development. What these conditions are is not well understood, nor can any estimate be made as to the extent of their operations.

Most of the nitrifying bacteria perform their functions only under a limited access of oxygen, while others can operate in the presence of a more liberal supply; but, in general, thorough aëration of the soil practically prevents denitrification. Straw and dung apparently carry an abundant supply of denitrifying organisms, and also furnish a supply of carbohydrates which favors their action, so that stable manure is very likely to undergo denitrification, and straw or coarse stable manure are conducive to the growth of denitrifying bacteria in the soil.

Under ordinary farm conditions, denitrification is of no significance in the soil where proper drainage and good tillage are practiced. Warington showed that, if an arable soil be kept saturated with water to the exclusion of air, nitrates added to the soil are decomposed, with the evolution of nitrogen gas. As lack of drainage is usually most pronounced in the early spring, when the soil is likely to be depleted of nitrates, it is not likely that much loss arises in this way unless a nitrate fertilizer has been added. Of the many difficulties arising from poor drainage, denitrification of an expensive fertilizer may be very considerable item.

The addition of a nitrate fertilizer to a soil receiving stable manure is not likely to result in a loss of nitrates unless the dressings of manure have been extremely heavy. Hall states that at Rothamsted, where large quantities of nitrate of soda are used every year in connection with annual dressings of farm manure, the nitrate produces nearly as large an increase when added to the manured as when added to the unmanured plat. There appears, in other words, to be no loss of nitrate by denitrification.

It is possible to reach a point in manuring where denitrification may take place. Market gardeners sometimes reach this point where fifty tons or more of farm manure, in addition to a nitrate fertilizer, are added to the soil. Plowing under heavy crops of green manure may produce the same result. In either case, the best way to overcome the difficulty is to allow the organic matter to partly decompose before adding the fertilizer. The removal of the easily decomposable carbohydrates needed by the denitrifying organisms decreases or precludes their activity.

287. Nitrogen fixation through symbiosis with higher plants.—It has long been recognized by farmers that certain crops like clover, alfalfa, peas, beans, etc., improve the soil, making it possible to grow larger crops of cereals after these crops have been upon the land. The benefit was, within the past century, traced to an increase in the nitrogen content of the soil, and the specific plants so affecting the soil were found to be, with perhaps a few exceptions, those belonging to the family of legumes. It has furthermore been demonstrated that these plants utilize, under certain conditions, the uncombined nitrogen of the atmosphere, and that they contain, both in the aërial portions and in the roots, a very high percentage of nitrogen. In consequence, the decomposition of even the roots of the plants in the soil leaves a large amount of nitrogenous matter.

288. Relation of bacteria to nodules on roots.—It has also been shown that the utilization of atmospheric nitrogen is accomplished through the aid of certain bacteria that live in nodules (tubercles) on the roots of the plants. These bacteria acquire the free nitrogen from the air in the soil, and the host plant secures it in some form from the bacteria or their products. The presence of a certain species of bacteria is necessary for the formation of tubercles. Leguminous plants grown in cultures or in soil not containing the necessary bacteria do not form nodules, and do not utilize atmospheric nitrogen, the result being that the crop produced is less in amount and the percentage of nitrogen in the crop is less.

It has for some years been the belief that the organism which produces the nodules and utilizes the uncombined nitrogen is the *Pseudomonas radicicola,* but this has very lately been called in question.

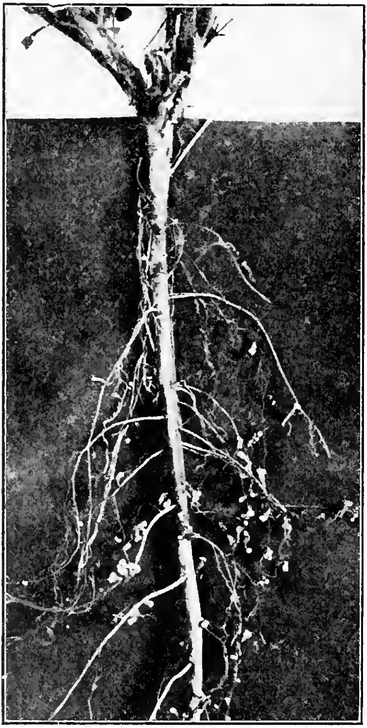

FIG. 114. Nodules on the roots of an alfalfa plant Bacteria live in these nodules, or tubercles, and have the power of utilizing the free nitrogen of the air in their growth.

The nodules are not normally a part of leguminous plants but are evidently caused by some irritation of the root surface, much as a gall is caused to develop on a leaf or branch of a tree by an insect. In a culture containing the proper bacteria, the prick of a needle on the root surface will cause a nodule to form in the course of a few days. The entrance of the bacteria is effected through a root-hair which it penetrates, and may be seen as a filament extending the entire length of the hair, and into the cells of the cortex of the root, where the growth of the tubercle starts.

Even where the causative bacteria occur in cultures or in the soil, leguminous plants may not secure any atmospheric nitrogen, or perhaps only a small quantity, if there is an abundant supply of readily available combined nitrogen upon which the plant may draw. The bacteria have the ability to utilize combined nitrogen as well as uncombined nitrogen, and prefer to have it in the former condition. On soils rich in nitrogen legumes may, therefore, add little or no nitrogen to the soil, while in properly inoculated soils deficient in nitrogen an important gain of nitrogen results.

While *P. radicicola* has been considered the organism common to all leguminous plants, it is now known that the organisms from one species of legume are not equally well adapted to the production of tubercles on each of the other species of legumes. They show greater activity on some species than on others, but do not develop so successfully on any species as on the one from which the organisms were taken. It was quite generally believed at one time that the longer any species of legume is in contact with the organisms from another species the more active they become, and the greater the utilization of atmospheric nitrogen. Considerable doubt has been cast upon this view in recent years, and it is now generally conceded that the bacteria of certain legumes are not capable of inoculating certain other species of legumes.

289. Transfer of nitrogen to the plant.—It has been shown by several investigators that bacteria from the nodules of legumes are able to fix atmospheric nitrogen even when not associated with leguminous plants. There would seem to be no doubt, therefore, that the fixation of nitrogen in the tubercles of legumes is accomplished directly by this organism, and not by the plant itself, or through any combination of the plant and organism,—both of which hypotheses have been advanced. The part which the plant plays is doubtless to furnish the carbohydrates required in large quantities by all nitrogen-fixing organisms and which the legumes are able to supply in large amounts. The utilization of large quantities of carbohydrates by the nitrogen-fixing bacteria in the tubercles may also account for the small proportion of non-nitrogenous organic matter in the plants.

How the plant absorbs this nitrogen after it has been secured by the bacteria is less well understood. Early in the growth of the tubercle, a mucilaginous substance is produced which permeates the tissues of the plant in the form of long, slender threads, and which contain the bacteria. These threads develop by branching or budding, and form what have been called Y and T forms known as bacteroids, which are peculiar to these bacteria, and not produced by them when grown in the media of the laboratory. The threads finally disappear, and the bacteria diffuse themselves more or less, through the tissues of the root. What part the bacteroids play in the transfer of nitrogen is not known. It has been suggested that in this form the nitrogen is absorbed by the tissues of the plant. It seems quite likely that the nitrogen compounds produced within the bacteria cells are diffused through the cell-wall and absorbed by the plant.

In a recent report, De Rossi states that *Pseudomonas radicicola* is not the causative agent in the fixation of nitrogen in the nodules of leguminous plants, and that he has isolated other bacteria that do possess this property. These bacteria produce the Y and T forms in artificial media, which is in itself an indication of their identity with the bacteria concerned in nitrogen-fixation. De Rossi's work may also explain why what was formerly considered to be one form of bacterium, *Pseudomonas radicicola*, common to all leguminous plants, is not capable of inoculating one species of legume when transferred from another. It may be that there are a number of different forms, each adapted to certain species of legumes.

290. Soil-inoculation for legumes.—The possibility of securing a better growth of leguminous crops on soils not having previously grown such a crop successfully, was conceived immediately following the discovery of the nitrogen-fixing bacteria. Extensive experiments showed the practicability of inoculating land for a certain leguminous crop by spreading upon its surface soil from a field on which the same crop is successfully growing. It is manifestly much better to apply the organisms or a certain species of legume from a field having grown the same species than to attempt to use organisms from another species of legume. The fact that soil-inoculation by means of soil from other fields may possibly transmit weed seeds and fungous diseases, and also necessitates the transportation of a great bulk and weight of material, has led to numerous efforts to inoculate soil by means of pure cultures. The pure culture may also make it possible to bring to the soil bacteria of greater physiological efficiency than those already there.

The first attempt at inoculation by pure cultures was made in Germany, the cultures being sold under the name of "Nitragin." Careful experiments made with this material previous to the year 1900 did not show it to be very efficient; but, of recent years, improvements in the method of manipulating the cultures have resulted in much greater success. In "Nitragin," the medium used for growing the organisms is gelatin, and, before use, this was formerly dissolved in water; but now a solution of greater density is used in order to prevent a change of osmotic pressure, which may cause plasmolysis and result in the destruction of the bacteria.

Within recent years, a number of cultures for soil-inoculation have been offered to the public. The first of these utilized absorbent cotton to transmit the bacteria in a dry state from the pure cultures in the laboratory to the user of the culture, who was to prepare therefrom another culture to be used for inoculating the soil. Careful investigation of this method showed that its weakness lay in drying the cultures on the absorbent cotton which frequently resulted in the death of the organisms. More recently, liquid cultures have been placed on the market in this country, but they have not yet been sufficiently well tested to prove their efficiency. It is undoubtedly only a question of time until a successful method of inoculating soil from artificial cultures will be found. In the meantime, inoculation by means of infested soil is the most practical method.

291. Nitrogen-fixation without symbiosis with higher plants.—If a soil be allowed to stand idle, either without vegetation or in grass, it will, under favorable moisture conditions, in the northern states, accumulate in one or two years an appreciable amount of nitrogen not present at the beginning of the period. At the Rothamsted Experiment Station, one of the fields in volunteer plants, consisting mainly of grass without legumes, gained in the course of twenty years about twenty-five pounds of nitrogen per acre, annually. According to Hall, the nitrogen brought down by rain would account for about five pounds per acre per annum, and dust, bird-droppings, etc., for a little more. As pointed out by Lipman, there must also have been a greater total accretion of nitrogen during the twenty years than appears in the final result, as considerable must have been lost through removal of nitrates in drainage and escape of nitrogen in the ordinary processes of its transformation.

292. Nitrogen-fixing organisms.—Direct experiment has shown that certain bacteria have the ability to utilize atmospheric nitrogen and to leave it in the soil in a combined form. A bacillus—*Clostridium pasteurianum*— was first found to produce this result. Later, a commercial culture called "Alinit" was placed on the market in Germany, which culture it was claimed contained *Bacterium ellenbachensis,* with which the soil was to be inoculated, and that a large fixation of atmospheric nitrogen would result. A number of tests of this material failed to show that it caused any marked fixation of atmospheric nitrogen.

A number of other nitrogen-fixing organisms have since been discovered. There are: (1) Several members of the group designated Azotobacter, which are aërobic bacteria, and which some investigators hold to be capable of fixing atmospheric nitrogen when grown in pure cultures, and others believe to be able to do so, at least in large amounts, only in the presence of certain other organisms. (2) Members of the Granulobacter group, which are large spore-bearing bacilli of anaërobic habits. (3) *B. radiobacter*, which appear to be closely related to or identical with the *B. radicicola* of legume tubercles. The latter has been shown to be able to fix atmospheric nitrogen even when not growing in symbiosis with legumes.

There are doubtless many other nitrogen-fixing organisms still to be discovered.

A peculiarity of these nitrogen-fixing organisms is their use of carbohydrates, which they decompose in the process of nitrogen-fixation. They secure more atmospheric nitrogen when in a nitrogen-free medium. The presence of soluble lime or magnesium salts, especially carbonates, is necessary for the best performance of the nitrogen-fixing function, as is also the presence of a somewhat easily soluble form of phosphorus. They are exceedingly sensitive to an acid condition of the soil.

293. Mixed cultures of nitrogen-fixing organisms.—Mixed cultures of the various organisms mentioned fix larger amounts of nitrogen than do the pure cultures of any one of them, while some forms are incapable of fixing nitrogen in pure cultures. Certain algæ, particularly the blue-green algæ, aid greatly in promoting growth and nitrogen-fixation by these organisms. This they probably do by producing carbohydrates, which are used by the bacteria as a source of energy for nitrogen-fixation, the bacteria furnishing the algæ with nitrogenous compounds. To what extent the relation is symbiotic is not known at present, but it seems probable that a relation may exist similar to that between leguminous plants and the nitrogen-gathering bacteria in their nodules.

294. Nitrogen-fixation and denitrification antagonistic.—Nitrogen-fixation and denitrification are reverse processes. The former is, for most bacteria, favored by an abundant air-supply and a moderately high temperature. Thus, at 75° Fahr., fixation was rapid; at 59° Fahr., it was decreased, and at 44° Fahr, there was none. Denitrification is favored by a somewhat limited supply of oxygen.

There is no reason to believe that the practical importance of nitrogen-fixation without legumes is equal, under the most favorable conditions, to that with legumes. A further knowledge of the organisms effecting fixation and of their habits will doubtless make possible a greater utilization of their powers, to supplement the use of legumes, as a source of combined nitrogen in the soil.

E. THE SOIL AIR

I. FACTORS DETERMINING VOLUME

The amount of air that soils contain varies with different soils, and in any one soil it varies with certain changes to which it is subject from time to time. The factors affecting the volume of air in soils are: (1) The texture. (2) The structure. (3) The organic matter. (4) The moisture content.

295. Texture.—The size of the soil particles affect the air capacity of the soil in exactly the same way as it does the pore-space (see page 92), since the two are identical. A fine-textured soil in a dry condition would, therefore, contain as large a volume of air as a coarse-textured one, provided the particles were spherical and all of the same size.

Under the conditions actually existing in the field, those soils composed of small particles generally possess the larger air-space.

296. Structure.—The volume of air in a water-free soil being identical with the pore space, the formation of aggregates of particles is favorable to a large air volume. The volume of air in any soil, therefore, changes from time to time; and particularly is this true of a fine-grained soil, in which the changes in structure are greater than in a soil with large particles. A change in soil structure may greatly alter the volume of air contained, by altering the pore space, thereby influencing the productiveness. Clay is most affected in this way.

297. Organic matter.—Organic matter being more porous than any size or arrangement of mineral particles, the effect of that constituent is always to increase the volume of air. While this is generally beneficial in a humid region, it is often very injurious in an arid one. Unless sufficient water falls upon the soil to wash the soil particles around the organic matter and to maintain a supply sufficient to promote decomposition, the presence of vegetable matter leaves the soil so open that the capillary rise of moisture is interfered with, and the large movement of air keeps the soil dry, with the result that the portion of the soil layer mixed with and lying above the organic matter, is too dry to germinate seeds or support plant growth.

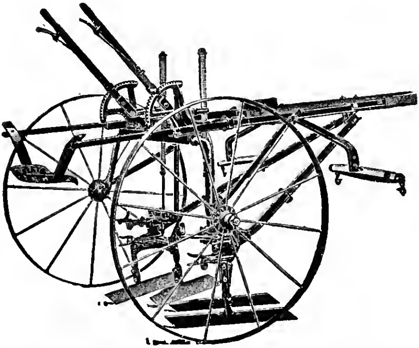

FIG. 115. Blade cultivator, with hammock seat. For surface work.

298. Moisture content.—It is quite evident that the larger the proportion of the interstitial space filled with water the smaller will be the quantity of air contained. This does not necessarily mean that the higher the percentage of water in the soil the smaller the volume of air, as the amount of pore space determines both the water and the air capacity. A soil with 30 per cent moisture may contain more air than one with a water content of 20 per cent because of the tendency of moisture to move the soil particles further apart.

In soils in the field, the average diameter of the cross-section of the pore space is the most potent factor in determining the volume of air. Small spaces are likely to hold water, while the larger ones, not retaining water against gravity, are filled with air.

In a clay soil, the volume of air is increased, other things being equal, by the formation of granules, and decreased by deflocculation or compaction.

II. COMPOSITION OF SOIL AIR

The air of the soil differs from that of the outside atmosphere in containing more water vapor, a much larger proportion of carbon dioxid, a correspondingly smaller amount of oxygen, and slightly larger quantities of other gases, including ammonia, methane, hydrogen sulphid, etc., formed by the decomposition of organic matter.

299. Analyses of soil air.—The composition of the air of several soils, as determined by Boussingault and Lewy, is quoted by Johnson in the table on the following page.

There are several factors influencing the composition of the soil air, those of greatest importance being the production and the escape of carbon dioxid, while of

Table LXV

Character of soil	Volume in one acre of soil to depth of 14 inches		Composition of 100 parts soil-air by volume		
	Air	Carbon dioxid	Carbon dioxid	Oxygen	Nitrogen
	Cu. ft.	Cu. ft.			
Sandy subsoil of forest	4,416	14	0.24	....	....
Loamy subsoil of forest	3,530	28	0.79	19.66	79.55
Surface soil of forest	5,891	57	0.87	19.61	79.52
Clay soil	10,310	71	0.66	19.99	79.35
Soil of asparagus bed not manured for one year	11,182	86	0.74	19.02	80.24
Soil of asparagus bed freshly manured	11,182	172	1.54	18.80	79.66
Sandy soil, six days after manuring	11,783	257	2.21	....	....
Sandy soil, ten days after manuring (three days of rain)	11,783	1,144	9.74	10.35	79.91
Vegetable mold compost	21,049	772	3.64	16.45	79.91

less influence is the excretion of carbon dioxid and utilization of oxygen by plant roots.

300. Production of carbon dioxid as affecting composition.—Although the formation of carbon dioxid in the soil depends upon the decomposition of organic matter, it is not always proportional to the quantity of organic matter present. The rate of decomposition varies greatly, and where this is depressed, as is sometimes seen in muck or forest soils, the content of carbon dioxid is low. A high percentage of organic matter is in itself likely to prevent a proportional formation of carbon dioxid by the accumulation of the gas inhibiting further activity of the decomposing organisms.

Ramann states that the percentage of carbon dioxid in the soil air has the following relations:

The carbon dioxid increases with the depth.

In general the percentage of carbon dioxid rises and falls with the temperature, being higher in the warm months and lower in the cold months.

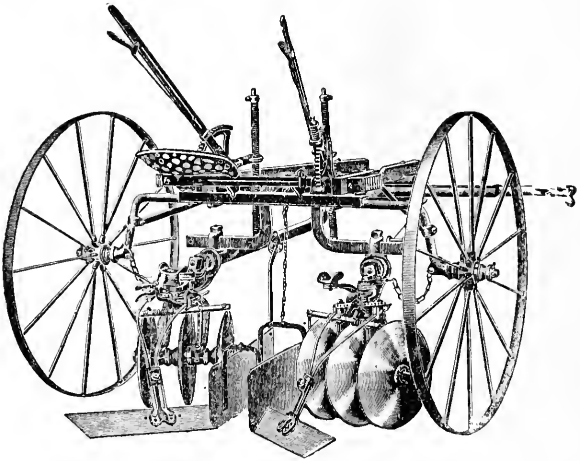

FIG. 116. Disc cultivator fitted with fenders.

Changes in temperature and air pressure change the percentage of carbon dioxid.

In the same soil the content of carbon dioxid varies greatly from year to year.

An increase of moisture in the soil increases the percentage of carbon dioxid.

The amount of carbon dioxid varies in different parts of the soil.

301. Escape of carbon dioxid as affecting composition.

—The movement of carbon dioxid from the soil depends chiefly upon diffusion into the outside atmosphere. The conditions governing diffusion, which will be discussed later (page 439), therefore largely determine the rate of loss of carbon dioxid from the soil.

302. Effect of roots upon composition.—The absorption of oxygen and excretion of carbon dioxid by roots has a real, but as yet unmeasured influence upon the composition of the soil air. It is worthy of note, however, that the carbon dioxid thus excreted is in a position where its aqueous solution can be of the greatest benefit to the plant in its solvent action upon the soil, as it is in direct contact with the absorbing portion of the roots.

III. FUNCTIONS OF THE SOIL AIR

Both carbon dioxid and oxygen as they exist in the air of the soil have important relations to the processes by which the soil is maintained in a habitable condition for the roots of plants. Deprived of these gases, the soil would soon reach a sterile condition.

303. Oxygen.—An all-important process in the soil is that of oxidation, because by it the organic matter that would soon accumulate to the exclusion of higher plant life is disposed of, and the plant-food materials are brought into a condition in which they may be absorbed by plant-roots. The presence of oxygen is essential to the life of the decomposing organisms and to the complete decay of organic matter. Through this process, roots of past crops, as well as other organic matter that has been plowed under, are removed from the soil.

The process of decay gives rise to products, chiefly carbon dioxid, that are solvents of mineral matter, and leaves the nitrogen and ash constituents more or less available for plant use.

Oxygen is also necessary for the germination of seeds and the growth of plant-roots. These phenomena, although not involving the removal of large quantities of oxygen, are yet entirely dependent upon its presence in considerable amounts.

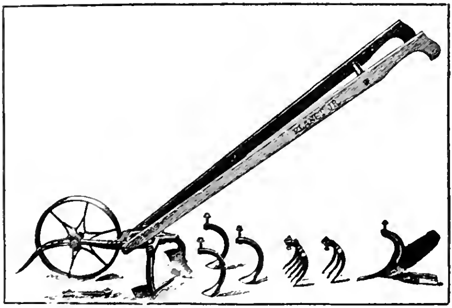

FIG. 117. Hand cultivator, or wheel hoe, with attachments.

304. Carbon dioxid.—The solvent action of carbon dioxid is its most important function in the soil. By its solvent action it prepares for absorption by plant-roots most of the mineral substances found in the soil. Although a weak acid when dissolved in water its universal presence and continuous formation during the growing season results in a large total effect.

Carbonic acid dissolves from the soil more or less of all the nutrients required by plants. The amounts so dissolved are appreciably greater than those dissolved in pure water. The constant formation of carbon dioxid by decomposition of organic matter keeps this solvent continually in contact with the soil.

Carbon dioxid serves a useful purpose in combining with certain bases to form compounds beneficial to the soil. Particularly is this the case with calcium carbonate, which is of the greatest benefit to the soil in maintaining a slight alkalinity very favorable to the development of beneficial bacteria and to the maintenance of good tilth.

When combined as sodium or potassium carbonate in considerable quantity, as in certain alkali soils, a very injurious action upon plant-roots, and upon soil-structure results. Upon plants it acts as a direct poison. (See page 312.) The effect upon soil structure is to deflocculate the particles producing the separate grain or compact arrangement. (See page 116.)

IV. MOVEMENT OF SOIL AIR

There is a constant movement of the air in the interstitial spaces of the soil, and an exchange of gases between the soil atmosphere and the outside atmosphere, as well as a more general but probably less effective, movement of the air out of, or into the soil, as the controlling conditions may determine.

The movement may be produced by any one or more of the following phenomena: (1) Gaseous diffusion. (2) Movement of water. (3) Change of atmospheric pressure. (4) Change of temperature in soil or atmosphere. (5) Suction produced by wind.

305. Diffusion of gases.—The wide difference in the composition of soil and atmospheric air gives rise to a movement of gases due to a tendency for the external and internal gases to come into equilibrium. According to Buckingham, the interchange of atmospheric and soil air is due in large measure to diffusion.

The rate of movement of the soil air due to diffusion is dependent upon the aggregate volume of the interstitial spaces, and not upon their average size. Thus it is the porosity of the soil that influences most largely the diffusion of the air from it, and consequently the size of the particles is not a factor, but good tilth permits diffusion to take place more rapidly than does a compact condition of soil, as the volume of the pore space is thereby increased. Compacting the soil in any way, as by rolling or trampling, has the opposite effect.

306. Movement of water.—As water, when present in a soil, fills certain of the interstitial spaces, it thus decreases the air space when it enters the soil and increases it when it leaves. The downward movement of rain-water produces a movement of soil air by forcing it out through the drainage channel below, while at the same time a fresh supply of air is drawn in behind the wave of saturation, as the water passes down from the surface. The movement thus occasioned extends to a depth where the soil becomes permanently saturated with water. Twenty-five per cent of the air in a soil may be driven out by a normal change in the moisture content of the soil.

307. Changes in atmospheric pressure.—Waves of high or low atmospheric pressure, frequently involving a change of .5 inches on the mercury gage, cross the continent alternately every few days. The presence of a low pressure allows the soil air to expand and issue from the soil, while a high pressure following, causes the outside air to enter in order to equalize the pressure. An appreciable, but not important movement of soil air is produced in this way.

The size of the interstitial spaces is more potent than their volume in effecting soil ventilation by this and the following methods.

308. Changes in temperature.—A movement of soil air may be induced by a change of temperature in the atmosphere or in that of the soil itself. Changes in atmospheric temperature act in the same way as do changes in atmospheric pressure; in fact, it is the effect of temperature upon air pressure that causes the movement. Like the movement due to atmospheric pressure, it is not great; but where the soil immediately at the surface of the ground attains a temperature of 120° Fahr. at mid-day, as occurs in the corn-belt, the movement must be appreciable.

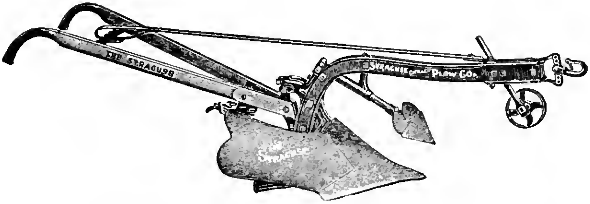

FIG. 118. The hillside plow. The hinged share and moldboard permit continuous plowing on one side of the land.

The diurnal change in soil temperature decreases rapidly from the surface downward, due to the absorption and slow conduction of heat. (See page 455.) At the Nebraska Experiment Station, the average diurnal range for the month of August, 1891, was as follows:

DIURNAL RANGE OF AIR AND SOIL TEMPERATURES

	Degrees Fahr.
Air 5 feet above ground	14.4
Soil 1 inch below surface	17.9
Soil 3 inches below surface	14.8
Soil 6 inches below surface	9.2
Soil 9 inches below surface	6.6
Soil 12 inches below surface	4.3
Soil 24 inches below surface	0.5
Soil 36 inches below surface	0.0

This soil contains about 50 per cent of pore space, in the upper foot of which 40 per cent is normally filled with water during the summer months. This leaves 518 cubic inches of air in the upper cubic foot of soil. With an increase in temperature, the air expands $\frac{1}{491}$ in volume for each degree Fahr. The average increase of temperature is, in this case, about 11° Fahr. for the first foot. The air exhaled or inhaled by each cubic foot of soil would then be

$$\frac{518 \times 11}{491} = 11.6 \text{ cubic inches.}$$

As this is slightly over 2 per cent of the air contained in the upper foot of soil, and as the movement below that depth is negligible, the change in composition at any one time is not great; but this pumping effect is kept up day after day, although less energetically in the cooler portion of the year. In proportion as poor drainage equalizes the temperature it would prevent this type of circulation. The total effect assisted by diffusion is to aid materially in ventilating the soil. Owing to diffusion of air in the interstitial spaces, the air expelled is different in composition from that inhaled.

309. Suction produced by wind.—The movement of wind, being almost always in gusts, alternately increases and decreases the atmospheric pressure at the surface of the soil. There is a tendency, therefore, for the soil air to escape and for atmospheric air to penetrate the soil with each change in pressure. The effect presumably influences only the superficial air spaces, but it must be very frequent in its action. No measurements have been made and no definite estimate of its effect can be arrived at.

V. METHODS FOR MODIFYING THE VOLUME AND MOVEMENT OF SOIL AIR

The conditions that affect the ventilation of soils are: (1) The volume and size of the interstitial spaces. (2) The moisture content. (3) The daily and annual range in temperature.

Although the size of the interstitial spaces does not appear to influence greatly the diffusion of gases from a soil, it has a marked effect upon certain of the other processes by which air enters and leaves the soil. A sandy soil, a soil in good tilth, and, particularly, a soil composed of clods, permit of more rapid movement of air than does a compact soil.

While a certain movement of air through the soil is desirable, and indeed necessary, for the reasons already stated, a very large movement is injurious unless there is an abundant rainfall. The effect of air movement through the soil is to remove soil moisture. In a region of small rainfall and low atmospheric humidity, this may be disastrous if the soil is not kept compact by careful tillage. On the other hand, in a humid region and in clay soil, there is likely to be too small a supply of oxygen for the use of crops and lower plant life unless the soil is well stirred.

310. Tillage.—The ordinary operations of tillage influence greatly the ventilation of the soil. When a soil is plowed, the soil at the bottom of the furrow is exposed directly to the air at the surface, and, by the separation of adhering particles and aggregates of particles, air is brought in contact with particles that may previously have been completely shut off from the air. It is largely because of its effect upon soil ventilation that plowing is beneficial, and the necessity for its practice is greater in a humid region and upon a heavy soil than in a region of small rainfall and on a light soil. The practice of listing corn, by which the soil is sometimes left unplowed for a number of years, although in the semi-arid region, productive of crops of sufficient yield to make them

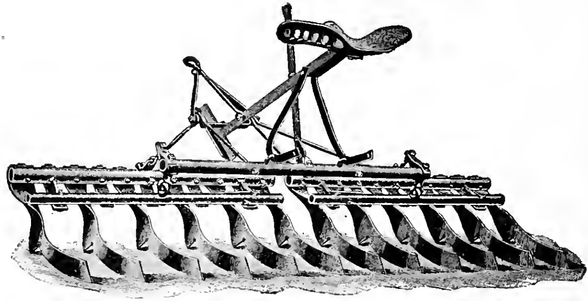

FIG. 119. The Acme harrow. An efficient pulverizer on clean soil, free from stones.

Fig. 120 A heavy sod freshly broken. Such a sod adds a large quantity of organic matter to the soil and the numerous root passages greatly facilitate aëration

profitable, would fail utterly on the heavy soils of a humid region.

Subsoiling by loosening the subsoil increases the ventilation to a greater depth. Rolling and sub-surface packing both diminish the volume and movement of air. Their essential difference is in their effect upon moisture rather than upon air. (See page 111.) Harrowing and cultivation have the opposite effect, and both increase the production of nitrates in the soil by promoting aëration. The tillage which is most beneficial is that which increases the porosity of the soil, and not the size of the interstitial spaces.

311. Manures.—Farm manures, lime and those amendments that improve the structure of the soil, have to the same degree a beneficial action upon soil aëration. By their effect upon the physical condition of the soil, they increase its permeability, and by their action in contributing to the production of carbon dioxid they stimulate diffusion.

It is chiefly through its effect in increasing the volume of air space in soils that farm manure is injurious in light soils of the semi-arid region. It may thus be injurious as well as beneficial, if used under certain conditions.

312. Underdrainage.—By lowering the water table, underdrainage by means of tiles removes from the soil the water from all but the small capillary spaces, and leaves free to the air the remainder of the interstitial spaces. There is also a very considerable movement of air through the drains, and a movement of air upward from the drains to the surface of the soil, which, serves to aërate, to some extent, this intervening layer. The aëration of the soil brought about by underdrainage is one of its beneficial features.

313. Irrigation.—The influence of irrigation upon the soil is much like that of rainfall. The alternate filing and emptying of the interstitial spaces with water and air causes a very considerable change of air.

314. Cropping.—The roots of plants left in the soil after a crop has heen harvested decay and leave channels in the soil through which the air penetrates. Below the furrow slice, where the soil is not stirred and where it is usually more dense than at the surface, this affords an important means of aëration. The growth of leguminous plants and other deep-rooted crops is in this way, among others, beneficial to the soil. The absorption of moisture from the soil by roots also causes the air to penetrate, in order to replace the water withdrawn.

F. HEAT OF THE SOIL

I. FUNCTION OF THE HEAT OF THE SOIL IN ITS RELATION TO PLANT GROWTH

The heat of the soil has three general functions with reference to plant growth. These are: (1) Biological. (2) Chemical. (3) Physical.

315. Biological.—Heat is the motive power in plant growth. A certain degree of heat is necessary for the normal action of all of the functions of the plant. When the soil, as well as the atmospheric temperature, passes beyond a certain maximum or minimum degree, growth is inhibited. These points differ for different species and groups of plants, and they may be different for different individuals of the same species. Somewhere between the maximum and the minimum temperature which any plant can withstand and still live, is the optimum or best temperature for growth. These relations may be divided into the following three groups. The best soil temperature for: (1) Germination. (2) Growth and vegetation. (3) Proper activity of the soil organisms.

316. Germination.—This takes place at widely different temperatures for different plants. Ordinarily, the optimum temperature for germination is several degrees below the optimum temperature for growth during the average period of vegetation.

The range for a few common plants is shown in the following table:

Table LXVI

	Temperatures for germination in degrees Fahrenheit		
	Minimum	Optimum	Maximum
Melons	55–65	88–100	110–120
Tobacco	50–60	75– 90	90–110
Maize	45–50	75– 85	90–100
Red clover and alfalfa	40–45	75– 95	100–110
Barley and vetch	38–45	60– 75	100–105
Turnips	36–45	85– 90	100–110
Oats	32–45	70– 85	90–100
Flax	32–40	75– 80	85– 95
Rye	32–40	60– 75	90–100
Mustard	32–38	60– 85	90–100

These figures show that germination may take place as low as 32° Fahr. for some seeds, but that the best temperature is from 60° to 90° Fahr., with the average near 85°. Few seeds germinate at temperatures much above 100° Fahr. At temperatures below the optimum, the time required is correspondingly increased,—as shown, for example, by Nobbe, who found that musk-melon seeds required 290 hours to germinate at 60.5° Fahr., but at 88° Fahr. they germinated in forty-eight hours. The long period may give opportunity for certain fungous diseases to destroy the seed.

317. Growth and vegetation.—Growth seldom takes place below a temperature of from 40° to 50° Fahr., and a much higher temperature is necessary for vigorous growth. Hall presents the following table, showing the relation of temperatures to the growth of some common crops.

TABLE LXVII

	Temperature for growth in degrees Fahrenheit		
	Minimum	Optimum	Maximum
Mustard	32	81.0	99.0
Barley	41	83.6	99.8
Wheat	41	83.6	108.5
Maize	49	92.6	115.0
Kidney bean	49	92.6	115.0
Melon	65	91.4	111.0

The figures in the above two tables indicate that the temperature of the soil has a large influence on germination and growth of different plants. Those individuals which require a high temperature should not be planted until the soil attains the desired degree of heat. If planted before this point is reached, the seed will be slow to germinate and may be destroyed by disease. If it succeeds in germinating, the growth will be slow and unsatisfactory; and, even if the proper soil temperature is attained, the vigor of the plant will have been so reduced that the maximum yield can not be produced. The soil temperature also makes it impossible to grow certain crops where others thrive. This is a large factor in the distribution of crops and wild species of plants.

318. Activity of the soil organisms.—The activity of all soil organisms is reduced by low temperatures. Consequently those biological changes which increase soil fertility are less pronounced during periods of low than during periods of high temperature. One of the most important of these relations is the formation of nitrates, which takes place most actively at a temperature of 80° to 100° Fahr., and ceases at about 40° Fahr.

319. Chemical changes.—In the soil chemical changes are greatly accelerated by a high temperature, and are correspondingly retarded by low temperature. But, unlike biological activity, they never wholly cease as a result of temperature changes, though the type of change in the different compounds may be altered. Warm temperatures increase particularly the solubility of the soil constituents, by which they are made available to plants.

320. Physical changes.—As a result of temperature, physical changes are less marked than the chemical and biological, except when the freezing point is reached, when the soil moisture is solidified and renders nutrition of higher plants impossible. The movement of moisture and gases through the soil is greatly facilitated by the higher temperatures within the range of plant growth.

II. SOURCES OF THE HEAT OF THE SOIL

There are three direct sources of heat which reach the soil. These are: (1) Solar radiation. (2) Conduction from the interior of the earth. (3) Organic decomposition.

Under field conditions, the first of these sources is far the most important.

321. Solar radiation.—Solar radiation of heat reaches the soil in three ways.

(1) By direct radiation from the sun in the form of sunshine.

(2) Indirectly through the radiation which is imparted to the atmosphere, from which it is radiated to the soil or is given up by direct contact of the atmosphere with the soil. Clouds in the atmosphere reflect back to the soil some heat which has been received by the soil and is again given off. They may serve as a cover or blanket.

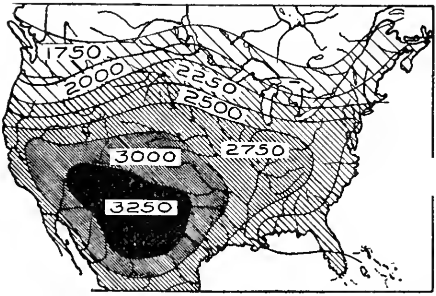

Fig. 121. Mean annual sunshine of Canada and the United States. The figures indicate the number of hours of bright sunshine in a year. (From Bartholomew's Atlas of Meteorology.)

(3) In the spring, rain-water carries a large amount of heat into the soil. The percolation of warm spring rain is a means of rapidly warming up the soil, and its strong influence is shown by the large quickening of growth which follows such rainfall.

322. Conduction.—Conduction of heat from the interior of the earth is negligible as an appreciable source of soil heat.

323. Organic decay.—Organic decay liberates heat, and may be so rapid as to greatly change the temperature of the soil. This is exemplified by the heating of manure heaps and in the use of the hotbed. The same amount of heat is set free by decomposition as would result from ignition of the material, but its liberation is distributed over a much longer period of time according to the conditions for decay.

III. TEMPERATURE OF THE SOIL

The temperature which the soil in any given position will attain depends upon a number of factors. The more important of these are as follows: (1) Heat supply. (2) Specific gravity of the soil. (3) Specific heat of the soil. (4) Color of the soil. (5) Attitude of the surface. (6) Conductivity of the soil. (7) Circulation of air above the soil. (8) Water-content of the soil.

324. Heat supply.—The heat supply is obviously the most direct factor contributing to the soil temperature. This is reflected in the seasonal, daily and hourly variations in the temperature. The hourly variations in temperature at a depth of one foot below the surface are shown by the following table and curves:

Table LXVIII

	June 1—Readings in two-hour periods											
	6	8	10	N	2	4	6	8	10	M	2	4
1. Clay loam, Penn.	60.5	61.0	61.0	61.3	62.0	62.5	63.0	63.5	63.6	63.6	63.3	63.0
2. Loam, Penn. . . .	..	..	61.0	60.3	60.3	60.6	61.2	61.7	62.0	62.1	62.1	62.1
3. Silt loam, N. C. . .	72.0	70.0	70.0	69.8	70.0	69.8	69.7	69.5	69.3	69.0	68.5	68.0
4. Sandy loam, N.C.	72.5	71.0	69.5	69.8	69.5	69.2	69.0	69.0	68.8	68.0	67.5	67.2

	June 2—Readings in two-hour periods											
	6	8	10	N	2	4	6	8	10	M	2	4
1. Clay loam, Penn.	62.8	62.5	62.5	62.7	63.0	64.0	64.5	65.0	65.0	65.0	64.8	64.5
2. Loam, Penn.	62.0	61.8	61.5	61.4	61.3	61.8	62.2	62.8	63.3	63.3	63.3	63.2
3. Silt loam, N.C. . .	68.0	67.3	67.2	67.2	67.8	68.3	68.7	68.8	68.8	68.5	68.0	67.8
4. Sandy loam, N.C.	67.0	66.5	66.0	66.5	67.5	68.2	68.8	69.0	68.7	68.3	68.0	67.5

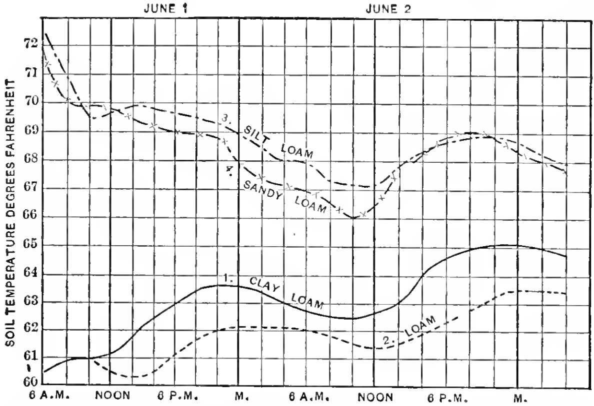

FIG. 122. Curves showing the daily range of soil temperature near the surface on soils of different texture in Pennsylvania and North Carolina. Table LXVIII.

The following table and curves show the average mean monthly range in temperature of the air and soil at different depths at Lincoln, Nebraska for a period of twelve years.

TABLE LXIX. TEMPERATURE IN DEGREES FAHRENHEIT

Position	January	February	March	April	May	June	July	August	September	October	November	December
1. Air	25.2	24.2	35.8	52.1	61.9	71.0	76.0	74.5	67.6	55.5	38.7	28.3
2. Soil, 1 in.......	27.3	27.7	38.2	57.5	68.7	78.1	85.1	82.9	73.8	56.7	38.7	31.6
3. Soil, 6 in.......	28.6	27.8	36.6	53.3	65.1	75.7	81.6	80.1	72.0	57.8	41.5	32.0
4. Soil, 12 in.	31.2	30.2	35.4	49.3	60.7	69.9	75.7	75.7	69.2	57.8	44.7	35.2
5. Soil, 36 in......	38.5	35.5	35.8	43.8	53.5	61.3	67.4	69.8	67.6	61.3	52.2	43.3

There is a large daily as well as annual range in the temperature of the soil. At the surface, the range is considerably greater than in the air above, and this excess extends to a depth of nearly one foot. At greater depths in the soil, the range in temperature is less than in the air and much less than at the surface, and the waves of temperature change fall successively behind those of the atmosphere. These variations are associated directly with the amount and intensity of the sunshine.

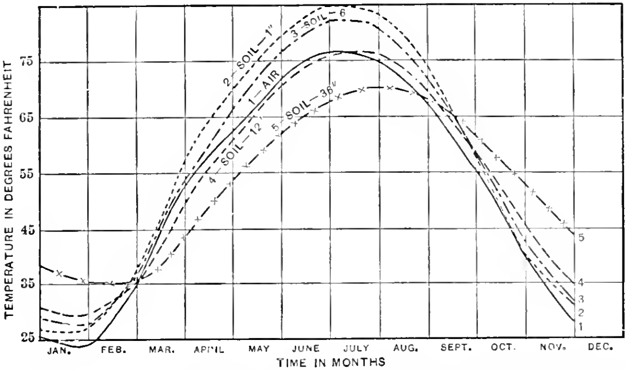

FIG. 123. Curves showing the mean monthly range in temperature of the air, and of the soil at different depths, as given in Table LXIX. Note the influence of the rate of heat conduction, as shown by the curves.

325. The specific gravity and specific heat.—The first of these directly affects the temperature to only a small degree. The larger the mass, the more heat required to change its temperature. Hence, the more dense the soil, the more heat absorbed in each layer.

The specific heat of the soil has a considerable influence on its temperature and, because of its marked difference from that of water, has an important practical bearing. Drainage owes one of its largest beneficial effects to this fact.

Warington quotes from Lang the following table of specific heat of soil constituents.

Table LXX

	Relative specific heat of	
	Equal weights	Equal volumes
Water	1.000	1.000
Ferric oxide	0.163	0.831
Calcium carbonate	0.206	0.561
Magnesium carbonate	0.260	0.754
Quartz, orthoclase, granite	0.189	0.499
Humus (peat)	0.477	0.587
Clay	0.233	0.568

In the above table, the specific heat of equal volumes is more nearly representative of field conditions than is that of equal weights. On this basis, dry soil has about one-half the specific heat of water; that is, a given amount of heat would raise a mass of soil to nearly twice the temperature that it would the same volume of water.

326. Color of the soil.—A dark-colored soil absorbs heat much more rapidly than does a light-colored one, and therefore warms up more rapidly. The effect of a thin layer of carbon-black and chalk on the temperature of dry, fine sand, one inch below the surface, when exposed to the sun in thick wooden boxes, is shown in the following table:

TABLE LXXI

Fine Sand Soil	Time in minutes from start							
	0	10	20	30	40	50	60	70
	Deg. F.	Deg. F.	Deg. F.	Deg. F.	Deg. F.	Deg. F.	Deg. F.	Deg. F.
1. Carbon black .	61	65.2	71.6	75.3	78.6	81.5	84.3	87.0
2. Chalk (white)..	61	63.5	65.8	68.6	69.5	70.8	72.2	73.5
Difference.......	0	1.7	5.8	6.7	9.1	10.7	12.1	13.5

These figures agree with those of Schubler, who found that, at one-eighth of an inch below the surface, blackened soil attained a temperature from 12° to 15° Fahr. warmer than the same soil whose surface was made white by magnesia.

Humus, because of the black or dark color it imparts to the soil, has a large effect on the soil tempera-

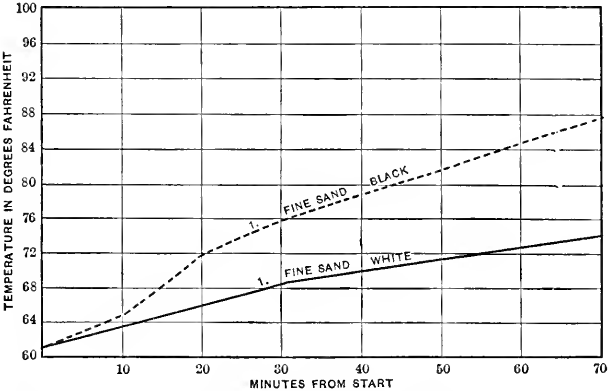

FIG. 124. Curves showing the temperature of a dry sandy loam soil, covered by a very thin layer of powdered chalk and carbon black respectively, after exposure in bright sunshine.

ture. Its effect due to color is reduced by the higher water-content which such a soil normally retains. (See page 101.) Red soils absorb more heat than yellow or gray ones, and yellow soils absorb more heat than gray ones.

327. Slope of the soil.—A smooth surface absorbs more heat than a rough or rigid surface. The effect of the direction and angle of slope on the amount of heat received from the sun is shown by the following diagram.

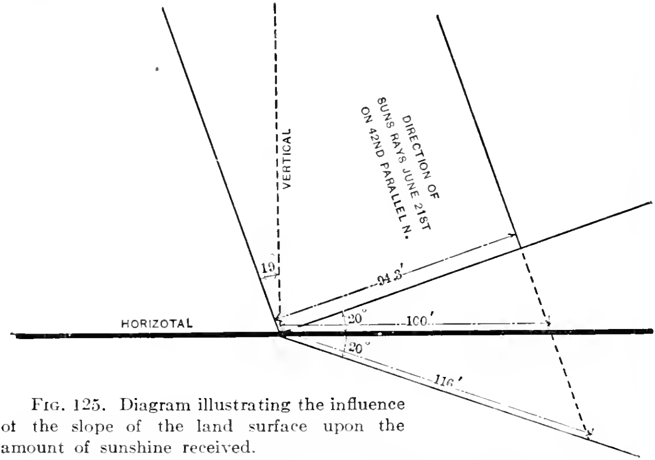

Fig. 125. Diagram illustrating the influence ot the slope of the land surface upon the amount of sunshine received.

On the 21st of June, on the 42d parallel, the sunbeam which falls on a given level area would be distributed over almost 6 per cent *less* area when the slope is toward the sun at an angle of 20°, while on a slope of 20° away from the sun the same amount of sunshine would fall upon 16 per cent *greater* area. The area which sloped away from the sun would also receive the sun's rays for a shorter period of each day. Wollny found in Germany that the temperature of a sandy soil at six inches depth on a south slope of 30° averaged 3.1° Fahr. warmer than the corresponding slope to the north. King found the following differences in temperature between the level and an 18° south slope, in Wisconsin, in July.

TABLE LXXII

	First foot	Second foot	Third foot
	Degrees Fahr.	Degrees Fahr.	Degrees Fahr.
South slope, 18 degrees	70.3	68.1	66.4
Level	67.2	65.4	63.6
Difference	3.1	2.7	2.8

The north slope ordinarily has the most uniform temperature.

328. Conductivity.—The conductivity of the soil for heat depends upon four factors. These are: (1) Composition. (2) Texture. (3) Structure. (4) Moisture content. The relative influence of these factors, as reported by Warington from the results of Pott, are shown in Table LXXIII on page 460.

Quartz has the largest power to conduct heat of any of the soil constituents studied. The effect of limestone and quartz stone is probably a textural one, as is shown by the fact that the coarser the texture the greater the conductivity. A compact soil conducts heat more readily than a loose one. But, while a compact soil will receive heat most rapidly, it also gives

TABLE LXXIII

	Composition	Texture	Structure Loose quartz powder =100		Moisture content
	Quartz powder =100	Fine quartz sand =100	Loose	Compact	Dry quartz powder =100
Quartz, sand fine	....	100.0	....	....	....
Quartz sand, medium	....	103.6	....	....	....
Quartz sand, coarse	....	105.3	....	....	....
Quartz powder	100.0	....	100.0	106.7	201.7
Chalk	85.2	....	85.2	92.6	153.2
Peat	90.7	....	90.7	98.1	94.3
Kaolin	90.7	....	90.7	96.4	155.6
Clay	94.1	....	....	....	....
Clay with limestones	112.1	....	....	....	....
Clay with quartz stones	115.6	....	....	....	....

it up most readily. The effect of the mulch is therefore to maintain a more uniform soil temperature. The presence of stone in the soil increases its temperature. The movement of heat through the soil is also increased decidedly by the presence of moisture. Pott found that when a dry sand conducted 100 units of heat, the same sand in a moist state conducted 174 units, and when wet, 189 units, or nearly twice that for the dry sand. The operation of rolling by compacting the soil increases its conductivity for heat, and consequently its average temperature. King found, as an average of several trials on different soils, that at a depth of 1.5 inches, rolled soil was 3.1° Fahr. warmer than the unrolled soil, and at a depth of three inches the difference in favor of rolling was 2.9° Fahr. In extreme cases, he has found differences nearly three times as great as the above figures between the temperature of rolled and unrolled land. Rolling generally favors deep warming. The movement of heat in the soil is illustrated by the curves of soil temperature on page 455. The change in temperature in the subsoil lags considerably behind that at the surface, and is also more uniform.

329. Circulation of air.—This is due, first, to direct conduction between the air and the soil; and, second, to the influence of wind on evaporation. Tillage of the soil, particularly in the spring, increases the rate of warming, because at that season the air is usually warmer than the soil, and, by bringing all parts of the soil to the surface successively, it is warmed by contact with the air and by the direct receipt of the sun's heat. Wind hastens the change in temperature of the soil in either direction by increasing the volume of air with which the soil comes in contact.

330. Water-content.—The water-content of the soil is the largest factor, after the heat supply, in determining the temperature of the soil. This is due to two things: (1) The high specific heat of water as compared to soil. (2) The heat absorbed in the evaporation of water.

The specific heat of water, as compared with an equal volume of soil, is shown by the table on page 456 to be nearly twice as great. Consequently, the more water a soil contains, the more slowly will its temperature change with a given heat supply. The tempering influence of large bodies of water upon adjacent land areas is an example of this fact.

In the evaporation of water, a large amount of heat is absorbed. The vaporization of one pound of water at the boiling point requires 5.3 times as much heat as is necessary to raise its temperature from the freezing point to the boiling point. It is this large absorption of heat which renders evaporation such a large cooling operation. The more evaporation which takes place from the soil moisture, the more will the temperature be kept down. Any treatment which reduces evaporation, such as the mulch, will favor a higher soil temperature.

This influence of the moisture content has given rise to popular descriptive terms, such as "warm," and "cold" soils; "early" and "late" soils. A "warm soil" is one which retains naturally a relatively small amount of water, that is, soils of coarse texture. "Cold soils," on the other hand, are those which retain a relatively large amount of water, that is, those of fine texture. The difference in the amount of heat required to warm the water contained in the soil, as well as that lost in evaporation, which is of course greatest in the soil containing most water, is the source of their normal differences in temperature.

An "early soil" is one which retains a relatively small amount of water. It therefore warms up most rapidly under a given heat supply, and is in condition to permit seeding earlier in the season. A late soil retains much water, and, consequently, is slow in warming up. Its planting must therefore be deferred until later in the season. Coarse-textured soils are "early," and fine-textured ones are "late." Wollny concluded, from extensive experiments, that in summer sandy soils are warmest, followed by humus, lime and loam soils. In winter this order is reversed.

The large effect of drainage on the soil temperature is due to these heat relations of the soil moisture. If the excess of water is removed by evaporation, it keeps the soil unduly cold. King observed differences in temperature of from 2.5° to 12.5° Fahr. between drained and undrained soil on different days in April. These results are abundantly borne out by practical experience. The removal of the excess water by drainage conserves heat.

IV. MEANS OF MODIFYING THE SOIL TEMPERATURE

The means of modifying the soil temperature are obvious from the above principles. The practices which may be used for this purpose are:

(1) Modification of the texture and structure of the soil by appropriate tillage.

(2) Modification of the color of the soil, chiefly through the addition of organic matter.

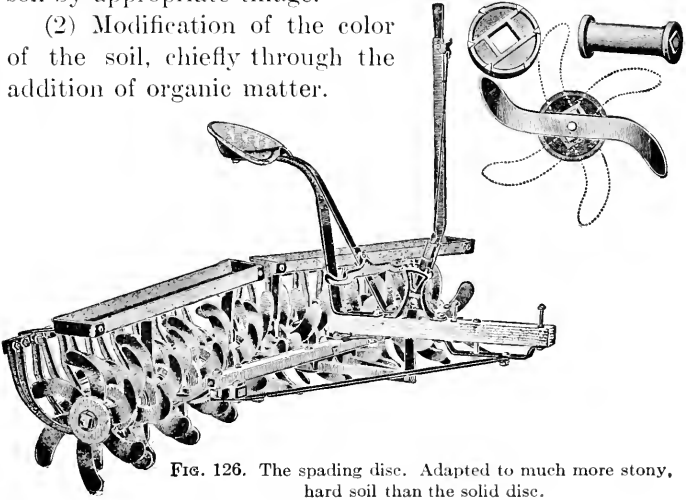

Fig. 126. The spading disc. Adapted to much more stony, hard soil than the solid disc.

(3) Modification in the moisture content by the use of mulches, irrigation, and especially by drainage, where there is an excess of water.

(4) The attitude of the surface may be somewhat changed by tillage, especially in the matter of rough or smooth surface. Of course, the general slope cannot be altered.

(5) Promotion of organic decay through the addition of organic matter to the soil, in such a state and under such conditions as will promote favorable decay by which its heat may be liberated. The high temperature attained in hotbeds in the winter and early spring exemplifies this practice. The application of manure under field conditions may appreciably alter the soil temperature, due perhaps to several effects. Wagner observed an increase of 5° Fahr. as a result of the application of twenty tons of manure per acre, and during a period of several weeks there was an average excess of 1° of temperature on the manured land. Georgeson observed, through a period of twenty days following the application of different amounts of manure in the fall, temperature differences amounting to .9° for ten tons, 1.7° for twenty tons, 2.3° for forty tons, and 3.4° for an application of eighty tons per acre.

(6) Construction of shelters may modify the soil temperature. Coldframes and greenhouses make use of this principle by preventing the circulation of air and by entrapping the sun's rays. Partial shade influences the soil temperature, usually producing a lower average and a greater uniformity.

G. EXTERNAL FACTORS IN SOIL MANAGEMENT

In the foregoing chapters, some of the principles underlying the management of the soil have been pointed out. In addition to these are several practices associated with soil management resting upon the principles that have been explained, which are so fundamentally important as to warrant their separate discussion in this connection.

I. MEANS OF MODIFYING THE SOIL

In the art of soil management, one has a number of practices which may be used to modify the soil.

331. Summary of practices.—The most prominent of these practices are: (1) The manipulation of the soil by means of implements. (2) Drainage. (3) Irrigation. (4) Application of amendments, including all forms of organic materials. (5) Application of chemical manures. (6) Inoculation. (7) Rotation. (8) Crop-adaptation.

Each of these practices has a primary function. That of drainage is to remove excess water from the soil; of chemical manures to add food elements; of inoculation, to introduce organisms; of tillage, to modify the structure of the soil. But, in the exercise of their primary function, each practice also has many secondary or indirect effects on the soil, which may sometimes be more important to the productive qualities of the soil than its direct effect. This complex effect is well illustrated by drainage, which not only removes excess water and admits air, but it thereby affects the soil temperature, growth of organisms and the elaboration of plant-food. Similarly, tillage, first of all, is designed to alter the structure of the soil, and through this alteration in structure, the retention of moisture, aëration and root-penetration, not to mention many other relations, are changed. In fact, every practice which may be applied to the soil influences in some degree every phase of the soil mechanism. The relative prominence of these different effects depends on the character and condition of the soil.

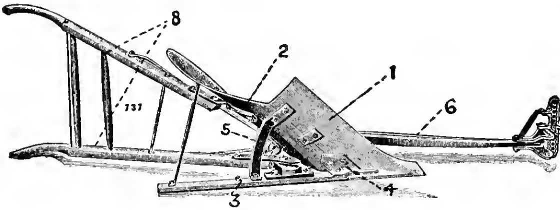

FIG. 127. Bottom view of a modern plow, showing the parts. 1, share; 2, moldboard; 3, landside; 4, frog; 5, brace; 6, beam; 7, clevis; 8, handle.

The application of these various practices has been indicated in the foregoing pages, in connection with the principles discussed.

II. TILLAGE

Tillage, or the manipulation of the soil by means of implements, is so general in its application and so pronounced in its effects, as well as complex in its modes of operation, that it is given a separate treatment.

332. Objects of tillage.—Tillage rests upon three primary objects. These are: (1) Modification of the texture and structure of the soil. (2) Disposal of rubbish or other coarse material on the surface, and the incorporation of manures and fertilizers in the soil. (3) To deposit seeds and plants in the soil in position for growth.

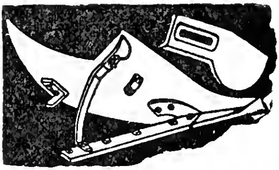

FIG. 128. Heel plate for regulating the width at the heel.

The most prominent of these objects is the modification of the soil structure. No perceptible change in the soil texture can be effected but through changes in structure, by which it is made either more open 'or more compact. Thereby the retention and movement of moisture is affected, aëration is altered, the absorption and retention of heat is influenced, the growth of organisms is either promoted or retarded; through all of these the composition of the soil solution is affected and, lastly, the penetration of plant roots is influenced. The creation of a soil mulch is simply a change in the structure of the soil at such time and in such manner as will prevent evaporation of moisture. For this reason, it is essential to appreciate the relation of soil structure to movement of moisture in managing the mulch. In fine-textured soils, where the granular or crumbly structure is most desired, tillage may have an important influence on the promotion or destruction of these granules. As has been pointed out (page 105), any treatment which increases the number of lines of weakness in the soil structure facilitates the action of the moisture films in solidifying the soil granules. Tillage shatters the soil and breaks it into many small aggregates of particles, which may be further drawn together and loosely cemented by the further evaporation of moisture. The more numerous the lines of weakness produced, the more pronounced the granulation; and, conversely, the fewer the lines of weakness which result, the more coarse and cloddy the structure.

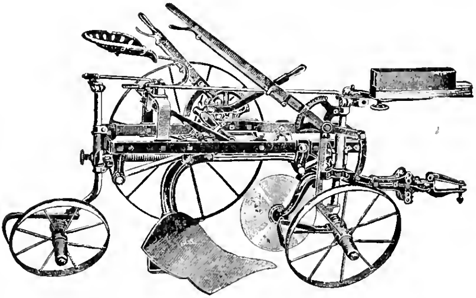

FIG. 129. The modern sulky riding plow.

333. Implements of tillage.—The number of implements adapted to the manipulation of the soil is very large, and they embrace many types and patterns. Many operations are comprehended by the term tillage. It includes the use of all those implements which are used to move the soil in any way in the art of crop-production. It includes the smallest hand implements, as well as the largest traction implements.

334. Effect on the soil.—All these operations may be divided into two groups, according to their effect on the soil: (1) Those which loosen the soil structure. (2) Those which compact the soil structure. In the subsequent paragraphs of this chapter the effect of the more common types of tillage implements on the soil are pointed out as a guide to their selection for the accomplishment of a particular desired modification. For, good soil management consists, first, in analyzing the soil conditions, to determine the change which should be effected; second, in the selection of the implement or other treatment which will most readily and economically accomplish the object.

335. Mode of action.—According to their mode of action, tillage implements may be divided into three groups: (*a*) Plows. (*b*) Cultivators. (*c*) Crushers and packers.

336. Plows.—The primary function of a plow is to take up a ribbon of soil, twist it upon itself, and lay it down again bottom side up, or partially so. In the process two things result. (1) If the soil is in proper condition for plowing, it will be shattered and broken up. (2) The soil is inverted, and any rubbish is put beneath the surface.

337. Pulverizations.—In twisting, the soil tends to shear into thin layers, as pointed out by King. These layers are moved unequally upon each other, as, when the leaves of a book are bent, they slip past each other. The result should be a very complete breaking up of the soil. How thorough the breaking-up will be will depend upon (*a*) the condition of the soil, and (*b*) the type of plow. As to the condition of the soil, there is a certain optimum moisture content at which the best results will be obtained. Any departure from this moisture content will result in less efficient work. It has been said that, in proportion to the amount of energy required, the plow is the most efficient pulverizing implement available to the farmer. The optimum moisture content for plowing is indicated by that nicely moist condition in which a mass of the soil when pressed in the hand will adhere without puddling, but may be readily broken up without injury to the intimate soil structure. This is a much more critical stage for fine-textured soils than for coarse-textured ones. Sandy soils are not greatly altered by plowing when out of optimum moisture condition. On the other hand, if a clay soil is plowed when it is saturated with water, it

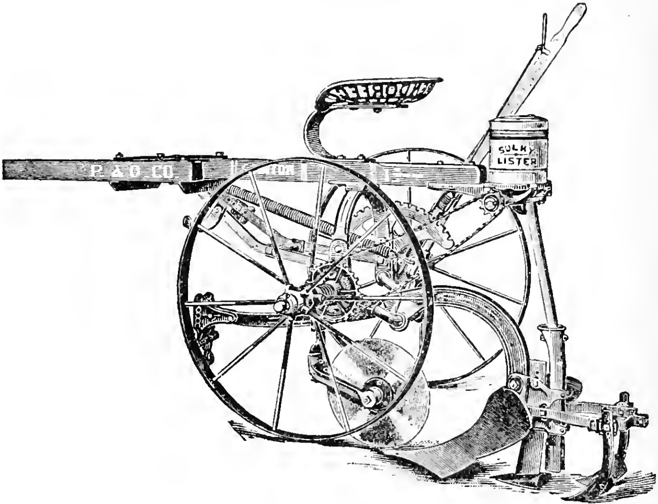

Fig. 130. Sulky Lister

will be thoroughly puddled, and will dry out into a hard lumpy condition. Such a structure requires a considerable time to overcome.

As to the second factor, there are two general types of turning plows: (1) The common moldboard plow. (2) The disc plow. The mode of action of the two is quite different, although, so far as the soil is concerned, the result is much the same. The moldboard plow seems to have a wider application than the disc plow, although both have a particular sphere of usefulness.

For any given texture of soil and any given soil condition, there is a type of plow, a shape of mold-

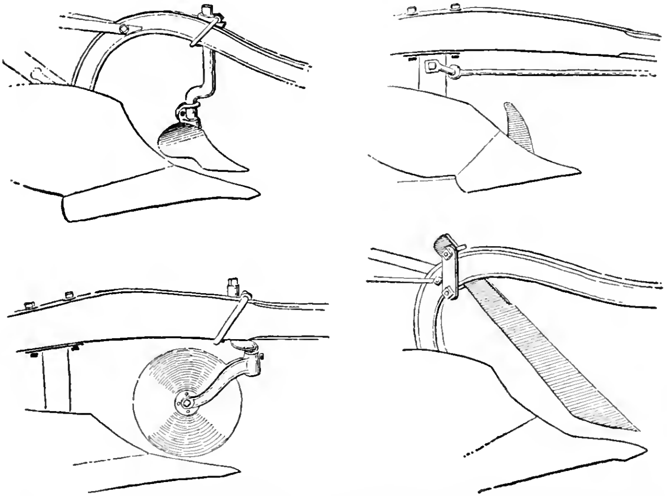

Fig. 131. Types of coulters. Lower right hand, knife coulter; lower left hand, rolling coulter; upper right hand, fin coulter; upper left hand, jointer. The last-named attachment assists in turning trash under the surface as well as to cut the soil.

board, and a depth of furrow slice, which are calculated to give the best results. This fact is to be kept constantly in mind in plowing soil. Sod land requires a different shape of plow from fallow land, sandy land from clay land. Rubbish on the surface may be handled by one plow and not by another. Wet clay should have the use of a different shape of plow from dry soil.

There are several different shapes of plow. Among these the most prominent types are the moldboard, the disc, the hillside and the subsoil.

Of the moldboard type there are two general shapes: (1) The long, sloping moldboards, with little or no overhang, found on what is called the sod plow. This neatly cuts off the roots at the bottom of the slice, and slowly and gradually twists the soil over without breaking the sod, and lays it smoothly up to the previous furrow-slice. It is seldom desirable to completely invert the soil. According to depth of plowing, the furrow-slice should be laid at an angle with the horizontal of from 25° to 50°, so that the projecting edge of the slice may be worked down for a seed-bed, while the roots and rubbish on the surface is somewhat uniformly distributed through a considerable depth of soil, instead of occupying a single layer in the bottom of the furrow. (2) The short, steep moldboard with a marked overhang. This is not adapted to sod land, because it breaks up the sod and shoots it over in a rough, jagged manner with uneven turning. But on fallow land, to which it is adapted, it very completely breaks up the soil and throws it over in a nearly level mellow mass. The pulverizing effect is obviously much greater than with the sod plow. Since the steep moldboard or fallow-ground plow exerts the most force on the soil in a given time at a given speed of movement, it follows that if a particular soil is over-wet it should be plowed with the sod-plow, while, if it must be plowed when too dry, the fallow-ground plow will be more effective,—disregarding the draft which will probably be large in the latter case.

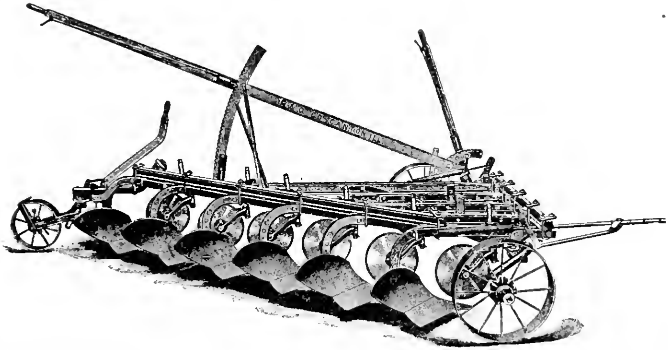

FIG. 132. Six-gang plow. Usually operated by steam engine. Adapted to large, level areas of uniform soil, relatively free from stone.

There is a general relation between the width of the furrow-slice and its depth. In general, it may be said that this ratio is about two in width to one in depth. The greater the depth, the less in proportion may he the width of the furrow-slice.

On clay soil in particular, there is also a relation between depth and condition. A wet soil should be plowed more shallow, other things equal, than a dry soil, because the puddling action is less. On a dry soil, the depth should be increased, to increase the pulverization.

Combining these principles, then, it may be said that if a clay soil must be plowed when too wet, it should be plowed with a sod plow, and to as shallow a depth as is permissible. But, on an over-dry soil, the opposite conditions should be fulfilled,—that is, steep moldboard and increased depth. Likewise, on sandy soil, where the aim is generally to compact the structure, this may be furthered by deep plowing with steep moldboard when the land is over-wet.

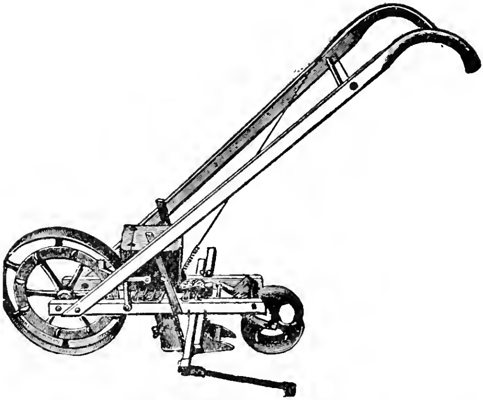

FIG. 133. The modern garden seeder. It modifies the soil structure

In connection with this phase of the subject, it is important to consider what Professor Roberts called the plow sole. That is, the soil at the bottom of the furrow which bears the weight of the plow and trampling of the team, and which, under uniform depth of plowing, does not become loosened. In clay soil, especially, it gradually becomes more compact, in time developing something of a "hard-pan" character, which is detrimental to the circulation of air and moisture and interferes with the penetration of plant roots. Consequently, occasional deep plowing or even subsoiling is recommended to break up this unfavorable soil structure, commonly called the "plow sole." There is less tendency for the disc than the moldboard plow to form the "sole."

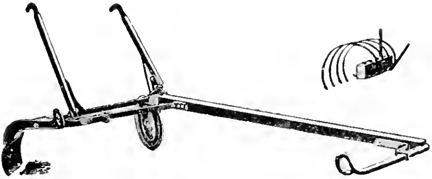
Fig. 134. Berry hoe or ridger. For close tillage of berries, vines and low-headed trees.

The hillside plow is a modified form of the moldboard plow, which has a double curvature to the moldboard, so that it is essentially two plows in one. This swings on a swivel in such a way that it may be locked on either the right or the left side. It removes the necessity of plowing in beds, and, by permitting all of the work to be done from one side, enables the plowman to lay the furrow slices in one direction. On the hillside this direction is down the slope, because of the greater ease in turning the soil in that direction. It also removes the difficulty of pulling up and down the hill. There is another type of compound moldboard plow designed to eliminate "dead furrows" and "back furrows." The former is developed by turning the last furrow slices of two lands in opposite directions, thereby leaving a gulley between which, by reason of its frequent unproductive character, is termed the "dead furrow." The back furrow consists of two furrow slices thrown together, usually forming a ridge more productive than the average of the land.

The disc plow is essentially a large revolving disc set at such an angle that it cuts off and inverts the soil, at the same time pulverizing it quite effectively after much the same manner as the moldboard plow. One advantage claimed for it is its lighter draft for the same amount of work done, because it has rolling friction in the soil instead of sliding friction. In practice, it appears to be especially effective on very dry, hard soil and in turning and covering rubbish.

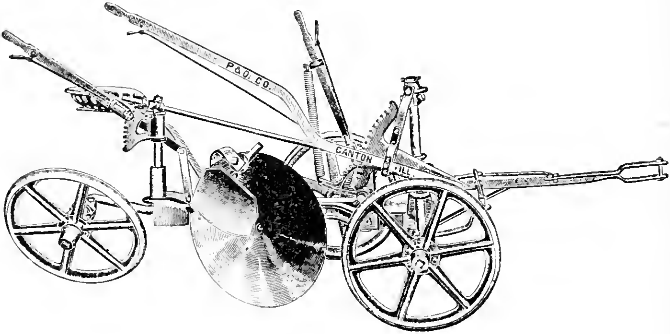

FIG. 135. Disc plow.

338. Covering rubbish.—The secondary function of the plow is to cover weeds, manure and rubbish which may be upon the surface. This also the turning plow does very effectively. The cutting and turning of the sod, rubbish and weeds is facilitated by several attachments. These are: (1) Coulters. (2) Jointers. (3) Drag-chains. There are several types of coulters. Blade coulters are attached to the beam or to the share in such a manner as to cut the furrow slice free from the land side. They should be adjusted so as to cut the soil after it has been raised and put in a stretched condition, when the roots are most easily severed. This position is a little back of the point of the share. A knife edge attached to the share is commonly called a fin coulter. A jointer is a miniature moldboard attached to the beam for cutting and turning under the upper edge of the furrow slice, so that a neat, clean turn is effected without the exposure of a ragged edge of grass which may continue growth. This is used chiefly on sod land. A drag-chain is an ordinary heavy log-chain, one end of which is attached usually to the central part of the beam, and the other to the end of the double tree on the furrow side, and with enough slack so that it drags down the vegetation on the furrow slice just ahead of its turning point. It is used, primarily, in turning under heavy growths of weeds or green-manure crops.

There is a third type of plow, the so-called subsoil

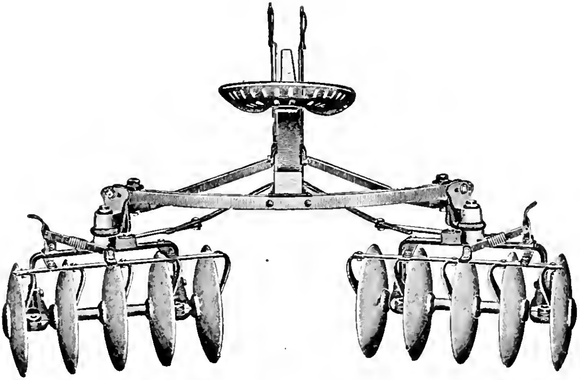

FIG. 136. The orchard disc. Adjustable and suited to working close up to low-headed trees.

plow. The purpose of this implement is to break up and loosen the subsoil without mixing the material with the soil. It consists essentially of a small mole-like point on a long shin. This implement is drawn through the bottom of the furrow, and fractures and loosens the subsoil to a depth of eighteen inches or two feet. It is often useful on soils having a dense, hard subsoil, but its use requires the exercise of judgment, as the process may prove very injurious if done out of season. As a general rule, it is best to use the subsoiler in the fall when the subsoil is fairly dry, and in order that the subsoil may in a measure be recompacted by the winter rain. Spring subsoiling is seldom advisable in humid regions, owing to the danger of puddling the subsoil or the possibility of its remaining too loose for best root development, if performed when the subsoil is too dry to puddle.

339. Cultivators.—There are more types of cultivators than of any other form of soil-working implements. These may be grouped into: (1) Cultivators proper. (2) Leveler and harrow type of cultivators. (3) Seeder cultivators. These implements agree in their mode of action on the soil, in that they lift up and move it sidewise with a stirring action which loosens the structure and cuts off weeds, and to a slight degree covers rubbish. However, the action is primarily a stirring one, and, in general, it is much more shallow than that of the plow. One important fact should be kept in mind in cultural operations, especially just following the plow. That is, to do the work when the soil is in the right moisture condition. Particularly is this true in the pulverization following the plow. Plowing, if it be properly done, leaves the soil in the best possible condition to be pulverized. It is properly moistened, and if the clods are not shattered they are reasonably frail and may be much more readily broken down than when they are permitted to dry out. In drying, they are somewhat cemented together and thereby hardened. Not only is it desirable in almost all cases to take advantage of this condition of the soil, but the leveling and pulverizing of the soil reduces drying and improves the character of the seed bed.

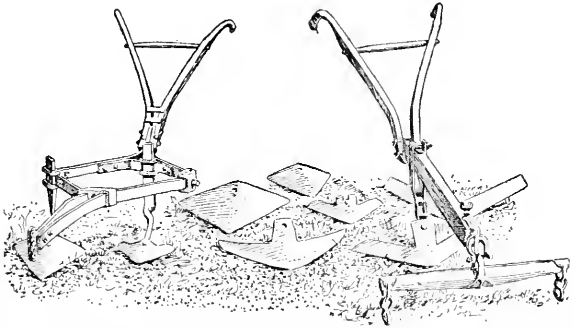

FIG. 137. "Sweeps" used extensively in the southern states, particularly for shallow cultivation of cotton and corn. (Hartley.)

340. Cultivators proper.—There is a great variety in types and patterns of cultivators. They may be divided into: (*a*) Large shovel forms. (*b*) Small shovel forms. The former have a few comparatively large shovels set rather far apart, which vigorously tear up the earth to a considerable depth and leave it in large ridges. There is a lack of uniform action, and the bottom of the cultivated portion is left in hard ridges. Such implements are now much less used than formerly, and may be considered to supplant in a measure the use of the plow, where deep working without turning is desired. Some of the wheel-hoes used in orchard tillage belong to this type. The old single and double shovel-plows are earlier types of the same implement.

The small shovel-cultivators have very generally supplanted the large shovel type in most cultural work.

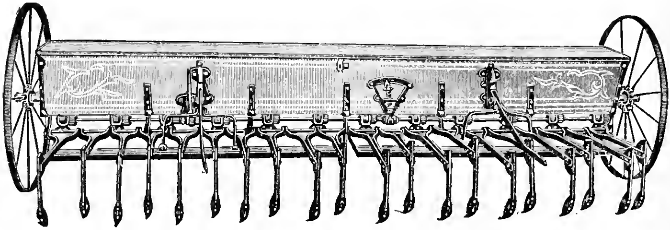

FIG. 138. Broadcast seeder, which also cultivates the soil.

The decrease in size of shovels is made up by the great increase in number. Ordinarily they operate shallow, but very thoroughly and uniformly. They are now much preferred in all inter-tillage work for eradication of small weeds and the formation of a loose surface mulch. A modification from these in shape of shovel is the sweep, much used in the southern states, especially in cotton-growing. It consists of broad blunt knife-like blades, which pass along a few inches beneath the surface of the soil and raise it an inch or two, then permit it to drop back in place in a much broken condition. It works best on soil relatively free from stone.

In addition to being a good implement to form a shallow mulch and keep the surface level, it is very effective as a weed-killer.

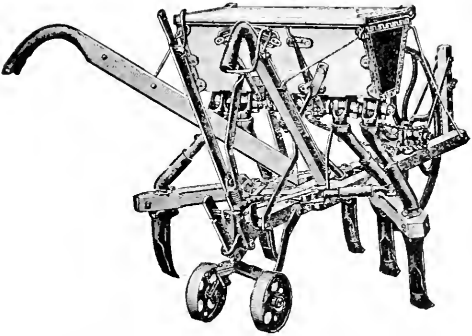

FIG. 139. Small, one-horse grain drill for seeding in standing corn. Its use is equivalent to cultivation.

Another classification, which has less relation to utility than to the convenience and comfort of the operation, is based on the presence or absence of wheels. There is a strong movement toward the use of wheel-cultivators, carrying a seat for the operator. These have a wider range of operation as to depth and facility of movement than have the cultivators without wheels.

Still further, there is the distinction of shovels from discs. Discs are used on the larger cultivators; seldom on the small ones.

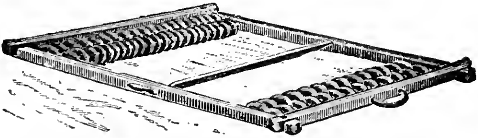

FIG. 140. Meeker disc pulverizer. See also Fig. 37.

Cultivators are also adapted to till one or more rows at a time.

341. Leveler and harrow type of cultivator.—In this group come the spike-toothed harrow, smoothing harrow, the spring-toothed harrow, disc harrow, spading harrow, weeders and the Acme harrow.

The spike-toothed harrow is essentially a leveling implement, adapted to very shallow cultivation of loose soils. It is also something of a cleaner, in that it picks up surface rubbish. The spring-toothed harrow works more deeply than the spike-toothed harrow, and can therefore be used in many situations to which the latter is not adapted. In working down cloddy soil it brings the lumps to the surface, where they may be crushed. The disc harrow depends for its primary advantage upon the conversion of sliding friction into rolling friction. Its draft is, therefore, less for the same amount of work done. It has a vigorous pulverizing action similar to the plow, and more so than shovel-cultivators.

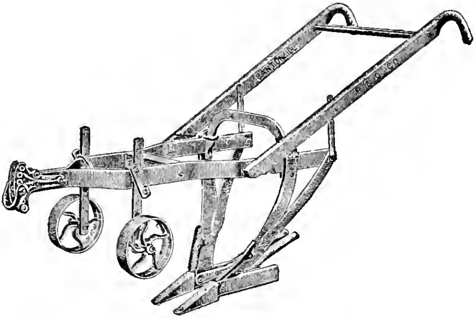

FIG. 141. Plow for loosening beets and other root crops. Cultivates the soil deeply.

Disc implements are not adapted to stony soil, whereas toothed forms are as effective here as on soil free from stone, so long as the stones are not large enough to collect in the implement. On the other hand, on land full of coarse manure, sod, etc., the disc implement is the more efficient. The spading harrow (cutaway disc) is very little different from the disc harrow, except that it takes hold of the soil more readily. A recent attempt to accomplish a large amount of pulverization, and with greater uniformity, is represented by the double-disc implements. In these implements there are two sets of discs, one set in front of and zig-zagged with the other, and also adjusted to throw the soil in opposite directions.

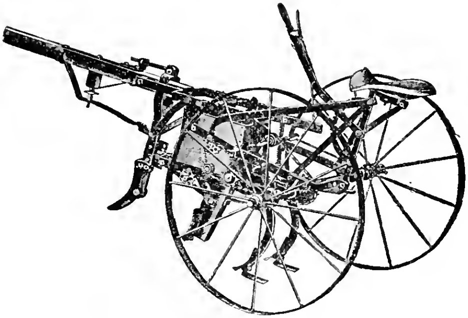

Fig. 142. Riding cotton- and corn-planter. It also cultivates the soil.

Weeders are a modified form of the spring-toothed harrow, adapted to shallow tillage of friable, easily worked soil, where the aim is to kill weeds and create a thin surface mulch. They are wide and are fitted with handles, and therefore stand intermediate between cultivators proper and harrows. They are much used for the intertillage of young crops.

The Acme harrow consists of a series of twisted blades which cut the soil and work it over. They are most useful in the latter stages of pulverization on soil relatively free from stone. The Meeker harrow is a modified form of disc, used primarily for pulverization. It consists of a series of lines of small discs arranged on straight axles, and is especially adapted to breaking up hard, lumpy soil. In this particular, it may be considered to belong to the third set of implements, the clod crushers. But, as compared with the roller on hard soil, it is more efficient.

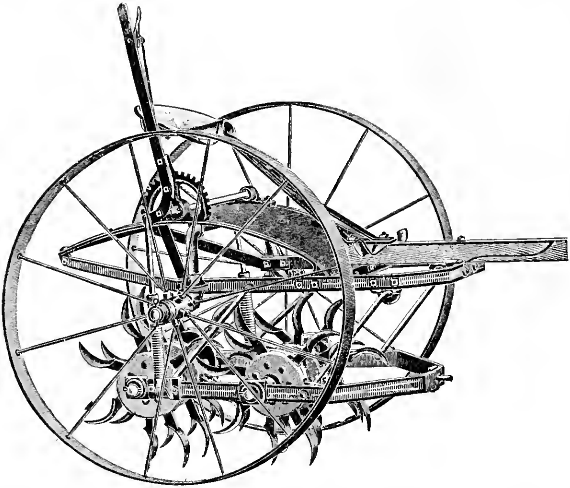

FIG. 143. Stubble digger used to fit light, mellow soils for seeding.

342. Seeder cultivators.—Many implements used primarily for seeding purposes are also cultivators, and their use is equivalent to a cultivation. The grain drill is a good example of this group. It is essentially a cultivator—either shoe or disc—adapted to depositing the grain in the soil at the proper depth. All types of planters which deposit the grain in the soil have a similar action on the structure of the soil. The ordinary two-row maize planter, the potato planter, etc., while of low efficiency, as cultivators, still have an effect which is measureable. This action is well seen in the lister, used for planting maize, by which the grain is deposited beneath the furrow, which is filled by cultivation after the grain is up. The lister is generally used without previously plowing the ground, and its use is limited to regions of low rainfall where the soil is aërated by natural processes. Lately, plowed ground listers have been introduced, which combine the advantages of deep planting with proper preparation of the soil.

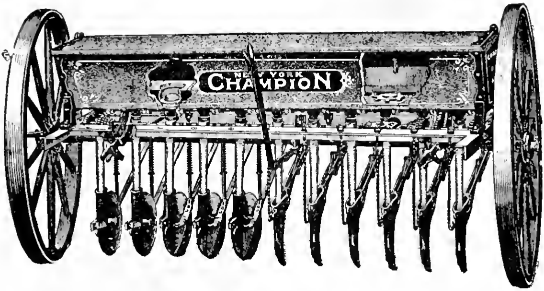

Fig. 144. Grain drill with either hoes or discs, and having fertilizer-spreading attachment.

There is also a very considerable tillage action in many harvesting implements. The potato-digger, for example, very thoroughly breaks up and cultivates the soil, which process is one important reason for the general high yield of crops following the potato crop. Bean-harvesters and beet-looseners also have a similar action on the soil.

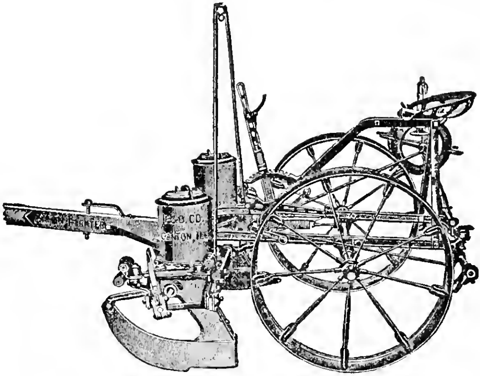

FIG. 145. Corn planter; also compacts the soil over the seed and establishes capillarity with the lower soil, thus bringing more moisture in contact with the seed.

343. Packers and crushers.—These may be divided into two groups: (*a*) Those implements which aim to

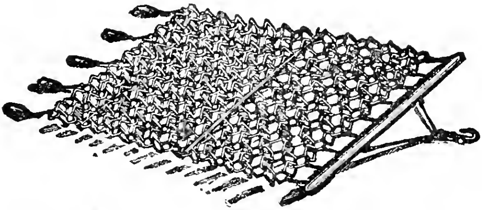

FIG. 146. Scotch chain harrow. A good pulverizer and very effective on pastures in breaking up and spreading "droppings."

compact the soil. (*b*) Those whose primary purpose is to pulverize the soil by crushing the lumps. Both sets of implements have something of the same action on the soil. That is to say, any implement which compacts the soil does a certain amount of crushing; and, conversely, any implement which crushes the soil does some compacting.

344. Rollers.—The type of the first group is the solid or barrel roller, which by its weight aims to force the particles of soil nearer together and to level the surface. The smaller the diameter in proportion to its weight, the greater the effectiveness of the roller. Its draft is correspondingly greater. As a crusher, the roller is relatively inefficient on hard, lumpy soil, because of its large bearing surface. Lumps are pushed into the soft earth rather than crushed.

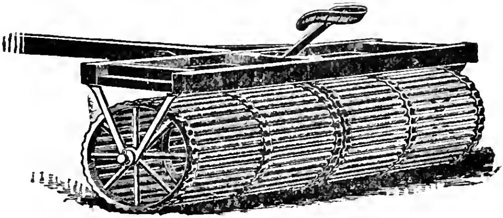

FIG. 147. The bar roller and pulverizer.

It should be mentioned that there is one condition where the roller is effective in loosening up the soil structure. This is on fine soil on which a crust has developed as a result of light rainfall. Here the roller may break up the crust and restore a fairly effective soil mulch.

Another form of roller is the sub-surface packer. One type of this implement consists of a series of wheels with narrow V-shaped rims, which press into the soil and compact it, while leaving the surface loose. (Fig. 67.) They are designed primarily to level the land after plowing, and to bring the furrow slices close together and in good contact with the subsoil, in order to conserve moisture and promote decay of organic material, which may be plowed under. This implement has been developed chiefly in semi-arid and arid sections of country where the conservation of moisture is especially important, but they might well have a much larger use for the same purpose in those sections of the country which are subject to late summer and fall droughts. While compacting the soil, these implements leave a mulch behind.

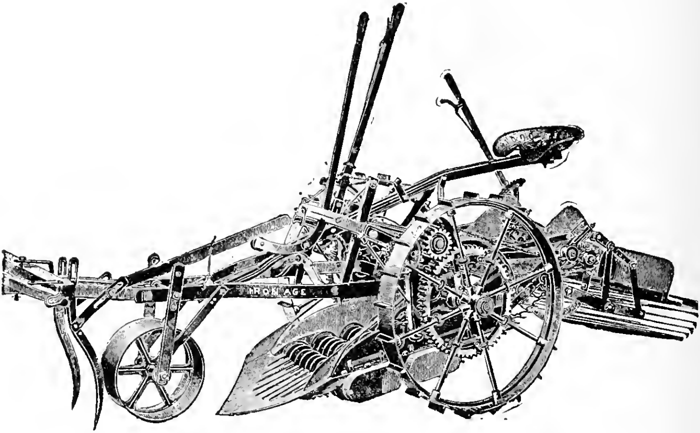

Fig. 148. Potato digger which is also very effective in stirring the soil.

345. Clod-crushers.—The aim of these implements is to break up lumps. As to mode of action, there are several forms. The bar roller and the "clod-crusher" (see Fig. 71) concentrate their weight at a few points, and are open enough so that the fine earth is forced up between the bearing surfaces. They are very effective in reducing lumpy soil to comparatively fine tilth. They have very little leveling effect further than the breaking down of lumps.

The planker, drag or float, variously so-called, consists essentially of a broad, heavy weight without teeth, which is dragged over the soil. The lumps are rolled under its edge and ground together in a manner which very effectively reduces their size. At the same time, the soil is leveled, smoothed, and, to a degree, compacted. It may well be used in the place of the roller as a pulverizer, on many occasions. It is constructed in many forms.

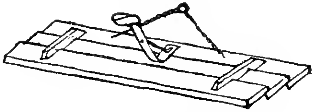

FIG. 149. Float or smoother made of planks.

III. OTHER PHASES OF TILLAGE OPERATION

In addition to the modification of food, moisture, air and heat of the soil, through changes in its structure as a result of tillage and other cultural practices, other important soil conditions may be changed. Two of the most important of these are: (1) The destruction of weeds. (2) The control of erosion.

346. Weeds in their relation to crop-production.—A weed has been defined as a plant out of place. By this definition any plant which grows where it is not desired is a weed.

347. Objectionable qualities of weeds.—Weeds are objectionable for several reasons. Some of the objectionable effects of weeds are: (1) They may remove moisture needed by the crop. (2) They may use food needed by the crop. (3) They usurp the light and heat supply. (4) They interfere with tillage and harvesting. operations, and perhaps also with the planting of the following crop. (5) They leave the soil in a condition unfavorable to the growth of the following crop. (6) They decrease the value of the crop by introducing impurities which are both injurious and expensive to eliminate.

348. The control of weeds.—The control of weeds depends on their character and habits of growth. Each situation develops its own peculiar crop of weeds. They arise as a result of the character and condition of the soil, and the character and habits of the regular crop. It is a type of the natural association of plants. In the wheat fields of the Northwest, mustard is troublesome; in maize, it may be quack-grass, sonchus, daisy or morning-glory. In meadows, it may be the thistle, yarrow or daisy. These weeds gain a foothold because their cycle of growth so closely corresponds with that of the crop. According to the character and occurrence of the weed, one of two methods of control or eradication must be employed: (*a*) If its propagation is dependent on seed-production, then seed-production should be prevented. (*b*) If propagated vegetatively, then the development of the aërial portion must be prevented for a sufficient time to kill the root or other propagative parts. In this direction, much may be accomplished through change in the rotation and in cutting the weeds at the proper time. But much may be accomplished by tillage. This may be largely accomplished in tillage for other purposes. Some of the practices which aid the process are:

(1) Early and frequent tillage. Weeds are most easily killed when young. Soon after the seed has germinated, they are most delicate. Stirring the soil at this period may so change their relation to it as to cause

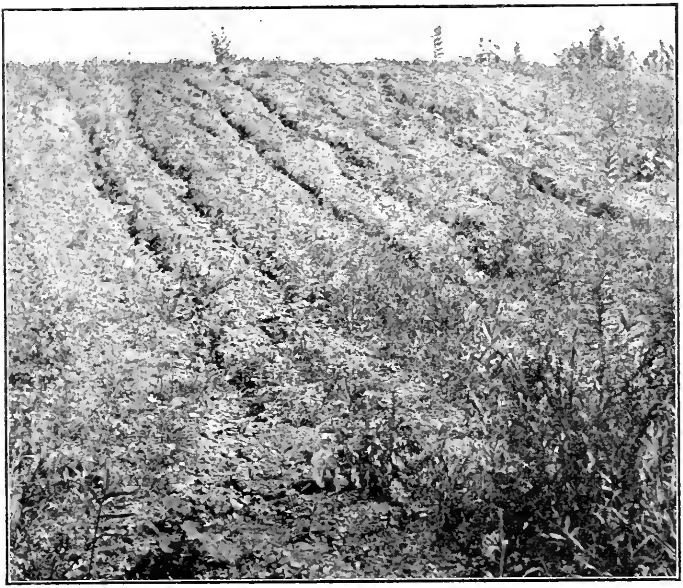

FIG. 150. Erosion on a gravelly hillside.

their death. Tillage in hot, dry weather is especially effective in killing most weeds. They soon dry out from lack of moisture.

(2) Small-toothed implements which very thoroughly stir the soil are more effective in killing small weeds than are large shovels which may slide past the weed. Thorough stirring of the soil is the essential point to be aimed at.

(3) Where weeds are beyond the reach of the cultivator, as in the row in maize that has reached a considerable size, they may often be killed by covering with soil by use of large shovels.

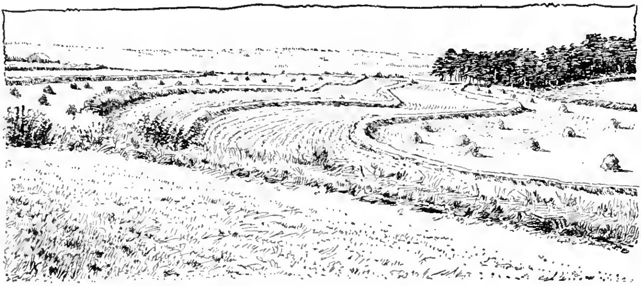

FIG. 151. Terracing to prevent erosion of hillside.

Shading by a rapid-growing leafy crop and spraying with chemicals for some species are also effective aids in weed control.

349. Erosion.—Erosion is often a serious menace to the productiveness of the soil. It may result from two causes: (1) The action of running water. (2) The action of wind. The soil is removed and causes injury to the productiveness of the land, first, by carrying away the

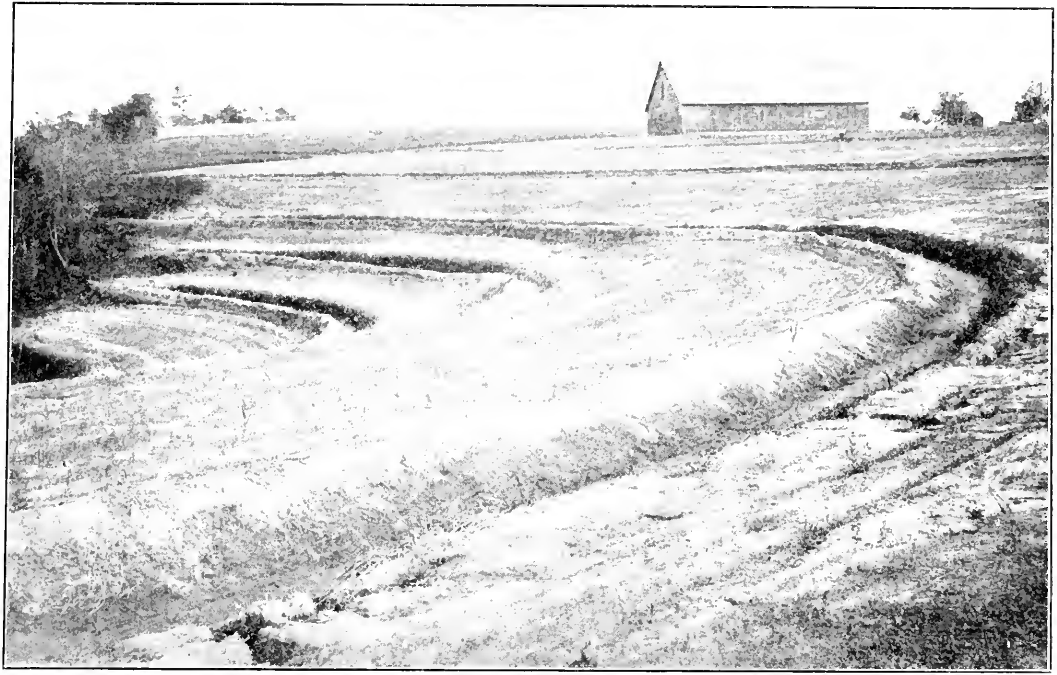

FIG. 152. Side-hill ridges, arranged on contours to prevent erosion. The upper face of these ridges has a slight grade, to assist in the removal of the excess of water without serious injury to the land. Florida.

most fertile portion; second, by such changes in the physical condition of the land as greatly interferes with all cultural operations. This is especially true where large gullies are formed, as happens on some soil types, or where ridges and mounds are formed by wind action. In some sections and on certain classes of soil, wind erosion is most serious; notably in dry regions of high winds. Under other conditions, erosion by water is most serious.

350. Erosion by water.—This type of erosion is a function of flowing water. It therefore occurs almost entirely on sloping land. The exception is where the soil is underlain by a stratum of fine sand which flows with the water when saturated. The removal of sand below permits the soil to cave down. As has been noted in another connection, erosion is greatly increased by material carried by the water and which becomes its tool. Some of the most effective practices for the control of this type of erosion are: (1) Deep plowing on heavy soil, by which a larger part of the rainfall is absorbed and retained. (2) Increased granulation of the soil, which may be produced by the means explained on page 104. The absorptive power and water capacity of the soil is thereby increased so that there is a less amount to flow away. (3) Addition of organic matter, which not only aids granulation, but binds the soil together. It also increases the water capacity of the soil. (4) Underdrainage reduces erosion where the soil is saturated with water. Instead of its flowing away violently in rills, it is gradually removed in the drainage channels, which are not subject to erosion. (5) Various protective coverings and binding materials may be kept on the soil. The most effective of these are fine-rooted crops, which not only hold the soil togther, but protect it against the force of the water. In those sections where

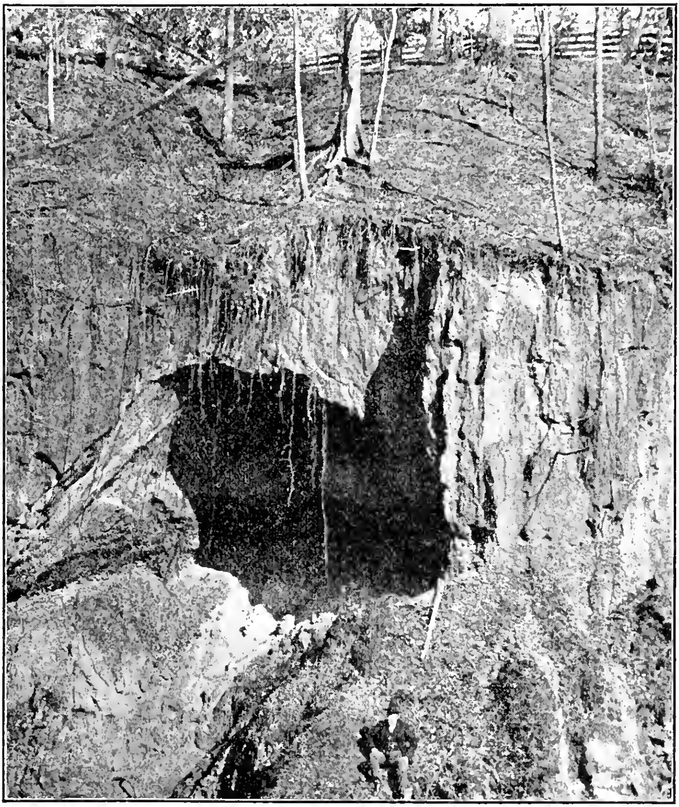

Fig. 153. Characteristic erosion of loess. The binding power of roots is illustrated by the tree roots at the surface.

it thrives, blue grass is permitted to occupy those areas of the hillside most subject to erosion. Trees afford a similar protection and are valuable in reclaiming eroded land. It is a general custom to retain in some cover-crop those steep areas of land most subject to erosion. (6) Contour farming, that is, the performance of all tillage operations around the hill at a uniform level, instead of up and down the slope, creates a succession of small ridges which hold the water, to a certain extent. (7) Side-hill ditches are employed where contour farming does not create sufficiently large ridges to hold the water. The two are usually combined. These side-hill ditches are usually given a small grade along the face of the slope, to gradually carry away the water. (8) Terracing is preferred in some sections as a method to prevent erosion as well as to facilitate tillage. The water is, of course, held on each level strip throughout the succession of terraces. Where gullies have already formed, there extension may usually be prevented by filling with some porous material, such as straw, brush or stone, which checks the flow of water and accumulates the sediment. Cross-embankments are also useful. When these are combined with the growth of grass, trees or other plants, to bind the soil together and further protect it, such land can frequently be reclaimed.

351. Erosion by wind.—Erosion by wind, including the drifting of sand, may be checked by means of: (1) Windbreaks, and in some cases, by keeping the surface rough. (2) A surface covering such as stone or vegetation, the latter to bind the soil together and break the force of the wind. (3) The addition of organic matter, which will hold the soil together and increase its moisture content, which latter also greatly aids the process. (4) In fine-textured soil, such as silt and very fine sand, by the promotion of granulation and by the avoidance of a loose fallow surface at that season of the year when wind erosion is likely to be serious.

The aggregate of soil moved from tilled fields by erosion of these two types is large, and it usually concerns the most productive portion. The encroachment of sand-dunes upon valuable land is often a serious menace. Reforestation and the planting of sand-binding grasses are the chief protective measures available.

IV. ADAPTATION OF CROPS TO SOIL

It is a matter of common observation that all crops do not grow equally well upon the same soil.

352. Philosophy of crop-adaptation.—Each plant is adapted to make its best growth on a particular soil and under a particular climate. Any departure from these ideal conditions results in changing the character of the plant and reduction in its value. This peculiar adaptation of crop to soil is the result of centuries of natural selection. The basis of all the tillage operations which have for their object the modification of the soil conditions is to bring the soil more nearly to the ideal condition required to nourish plants. This wide difference in the preferences of crops is well known. On the other hand, there are hundreds of different kinds of soil,—that is, soils which normally maintain different conditions for growth. Some are fine, others are coarse;

some are deep, others are shallow; some have one chemical composition, others have a different composition; some are dark, others are light-colored; some are wet, others are dry; some occur under one climate, others under another climate. It is the combination of all these factors which affect plant growth that gives rise to the great variety of soil conditions. The great variety of plants is a reflection of this great variety in the conditions of growth. In any given situation, those crops which are adapted to that situation persist and thrive.

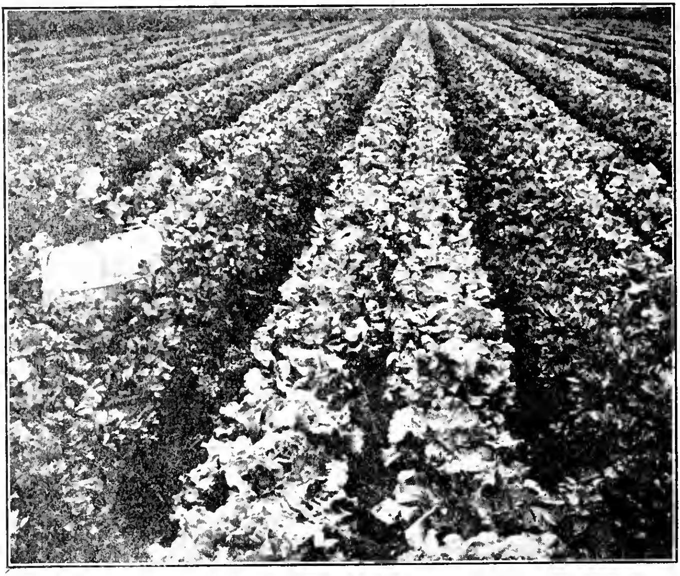

FIG. 154. Lettuce and celery growing on muck soil. Such soil usually requires special fertilization.

The range of conditions upon which a particular crop will grow is limited. It is wider for some crops than for others. Likewise, the range of crops which can be grown on any particular soil is also limited. The more extreme the soil condition, the more limited is this range of crop-adaptation. It is the soil of intermediate properties—texture, organic content, drainage and food supply—which is adapted to the greatest variety of crops. In the largest utilization of any particular soil, this adaptation of crop to soil must be made use of, as well as modification of the soil.

353. Factors in crop-adaptation.—The determining factors in crop-adaptation are of two sorts: (1) The physiological requirements of the plant. (2) The capacity of a given soil and climatic condition to fulfil those physiological requirements.

354. Physiological requirements of the plant.—The physiological requirements of the plant are of both a physical and a chemical character.

(1) The physical requirements relate to the habits of growth of the plant, particularly the type of its root system and the intensity of sunshine, temperature and wind it is able to withstand. Especially important is the root system. Deep- or tap-rooted plants have a very different feeding ground from shallow-, fibrous-rooted plants.

(2) The chemical requirements relate to food elements necessary to growth, and especially to the presence or absence of accessory substances which the plant is able to withstand. For example, some plants will not grow in a soil rich in lime; others require this condition.

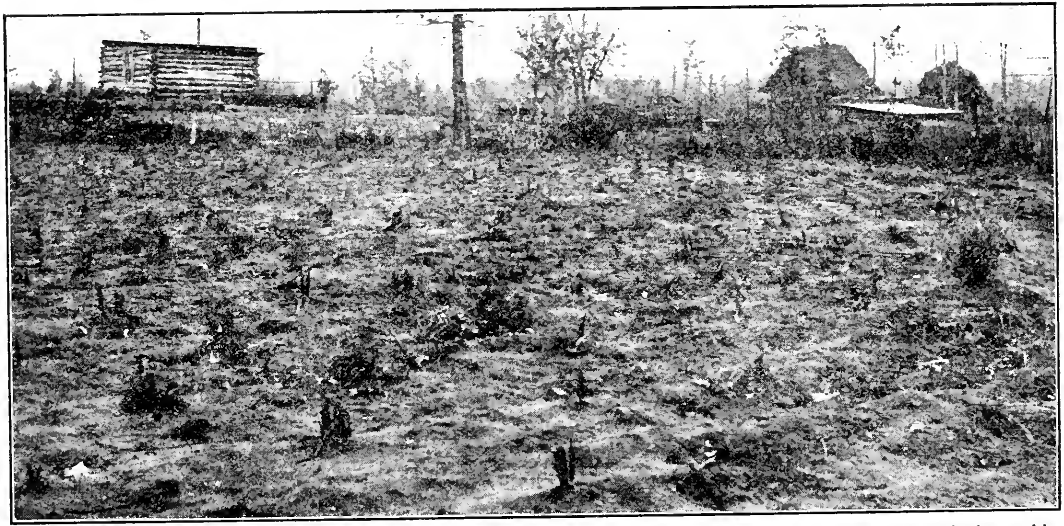

FIG. 155. Influence of soil type on agricultural development. Farm scene on a very light, deep sand. Entirely incapable of the high degree of agricultural development shown in Fig. 156.

In arid soils some plants are able to withstand alkali conditions where others quickly succumb. There may be toxic substances in the soil injurious to one plant and not to another. These may arise from the growth of other crops, and so determine the plants which may be associated with that crop. This bears on crop-rotation.

355. Requirements for growth supplied by the soil.—The internal conditions of different soils may be very different. On a puddled clay soil saturated with water, only a few plants may thrive. On a dry sandy soil, only certain other plants can secure the essentials for growth. On a very shallow soil, shallow-rooted, early-maturing crops may be grown where trees would utterly fail. On soils subject to midsummer drought, early-maturing crops may be grown where late-maturing crops would fail. Thus, the soil conditions are the arbiter in the selection of crops to be produced. The distribution of different crops and types of agriculture is a reflection of this adaptation. Many failures result from failure to recognize these relations.

Full knowledge for the accurate adaptation of crops to soil, or soil to crops, is yet to be gained. Such information is often not to be derived by definite experimentation. It comes of long experience. But many striking examples of adaptation are known. They are governed by soil conditions broadly considered, rather than by any single factor. One of the most general of these relations is the adaptation of early truck crops to light, sandy soil; of grass, to heavy soil. Certain varieties of apple grow to their highest perfection on

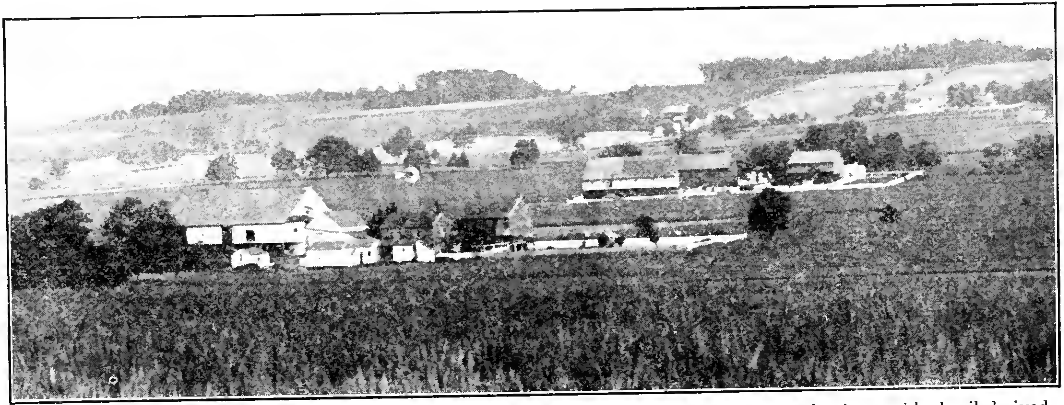

Fig. 156. Influence of soil type on agricultural development. Farm scene on a very productive residual soil derived from limestone. This soil is especially adapted to the growth of blue grass and is the basis of the blue-grass region of Kentucky and adjacent states.

certain types of soil. Cherries and peaches succeed best on a lighter soil than apples may be best grown on. Muck soils are eminently adapted to the growth of celery, onions, etc. With the extension of careful soil and crop surveys, these relations are becoming better known and are extending from groups of plants to species and varieties of plants. By the same methods our information concerning these relations must be extended until the production of crops rests upon definite knowledge of the plant requirements on the one hand, and the soil capacity and the means available to alter the soil environment on the other hand. Really intelligent husbandry can rest only upon the basis of exact knowledge concerning these two groups of facts and principles.

V. RELATION OF SOIL PRODUCTIVENESS TO CROP-ROTATIONS

At an early time in the development of agriculture, it was understood that a succession of different crops upon any piece of land gave better returns than one crop raised continuously. The plan of changing the crops grown each year thus became customary, and the universality with which it was practiced by European peoples shows that its value must have been discovered independently in many communities, as ideas, particularly agricultural ones, traveled very slowly in the middle ages.

In Great Britain and some of the countries of Europe, crop rotations have been most systematically and effectively developed. This has been the natural result of the incentive arising from diminishing productiveness of the soil consequent upon long-continued cultivation, coupled with an increasing population. Countries having undepleted and uninfested soil, or an unprogressive people, have done little with crop-rotations.

Another condition that discourages the use of crop-rotation is the suitability of a region to the production of some one crop of outstanding value, combined, perhaps, with a relatively cheap supply of fertilizing material. The abundant use of fertilizers may postpone for a long time the recourse to crop rotations.

356. Principles underlying crop-rotation.—There are many benefits to be derived from a proper rotation of crops that are not directly concerned with soil-productiveness. The practice of crop-rotation must depend upon certain principles in soil management, some of the most prominent of which are mentioned below, and are modified by climatic, topographic, geographic and economic features, and many other factors, that cannot be treated here.

357. Nutrients removed from the soil by different crops.—Some crops require large amounts of one fertilizing constituent, while others take up more of another. As before pointed out (see page 294), cereal crops are able to utilize the potassium and phosphorus of the soil to a considerable degree but have less ability to secure nitrogen. They are, therefore, usually much benefited by the application of a nitrogenous manure and leave a considerable residue in the soil. A number of other crops, as, for instance, beets and carrots, can utilize this residual nitrogen. Grasses remove comparatively little phosphoric acid. Potatoes remove very large amounts of potassium. A rotation of crops is, therefore, less likely to cause a deficiency of some one constituent than is a continuous growth of one crop, and it utilizes more completely the available nutrients.

358. Root systems of different crops.—Some crops have roots that penetrate deeply into the subsoil, while others are only moderately deeply rooted, and others quite shallow-rooted. Among the deeply rooted plants are alfalfa, clover, certain of the root crops, and some of the native prairie grasses. Representing those having moderately long roots, are oats, maize, wheat, meadow fescue, grass, etc., and among those having shallow roots are barley, turnips and many of the cultivated grasses. As plants draw their nourishment from those portions of the soil into which their roots penetrate, the deeper soil is not called upon to provide food for the shallow-rooted crops, and the deep-rooted crops remove relatively less of the nutrients from the surface soil. It therefore happens that a rotation involving the growth of deep- and shallow-rooted crops effects, by utilizing a larger area of the soil, a more economical utilization of plant nutrients than would a continuous growth of either kind.

359. Some crops or crop treatments prepare food for other crops.—It is quite evident that the growth of leguminous crops, even when not plowed under, leave in the soil an accumulation of organic nitrogen transformed by bacteria from atmospheric nitrogen. This, in the natural course of decomposition and nitrification, becomes available to cereal or other crops that may follow in the rotation. The presence of a grass crop upon the land for several years favors the action of non-symbiotic nitrogen-fixing bacteria, as already explained (see page 429). The grass crops also leave a very considerable amount of organic matter in the soil, which by its gradual decomposition contributes both directly and indirectly to the supply of available nutrients. As the organic matter left by the legumes and grasses decomposes slowly, these crops should be followed by a coarse feeding crop, like corn or potatoes, and one which is at the same time a cultivated crop, as are these. Stirring the soil at intervals during the summer greatly facilitates decomposition, and leaves a supply of easily available food for more delicate feeders, like wheat or barley, that may follow the cultivated crop. The introduction of cultivated crops in the rotation thus serves to prepare food for the non-cultivated ones. Although practical difficulties sometimes make it impossible to follow the cultivated crops with winter wheat, the practice, where proper preparation of the seed-bed is possible, is a good one.

360. Crops differ in their effect upon soil structure.— Plants must be included among the factors affecting the arrangement of soil particles. The result of practically all root growth is to improve the physical conditions of the soil, to a greater or less degree. In general, crops with rather shallow and very fibrous roots are most beneficial, at least to the surface soil. Millet, buckwheat, barley, and to a less extent wheat, leave the soil in a friable condition. It is upon heavy soils that this property is most beneficially exercised.

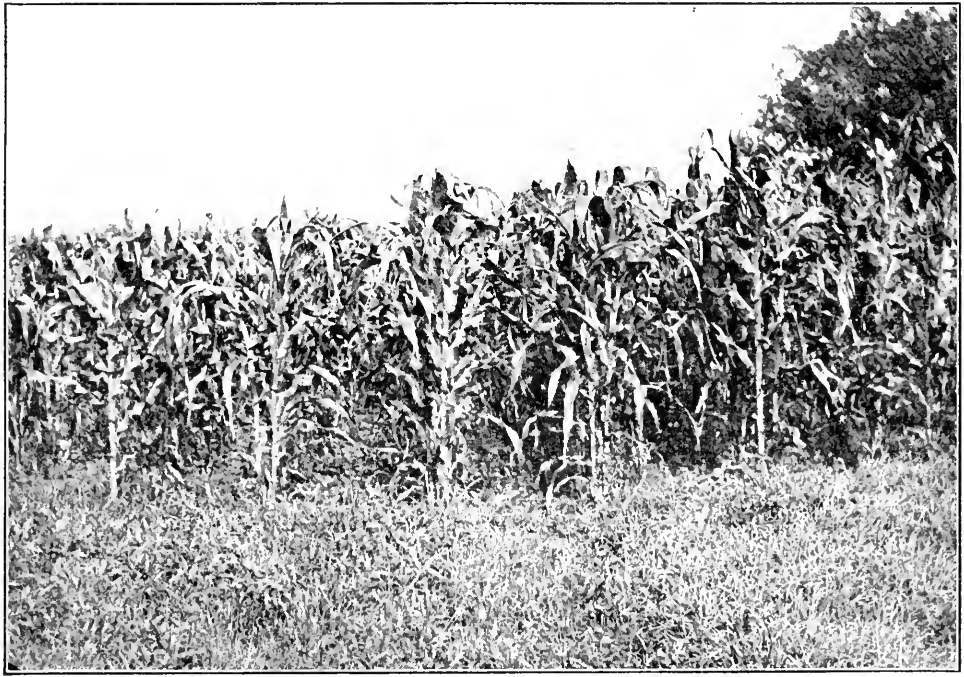

Fig. 157. Showing effect of sod on succeeding maize crop. The land on the right of the picture had been in grass for three years. That on the left had been cropped continuously.

Tap-rooted plants, and others with few surface roots, do not exhibit this action. Alfalfa and root crops are likely to leave the soil quite compact as compared with the crops mentioned above.

The effect of sod is generally beneficial, and this is one of the reasons for using a grass crop in a rotation.

361. Certain crops check certain weeds.—By rotating crops, the weeds that flourish during the presence of one crop upon the land may be greatly checked by succeeding crops. Some weeds are best destroyed by smothering, for which purpose small grain and notably corn or sorghum sown for fodder are effective. Others are most injured by cultivation, to accomplish which the hoed crops are needed; while others can best be checked by the presence of a thick sod on the ground for a number of years. In the warfare against weeds that must be carried on wherever crops are raised, the use of different crops involving different methods of soil treatment is of great service.

362. Plant diseases and insects checked by removal of hosts.—Many plant diseases and many insects spend their resting stages and larval existence in the soil. A continuous growth of any one crop upon the soil favors the increase of these species by providing each year the particular plant upon which they thrive. A change of crops, by removing the host plants, causes the destruction of many diseases and insects through their inability to reach their host plants. A long rotation, such as is frequently used in Great Britain, is particularly effective in eradicating those diseases that persist in the soil for a number of years. In the case of diseases that affect more than one species of plant, as does the beet and potato scab, there is need for special care in arranging the rotation. Such considerations may frequently make it desirable to change the plan of a rotation.

Another feature of the relation of crop rotation to plant diseases is that the more thrifty growth obtainable under rotation assists the crop to withstand many diseases.

363. Loss of plant-food from unused soil.—A system of crop-rotation permits a more constant use of the land than is possible with most annual crops. As a soil bearing no crop upon it always loses more plant-food than one bearing a crop, it is thus possible, by a well-chosen rotation, to save plant-food that would otherwise be lost.

364. Accumulation of toxic substances.—That the soil frequently contains organic substances that exert an injurious effect upon the growth of certain plants is indicated by recent experiments and was surmised by some early writers upon the subject. De Candolle was probably the first to advance the idea in 1832. He suggested that at least some plants excrete from their roots substances that are injurious to themselves, although harmless or even beneficial to other plants. This he considered one of the reasons for the failure of many crops to succeed when grown continuously upon the land, while that same soil may be productive under a rotation of crops. Liebig, in his first report to the British Association in 1840, made a similar statement.

Recently, Pouget and Chonchak, working with alfalfa soils, have reached the conclusion that alfalfa plants excrete a toxic substance which, gradually accumulating in the soil, injuriously affects the growth of alfalfa plants. Whitney, Livingston, Schreiner and their associates conclude that certain soils contain toxic substances of organic nature which may be produced by plant roots, or possibly by certain processes of decomposition of organic matter. They have isolated from soils organic compounds that are poisonous to plants.

It is found, for instance, that cumarin, which is a normal constituent of sweet clover (*Medicago alba,* L and M., *officinalis,* P), may be obtained from certain soils, and that it is toxic to wheat seedlings,—from which it may be supposed that it is more or less toxic to other plants. Dihydroxystearic acid was isolated from certain soils by Schreiner and Shorey, who found that it is acid to litmus and decomposes $BaCO_3$ and $CaCO_3$, forming the corresponding salts. The extracts of the soil containing this substance were toxic to wheat seedlings. The relation of soil acidity and soil toxicity is thus suggested.

Working with different media in which wheat and other seedlings were grown, it was shown that, where the nutrient solutions were very dilute, so as not to enable the plant to overcome the effects of small quantities of toxic matter, the wheat plants grew much better when following other plants; and that, in spite of a renewal of the supply of nutrients, the wheat plants grew less well when one crop succeeded another. The cause of the lessened growth was attributed to the excretion from the plant roots of substances which, while more or less toxic to other plants, are especially so to plants of the same species.

Although there are yet many phases and details of this subject to be worked out, there seems to be some relation between the presence in the soil of organic substances poisonous to plants and the continuous growth of one crop; and this may be considered to be one reason for the benefit derived on some soils, at least, from the practice of crop-rotation.

INDEX

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