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THE ROTHAMSTED MONOGRAPHS ON AGRICULTURAL SCIENCE

EDITED BY

SIR E. JOHN RUSSELL, D.Sc. (LOND.), F.R.S.

SOIL CONDITIONS AND PLANT GROWTH

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8vo.

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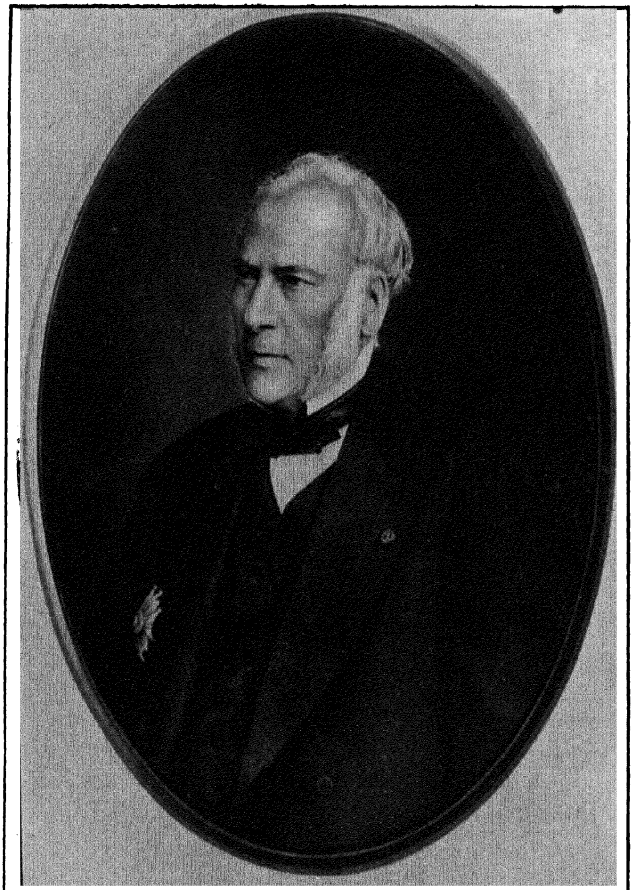
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JEAN BAPTISTE JOSEPH DIEUDONNE BOUSSINGAULT
1802 - 1887

The Founder of Modern Agricultural Chemistry.

SOIL CONDITIONS

AND

PLANT GROWTH

BY

EDWARD J. RUSSELL

D.Sc. (LOND.), HON. D.Sc. (MANCH.; TORONTO; WALES), F.R.S.

DIRECTOR OF THE ROTHAMSTED EXPERIMENTAL STATION, HARPENDEN

WITH ILLUSTRATIONS

FIFTH EDITION

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PREFACE TO FIFTH EDITION.

THIS edition has been delayed for some months by reason of my absence from England on agricultural journeys in the Sudan, in Canada, in the United States and in other countries. While this has necessitated the book remaining out of print for some months, it has had the advantage of giving me many opportunities for seeing the work of other stations and discussing problems and points of view with other investigators. What this means is obvious to anyone who knows how rapid is now the rate of publication of papers on agricultural science. The general habit of publishing students' exercises for University Degrees is partly responsible, but the main factor is the widespread activity of the Experiment Stations, the Universities, and individual workers. The mass of papers is now too great to be read by any one person; unfortunately also some are written in such a way that their meaning cannot always be clearly apprehended. New words are freely coined, new and variable uses of old words are silently adopted, and new methods of nomenclature are set up, all of which tend to make the reading of scientific papers difficult.

Perhaps the most striking advances since 1921 have been in the chemistry of the soil. Once more the general rule in scientific progress has been exemplified. The study of the soil was for long supposed to be

entirely a matter for chemists. Then came the brilliant investigations of the bacteriologists which brought soil microbiology very much to the fore; soil physics also came into great prominence and soil chemistry fell into the background. This was not the result of caprice on the part of investigators; soil chemistry had gone as far as its methods allowed, and it was brought to a standstill by the sticky colloids of the soil. But with the development of methods for studying colloids in laboratories devoted to pure science, further possibilities of advance in soil chemistry have been opened up, and these have been eagerly seized by enthusiastic workers in Europe, America, and elsewhere. Once again it has been shown that progress in applied science is limited by the state of knowledge of pure science, and that the surest way of solving technical problems is to investigate the underlying principles and causes.

All branches of the subject have advanced, however, and it has been necessary to rewrite all except the historical portions of the book.

My thanks are due to my colleagues on the Rothamsted staff who have helped me with references, summaries, notes and discussions, especially to Miss K. Warington, Miss Aslin, Miss Dick, Mr. Page and the Staff of the Chemical Department, Dr. Keen, Messrs. Thornton and Cutler, Drs. E. M. Crowther, Gregory, and Maskell. Many investigators elsewhere have helped me with notes and suggestions, and others I hope will do the same. It is the only way in which a useful book can be produced now that the subject is growing so rapidly.

ROTHAMSTED EXPERIMENTAL STATION,
HARPENDEN.

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CHAPTER I.

HISTORICAL AND INTRODUCTORY.

In all ages the growth of plants has interested thoughtful men. The mystery of the change of an apparently lifeless seed to a vigorous growing plant never loses its freshness, and constitutes, indeed, no small part of the charm of gardening. The economic problems are of vital importance, and become more and more urgent as time goes on and populations increase and their needs become more complex.

There was an extensive literature on agriculture in Roman times which maintained a pre-eminent position until comparatively recently. In this we find collected many of the facts which it has subsequently been the business of agricultural chemists to classify and explain. The Roman literature was collected and condensed into one volume about the year 1240 by a senator of Bologna, Petrus Crescentius, whose book [1] was one of the most popular treatises on agriculture of any time, being frequently copied, and in the early days of printing, passing through many editions—some of them very handsome, and ultimately giving rise to the large standard European treatises of the sixteenth and seventeenth centuries. Many other agricultural books appeared in the fifteenth and early sixteenth centuries, notably in Italy, and later in France. In some of these are found certain ingenious speculations that have been justified by later work. Such, for instance, is Palissy's remarkable statement in 1563 (222) [2]: "You will admit that when you bring dung into the field it is to return

[1] *De agricultura vulgare*, Augsburg, 1471, and many subsequent editions.

[2] The numbers in brackets refer to the Bibliography at the end of the book.

to the soil something that has been taken away. . . . When a plant is burned it is reduced to a salty ash called alcaly by apothecaries and philosophers. . . . Every sort of plant without exception contains some kind of salt. Have you not seen certain labourers when sowing a field with wheat for the second year in succession, burn the unused wheat straw which had been taken from the field? In the ashes will be found the salt that the straw took out of the soil; if this is put back the soil is improved. Being burnt on the ground it serves as manure because it returns to the soil those substances that had been taken away." But for every speculation that has been confirmed will be found many that have not, and the beginnings of agricultural chemistry must be sought later, when men had learnt the necessity for carrying on experiments.

The Search for the "Principle" of Vegetation, 1630-1750.

The earlier investigators sought for a "principle" of vegetation to account for the phenomena of soil fertility and plant growth. The great Lord Bacon (8) believed that water formed the "principal nourishment" of plants, the purpose of the soil being to keep them upright and protect them from excessive cold or heat, but he also considered that each plant drew a "particular juyce" from the soil for its sustenance, thereby impoverishing the soil for that particular plant and similar ones, but not necessarily for other plants. Van Helmont regarded water as the sole nutrient for plants, and his son thus records his famous Brussels experiment (131): "I took an earthen vessel in which I put 200 pounds of soil dried in an oven, then I moistened with rain water and pressed hard into it a shoot of willow weighing 5 pounds. After exactly five years the tree that had grown up weighed 169 pounds and about three ounces. But the vessel had never received anything but rain water or distilled water to moisten the soil when this was necessary, and it remained full of soil, which was still tightly packed, and, lest any dust from outside should get into the soil, it was covered with a sheet of iron coated with tin

but perforated with many holes. I did not take the weight of the leaves that fell in the autumn. In the end I dried the soil once more and got the same 200 pounds that I started with, less about two ounces. Therefore the 164 pounds of wood, bark, and root, arose from the water alone."

The experiment is simple and convincing, and satisfied Boyle (50), who repeated it with "squash, a kind of Indian pompion" and obtained similar results. Boyle further distilled the plants and concluded, quite justifiably from his premises, that the products obtained, "salt, spirit, earth, and even oil (though that be thought of all bodies the most opposite to water), may be produced out of water." Nevertheless, the conclusion is incorrect, because two factors had escaped Van Helmont's notice—the parts played by the air and by the missing two ounces of soil. But the history of this experiment is thoroughly typical of experiments in agricultural chemistry generally: in no other subject is it so easy to overlook a vital factor and draw from good experiments a conclusion that appears to be absolutely sound, but is in reality entirely wrong.

Some years later—about 1650—Glauber (109) set up the hypothesis that saltpetre is the "principle" of vegetation. Having obtained saltpetre from the earth cleared out from cattle sheds, he argued that it must have come from the urine or droppings of the animals, and must, therefore, be contained in the animal's food, *i.e.* in plants. He also found that additions of saltpetre to the soil produced enormous increases in crop. He connected these two observations and supposed that saltpetre is the essential principle of vegetation. The fertility of the soil and the value of manures (he mentions dung, feathers, hair, horn, bones, cloth cuttings) are entirely due to saltpetre.

This view was supported by Mayow's experiments (195). He estimated the amounts of nitre in the soil at different times of the year, and showed that it occurs in greatest quantity in spring when plants are just beginning to grow, but is not to be

found " in soil on which plants grow abundantly, the reason being that all the nitre of the soil is sucked out by the plants." J. A. Külbel,[1] on the other hand, regarded a *magma unguinosum* obtainable from humus as the " principle " sought for.

The most accurate work in this period was published by John Woodward, in a remarkable paper in 1699 (316). Setting out from the experiments of Van Helmont and of Boyle, but apparently knowing nothing of the work of Glauber and of Mayow, he grew spearmint in water obtained from various sources with the following results among others :—

Source of Water.	Weight of Plants.		Gained in 77 days.	Expense of Water (*i.e.* Transpiration).	Proportion of Increase of Plant to Expense of Water.
	When put in.	When taken out.			
	Grains.	Grains.	Grains.	Grains.	
Rain water . .	28¼	45¾	17½	3004	1 to 171⅜⅞
River Thames . .	28	54	26	2493	1 to 95⅝⅛
Hyde Park conduit	110	249	139	131140	1 to 94$\frac{74}{139}$
1½ ozs. garden mould +	92	376	284	14950	1 to 52⅛⅜⅝

Now all these plants had abundance of water, therefore all should have made equal growth had nothing more been needed. The amount of growth, however, increased with the impurity of the water. " Vegetables," he concludes, " are not formed of water, but of a certain peculiar terrestrial matter. It has been shown that there is a considerable quantity of this matter contained in rain, spring, and river water, that the greatest part of the fluid mass that ascends up into plants does not settle there but passes through their pores and exhales up into the atmosphere: that a great part of the terrestrial matter, mixed with the water, passes up into the plant along with it, and that the plant is more or less augmented in proportion as the water contains a greater or less quantity of that matter; from all of which we may reasonably infer, that earth, and not water, is the matter that constitutes vegetables."

[1] *Cause de la fertilité des terres*, Bordeaux, 1741.

He discusses the use of manures and the fertility of the soil from this point of view, attributing the well-known falling off in crop yield when plants are grown for successive years on unmanured land to the circumstance that "the vegetable matter that it at first abounded in being extracted from it by those successive crops, is most of it borne off. . . . The land may be brought to produce another series of the same vegetables, but not until it is supplied with a new fund of matter, of like sort with that it at first contained; which supply is made several ways, either by the ground's being fallow some time, until the rain has poured down a fresh stock upon it; or by the tiller's care in manuring it." The best manures, he continues, are parts either of vegetables or of animals, which ultimately are derived from vegetables.

In his celebrated textbook of chemistry Boerhaave (40) taught that plants absorb the juices of the earth and then work them up into food. The raw material, the "prime radical juice of vegetables, is a compound from all the three kingdoms, *viz. fossil* bodies and putrified parts of *animals* and *vegetables*." This "we look upon as the *chyle of the plant;* being chiefly found in the first order of vessels, *viz.* in the roots and the body of the plant, which answers to the stomach and intestines of an animal."

For many years no such outstanding work as that of Glauber and Woodward was published, if we except Hales' *Vegetable Staticks* (119), the interest of which is physiological rather than agricultural.[1] Advances were, however, being made in agricultural practice. One of the most important was the introduction of the drill and the horse hoe by Jethro Tull (282), an Oxford man of a strongly practical turn of mind, who insisted on the vital importance of getting the soil into a fine crumbly state for plant growth. Tull was more than an inventor; he discussed in most picturesque language the sources of fertility in the soil. In his view it was not the juices of the earth, but the very minute particles of soil

[1] He shows, however, that air is "wrought into the composition" of plants.

loosened by the action of moisture, that constituted the "proper pabulum" of plants. The pressure caused by the swelling of the growing roots forced these particles into the "lacteal mouths of the roots," where they entered the circulatory system. All plants lived on these particles, *i.e.* on the same kind of food; it was incorrect to assert, as some had done, that different kinds of plants fed as differently as horses and dogs, each taking its appropriate food and no other. Plants will take in anything that comes their way, good or bad. A rotation of crops is not a necessity, but only a convenience. Conversely, any soil will nourish any plant if the temperature and water supply are properly regulated. Hoeing increased the surface of the soil or the "pasture of the plant," and also enabled the soil better to absorb the nutritious vapours condensed from the air. Dung acted in the same way, but was more costly and less efficient.

So much were Tull's writings esteemed, Cobbett tells us, that they were "plundered by English writers not a few and by Scotch in whole banditti."

The position at the end of this period cannot better be summed up than in Tull's own words: "It is agreed that all the following materials contribute in some manner to the increase of plants, but it is disputed which of them is that very increase or food: (1) nitre, (2) water, (3) air, (4) fire, (5) earth."

The Search for Plant Nutrients.

1. *The Phlogistic Period*, 1750-1800.

Great interest was taken in agriculture in this country during the latter half of the eighteenth century. "The farming tribe," writes Arthur Young during this period, "is now made up of all ranks, from a duke to an apprentice." Many experiments were conducted, facts were accumulated, books written, and societies formed for promoting agriculture. The Edinburgh Society, established in 1755 for the improvement of arts and manufactures, induced Francis Home (137) "to try how

far chymistry will go in settling the principles of agriculture." The whole art of agriculture, he says, centres in one point: the nourishing of plants. Investigation of fertile soils showed that they contain oil, which is therefore a food of plants. But when a soil has been exhausted by cropping, it recovers its fertility on exposure to air,[1] which therefore supplies another food. Home made pot experiments to ascertain the effect of various substances on plant growth. " The more they (*i.e.* farmers) know of the effects of different bodies on plants, the greater chance they have to discover the nourishment of plants, at least this is the only road." Saltpetre, Epsom salt, vitriolated tartar (*i.e.* potassium sulphate) all lead to increased plant growth, yet they are three distinct salts. Olive oil was also useful. It is thus clear that plant food is not one thing only, but several; he enumerates six: air, water, earth, salts of different kinds, oil, and fire in a fixed state. As further proof he shows that " all vegetables and vegetable juices afford those very principles, and no other, by all the chymical experiments which have yet been made on them with or without fire."

The book is a great advance on anything that had gone before it, not only because it recognises that plant nutrition depends on several factors, but because it indicates so clearly the two methods to be followed in studying the problem—pot cultures and plant analysis. Subsequent investigators, Wallerius (291), the Earl of Dundonald (90), and Kirwan (149) added new details but no new principles. The problem, indeed, was carried as far as was possible until further advances were made in plant physiology and in chemistry. The writers just mentioned are, however, too important to be passed over completely. Wallerius, in 1761, professor of chemistry at Upsala, after analysing plants to discover the materials on which they live, and arguing that *Nutritio non fieri potest a rebus heterogeneis, sed homogeneis*, concludes that humus, being *homogeneus*, is the source of their food—the *nutritiva*—while the other soil

[1] Recorded by most early writers, *e.g.* Evelyn (*Terra*, 1674) (97).

constituents are *instrumentalia*, making the proper food mixture, dissolving and attenuating it, till it can enter the plant root. Thus chalk and probably salts help in dissolving the "fatness" of the humus. Clay helps to retain the "fatness" and prevent it being washed away by rain: sand keeps the soil open and pervious to air. The Earl of Dundonald, in 1795, adds alkaline phosphates to the list of nutritive salts, but he attaches chief importance to humus as plant food. The "oxygenation" process going on in the soil makes the organic matter insoluble and therefore useless for the plant; lime, "alkalis and other saline substances" dissolve it and change it to plant food; hence these substances should be used alternately with dung as manure. Manures were thus divided, as by Wallerius, into two classes: those that afford plant food, and those that have some indirect effect.

Throughout this period it was believed that plants could generate alkalis. "Alkalies," wrote Kirwan in 1796, "seem to be the product of the vegetable process, for either none, or scarce any, is found in the soils, or in rain water." In like manner Lampadius thought he had proved that plants could generate silica. The theory that plants agreed in all essentials with animals was still accepted by many men of science; some interesting developments were made by Erasmus Darwin in 1803 (77).

Between 1770 and 1800 work was done on the effects of vegetation on air that was destined to revolutionise the ideas of the function of plants in the economy of Nature, but its agricultural significance was not recognised until later. In 1771 Priestley (230), knowing that the atmosphere becomes vitiated by animal respiration, combustion, putrefaction, etc., and realising that some natural purification must go on, or life would not longer be possible, was led to try the effect of sprigs of living mint on vitiated air. He found that the mint made the air purer, and concludes "that plants, instead of affecting the air in the same manner with animal respiration, reverse the effects of breathing, and tend to keep the atmosphere pure and

wholesome, when it is become noxious in consequence of animals either living, or breathing, or dying, and putrefying in it." But he had not yet discovered oxygen, and so could not give precision to his discovery: and when, later on, he did discover oxygen and learn how to estimate it, he unfortunately failed to confirm his earlier results because he overlooked a vital factor, the necessity of light. He was therefore unable to answer Scheele, who had insisted that plants, like animals, vitiate the air. It was Ingen-Housz (142) who reconciled both views and showed that purification goes on in light only, whilst vitiation takes place in the darkness. Jean Senebier at Geneva had also arrived at the same result. He also studied the converse problem—the effect of air on the plant, and in 1782 argued (258) that the increased weight of the tree in Van Helmont's experiment (p. 2) came from the fixed air. "Si donc l'air fixe, dissous dans l'eau de l'atmosphère, se combine dans la parenchyme avec la lumière et tous les autres élémens de la plante; si le phlogistique de cet air fixe est sûrement précipité dans les organes de la plante, si ce précipité reste, comme on le voit, puisque cet air fixe sort des plantes sous la forme d'air déphlogistiqué, il est clair que l'air fixe, combiné dans la plante avec la lumière, y laisse une matière qui n'y seroit pas, et mes expériences sur l'étiolement suffisent pour le démontrer." Later on Senebier translated his work into the modern terms of Lavoisier's system.

2. *The Modern Period*, 1800-1860.

(*a*) *The Foundation of Plant Physiology.*—We have seen that Home in 1756 pushed his inquiries as far as the methods in vogue would permit, and in consequence no marked advance was made for forty years. A new method was wanted before further progress could be made, or before the new idea introduced by Senebier could be developed. Fortunately, this was soon forthcoming. To Théodore de Saussure, in 1804 (244), son of the well-known de Saussure of Geneva, is due the quantitative experimental method which more than anything else

has made modern agricultural chemistry possible: which formed the basis of subsequent work by Boussingault, Liebig, Lawes and Gilbert, and, indeed, still remains our safest method of investigation. Senebier tells us that the elder de Saussure was well acquainted with his work, and it is therefore not surprising that the son attacked two problems that Senebier had also studied—the effect of air on plants and the nature and origin of salts in plants. De Saussure grew plants in air or in known mixtures of air and carbon dioxide, and measured the gas changes by eudiometric analysis and the changes in the plant by "carbonisation." He was thus able to demonstrate the central fact of plant respiration—the absorption of oxygen and the evolution of carbon dioxide, and further to show the decomposition of carbon dioxide and evolution of oxygen in light. Carbon dioxide in small quantities was a vital necessity for plants, and they perished if it was artificially removed from the air. It furnished them not only with carbon, but also with some oxygen. Water is also decomposed and fixed by plants. On comparing the amount of dry matter gained from these sources with the amount of material that can enter through the roots even under the most favourable conditions, he concludes that the soil furnished only a very small part of the plant food. Small as it is, however, this part is indispensable: it supplies nitrogen—*une partie essentielle des végétaux*—which, as he had shown, was not assimilated direct from the air; and also ash constituents, *qui peuvent contribuer à former, comme dans les animaux, leur parties solides ou osseuses.* Further, he shows that the root is not a mere filter allowing any and every liquid to enter the plant; it has a special action and takes in water more readily than dissolved matter, thus effecting a concentration of the solution surrounding it; different salts, also, are absorbed to a different extent. Passing next to the composition of the plant ash, he shows that it is not constant, but varies with the nature of the soil and the age of the plant; it consists mainly, however, of alkalis and phosphates. All the constituents of the ash occur in humus. If a

plant is grown from seed in water there is no gain in ash: the amount found at the end of the plant's growth is the same as was present in the seed excepting for a relatively small amount falling on the plant as dust. Thus he disposes finally of the idea that the plant *generated* potash.

After the somewhat lengthy and often wearisome works of the earlier writers it is very refreshing to turn to de Saussure's concise and logical arguments and the ample verification he gives at every stage. But for years his teachings were not accepted, nor were his methods followed.

The two great books on agricultural chemistry then current still belonged to the old period. Thaer and Davy, while much in advance of Wallerius, the textbook writer of 1761, nevertheless did not realise the fundamental change introduced by de Saussure; it has always been the fate of agricultural science to lag behind pure science. Thaer published his *Grundsätze der rationellen Landwirtschaft* in 1809-1812: it had a great success on the Continent as a good, practical handbook, and was translated into English as late as 1844 by Cuthbert Johnson. Davy's book (79) grew out of the lectures which he gave annually at the Royal Institution on agricultural chemistry between 1802 and 1812; it was published in 1813, and forms the last textbook of the older period. Whilst no great advance was made by Davy himself (indeed his views are distinctly behind those of de Saussure) he carefully sifted the facts and hypotheses of previous writers, and gives us an account, which, however defective in places, represents the best accepted knowledge of the time, set out in the new chemical language. His great name gave the subject an importance it would not otherwise have had.[1] He did not accept de Saussure's conclusion that plants obtain their carbon chiefly from the carbonic acid of

[1] Thus Charles Lamb, *Essays of Elia* (1820-1823) in the "Old and New Schoolmaster," writes: "The modern schoolmaster is required to know a little of everything because his pupil is required not to be entirely ignorant of anything. He is to know something of pneumatics, of chemistry, the quality of soils, etc. . . ."

the air: some plants, he says, appear to be supplied with carbon chiefly from this source but in general he supposes the carbon to be taken in through the roots. Oils are good manures because of the carbon and hydrogen they contain; soot is valuable, because its carbon is "in a state in which it is capable of being rendered soluble by the action of oxygen and water." Lime is useful because it dissolves hard vegetable matter. Once the organic matter has dissolved there is no advantage in letting it decompose further: putrid urine is less useful as manure than fresh urine, whilst it is quite wrong to cause farmyard manure to ferment before it is applied to the land. All these ideas have long been given up, and indeed there never was any sound experimental evidence to support them. It is even arguable that they would not have persisted so long as they did had it not been for Davy's high reputation. His insistence on the importance of the physical properties of soils—their relationship to heat and to water—was more fortunate and marks the beginning of soil physics, afterwards developed considerably by Schübler (254). On the Continent, to an even greater extent than in England, it was held that plants drew their carbon and other nutrients from the soil humus, a view supported by the very high authority of Berzelius.[1]

(*b*) *The Foundation of Agricultural Science.*—Hitherto experiments had been conducted either in the laboratory or in small pots: about 1834, however, Boussingault, who was already known as an adventurous traveller in South America, began a series of field experiments on his farm at Bechelbronn in Alsace. These were the first of their kind: to Boussingault, therefore, belongs the honour of having introduced the method by which the new agricultural science was to be developed. He reintroduced the quantitative methods of de Saussure, weighed and analysed the manures used and the crops obtained, and at the end of the rotation drew up a bal-

[1] J. J. Berzelius, *Lehrbuch d. chemie*, ubersetz. v. F. Wöhler, 3 Aufl., 1839, Bd. 8.

ance sheet, showing how far the manure had satisfied the needs of the crop and how far other sources of supply—air, rain, and soil—had been drawn upon. The results of one experiment are given in Table I. on this page. At the end of the period the soil had returned to its original state of productiveness, hence the dry matter, carbon, hydrogen, and oxygen not accounted for by the manure must have been supplied by the air and rain, and not by the soil. On the other hand, the manure afforded more mineral matter than the crop took off, the balance remaining in the soil. Other things being equal, he argued that the best rotation is one which yields the greatest amount of organic matter over and above what is present in the manure. No fewer than five rotations were studied, but it will suffice to set out only the nitrogen statistics (Table II. on page 14), which show a marked gain of nitrogen when the newer rotations are adopted, but not where wheat only is grown.

TABLE I.—STATISTICS OF A ROTATION. BOUSSINGAULT (45).

	Weight in kilograms per hectare of					
	Dry Matter.	Carbon.	Hydrogen.	Oxygen.	Nitrogen.	Mineral Matter.
1. Beets	3172	1357·7	184·0	1376·7	53·9	199·8
2. Wheat	3006	1431·6	164·4	1214·9	31·3	163·8
3. Clover hay	4029	1909·7	201·5	1523·0	84·6	310·2
4. Wheat	4208	2004·2	230·0	1700·7	43·8	229·3
Turnips (catch crop)	716	307·2	39·3	302·9	12·2	54·4
5. Oats	2347	1182·3	137·3	890·9	28·4	108·0
Total during rotation	17478	8192·7	956·5	7009·0	254·2	1065·5
Added in manure	10161	3637·6	426·8	2621·5	203·2	3271·9
Difference not accounted for, taken from air, rain, or soil	+7317	+4555·1	+ 529·7	+4387·5	+ 51·0	−2206·4

1000 kilograms per hectare = 16 cwt. per acre.

TABLE II.—NITROGEN STATISTICS OF VARIOUS ROTATIONS. BOUSSINGAULT (45).

Rotation.	Kilograms per hectare.			
	Nitrogen in Manure.	Nitrogen in Crop.	Excess in Crop over that supplied in Manure.	
			Per Rotation.	Per Annum.
(1) Potatoes, (2) wheat, (3) clover, (4) wheat, turnips,[1] (5) oats .	203·2	250·7	47·5	9·5
(1) Beets, (2) wheat, (3) clover, (4) wheat, turnips,[1] (5) oats .	203·2	254·2	51·0	10·2
(1) Potatoes, (2) wheat, (3) clover, (4) wheat, turnips,[1] (5) peas, (6) rye	243·8	353·6	109·8	18·3
Jerusalem artichokes, two years .	188·2	274·2	86·0	43·0[2]
(1) Dunged fallow, (2) wheat, (3) wheat	82·8	87·4	4·6	1·5
Lucerne, five years . . .	224·0	1078·0	854	170·8

Now the rotation has not impoverished the soil, hence he concludes that " l'azote peut entrer directement dans l'organisme des plantes, si leur parties vertes sont aptes à le fixer." Boussingault's work covers the whole range of agriculture and deals with the composition of crops at different stages of their growth, with soils, and with problems in animal nutrition. Unfortunately the classic farm of Bechelbronn did not remain a centre of agricultural research and the experiments came to an end. Some of the work was summarised by Dumas in a very striking essay (88, see also 46) that has been curiously overlooked by agricultural chemists.

During this period (1830-1840) Carl Sprengel was studying the ash constituents of plants, which he considered were probably essential to nutrition (268). Schübler was working at soil physics (254), and a good deal of other work was quietly being done. No particularly important discoveries were being made, no controversies were going on, and no great amount of interest was taken in the subject.

[1] Catch crop, *i.e.* taken in autumn after the wheat.

[2] This crop does not belong to the leguminosæ, but it is possible that the nitrogen came from the soil, and that impoverishment was going on.

But all this was changed in 1840 when Liebig's famous report to the British Association upon the state of organic chemistry, afterwards published as *Chemistry in its Application to Agriculture and Physiology* (168*a*), came like a thunderbolt upon the world of science. With polished invective and a fine sarcasm he holds up to scorn the plant physiologists of his day for their continued adhesion, in spite of accumulated evidence, to the view that plants derive their carbon from the soil and not from the carbonic acid of the air. "All explanations of chemists must remain without fruit, and useless, because, even to the great leaders in physiology, carbonic acid, ammonia, acids, and bases, are sounds without meaning, words without sense, terms of an unknown language, which awake no thoughts and no associations." The experiments quoted by the physiologists in support of their view are all "valueless for the decision of any question." "These experiments are considered by them as convincing proofs, whilst they are fitted only to awake pity." Liebig's ridicule did what neither de Saussure's nor Boussingault's logic had done: it finally killed the humus theory. Only the boldest would have ventured after this to assert that plants derive their carbon from any source other than carbon dioxide, although it must be admitted that we have no proof that plants really do obtain all their carbon in this way. Thirty years later, in fact, Grandeau (112) adduced evidence that humus may, after all, contribute something to the carbon supply, and his view found some acceptance in France;[1] for this also, however, convincing proof is lacking. But for the time carbon dioxide was considered to be the sole source of the carbon of plants. Hydrogen and oxygen came from water, and nitrogen from ammonia. Certain mineral substances were essential: alkalis were needed for neutralisation of the acids made by plants in the course of their vital processes, phosphates were necessary for seed formation, and potassium silicates for the development of grasses and cereals.

[1] See *e.g.* L. Cailletet (*Compt. Rend.*, 1911, **152**, 1215-1217), Jules Lefèvre (*Compt. Rend.*, 1905, **141**, 211-213), and J. Laurent, *Rev. gén. bot.*, 1904, **16**, 14.

The evidence lay in the composition of the ash: plants might absorb anything soluble from the soil, but they excreted from their roots whatever was non-essential. The fact of a substance being present was therefore sufficient proof of its necessity.

Plants, Liebig argued, have an inexhaustible supply of carbonic acid in the air. But time is saved in the early stages of plant growth if carbonic acid is being generated in the soil, for it enters the plant root and affords extra nutriment over and above what the small leaves are taking in. Hence a supply of humus, which continuously yields carbonic acid, is advantageous. Further, the carbonic acid attacks and dissolves some of the alkali compounds of the soil and thus increases the mineral food supply. The true function of humus is to evolve carbonic acid.

The alkali compounds of the soil are not all equally soluble. A weathering process has to go on, which is facilitated by liming and cultivation, whereby the comparatively insoluble compounds are broken down to a more soluble state. The final solution is effected by acetic acid excreted by the plant root, and the dissolved material now enters the root.

The nitrogen is taken up as ammonia, which may come from the soil, from added manure, or from the air. In order that a soil may remain fertile it is necessary and sufficient to return in the form of manure the mineral constituents and the nitrogen that have been taken away. When sufficient crop analyses have been made it will be possible to draw up tables showing the farmer precisely what he must add in any particular case.

An artificial manure known as Liebig's patent manure was made up on these lines and placed on the market.

Liebig's book was meant to attract attention to the subject, and it did; it rapidly went through several editions, and as time went on Liebig developed his thesis, and gave it a quantitative form: "The crops on a field diminish or increase in exact proportion to the diminution or increase of the

mineral substances conveyed to it in manure." He further adds what afterwards became known as the Law of the Minimum, " by the deficiency or absence of *one* necessary constituent, all the others being present, the soil is rendered barren for all those crops to the life of which *that one* constituent is indispensable." These and other amplifications in the third edition, 1843, gave rise to much controversy. So much did Liebig insist, and quite rightly, on the necessity for alkalis and phosphates, and so impressed was he by the gain of nitrogen in meadow land supplied with alkalis and phosphates alone, and by the continued fertility of some of the fields of Virginia and Hungary and the meadows of Holland, that he began more and more to regard the atmosphere as the source of nitrogen for plants. Some of the passages of the first and second editions urging the necessity of ammoniacal manures were deleted from the third and later editions. " If the soil be suitable, if it contain a sufficient quantity of alkalis, phosphates, and sulphates, nothing will be wanting. The plants will derive their ammonia from the atmosphere as they do carbonic acid," he writes in the *Farmer's Magazine*.[1] Ash analysis led him to consider the turnip as one of the plants " which contain the least amount of phosphates and therefore require the smallest quantity for their development." These and other practical deductions were seized upon and shown to be erroneous by Lawes (161) who had for some years been conducting vegetation experiments. Lawes does not discuss the theory as such, but tests the deductions Liebig himself draws and finds them wrong. Further trouble was in store for Liebig; his patent manure when tried in practice *had failed*. This was unfortunate, and the impression in England at any rate was, in Philip Pusey's words: " The mineral theory, too hastily adopted by Liebig, namely, that crops rise and fall in direct proportion to the quantity of

[1] *Farmer's Magazine*, 1847, vol. xvi., p. 511. A good summary of Liebig's position is given in his *Letters on Chemistry*, 34th letter, 3rd edition, p. 519, 1851.

mineral substances present in the soil, or to the addition or abstraction of these substances which are added in the manure, has received its death-blow from the experiments of Mr. Lawes."

And yet the failure of the patent manure was not entirely the fault of the theory, but only affords further proof of the numerous pitfalls of the subject. The manure was sound in that it contained potassium compounds and phosphates (it ought, of course, to have contained nitrogen compounds), but it was unfortunately rendered insoluble by fusion with lime and calcium phosphate so that it should not too readily wash out in the drainage water. Not till Way had shown in 1850 that *soil precipitates soluble salts of ammonium, potassium, and phosphates* was the futility of the fusion process discovered, and Liebig saw the error he had made (168*b*).

Meanwhile the great field experiments at Rothamsted had been started by Lawes and Gilbert in 1843. These experiments were conducted on the same general lines as those begun earlier by Boussingault, but they have the advantage that they are still going on, having been continued year after year on the same ground without alteration, except in occasional details, since 1852. The mass of data now accumulated is considerable and it is being treated by modern statistical methods. Certain conclusions are so obvious, however, that they can be drawn on mere inspection of the data. By 1855 the following points were definitely settled (164*c*) :—

(1) Crops require phosphates and salts of the alkalis, but the composition of the ash does not afford reliable information as to the amounts of each constituent needed, *e.g.* turnips require large amounts of phosphates, although only little is present in their ash. Some of the results are :—

Composition of ash, per cent. (1860 crop)—		Yield of turnips, tons per acre (1843)—	
K_2O . . .	44·8	Unmanured . . .	4·5
P_2O_5 . . .	7·9	Superphosphate . .	12·8
		„ + potassic salts	11·9

(2) Non-leguminous crops require a supply of some nitrogenous compounds, nitrates and ammonium salts being almost

equally good. Without an adequate supply no increases of growth are obtained, even when ash constituents are added. The amount of ammonia obtainable from the atmosphere is insufficient for the needs of crops. Leguminous crops behaved abnormally.

(3) Soil fertility may be maintained for some years at least by means of artificial manures.

(4) The beneficial effect of fallowing lies in the increase brought about in the available nitrogen compounds in the soil.

Although many of Liebig's statements were shown to be wrong, the main outline of his theory as first enunciated stands. It is no detraction that de Saussure had earlier published a somewhat similar, but less definite view of nutrition: Liebig had brought matters to a head and made men look at their cherished, but unexamined, convictions. The effect of the stimulus he gave can hardly be over-estimated, and before he had finished, the essential facts of plant nutrition were settled and the lines were laid down along which scientific manuring was to be developed. The water cultures of Knop and other plant physiologists showed conclusively that potassium, magnesium, calcium, iron, phosphorus, along with sulphur, carbon, nitrogen, hydrogen, and oxygen are all necessary for plant life. The list differs from Liebig's only in the addition of iron and the withdrawal of silica; but even silica, although not strictly essential, is advantageous to cereals.

In two directions, however, the controversies went on for many years. Farmers were slow to believe that "chemical manures" could ever do more than stimulate the crop, and declared they must ultimately exhaust the ground. The Rothamsted plots falsified this prediction; manured year after year with the same substances and sown always with the same crops, they even now, after sixty years of chemical manuring, continue to produce good crops, although secondary effects have sometimes set in. In France the great missionary was

Georges Ville, whose lectures were given at the experimental farm at Vincennes during 1867 and 1874-1875 (284). He went even further than Lawes and Gilbert, and maintained that artificial manures were not only more remunerative than dung, but were the only way of keeping up fertility. In recommending mixtures of salts for manure he was not guided by ash analysis but by field trials. For each crop one of the four constituents, nitrogen compounds, phosphates, lime, and potassium compounds (he did not consider it necessary to add any others to his manures) was found by trial to be more wanted than the others and was therefore called the "dominant" constituent. Thus for wheat he obtained the following results, and therefore concluded that on his soil wheat required a good supply of nitrogen, less phosphate, and still less potassium :—

	Crop per acre. Bushels.
Normal manure	43
Manure without lime	41
„ „ potash	31
„ „ phosphate	26½
„ „ nitrogen	14
Soil without manure	12

Other experiments of the same kind showed that nitrogen was the dominant for all cereals and beetroot, potassium for potatoes and vines, phosphates for the sugar cane. An excess of the dominant constituent was always added to the crop manure. The composition of the soil had to be taken into account, but soil analysis was no good for the purpose. Instead he drew up a simple scheme of plot trials to enable farmers to determine for themselves just what nutrient was lacking in their soil. His method was thus essentially empirical, but it still remains the best we have; his view that chemical manures are always better and cheaper than dung is, however, too narrow and has not survived.

The second controversy dealt with the source of nitrogen in plants. Priestley had stated that a plant of *Epilobium hirsutum* placed in a small vessel absorbed during the course of the month seven-eighths of the air present. De Saussure,

however, denied that plants assimilated gaseous nitrogen. Boussingault's pot-experiments showed that peas and clover could get nitrogen from the air while wheat could not (44), and his rotation experiments emphasised this distinction. He himself did not make as much of this discovery as he might have done, but Dumas (88) fully realised its importance.

Liebig, as we have seen, maintained that ammonia, but not gaseous nitrogen, was taken up by plants, a view confirmed by Lawes, Gilbert, and Pugh (163) in the most rigid demonstration that had yet been attempted. Plants of several natural orders, including the leguminosæ, were grown in surroundings free from ammonia or any other nitrogen compound. The soil was burnt to remove all trace of nitrogen compounds while the plants were kept throughout the experiment under glass shades, but supplied with washed and purified air and with pure water. In spite of the ample supply of mineral food the plants languished and died: the conclusion seemed irresistible that plants could not utilise gaseous nitrogen. For all non-leguminous crops this conclusion agreed with the results of field trials. But there remained the very troublesome fact that leguminous crops required no nitrogenous manure and yet they contained large quantities of nitrogen, and also enriched the soil considerably in this element. Where had the nitrogen come from? The amount of combined nitrogen brought down by the rain was found to be far too small to account for the result. For years experiments were carried on, but the problem remained unsolved. Looking back over the papers [1] one can see how very close some of the older investigators were to the discovery of the cause of the mystery: in particular Lachmann (158) in 1858 carefully examined the structure of the nodules, which he associated with the nutrition of the plant, and showed that they contained "vibrionenartige" organisms. But his paper was published in an obscure journal and attracted little

[1] A summary of the voluminous literature is contained in Löhnis *Handbuch der Landw. Bakteriologie*, pp. 646 *et seq.*

attention, and once again an investigation in agricultural chemistry had been brought to a standstill for want of new methods of attack.

The Beginnings of Soil Bacteriology.

It had been a maxim with the older agricultural chemists that "corruption is the mother of vegetation." Animal and vegetable matter had long been known to decompose with formation of nitrates: indeed nitre beds made up from such decaying matter were the recognised source of nitrates for the manufacture of gunpowder during the European Wars of the seventeenth and eighteenth centuries.[1] No satisfactory explanation of the process had been offered, although the discussion of rival hypotheses continued up till 1860, but the conditions under which it worked were known and on the whole fairly accurately described.

No connection was at first observed between nitrate formation and soil productiveness. Liebig rather diverted attention from the possibility of tracing what now seems an obvious relationship by regarding ammonia as the essential nitrogenous plant nutrient, though he admitted the possible suitability of nitrates (168*c*). Way came much nearer to the truth. In 1856 (298*b*) he showed that nitrates were formed in soils to which nitrogenous fertilisers were added. Unfortunately he failed to realise the significance of this discovery. He was still obsessed with the idea that ammonia was essential to the plant, and he believed that ammonia, unlike other nitrogen compounds, could not change to nitrate in the soil, but was absorbed by the soil by the change he had already described (p. 17). But he only narrowly missed making an important advance in the subject, for after pointing out that nitrates are comparable with ammonium salts as fertilisers he writes: "Indeed the French chemists are going further, several of them now advocating the view that it is

[1] "Instructions sur l'établissement des nitrières, publié par les Régisseurs généraux des Poudres et Salpétre." Paris, 1777.

in the form of nitric acid that plants make use of compounds of nitrogen. With this view I do not myself at present coincide: and it is sufficient here to admit that nitric acid in the form of nitrates has at least a very high value as a manure."

It was not till ten years later, and as a result of work by plant physiologists, that the French view prevailed over Liebig's and agricultural investigators recognised the importance of nitrates to the plant and of nitrification to soil fertility. It then became necessary to discover the cause of nitrification.

During the sixties and seventies great advances were being made in bacteriology, and it was definitely established that bacteria bring about putrefaction, decomposition, and other changes; it was therefore conceivable that they were the active agents in the soil and that the process of decomposition there taking place was not the purely chemical "eremacausis" Liebig had postulated. Pasteur himself had expressed the opinion that nitrification was a bacterial process. The new knowledge was first brought to bear on agricultural problems by Schloesing and Müntz (245) in 1877 during a study of the purification of sewage water by land filters. A continuous stream of sewage was allowed to trickle down a column of sand and limestone so slowly that it took eight days to pass. For the first twenty days the ammonia in the sewage was not affected, then it began to be converted into nitrate; finally all the ammonia was converted during its passage through the column, and nitrates alone were found in the issuing liquid. Why, asked the authors, was there a delay of twenty days before nitrification began? If the process were simply chemical, oxidation should begin at once. They therefore examined the possibility of bacterial action and found that the process was entirely stopped by a little chloroform vapour, but could be started again after the chloroform was removed by adding a little turbid extract of dry soil. Nitrification was thus shown to be due to

micro-organisms—" organised ferments," to use their own expression.

Warington (295-296) had been investigating the nitrates in the Rothamsted soils, and at once applied the new discovery to soil processes. He showed that nitrification in the soil is stopped by chloroform and carbon disulphide; further, that solutions of ammonium salts could be nitrified by adding a trace of soil. By a careful series of experiments described in his four papers to the Chemical Society he found that there were two stages in the process and two distinct organisms: the ammonia was first converted into nitrite and then to nitrate. But he failed altogether to obtain the organisms, in spite of some years of study, by the gelatin plate methods then in vogue. The reason was discovered later: the organisms will not grow in presence of nitrogenous organic matter. Not till 1890 did Winogradsky (311) succeed in isolating them, and thus completing the evidence.

Warington established definitely the fact that nitrogen compounds rapidly change to nitrates in the soil, so that whatever compound is supplied as manure plants get practically nothing but nitrate as food. This closed the long discussion as to the nitrogenous food of non-leguminous plants; in natural conditions they take up nitrates only (or at any rate chiefly), because the activities of the nitrifying organisms leave them no option. The view that plants assimilate gaseous nitrogen has from time to time been revived,[1] but it is not generally accepted.

The apparently hopeless problem of the nitrogen nutrition of leguminous plants was soon to be solved. In a striking series of sand cultures Hellriegel and Wilfarth (130*c*) showed that the growth of non-leguminous plants, barley, oats, etc., was directly proportional to the amount of nitrate supplied, the duplicate pots agreeing satisfactorily; while in the case of

[1] *e.g.* Th. Pfeiffer and E. Franke, *Landw. Versuchs. Stat.*, 1896, **46**, 117; Thos. Jamieson, *Aberdeen Research Assoc. Rpts.*, 1905-1908; C. B. Lipman and J. K. Taylor, *Journ. Franklin Inst. Calif.*, 1924, 475-506.

leguminous plants no sort of relationship existed and duplicate pots failed to agree. After the seedling stage was passed the leguminous plants grown without nitrate made no further progress for a time, then some of them started to grow and did well, while others failed. This stagnant period was not seen where nitrate was supplied. Two of their experiments are given in Table III.:—

TABLE III.—RELATION BETWEEN NITROGEN SUPPLY AND PLANT GROWTH. HELLRIEGEL AND WILFARTH (130*c*).

Nitrogen in the calcium nitrate supplied per pot, grams	none.	·056	·112	·168	·224	·336
Weight of oats obtained (grain and straw)	·3605 ·4191	5·9024 5·8510 5·2867	10·9814 10·9413	15·9974	21·2732 21·4409	30·1750
Weight of peas obtained (grain and straw	·551 3·496 5·233	·9776 1·3037 4·1283	4·9146 9·7671 8·4969	5·6185	9·7252 6·6458	11·3520

Analysis showed that the nitrogen contained in the oat crop and sand at the end of the experiment was always a little less than that originally supplied, but was distinctly greater in the case of peas; the gain in three cases amounted to ·910, 1·242, and ·789 grm. per pot respectively. They drew two conclusions: (1) the peas took their nitrogen from the air; (2) the process of nitrogen assimilation was conditioned by some factor that did not come into their experiment except by chance. In trying to frame an explanation they connected two facts that were already known. Berthelot (26) had made experiments to show that certain micro-organisms in the soil can assimilate gaseous nitrogen. It was known to botanists that the nodules on the roots of leguminosæ contained bacteria.[1] Hellriegel and Wilfarth, therefore, supposed that the bacteria in the nodules assimilated gaseous nitrogen, and then

[1] This had been demonstrated by Lachmann in 1858 (158) (p. 21) and by Woronin in 1866 (317). Eriksson in 1874 (Doctor's dissertation, abs. in *Botan. Ztg.*, 1874, **32**, 381-384) carried on the investigation, while Brunchorst in 1885, *Ber. d. Deutsch. Bot. Ges.*, iii., 241-257, gave the name "bacteroids."

handed on some of the resulting nitrogenous compounds to the plant. This hypothesis was shown to be well founded by the following facts:—

1. In absence of nitrates peas made only small growth and developed no nodules in sterilised sand; when calcium nitrate was added they behaved like oats and barley, giving regular increases in crop for each increment of nitrates (the discordant results of Table III. were obtained on unsterilised sand).

2. They grew well and developed nodules in sterilised sand watered with an extract of arable soil.

3. They sometimes did well and sometimes failed when grown without soil extract and without nitrate in *unsterilised* sand, which might or might not contain the necessary organisms. An extract that worked well for peas might be without effect on lupins or serradella. In other words, the organism is specific.

Hellriegel and Wilfarth read their paper and exhibited some of their plants at the Naturforscher-Versammlung at Berlin in 1886. Gilbert was present at the meeting, and on returning to Rothamsted repeated and confirmed the experiments. At a later date Schloesing fils and Laurent (247) showed that the weight of nitrogen absorbed from the air was approximately equal to the gain by the plant and the soil, and thus finally clinched the evidence.

	Control.	Peas.	Mustard.	Cress.	Spurge.
Nitrogen lost from the air, mgm. .	1·0	134·6	−2·6	−3·8	−2·4
„ gained by crop and soil, mgm.	4·0	142·4	−2·5	2·0	3·2

The organism was isolated by Beijerinck (p. 278) and called *Bacterium radicicola.*

Thus another great controversy came to an end, and the discrepancy between the field trials and the laboratory experiments of Lawes, Gilbert, and Pugh was cleared up. The

laboratory experiments gave the correct conclusion that leguminous plants, like non-leguminous plants, have themselves no power of assimilating gaseous nitrogen; this power belongs to the bacteria associated with them. But so carefully was all organic matter removed from the soil, the apparatus, and the air in endeavouring to exclude all trace of ammonia, that there was no chance of infection with the necessary bacteria. Hence no assimilation could go on. In the field trials the bacteria were active, and here there was a gain of nitrogen.

The general conclusion that bacteria are the real makers of plant food in the soil, and are, therefore, essential to the growth of all plants, was developed by Wollny (314*b*) and Berthelot (28). It was supposed to be proved by Laurent's experiments in 1886 [1] (160). He grew buckwheat on humus obtained from well-rotted dung, and found that plants grew well on the untreated humus, but only badly on the humus sterilised by heat. When, however, soil bacteria were added to the sterilised humus (by adding an aqueous extract of unsterilised soil) good growth took place. The experiment looks convincing, but is really unsound. When a rich soil is heated some substance is formed toxic to plants. The failure of the plants on the sterilised humus was, therefore, not due to absence of bacteria, but to the presence of a toxin. No one has yet succeeded in carrying out this fundamental experiment of growing plants in two soils differing only in that one contains bacteria while the other does not.

Similarly Caron [2] thought he had direct evidence of the beneficial effect of bacteria in plant growth, but in reality the evidence is unsatisfactory.

The close connection between bacterial activity and the nutrition of plants is, however, fully justified by many experiments, and forms a considerable part of our modern conception of the soil as a producer of crops, as will appear in the following chapters.

[1] See also, E. Duclaux, *Compt. Rend.*, 1885, 100, 66.

[2] *Landw. Versuchs. Stat.*, 1895, 45, 401-418.

The Rise of Modern Knowledge of the Soil: the Search for Fresh Factors and for Mathematical Expressions.

Further investigation of soil problems has shown that they are more complex than was at first supposed. The older workers had thought of soil fertility as a simple chemical problem; the early bacteriologists thought of it as bacteriological. It was demonstrated by F. H. King at Wisconsin (147) that physical considerations must also be taken into account. Van Bemellen showed that soil has colloidal properties and present-day workers have observed in the soil many of the phenomena investigated in laboratories devoted to the study of colloids. Whitney and Cameron at Washington greatly widened the subject by revealing the importance of the soil solution and introducing the methods and principles of physical chemistry. Russell and Hutchinson at Rothamsted showed that bacterial action alone would not account for the biological phenomena in the soil, but that other organisms are also concerned, and subsequent work in the Rothamsted laboratories has revealed the presence of a complex soil population, the various members of which react on one another and on the growing plant. Fresh advances are continually being made in the vigorous experiment stations in the United States, the British Empire, Japan, and Europe.

In the main the work is analytical and involves a search for new factors: synthesis is hardly attempted as yet. As the factors are discovered attempts are made to give them mathematical expression. Thus Liebig's Law of the Minimum and F. F. Blackman's Limiting Factors are expressed mathematically by Mitscherlich (p. 34): V. H. Blackman[1] expresses plant growth by the "compound interest law": Miyake (pp. 253 and 259) brings ammonification and nitrification within the equation for autocatalytic actions; and the modern agricultural chemist is acquiring a taste for mathematical formulæ and constants unknown to the older generation of workers.

[1] *Annals of Botany*, 1919, 33, 353.

This attempt to find mathematical expressions has been resisted on two grounds: some suppose that phenomena associated with life cannot in any case be expressed mathematically and that nothing but a hollow appearance of agreement can be obtained; others consider that the mathematical formula, if it is to hold at all, must be expressed in such general terms as to become meaningless, *e.g.* many of the actions going on in Nature can be expressed by exponential equations if the terms are chosen with sufficient ingenuity. The soil investigator, however, will be wise to secure all the assistance he can, as the subject is complex, and it cuts across the conventional divisions of science.

In modern Experimental Stations the tendency is towards team work. As an instance chosen because it is best known to the writer: at the Rothamsted Experimental Station, instead of a number of isolated individuals, there is a body of workers investigating the subject, each from his own special point of view, but each fully cognisant of the work of the others, and periodically submitting his results to discussion by them. Separate workers investigate respectively the bacteria, protozoa, fungi, algæ, helminths, and insects of the soil; in addition physical and organic chemists are studying the soil conditions, while others are concerned in the study of the growing plant. A body of workers by harmonious co-operation is able to make advances that would be impossible for any single individual, however brilliant.

The nature of the subject necessitates a further departure from the usual procedure. In purely laboratory investigations it is customary to adopt the Baconian method in which factors are studied one at a time, all others being kept constant except the particular one under investigation. In dealing with soils in natural conditions, however, it is impossible to proceed in this way: climatic factors will not be kept constant, and however careful the effort to ensure equality of conditions there is always the probability, and sometimes the certainty, that the variable factor under investigation is interacting with

climatic factors and exerting indirect effects which modify or even obscure the direct effects it is desired to study.

Of recent years statisticians have devised methods for dealing with cases where several factors are varying simultaneously. The data obtained by the various workers at Rothamsted are therefore examined by a statistician who endeavours to disentangle the effects of various factors and to state a number of probable relationships which can then be investigated in the laboratory by the ordinary single factor method.

The modern methods as applied at Rothamsted include three distinct processes :—

1. Observations or experiments in the field by a group of specialists working independently, but with full cognisance of each other's results.

2. Examination of the data by modern statistical methods so as to ascertain the probable effects of the known factors and to indicate where known factors are insufficient to account for the results, and where, therefore, new factors must be sought.

3. Laboratory studies by the specialist staff of the relationships indicated by the statistical examination, these being reduced to single factor problems.

CHAPTER II.

SOIL CONDITIONS AFFECTING PLANT GROWTH.

THE five following soil factors profoundly affect the growth of plants :—

1. Water supply.
2. Air supply.
3. Temperature.
4. Supply of plant nutrients.
5. Various injurious factors.

The plant may be affected in three general ways—in the rate of growth over definite periods, the amount of yield finally obtained (*i.e.* the total amount of dry matter formed), or the habit or other characteristic of growth. The two former are susceptible of quantitative investigation, the latter is not, or only with difficulty; it has, therefore, proved less attractive to investigators.

The Effect on the Amount of Growth.

1. *The Study of Single Factors.*

(*a*) *Manurial Factors.*

Of the five factors concerned plant nutrients are, on the whole, the easiest to investigate quantitatively. The general relationship between the supply of a given plant nutrient and the amount of dry matter formed was assumed by Liebig to be one of simple proportion, but the first good experimental investigation was made by Hellriegel at Dhame in the eighties of the last century. Barley was grown in pots of sand, all necessary factors were amply provided, excepting only one

nutrient salt, the amount of which varied in the different pots. The weights of dry matter formed are shown in Table IV.:—

TABLE IV.—EFFECT OF NITROGENOUS FOOD SUPPLY ON THE GROWTH OF BARLEY IN SAND CULTURES. HELLRIEGEL (130c).

Milligrams of nitrogen supplied	0	56	112	168	280	420
Dry matter in crop, grams .	·742	4·856	10·803	17·528	21·289	28·727
Increased yield for each extra 56 mgms. nitrogen . .	—	4·114	5·947	6·725	1·880	2·975
Grain, per cent. of dry matter in crop	11·9	37·9	38	42·6	38·6	43·4
Weight of one grain, mgms. .	19·5	30	33	32	21	30

EFFECT OF POTASSIUM SALTS ON GROWTH OF BARLEY. HELLRIEGEL (130d).

Mgms. of K_2O per pot	0	23·5	47	70·5	94	188	282
Dry matter formed when							
KCl was given .	2·271	5·414	9·024	9·963	15·322	21·246	24·417
K_2SO_4 ,, .	2·549	5·140	5·283	13·363	14·768	21·593	23·774
KNO_3 ,, .	—	4·552	6·621	9·949	14·576	21·499	24·206
KH_2PO_4 ,, .	—	4·687	6·346	9·931	12·377	17·171	—
K_2HPO_4 ,, .	—	—	6·684	—	11·736	20·255	—
Average .	2·410	4·948	6·791	10·801	13·755	20·357	24·132

The results for varying nitrogen supply are plotted on Fig. 1. The first increment of nitrogen produces a certain increase in yield; but the second and third increments produce proportionately more, thus giving a greater return than is expected, if, as Liebig assumed, the effect be simply proportional to the amount present. The fourth and fifth increments, however, produce less effect. The curve, therefore, resembles an S and is described as sigmoid; this is a common shape for curves showing total growth made after the lapse of a definite period of time, though perhaps less common for curves relating to environmental factors. The results for potassium also give a sigmoid curve; this is confirmed by the recent figures of H. Weissmann.[1] Field experiments lead to similar results: those obtained at Rothamsted are set out in Table V.

[1] H. Weissmann, *Zeit. Pflanz. Düngung*, 1923, **2**, A, 1-79.

Other experiments do not always give sigmoid curves, but sometimes a simpler shape showing a continuous fall in effect of the nutrient, the first increment producing the largest effect and subsequent increments less and less effect till finally no additional gain and sometimes even disadvantage ensues.

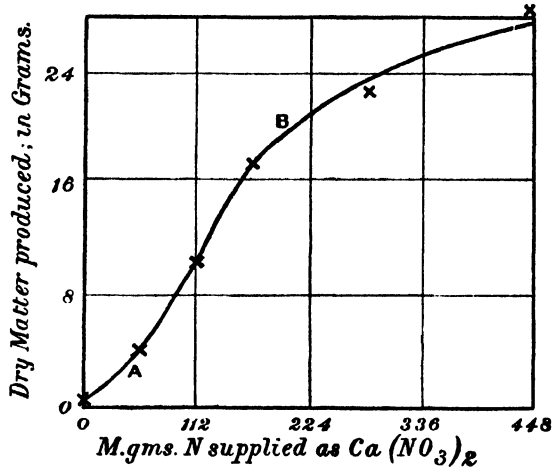


FIG. 1.—Effect of nitrogenous food supply on the growth of barley. (Hellriegel.)

Whether the sigmoid or the continuously falling curve more nearly represents the normal effect of nutrients on plant growth is not known. It is possible in these cases that the first increment was too great so that the point of inflection was missed.

TABLE V.—BROADBALK WHEATFIELD, AVERAGE YIELDS, FIFTY-SIX YEARS, 1852-1907.

	Plot 5.	Plot 6.	Plot 7.	Plot 8.
Nitrogen supplied in manure, lb. per acre .	0	43	86	129
Total produce (straw and grain), lb. per acre	2315	3948	5833	7005
Increase for each 43 lb. nitrogen . .	—	1633	1885	1172

The effect is not simple, there being at least two types of factors concerned, those causing new growth, increasing the

area of the leaf; and those maintaining the growth already formed.

The smoothness of the curve suggests that it can be expressed by a mathematical equation, and E. A. Mitscherlich has attempted to do this, proceeding in the following manner:

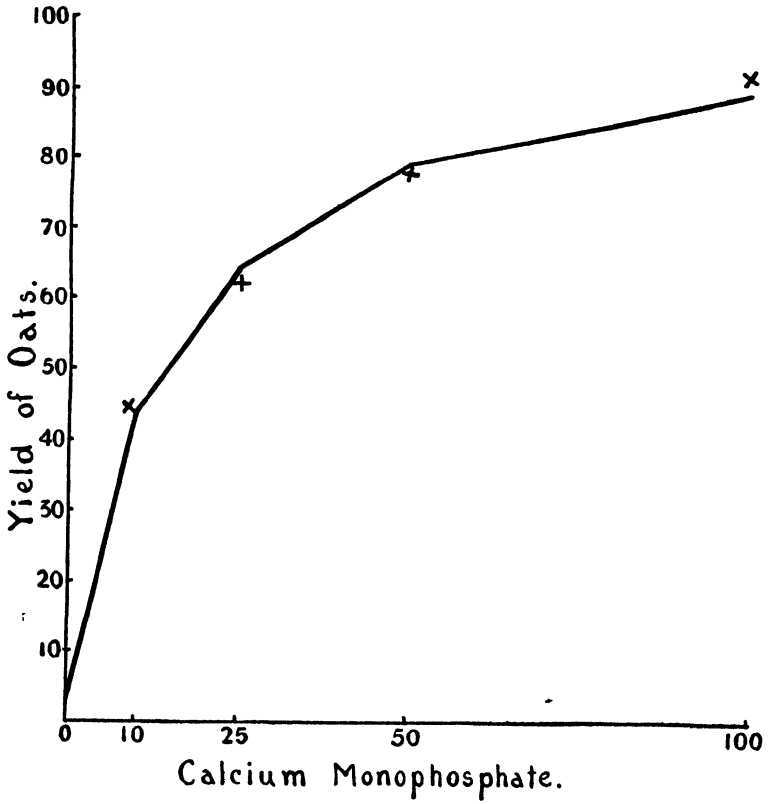


FIG. 2.—Mitscherlich's curve, showing relation between yield of oats and amount of phosphate supplied.

If all the conditions were ideal, a certain maximum yield would be obtained, but in so far as any essential factor is deficient there is a corresponding shortage in the yield. The yield rises if some of the lacking factor is added, and goes up all the further the lower it had previously fallen. Mitscherlich put

this as follows: the increase of crop produced by unit increment of the lacking factor is proportional to the decrement from the maximum. The advantages of this form is that it can be expressed mathematically:—

$$\frac{dy}{dx} = (A - y)k \text{ or } \log_e (A - y) = c - kx,$$

where y is the yield obtained when x = the amount of the factor present and A is the maximum yield obtainable if the factor were present in excess, this being calculated from the equation. Mitscherlich's experiments were made with plants grown in sand cultures supplied with excess of all nutrients excepting the one under investigation. Table VI. shows the

TABLE VI.—YIELD OF OATS WITH DIFFERENT DRESSINGS OF PHOSPHATES. MITSCHERLICH (200*a*).

P_2O_5 in Manure.	Dry Matter Produced.	Crop Calculated from Formula.	Difference.	Difference Expressed in Terms of Probable Error.[1]
Grams.	Grams.	Grams.		
0·00	9·8 ± 0·50	9·80	—	− 0·8
0·05	19·3 ± 0·52	18·91	− 0·39	− 0·3
0·10	27·2 ± 2·00	26·64	− 0·56	− 2·8
0·20	41·0 ± 0·85	38·63	− 2·37	+ 2·9
0·30	43·9 ± 1·12	47·12	+ 3·22	+ 0·7
0·50	54·9 ± 3·66	57·39	+ 2·49	+ 3·0
2·00	61·0 ± 2·24	67·64	+ 6·64	—

results obtained with oats and monocalcic phosphate. If the formula correctly expressed the results, the proportionality factor k (called "Wirkungswert," or "faktor" in Mitscherlich's papers) would be a constant for each fertiliser, independent of the crop, the soil, or other conditions. Knowing its value, an experimenter could, from a single field trial, predict the yields obtainable from any given quantities of the fertiliser, a result of great practical value. Further, it would be possible to estimate by direct pot experiment the amount of available plant food in a soil, one of the most difficult of all soil

[1] If this figure is less than 3 the agreement is considered satisfactory.

problems. Mitscherlich has, indeed, used his formula for this purpose,[1] and in the fourth edition (1923) of his very interesting *Bodenkunde* he applies the expression in a variety of ways, though, it must be admitted, not very convincingly.

Mitscherlich's colleagues in Germany do not all accept his equation. Pfeiffer [2] points out that the curves must be profoundly modified by other factors influencing plant growth, while Frölich took exception, and with considerable justice, to the method of calculating, or rather of selecting, the result.[3] In England Briggs has seriously criticised Mitscherlich's whole treatment of the problem.[4] B. Baule (10) recognised these criticisms, and modified the expression while retaining the

[1] In *Die pflanzenphysiologische Lösung der chemischen Bodenanalyse* (*Landw. Jahrb.*, 1923, 58, 601-617).

[2] Th. Pfeiffer, E. Blanck, and M. Flügel, *Wasser und Licht als Vegetationsfaktoren und ihre Beziehungen zum Gesetze von Minimum* (*Landw. Versuchs-Stat.*, 1912, lxxvi., 169-236).

[3] The method of calculation is as follows: Obtain two equations by substituting two of the numerical values of x and y obtained experimentally. Calling these numbers x_1, x_2, etc., the equations are

$$\log_e (A - y_1) = c - kx_1 \quad . \quad . \quad . \quad . \quad . \quad (1)$$
$$\log_e (A - y_2) = c - kx_2 \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Then by subtraction $\log (A - y_1) - \log (A - y_2) = k(x_2 - x_1)$ . . (3)
Obtain another equation like (3) but select the numerical values so that

$$x_3 - x_2 = x_2 - x$$
$$\log_e (A - y_2) - \log_e (A - y_3) = k(x_3 - x_2) \quad . \quad . \quad . \quad (4)$$

By subtracting (4) from (3) $\log_e (A - y_1) + \log_e (A - y_3) = 2 \log_e (A - y_2)$,

$$i.e. \quad \frac{(A - y_3)(A - y_1)}{(A - y_2)^2} = 1 \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Since y_1, y_2, and y_3 are all known, the value of A is easily calculated.
The value of k is then found from equation (3)—

$$k = \frac{\log_e (A - y_1) - \log_e (A - y_2)}{x_2 - x_1}.$$

As all the quantities on the right-hand side are known the value of k is readily obtained. A difficulty is that different values for A are, in fact, obtained when other equations like (3) are worked out. If there were a very large number of points, a probable value for A could be obtained: with a small number, such as almost necessarily are obtained in practice, some selection apparently has to be made, which is objectionable. This was done by Mitscherlich in the case quoted in Table VI.

[4] *Annals of Botany*, 1925, 39, 475-502.

fundamental assumption. He supposes that each of the factors influencing plant growth acts in accordance with Mitscherlich's assumption, and that the final yield is the product of all the separate expressions. Writing the equation in its integrated form—

$$\frac{y}{A} = 1 - e^{-cx}$$

the yield becomes

$$\text{Yield} = A(1 - e^{-c_1x_1})(1 - e^{-c_2x_2})(1 - e^{-c_3x_3}), \text{ etc.}$$

The efficiency of the nutrient or other factor, called by Baule the " Wirkungsmenge " is then expressed by

$$h = \frac{\log_e 2}{c} = \frac{0{\cdot}7}{c}$$

where c = Mitscherlich's " Wirkungsfactor." [1]

Baule has made several interesting deductions. If two factors vary simultaneously, each produces its own effect independent of the other: when oats were grown in sand, both water and phosphate supply varying, the relative effects of the doses of water remained the same no matter how much phosphate was given (Table VII.).

The theoretical curves expressing the yields are sigmoid if the " Wirkungsmengen " of the two factors are approximately of the same order; but if one greatly preponderates the curve remains logarithmic (Fig. 3).

Baule's expression is difficult to apply in practice, and his method of calculating the very important factor A is tedious. Being based on Mitscherlich's assumption it is, of course,

[1] The " Wirkungsmenge " is defined as the amount of the factor needed to give half of the maximum yield obtainable by increasing the factors, all other factors remaining constant.

$x = h$, when " x " is such that
$y = \frac{1}{2}A$
$1 - e^{-ch}$ then $= \frac{1}{2}$
and $h = \frac{\log_e 2}{c} = \frac{0{\cdot}7}{c}$.

TABLE VII.—YIELD OF OATS IN POT EXPERIMENTS WITH VARIED PHOSPHATE DRESSINGS AND VARIED WATER.

(*Adapted from Mitscherlich.*)

Calcium Phosphate.	Water 1 dose. (*a*)	Water 2 doses. (*b*)	Ratio $\frac{b}{a}$
x = 0	6·4	11·0	1·72
,, = 1	14·6	25·6	1·75
,, = 2	22·6	36·6	1·62
,, = 4	29·7	53·1	1·79
,, = 8	41·3	70·5	1·71
,, = 16	50·8	77·5	1·53
,, = 32	55·7	88·5	1·59

liable to the same general criticisms. But the possibilities are attractive and deserve dispassionate investigation.

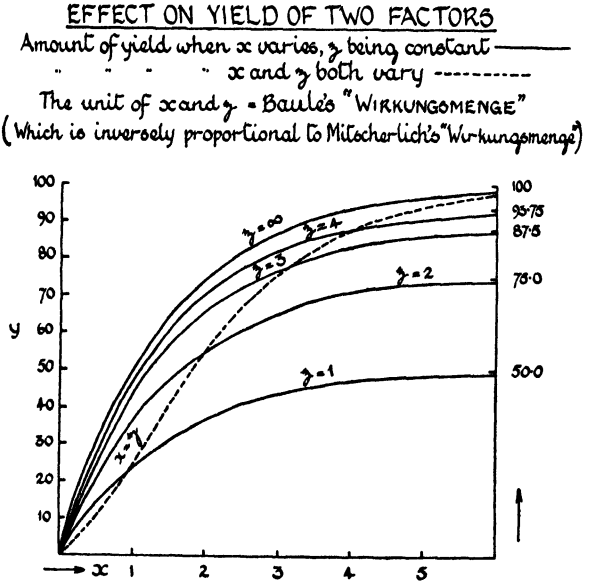


FIG. 3.—Effect on yield when two factors vary. Plain lines: yields for different values of x, each remaining constant while y varies. Dotted line: yield when x and y vary simultaneously, each having the value of its "Wirkungsmenge".

Mitscherlich disregards the harmful effects evident when the factor is present in excess, but possibly operating the whole

time. K. A. Bondorff [1] modifies the equations to allow for this, writing it:—

$$y = cx^m - kx^n + a,$$

y being the yield, x the amount of factor, c, k, m, and n being constants and "a" the yield when none of the factor is present.

cx^m expresses the beneficial effect and kx^n the harmful effect of the factor. For most experiments with fertilisers $m = 1$: sometimes, however, it is greater than 1 and the curve is then sigmoid; for temperature it usually is so.

(*b*) *Temperature.*

The influence of varying water supply and temperature on crop yield has been studied, but owing to greater experimental difficulties, the data are not well suited to mathematical treatment. The temperature results bring out the marked effect of the time factor which causes an important difference of degree, though not of kind, between sustained growth and the individual processes of assimilation, etc., when studied over short periods of time in the laboratory. In the classical experiments of F. F. Blackman and of Miss Matthaei (now A. G. L. Howard) [2] the effect of temperature on assimilation resembled that obtaining in an ordinary chemical reaction when other factors were maintained at such a level that they did not limit its assimilation rate; so also for respiration. Miss Matthaei found that the amounts of carbon dioxide assimilated by a cherry laurel leaf per 30 sq. cms. (about 8 sq. ins.) per hour at various temperatures were:—

Temperature, deg. C.	−6°	+8·8°	11·4°	15°	23·7°	30·5°	37·5°	40·5°	43° [3]
Weight of CO_2 assimilated, grams .	·0002	·0038	·0048	·0070	·0102	·0157	·0238	·0149	·0102

[1] *Nord. Jordbr.-forskn*, 1923, p. 136, and *Kgl. Veter. Landbo. Medd.*, 3, 1924 (French summary).

[2] *Phil. Trans.*, 1905, 197*b*, 47-105.

[3] The rates were maintained only for a short time at the higher temperatures.

By interpolation, the values at 0°, 10°, 20°, etc., can be found, and the rate of assimilation is thus seen approximately to double for every increase of 10°, the usual order of increase in chemical reactions :—[1]

Temperature	0°	10°	20°	30°	37°
Amount of CO_2 assimilated per hour	17·5	42	89	157	238
Increased rate for 10° C. . .	—	2·4	2·1	1·8	1·8

But the total dry weight produced during the whole life of the plant does not increase with temperature in this way. Bialoblocki's (36) results with barley were as follows :—

Temperature	(0)	10°	20°	30°	40°
Dry matter formed, grams . .	(nil)	7·64	8·22	3·85	0·93

The two curves are shown in Figs. 4 and 5.

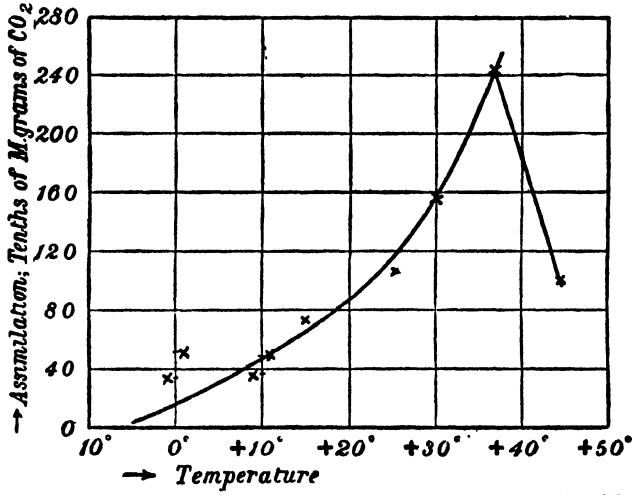


FIG. 4.—Relation between temperature and assimilation. (Miss Matthaei.)

Each of the separate processes—assimilation, respiration, etc., gives, so far as is known, curves like Fig. 4, continuous

[1] More recent values and a full discussion are given by H. Lundegardh, *Die Temperatur faktor bei Kohlensäureassimilation und Atmung* (*Biochem. Zeitsch.*, 1924, 154, 195-234). At temperatures below 15° the values exceed 2; above 20° they are below 2.

over the whole range of temperature nearly up to the death point. Above a certain temperature, however, the curve holds good only for a short time as the protoplasm soon becomes injured.

For satisfactory growth of the plant it is necessary that all the processes should work harmoniously together, and that the protoplasm should remain healthy and vigorous during the whole life of the plant. This is possible only over a restricted temperature range; beyond a certain point, which varies with different plants, further temperature increases do not cause more growth, but throw the adjustment out of gear. Thus the curve begins to bend over (Fig. 5).

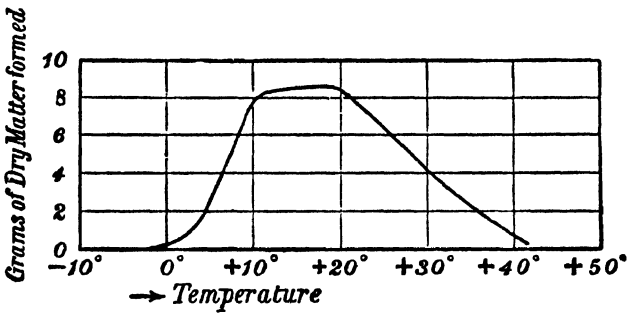


FIG. 5.—Relation between temperature and plant growth. (Bialoblocki.)

The student will observe a close similarity between this curve and that obtained by Duclaux [1] for the relation between enzyme action and temperature. In Fig. 6 AB shows the relation between enzyme action and temperature so long as the activity remains unimpaired; CD shows the relation between temperature and quantity of enzyme, the enzyme being destroyed as the temperature rises; AOE is the resultant curve showing the relation between temperature and the activity of a given initial quantity of enzyme.

In this case the falling off in activity at higher temperatures (OE) is due to the destruction of the enzyme; in the

[1] E. Duclaux, *Traité de Microbiologie*, Tome 2, Paris, 1899.

case of the plant it is attributable to two factors, disadjustment of processes and injury to protoplasm.

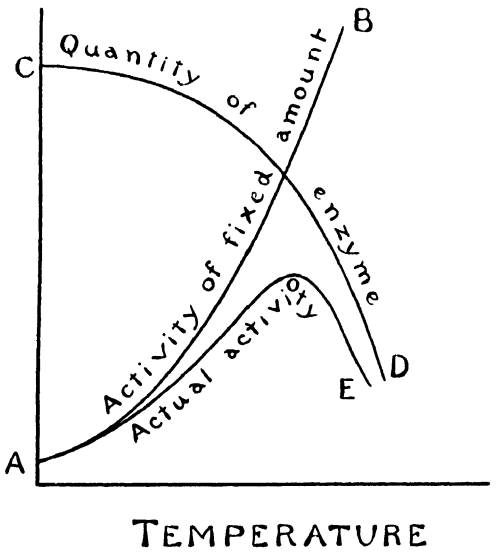


FIG 6.—Influence of temperature on enzyme action, showing fall in quantity but increase in activity as temperature rises. (Duclaux.)

(2) *Variation of Two or more Factors.*

The simple case presented by single factor variation is unusual in natural conditions: more generally two or more factors are present in quantities insufficient for perfect growth. This case has been discussed by F. F. Blackman who has introduced the very happy phrase "limiting factor" to express a conception previously used by H. T. Brown under the name "throttle valve." Generally speaking, the effect of each separate factor is expressible by the single factor curve up to the point where a second factor begins to be insufficient, and then the curve alters considerably: instead of going on continuously the increase of growth falls off considerably or even is brought to an end. A factor that thus proves insufficient and stops or greatly retards what ought to be a continuous process is called a "limiting factor." Growth is once more resumed when the amount of the limiting factor is increased

until again this factor proves insufficient, or some new factor becomes insufficient. The conception of limiting factors, however, must not be used too rigidly. The effects of the various factors are interrelated and the depression of one factor may impede the activity of the others.[1]

These phenomena are illustrated by von Seelhorst's investigations on the effect of water supply on plant growth. In one of their investigations Tucker and von Seelhorst (256) put up three series of soil pots in which the water was kept at a definite amount; one was just moist, another was moister, and a third still moister. These were then each subdivided into three others, one receiving no nitrogen compounds, another one dose, and the third two doses. Oats were sown in all nine sets with results that are given in Table VIII.:—

TABLE VIII.—INFLUENCE OF WATER SUPPLY ON THE EFFECTIVENESS OF MANURES. VON SEELHORST AND TUCKER (256).

Dry Weight of Oat Crop.

Manuring.	Nitrogen Series.			Increased Crop for	
	KP.	KPN.	KP_2N.	First Increment of Nitrogen.	Second Increment of Nitrogen.
I. Moist soil[2]	67·5	68·5	68·5	1·0	0
II. Moister soil	83·6	93·4	94·0	9·8	·6
III. Wettest soil	99·5	119·5	135·0	20·0	15·5

K = 1 grm. of K_2O as K_2CO_3 per pot; P = 1 grm. of P_2O_5 as $Ca(H_2PO_4)_2$ per pot; N = ·5 grm. of N as $NaNO_3$ per pot.

Manuring.	Phosphate Series.				First Increment of P.	Second Increment of P.	Increase for Complete Manure. KNP.
	None.	KN.	KNP.	KN_2P.			
I. Moist soil[2]	41·5	38·5	68·5	79·2	30·0	10·7	27
II. Moister soil	47·2	40·0	93·4	108·0	53·4	14·6	46·2
III. Wettest soil	68·5	63·5	119·5	127·5	56·0	8	51

[1] For a critical discussion see R. Harder, *Kritische Versuche zu Blackman's theorie der begrenzenden Faktoren bei den Kohlensäureassimilation* (*Jahrb. f. Wiss. Bot.*, 1921, 60, 531-571).

[2] The moist soil contained 14·35 per cent. of water (41·6 per cent. of saturation), the moister soil 15·41 per cent. at the beginning, increasing to 18·43 (51·7 per cent. of saturation) as the experiment proceeded, and the wettest soil, 16·44 per cent. at the beginning, increasing to 22·59 (63·7 per cent. of saturation).

When only little water is present there can be only little growth, for which the supply of nitrogen in the soil is adequate. The added 0·5 grm. therefore causes no further growth, though some of it is assimilated by the plant. With larger water supply more growth is possible and this additional nitrogen can be utilised: the crop is now raised by 10 grms. Again, however, the water supply sets a limit, and the second 0·5 grm. of nitrogen is without effect. When a liberal supply of water is added the first 0·5 grm. of nitrogen gives 20 grms. of crop, double the previous increment; but even this does not repre-

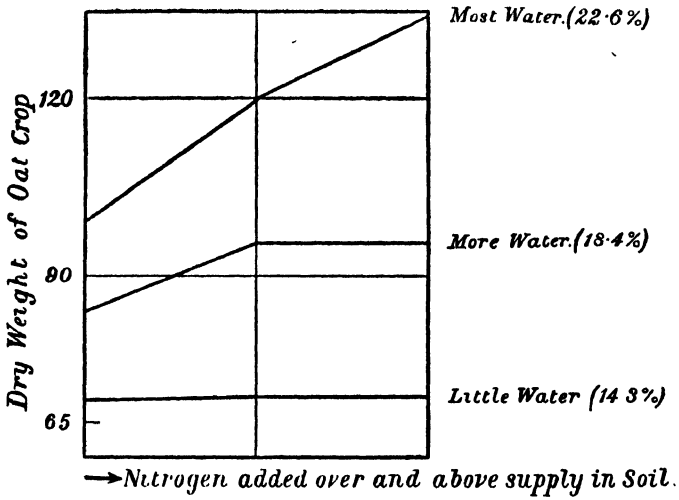


FIG. 7.—Influence of water supply on the effectiveness of manures. (Von Seelhorst and Tucker.)

sent the whole possibility, for the second 0·5 grm. of nitrogen gives a still further increase of 15·5 grms.

The results of the phosphate series are somewhat different in detail, but not in principle. The first dose of P_2O_5 in the soil of lowest water content gives an increased crop, and so does the second, the first not having been large enough; in the wetter soil, however, the increase is much larger. There is a still further increase in the wettest soil, but less than before, some other limiting factor now coming in. These relations are shown in the curves of Fig. 7.

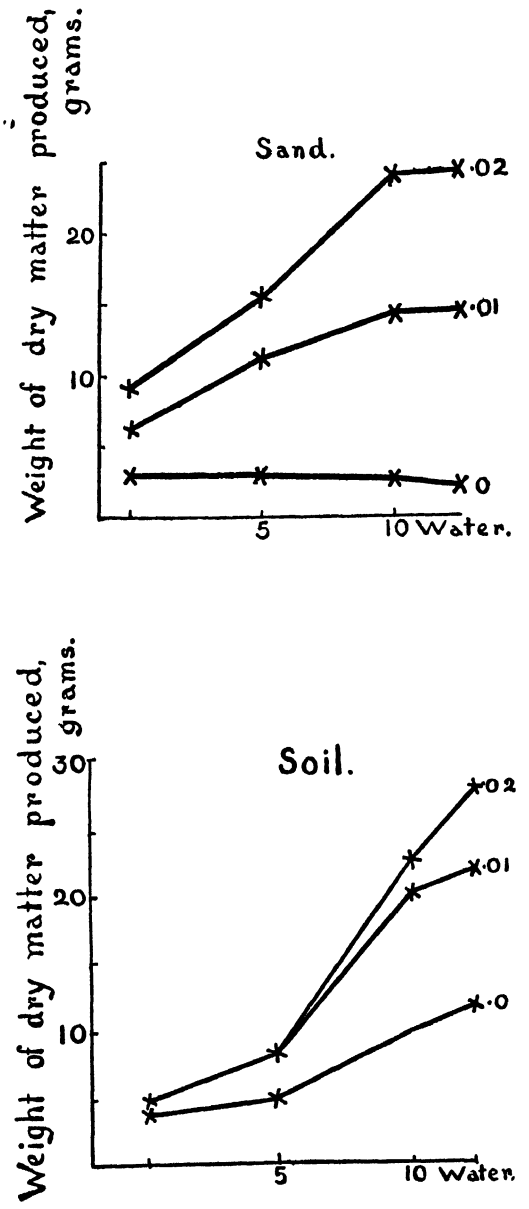


FIG. 8.—Effect of varying water and nitrate supply on the growth of tomatoes in pots of sand and of soil. (E. J. Russell.)

A further illustration is afforded by experiments made by the writer on the growth of tomatoes in pots of sand in which supplies both of water and of nitrate were varied. The results are shown in the curves of Fig. 8. The series of curves is expressible by a surface, which is the proper way of representing the effect of two varying factors on plant growth.[1] No account was taken of temperature variations : to do this would necessitate the construction of a series of surfaces each valid for a particular temperature, or to adopt some mathematical device equivalent to projection in a fourth dimension.

In all these experiments it has been assumed that the ob-

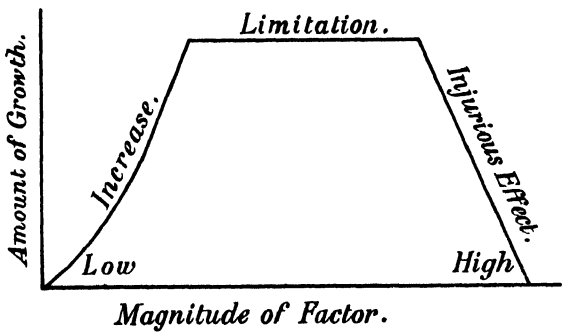


FIG. 9.—General relation between any particular factor and plant growth. An increment in the factor causes increases in growth up to the point when some second factor sets a limit; further increases then have no effect. Finally, excess of the factor brings into prominence any injurious effects it may exert.

served effect is caused by the direct action of the added substance on the plant, and the assumption is justifiable because the plant is grown in sand which is very inert. When, however, a step nearer to natural conditions is taken, and the experiment is carried out in soil it is no longer safe to assume that the soil remains unaltered while the conditions are varied.

Experiments on the growth of tomatoes in soil made simultaneously with those in sand gave a very different result owing to interactions in the soil which will be discussed later.

[1] This has been done by J. A. Prescott in his investigations on the spacing of crops in Egypt (*Sultanic Agric. Soc. Bull.*, No. 13, 1924).

While the curve is still of the general type it differs from those obtained in sand in that there are now more factors at work so that the results are more difficult to interpret.

By using statistical methods it is possible to obtain considerable information about the effects and modes of interaction of the separate factors affecting plant growth, even when a number are acting simultaneously. These methods are used at Rothamsted to study the effects of climatic factors on crop yields (see p. 58).

Effect on Rate of Growth, Habit of Growth or other Plant Characteristics.

Until recently agriculturists have studied only final yields on the grounds that these are the figures of chief agricultural interest, but the results do not entirely represent the effect of the factor under investigation; they are much influenced, and in some seasons determined, by climatic factors, rainfall, temperature, etc., which are unpredictable and vary from year to year. There being until the recent statistical investigations no method of assessing the effects of these fluctuating factors, it has been usual to eliminate them as far as possible by repeating field experiments for a number of years. Lawes and Gilbert usually waited twenty years before discussing results at length; more recent workers, having less time, find four or five years sufficient.

The difficulty about final yields is that they give no indication of what has happened during the plant's life, so that they offer no explanation of why they are sometimes high and sometimes low. The life of the plant falls into several well-defined stages. At the outset it is largely dependent on the endosperm of the parent seed for its nutrients; later on it develops its root and leaf system, assimilating nutrients from the soil and CO_2 from the air, and growing at its maximum rate. Still later growth slackens and the ripening processes begin.

During these different stages the plant is very differently affected by external conditions, and it grows at widely different rates. These growth rates have been studied by plant physiologists for some time past, and they are now being applied on the field plots at Rothamsted. They have the advantage of representing the components of which the final yield is the total summation, showing, in greater detail and more definitely than final yields, the influence of the various conditions, nutrients, etc., on plant growth, and allowing also of a better evaluation of the effects of temperature, rainfall, and other factors. For these effects show up in the forms of the growth curves as irregularities which can be correlated with meteorological and other data.

Several methods are used in the measurement of growth.

(1) Rate of increase of dry weight.

(2) Rate of extension of leaf area obtained by some planimeter or other measurement; these rates were much used by Kreusler (155) in his studies on agricultural crops.

(3) Rate of increase in height of cereals.

For purposes of discussion these quantities can be related to one another: a useful rate is the increase of dry weight per unit leaf area per unit time ("Unit Leaf Rate," West, Briggs and Kidd; Gregory's "Net Assimilation Rate"), which during the early stages of growth seems to change but little with increasing age or dry weight of the plant, or variations in amount of nitrogenous manure (p. 75), but is controlled by radiation, temperature, water, and vapour pressure factors. (Gregory, 115.)

Rate of Increase of Dry Matter.—The increase in dry matter per unit time (a week or ten days makes a convenient unit) can be measured by pulling up a fair sample of the plants from the experimental group at the end of each unit of time, drying them in a steam oven and weighing them; from the successive results the average rate of increase for the whole population over the period can be calculated. The curves showing the rates are usually—though not always—of

the S or sigmoid shape of Fig. 1 ; [1] they may be used for comparing one set of conditions with another, or for correlating external conditions with growth rates.[2] Inspection of the results shows that the plant life does not run a uniform course but is divided into periods which must be kept clearly distinct in these studies. In the first period the plant is pushing out its roots and absorbing considerable quantities of nutrients from the soil without producing a corresponding amount of dry matter. Later on it produces much leaf and stem ; this is the period of active vegetative growth ; still later the stored-up material is translocated to the seed which is now being formed.

Biologists have not been content, however, with studying the curves simply by inspection ; they have made use of the fact that curves can be expressed by mathematical equations. An equation has a satisfying look of completeness and accuracy ; like the camera it cannot lie but it can mislead. The general form of equation which fits any curve is

$$(1) \qquad \frac{dw}{dt} = a + bw + cw^2 + dw^3 + \ldots \text{ etc.}$$

Applied to a growth curve w is the dry weight produced in time t, and a, b, and c, etc., are " constants," in the sense that they are independent of w. They may, however, vary with the time, increasing or decreasing in value as the plant grows older. In that case they are called " functions " of the time. This equation satisfies the essential condition of according with the facts that

(1) The rate of growth of any plant depends on the quantity of leaf and root already formed, and alters as the plant grows larger and extends its absorbing and assimilative surfaces.

[1] The curves showing total growth against time are sigmoid, while those showing relative growth rate against time may be roughly an inverted sigmoid with sometimes a preliminary rise.

[2] For an example, see C. West, G. E. Briggs, and F. Kidd, *New Phytologist*, 1920, 19, 200-207.

(2) Growth does not continue indefinitely, but after a time slows down and comes to an end.

(3) The growing plant is changing all the time: rates of growth are, therefore, not rigidly constant, but are affected by the changes in the plant.

But its widely general nature makes it too indefinite to be particularly helpful to the biologist or to the soil investigator. It has to be simplified before it can be used, and the process of simplification necessitates the making of assumptions. Now the danger of mathematical equations lies in the assumptions they conceal. It would not be difficult to find examples in scientific literature where assumptions have been accepted in a mathematical equation that would have caused some surprise had they been put forward as independent statements.

The equation becomes reduced to its simplest form by omitting the second and all higher powers :—

$$\frac{dw}{dt} = bw,$$

or as it is more usually written,

$$\frac{dw}{dt} = rw. \tag{2}$$

On integration this becomes

$$w = w_0 e^{rt} \text{ or } \log_e \frac{w}{w_0} = rt,$$

where w_0 = initial weight, w = weight after time t,
e = base of natural logarithms,
r = rate of increase per unit time.

This equation states that the rate of growth at any time is proportional to the amount of growth already made, and it expresses in definite form the well-known fact that an increase in leaf area is followed by an increase in weight of the whole plant. The same equation expresses the facts of compound interest, and in applying it to plant growth V. H. Blackman

calls it the " Compound Interest Law," and calls the rate of increase " r " the efficiency index, because it represents the efficiency of the plant as a producer of new material.

The equation can obviously be applied only to the first part of the plant's life since it assumes that growth goes on continuously at an increasing rate. It can no longer be applied when the curve begins to fall off.

The fact of decrease and ultimate cessation of growth can be expressed if the simplification is not carried quite so far and if the second term is left in. The equation then becomes

$$\frac{dw}{dt} = \mathrm{K}w(\mathrm{W} - w) \tag{3}$$

or, if t_1 is the time when half the total growth has been made,

$$\log_e \frac{w}{\mathrm{W} - w} = k(t - t_1)$$

where k is a constant and W = the amount of dry matter finally formed. This equation states that the rate of growth at any time is proportional to the amount of growth already made, and to the amount still to be made before the plant attains the maximum weight. It thus indicates a growth rate that first rises and then falls, becoming zero when full weight is reached; in short, it is the expression for the sigmoid curve in Fig. 1. It fits fairly well the values obtained in certain studies of rates of numerical increase of unicellular organisms. It is also the equation for chemical autocatalysis, and so Brailsford Robertson [1] and his followers have assumed that growth is an autocatalytic process. The identity of the equations, however, proves nothing, and the hypothesis of autocatalysis must stand or fall by its own direct evidence. Many rates of change in which there is no suggestion of autocatalysis can be represented by a sigmoid curve; *e.g.* the speed of a train from its start at one station to its finish at another. Moreover, Gregory finds that the equation does

[1] On the normal rate of growth of an individual and its biological significance, *Arch. f. Entwichlungsmechanik*, 1908, xxv. See also P. Enriques, *Wachstum und seine analytische Darstellung. Biol. Centralblatt*, 1909, xxix., 331.

not fit the data obtained in the actively growing period of barley, although it does fit the data obtained later.

In using the equation in these simple forms, even when restricted to the active period of plant growth, however, it must be clearly remembered that each successive simplification has necessitated further assumptions.

Equation (2) implies :—

(1) That the whole or a constant proportion of the dry matter of the plant is effective in producing new growth.

(2) That the relative growth rate [1] is constant and does not alter as the plant grows older.

Equation (3) implies a change in the relative growth rate determined only by the weight of the dry matter, not *e.g.* by age alone. It is improbable that either of these assumptions is strictly correct, or that either equation rigidly expresses growth rates. The criterion of the value of the mathematical expression is the purely pragmatic test whether or not it serves any useful purpose. Time alone will show this.[2]

Habit of Growth.—Observations in the plant culture house or the field show that variations in soil or climatic conditions may cause considerable differences in the appearance of plants, in the proportion of root or of seed to leaf and stem, in degree of maturation and in other respects. These differences are often of considerable technical importance, profoundly affecting the value of the crop, and they are of great interest as indicators of soil conditions. It cannot, of course, be assumed that a certain appearance or character in the plant is always and necessarily produced by the same soil conditions, but the appearances are often symptomatic

[1] *I.e.* the rate of growth per unit weight.

[2] For further discussion see Gregory (115); C. West, G. E. Briggs, and F. Kidd, *Ann. Appl. Biol.*, 1920, 7, and *New Phytologist*, 1920, 19, 200-207 (there are several misprints in the formulæ on p. 204); R. A. Fisher, *Ann. Appl. Biol.*, 1921, 7, 367-372; Rippel, *J. Landw.*, 1922, 70, 9-44 For studies of the flowering curve of cotton on these lines see W. L. Balls, *The Cotton Plant in Egypt.*, 1912, and J. A. Prescott, *Annals Botany*, 1922, 36, 121-130; and for a different method of treatment, E. A. Mitscherlich, *Landw. Jahrb.*, 1919, 53, 167-182.

and serve to narrow the problem. The detailed discussion of these differences is the province of the modern science of Ecology, but the general results are of great importance to the soil student.[1] They will be dealt with under the headings of the separate factors.

Effect of Water Supply.

Water.—The relationship between the amount of growth and the supply of water is shown by Hellriegel's experiments (130*a*, Table IX.) with barley grown under favourable conditions in sand cultures.

TABLE IX.—GROWTH OF BARLEY WITH VARYING SUPPLY OF WATER. HELLRIEGEL (130*a*).

Amount of water . .	5	10	20	30	40	60	80
Dry matter in grain, grms.	nil.	0·72	7·75	9·73	10·51	9·96	8·77
Dry matter in straw, grms.	·12	1·80	5·50	8·20	9·64	11·00	9·47
1 grain weighed, mgms. .	—	23	35	36	34	32	32

100 represents the amount of water required to saturate the sand.

The yield rises as the water increases up to a certain point, and then falls off because the excess of water reduces the air supply for the roots.

The grain suffers sooner than the leaves and stems. When a series of plants is grown in this way, with varying water supply, certain important qualitative differences are revealed. Those receiving only small amounts of water have small glaucous leaves and tend early to form seed. As the water supply increases, the root system increases rapidly both in extent and in fineness; with further supplies the leaves become successively larger and greener in colour, ripening becomes delayed, but the root system becomes restricted and alters in character, finally consisting of a few stout roots only. Von Seelhorst (256) has made quantitative determinations of

[1] For an example of a survey carried out on these lines, see T. H. Kearney; L. J. Briggs, H. L. Shantz, J. W. McLane, and R. L. Piemeisel, *Indicator Significance of Vegetation in Tooele Valley, Utah* (*Journ. Ag. Research*, 1914, 1, 365-417).

the proportions of root system to entire plant under conditions of varying water supply.[1]

The amount of moisture in the soil affects the concentration and osmotic pressure of the cell sap (Table X.): a low concentration seems to be associated with rapid growth, and a high concentration with slow growth and fruit bud formation.[3] The proportions of sugar, starch, and fibre in the tissues are affected, and even the seed is altered in composition, although this is, of all the parts of the plant, the least susceptible to change, being but little altered by the soil variations produced by manuring. The phenomena have been considerably studied at the Utah Experimental Station, where irrigation problems are of great importance.

TABLE X.—CHANGE IN OSMOTIC PRESSURE OF PLANT CELL WITH CHANGES IN MOISTURE CONTENT OF SOIL. ILJIN (141).

Ratio of Soil Moisture to Absolute Water Capacity of Soil.	Osmotic Pressure when that of Normal Solution of NaCl = 1[2]	
	Helianthus annuus.	Zea Mays.
80 per cent.	0·14-0·16	0·17
60 „	0·25-0·28	0·19
30 „	0·41-0·45	0·49

TABLE XI.—PERCENTAGES OF NITROGEN, ASH, PHOSPHORUS, POTASSIUM, CALCIUM, AND MAGNESIUM IN WHEAT GRAIN GROWN UNDER IRRIGATION. J. E. GREAVES AND E. G. CARTER (114e).

Amount of Irrigation Water.	Calcium.		Magnesium.		Nitrogen.		Ash.		Phosphorus.		Potassium.	
	Per Cent.	lb. per Acre.	Per Cent.	lb. per Acre.	Per Cent.	lb. per Acre.	Per Cent.	lb. per Acre.	Per Cent.	lb. per Acre.	Per Cent.	lb. per Acre.
None .	0·103	2·31	0·170	3·82	2·39	53·82	1·56	35·12	0·295	6·64	0·396	8·92
5 ins..	0·107	2·02	0·171	3·54	2·16	44·88	1·56	34·17	0·301	6·38	0·414	8·97
10 „ .	0·122	2·63	0·172	3·65	2·18	47·14	1·57	35·90	0·306	6·38	0·439	9·49
15 „ .	0·165	3·53	0·172	3·23	1·99	42·38	1·71	36·38	0·323	6·87	0·491	10·47
20 „ .	0·195	3·78	0·198	3·77	1·98	37·75	2·01	38·45	0·371	7·08	0·490	9·35
35 „ .	0·211	4·72	0·207	4·64	2·01	45·12	2·28	51·13	0·458	10·24	0·534	11·95
67·5 „	0·262	5·64	0·224	4·80	2·06	44·70	2·194	47·13	0·424	9·12	0·535	11·50

[1] For other work, see J. E. Weaver, *Root Development of Field Crops*, McGraw-Hill, 1926.

[2] 0·1 per cent. NaCl has an osmotic pressure of approximately four atmospheres.

[3] H. S. Reed, *Journ. Ag. Research*, 1921, 21, 81-98.

The nitrogen content and the ash content of cereal grains are both affected by irrigation, the nitrogen falling to a minimum, and the ash constituents rising to a maximum as the water increases (Table XI.).

Similar changes have been observed as the result of variations in rainfall [1] and of moisture content (induced by variations in the amount of organic matter) of soils under the same rainfall. F. T. Shutt [2] records that wheat grown in newly cleared scrubland in parts of North West Canada is softer, more starchy, and poorer in nitrogen than that grown on adjoining land which, through long cultivation, has lost some of its organic matter and, therefore, its capacity to hold moisture (Table XII.).

The reduction in nitrogen content of the grain with

[1] C. H. Bailey, *Minnesota Expt. Sta. Bull.*, 131, 1913, has drawn up the following table, showing the protein content of the wheat and flour of the hard spring wheat grown in sixteen counties in Minnesota (1st April to 1st September, 1911). Protein = N × 5·7.

Rainfall.	Protein per Cent. Wheat.	Protein per Cent. Flour.
Between 12-14 ins.	14·93	13·47
,, 14-16 ,,	13·73	12·61
,, 16-18 ,,	12·21	12·56
,, 18-20 ,,	13·42	12·29
,, 20-22 ,,	12·88	11·87
,, 22-24 ,,	11·63	10·65

Stewart and Hirst, *Utah Expt. Sta. Bull.*, 125, p. 145, obtained the following results at Utah, showing the effects of irrigation:—

Irrigation.	Protein per Cent.
25 ins.	16·23
15 ,,	12·92
No irrigation.	13·62

For the small effect of soil conditions see *Washington Ag. Expt. Sta. Bull.*, 111, and A. D. Hall, *Journ. Bd. Agric.*, 1904, 2, 321. Sodium hydroxide and magnesium oxide affect composition (p. 93).

See also H. F. Roberts, *J. Ag. Sci.*, 1920, 10, 121-134, and McGuinnis Taylor, *J. Ag. Res.*, 24, 1041. Further data are given by Olsen, *Journ. Ag. Research*, 1923, 24, 939, and by W. F. Gericke, *Science*, 1920, 52, 446, and *Rep. Cal. Expt. Sta.*, 1921-22, 115.

[2] *Journ. Bd. Agric.*, 1910, 17, Supplement, 56-65; also *Canadian Chemistry and Metallurgy*, September, 1925.

TABLE XII.—EFFECT OF SOIL MOISTURE ON NITROGEN CONTENT OF WHEAT GRAIN. F. T. SHUTT.

	Nitrogen in Wheat.		Organic and Volatile Matter in Soil.	Moisture in Soil, per Cent.	
	In Seed.	In Crop.	Per Cent.	May-July.	August.
New Land	2·16	1·94	20·9	36·5-30·5	30·4-32·8
Old Land		2·46	12·8	23·4-21·2	13·2-18·3

increasing water supply is lessened if the water is given frequently in small doses, or, according to Widtsoe and Stewart, (306) applied mostly in the early period of the plant's life, and it is avoided altogether by maintaining the nitrate supply in the soil. Greaves and Carter attribute it to the washing away of soil nitrates, but this will not explain the marked increase in total nitrogen of grain and straw (mainly the latter) recorded in some of the experiments (Table XIII.).

TABLE XIII.—NITROGEN AND ASH IN GRAIN AND STRAW GROWN UNDER IRRIGATION. WIDTSOE AND STEWART (306).

Depth of irrigation, inches	5·0	7·5	10·0	15·0	25·0	35·0	50·0
Nitrogen in grain per cent.	3·167	2·995	2·967	2·886	2·846	2·788	2·804
Nitrogen in straw, per cent.	·858	·910	·893	·845	·840	·802	·923
Nitrogen in grain, lb.	70·00	71·75	72·28	74·04	73·33	75·61	73·68
Nitrogen in straw, lb.	23·84	28·64	28·96	31·36	34·40	36·16	49·60
Total, lb.	93·84	100·39	101·24	105·40	107·73	111·77	123·28
Ash in grain, lb.	57	48	—	53	63	75	68
Ash in straw, lb.	244	318	316	397	455	612	597
Total, lb.	301	366	—	450	518	687	665

The problem is of interest in Great Britain in relation to barley. High malting quality is usually (though not always) associated with low nitrogen content, but as a rule in this

country low nitrogen content and high quality occur in barley grown in dry rather than in wet districts and seasons. This problem deserves fuller investigation.[1]

Variations in habit of growth brought about by variations in water supply are among the commonest of field phenomena. The effects are partly direct and partly indirect, changes being produced in the soil itself which react on the plant.

On moist soils—clays and loams—the plants usually have large wide leaves and grow to a considerable size, whilst on the drier sands the vegetation is narrow leaved and more stunted, but the root system is well developed. A copious water supply leads to a more protracted growth and to a retardation of the ripening processes; indeed, in very wet districts, wheat and barley are grown only with difficulty, if at all, because they are liable to be beaten down, and ripening may be so long delayed that frosts supervene and damage the crop. Oats are less affected, as they are usually cut before they are ripe. Ripening is more affected by water supply than by any other factor excepting temperature.

Climatic Factors.

Water supply and temperature are the two chief factors determining the distribution of crops. In the warm, dry, eastern counties of Great Britain crops are grown for seed; great quantities of wheat and barley are grown in Norfolk, Suffolk, and the Isle of Thanet; mangold seed and turnip seed is produced in East Kent. Wetter districts are more favourable for swedes and oats; very wet districts for grass. The warm, moist, south-west of Cornwall is very favourable for early vegetables, cabbage, cauliflour, etc., whilst the cooler Lincolnshire and Cheshire are well suited to potatoes. It is possible by suitable operations to modify somewhat both the temperature and the water content of the soil, and so to make the soil conditions rather more favourable for any particular crop.

[1] For further data see von Seelhorst (256*b*) and Pfeiffer, Blanck, and Friske (225*c*).

Some interesting results are obtained in glass house practice. Tomato growers have learned to regulate water supply and temperature in such a way as to produce compact bushy plants, which they know by experience give more fruit than the softer, larger plants, obtainable under other conditions. Until the blossom is fertilised or has "set," therefore, vigorous growth is not encouraged, and, in many cases, while the atmosphere is artificially damped, water is actually withheld from the roots until, in the picturesque language of the grower, "the plants cry for it." After "setting," water is liberally supplied and top dressings of manure are given. Analysis of these effects has been begun. R. A. Fisher and his colleagues have studied by statistical methods the effect of rainfall and hours of sunshine on the yields of wheat and barley at Rothamsted (101) and F. G. Gregory has used growth rates successfully in studying the influence of climate on the growth of barley (115). Gregory brings out the important point that the different physiological processes making up plant growth are differently affected by changes in external conditions and thus tend to compensate one another so that the total change in growth is less than might be expected. Thus assimilation per unit area of leaf (net assimilation rate, p. 48) increases or is positively correlated with increasing temperature and radiation up to a point, while rate of growth of leaf area is negatively correlated with it. In fine weather the assimilation is good, but the leaf growth is poor; in poor weather the assimilation is less, but the leaf growth is better; variations in season, therefore, make less difference than might be expected.

Effect of Soil Conditions on Consumption of Water by the Plants.

Many determinations have been made of the weight of the water transpired by plants per gram of dry matter formed, the figure being called the *transpiration coefficient*. This mode of expression is convenient and it gives useful information to the practical grower in irrigated districts, but from the strictly

scientific point of view it suffers from the disadvantage that it implies a causal relationship between transpiration and assimilation when in reality there is none. The transpiration coefficient is in no sense a constant, but it tends to a lower range of values in certain plants, and even in certain varieties of the same plant, than in others (Table XIV.). Varieties are being bred or selected specially suitable to dry districts: unfortunately no correlation appears to exist between water requirements and plant structure, so that the breeder has no guide in his selection except direct and tedious trials.

The numerical value of the coefficient is much affected by the environmental conditions; it increases with the temperature and to some extent with the soil moisture, though not with the rainfall, since this is accompanied by altered temperature conditions; it decreases with increasing supplies of plant nutrients.[1] Table XIV. shows the values obtained by Briggs and Shantz, also by Toulaikoff working at Besentchuck, Samara, Russia,[2] in different years. Richardson finds a consistent relationship between the transpiration coefficient and the rate of evaporation from a free water surface during the period of maximum transpiration.[3]

TABLE XIV.—TRANSPIRATION COEFFICIENTS, *i.e.* WEIGHT OF WATER TRANSPIRED DURING THE PRODUCTION OF UNIT WEIGHT OF DRY MATTER. TOULAIKOFF.

	1911.	1912.	1913.	1914.
Character of season . .	Very dry	Average	Very wet	Rather dry
Wheat, var. Polltawka .	628·4	444·5	338·6	387·6
,, ,, Bieloturka .	756·3	475·9	316·5	397·1
Oats ,, Giant . .	655·1	510·3	347·4	369·9
Barley ,, Moravian. .	617·9	461·6	230·3	413·3

[1] For the effect of light see W. W. Garner, C. W. Bacon, and H. A. Allard, *Journ. Ag. Res.*, 1924, **27**, 119-156.

[2] *Journ. Opitnoi. Agronomii*, 1915, **16**, 36, 37. Abs. in *Bull. Int. Inst.*, Rome, 1915, **6**, 813.

[3] A. E. V. Richardson, *Journ. Dept. Agric.*, Victoria, Australia, 1923, **21**, 193 *et seq.*

BRIGGS AND SHANTZ (55*c*).

Crop.	Extreme Values for Different Varieties.	Mean Value for Genus.
Proso	268 to 341	293
Millet	261 to 444	310
Sorghum	285 to 467	322
Maize	315 to 413	368
Wheat	473 to 559	513
Barley	502 to 556	534
Oats	559 to 622	597
Flax	—	905
Sugar beet	—	397
Potato	—	636
Cow pea	—	571
Clover	789 to 805	797
Lucerne	651 to 963	831
Grasses	—	861
Various native plants (*i.e.* weeds)	277 to 1076	—

The effect of variations in water and food supply on the water requirements of plants was studied by Hellriegel, by von Seelhorst at Göttingen (256), and more recently at the Utah Experiment Station (Fig. 10), and by Richardson in Victoria, Australia.

TABLE XV.—EFFECT OF VARYING WATER SUPPLY [1] AND FOOD SUPPLY ON THE WATER REQUIREMENTS OF OATS. VON SEELHORST.[2]

	Dry Matter Produced, Grams.			Total Water Transpired, Grams.			Water Transpired per Gram of Dry Matter.		
	Soil Moist.	Soil Moister.	Soil still Moister.	Soil Moist.	Soil Moister.	Soil still Moister.	Soil Moist.	Soil Moister.	Soil still Moister.
No manure	39·6	48·8	52·6	10·215	15·245	16·290	259·9	312·9	307·1
Complete manure	49·9	86·7	95·1	11·170	20·490	23·030	225·1	236·8	231·6

[1] The variations in water supply were :—

	5 to 12 May.	12 May to 1 June.	1 June to 1 July.
Soil moist	54·4	54·4	44·8
Soil moister	59·2	64·0	59·2
Soil still moister	64·0	73·9	73·6

Where 100 = saturation of the soil.

[2] *I. f. Landw.*, 1899, **47**, 369-378.

Similar results have been obtained by Wilfarth (Table XVI.) (309*a*) with sugar beets grown in pots of soil containing known but varying amounts of nitrate:—

TABLE XVI.—EFFECT OF VARYING FOOD SUPPLY ON THE WATER REQUIREMENTS OF SUGAR BEET. WILFARTH.

Nitrogen supplied, grams .	·42	1·26	2·10	2·94	3·36	3·78
Weight of dry matter produced, grams . .	23·0	73·9	96·5	132·4	167·6	188·8
Water transpired, grams .	13,100	34,570	39,420	55,190	62,600	72,280
Stated as inches of rain .	3·6	9·4	10·7	15·8	17·0	19·6
Water used per gram of dry matter formed . .	569	468	409	417	374	383

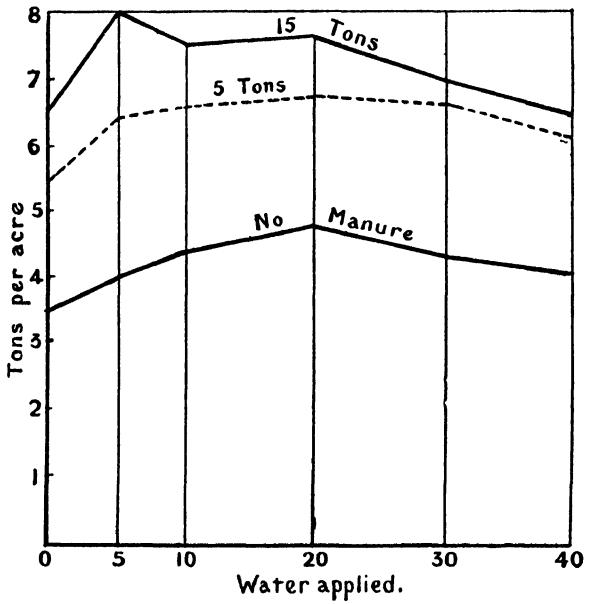


FIG. 10.—Effect of water supply on the effectiveness of farmyard manure. Yield of maize (stover and grain) in tons per acre for 0 to 40 inches irrigation water. (Harris and Butt, Utah, 124.)

Two deductions may be drawn: (1) water is economised by increasing the food supply; (2) the total amount of water required during the growing season to secure the maximum growth permitted by the other conditions may be greater than

is supplied by the rain, in which case the balance must be otherwise provided, or full growth cannot be attained.

Over large areas of the world the rainfall is insufficient, and recourse is had to irrigation. Two further considerations have then to be kept in view: (1) excessive watering has secondary injurious effects on the soil, such as the deterioration of the physical condition, the accumulation of alkali salts, or the formation of toxic reduction products; (2) the requirements of the plant are not always the same, more water being needed during the period of active growth than during germination or ripening.

Some of the results obtained in Utah are set out in Table XVII. and in Fig. 10:—

TABLE XVII.—AVERAGE YIELD OF DRY MATTER AND NITROGEN FROM THE EXPERIMENTAL PLOTS ON GREENVILLE FARM, UTAH. GREAVES, STEWART, AND HIRST (114*b*).

(Expressed as lb. per Acre.)

Water Applied.	Lucerne.		Potatoes.	
	Hay.	Nitrogen.	Tubers.	Nitrogen.
ins.				
37·5	10,464	282·5	1,464	20·4
25·0	9,963	265·0	1,540	24·8
15·0	9,779	259·1	1,759	33·2
None	6,808	170·1	1,075	19·1

Water Applied.	Oats.			Maize.		
	Grain.	Straw.	Nitrogen.	Grain.	Stover.	Nitrogen.
ins.						
37·5	2,273	2,989	89·5	2,080	3,316	66·3
25·0	2,093	2,581	83·9	1,995	3,332	69·6
15·0	1,885	1,821	71·7	2,179	3,605	76·6
None	1,560	1,928	64·0	1,600	3,280	62·3

Field experiments like those conducted by the Punjab Irrigation Department [1] have shown that the cultivator every-

[1] These and similar experiments are discussed by A. and G. L. C. Howard in *Wheat in India: Its Production, Varieties, and Improvement* (Imperial De-

where tends to take too much water, with loss not only to others on the same irrigation system, but also to himself.

Air Supply.[1]

It is well known among farmers and gardeners that soil aeration is essential to fertility, but exact measurements are difficult to obtain. The phenomena are more complex than appears at first sight, involving two wholly distinct factors :—

1. The necessity of a supply of oxygen to the plant root.

2. The toxic effect of the carbon dioxide which invariably accumulates in a non-aerated soil or other medium.

Plants vary considerably in their sensitiveness to these factors. They do not all stand in equal need of oxygen for their roots. E. E. Free (103) grew buckwheat in water cultures, blowing air through one set, and nitrogen, oxygen, and carbondioxide respectively through others. The plants supplied with nitrogen were indistinguishable from those supplied with air or oxygen: they all grew normally to maturity. Buckwheat roots, therefore, apparently need but little gaseous oxygen. When, however, carbon dioxide was given, the plants sickened and wilted within a few hours and died in a few days. Barley, on the other hand, is more sensitive to deficient oxygen supply.

Stiles and Jörgensen (270) have confirmed this difference between barley and buckwheat.

Soil experiments lead to similar results though they are more difficult to carry out. B. E. Livingstone and E. E. Free (174) showed that different plants varied in their susceptibility to the exclusion of oxygen; *Coleus blumei* and *Heliotropium peruvianum* were the most sensitive, the intake of water in their roots ceasing within twelve to twenty-four hours

partment of Agriculture, India, 1909). German experience is recorded in *Erfahrung bei der Ackerbewässerung* (*Jahrb. Deutsch. Landw. Gesell.*, 1913, 28, 76). For work on cotton see W. L. Balls, *Cotton Plant in Egypt*, and J. A. Prescott, *Sultanic Agric. Soc. Bull.*, 14, 1924.

[1] For an extensive bibliography see *Aeration and Air Content*, F. E. Clements, Carnegie Pub., 315, 1921.

owing to death of the roots, and the entire plants ultimately died when oxygen was replaced by nitrogen.

The extended investigation of Cannon (66) indicate two " cardinal concentrations " of oxygen in the soil air : a lower one beyond which the roots cease to grow, and an upper one at which growth is normal and beyond which further additions of oxygen have no effect ; indeed, much more oxygen may do harm.[1] The concentrations differ with different plants ; some, such as rice and certain of the *salix* family, can continue root growth when the percentage of oxygen is as low as 0·5 ; others, such as maize and peas, need much more, indeed, for full growth, the 20·97 per cent. of ordinary air is not enough. Even for the same plant the values are not constant but vary with the temperature, being lower at low temperatures than at higher ones, apparently because water has greater power of absorbing oxygen at lower temperatures. The values also depend on the diluting gas, being considerably lowered by the substitution of helium for nitrogen, oxygen diffusing so much more rapidly through helium.

Plants differ also in their behaviour to carbon dioxide, the effects depending on the stage of growth. Germination of all seeds is retarded or inhibited so long as sufficient carbon dioxide is present, but some seeds, *e.g.* peas, beans, cabbage, barley, and onions, germinate soon after its removal, while others, such as charlock (*Brassica alba*), do not. Kidd has shown (146) that the seeds in this latter group behave as if narcotised by the carbon dioxide and will not germinate until they have been thoroughly dried and rewetted. He thus explains the remarkable appearance of charlock in English crops after a deeper ploughing than usual, in circumstances suggesting that its seed had lain buried for many years without losing its viability.[2]

[1] Even the normal concentration of oxygen is above the optimum for the germination of some seeds (T. Morinaga, *Boyce Thompson Institute*, 1926, 1, 100).

[2] Direct experiments by W. E. Brenchley showed the presence of viable seeds of *Atriplex patula, Polygonum aviculare, Veronica Tournefortii*, and

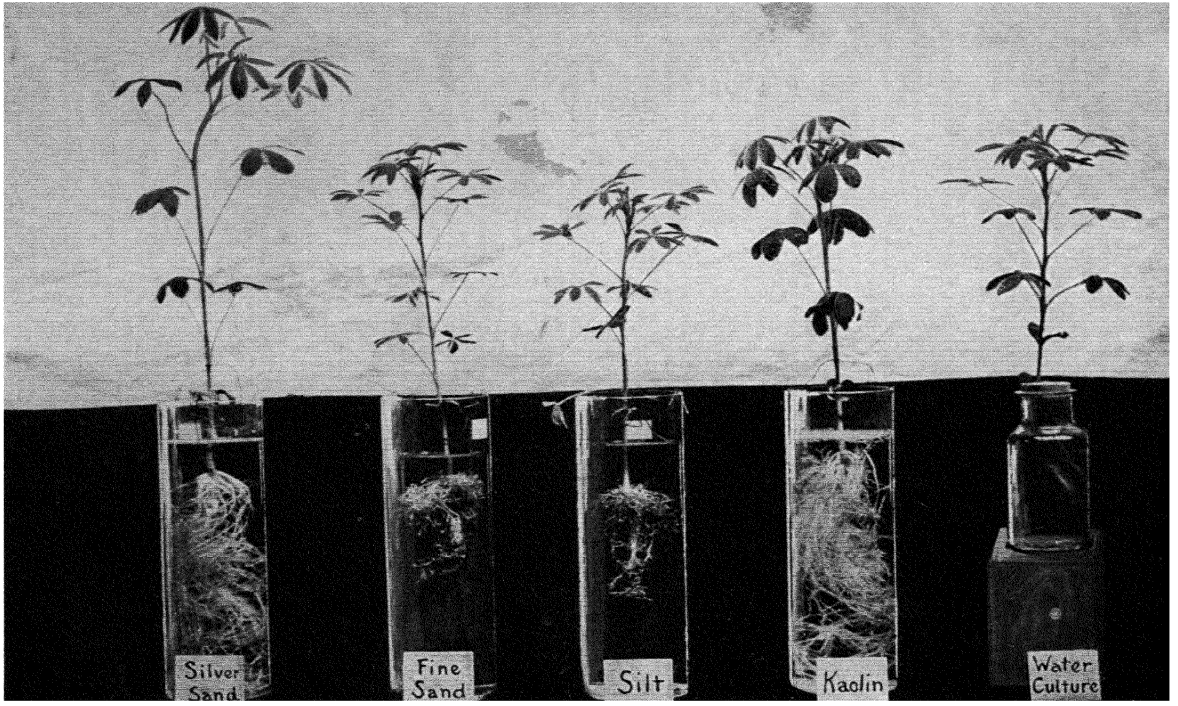


FIG. 11.—Influence of medium on root development of lupines (121*d*).

Growth is but little influenced by the small amounts of carbon dioxide usually found in the soil air. Mitscherlich,[1] in testing the German proposal for increasing yields by artificially enriching the atmosphere of glass house soils with carbon dioxide, found that small additions of carbon dioxide to the soil gave no increases in growth, sometimes, indeed, a decrease. Cannon (66) gives figures showing the variations in resistance of different plants.

In field conditions it is not usually possible to distinguish between the two factors of oxygen deficiency and carbon dioxide poisoning. The total effect on the growing plant is shown in the experiments of Hall, Brenchley, and Underwood (121*d*) with lupins grown in various materials. Root development was good in those allowing easy diffusion of air; it was less where diffusion was more difficult. The yields were :—

	Weight of Dry Matter Formed, Grams.
Material allowing diffusion of air : Coarse sand .	2·474
,, ,, ,, Kaolin . .	1·833
Material allowing less diffusion of air : Fine sand .	1·131
,, ,, ,, Silt . .	1·393
,, ,, ,, Water .	1·942

The results are illustrated in Fig. 11.[2] The harmful effect of restricted air supply to the roots becomes very marked when soil is water-logged, and may lead to cessation of growth, to disease, or even to the death of the plant. Nearly fifty years ago Sorauer showed[3] how deficient root aeration may

other arable weeds, but not of charlock, at a depth of 5 inches below the surface of soil that had been laid down to grass for 60 years (*Journ. Agric. Sci.*, 1918, 9, 1·31).

[1] *Landw. Jahrb.*, 1910, 39, 157.

[2] For other papers see C. A. Shull, *Bot. Gaz.*, 1911, 52, 453-477, and W. A. Cannon and E. E. Free, *Science*, 1917, 45, 178-180.

[3] *Handbuch du Pflanzenkrankheiten*, successive editions, 1879, 1886, 1895, 1909. U. Brizi (*Ann. Inst. Agrar.*, Milan, 1905, 6, 84), traced the *Brusone* disease of paddy rice to lack of aeration of the roots and showed that it did not occur if algæ are present.

bring on plant diseases: Warming (297) has discussed its ecological significance. Lawrence Balls [1] has shown that the growth of the cotton plant in Egypt is stopped and the roots killed when the water rises in the soil: as the water falls, however, young roots are sent out again. A. and G. L. C. Howard in India (139) have shown that deficient soil aeration leads to the serious indigo wilt. Improved aeration eliminated the disease and increased the yield. Some of the results obtained by reduction in irrigation or by addition of potsherds to the soil are given in Table XVIII.:—

TABLE XVIII.—THE EFFECT OF DILUTING THE PUSA SOIL WITH POTSHERDS OR SAND. A. AND G. L. C. HOWARD (139).

Crop.	Yield per Acre of Control Plot.	Yield per Acre with 1 in. of Potsherds.	Increase per Acre.	Percentage Increase.
	lb.	lb.	lb.	
Oats . . .	1954	2312	358	18
Wheat . .	1316	1580	264	20
Tobacco . .	1680	1846	166	10

EFFECT OF REDUCING IRRIGATION AND THEREBY INCREASING AIR SUPPLY. WHEAT.

	Three Waterings.	Two Waterings.	One Watering.
Yield of wheat:			
Grain, lb. .	1222	1302	788
Straw, etc., lb.	1764	2004	1714

Temperature.

It is difficult to separate soil temperature effects from temperature effects in general, and in practice the distinction is unnecessary since the temperature of the air is largely determined by that of the soil.

The effect of temperature shows itself in three ways:—

[1] *The Cotton Plant in Egypt*, 1912. See also first Annual Report, Cotton Research Board, Cairo, 1921.

1. It profoundly affects the rate of growth of plants, and thus determines what plants can be grown and what cannot be grown in a given area.

If the temperature is too low a yellow or purplish colour may appear in the leaf, and the plant grows so slowly that it is liable in its early stages to succumb to insect pests, such as wireworms, and in its later stages to be cut down by autumn frosts before it has time to ripen. If, on the other hand, the temperature is too high, the plant becomes taller than usual, less robust, and, when much water is also supplied, liable to fungoid pests that prove very troublesome in commercial glasshouses. Only over a comparatively restricted range of temperature is it possible to obtain the compact sturdy habit aimed at by the grower. This favourable range has not yet been correlated with other properties of the plant and has to be discovered empirically; it is, on the whole, lower for the seedling than for the growing plant, but it is highest for the period of maturation. It varies for different crops; wheat requires a cool time for sowing but a hot time for ripening, barley requires a cool, and oats a still cooler time throughout. It varies even for different varieties of the same crop; plant breeders are continually trying to evolve strains suited to particular ranges, *e.g.* wheats have been bred at Ottawa to ripen in the northern parts of Canada.

2. It affects the lengths of the periods of vegetative growth and of maturation, and therefore causes certain modifications in the plant itself.

A long ripening period gives wheat a plump kernel with a low percentage of protein, while a short ripening period gives an increased protein content (Lawes and Gilbert in 1857, 164).

Turnips in the south of England not only make less growth than in the north, but have a somewhat different composition. Oat straw in Scotland differs in composition from that in England, the translocation of material to the grain being apparently less complete.

3. The temperature at the time of ripening profoundly affects the germination capacity of the seed.[1]

Broadly speaking, roots flourish best at a lower temperature than the shoots, and they suffer considerably if the temperature rises too high. W. E. Brenchley [2] records some striking examples of injury, and even death, from high root temperatures in water cultures. High temperatures are tolerated provided they do not last too long and provided also that they are followed by sufficiently low temperatures. Fluctuating temperatures proved better than steady ones.[3] Soil observations are complicated by the fact that besides its direct effect on root growth, temperature also modifies the effect of other factors. Thus rise of temperature lowers the solubility of oxygen in water and thus alters the aeration conditions; both the maximum and the optimum temperatures of root growth are lowered by decreasing the partial pressure of oxygen in the soil air. No quantitative expression can, therefore, be expected for these relationships between soil temperature and plant growth, and qualitative observations are difficult to summarise. W. H. Cannon [4] has studied the influence of soil temperature on the roots of desert plants,

[1] For a discussion of the physiological effects produced by temperature see—
Action de la Chaleur et du froid sur l'activité des êtres vivants : par Georges Matisse. Paris (Larose), 1919.
Darwin, Francis, *On the Growth of the Fruit of "Cucurbita"* (*Annals of Botany*, 1893, 27, 459-487).
Lehenbauer, P. A., *Growth of Maize Seedlings in relation to Temperature* (*Physiol. Researches*, 1914, 1, 247-288).
Groves, J. F., *Temperature and Life Duration of Seeds* (*Bot. Gazette*, 1917, 63, 169-189).
Livingstone, B. E., and Livingston, Grace J., *Temperature Coefficients in Plant Geography and Climatology* (*Bot. Gazette*, 1913, 56, 349-375. Abs. in *Journ. Ecol.*, 1914, 2, 179).
And more recently F. G. Gregory, *Ann. Botany*, 1921, 35, 93-123, and 1926, 40, 1-26.

[2] W. E. Brenchley, *Ann. Applied Biol.*, 1920, 6, 211-244; W. E. Brenchley and Kharak Singh, *ibid.*, 1922, 9, 197-209.

[3] F. G. Gregory, *Ann. Bot.*, 1926, 40, 17.

[4] W. H. Cannon, *Amer. Journ. Bot.*, 1915, 2, 211-224; *Carnegie Inst. Year Book*, 1917, 91-92, and 1918, 83-85; see also *Science*, 1923, 58, 331-332.

and in summarising his general experience he suggests that roots which penetrate deeply and ordinarily grow on fine textured soils are less responsive than surface roots to changes in temperature and aeration.

Light.

Although light is not a soil factor it nevertheless indirectly affects the soil by modifying the flora which, as we shall subsequently see, largely determines the nature and amount of the organic matter of the soil. Tall vegetation keeps off light from the lower growing plants and more or less suppresses them.[1] Thus on the Rothamsted grass plots clover is seriously reduced in amount by nitrate of soda which causes tall growing grasses to flourish: Lathyrus, on the other hand, in consequence of its tall growing habit is not adversely affected but grows vigorously. Numerous other instances are recorded in the *Journal of Ecology*.[2] The extreme case is seen in wood-land where there is very little undergrowth and where, therefore, organic matter has not accumulated in the soil. Adjacent pieces of land at Rothamsted, both untreated and differing only in the flora, showed the differences in composition recorded in Table XIX.:—

TABLE XIX.—EFFECT OF VEGETATION TYPE ON SOIL COMPOSITION.

	Long Established.		Established 40 years.	
	Open Land. Flora of Grass and Clover.	Wood-land. No Green Plants.	Open Land. Flora of Grass and Clover.	Wood-land. No Green Plants.
Organic matter—				
0 — 9 ins.	8·5	6·7	7·9	8·1
9 — 18 „	4·8	4·8	6·7	5·2
Nitrogen—				
0 — 9 ins.	0·256	0·185	0·182	0·173
9 — 18 „	0·097	0·093	0·084	0·081

[1] The importance of good light for flower and seed production deserves investigation.

[2] See *e.g.* E. Farrow, *Journ. Ecology*, 1916, 4.

One of the most effective ways of suppressing weeds is to grow a heavy crop which, in the farmer's language, "smothers" them by excluding light and by exerting certain root effects. Strong radiation, on the other hand, tends to inhibit leaf growth quite apart from any effect of high temperature, with which it is associated (Gregory, 115). This may be an important factor in restricting the vegetation in open country in the tropics as compared with the more extensive flora of the wooded and shaded areas.

Food.

The nutrition of plants is complicated by the fact that plants synthesise their own food from various substances taken out of the air and the soil. It is common in farmers' lectures to speak of these as the actual foods, but the student must be perfectly clear in his own mind that they are only the raw materials out of which the food is made. It is convenient to make a distinction between the elements necessary in large quantities, and those of which mere traces suffice: the effect of the former can readily be demonstrated in water and sand cultures; the latter are more difficult to study, as traces are always present in the seed, and often also in the nutritive medium, or the vessel in which the plant is grown.

The substances needed in quantity are carbon dioxide, water, oxygen, and suitable compounds of nitrogen, phosphorus, sulphur, potassium, calcium, magnesium, and iron. Of these nitrogen, phosphorus, and potassium compounds are required in such large amounts that they usually have to be added to soils as artificial fertilisers in order to obtain maximum yields in agricultural practice. The other nutrient elements are generally present in air, in soils or in rain, in sufficient amounts to exert their full effect, though cases are recorded where crops have responded to additional supplies of sulphates and magnesium. The function of these nutrients is to build up the plant substances.

A second group of substances is needed in small amounts

only. These have been studied at the Institut Pasteur, notably by Gabrielle Bertrand and by Mazé: also by Dr. Brenchley at Rothamsted. The elements proved to be essential are iron, manganese, and, for certain crops, boron. Others probably always present in the plant are fluorine, iodine, chlorine, copper, aluminium, zinc, cobalt and nickel; it is not known whether they serve some useful purpose or have simply been absorbed along with the nutrients proper. The essential elements of this group apparently serve two purposes :—

1. Catalytic, the promotion of oxidation or the essential reactions;

2. Stimulative, the setting in train of differentiations or other processes vitally important to the plant.

The catalytic elements probably include iron, which is essential to the formation of chlorophyll; manganese, apparently needed for the activation of oxydases or otherwise for oxidations in the plant; silicon, which somehow increases the effectiveness of phosphate and possibly also of potassium. The stimulative elements probably include boron, needed to stimulate the formation of the branch system of circulatory vessels that links up the nodules on the roots of leguminous plants with the main system.

Between nutritive effects and toxicity the margin appears to be narrow, and almost all the elements essential to plant nutrition are capable of producing toxic effects under other conditions. In the case of the major nutritive elements toxicity occurs only when a sufficiently large excess is present to alter considerably the osmotic relationships or the proper physiological balance of the nutrient medium: the transition from beneficial to harmful effects is very gradual and proceeds through the long inert stage shown in Fig. 9. In the case of elements of which only small amounts are needed the transition is much sharper: the limits are easily overstepped and toxic effects set in when the minute beneficial amount is exceeded.

Group. I. Elements needed in relatively large amounts to build up the Plant Tissues.

Carbon.—It is generally assumed that plants derive all their carbon from the air, but the French investigators have persistently held the view that some may come from the soil (p. 15). The physiological work has usually been done in water cultures. Knudson [1] finds that saccharose, glucose, maltose, and fructose are directly absorbed and utilised by green maize, Canada field pea, timothy, radish, vetch, etc., giving rise to a characteristic branched root system. While these substances do not occur in the soil other soluble carbon compounds are present, especially in glasshouse soils, and may exert important effects.

There is considerable evidence, however, that by far the larger portion of the carbon of the plant is taken up from the atmosphere and not from the soil, but the phenomena are not wholly independent of the soil. The amount of carbon dioxide in the atmosphere is subject to slight variations which may arise from variations in biochemical activity in the soil, and may be a factor of importance in crop production. Brown and Escombe [2] found that the amount varied at Kew from 2·43 to 3·60 [3] volumes per 10,000 volumes of air, the average being 2·94. Taking the month of July as an example, the average values were :—

	1898.	1899.	1900.	1901.
CO_2 in 10,000 volumes of air .	2·83	2·88	2·86	3·11

It is probable that the plant as a whole would respond to variations of this order, making greater or less growth as the amount of carbon dioxide rises or falls.[4]

Nitrogen.—Of all the nitrogen compounds yet investigated nitrates are the best, and, in natural conditions, probably the only nitrogenous food for non-leguminous plants. The seed-

[1] *Cornell Repts.* (Ithaca, N.Y.), 1917, 747-813 (Memoir 9 of 1916).

[2] *Proc. Roy. Soc.*, 1902, 70, 118-121.

[3] Only on one occasion was so high a number obtained.

[4] See E. Demoussy (84), Otto Warburg, *Biochem. Zeitsch.*, 1919, 100, 230, and especially H. Lundegardh, *Der Kreislauf der Kohlensäure in der Natur*, Jena, 1924.

ling, still drawing its sustenance from the seed, lives on other compounds: H. T. Brown[1] found that asparagine was the most effective nutrient for the detached embryo of barley, followed by other relatively simple substances like nitrates, glutamic and aspartic acids, ammonium sulphate, etc., the more complex substances being less useful. The experimental study of the nitrogen nutrition of adult plants is complicated by the difficulty of growing plants under sterile conditions in which the decompositions effected by bacteria are obviated; much of the earlier work is vitiated by this circumstance. Later work has satisfactorily shown that ammonia is readily assimilated from solutions of ammonium sulphate if the concentration is not too high; but even 0·1 per cent. was found injurious by Mazé (196). Krüger (156) concludes that ammonium sulphate is less beneficial than sodium nitrate for mangolds; both compounds are equally useful for oats, barley, and mustard, while ammonium sulphate is better for potatoes. Brigham[2] maintains that maize also thrives better on ammonium sulphate than on sodium nitrate. Hutchinson and Miller (140*a*) found that peas assimilate nitrates and ammonium salts equally well, while wheat showed a decided preference for nitrates. Söderbaum[3] found that the effect varied with the salt: ammonium phosphate was more beneficial than the sulphate, while the chloride was harmful.

An interesting attempt has been made by Prianichnikow (229) to elucidate the phenomena of ammonia assimilation by plants. He supposes that the ammonia taken up by the roots is transformed in the plant into asparagine, which is then converted into protein. Some plants, *e.g.* barley, maize, pumpkin, etc., readily take up ammonia and effect the conversion; others, such as peas and vetches, do so only in presence of calcium carbonate; whilst others, such as lupin, will not normally take up ammonia at all. He attributes this difference

[1] *Trans. Guinness Lab.*, 1906, 1, Pt. 2, 288-299.
[2] *Soil Sci.*, 1917, 3, 155.
[3] *Kungl. Landt. Handlingar*, 1917, 56, 536-560.

to the different quantities of carbohydrates in the plant; with a plentiful supply even lupins could absorb ammonia and convert it into asparagine. Plants fed on ammonium salts contain a higher percentage of nitrogen than those fed on nitrates (Table XX.):—

TABLE XX.—PERCENTAGE OF NITROGEN IN DRY MATTER OF PLANTS.

	Fed on Nitrates.	Fed on Ammonium Salts.	Observer.
Maize . .	3·17	3·43	Mazé (196)
Mustard .	2·87	3·48	Krüger (156*b*)
Oats . .	1·80	2·05	,, ,,
Wheat . .	1·91	2·17	Hutchinson and Miller (140*a*)

Nitrites are also assimilated so long as the solution is not too concentrated or too acid.[1]

In spite of a considerable amount of work it is not known whether nitrogen compounds other than nitrates and ammonia are assimilated by plants. That many other compounds serve as nitrogen nutrients, even without the intervention of bacteria, seems to be certain (140*b*), but it has never been shown whether assimilation of the compound as a whole takes place, or whether there is decomposition at the surface of the root. Many of the supposed assimilated compounds are, as a matter of fact, more or less easily hydrolysable, or otherwise decomposable, with formation of ammonia, and the decomposition will obviously proceed as fast as the ammonia is removed by the plant. Two factors that determine how far a given compound serves as a nitrogen nutrient are: (1) the ease with which it splits off ammonia, (2) the effect on the plant of the other decomposition products: if these happen to be toxic the whole process stops as soon as they have sufficiently accumulated.

The normal nitrogenous food of plants is, however, a nitrate, and there is a close connection between the amount supplied and the amount of plant growth, which is well shown

[1] See Perciabosco and Rosso, *Staz. Speriment. Agrar. ital.*, 1909, xlii., 5.

in Hellriegel and Wilfarth's (130*c*) experiments (p. 32). Most of the nitrogen required by the plant is absorbed in its early days from the soil and stored in the meristematic tissues (*i.e.* the embryonic tissues capable of further growth).

The Effect of Nitrogenous Nutrients on the Plant.—Nitrogen starvation is characterised by stunted growth and sickly yellow colour of the leaf, the yellowing and dying being general all over the leaf, as distinct from the effect of potash starvation where the dying is from the tip and edges inwards (p. 84). Addition of nitrate causes an almost instant improvement in colour and a rapid growth of leaf. Gregory (115), working with barley, has shown that only the leaf area increases and not the assimilation rate, in contradistinction with phosphates and potassium, both of which increase the efficiency as well as the leaf area. This increased leaf growth is of great advantage in agriculture and leads to the consumption of large quantities of nitrogenous fertilisers. Particular use can be made of these substances in cold weather or when insects are attacking the crop.

Greater quantities of nitrate lead to the development of large dark-green leaves which are often crinkled, soft, sappy, and liable to insect and fungus pests possibly because of the thinning of the walls or changes in tissues or in composition of the sap. C. R. Hursch [1] shows that the amount of sclerenchyma is reduced in proportion to the collenchyma in the wheat plant, thus favouring the attack of *Puccinia graminis*, the mycelium of which can develop only in the collenchyma.

A further effect of a large supply of nitrogen relative to other nutrients is a retardation of ripening. Plants receiving differing amounts of nitrate are thus at somewhat different stages of their development at any given time, even though they were all sown on the same day, those supplied with large quantities of nitrate being less advanced than the rest. If they could all be kept under constant conditions till they had ripened this difference might

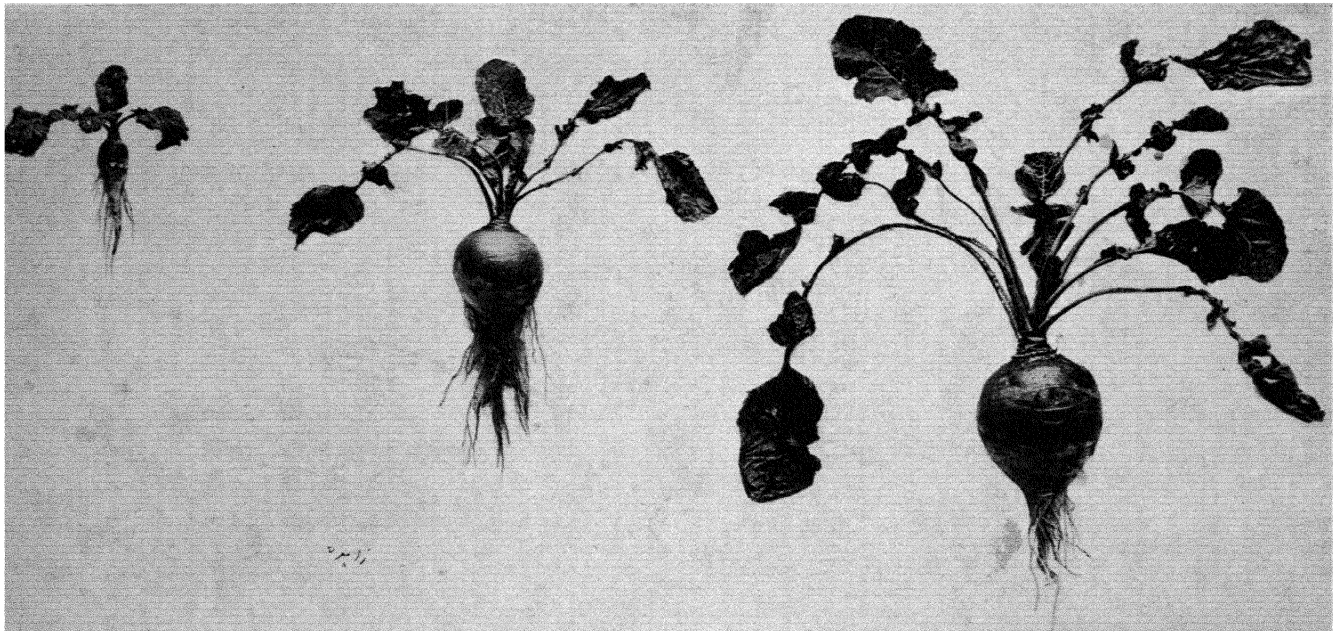
[1] *Journ. Agric. Research*, 1924, **27**, 381-412.

finally disappear, but in crop production it is not possible much to delay the harvest owing to the fear of damage by autumn frosts, so that the retardation is of great practical importance. Seed crops like barley that are cut dead ripe are not supplied with much nitrate, but oats, which are cut before being quite ripe, can receive larger quantities. All cereal crops, however, produce too much straw if the nitrate supply is excessive, and the straw does not commonly stand up well, but is beaten down or "lodged" by wind and rain. Swede and potato crops also produce more leaf, but not proportionately more root or tuber, as the nitrogen supply increases; no doubt the increased root would follow, but the whole process is sooner or later stopped by the advancing season—the increased root does, in fact, follow in the case of late-growing mangold. Tomatoes, again, produce too much leaf and too little fruit if they receive excess of nitrate. At the Cheshunt Experiment Station [1] the omission of nitrogen compounds from the fertiliser mixture has caused the yield of fruit to increase 11 per cent. With the variety Comet the following quantities of fruit have been obtained :—

	Lb. per Plant.				Tons per Acre.				Relative Weights, Average, 1916-1919.
	1916.	1917.	1918.	1919.	1916.	1917.	1918.	1919.	
Complete artificials	4·9	5·11	3·32	5·57	38·7	35·8	25·8	42·2	100
No nitrogen . .	5·7	5·60	3·62	5·98	45·0	39·2	28·2	47·4	111

On the other hand, crops grown solely for the sake of their leaves are wholly improved by increased nitrate supply: growers of cabbages have learned that they can not only improve the size of their crops by judicious applications of nitrates, but they can also impart the tenderness and bright green colour desired by purchasers. Unfortunately the softness of the tissues prevents the cabbage standing the rough

[1] Annual Reports for 1917 *et seq.*



No manure. Superphosphate and potassic fertiliser. Nitrogen superphosphate and potassic fertiliser.

FIG. 12.—Swedes from Agdell field, Broadbalk: unmanured; superphosphates and potassic fertilisers; and complete fertiliser. (Lawes and Gilbert.)

handling of the market. These qualitative differences are of great importance in agriculture and horticulture.

Three cases are illustrated in Table XXI.; as the nitrogen supply is increased wheat shows increases in straw greater than those in grain; white turnips show increases in leaf greater than those in root, but mangolds show substantially the same increase both in leaf and root, because their growing period is so much longer than that of the other crops, continuing until the end of October. These effects are modified by the time when the nitrogenous manure is given. Late dressings are advantageous to swedes but not to potatoes; they appear also to increase the percentage of nitrogen in the grain of cereals.

TABLE XXI.—EFFECT OF VARYING SUPPLY OF NITROGENOUS MANURE ON THE GROWTH OF CROPS. ROTHAMSTED.

Nitrogen in Manure, lb. per Acre.	Wheat, 1000 lb. per Acre. (1852-1864).		Nitrogen in Manure, lb. per Acre.	White Turnips, 1000 lb. per Acre (1845-1848).		Nitrogen in Manure, lb. per Acre.	Mangolds, 1000 lb. per Acre (1906-1910).	
	Grain.	Straw.		Roots.	Leaves.		Roots.	Leaves.
none	1·06	1·86	none	18·37	6·05	none	11·84	2·55
43	1·68	3·03	47	22·18	9·63	86	40·12	8·51
86	2·18	4·28	137	22·96	13·78	134	65·67	13·88
129	2·27	4·78	—	—	—	—	—	—
172	2·29	5·22	—	—	—	—	—	—

Phosphorus.—Phosphates are by far the most efficient phosphorus nutrients known for plants. Their effects are less striking than those of nitrogen compounds, and can be recognised only by comparing plants receiving sufficient phosphate with those receiving but little.

The most obvious effects are on the root system, the tillering of cereals, and the production of seed. So long ago as 1847, Lawes (161) wrote: "Whether or not superphosphate of lime owes much of its effect to its chemical actions in the soil, it is certainly true that it causes a much enhanced development of the *underground* collective apparatus of the

plant, especially of *lateral* and fibrous *root*, distributing a complete network to a considerable distance round the plant, and throwing innumerable mouths to the surface." Dressings of phosphate are particularly effective wherever greater root development is required than the soil conditions normally bring about. They are invaluable on clay soils, where roots do not naturally form well, but, on the other hand, they are less needed on sands, because great root growth normally takes place on these soils. They are used for all root crops like swedes, turnips, potatoes and mangolds; in their absence swedes or turnip roots will not swell but remain permanently dwarfed like radishes (Fig. 12 shows one of Lawes and Gilbert's experiments): the introduction of superphosphate as a fertiliser revolutionised agriculture on some of the heavier soils by allowing better growth of these crops.

Cereals suffering from phosphate starvation have a stunted root system, especially in their early days, and an even more stunted leaf and stem; when phosphates are given the shoot increases more than the root, *i.e.* the ratio root, shoot is diminished and not increased as may happen with swedes. Phosphate starvation also depresses tillering, causing a decrease in total number of tillers and in number of tillers bearing seed. Similar stunting of the root and leaf is seen in phosphate-starved fruit trees.[1]

The leaves are not invariably affected in colour.[2] Phosphate-starved barley becomes reddish in the stem in water cultures and a sickly purple in the leaf in extreme cases in soil,[3] but only a dull greyish-green on the Hoos Field at Rothamsted. Phosphate-starved apple trees had bronze-purple coloured leaves carried mainly at the tops of the

[1] T. Wallace, *Journ. Pomology*, 1925, vols. 4 and 5.

[2] *E.g.* soy beans grown without phosphate were normal in appearance though very stunted (J. M. Ginsburg, *Soil. Sci.*, 1925, **20**, 1-13), so also was mustard (C. T. Gimingham, next footnote).

[3] *E.g.* an Offchurch soil in Warwickshire, C. T. Gimingham, *Agric. Education Assoc. Repts.*, 1922, p. 21.

shoots;[1] the phenomena are here somewhat complicated by acidity.

Later on in the life of the plant phosphates hasten the ripening processes, thus producing the same effect as a deficiency of water, but to a less extent; for this reason they are applied to the wheat crop in some of the northern districts of England, and the oat crop in the west, to bring on the harvest a few days earlier and obviate risk of loss by bad weather. The northern limit of growth of several crops may in like manner be extended. This ripening effect is well shown on the barley plots at Rothamsted; crops receiving phosphates are golden yellow in colour while the others are still green.

Certain indirect effects also follow: the head of the barley emerges from its ensheathing leaves a few days in advance of those receiving insufficient phosphate, and therefore has a better chance of escaping attack by the larvæ of the gout fly (*Chlorops tæniopus*, Meig.) which, hatching from their eggs on the top of the topmost leaf, crawl downwards seeking the head for food.

But addition of phosphate leads to no increase in the proportion of grain borne by the plant. On the Rothamsted plots supplied with nitrogen and potassium compounds, but no phosphate, the grain formed 44·9 per cent. of the total produce during the first ten years of the experiment (1852-1861), and almost exactly the same proportion (44·7 per cent.) during the fifth ten years (1892-1901) when phosphate starvation was very pronounced; it fell a little to 41·3 per cent. in the sixth ten years (1902-1911), but rose to 46·8 per cent. in the period 1913-1919. Even in sand cultures the difference is not very marked: Hellriegel (130*d*) grew barley with varying supplies of phosphate with results given in Table XXII. In absence of phosphate no grain was formed; when a little was added grain formation proceeded normally, and the resulting grain was nearly full weight per individual; as the phosphate supply

[1] T. Wallace, *Journ. Pomology*, 1925, vols. 4 and 5.

increased the percentage of grain increased, but soon reached a maximum beyond which it would not go.

TABLE XXII.—EFFECT OF VARYING PHOSPHATE SUPPLY ON THE GROWTH OF BARLEY IN SAND CULTURES. HELLRIEGEL (130*d*).

Weight of P_2O_5 supplied, mgms. per pot . .	0	14·2	28·4	56·8	85·2	113·6	142	213	284
Weight of dry matter in crop, grams per pot .	1·856	8·254	12·613	19·505	19·549	20·195	18·667	17·785	31·306
Grain per cent. of dry matter .	—	22·4	31·8	38·4	41·6	43·8	41·3	40·1	43·4
Weight of one grain, mgms. .	—	27	29	38	34	41	38	30	34

It is in the total growth of straw and of grain that the effect of phosphate is manifested, as shown in Table XXIII.

TABLE XXIII.—RESULTS OF WITHHOLDING PHOSPHATES, POTASSIUM COMPOUNDS, AND NITROGEN COMPOUNDS FROM BARLEY. HOOS FIELD EXPERIMENTS, ROTHAMSTED.

Plot.		Yield of Grain, 1000 lb. per Acre.							
		5 years, 1852-56.	5 years, 1857-61.	10 years, 1862-71.	10 years, 1872-81.	10 years, 1882-91.	10 years, 1892-1901.	10 years, 1902-11.	7 years, 1913-19.
7	Dung . . .	2·31	2·78	3·00	2·88	2·66	2·56	2·50	2·35
A 4	Complete manure (salts of NH_4, K and P) .	2·47	2·71	2·67	2·34	2·24	2·02	2·25	2·06
A 3	No phosphates .	2·27	1·71	1·99	1·68	1·38	1·26	1·23	1·38
A 2	No potassium .	2·42	2·70	2·76	2·29	2·01	1·63	1·81	1·88
O 4	No nitrogen .	1·86	1·57	1·39	·98	·92	·74	·94	1·31

Plot.		Yield of Straw, 1000 lb. per Acre.							
		5 years, 1852-56.	5 years, 1857-61.	10 years, 1862-71.	10 years, 1872-81.	10 years, 1882-91.	10 years, 1892-1901.	10 years, 1902-11.	7 years, 1913-19.
	Dung . . .	2·82	3·15	3·35	3·37	3·28	3·35	3·54	2·73
A 4	Complete manure (salts of NH_4, K and P) .	3·29	3·17	3·14	2·63	2·61	2·36	2·83	2·17
A 3	No phosphates .	2·86	2·03	2·20	1·75	1·64	1·56	1·75	1·57
A 2	No potassium .	3·21	3·03	3·07	2·30	2·20	1·9	2·16	1·78
O 4	No nitrogen .	2·03	1·58	1·42	·95	·94	·90	1·39	1·46

The Rothamsted results are plotted in Figs. 13 and 14. The effect of phosphate starvation shows itself in depressing the yield of straw and of grain, the straw being the first to suffer. Potash starvation takes longer to set in, not because potassium is less necessary but because the soil contains a larger quantity; it also affects the straw first. Nitrogen starvation sets in at once, rapidly bringing both grain and straw down to a very low level.

Phosphate starvation markedly affects the composition of crops, lowering their nutritive value to animals and their special quality values to men. Over large areas of the world soils are very deficient in phosphate. Those occurring in parts of South Africa carry a natural herbage which causes deficiency diseases in cattle; the affected animals devour bones with great eagerness, even putrefying bones when the deficiency is pronounced, so that they become liable to a particular ptomaine poisoning. The obvious remedy is to feed the cattle with bone meal.[1] Similar diseases occur in Australia, where also the arable land shows astonishing benefits from small dressings of superphosphate.[2] In the Romney Marsh the best fatting pastures are richer in phosphate than the poorer ones (121*c*); this is generally true of England and France. Paturel[3] has shown that the best wines contain most P_2O_5 (about 0·3 grm. per litre), the second and lower qualities containing successively less. Further, when the vintages for different years were arranged in order of their P_2O_5 content a list was obtained almost identical with the order assigned by the wine merchants. Davis[4] has emphasised the importance of phosphate supply for the indigo crop.

It is difficult to get behind these effects and ascertain

[1] See A. Theiler, H. H. Green, and P. J. du Toit, *Phosphorus in the Live Stock Industry* (*Journ. S. Africa Dept. of Agric.*, 1924, 8).

[2] *E.g.* at the Roseworthy Agric. College; ½ cwt. superphosphate per acre raised the yield of wheat from 15 bu. 20 lb. on the untreated land to 21 bu. 43 lb. per acre (fourth Report, 1910, p. 40).

[3] *Bull. Soc. Nat. Agric.*, 1911, p. 977.

[4] *Pusa Indigo Publications*, No. 6, 1920.

their causes. The function of phosphoric acid in the cell is not easy to discover; even when the problem is reduced to its simplest state by experimenting with Spirogyra in culture solutions little more has been ascertained than that phosphates are essential for mitotic cell division, doubtless because phosphorus is a constituent of the nucleus, and also for the normal

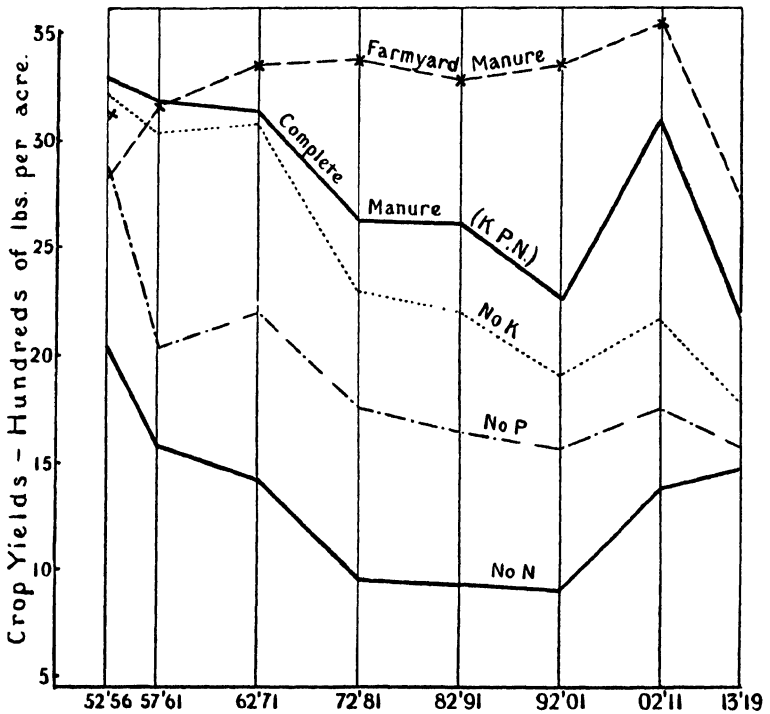


FIG. 13.—Effect on yield of grain of withholding various nutrients from barley. (Hoos Field, Rothamsted.)

transformations of starch. Loew (*176b*) found that fat and albumin accumulated in absence of phosphates, but the colour was yellow and there was no cell division; as soon as a trace of potassium phosphate was added, however, energetic cell division took place. Reed (234) showed that starch was formed in absence of phosphorus, but did not change to sugars; erythrodextrin was formed instead and also cellulose. The

same actions are observed in the higher plants. Phosphates appear to increase the development of meristem tissue and the efficiency of the chloroplast mechanism.

The close connection between cell division and phosphate supply may account for the large amount of phosphorus compounds stored up in the seed for the use of the young plant,

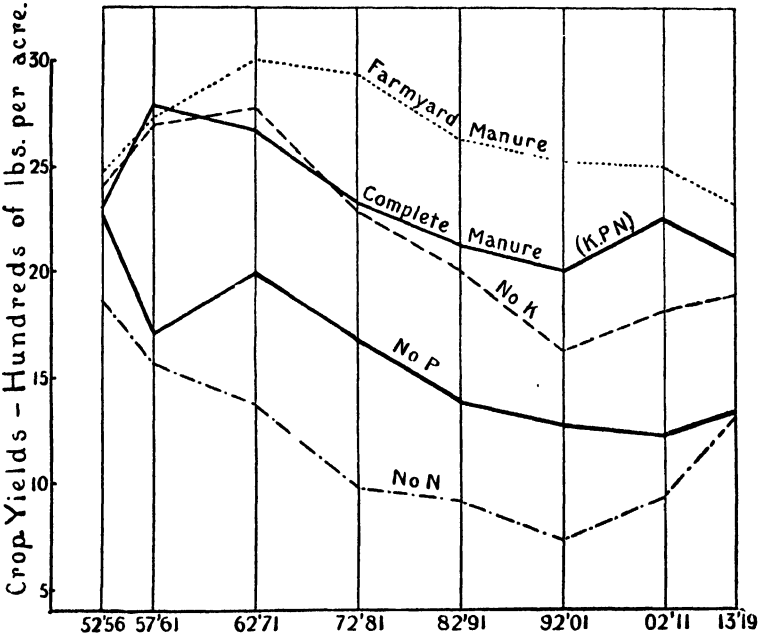


FIG. 14.—Effect on yield of straw of withholding various nutrients from barley. (Hoos Field, Rothamsted.)

and also the relatively large amounts of phosphate taken from the soil during the early life of the plant.

Excess of phosphate over the amount required to increase plant growth is liable to cause injury; instances have been recorded of barley[1] in Suffolk and potatoes in Lincolnshire,[2] while Gericke (108) has shown that the greatest growth is attained by supplying phosphates in the early life of the plant and withholding them later.

[1] *Journ. Inst. Brewing*, 1923, **29**, 631.
[2] *Journ. of the Min. of Agric.*, 1926, **32**, 893.

Potassium.—Four distinct effects are produced by potassium salts :—

(1) On the general health and vigour of the plant.

(2) On the efficiency of the leaves for synthesising and translocating carbohydrates.

(3) On certain processes occurring in leguminous plants.

(4) On the formation of grain.

The effect on the vigour of the plant is well seen in adverse climatic conditions or on soils containing very little potassium. The colour of the leaf becomes abnormal; the potash-starved grass plots at Rothamsted have a poor, dull colour, as also have the mangold plots; the leaves also tend to die early at the tips and along the edges, then inwards. The stem is weaker, so that the plant does not stand up well; this is apparently a turgidity effect,[1] although anatomical differences were observed by Miss O. N. Purvis.[2] Potash-starved plants are the first to suffer in a bad season, or to succumb to disease. The Broadbalk wheat plots receiving potassium salts give conspicuously better results than the others whenever the year is unfavourable to plant growth; taking the yield on the unmanured plot as an index of the character of the season, we obtain the following results for a series of good and of bad years respectively :—

TABLE XXIV.—YIELD OF WHEAT IN THOUSAND POUNDS PER ACRE. ROTHAMSTED.

	Plot No.	In Nine Bad Seasons.		In Nine Good Seasons.[3]	
		Grain.	Straw.	Grain.	Straw.
Unmanured	4	·55	·87	·88	1·08
Insufficient potassium . .	11	1·06	1·86	1·51	2·20
Sufficient potassium . .	13	1·70	3·02	1·98	3·16
Percentage increase due to potassium.	—	60·3	62·3	31·1	43·6

[1] See T. Weevers, *Rec. Trav. Bot. Neerland*, 1911, 8, 289-332.

[2] *Journ. Agric. Sci.*, 1919, 9, 360.

[3] The bad years were 1867, '71, '72, '75, '76, '77, '79, '86, '88; the good years were 1868, '69, '70, '81, '83, '85, '87, '89, '91.

In the bad years the average rainfall was 32·55 inches (harvest years, September-August), while in the good years it was 27·10 inches; the badness of the season may be connected with the high rainfall and corresponding low temperature. Similar results are obtained, however, if other unfavourable conditions set in.

The improvement in healthiness is well exemplified by the liability to disease. At Rothamsted the potash-starved wheat may be attacked by rust and the potash-starved mangolds by *Uromyces betæ*, especially where there is excess of nitrogen, while the surrounding plots, equally liable to infection, remain healthy. Flax growers in the north of Ireland have found that potassic fertilisers decrease the liability of the plant to the attacks of the wilt organism. In Wallace's sand cultures of fruit trees omission of potassium caused a characteristic leaf scorch and premature defoliation: the shoot growth of apples was much restricted. Garner (p. 93) found that potassium deficiency caused a "chlorosis" of tobacco leaf characterised by leaf spotting and distinct from that following magnesium deficiency, while H. S. Reed and A. R. C. Haas[1] observed a bronzed appearance on the leaves of young orange trees suffering from potassium starvation.

At Cheshunt Experimental Station, liberal treatment with potassic fertilisers makes the tomato plant less liable to the bacterial stripe disease: the numbers of plants affected out of a total of 120 in each plot were:—

	Complete Fertiliser.	No Potassic Fertiliser.
Var. Comet	40	78
Var Kondine Red . . .	13	33

The fruit is less liable to "blotchy ripening" if well supplied with potassic fertilisers. This is shown in Table XXV., which

[1] *Cal. Agric. Expt. Stn. Tech. Paper*, 11, 1923.

gives the results for tomato fruit grown with different amounts of nutrient salts :—[1]

TABLE XXV.—YIELD AND CHARACTER OF TOMATO FRUIT FROM PLANTS RECEIVING DIFFERENT AMOUNTS OF NUTRIENTS.

Dose of Nutrient.	Varying Potassium.		Varying Nitrogen.		Varying Phosphate.	
	Tons per Acre.	Per Cent. Blotchy Fruit.	Tons per Acre.	Per Cent. Blotchy Fruit.	Tons per Acre.	Per Cent. Blotchy Fruit.
0	45·00	18·07	40·56	3·75	44·60	2·22
1	45·19	6·22	48·72	0·78	44·53	1·37
2	46·73	4·39	51·00	0·16	44·60	0·18
3	50·99	3·57	53·88	0·27	47·92	0·44

Potassic fertilisers often afford the simplest method of dealing with fungoid diseases, and they are usually more effective than other fertilisers under glass. It does not necessarily follow that they alter the physiological susceptibilities of the plant to the disease ; their effect may be indirect, conditioned by the change in habit of growth or rate of maturation they bring about.[2] No absolute quantity of potassium can be indicated as necessary or desirable. Apparently the nitrogen/potassium ratio in the fertiliser is important; addition of more nitrogen in Bewley's experiments led to more disease, and in Wallace's experiments it enlarged the leaves but caused the leaf scorch characteristic of potash starvation. In like manner the ratio potassium/magnesium seems to be important; if it is too high symptoms of magnesium starvation appear.

Potassium thus appears as in some way complementary to

[1] *Cheshunt Expt. Stn., 11th Report*, 1925. The percentages of nutrients in the fertiliser were :—

Potash (K_2O)	2½	5	7½	10
Nitrogen	0	1¼	2½	5
Phosphates (as tricalcic phosphate)	0	8	16	24

[2] See E. C. Stakman and O. S. Aamodt, *Journ. Agric. Res.*, 1924, **27**, 341-380, for a recent discussion of this aspect of the problem as applied to stem rust of wheat in the United States.

nitrogen in plant nutrition, and their relative effects are rather sharply contrasted: for example, Bewley finds that tomatoes respond better to nitrogenous fertilisers in a sunny than in a dull, cold season, but better to potassic fertilisers in a dull, cold season than in a sunny one.

The loss of efficiency in synthesising carbohydrate when supplies of potassium are restricted was pointed out in 1870 by Nobbe (213). Mangolds, sugar beets, potatoes, and other sugar- and starch-forming crops reduce their production of sugar with decreasing potassium supply even before the leaf area has been diminished. Thus, in the mangold experiments

TABLE XXVI.—INFLUENCE OF POTASSIUM SALTS ON THE ACTION OF NITROGENOUS MANURES. ROTHAMSTED.

	Average Weights, Mangolds, 1906-1910.					
	Roots, 1000 lb. per acre.			Leaves, 1000 lb. per acre.		
Insufficient potassium (Series 5)	11·97	14·68	18·62	2·59	7·25	7·75
Sufficient potassium (Series 4) .	11·84	40·12	65·67	2·55	8·51	13·88
Nitrogen supplied in manure, lb. per acre	—	86[1]	184[2]	—	86[1]	184[2]

of Table XXVI., 7255 lb. of leaf give rise to 14,684 lb. of root where potassium is deficient, while very little more leaf, 8508 lb., give rise to nearly three times as much root, 40,128 lb., where more potassium salts are supplied. The harmful effect of potash starvation on carbohydrate production does not seem to be the result of a pathological condition of the chloroplastids. Reed found that they remained normal for two months, and even increased in numbers in potash-starved algæ. T. O. Smith and O. Butler maintain that potassium is not essential for the synthesis and translocation of starch in wheat,[3] and W. Newton reaches

[1] From 400 lb. ammonium salts.

[2] From 400 lb. ammonium salts and 200 lb. Rape cake.

[3] T. O. Smith and O. Butler, *Ann. Botany*, 1921, 35, 189.

the same conclusion for potatoes: these results deserve further experimental study.[1]

No explanation can yet be given for the marked effect of potassic salts on leguminous crops. In a mixed grass field, clovers have less capacity for absorbing potassium from the soil solution than the grasses [2] and in absence of potassic fertilisers they suffer from the competition: the potassium-starved grass plots at Rothamsted contain notably less clover than those fully manured, the actual depression fluctuating according to the season. It is not certain that these effects are connected with protein synthesis.[3]

The effect on ripening is well marked. Potassium-starved plants are not only stunted in growth like plants lacking nitrogen or phosphorus, but they may even fail to reach maturity.[4] With small supplies of potassium seed is formed, but it is small: unlike phosphates and nitrates, potassium compounds have a very marked effect on the weight of the individual grains, as may be seen by comparing Table XXVII.

TABLE XXVII.—EFFECT OF POTASSIUM SALTS ON THE DEVELOPMENT OF BARLEY. HELLRIEGEL (130*d*).

K_2O supplied, mgs. . .	0	23·5	47	70·5	94	188	282
Dry matter in crop, grams .	2·271	5·414	9·024	11·636	15·302	20·946	29·766
Grain, per cent. of dry matter	—	4·8	21·5	27·2	30·1	38·5	42·7
Weight of one grain, mgs. .	—	5	9·5	13	17	26	34

with the corresponding Tables IV. (p. 32) and XXII. (p. 80); indeed, to withhold potassium is the surest way of producing stunted grain. At Rothamsted the average weights per bushel of wheat for the ten years 1910-1919 were :—

No Manure. Plot 3.	Farmyard Manure. Plot 2.	Complete Artificials. Plot 7.	Artificials without Nitrogen. Plot 5.	Artificials without Potassium. Plot 11.
61·5	62·3	62·2	61·8	60·7

[1] W. Newton, *Journ. Amer. Soc. Agron.*, 1923, p. 392.

[2] Lawes and Gilbert, *Phil. Trans.*, 1900, **192**, p. 156.

[3] J. Stoklasa, *Biochem. Zeitsch.*, 1917, **82**, 310-323; T. Weevers, *ibid.*, 1917, **78**, 354.

[4] H. Weissmann, *Z. Pflanz. Düng.*, 1923, 2, A, 1.

Sodium does not appear to be essential even to salt marsh plants, although salicornia grew better in presence of salt than in its absence.[1] It can partially, but not completely, replace potassium as a plant nutrient; it thus delays the setting in of potash starvation, but will not keep it off altogether.[2] Hellriegel (130*d*) found that sodium salts always gave increases in crop even when potassium salts were present in quantity (Table XXVIII.).

TABLE XXVIII.—EFFECT OF SODIUM SALTS WITH SMALL AND WITH LARGE AMOUNTS OF POTASSIUM SALTS ON THE GROWTH OF BARLEY. HELLRIEGEL (130*d*).

K_2O supplied, mgs. . . .	0	94	188	282	376
Dry matter produced when sodium salts added	4·925	23·019	32·278	36·535	38·270
Dry matter produced when no sodium salts added	2·658	15·638	29·724	34·897	36·281
Difference due to sodium salts .	2·267	7·381	2·554	1·638	1·989

Breazeale (52*b*) has more recently obtained similar results in water cultures. It is well ascertained in farming practice that sodium salts can be used with great effect as manures wherever there is any deficiency of potash in the soil.[3]

J. A. Voelcker (286) has made the interesting observation that sodium hydroxide and sodium carbonate, unlike most other salts, cause an increase in the percentage of nitrogen in the wheat grain, besides increasing the yield of crop. The sulphate and the chloride increased the crop, but beyond a relatively low concentration limit further increases in amount of sodium chloride proved toxic.

[1] A. C. Halket, *Annals of Botany*, 1915, **29**, 143-154.

[2] For a discussion of the protective actions of sodium see W. J. Osterhout, *Univ. Cal. Publ. Bot.*, 1908, p. 331, and *Bot. Gaz.*, 1909, **48**, 98.

[3] For fuller details see *Rhode Island Expt. Sta. Rpts.*, 1905, 1908, **19**, 186; **20**, 299; **21**, 243; Krüger, *Zeitschr. Ver. Deut. Zuckerindus.*, 1914, 694-702; B. Schulze, *Beitrag zur Frage der Düngung mit Natronsalzen* (*Landw. Versuchs-Stat.*, 1913, **79-80**, 431, and 1915, **86**, 323-330); E. J. Russell, *Journ. Bd. Agric.*, 1915, **22**, 393-406,

Lithium salts, on the other hand, have a toxic action on plants. Gaunersdorfer's older experiments [1] have been confirmed by J. A. Voelcker (286, 1912), who found that amounts of the chloride, sulphate, or nitrate, corresponding to ·003 per cent. of the metal were distinctly injurious to wheat; smaller amounts, however, appeared to cause an increased growth.

Cæsium salts are less harmful (286).

Calcium.—Deficiency of calcium in the nutrient supply usually leads to the following effects :—

(1) Stunting and discolouring of the root. Maquenne and Demoussy [2] showed that root development of peas germinating in distilled water ceases after the third or fourth day, but is vigorously resumed on addition of even a trace of calcium sulphate: 0·01 mgm. per seed, representing an addition of calcium equal to 1/40,000 the weight of the dry seed, caused formation of root hairs and a 40 per cent. increase in root length. Reed and Haas [3] observed similar root effects with young orange trees, as did W. Newton [4] with potatoes, and J. M. Ginsburg with soy beans.[5]

(2) Brown spotting and subsequent death of leaves, the new ones often being mottled or chlorotic: observed both by van Raumer (232) in the first serious studies of the effect of calcium, and by Reed and Haas.

(3) Mobility of the fats in the plant so that they diffuse to the surface as shown in the thick cuticle and heavy suberin layers of the endodermis in plants growing in peat.[6]

None of these effects was observed by Wallace on fruit trees.

[1] *Landw. Versuchs-Stat.*, 1887, **34**, 171-206.

[2] *Compt. Rend.*, 1917, **164**, 979-985, and **165**, 45-51.

[3] H. S. Reed and A. R. C. Haas, *Cal. Agric. Expt. Stn. Tech. Papers*, 4 and 11, 1923, and *Amer. Journ. Bot.*, 1924, **11**, 15-18.

[4] W. Newton, *Journ. Amer. Soc. Agron.*, 1923, p. 392.

[5] *Soil Sci.*, 1925, **20**, 1-13.

[6] J. H. Priestley and Hinchcliff, *The Naturalist*, 1922, 263-268; also J. H. Priestley, *New Phytologist*, 1924, **23**, 1-19.

Van Raumer and the older physiologists associated calcium with the formation of the cell structure material and also of protein. Parker and Truog [1] explain the association with protein by supposing that calcium is necessary for precipitating the acids formed as by-products in the synthesis of protein in the plant: thus plants of high protein content, such as the leguminosæ, are rich in calcium: also young orange trees grown in sand culture had a high calcium content and a high Ca/N ratio.[2] J. D. Newton [3] rejects this view on the grounds that peas and barley in water cultures did not absorb nitrogen and calcium in proportional amounts. The high content of calcium in leguminous plants may have nothing to do with the nitrogen, but only with the CO_2 evolved from the plant roots.

There is some evidence that calcium assists in neutralising organic acids in the plant. The mottled leaves of citrus trees starved of calcium are considerably more acid, but contain distinctly less calcium, than normal leaves.[4] Part of the calcium is in crystals of calcium oxalate, found in the leaves, and part is as calcium pectate cementing the cells together.

In general the addition of calcium greatly helps plants suffering through abnormal nutrition. In the laboratory the harmful effects of pure water or of single salts are more readily mitigated by calcium salts than by any others.[5] Gypsum is used on alkali soils to counteract the harm done through excess of sodium; and lime is added when an excess of magnesium is causing injury. The absorption of calcium by plants and its movements in the tissues do not proceed quite on the same lines as in the case of other elements. Absorption of nitrogen, phosphorus, and potassium is rapid in the early days of the plant's life, but markedly falls off later so that the percentages of these substances in the dry matter decreases

[1] F. W. Parker and E. Truog, *Soil Sci.*, 1920, **10**, 49.
[2] H. S. Reed and A. R. C. Haas, *Journ. Agric. Res.*, 1923, **24**, 801-814.
[3] J. D. Newton, *Soil Sci.*, 1923, **15**, 181.
[4] W. P. Kelley and A. B. Cummins, *Journ. Agric. Res.*, 1920, **20**, 161.
[5] R. H. True, *Journ. Amer. Soc. Agron.*, 1921, **13**, 91-107.

as growth proceeds. Absorption of calcium on the other hand continues, and the percentage increases somewhat with the growth of the plant. As the leaf ages, and before it falls, much of the nitrogen and phosphorus are translocated back to the stems or seed,[1] but the calcium remains behind in the leaf, and so is returned to the ground or gets into the straw.

Barium and *strontium* cannot replace calcium in the nutrition of plants. McHargue (187) has shown that the carbonates are toxic, though in the presence of calcium carbonate they cause an increase in plant growth, strontium being more effective than barium. In Voelcker's experiments (286) the addition to the soil of even 0·1 per cent. of strontium sulphate, hydrate, or carbonate was without effect, but the chloride was distinctly toxic. In Loew's experiments on algæ (176*a*) strontium salts injuriously affected the chlorophyll bodies, causing loss of starch-making power and finally death.

Magnesium, like phosphorus, finally moves to the seed, and is thus in contrast with calcium and potassium, which remain behind in the leaf or the straw.[2] Willstätter has shown (310) chlorophyll to be a magnesium compound, an observation that accounts for the unhealthy condition of the chlorophyll bodies, and the final etiolation of magnesium-starved plants. The effect is well seen in water or sand cultures, and has been studied in detail for orange trees where chlorosis, due to magnesium starvation, spread from a narrow strip along the midrib,[3] for soy bean [4] where the leaves became spotted brown and fell off, and for fruit trees at Long Ashton: here the leaves developed characteristic brown patches in their centres and fell off prematurely,[5] a result which is the

[1] For citrus trees see W. P. Kelley and A. B. Cummins, *Journ. Agric. Res.*, 1920, **20**, 161-191.

[2] Kelley and Cummins, however, show that potassium goes, and magnesium remains, in the leaf of the citrus tree (*Journ. Agric. Res.*, 1920, **20**, 161).

[3] H. S. Reed and A. R. C. Haas, *Bot. Gaz.*, 1924, **77**, 291-299.

[4] J. M. Ginsburg, *Soil Sci.*, 1925, **20**, 1-13.

[5] T. Wallace, *Journ. Pomology*, 1925, vols. iv. and v.

more striking because omission of calcium was without appreciable effect.

Occasionally magnesium starvation occurs in nature. Wallace suggests that apples and raspberries may need magnesium salts where farmyard manure is not given, otherwise the magnesium deficiency causes premature defoliation. In contradistinction to calcium, magnesium starvation does not affect the roots till comparatively late. Tobacco sometimes suffers in this way; a chlorosis known as "Sand Drown" comes on in South Carolina, but it can be cured by supplying magnesium salts. This particular disease is aggravated by the presence of sulphates.[1] Potatoes sometimes respond to magnesium fertilisers, but the conditions are not clearly defined[2]; Marholt considers dung is essential to produce the effect.[3]

Further, magnesium seems to be necessary for the formation of oil, the globules being absent from algæ growing in solutions free from magnesium salts; oil seeds are richer in magnesium than starch seeds.

An excess of magnesium salts produces harmful effects which, however, are lessened by addition of calcium salts; Loew, indeed, considers (176*a*) that plants require a definite $\frac{CaO}{MgO}$ ratio in their food, but neither Gössel[4] nor Lemmermann[5] could confirm this.

In J. A. Voelcker's experiments[6] magnesium oxide, carbonate, and chloride had, like sodium hydroxide, the unusual effect of causing an increase in the nitrogen content of the wheat grain. The sulphate did not act in this way, although

[1] W. W. Garner, J. E. McMurtrey, C. W. Bacon, and E. G. Moss, *Journ. Agric. Res.*, 1923, **23**, 27-40.

[2] *Rothamsted Expt. Stat. Ann. Rept.*, 1921-22, p. 19; M. Popp and J. Contzen, *Landw. Jahrb.*, 1923, **58**, 313; E. A. Mitscherlich and H. Wagner, *ibid.*, p. 645.

[3] *Landw. Versuchs-Stat.*, 1923, **100**, 315.

[4] *Bied. Zentr.*, 1904, xxxiii., 226.

[5] *Landw. Jahrbuch*, 1911, xl., 173 and 255.

[6] *Journ. Roy. Agric. Soc.*, 1915, **76**, 354; 1916, **77**, 260.

in suitable small amounts it caused increases in yield of grain and of straw. The chloride proved toxic at higher concentrations.

Group II. Elements necessary or advantageous in Small Amounts Only.

There is considerable uncertainty as to the extent of this list: it has, indeed, been claimed that any element poisonous to the plant acts as a stimulant in small quantities.[1]

(*a*) *Metals.*

Iron.—Although chlorophyll contains no iron, its formation requires a small quantity of a ferric salt, more being needed in light of high than of low intensity.[2] Oddo and Polacci suggested that the magnesium salt of pyrrole carboxylic acid would serve instead, an interesting observation that deserves further investigation.[3] Boresch claims that chromates and manganates added together to culture solutions free from iron cause rebuilding of the chlorophyl exactly as if iron had been supplied.[4]

Usually soils contain sufficient iron for plant requirements,[5] so that additions are needed only for the water or sand cultures of plant physiologists; occasionally, however, soils carry a chlorotic vegetation which becomes normal only after iron salts have been added. The harmful effect of calcium carbonate on certain plants has been attributed to a precipitation of iron in the soil.[6]

Only little iron is found in plants and that is not all in an active form; part is deposited or precipitated as Fe_2O_3

[1] For the literature see W. E. Brenchley, *Inorganic Plant Poisons*: Cambridge Univ. Press, 2nd Ed., 1926.

[2] W. F. Gericke, *Bot. Gaz.*, 1925, **79**, 106-108.

[3] *Gaz. Chim. Ital.*, 1920, **50**, 54.

[4] K. Boresch, *Ber. Deutsch. Bot. Ges.*, 1924, **42**, 284-290.

[5] For some data see L. H. Jones and J. W. Shive, *Soil Sci.*, 1921, **11**, 93-100.

[6] For a discussion of such precipitations see H. S. Reed and A. R. C. Haas, *Iron Supply in a Nutrient Medium* (*Bot. Gaz.*, 1924, **77**, 290-299).

in the leaf or the tissues. The active compound is organic, and is likened by Maquenne [1] to Bunge's hæmatogen. It is continuously translocated towards the organs of active life and reproduction.

Manganese is an invariable constituent of plants and according to Bertrand [2] is essential to the functioning of the oxydases.[3] It seems of special importance to leguminous plants; it also benefited barley in small concentrations in W. E. Brenchley's water cultures (53*a*). Field experiments in Japan, Italy, and America have indicated some manurial value, but they gave negative results at Rothamsted.[4]

Beneficial effects are obtained only with small doses. Larger quantities cause injury to the roots and chlorosis of the leaves (p. 107).

Copper is invariably present in plants, and, according to Maquenne and Demoussy,[5] it migrates to points of greatest vitality as if it played an active part in intracellular metabolism. No direct evidence is available, however; no sign of benefit could be observed in W. E. Brenchley's water cultures, a harmful effect being produced even by 1 part of copper sulphate in 10,000,000 of water, and by the trace of copper present in ordinary distilled water (p. 107).

Cobalt and Nickel.—These elements are always present in plants,[6] but there is no evidence that they serve any useful function.

[1] L. Maquenne and R. Cerighelli, *Compt. Rend.*, 1921, **173**, 273. They estimated the total iron as 20-100 parts Fe per million of dry matter.

[2] G. Bertrand and M. Rosenblatt, *Compt. Rend.*, 1921, **173**, 333, show that supposed exceptions of Maumené (*ibid.*, 1884, **98**, 1416) all contain manganese.

[3] J. S. McHargue, *Journ. Agric. Res.*, 1923, **24**, 781.

[4] The Japanese experiments are recorded in the *Bull. Coll. Agric.*, Tokyo, 1906, *et seq.* (211*a*), and the Italian experiments in the *Studi e Ricerche di Chimica Agraria*, Pisa, 1906-8; pot experiments have also been made by J. A. Voelcker at the Woburn Experiment Station (*Journ. Roy. Agric. Soc.*, 1903, **64**, 348-364). See also E. P. Deatrick, *Cornell Mem.*, 1919, **19**, 371.

[5] *Compt. Rend.*, 1920, **170**, 87.

[6] G. Bertrand and Mokragnatz, *Ann. Sci. Agron.*, 1925, **42**, 225-229.

Aluminium is included by Mazé among the essential nutrients, and is also considered beneficial by Stoklasa.[1] In large quantities it is harmful, and it appears to be a partial cause of the injury suffered by plants on acid soils.[2]

(*b*) *Non-metals.*

Chlorine is not necessary to the plant in large quantities; Mazé finds, however, that small amounts are beneficial, and this is confirmed for lucerne by S. Lomanitz;[3] barley grain is improved in quality when the plant receives small quantities of chloride.[4] There is, however, considerable uncertainty as to its mode of action.[5] In a recent investigation C. Dupont[6] found that plants receiving chlorides in non-toxic quantities are greener, more turgid, and transpire less water than those receiving equivalent amounts of nitrates or sulphates; he suggests that the chlorine ion enters the plant more readily than these others.

Larger amounts are harmful, and injury by excess of sodium chloride is a common phenomenon on alkali soils or land liable to flood. The harmful effect is well marked where the cation is toxic (J. A. Voelcker, 286).

In natural conditions plants receive measurable quantities of chlorides (chiefly sodium chloride) in the rain, and the amount is greater in the wetter western parts of the country than in the east. At Rothamsted the amount of chlorine brought down averages 16 lb. per acre per annum and fluctuates between 10·3 and 24·4 lb.;[7] it comes chiefly in the winter months. But nearer the sea the amounts become very

[1] *Biochem. Zeitsch.*, 1918, **91**, 137.
[2] See p. 387; also K. Miyake, *Journ. Biol. Chem.*, 1916, **25**, 23-28.
[3] *Soil. Sci.*, 1924, **18**, 353.
[4] *Rothamsted Ann. Rept.*, 1924, p. 18.
[5] See F. Czapek, *Biochemie der Pflanzen*, 1920, ii., p. 518.
[6] *Ann. Sci. Agron.*, 1924, 369.
[7] E. J. Russell and E. H. Richards, *Journ. Agric. Sci.*, 1919, **9**, 309.

high, rising, according to N. H. J. Miller's determinations in rain water from the Hebrides,[1] to—

	Annual Rainfall.	Chlorine per Acre.
	ins.	lb.
Laudale . .	76·89	168·5
Butt of Lewis[2]	40·57	6884
Monach . .	47·21	2723
Barrahead[3] .	33·93	5753

In small quantities both *fluorine* and *iodine* appear to increase plant growth: this was first shown in Japan by Loew (177) and Suzuki and Azo (273): it is also accepted in France by Mazé (197). Gautier and Clausmann[4] go even further and claim that a dressing of 5 kgms. of amorphous calcium fluoride per acre was followed by increases in cereal crops of 5 to 18 per cent., and sometimes considerably more in the case of root crops.

Sulphur is an essential constituent of plants, and occurs in some quantity in the Brassica family, *e.g.* in cabbages and swedes. Dymond (93*b*) showed that sulphates increased the yield of heavy crops rich in protein, although they were not needed for cereals or permanent pastures. Pitz,[5] H. G. Miller,[5] C. B. Lipman, and W. F. Gericke (170*a*) and others have confirmed and extended these observations: the last-named authors found that sulphate of ammonia was superior to nitrate of soda for barley on certain Californian soils, though it was no better than a mixture of nitrate and sulphate of soda. Omission of sulphur from the culture solution led to yellowing and brown-spotting of the leaves of soy bean and brown discoloration of the roots,[6] and to a uniform chlorosis

[1] *Journ. Scottish Met. Soc.*, 1913, **16**, 141-158.

[2] Collected at 70 ft. above sea level.

[3] Collected at 620 ft. above sea level.

[4] *Compt. Rend.*, 1919, **168**, 976; and **169**, 115-122.

[5] Pitz, *Journ. Agric. Res.*, 1916, **5**, 771-780; H. G. Miller, *Journ. Agric. Res.*, 1919, **17**, 87-102; Hart and Peterson (128).

[6] J. M. Ginsburg, *Soil Sci.*, 1925, **20**, 1-13.

of tobacco plants, distinct from the chlorosis consequent on magnesium or potassium deficiency (see p. 93).

Silicon.—Great importance was attached by the older plant physiologists to silicon in the nutrition of the graminæ, it being supposed to give strength to the straw. Field experiments at Rothamstsd disproved this view, neither barley straw nor grass being strengthened by manuring with sodium silicate. But the interesting fact emerged that the silicate increased the yields of barley on plots deficient in phosphate (Table XXIX.). This result was later obtained for oats in water cultures by E. Wolff and C. Kreutzhage.[1] The phenomena were studied by Hall and Morison (120*c*), who conclude that silicates act by causing an increased assimilation of

TABLE XXIX.—EFFECT OF SILICATES ON THE GROWTH OF BARLEY, 1864-1904. ROTHAMSTED.

	Yield of Dressed Grain, bushels.		Yield of Straw, cwts.		Ratio $\frac{\text{Total Grain}}{\text{Straw}}$	
	Without Silicate.	With Silicate.	Without Silicate.	With Silicate.	Without Silicate.	With Silicate.
Nitrate only . . .	27·3	33·8	16·2	19·8	85·1	86·6
Nitrate + phosphate . .	42·2	43·5	24·6	25·8	87·2	85·8
Nitrate + potassium salts .	28·6	36·4	17·9	21·7	80·6	85·0
Nitrate + phosphate + potassium salts . . .	41·2	44·5	25·3	27·6	82·7	82·1

phosphoric acid by the plant, the seat of action being in the plant and not in the soil. W. E. Brenchley and E. J. Maskell show that the efficiency of the phosphorus is increased, thus intensifying the normal phosphatic effects, and producing more tillers, more ears and more fertile florets. There is no indication of partial replacement of phosphorus by silicon; this view accords with the Hoos field experience that silicates increase the rate of deterioration of grain yield while phosphates decrease it. As a possible practical application it has been suggested in Germany and in Japan that

[1] *Landw. Versuchs-Stat.*, 1884, 30, 161-197.



FIG. 15.—Influence of boric acid on the development of the broad-bean in culture solution. Each set receives "complete nutrients": that to the right nothing else: the other four receive traces of boric acid (K. Warington 293).

silicates or colloidal silica might partially replace imported phosphates.[1]

Titanium, given as sodium titanate or titano-citrate, increased the growth of mustard, peas, and lucerne in A. Němec and V. Káš' pot experiments,[2] but it is not known whether the action resembles that of silicon.

Boron is essential for the development of some, but not all, leguminosæ. Miss K. Warington (293) showed that broad beans attained full development only when a trace of boron was given: no other element could replace it (Fig. 15). The best results were obtained with quantities of the order of one part of H_3BO_3 per million of the culture solution; amounts greater than 1 in 5000 were harmful. Of the effects it produces, one of the most striking is on the development of the root nodules (p. 282). After the bacteria have entered the roots and begun to multiply the normal event is for the main vascular system in the root to throw off a branch circulatory system surrounding the bacteria, supplying them with sugar and other plant products, and removing the nitrogenous compounds made by the bacteria. W. E. Brenchley and H. G. Thornton (54) show that this branch system rarely form in absence of boron: the bacteria remain without energy supplies from the plant, and in consequence become parasitic on the protoplasm of the host cells.

Barley apparently does not need boron, and both in water cultures (53*b*) and in J. A. Voelcker's pot experiments (286) it was injured by small amounts.[3]

Physiological Balance.

It has long been recognised that neither unicellular organisms nor higher plants can live in pure water or in solutions

[1] Lemmermann and Wiesmann, *Z. Pflanz. Düng.*, 1922, i. A, 185. See also Jennings, *Soil Sci.*, 1919, **7**, 201, and Th. Pfeiffer, *Mitt. deutsch. Landw. Gessel.*, 1923, p 196, for the possible practical applications.

[2] *Biochem. Zeitsch.*, 1923, **140**, 583.

[3] See also F. C. Cook and J. B. Wilson, *Journ. Agric. Res.*, 1918, **13**, 451.

of a single salt; the effect is more than starvation, and amounts to positive injury, due to the movement of ions out from the plant into the solution and to other actions specific to the particular salt.[1] The plant continues to live only when its culture solution is sufficiently complex in composition.

Tottingham (280) and Shive (262) attached much importance to the ratios between the various nutrients, and drew up lists of "best," "medium," and "poor" ratios. Further experience makes it doubtful whether any "optimum" ratio exists: A. R. Davis[2] could find no statistically significant differences in weight of crop (though there are differences in composition), whether "best" or "medium" solutions were used, while Hoagland and Sharpe (136*c*) obtained satisfactory growth with a wide range of mixtures so long as the total supply and concentration of essential elements was adequate. R. H. True[3] shows that a certain minimum amount of calcium must be present, but otherwise the plant's power of adaptation and internal compensation enables it to grow equally well over a wide range of concentrations of the various salts.

There are, however, limits of variation beyond which the plant begins to suffer. Shive's "poor" solutions are inferior to the "good" ones. In the soil adverse effects are produced when the supply of nitrate much exceeds that of potassium (p. 86); possibly also potassium and magnesium and calcium and magnesium (p. 93) are somehow associated. There are no fixed optimum ratios, but certain minimum requirements of potassium, calcium, and, no doubt, other elements which vary with the composition of the nutrient medium.[4]

[1] For toxic effects of monopotassic phosphate and of ammonium sulphate to soy beans, see Shive (262*c*) and M. L. Wolkoff (*Soil Sci.*, 1918, 5, 123-150).

[2] *Soil Sci.*, 1921, 11, 1-32.

[3] *Journ. Amer. Soc. Agron.*, 1921, 13, 91-107.

[4] Another example is afforded by Ehrenberg's so-called "potash lime law" (*Landw. Jahrb.*, 1919, 54, 4), according to which lime reduces the amount of potassium taken up by the plant, and may therefore depress crop yields on soils poor in potassium.

Abnormal nutrient media are more readily corrected by calcium salts, especially calcium sulphate, than any other substance, hence the advantage of this salt in reclaiming alkali land. This observation and some of Osterhout's experiments (220) have led to the idea of " antagonism " between calcium and sodium, but it appears more probable that the effect is rather in the nature of a remedying of starvation or the influence of one ion on the uptake of another.[1]

As in other directions the requirements of the plant change as it grows older; nutrients essential at first seem unnecessary afterwards, and may apparently do harm. W. F. Gericke finds that wheat seedlings improve considerably in growth if after four weeks in a complete culture solution they are transferred to solutions devoid respectively of either phosphates, magnesium, or sulphur. Calcium and iron were needed longer while nitrogen was necessary all the time.[2]

Plant Appearances as Diagnostic of External Conditions.

From the foregoing pages it is possible to construct a table—at present only very incomplete—indicating the appearances in the growing plant corresponding with certain external conditions. The appearances vary in detail with different plants and combinations of conditions; many of them are not easily described, and if they are to be used in any but a general way they should be studied by setting up the appropriate vegetation experiments. References and further details will be found in the preceding pages under each factor.

[1] H. S. Reed and A. R. C. Haas, *Journ. Agric. Res.*, 1923, 24, 753-758; and *Cal. Expt. Sta. Tech.*, Paper 4, 1923; see also Carl Philipson, *Svensk. Bot. Tidskrift*, 1924, 18, 343-370 (written in English).

[2] *Bot. Gaz.*, 1925, 80, 410.

THE LEAF.

Poor leaf growth.		
(1) *Dwarf plants.*	Yellowish colour.	Lack of nitrogen.
	Greyish colour.	Lack of phosphate or potassium.
	glaucous appearance.	Difficulty of obtaining water, excess of soluble salts, etc.
(2) *Tall spindly plants.*	——	Lack of light near soil.
	——	Plants closely packed.
(3) *Fruit trees.*	Bronze purple colour.	Lack of phosphate (apples).
		Lack of potassium (orange).
	Yellowish, poor growth, premature defoliation.	Competition of grass and other herbage.
Chlorosis or yellowing of leaf.	Uniform all over the leaf.	Lack of iron.
		Excess of calcium magnesium, sodium or potassium carbonates.[1]
		Excess of manganese.
		Lack of sulphur (tobacco).
	Patchy, spreading from midrib outwards.	Lack of magnesium.
	Mottled.	Lack of calcium.
	Spotty.	Lack of potassium.
	Leaf yellowing and then dying at tip and from edges inwards.	Lack of potassium.
	Leaf yellowing and dying from midrib outwards.	Lack of nitrogen.
Patches on leaf.	Brown patches resembling scorch (fruit trees).	Lack of potassium.
	Brown patches chiefly in centre.	Lack of magnesium.
	Brown spots.	Lack of calcium.
Premature defoliation.	——	Lack of potassium, magnesium.
Rich green leaves and large thick stems.	——	Large supply of nitrogen.
Dark coloured leaves, tendency to crinkle.	——	Insufficient potassium in relation to nitrogen.
Patchy appearance of herbage, some dark-green, some lighter.	——	Acidity of soil.

Root.

Very stunted.	Acidity. Lack of calcium or phosphate: bad aeration: lack of drainage: clay soil.
Much fibrous development.	Good aeration: sandy soil.

Fruit.

Brilliant red (apples).	Competition of grass.
Blotchy (tomatoes).	Lack of potassium.

[1] See C. B. Lipman, *Soil Relationships and Citrus Chlorosis; Phytopathology*, 1921, II, 301-306.

	Seed.
Delayed ripening.	Excess of water: excess of nitrogen: lack of phosphate.
Failure to reach maturity.	Great lack of potassium.

Absence of Injurious Substances.

Acids and Alkalis, Hydrogen, and Hydroxyl Ions.—From the fact that plants do not grow well on acid or alkaline soils it has been concluded that hydrogen and hydroxyl ions are injurious. In large amounts they undoubtedly are; addition of sufficient strong acid or alkali, such as HCl or NaOH to culture solutions or soils rapidly kills plants. But the smaller intensities corresponding to the reaction values of natural soils present a more difficult problem because changes in reaction affect some of the nutrients, especially calcium and iron, precipitating or otherwise throwing them out of action. It is uncertain, therefore, whether the harmful effects are direct actions of hydrogen and hydroxyl ions on the plant, or indirect actions arising through deficiency of some essential nutrient.

The experiments are usually made in water or sand cultures. A wide range of *p*H values can be secured by using the mono- di- or tri-potassic or other phosphates in the nutrients.[1] Some difficulty arises from the circumstance that the absorption of nutrients by the plant causes continuous changes in the reaction of the medium; this is met by frequently changing the solution, or by using large volumes, or by some buffering device.

-OH ions are more toxic than -H ions. Hoagland has shown (136*a*) that an acid condition up to *p*H 5·16 [2] is favourable to the growth of barley seedlings, while stronger acidity is harmful, and 2·16 fatal. Alkalinity was decidedly more harmful than acidity: solutions stronger than *p*H 8·26 injured, and those stronger than *p*H 9·40 killed the plant.

[1] For examples see D. R. Hoagland (136*a*).

[2] For meaning of *p*H see p. 185. In the Rothamsted solution barley grows well at *p*H 3·8 (p. 388).

Salter and McIlvaine (243) obtained the best growth in slightly acid conditions; for wheat, soy beans, and lucerne pH = 5·94, and for maize pH = 5·16; 2·96 was harmful, and 2·16 fatal (Fig. 16).

At first sight these results seem wholly inconsistent with the fact that soils of pH values of 5 or 6 are greatly improved for these same crops by liming. It will be shown later, however (p. 214), that lime has several beneficial effects on the

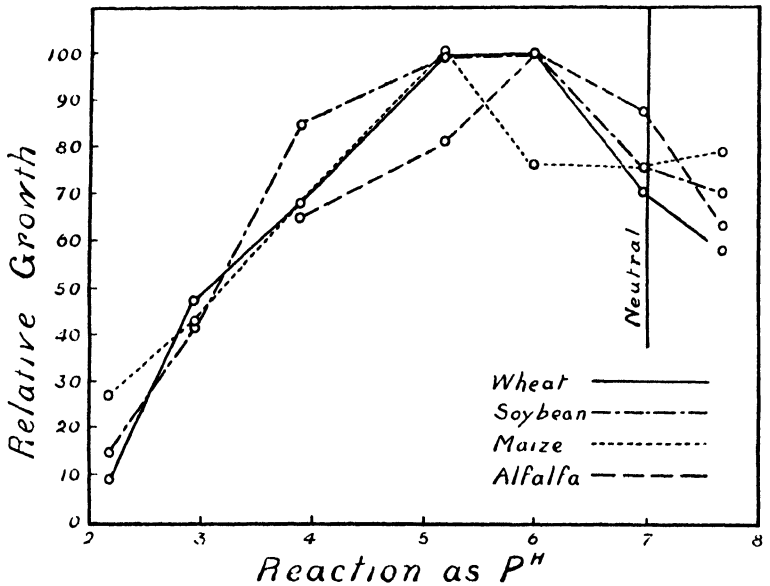


FIG. 16.—Relation between hydrogen-ion concentration (pH value) and growth of crops in water cultures. (Salter and McIlvaine, 243.)

soil, and that pH values of 5 or 6 are usually associated with undesirable fertility properties. Even in laboratory cultures indirect effects cannot be wholly avoided: A. G. McCall and J. R. Haag [1] show that part, at any rate, of the injury done by acidity (pH 4 to 7) to wheat is due to iron starvation, while H. S. Reed and A. R. C. Haas [2] attribute the ill-effects of high pH values (8 or 9) on walnut roots, chiefly to calcium

[1] *Soil. Sci.*, 1921, 12, 69-77.
[2] *Amer. Journ. Bot.*, 1924, 11, 78-84.

starvation; when more calcium was supplied the plant grew. J. J. Theron's measurements[1] show the possibility, and also the limitations, of direct action (Fig. 17); the acidity of the

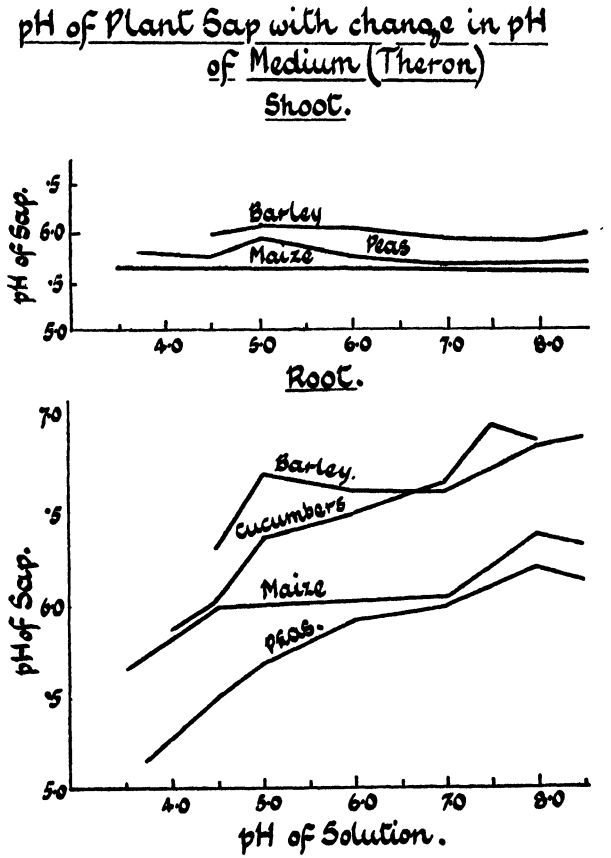


FIG. 17.—Reaction of cell sap as affected by reaction of medium. Upper curves, shoot; lower curves, root.

root sap increased somewhat as that of the medium increased, but the acidity of the sap of leaves and stem did not alter; it remained about *p*H 6. This seems a common value for plant juices; Kappen's measurements for root sap range

[1] *Cal. Pub. Agric. Sci.*, 1924, 4, 413-444.

about 5·5 to 6·5.[1] The *p*H of soils rarely passes beyond the limits 4·5 to 8·5 (p. 189).

The unsuitability of the atmosphere of industrial towns has been traced in part to the presence of acids, which affect the leaves as well as the roots. Wieler [2] found that assimilation of carbon dioxide was profoundly modified by sulphur dioxide, most injury being done in moist weather when the stomata were more widely opened and the gas could readily enter the leaf tissues. Crowther and Ruston (71) obtained the following yields from pots of Timothy, showing that acid water gradually kills the plant :—

TABLE XXX.—EFFECT OF ACID RAIN-WATER ON THE GROWTH OF TIMOTHY GRASS. CROWTHER AND RUSTON (71).

Weight of dry matter obtained when plants were regularly watered with—

	Country Rain Neutralised.	Leeds Rain (Acid).	Solution of Sulphuric Acid, Parts per 100,000 of Water.					
			1	2	4	8	16	32
1st crop, 1908 .	28·0 gms.	23·8 gms.	30·5	28·7	28·8	24·8	23·8	14·1
2nd crop, 1909 .	24·9 ,,	17·5 ,,	18·2	17·8	10·0	8·2	1·8	0
3rd crop, 1910 .	14·7 ,,	6·6 ,,	12·0	8·0	3·9	3·7	0	0

Metallic Salts.—Complaints are sometimes made by farmers in mining districts that their crops suffer damage from the waste products—generally metallic salts—turned into the streams from the works, especially where the water is wanted for irrigation, or where, as in Japan, rice is grown in the marshes. The damage done to pastures by the lead mines of Cardiganshire has been investigated by J. J. Griffith (116) at Aberystwyth. Clover is particularly susceptible. A heavy dressing of lime proved a useful remedy.

Zinc also causes injury in parts of Wales.[3]

[1] *Landw. Versuchs-Stat.*, 1918, **91**, 1-40. See also A. R. C. Haas, *Soil Sci.*, 1920, **9**, 341, and C. B. Clevenger, *Soil. Sci.*, 1919, **8**, 217.

[2] *Bied. Zentr.*, 1908, xxxvii., 572.

[3] The soil of an Anglesey garden examined at Rothamsted contained 0·78 per cent. of zinc. It proved, as might be expected, highly infertile.

Traces of zinc are regarded as essential by Mazé (197). Working with larger quantities, W. E. Brenchley (53*b*) was unable to find definite indications of stimulating action in water culture, although Javillier[1] claimed to obtain increases in soil. Ehrenberg (94*a*) concludes that zinc salts are always toxic when the action is simply on the plant, but they may lead to increased growth through some indirect action in the soil itself (see p. 342).

A vast number of experiments have shown that copper salts are very toxic in water cultures or where they actually come into contact with the plant, even the minute trace sometimes present in distilled water being harmful. This property finds useful application in removing algæ from water and in killing weeds. For example, a 3 per cent. solution of copper sulphate is sprayed over cornfields in early spring at the rate of fifty gallons per acre to destroy charlock (*Brassica sinapis*), one of the most troublesome weeds on light soils. The solution adheres to the rough horizontal leaves of the charlock and kills the plant, but runs off the smooth vertical leaves of the wheat without doing much damage. Even the insoluble complex copper salt present in Bordeaux mixture and sprayed on to fruit trees to kill fungoid pests, was found by Amos[2] to retard assimilation of carbon dioxide by the leaf.

Copper salts do not appear to be anything like so toxic in the soil as in water culture (Russell and Darbishire, 240*b*).

Manganese Salts.—Certain Hawaiian soils contain sufficient manganese salts to injure pine-apples, stunting the roots and causing chlorosis of the leaves. The symptoms are described by E. V. Wilcox and W. P. Kelley;[3] the effect is attributed to the manganese interfering with the iron in the plant.[4]

[1] 7th Inst. Congress App. Chem., Section VII., *Ag. Chem.*, 1910, 163.

[2] *Journ. Agric. Sci.*, 1907, ii., 257-266.

[3] *Hawaii Bul.*, 28, 1912. See also W. T. McGeorge, *Soil Science*, 1923, 16, 269.

[4] A. Rippel, *Biochem. Zeitsch.*, 1923, 140, 315.

Ferrous salts are toxic and are commonly regarded as one cause of the sterility of badly aerated soils.

Aluminium salts have been much studied as one of the causes of the injury formerly ascribed to acidity in acid soils (see p. 387). While in low concentrations they are apparently beneficial (p. 96), at higher concentrations they are harmful, especially in acid soils.

Salts of arsenious acid were found by W. E. Brenchley to be much more toxic than those of arsenic acid; they are used as weed-killers. Greaves has obtained evidence that arsenic compounds stimulate the nitrogen fixing organisms in the soil;[1] while Green has isolated bacteria which are capable of converting arsenites into arsenates, and *vice versâ*.[2]

Whenever infertility is traced to any of these metallic salts a good dressing of lime is usually found to be an effective antidote.

Various Other Substances.—Sulphuretted hydrogen is extremely toxic, so also is ammonium sulpho-cyanide which, in the early days, used to cause trouble as an impurity in ammonium sulphate made from gas liquor. It is rarely, if ever, found now. Toxic nitrogen compounds include nitrites, which have to be removed from synthetical calcium nitrate used for manure, the dicyano-diamide producible from calcium cyanamide, and ammonium salts at too high a concentration. None of these, however, are for long harmful in the soil, since all are ultimately converted into nitrites. Perchlorates are harmful and used sometimes to occur in sodium nitrate, but they are now carefully removed.

Substances Injurious in Large Quantities. Calcium Carbonate.—In large quantities calcium carbonate injures certain crops so much that they will not grow. The effect is apparently indirect, due partly to precipitation of the iron so that plants become chlorotic, partly also to a whole series of

[1] *Journ. Agric. Res.*, 1916, 6, 389-416.

[2] H. H. Green, 5th and 6th Report, *Veterinary Research*, South Africa, 1918, 593-624.

changes in chemical and physical properties of the soil resulting from so much calcium carbonate. It is discussed on pages 412 *et seq.*

Magnesium Salts.—The toxicity of magnesium salts was discovered by Tenant in the eighteenth century in studying the alleged harmful effects of certain limestones found near Doncaster (276). Modern investigations[1] on magnesian limestone, however, have failed to show any harmful effect; indeed, in the Woburn experiments (286) Voelcker has obtained an actual benefit both on wheat and on mangolds by using magnesia (MgO). But the soluble salts, the sulphate and especially the chloride, are harmful. Cases are reported by Loew where insoluble magnesium compounds have caused infertility; none, however, have fallen under the writer's observation in this country. The soil of the Greenville Experimental Farm, Utah, is rich in magnesia—containing over 6 per cent. of MgO—and is remarkably fertile. It also contains, however, 17 per cent. of CaO and 20 per cent. CO_2.[2] As already stated, any injurious effect can be overcome by treatment with lime (p. 93).

Soluble Salts of Alkali Soils.—Over great areas of the world where the average rainfall is less than 15 inches per annum the soil is liable to contain appreciable amounts of soluble salts, notably sodium carbonate and the chlorides and sulphates of magnesium, sodium, potassium, and calcium. Some of these (particularly the chlorides) may directly injure the plant; others apparently interfere with the supply of water or of nutrients.

The qualitative effect of these salts on plants growing in natural conditions is to give them a dull colour and to cause a waxy deposit on the surface of the leaves. Numerous investigations on the toxic limits have been made in the Western States and elsewhere; the figures differ widely,

[1] See, *e.g. New Jersey Bull.*, 267, 1914, and on the other side *Durham Coll. Bull.*, 12, 1915.

[2] J. E. Greaves, R. Stewart, and C. T. Hirst, *Journ. Agric. Res.*, 1917, 9, 301.

partly because they are affected by so many factors, partly because of the difficulty of measuring injury. In dilute solutions these salts stimulate germination, growth, and transpiration; in more concentrated solution they cause injury; and, in still more concentrated solutions, death. Plants differ in their sensitiveness, maize being very sensitive. Those less affected include sugar beet, barley, lucerne, and sweet clover (*Mellilotus alba* and *offic.*), which are therefore grown in cool alkali regions; and sorghum, cotton, rice, berseem and, least sensitive of all, the date palm, which can be grown in warm alkali regions. For individual plants the effect depends on their age, being greatest for seedlings and least for adults; much of the successful management of alkali soils depends on nursing the plants through their early growth by some device such as washing out the salts from the surface layers. Some plants are more tolerant than others in early stages; for this reason sweet clover is at times preferred to lucerne because it starts growth more readily in presence of salts.

The effect is also much modified by other salts, notably calcium salts, so that a harmful concentration of sodium chloride may become inocuous if calcium sulphate is added. The nature of the medium also affects the result; plants suffer more in water cultures than in sand and more in sand than in soil from a given concentration of a salt.

Sodium carbonate is the worst of the alkali salts, not, however, because it is most toxic, but because it produces harmful effects on the soil, thus intensifying the general injury to the plant. Sodium chloride is about equally harmful in water or sand culture where this soil effect is eliminated, and according to B. C. Buffum [1] sodium and potassium sulphates and chlorides are all equally harmful at the same osmotic pressure. At two atmospheres (0·27 per cent. NaCl) they stimulated germination and growth; at 7·1 atmospheres (0·97 per cent. NaCl) they caused injury.[2]

[1] *Wyoming Bulls.*, 29 (1896), and 39 (1898), and Reports, 1899 and 1900.

[2] A good summary of the voluminous literature is given by F. S. Harris in *Soil Alkali*. John Wiley, New York, 1920.

Stimulating Effects of Electricity and Possibly Radium.

The investigations of V. H. Blackman have shown that high tension electric discharges increase the growth of plants, thus settling a long controversy of old standing. It appears, however, that the normal atmospheric or air-earth current has but slight effect.[1]

Effect of Radium.—Sedimentary rocks and soils contain measurable amounts of radio-active substances; usually $1{\cdot}5 \times 10^{-12}$ grams of radium[2] and $1{\cdot}6 \times 10^{-5}$ grams of thorium[3] in each gram. Acid rocks (granites, etc.) contain more ($3{\cdot}3 \times 10^{-12}$ and $2{\cdot}3 \times 10^{-5}$ grams);[4] basic rocks (basalts) contain less ($1{\cdot}2 \times 10^{-12}$ and $2{\cdot}3 \times 10^{-5}$ grams).

Moreover, the potassium compounds of the soil are radio-active (emitting, however, β-rays only)[5], and owing to the large amount their total activity is comparable with that of radium and thorium.

In addition, the soil air contains radium emanations of the order of 10^{-10} curies per litre, this being many thousand times greater than the amount found in atmospheric air; these have been studied in detail by L. B. Smyth.[6]

Many experiments have been made to discover whether the rays or emanations have any effect on the growth of plants or micro-organisms. Gager[7] found that direct exposure to radium inhibited cell activities in younger and especially embryonic tissues, with a few exceptions. The action of radium through the soil, however, was different; the germination and growth were both accelerated, and the plants farthest away were stimulated most. Acqua[8] found that different

[1] V. H. Blackman, *Journ. Agric. Sci.*, 1924, **14**, 240-267; also with A. T. Legg, *ibid.*, 268-286.

[2] A. L. Fletcher, *Phil. Mag.*, 1912, **23**, 279.

[3] J. H. J. Poole, *Phil. Mag.*, 1915, **29**, 483.

[4] J. H. J. Poole and J. Joly, *ibid.*, 1924, **48**, 819.

[5] A. Holmes and R. W. Lawson, *Nature*, 1926, **117**, 621.

[6] L. B. Smyth, *Phil. Mag.*, 1912, **24**, 632.

[7] *Mem. New York Bot. Gard.*, 1908.

[8] *Ann. Bot.* (Rome), 1910, **8**, 223-238.

plants, and even different organs of the same plant, were differently affected, the root system in general responding more markedly than the aerial parts, and in his experiments being arrested in their development. The effect depends on the intensity of the radiation, however; weak emanations up to 1·5 microcuries per 2 litres of air stimulated germination and development of *Linum catharticum* seedlings, while stronger emanations, up to 40 microcuries per litre of air, caused retardation.[1] H. Molisch [2] obtained a like result; young plants of vetches, beans, sunflower, etc., were stimulated in growth by weak emanations, but checked, or entirely stopped, by stronger ones. The " rest period " was broken by the radium emanation, and lilac forced into bloom in November by small quantities of radium chloride attached in pipettes to the terminal buds.[3] In his earlier experiments he, like Dixon and Wigham,[4] failed to detect any radiotropism, but later on he found indications in the case of certain heliotropically-sensitive plants, *e.g.* oats and vetches.[5]

These, and similar results, naturally suggested that the residues left after the extraction of radium, but still containing radio-active material, might have definite manurial value, and it was not long before definite statements were forthcoming. Baker [6] claimed that increased yields of wheat and radishes had been obtained by mixing 1 part of radio-active material (2 mgs. Ra per ton) with 10 of soil. It is true that Stoklasa's [7] results were negative (although in his other experiments radium emanations increased growth to a marked extent), but this did not prevent the introduction of radio-active fertilisers, and the enterprising syndicates and companies concerned were by no means loth to push their wares. These

[1] G. Fabre, *Compt. Rend. Soc. Biol.* (Paris), 1911, **70**, 187-188.
[2] *Umschau*, 1913, **17**, 95-98.
[3] *Oesterr. Gart. Ztg.*, 1912, **7**, 197-202.
[4] *Proc. Roy. Soc.*, Dublin, 1904, **10**, 178-192.
[5] *Sitzber. K. Akad. Wiss.* (Vienna), 1911, **120**, 305-318.
[6] *Journ. Roy. Soc. Arts*, 1913, **62**, 70-78.
[7] *Chem. Ztg.*, 1914, **38**, 841-844.

were investigated by Martin H. F. Sutton,[1] the experiments being made with radishes, tomatoes, potatoes, onions, carrots, and marrows, some grown in pots, others in plots out of doors. Eight different radium residues were used, in addition to pure radium bromide; the dressings were so arranged that equivalent quantities of radium were given in each case ($\frac{1}{400}$ grm. radium bromide to 15 lb. of soil: $2\frac{1}{2}$ times this amount per sq. yard to the plots).

In no case was there any clear evidence of increased growth, even the pure radium bromide seemed to be without action. Wallace also obtained negative results at Long Ashton,[2] and so far as present evidence goes, the radium fertilisers periodically offered to farmers are worthless.

[1] Messrs. Sutton's Bull., No. 6, 1916.
[2] *Rpt.*, 1921, p. 145.

CHAPTER III.

THE COMPOSITION OF THE SOIL.

It is well known that only the top six or eight inches of the soil is suited to plant life, and that the lower part, or subsoil, plays only an indirect part in plant nutrition. We shall, therefore, confine our attention mainly to the surface layer.

The soil was in the first instance derived from rocks, partly by disintegration and partly by decomposition. In general, the fragments split off were sooner or later carried away by water and deposited at the bottom of a river or sea. There they mingled with residues of living organisms which have subsequently played an important part in the history of the soil as its chief source of calcium carbonate and calcium phosphate. In course of time the material accumulated to considerable depths; then, as the result of some earth change, the water retreated, leaving the deposited material as dry land or rock. No sooner was this exposed to the air than it began once again to undergo disintegration, decomposition, and erosion. Air, water, and frost all played a part in the disintegration process; wind, water, and sometimes ice have acted as transporting agents. For immense ages the particles have been subjected to these actions, and the fact that they have survived shows them to be very resistant and practically unalterable during any period of time that interests us. Reference to Tables XCIV. and XCVIII. (pp. 442 and 448), shows that the particles in the surface soil which have been exposed to weathering ever since the soil was laid down, and even to hundreds of years of cultivation, are almost indistinguishable

in size from those in the subsoil which have been protected from all these changes.

However, the soil particles are not wholly unalterable. The rain water and its dissolved carbonic acid exert a slight solvent action, and the soil water always contains small amounts of calcium and magnesium compounds, silica, and other substances in solution. Each individual particle loses only a minute amount of substance to the soil water, and its life is extraordinarily long. Nevertheless, dissolution is perpetually taking place, and the surface soil contains less of the smallest, and, therefore, most easily attacked, particles than the subsoil. Moreover, although the larger particles are chemically inert, some of the decomposition products—probably alumino-silicates—are chemically active, and enter into reactions of considerable importance in the economy of the soil. The smallest of the particles, and apparently also the reactive silicates, possess the properties of electro-negative colloids.

In any region where the rainfall and temperature conditions are favourable, soil rapidly covers itself with vegetation; even a bare rock surface is not without its flora. The first vegetation must obviously have obtained its mineral food from the dissolved material of the soil particles, but when it died and decayed all the substances taken up were returned to the soil, so that subsequent vegetation has food from two sources: from the substances dissolved direct out of the soil particles during the life of the plant, and from those dissolved out at earlier times and taken up by previous races of plants. Thus in the natural state, and where the vegetation is not removed, the mineral plant food can be used over and over again and indeed tends to accumulate as fast as it is extracted from the soil particles by the rain water.

This dead vegetation may either (*a*) lie on the surface of the soil when it decays to form peat, or (*b*) mingle with the soil as a result of the activity of various living organisms when it forms humus. The second is the more usual course

and the one to which the discussion in this chapter will be confined.

The residues of the dead plant return to the soil more than the living plant had taken away; during its life it has been synthesising starch, cellulose, protein, and other complex material, much of which falls back on the soil when it is dead. This added organic matter introduces a fundamental change because it contains stored-up energy fixed from sunlight by the plant's chlorophyl; the difference between the soil as it now stands and the original heap of mineral matter is that the soil contains sources of energy while the mineral matter does not. Hence it soon becomes the abode of a varied set of organisms, drawing their sustenance and their energy from the organic matter, and bringing about certain changes to be studied later; some, as we shall see, are capable of fixing gaseous nitrogen and so increasing the supply of protein-like compounds, whilst others can assimilate carbon dioxide.

Thus the complex that we speak of as the soil consists of four parts :—

1. The mineral matter derived from rock material, which constitutes the frame-work of the soil and is in the main unalterable in short periods of time, but it contains some reactive decomposition products.

2. The calcium carbonate and phosphate (the latter being usually in much smaller amount), and organic matter derived from marine or other organisms deposited simultaneously with the soil.

3. The soil water, a dilute solution of carbonic acid containing small quantities of any soluble soil constituent.

4. The residues of plants that have grown since the soil occupied its present position, consisting of the mineral plant food taken up from the soil water and of part of the complex organic matter synthesised during their life period. This is the source of energy for the soil population and may be regarded as the distinguishing characteristic of soils.

These four constituents are invariably present, but not in the same proportion; their relative abundance affords the basis on which soils are classified. From the agricultural point of view we thus have: (*a*) mineral soils consisting mainly of rock material, subdivided into sands, loams, and clays; (*b*) calcareous soils containing notable amounts of chalk or limestone; (*c*) alkali soils rich in soluble, saline matter; (*d*) acid humus or peat soils where much organic matter has accumulated in absence of calcium carbonate; (*e*) neutra humus soils where much organic matter has also accumulated, but in presence of sufficient calcium carbonate to prevent acidity.

By far the greater proportion of agricultural soils belong to the first group.

The Mineral Portion of the Soil.

Its Origin and History.

The mineral portion consists of (1) undecomposed and merely disintegrated rock fragments; (2) decomposition products. The decomposition proceeds so slowly that little has occurred in soils formed direct from igneous or palæozoic rocks since late glacial periods; in these the particles are simply fragments of the original rock. It has, however, gone further in older soils, or soils derived from rocks which have themselves been formed by disintegration and decomposition of still older rocks. Its first stage consists in the removal of silica and potash and the formation of a simpler silicate (commonly an alumino-silicate): this has been represented by the following equation, which, however, is to be taken as an illustration, and not an exact representation of the facts:—[1]

$$K_2O \cdot Al_2O_3 \cdot 6SiO_2 + CO_2 + 2H_2O = Al_2O_3 \cdot 2SiO_2 2H_2O + K_2CO_3 + 4SiO_2$$

Complex rock silicate — Simpler silicate (Kaolin)

[1] For a recent discussion see R. Schwarz and R. Walcker (*Z. Anorg Chem.*, 1925, 145, 304-310)

Subsequent changes depend on the climatic conditions, and particularly on the reaction of the soil water.

Where the water is acid (*e.g.* where there is much organic matter and a restricted air supply, see p. 161) all the minerals are attacked, and the basic oxides (Fe_2O_3, Al_2O_3, CaO, etc.), gradually dissolve and are washed out, leaving only the highly resistant quartz.

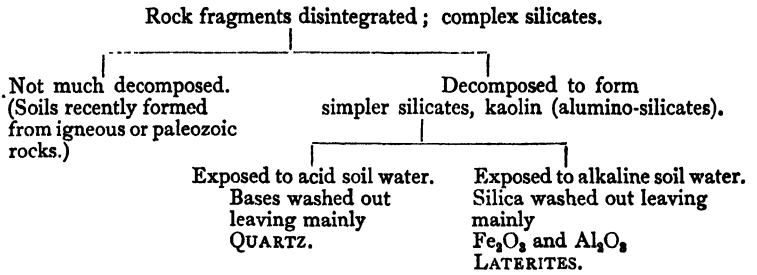
The rapidity of this action depends on the degree of acidity of the water and the amount of calcium carbonate present; it is easily observed in soils overlaid by peat; it is very much slower in soils containing some calcium carbonate, but only little organic matter. But it goes on continuously, and in the secondary and tertiary soils of the midlands and south of England it has proceeded so far that little except quartz has survived, excepting only in the finest particles which contain the decomposition products.

A second type of change takes place where the soil water is alkaline. Here the silica is washed out before the iron and aluminium oxides; the iron oxide also tends to be removed, leaving finally only the alumina. These soils are called laterites; they are found in tropical conditions under heavy rainfall where vegetation has been luxuriant; they are characterised by their red colour, so long as they contain enough iron, and special cultural and vegetation properties.[1]

Four processes must, therefore, be distinguished in soil formation :—[2]

[1] For an account of laterites see C. O. Swanson (*The Origin, Composition, and Distribution of Laterite, Journ. of the Amer. Ceramic Soc.*, p. 1248, vol. vi., No. 12, Dec., 1923), and Max Bauer (*Beitrag zur Kenntniss des Laterits, insbesondere dessen von Madagascar. Neues Jahrbuch für Mineralogie, Geologie und Paläontologie*, Festband, 33-90, 1807-1907); for the laterites of French Guiana and Madagascar see La Croix (*Les Laterites de la Guinée et les Produits d'Alteration qui leur sont Associates, Nouvelles Archives du Musee*, 1914, 5, (5), 255-256); for Italian soils (*Terra rossa*, probably not true laterites), C. Ulpiani, *Staz. Sper. Agric. Ital.*, 1913, 45, 629. See also T. H. Holland, *Geol. Mag.*, 1903, 10, 55-69 (*Laterites of India*). A good recent account is in Mohr, *De Boden von Java.*

[2] For a recent discussion see R. Ganssen (*Mitt. Preussischen Geolog., Heft.* 4, 1922) and H. J. Page's summary in *Chem. Soc. Reports.*, 1925.



Examples of soils formed mainly of disintegrated soil fragments, and therefore containing much undecomposed mineral silicate, are found in North Wales (G. W. Robinson, 237); Aberdeen (Hendrick and Ogg, 132); in South France (Delage and Lagatu, 83), and in various parts of the United States. There is always some decomposition, and between the extreme cases of unaltered rock fragments on the one hand and complete elimination of everything except quartz on the other, comes an infinite gradation of soils in which no lines of demarcation can be drawn. The grades are well illustrated by McCaughey and Fry's estimations (186) of the percentages of the various minerals present in the sand and silt fractions separated from United States soils:—

Method of Formation.	Soil Type.	Sand Fractions. Percentage of		Silt Fractions. Percentage of	
		Minerals other than Quartz.	Quartz.	Minerals other than Quartz.	Quartz.
Chiefly disintegration	Arid . .	37	62	42	58
Intermediate —	Residual .	15	85	21	79
	Glacial and loessial .	12	88	15	85
Chiefly decomposition	Marine .	5	95	8	92

Failyer, Smith, and Wade's (98) analyses show the successive eliminations of minerals other than quartz in these grades of soil:—

		Percentage of K_2O in			Percentage of CaO in			Percentage of P_2O_5 in		
		Sand.	Silt.	Clay.	Sand.	Silt.	Clay.	Sand.	Silt.	Clay.
Type 1 .	Arid . .	3·05	4·15	5·06	4·09	9·22	8·03	·19	·24	·45
Type 2 .	Glacial .	1·72	2·30	3·07	1·28	1·30	2·69	·15	·23	·86
	Residual .	1·60	2·37	2·86	·50	·82	·94	·07	·22	·70
Type 3	Coastal .	·37	1·33	1·62	·07	·19	·55	·03	·10	·34

Table XXXI. shows the difference in composition between the fractions obtained by Hendrick and Ogg from the Aberdeen soil, belonging to the intermediate grade, and the more completely washed and weathered soils studied by Hall and Russell, where practically nothing but quartz had survived in the coarse particles.

Some of the soils of North Wales differ even more from those of South-east England, the silica being highest in the intermediate fractions (Robinson, 237).

Components of the Soil.

The Physical Fractionation of the Soil.—The first analyses of the soil made by Davy, Schübler, and the earlier workers were physical, the soil being broken up into fractions of larger and smaller sizes. It was assumed that the air and water relationships which interested these earlier workers were determined more by the size than by the composition of the particles. Further work has justified this assumption, and physical analysis is now one of the most important methods in soil investigation.

The estimate of size is made indirectly from the rate of sedimentation in water, no practicable direct method having been devised. Unfortunately, the particles vary so much in shape that they cannot be assigned definite dimensions. A convention is therefore adopted, and the particles are specified by the diameter they would possess if they were spheres of

TABLE XXXI.—SHOWING COMPOSITION OF THE FRACTIONS OBTAINED FROM MUCH WASHED AND WEATHERED SOIL (S.E. ENGLAND) WHERE PRACTICALLY NOTHING BUT QUARTZ SURVIVES IN THE COARSE PARTICLES, IN COMPARISON WITH THE LESS DECOMPOSED SOIL FROM ABERDEEN, WHERE MORE OF THE ROCK MINERAL (GRANITE) SURVIVES. (HALL AND RUSSELL (121*b*) FOR S.E. ENGLAND, AND HENDRICK AND OGG (132) FOR ABERDEEN.)

CHEMICAL ANALYSIS OF MECHANICAL FRACTIONS, CALCULATED AS PERCENTAGES OF DRY MINERAL MATTER.

	SiO_2		Al_2O_3		Fe_2O_3		CaO		MgO		K_2O		P_2O_5	
	S E. of England.	Aberdeen.	S.E. of England.	Aberdeen.	S.E. of England.	Aberdeen.	S.E. of England.	Aberdeen.	S.E. of England.	Aberdeen.	S.E. of England.	Aberdeen.	S.E. of England.	Aberdeen.
Fine gravel	94·4	85·0	3·0	8·6	2·1	1·1	0·4	0·9	0·8	0·4	0·6	1·5	0·06	0·07
Coarse sand	93·9	83·9	1·6	9·3	1·2	1·1	0·4	1·8	0·5	0·4	0·8	1·8	0·05	0·08
Fine sand	94·0	73·9	2·0	13·5	1·2	4·2	0·4	3·0	0·04	1·0	1·5	1·7	0·02	0·1
Silt . .	89·4	70·1	5·1	14·0	1·5	5·8	0·8	2·1	0·3	1·1	2·3	1·5	0·03	0·2
Fine silt	[1]84·1	67·2	7·2	18·9	2·6	7·8	1·1	1·4	0·2	1·6	3·2	2·5	0·1	0·3
	[2]64·3		19·3		7·6		2·2		0·4		5·		0·4	
Clay .	[3]53·2	44·1	21·2	27·6	13·2	21·8	1·6	0·6	1·0	1·6	4·9	1·1	0·4	0·4
	[4]49·0		29·8		13·1		1·5		1·0		3·4		0·7	

[1] Fraction ·01 to ·004 mm. [2] Fraction ·004 to ·002 mm. These two fractions together constitute fine silt.
[3] From fertile soils. [4] From less fertile soils.

such size as to sink in water at the same rate. These are called the " equivalent diameters."

Unfortunately, three separate groupings are in use; the American, the British, and the Continental, and in each country so many analyses have been made that change is now very difficult. The groups and their equivalent diameters are given in Table XXXII.

The details of the British method are given on page 460. By a simple modification—the splitting of the " fine silt " fraction into two ranging respectively from 0·01 to 0·005, and from 0·005 to 0·002 mm. diameter—the British grouping can be brought nearly into line with the American.

The fundamental weakness of the method is that the grouping is quite arbitrary, sharp lines being drawn where none exist in Nature, and the soil is represented as a mixture of five or six different substances when in point of fact the number of components is indefinitely large. When the figures are obtained it is difficult to use them for further investigations; they cannot be plotted on curves [1] or reduced to simple terms, though they can be set out in columns which are very convenient for lecture purposes. Some limited success has followed the attempts to relate them to other soil properties, as will be shown later; but in the main the figures obtained have not proved fruitful to investigators, though the broad general results have been useful.

Many of these difficulties would disappear if it were possible to divide the soil into an indefinitely large number of groups which could be plotted as contiguous columns. The curve joining the tops of these columns is known as the mass distribution curve. There is still some degree of artificiality, it being necessary to retain the conventional " effective " or " equivalent " diameters, dealing with the particles, not as they are, but as they would be if they were perfect spheres. But the method has the great advantage of giving curves

[1] See G. W. Robinson (*Journ. Agric. Sci.*, 1924, 14, 626-633), for an ingenious attempt to get round this difficulty.

TABLE XXXII.—NAMES AND SIZES OF FRACTIONS OBTAINED BY MECHANICAL ANALYSES OF SOILS IN DIFFERENT COUNTRIES.

British.		American (Bureau of Soils).		German older work [1] (Verband landw. Versuchs-Stat.).		Atterberg [2] (Suggested for International Use and adopted in Germany).[3]	
Name of Fraction.	Limits of Diameter of Particles, mm.	Name of Fraction.	Limits of Diameter of Particles, mm.	Name of Fraction.	Limits of Diameter of Particles, mm.	Name of Fraction.	Limits of Diameter of Particles, mm.
				Steine	above 5		
				Grand	5-2	Kies	above 2
Fine gravel	3-1	Fine gravel	2-1	Sehr grober sand	2-1		
Coarse sand	1-0·2	Coarse sand	1-0·5	Grober sand	1-0·5	Sand	2·0-0·2
		Medium sand	0·5-0·25	Mittel korniger sand	0·5-0·2		
Fine sand	0·2-0·04	Fine sand	0·25-0·10	Feiner sand	below 0·2	Mo	0·2-0·02
						or Fein sand	0·2-0·06
		Very fine sand	0·10-0·05	Sehr feiner sand		Mehl sand	0·06-0·02
Silt	0·04-0·01	Silt	0·05-0·005	Mineral staub		Schluff (or Staub)	0·02-0·002
						or grober Schluff	0·02-0·006
Fine silt	0·01-0·002			Ton		feiner Schluff	0·006-0·002
Clay	below 0·002 [4]	Clay	below 0·005			Schlamm (or Ton)	below 0·002

[1] *Landw. Versuchs-Stat.*, 1892, 42, 154, and 1893, 43, 335. The first five fractions are separated by sieves, and the others in Kühn's sedimenting cylinder. Ramann adopts the American limits but divides the clay into *Feiner Staub* 005-·0015 mm., and *Schlamm*, below ·0015 mm.

[2] *Internat. Mitt. f. Bodenkunde*, 1912, 2, 312-342.

[3] *Ibid.*, 1914, 4, 31.

[4] Probably smaller: the calculated value for the upper limit is 0·0014.

much more suited to detailed study than the data yielded by the older methods of mechanical analysis.

Odén has obtained mass distribution curves by ascertaining the time taken for successive constant but small weights of soil to settle out from a column of suspension in water. The pan of the balance is placed in the cylinder containing the suspension of the soil in water, and the time when the sediment in the pan equals the weight on the other side is recorded by an electrical device set in operation by the beam as it moves; at the same time an additional weight is dropped by the same

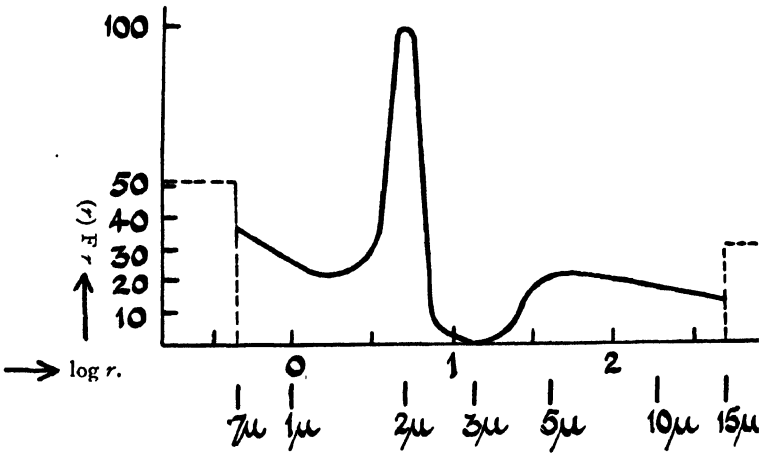


FIG. 18.—Mass distribution curve obtained by Odén's method of soil analysis.

device into the weight pan in readiness for the next quantity of sediment. The balance has been developed to a high degree of accuracy by Odén and Keen;[1] it still suffers, however, from the defect that the interception of part of the sediment in the pan causes a difference in density between the liquid immediately under the pan and that at the sides, with resulting eddies about the edge of the pan.[2]

One of Odén's curves is shown in Fig. 18.[3] On the hori-

[1] J. R. H. Coutts, E. M. Crowther, B. A. Keen, and S. Odén, *Proc. Roy. Soc.*, A., 1924, **106**, 33-51.

[2] J. R. H. Coutts and E. M. Crowther, *Trans. Faraday Soc.*, 1925, **21**.

[3] *Trans. Faraday Soc.*, 1922, **17**, 338.

zontal axis are plotted successive values of the radii. The axis of y represents a complex function which gives the percentage weight of particles comprised between successive integral values of μ. Thus the percentage weight of particles between 1 μ and 2 μ in diameter is the area bounded by ordinates drawn at points 1 and 2 on the axis of x.

A simpler apparatus has been devised by G. Wiegner,[1] but it is less accurate.

Properties of the Fractions and their Influence in the Soil.

Coarse Sand (1 to 0·2 mm. in diameter) is, of all the soil constituents, perhaps the most variable in amount, its proportion ranging from less than 1 to more than 90 per cent. It exercises a great influence on soil fertility, largely through the negative nature of its properties. Through its lack of cohesion it keeps the soil open and friable ; in moderate amounts it facilitates working, but in excess it increases drainage and evaporation so much as to interfere seriously with the water-holding capacity of the soil. Many good loams contain less than 4 per cent., and in general strong or tenacious soils contain less coarse sand than one-half the quantity of clay present. When the coarse sand exceeds the clay in amount the soil becomes light, unless the clay is above 15 or 20 per cent., when the soil is usually heavy. Not being a colloid, it possesses no power of absorbing water or soluble salts. Soils containing 40 per cent. or more of coarse sand and less than 3 per cent. of clay are cultivated only where large quantities of dung are available, or where the water supply is exceptionally good. As the amount of coarse sand increases, the soils become less and less suited to cultivation, till finally the sand dune condition may be reached, though in adequately moist conditions cultivation may still continue, even when 90 per cent. of coarse sand and no clay are present (*e.g.* part of Anglesea).

[1] *Landw. Versuchs-Stat.*, 1918, 91, 41-80.

Fine Sand (0·2 to 0·04 mm. in diameter), forms a considerable fraction—usually 10 to 30 per cent. or more—of nearly all soils. The dimensions of the particles being smaller, surface properties begin to show; there is some power of holding water and a certain degree of cohesiveness causing the particles to cake together. Soils containing 40 per cent. or more of fine sand tend to form, after rain, a hard crust on the surface, through which young plants make their way with difficulty until it has been broken by a roller. But they have no great water-holding capacity or retentive power such as appears when the still finer fractions predominate, and they are not infrequently described by their cultivators as hungry soils that cannot stand drought. The notoriously infertile Bagshot sands and the barren Hythe beds in West Surrey are largely composed of this fraction, as much as 70 per cent. sometimes being present; the percentage of clay, however, is low and the situation dry. Better results are obtained when the clay exceeds 8 or 9 per cent., or when the water supply is better, especially if the amounts of coarse sand and gravel are not too high. Some of the good fruit soils of the west of England contain 40 to 50 per cent. of fine sand.

The coarser grade of *silt* (0·04 to 0·01 mm. in diameter) appears to be very valuable, and constitutes 30 to 40 per cent. of many of the loams most famous in the south-east of England for carrying their crops well and not drying out. The fertile loess soils of the United States are also rich in silt, containing 55 or more per cent. of material of ·05 to ·005 mm. diameter.[1] Light, sandy loams, on the other hand, may contain only 10 to 20 per cent.; some of these are highly fertile, but as a rule they require large dressings of dung, or a situation favourable for water-supply. Probably silt plays a very important part in maintaining the even conditions of moisture so desirable for plant growth. It is fine enough to retard, but not to prevent, percolation, and it facilitates capillary movement of water.

[1] J. G. Mosier and A. F. Gustafson, *Soil Physics and Management*, 1917, p. 64.

In *fine silt*, owing to the smallness of the particles, the surface properties are much emphasised. The cohesiveness and power of holding water are considerable. Further, fine silt is beginning to show some of the properties associated with colloids, especially suspensoids;[1] its suspensions in water are readily flocculated by small quantities of salts but not by alkaline bases. Thus it is flocculated by calcium nitrate much more readily than by calcium hydroxide; this is the normal behaviour of suspensoids. Soils containing more than 15 to 20 per cent. of fine silt are often difficult to work and do do not become more tractable by treatment with lime, nor, indeed, by any other device; instances are found on the coal measures, the Lower Wealden strata, and elsewhere.

The Clay Fraction.—The voluminous literature of clay is almost hopelessly complicated by the circumstance that different writers use the word in different senses; ceramic workers apply it to all material less than 0·1 mm. in diameter, while soil investigators in the United States restrict it to material below 0·005 mm. in diameter, and in Great Britain to that below 0·002 mm. in diameter. Modern supercentrifuges have effected still further division, separating out an "ultra clay," the particles of which fall below 0·001 mm.[2] in diameter in which the clay properties are much intensified.

In spite of variations in the material studied by different workers, certain properties stand out clearly as possessed by the various clays but not by fine silt or the coarse fractions. The most characteristic is that when well rubbed with water, clay swells up, becomes very sticky, impervious to air and water, and so plastic that it can be moulded into shapes which remain permanent, although shrunken, on drying or baking. The swelling on wetting is accompanied by an

[1] See footnote on p. 130.

[2] In contrasting this magnitude with others it may be remembered that—

·001 mm. = 1000 $\mu\mu$.
Wave-length of light (NaD_2) = 589 $\mu\mu$.
Diameter of molecule of hydrogen = 0·24 $\mu\mu$.
1 Ångström unit = 0·1 $\mu\mu$.

evolution of heat, and the shrinkage on drying by an absorption of heat. The separate particles of clay are so small that, when placed in water, they assume a state of Brownian movement and sink only very slowly in spite of their high specific gravity. Traces of electrolytes have a profound effect on these properties; small quantities of acids or salts cause the temporary loss of plasticity, impermeability, and the property of remaining long suspended in water without settling; the clay is now said to be flocculated. The change can be watched if a small quantity of any flocculating substance is added to the turbid liquid obtained by shaking clay with water; the minute particles are then seen to unite to larger aggregates which settle, leaving the liquid clear. There is, however, no permanent change; deflocculation takes place and the original properties return as soon as the flocculating agent is washed away. Alkalis (caustic soda, caustic potash, ammonia and their carbonates, but not calcium hydroxide) produce the reverse effect; they deflocculate clay, intensifying its stickiness and impermeability and causing it to remain suspended in water for long periods [1] (see p. 130).

Further, it appears to act as a semipermeable membrane in relation to the movement of water: [2] this property might cause some peculiarities of behaviour on sandy soils, such as the Bagshot beds, where there are thin partings of clay.

A remarkable change sets in when clay is sufficiently heated, and it permanently loses all its special properties.

Soil investigators have, in the past, set up special hypotheses to account for the clay properties; they no longer do so, because they now recognise that these properties are not peculiar to clay, but are possessed by the group of "electronegative" colloids, so called because their particles take on a

[1] Leoncini and Masoni (167) were unable to find that the modification in permeability in soil caused by saline solutions had any relation to their powers of flocculating clay.

[2] Lynde, *Journ. Phys. Chem.*, 1912, 16, 759-778, and *Journ. Amer. Soc. Agron.*, 1913, 5, 102-106.

negative charge when suspended in water. Investigators now apply to clay the hypotheses already recognised by colloid workers. It must not be imagined that this simplifies matters; on the contrary, the literature of colloids is considerably more extensive than even that of clay. But it has had the useful effect of bringing investigations on clay into line with those on colloids and furnishing soil investigators with new methods and ideas. One difference must always be borne in mind; the colloids in the soil are mainly in the "gel" state, while the laboratory investigations have been concerned almost entirely with "sols" for which easier quantitative methods are possible.

The properties of clay are now associated with—

(1) The constitution and the very small size of its particles;
(2) Their affinity for water;[1]
(3) The negative electric charge which they take on in presence of water.

The negative charge on the clay particles causes them to be deposited at the anode when an electric current is passed through a clay suspension: this property may be used to purify clay. Another way of stating this result is that water is deposited at the cathode when an electric current is passed through clay. Crowther and Haines have reduced the draught in ploughing by passing a current generated by the tractor through the soil: the mould board being the cathode, is, therefore, continuously lubricated by the deposited water film.[2]

The plasticity and cohesion of clay have been studied by Atterberg (7), who has devised some ingenious experimental methods, and by Haines, who has applied to soil the conceptions of Bingham on plasticity.[3]

Flocculation.—Of all clay properties none has been so

[1] Studied by van Bemmelen (25).

[2] E. M. Crowther and W. B. Haines, *Journ. Agric. Sci.*, 1924, 14, 221-231.

[3] W. B. Haines, *Journ. Agric. Sci.*, 1925, 15, 178-200; E. C. Bingham, *Fluidity and Plasticity*. McGraw-Hill Book Co., 1922. For a useful discussion see J. W. Mellor, *Trans. Faraday Soc.*, 1922, 17, 354-365.

much investigated as the flocculation produced when small quantities of electrolytes are added to suspensions of clay in water. The general appearance has been already described (p. 128). Three methods of investigation are used:—

1. The oldest and still the commonest method is to observe the change in the appearance of the liquid at a given time after the addition of the electrolyte.

2. Counting by means of the ultramicroscope the number of particles in a known volume of the suspension at definite intervals after addition of the electrolyte. This is probably the best method, but it is tedious. Electrolytes are compared by ascertaining the concentrations of the various salts which bring about the same percentage decrease in the number of particles in standard time. This method was used in three important investigations which must be studied by all students of flocculation: Wiegner (308*b*), Gallay (104), and Mattson (193).

3. Measuring the change in viscosity by the Ostwald viscosimeter. This was used by Gallay.

The effects of single salts have been frequently studied. In general their effects are much the same as on other electronegative suspensoid sols.[1] Small additions of an electrolyte to a clay suspension cause a slow coagulation of the clay, the speed of which is proportional to the amount of electrolyte added; larger quantities cause a rapid coagulation, which is independent of the amount added. The coagulating power of a series of salts of the same acid increases with the valency of the cation; the univalent bases being least effective, the bivalent next, and the trivalent most. The hydrogen ion is, however, more potent than other univalent ions, being more nearly comparable with bivalent ions, and the coagulation

[1] Colloids which do not combine with the liquid in which they are suspended, but may be supposed to have their surface sharply separated from it, are called suspensoids; while those which do combine with the medium and therefore possess no sharp dividing surface are emulsoids. The distinction is not sharp nor is it universally accepted.

effected by trivalent ions shows certain peculiarities, particularly a tendency to proceed in zones.

The power of the ions to flocculate increases with their atomic weight. In the univalent group the order of effectiveness is Li<Na<K<Rb, while in the bivalent group the order is Mg<Ca<Sr<Ba. The sediments produced, however, are not the same for the different flocculants. For equivalent concentrations of added electrolytes, the cation of highest atomic weight and lowest hydration gives the most viscous and most hydrated sediment and the flocculation proceeds most rapidly.

The different salts of the same metal have somewhat different powers of coagulation, but interest has centred round calcium salts and especially calcium hydroxide because of its great importance in agriculture. Suspensions of kaolin or silt are less easily flocculated by calcium hydroxide than by calcium chloride or nitrate. This accords with expectation, since -OH ions usually increase the negative-charge on suspended particles. Suspensions of clay behave in the same way if the solutions are very dilute but in the opposite way if the solutions are a little stronger; they are then more easily flocculated by calcium hydroxide than by other calcium salts. This abnormal flocculation of clay [1] has been studied first by Comber (69) and afterwards by Mattson (193). Comber explains it by supposing that the clay particle is composed of a solid core, which behaves like silt, surrounded by a coating of an emulsoid gel such as silica. This gel reacts with calcium hydroxide, producing a very bulky precipitate which drags down the clay.[2] The precipitate can be hydrolysed by washing when the clay again goes into suspension. In support of this explanation Comber showed that other suspensions such as ferric oxide which are not flocculated by calcium

[1] Anomalous flocculations of lateritic clays and especially of the colloidal alumina, iron oxide, and silica of which the laterites are built up are collected and discussed in a comprehensive paper by F. Hardy, *Journ. Phys. Chem.*, 1926, 30, 254.

[2] *Faraday Soc. Trans.*, 1922, 17, 349-353.

hydroxide readily become flocculated if previously treated with a little colloidal silicic acid.

Mattson has studied this abnormal coagulation as produced by mixtures of calcium salts with small quantities of alkalis. The -OH ions increased the capacity of the clay to absorb calcium and also had a remarkable effect on its electric charge. Normally the clay is flocculated only when its charge falls below a certain amount: calcium sulphate, for example, always decreases its charge: in presence of alkali, however, coagulation may occur without this fall of charge. Mattson assumes a preferential absorption of the -OH ions, thereby raising the charge and increasing the absorption of calcium ions; as the calcium ion is bi-valent he further assumes that each ion could hold two clay particles together, and would therefore tend to bring them down. The idea is simple, but to explain Gedroiz' discovery that sodium salts behave in exactly the same way it would be necessary to assume that the clay particles are held together by the secondary valencies of sodium.

Some of the apparent abnormalities in the phenomena of flocculation may arise from the circumstance that clay reacts immediately with the added salts, cations being exchanged (see p. 139), so that the electrolyte added is not necessarily the agent causing the flocculation. Comber distinguishes three kinds of flocculation of clay:—

1. Normal flocculation, which resembles that of any other electro-negative suspensoid; iron and aluminium salts behave in this way.

2. Indirect flocculation, where the added electrolyte reacts with the clay and brings into solution other substances which cause flocculation. Acids and certain neutral salts afford examples.

3. Abnormal flocculation, brought about by a reaction between the added flocculant (*e.g.* calcium hydroxide) and the emulsoid surface of the clay particle.

While the flocculation of clay most familiar to agricul-

tural students happens to be the abnormal one, the majorit of the flocculations are normal. It therefore seems justif able to bring clay into line with other suspensoid sols an apply the usual hypotheses to explain the normal resul The phenomena become more complex when the hydroge ion concentration of the solution is varied along with change in concentration of the salts.[1]

These clay properties are of great importance to the fe tility of the soil, and no constituent is more necessary in prope proportions, or more harmful in excess. Clay impedes th movement of water in the soil and keeps it in the surfac layers within reach of the plant roots, thus making the so retentive of water. Excess of clay, however, interferes to much with the water movements, parching the soil in dr seasons, even though the permanent water level is near th surface, but making it water-logged in wet weather, thu impeding the movement of air to the roots and lowering th temperature of the soil. The adhesive properties of clay caus the soil particles to bind together into those aggregates o which " tilth " depends ; soil without clay would be very lik a sand heap. Here, also, however, excess of clay does har and makes the soil so adhesive that it sticks to the tillag implements and retards their movements ; it also tends t form large clods unfavourable to vegetation. These effec are intensified in wet weather ; the soil becomes sticky c " poached " and must not be worked or the tilth is injured fc a long time. Another effect of a large amount of clay is t make the soil shrink very much on drying, so that larg cracks appear in the fields in summer time. The swelling c the clay in wetting may be harmful.[2] These effects are r duced by flocculation effected by dressings of lime or chal and by organic matter ; on the other hand, they are intensifie

[1] W. O. Kermack and W. T. H. Williamson, *Proc. Roy. Soc. Edin.*, 192 1925, 45, 59-70.

[2] When the Gezira (Sudan) was first irrigated the swelling of the clay w so great as to force the masonry of the regulators out of position, sometimes much as 10 cm., thereby causing considerable trouble.

by the deflocculation resulting from excessive or improper use of liquid manure, or sodium nitrate. Further, as will be shown later, clay "fixes" and retains the ammonia and potassium supplied as manure. In general, 8 to 16 per cent. is a satisfactory proportion of clay in a soil where the rainfall is 20 to 30 inches per annum; higher proportions up to 40 per cent. occur on Lower Lias and London clay soils. Fortunately, clay is unstable under high rainfall, so that the soils of wet regions rarely contain much; in North Wales the fine material is mainly fine silt (237), in arid conditions, however, it persists; Joseph records up to 76 per cent. in parts of the Sudan.[1]

The Chemical Composition of the Mineral Matter.

(*a*) *The Soil as a Whole.*

The older chemists treated the mineral matter of the soil as a whole and made a number of complete analyses; the figures, however, did not prove particularly useful. Subsequent investigation showed that as a rule only a small proportion of any individual soil constituent is chemically effective in determining vegetation relationships; the larger part is inert. The distinction between "active" and "dormant" plant nutrients in the soil was recognised by Daubeny in 1845 (78), and seven years later Way (298), showed that some of the silicates in the soil were very different in chemical properties from the rest. Way's investigation has led to great developments in the study of the soil; but it is also of interest as showing how a practical farm problem may open up a new line of work of great scientific importance. Farmers had long been troubled by the loss of ammonia from manure heaps and stable runnings, and a Yorkshire gentleman, Mr. H. S. Thompson,[2] of Moat Hall, York, found that the soil

[1] *Journ. Agric. Sci.*, 1924, 14, 490; also Wellcome Research Labs., Khartoum, *Chem. Pub.*, 39, 1925.

[2] Later on, as Sir Henry S. Meysey-Thompson, he became one of England's foremost agriculturists. In these experiments he was helped by John Spence, a Quaker, a chemist of York. The work was done in 1845 and published in 1850 (278).

could absorb this ammonia and so stop the loss. Way recognised the importance of the discovery and followed it up. He found that the absorbed ammonia displaced an equivalent amount of calcium. He therefore regarded the action as an ordinary double decomposition or precipitation, and proceeded to discover the soil constituent with which the interchange took place. It was neither the calcium carbonate, the sand, the undecomposed rock, however finely ground, nor the organic matter.[1] The active constituent was in the clay, and, moreover, it lost its power on ignition. No known simple silicates showed these properties, but he prepared a number of " double silicates " of lime and alumina, etc., that did; thus they reacted, like clay, with ammonium salts to form an almost insoluble double ammonium silicate and a soluble calcium salt, and also, like clay, they lost this property after ignition. Although he did not establish the existence of such double silicates in soil, their resemblance to the reactive constituent in the soil was so close that he considered himself justified in assuming their presence.

This view was generally adopted in England but not on the Continent. The whole weight of Liebig's influence was thrown in favour of a physical explanation, the phenomena being regarded as similar to the absorption of ammonia by charcoal. Neither Way nor any of his English colleagues or successors developed the chemical hypothesis experimentally, but it became more definite when mineralogists showed that the zeolites, a group of reactive crystalline silicates formed by the decomposition of the feldspars of basic igneous rocks, possess the chemical properties of Way's double silicates. It was then generally assumed that zeolites are present in soil and are the reactive silicates.

No direct evidence of the presence of zeolites, however, has been obtained, and the idea has gradually been given up

[1] It was subsequently shown by Konig (*Landw. Jahrb.*, 1882, 11, 1-56) that soil organic matter has a marked power of absorbing ammonia from ammonium phosphate.

although the reactive bodies are still often described as being like them.[1]

Lemberg afterwards showed that many other silicate minerals besides zeolites are reactive and exchange bases in salt solutions, but his work was not known to agricultural chemists.[2]

The subject was further developed by van Bemmelen, a brilliant Dutch chemist who, though he never went to Java, became interested in its remarkable laterite soils and so began the important soil investigations which he continued for many years in Holland, and, equally important, started a tradition which has since been maintained by a distinguished line of successors, Hissink, van Baren, Mohr, and others.

In studying the origin of laterite, van Bemmelen (20) investigated the weathering of mineral silicates to form soil. He divided the soil silicates into two groups :—

1. The unweathered portion which occurs even in clay as crystals to which chemical formulæ can be assigned ;

2. The weathered portion which contains two groups of silicates :—

Silicate A, completely decomposed by boiling concentrated hydrochloric acid, in which the molecular ratio $\frac{SiO_2}{Al_2O_3}$ varied between 3 and 6.[3] The bases are weakly held, and he regarded the combination as rather in the nature of an absorption complex SiO_2, p Al_2O_3, q Fe_2O_3, r CaO, etc., than of a chemical compound expressible by a definite formula. This silicate is colloidal.

Silicate B, not affected by hydrochloric acid, but decom-

[1] F. Scurti (*Ann. Chem. Appl.*, 1923, **13**, 161) and A. Demolon (*Compt. Rend.*, 1925, **181**, 673-675) have revived the idea that they are zeolitic silicates.

[2] *Zeit. deutsch. geol. Gesell.*, 1870, **22**, 335, 803 ; 1872, **24**, 187 ; 1876, **28**, 537 ; 1877, **29**, 483. For a summary of this important investigation see E. A. Fisher, *Trans. Faraday Soc.*, 1922, **17**, 305-316.

[3] For Dutch soils Hissink gives the average composition of Silicate A as $Al_2O_3 . 0{\cdot}56Fe_2O_3 . 3{\cdot}6SiO_2 . 2{\cdot}9H_2O$.

posed only by hot concentrated sulphuric acid. The ratio $\frac{SiO_2}{Al_2O_3}$ varies between 2 and 3. The bases are very strongly held, and this part of the silicates has but little effect on soil productiveness. It resembles kaolin.

He had already (20) observed the important part which the weathered silicates—the "amorphous zeolitic silicates which arise by weathering" to use his own words—play in determining certain properties of the soil; they could be flocculated; they dried to hard compact masses; further, they absorbed various substances from solution and interacted by double decomposition with various salts. His analysis of the weathered silicate into the two substances A and B suggested that Silicate A was the reactive body causing the Way phenomena, and was also in part responsible for the colloidal properties of the soil. This view was widely adopted, and hydrochloric acid was generally used for estimating the amount of zeolitic or reactive bases in the soil.[1]

An important investigation by Gedroiz (107), however, showed that Silicate A, as defined above, included more than the reactive constituents. The hydrochloric acid brought out from soils larger quantities of base than could be displaced in interaction with dissolved salts. Ammonium chloride solution, on the other hand, dissolved only the bases that could be so displaced and no more. A great mass of work on base exchange has confirmed this result and shown that a definite part of the soil bases is quite different from the rest and can be replaced and put back again without fundamentally altering the soil.

Subsequent workers have shown that dilute acids in certain circumstances dissolve out only these replaceable bases and nothing more, leaving the soil with unimpaired power of absorbing bases from their solutions. But with higher concentrations more base is extracted and the clay complex is

[1] See Hissink (135*a*), and Gans (105) for some results.

fundamentally altered; it can no longer absorb the same quantity of base as before. If iron and alumina are dissolved out from neutral soils there is a strong presumption that these larger changes have occurred.

The mineral compounds of the soil are, therefore, grouped as follows:—

1. Replaceable bases which can easily be exchanged by others or by hydrogen without permanently altering the soil.

2. Silicates easily decomposed by hydrochloric acid (van Bemmelen's Silicate A).

3. Silicates not easily decomposed by boiling HCl, but broken down by long-continued action of sulphuric acid or by fusion with sodium carbonate, ammonium fluoride, etc. It is common to neglect these altogether in soil work, and to speak of the sum of "replaceable" or "exchangeable" and "acid soluble" bases as the "total bases."

The distribution of these various groups is illustrated by Table XXXIII., giving Hissink's data for Dutch clays:—

TABLE XXXIII.—AMOUNTS OF "REPLACEABLE" OR "EXCHANGEABLE" AND "ACID SOLUBLE" BASES OF SILICATE A IN CERTAIN DUTCH SOILS. (HISSINK.[1])

Base.	Percentage of			Percentage Exchangeable Bases in Total Bases.	For every 100 Parts of Bases there are Present:		
	Exchangeable Bases.	Acid-soluble Bases.	Sum = Total Bases.		In Exchangeable Form.	In Acid Sol. Form.	As Total.
CaO	0·834	0·251	1·085	76·9	84·2	8·8	28·2
MgO	0·080	1·340	1·420	5·6	11·3	65·5	51·6
K_2O	0·024	0·826	0·850	2·8	1·4	17·2	13·1
Na_2O	0·033	0·270	0·303	10·9	3·1	8·5	7·1
					100	100	100

[1] *Intern. Mitt. für. Bodenkunde*, xii., 110-111.

The "Exchangeable Bases" in the Soil.

These are defined as the bases which are instantaneously extracted from soil on treatment with a solution of a salt. Apart from secondary reactions, different methods of treatment extract substantially the same amounts of bases, indicating a real distinction between the "exchangeable" and the other bases of the soil. All methods are founded on one introduced by Knop in 1868, in which soil was extracted with a solution of ammonium chloride (p. 372). Suitable modifications to overcome the difficulty that this salt dissolves a certain amount of calcium carbonate have been worked out by Gedroiz (107), Hissink[1] (135*c*), and Kelley and Brown (144). The amounts of exchangeable bases found in different

TABLE XXXIV.—PERCENTAGE COMPOSITION OF EXCHANGEABLE BASES FROM VARIOUS SOILS (KELLEY AND BROWN, 145); 100 PARTS OF TOTAL REPLACEABLE BASE CONTAIN :—

Soil No.	Acid Soils. California.				Normal Neutral Soils.					Alkaline Soils. California.				
						Russia (*b*).		Holland (*c*).						
	3232.	6276.	6277.	6251.	California (*a*).	Tschernoziem.	Podsol.	Clay.	Sand Humus.	1869.	5190.	5696.	6145.	6155.
Ca	50	14	25	31	63	82	80	79	76	Nil.	Nil.	Nil.	Nil.	Nil.
Mg	11	12	15	21	25	15·5	13·5	13	13	Nil.	Nil.	Nil.	Nil.	54
Na	7	11	16	10	8	Nil.	Nil.	6	8	65	60	97	81	34
K	3	3	3	3	4	3·0	6·4	2	3	35	40	3	19	12
Al	20	15	4	25	Nil.	Nil.	Nil.	Nil.	Nil.	Nil.	Nil.	Nil.	Nil.	Nil.
Fe	Nil.	7	1	Nil.	Nil.	Nil.	Nil.	Nil.	Nil.	Nil.	Nil.	Nil.	Nil.	Nil.
Mn	9	38	36	10	Nil.	Nil.	Nil.	Nil.	Nil.	Nil.	Nil.	Nil.	Nil.	Nil.
Total, in mgm. equivalents[2] per 100 grm. soil:					30·3	55·0	6·25	38·3	19·8					

(*a*) Kelley and Brown (145), seven samples.
(*b*) Gedroiz.
(*c*) Hissink.

[1] Described in the Appendix, page 459.
[2] *I.e.*, the sum of the separate bases as determined.

soils vary with the type of manuring and other conditions (see p. 204), but the relative proportions of the different bases show a striking general similarity for soils of similar reaction.

In neutral soils calcium and magnesium predominate: aluminium, iron, and manganese are absent.

In acid soils all these bases may be present.

In alkali soils sodium, and, to a less extent, potassium predominate: calcium, iron, aluminium, and manganese are absent.

These are simple consequences of the reactions described on pages 135 *et seq.* Figures are given in Table XXXIV. (p. 139). They may be compared with Page and Williams' data for some of the Rothamsted Broadbalk soils, and Smith's [1] and Rice Williams' for Scotch and Welsh soils respectively:—

	No Manure.	Farmyard Manure.	Artificial Manures.		17 Scottish Soils.	Welsh Soils.	
			Complete (1).	Without (2) Potash.		(*a*)	(*b*)
Calcium .	92	85	88	94	88	78	81
Magnesium	5	8	5	4	7	12	trace
Sodium .	trace.	trace.	trace.	trace.	3	10	19
Potash .	3	7	7	2	2·5		
Total mgm. equivalents per 100 gram. soil	14·74	19·82	16·63	17·13	11·24	10·6	7·9

(1) Plot 7. (2) Plots 11 and 12 (identical values). (*a*) Aber, (*b*) Brynodol, Nevin.

Soluble Iron, Aluminium and Manganese Compounds.

So long as the soil reaction remains about neutrality the compounds of these metals present in the soil are practically insoluble and apparently without effect on plant growth. But when the acidity or alkalinity increases beyond certain limits they come into solution and may considerably injure plants

[1] A. M. Smith, *Journ. Agric. Sci.*, 1925, 15, 466-475.

(pp. 107-108). The range over which they remain insoluble appears to be :—

For aluminium about *p*H 5·5 to 8·0.
For iron ,, *p*H 5·5 to 9·0.
For manganese ,, *p*H 7·0 to 9·0.

As an illustration, Magistad [1] found the following amounts of aluminium in the soil solutions of natural soils :—

*p*H	4·87	5·14	5·30	5·50	6·90	9·01
Al_2O_3	1·2	2·0	0·7	0·3	0·7	31·0

(parts per million of solution).

The Silicates of the Soil.

These have been little studied by soil workers; though some interesting results have been obtained by identification of the minerals, wherever this was possible.

Mineralogical Examination.—Mineralogical methods suitable for soils were developed by Delage and Lagatu (83) and Van der Kolk in 1906 (152), and improved by later workers; [2] they can be applied to the coarse fractions but not to the fine silt or the clay. The minerals found include: andalusite, apatite, augite, biotite, calcite, chalcedony, corundum, epidote, glauconite, garnet, glaucophane, gypsum, halotrichite, hornblende, hypersthene, ilmenite, limonite, magnetite, muscovite, orthoclase, plagioclase, quartz, rutile, staurolite, titanite, tourmaline, topaz, zircon.

[1] *Soil Sci.*, 1925, **20**, 195; see also R H. Carr and P. H. Brewer, *Journ. Ind. Eng. Chem.*, 1923, **15**, 634.

[2] V. Mosseri, *Les dépôts Nilotiques des Gazayer et Saouahel d'Egypte. Bull. de l'Inst. d'Egypte*, 1919, **1**, 151-180. H. Loos, *Bijdrage tot de kennis van Eenige bodensoorten van Java en Sumatra, Wageningen*, 1925. F. Steinriede, *Anleitung zur mineralogischen Bodenanalyse unter Anwendung der neueren petrographischen Untersuchungsmethoden*, Leipzig, 1921 (2nd edition). J. Hendrich and Ogg (132), and G. Newlands (132); these authors use flotation and magnetic separation to effect preliminary division into three groups, characterised respectively by orthoclase, quartz, and ferro-silicates. P. G. H. Boswell, *Proc. Liverpool Geolog. Soc.*, 1924, **14**, pp. 2-33 and 164-180 (Presidential Address). See also Adolf Wulff's admirable *Bibliographia Agrogeologia*, Wageningen, 1921.

It is not known whether these minerals exert specific effects on the soil properties or whether, as physicists assume, their influence is determined solely by the size of the particles.

Summary of Compounds of the Various Bases in the Soils.

Calcium, Magnesium, Sodium and Potassium Compounds in the Soil.

Of these the calcium compounds are the most important, and usually the largest in quantity. They fall into five groups :—

1. *Calcium Carbonate.* — Perhaps the most important single substance in the soil, the functions of which are discussed on pages 214 *et seq.*

2. *Simple Salts.*

   (*a*) Calcium nitrate, usually present only to a very small extent (in British soils the quantity is of the order of 0·01 per cent.), but highly important as the chief source of nitrogen for vegetation.

   (*b*) Calcium phosphate (p. 181).

   (*c*) Calcium sulphate.

The amounts of both (*b*) and (*c*) are small and in analysis are included under (3) and (4).

3. The " exchangeable " calcium, *i.e.* in combination with humic acid and the clay acids (presumably aluminosilicic acids) easily and instantaneously replaced by other bases by simple double decomposition reactions with solutions of salts (see p. 135).

4. " Acid soluble " calcium, in combination with silicates which are easily decomposed by boiling HCl, yet not sufficiently reactive to undergo instantaneous double decomposition with solutions of salts. These are part of van Bemmelen's Silicate A (p. 136).

5. Stable insoluble calcium silicates usually ignored in soil investigations.

Shorey, Fry, and Hazen (263), found the following calcium minerals in American soils :—

Frequently—

Hornblende, chiefly $Ca(MgFe)_3Si_4O_{12}$ with $Na_2Al_2Si_4O_{12}$ and $(MgFe)_2(AlFe)_4Si_2O_{12}$.

Plagioclase, isomorphous mixtures of $CaAl_2Si_2O_8$ and $NaAlSi_3O_8$.

Epidote, $Ca_2H(AlFe)_3Si_3O_{13}$.

Occasionally—

Calcite, $CaCO_3$.

Titanite, $CaTiSiO_5$.

Garnet $(Ca, Mg, Fe, Mn)_3(Al, Fe, Cr, Ti)_2(SiO_4)_3$.

Rarely—

Dolomite $(Ca, Mg)CO_3$.

Augite, $CaMgSi_2O_6$ with $(Mg, Fe)(Al, Fe)_2SiO_6$.

Gypsum, $CaSO_4 + 2H_2O$.

Pairs of soils having the same total quantity of CaO sometimes differed considerably in their content of the various calcium compounds (Table XXXV.) :—

TABLE XXXV.—CALCIUM COMPOUNDS IN SOIL (SHOREY, FRY & HAZEN) (263)).

Soil No.	Total CaO.	$CaCO_3$.	CaO as :—		
			Easily Decomposable Silicates.	Difficultly Decomposable Silicates.	Humus [1] Combination.
58	5·37	2·50	0·54	2·33	Nil.
61	4·64	0·06	0·11	4·34	0·13
24	1·98	0·12	0·02	1·84	Nil.
36	1·92	0·49	0·34	0·98	0·11

Magnesium compounds generally come second in amount to calcium ; they are found in each of three groups : "exchangeable," "acid soluble," and "stable insoluble" ; in some soils the carbonate is present in notable quantities, and

[1] Hissink does not accept the method of arriving at these figures for Humus combination (*Internat. Mitt. Bodenkunde*, 1922, 12, 87).

occasionally, as in the Wealden clays, there is a fair amount of the sulphate. Soils containing much more magnesium than calcium have been said to show some vegetation peculiarities (p. 109).

Potassium and sodium compounds also occur as "exchangeable," "acid soluble," and "stable insoluble"; the proportions in Dutch clays are shown in Table XXXIII. There is the important difference between potassium and sodium that the former is more readily retained by soil than the latter.

In arid conditions the sulphates, chlorides, and carbonates of sodium, potassium, and magnesium may occur in sufficient amount to injure vegetation. The soils are then described as alkali soils (p. 210). In humid conditions these salts are washed out by the rain-water; no clear case is known in Britain where they accumulate apart from flooding with sea water (p. 208). It is possible, however, that some of the abnormal clays, such as the Wealden and Lower Lias clays, may contain injurious quantities.

The chief potassium compounds in the soil are silicates, but their effect on plant growth is much greater when they occur in the finer, than in the coarser, portions of the soil. Dumont[1] instances two soils of nearly equal potassium content, one from la Creuse responding to potassic fertilisers, while the other from Grignon does not: in the former the potassium is present mainly in the coarser material, in the latter mainly in the finer (Table XXXVI.):—

TABLE XXXVI.—DISTRIBUTION OF POTASSIUM AMONG SOIL PARTICLES. DUMONT.

	Per Cent of K_2O in Soil.	Response to Potassic Fertilisers.	Per Cent. of "Argile."	Per Cent. K_2O in Argile.	Percentage Distribution of Potash in Soil.		
					Sable Grossier.	Sable Fin.	Argile.
Grignon .	0·85	Nil	16·8	0·94	16·6	65·8	17·7
La Creuse	0·89	Good	4·5	0·51	70·9	26·4	2·7

[1] *Compt. Rend.*, 1904, **138**, 215-217.

(*b*) *Chemical Study of the Physical Fractions of the Soil.*

The chemical investigation of the soil has been greatly helped by the fractionations introduced by physicists for the study of its physical properties (p. 120). Chemical study of these fractions has brought out the interesting and important fact that the chemical and physical methods agree in their division of the soil. The resistant silica and silicates of the chemist are identical with the gravel, coarse sand and fine sand of the physicist, while the reactive "Silicate A" is included in, if not identical with, the fine silt and the clay. The reactive silicates with exchangeable bases are probably the finest part of the clay though they probably also occur in jelly form.

The chief chemical property of the gravel, sand, and coarse silt is their inertness; it is, indeed, this that has enabled them to survive. All the evidence shows that the physicists are correct in assuming that their chemical composition is comparatively unimportant.

The Clay.—It is quite otherwise with the clay. Its chemical composition does matter, for it is reactive, taking part in certain important chemical changes in the soil. Analysis shows that the clay fractions of fertile soils differ chemically from that of infertile soils; Hall and Russell's results are given in Table XXXI. (p. 121), others are recorded by Robinson (237). Ganssen[1] makes the generalisation that the ratio $SiO_2 : Al_2O_3 :$ bases (CaO, MgO, K_2O,Na_2O) = 3 : 1 : 1 in fertile soils and 3 : 1 : less than 1 in infertile soils. In the English fertile soils the ratio Al_2O_3 : bases is 1 : 1, while in infertile soils it is 1 : less than 1, but the ratio SiO_2: Al_2O_3 is not 3 : 1, but 5 : 2 and 5 : 3. In soils examined by E. Blanck and F. Preiss,[2] the finer part of the clay (which was further fractionated by elutriation) had in successive fractions the constant composition $Al_2O_3 . 2SiO_2 . 2H_2O$.

The difficulty of chemically investigating clay arises from

[1] Formerly written Gans (105).

[2] *Journ. Landw.*, 1921, **69**, 73-78.

its complexity, the inertness of its non-reactive part below 600° C. (above which temperature it is broken down to silica, alumina, and water), and the apparent impossibility of producing readily soluble salts corresponding to the acids. This difficulty led to a variety of conflicting views on the constitution of clay from which, however, there has emerged as the best the hypothesis that clays are compounds of alumino-silicic acids and feldspars, and allied minerals are their normal salts.[1] The separation of the clay from the soil has recently been much improved. The old methods were slow and gave but little material. Schloesing's process yielded a true "colloidal clay," but it involved sedimentation for several months (245*d*). Other investigators used simpler methods, but obtained coarser sediments. The Sharples super centrifuge has revolutionised clay investigations by greatly reducing the time necessary for isolating the clay and also enabling the investigator to fractionate it into portions ranging from suspensoids to emulsoids.[2] The finest part—the emulsoid portion—is often called "ultra clay." It is now being studied in several laboratories, among others those of the United States Department of Agriculture, Bureau of Soils; the Missouri Experiment Station, by Richard Bradfield; the Wellcome Research Laboratories, Khartoum, by A. F. Joseph and his colleagues; and Rothamsted.[3]

Ultra-clay.—The material thus obtained has three striking characteristics :—

1. It is of the same general nature in different soils, different samples differing only in degree and not in kind, in their chemical and physical properties.

[1] See for fuller details A. B. Searle, *Chemistry and Physics of Clays*, Benn, 1924; W. and D. Asch, *The Silicates in Chemistry and Commerce*, Constable; and for suggestive formulæ J. W. Mellor, *Trans. Eng. Ceramic Soc.*, 1910-1911, 10, 94.

[2] See p. 130 for the distinction.

[3] For details of methods see: W. H. Fry, H. E. Middleton, C. J. Moore, *Determination of Colloids in the Soil* (*Journ. Ind. Eng. Chem.*, 1921, 13, 527); P. L. Gale, and others, *U.S. Dept. of Agric. Bull.*, 1193, 1924; W. O. Robinson, and R. S Holmes, *Bull.*, 1311, 1924 (method used in the Bureau of Soils, Washington); R. Bradfield, *Mo. Bull.*, 60.

2. It easily loses bases (especially calcium) and then behaves like a weak acid, showing all the usual titration phenomena with sharp end points.[1]

3. Its physical properties are related to its chemical composition varying approximately as the ratio $\frac{SiO_2}{Al_2O_3 + Fe_2O_3}$ and to some extent as the replaceable bases.

These characteristics and the deductions that have been drawn from them must now be considered.

An ingenious investigation was made by Bradfield to ascertain whether the colloid is wholly a mixture or mainly some kind of compound.

He separated the ultra-clay from the fresh subsoil of the Putnam silt loam, the common soil of the prairies of north-east Missouri, and found it contained 24·5 per cent. Al_2O_3, 7 per cent. Fe_2O_3, 45·5 per cent. SiO_2, 1·7 per cent. CaO, 1·4 per cent. MgO, 0·3 per cent. K_2O, almost all of which (except the silica) dissolved in hot hydrochloric acid. He then prepared an artificial mixture of the colloidal oxides in the proper proportions and compared this with the natural clay. The properties were entirely different:—

Property.	Natural Colloid.	Mixture of Oxides in Colloidal State.
Electric charge (Cataphoresis studies)	Negative.	Positive.
Flocculation most readily effected by	Polyvalent cations in acid medium.	Polyvalent anions in alkaline medium.
Buffer action.	——	Much stronger than for natural colloid.

The migration velocities differed, as also did the results of fractionating with dilute acids and alkalis.

The results suggest that the natural colloid is not a mixture of colloidal oxides. From the circumstance that the

[1] R. Bradfield, *Journ. Amer. Chem. Soc.*, 1923, 45, 2669; with further evidence in *Journ. Phys. Chem.*, 1924, 28, 170.

natural colloid is flocculated most easily in an acid medium Bradfield argues that not much of the silica can be free, since colloids protected by silica are most readily flocculated in an alkaline medium.[1] Further, the Al_2O_3 is not removed by neutral salts, in spite of the fact that they develop acidity in the solution, unless the resulting acidity is more intense than corresponds with a *p*H value of 4. While the proof is not rigid, it seems probable that the colloid is a complex alumino-silicate, and the average of Bradfield's samples, which do not differ greatly among themselves, gives a molecular ratio $Al_2O_3 : SiO_2 = 1 : 3$.

Hissink, using a less effective method of separation, is not only satisfied that clay is an alumino-silicate, but has even estimated the equivalent weight of the acid by a conductometric method; the value lies between 1000 and 2000. Bradfield assigns to it a dissociation constant of the same order of magnitude as carbonic acid (3×10^7).

Chemical Composition and Physical Properties.—The relationship between the chemical composition of the complex (which one may regard as the acid radicle) and physical properties has been studied by Anderson in the United States, and Joseph in the Sudan and their colleagues. Joseph and Hancock[2] confined themselves to the ratios of $SiO_2 : Al_2O_3$ in different clays, and obtained relationships with physical properties shown in Table XXXVII.

M. S. Anderson and S. E. Mattson (3), trace a close relationship between the ratio $\frac{SiO_2}{Al_2O_3 + Fe_2O_3}$ (which varied from 1·20 to 3·23) and the heat of wetting and power of absorbing ammonia, a high ratio being associated with high values for

[1] This statement does not accord with Comber's (p. 131), but colloid literature is full of such disagreements, small differences in conditions much affecting the results. The authors agree at any rate that small amounts of alkali deflocculate.

[2] A. F. Joseph and J. S. Hancock, *Trans. Chem. Soc.*, 1924, 125, 1888-1895. In this investigation the clay was obtained by sedimentation (·002 mm. diameter).

these two properties (Fig. 19). Other instances are quoted by Gile.[1]

TABLE XXXVII.—RELATIONSHIP OF PHYSICAL PROPERTIES TO CHEMICAL COMPOSITION OF CLAY. A. F. JOSEPH and J. S. HANCOCK.

Material.	Ratio $\frac{SiO_2}{Al_2O_3}$.	Plasticity.	Moisture Equivalent, Change on Ignition (1).	Chemical Reactivity.		
				Towards Alkali (2).	Towards Salts (3).	
China clay .	2·11	Low	+ 14	3	Nil	pH 7·16
Loess clay .	3·90	Higher	− 26·7	6	2	pH 5·14
Blue clay .	4·8	Higher	− 35	—	—	—
Bentonite .	6·9	Highest	− 71	9	3	pH 4·12

(1) The moisture equivalent is the percentage of water retained by the material after being saturated for twenty-four hours and then drained in a Briggs-McLane centrifuge for forty minutes by a force equal to 1000 times that of gravity.

(2) Measured by the reduction in conductance when suspensions of the clays are added to N/100 NaOH, and the mixture kept for twenty-four hours.

(3) Increase in acidity when suspensions of the clays are added to NaCl solution; the pH value of 7·16 for China clay is practically neutral. The lower values signify increased acidity, *i.e.*, interaction with the NaCl.

The facts could be explained by assuming a mixture of complex-silicates with varying amounts of silica or alumina, but they also accord with the assumption of a series of alumino-silicic acids.

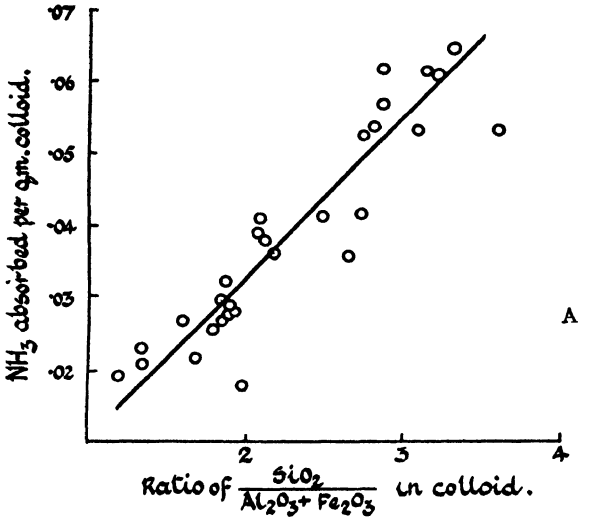
The Bases in Clay.—Dilute acids dissolve out from clay all the calcium and part of the potassium and magnesium, but little else.[2] It is inferred, therefore, that the calcium is present entirely as exchangeable base while the others occur partly in some other form; there may also be hydrogen ions. The proportions of exchangeable base may be altered by treating the clay with solutions of various salts, and the new clays differ somewhat in their physical properties. Gedroiz [3]

[1] P. L. Gile, *Colloid Symposium Monograph*, Chemical Catalog Co., New York, 1925.

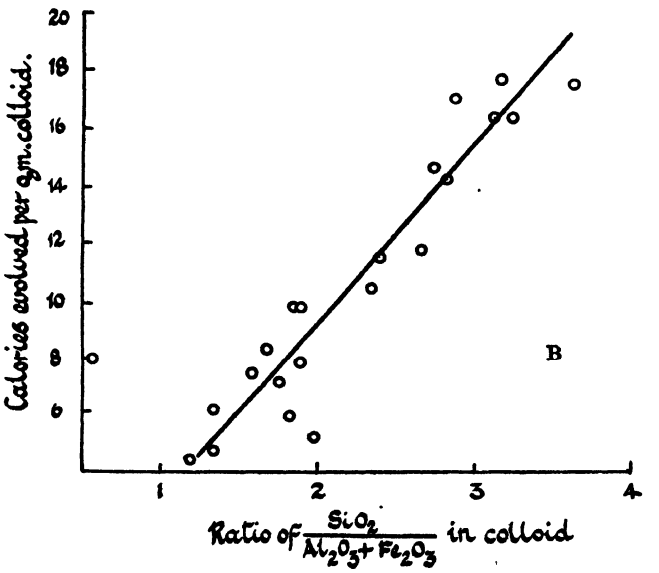
[2] *Ibid.*

[3] *Journ. Expt. Agron.*, 1924, **22**, 29.

Relation between the NH_3 absorbed by soil colloids and their $\frac{SiO_2}{Al_2O_3+Fe_2O_3}$ ratios.



Relation between the heat of wetting and the $\frac{SiO_2}{Al_2O_3+Fe_2O_3}$ ratio of soil colloids.



found that their particles remained longer suspended in water (*i.e.* the dispersion increased), and therefore presumably became smaller and smaller, in the order of $H<K<NH_4<Na<Li$. In one experiment a subsoil containing 39·9 per cent. of clay, with particles chiefly between 1 and 0·3 μ diameter, gave, after treatment with sodium chloride and washing, 59·8 per cent. of clay with particles mainly less than 0·2 μ diameter. The magnesium clay was also highly dispersed, but the calcium, barium, iron, and aluminium clays were not. The calcium clay is more readily flocculated than the sodium potassium or ammonium clays, which are all about equally sensitive (Wiegner and Gallay).

Clay is thus built up like a salt of an acidic and a basic radicle, or, in modern parlance, of an anion and cation, and, like salts, it can enter into double decomposition with other salts, the cations being exchanged in equivalent quantities in accordance with the usual stoichiometric laws. The interchange may be represented thus :—

$$\overline{|SiO_3.nAl_2O_3|}\begin{Bmatrix}Ca^{\cdot\cdot}\\Mg^{\cdot\cdot}\\K^{\cdot}\\Na^{\cdot}\\H^{\cdot}\end{Bmatrix} \underbrace{+K^{\cdot}+Cl'} = \overline{|SiO_3.nAl_2O_3|}\begin{Bmatrix}K+\underbrace{[Ca^{\cdot\cdot}+Mg^{\cdot\cdot}+K^{\cdot}+Na^{\cdot}+H^{\cdot}]}+\end{Bmatrix}$$

Solid phase. Solution. Solid phase. Solution.

The hydrogen ions as well as the bases must be taken into account in quantitative studies of the exchange.

While the clay is thus of the same general nature as a salt, it is much more complex in structure. In the first place it is enormously larger. A simple ion may have a diameter of the order of 0·5 $\mu\mu$. Bradfield's emulsoid particles probably averaged 50 $\mu\mu$ in diameter : the relative sizes would be roughly as a mustard seed is to a football. The rapidity of the exchange of cations when clay is brought into a salt solution suggests that the clay cations are all on the surface of the particle, as also does the fact that clay suspended in water develops an electro-negative charge, as would be expected if some of the cations escape into the solution.

This piling up of cations on the surface of the particle implies as a necessary consequence that the acidic part of the clay—the anions—should be immediately below the surface or the cations would not be held. Hissink makes the conception more definite by assuming, in accordance with a well-known colloid hypothesis, that the clay particle when suspended in water becomes surrounded by a Helmholtz double electric layer; the negative layer (the anions) being the inner, and the positive layer (the cations) the outer.

There are apparently some difficulties in assuming that the particles are spherical. Wiegner, one of the most ingenious of the workers on this subject, has argued [1] that the number of cations necessary to account for the observed facts could not possibly be packed on to a surface of a sphere of the diameter of the clay particle; he therefore assumes that the particle is perforated or made up of a cluster of small particles; *e.g.* that a particle of 0·5 μ diameter is made up of a number of others of 0·007 μ diameter, when it would have sufficient surface to hold the necessary cations.

The conception of the clay "molecule" that is provisionally put forward as a working hypothesis, and in the full expectation that it will be seriously modified, if not entirely overturned, by subsequent work, is somewhat as follows:—

The particles are perforated like sponges so that their surface is much greater than would be expected from their diameters. When suspended in water they become surrounded by a double electric layer; the outer one consists of the positively charged cations (mostly $Ca^{\cdot\cdot}$, but with some $Mg^{\cdot\cdot}$ and smaller quantities of $K^{\cdot}$, $Na^{\cdot}$, $H^{\cdot}$, etc.), the inner with negatively charged anions, a complex alumino-silicic acid of unknown constitution, but obeying the usual stoichiometrical laws. Some of the cations split off by dissociation, leaving a balance of negative charge. Changes in the cations are accompanied by changes in the physical properties of the clay. Wiegner (308*b*) supposes that a cation linked up with

[1] Internat. Soil Congress, Rome, 1924.

many molecules of water, such as sodium, could not approach the complex anion as closely as cations which are less hydrated, like calcium; the effective distance between the two electric layers is increased and the potential of the inner layer increases. This increased potential increases the power to remain suspended in water and the chemical instability. This view accords with Gedroiz's results that cations [1] are absorbed in the order of their valencies, and within the valency groups of their atomic weights. Thus aluminium is of all cations the one most readily absorbed, giving the most compact deposit in water: calcium is less readily absorbed, giving a more bulky deposit, but sodium and lithium are least easily absorbed; they give the bulkiest and most hydrophilous deposit, having also the finest particles (see p. 131), and the cations are most easily lost by hydrolysis. This explains why among the replaceable bases of normal soils, calcium occurs in larger quantity than magnesium, which, in turn, is in larger quantity than potassium, while sodium is least common and may be absent: it explains also why sodium is the predominating ion in sea water.

In so new a subject alternative hypotheses are desirable if only to stimulate discussion. Gile,[2] emphasising the fact that the colloid material always contains some ten or twelve constituents, presumably admixed, since their proportions are not constant, sets forth a vaguer, and therefore safer view. The dispersed particle is likened to a loose mosaic made up of stones of different sizes with an internal pore space. Silica and organic matter are scattered throughout the mosaic in such a way as to preserve the heterogeneity and to form most of the bounding surfaces exposed to a liquid. This surface holds the replaceable bases, but part of the basic ions diffuse into the liquid and form a Helmholtz layer.

[1] In order to eliminate disturbing effects of base exchange it is, of course, necessary to begin with a clay saturated with one base only. Gedroiz used the whole series of clays for this investigation; he did not separate the clay fraction but used a subsoil containing 40 per cent. of clay.

[2] P. L. Gile, *Colloid Symposium Monograph*, Chemical Catalog Co., New York, 1925.

The constitution of the complex anion—the "acidoid," to use Michaelis' term—the core of the particle, is unknown, and has hardly been even guessed at. It is stable so long as it remains fairly well saturated with cations, but, as Gedroiz has shown, it becomes less stable as it is less saturated, and when the *p*H falls below a certain value it tends to give up iron and aluminium oxides.

While the resemblances in chemical reactivity suggest that simple salts and clay are fundamentally of the same design the great differences in physical properties show how far they are separated in structure. In Nature, however, there are few unbridged gaps, and an intermediate in general character between salts and clays is found in permutit.

The So-called Abnormal Clays: Acid Clay and Sodium Clay.

The normal clay of fertile soils is a calcium clay, but, as we have seen, the calcium can easily be replaced by other bases or by hydrogen; a new clay then arises.[1] Two of these clays, the acid and the sodium, occur somewhat frequently in Nature. They differ in character and in vegetation properties from the calcium clays, and are therefore abnormal or unusual in their natural floras, and unresponsive to the agricultural methods evolved for the calcium clay, so that they are classed as infertile and may be left as uncultivated wastes.

Farmers have learnt empirically, however, that they become responsive when treated with calcium carbonate or calcium sulphate: the explanation is that the calcium clay is thus formed. The principle underlying this method of reclamation is therefore to convert the clay into a calcium clay, and then treat it in the usual manner.

There is, however, another principle which can be adopted in those extensive areas where applications of calcium com-

[1] For a classification of soil founded on exchangeable bases and the clay complex, see Gedroiz, *Nosow Pub.*, 38, 1925.

pounds in sufficient quantity is impracticable. The clay may be accepted as such; its properties studied; new methods of cultivation worked out and new varieties of crops found or bred suited to the conditions. This method is already being used on acid soils, and it offers considerable prospects of success on the other non-calcium clays.

The Acid Clay.

Clay becomes acid when the calcium is replaced by hydrogen ions. Its distinguishing properties are that it gives acid suspensions in water and liberates titratable amounts of acid from salt solutions. The interaction proceeds in the usual way, the quantity of base taken from the salt being equivalent to the quantity of base and of hydrogen ions given up by the clay. The extent to which the reaction proceeds depends on the strength of the acid from which the salt is formed; if this is weak (*i.e.* not highly dissociated), a considerable exchange may be effected before the hydrogen ions attain their limiting concentration; if it is strong, equilibrium is reached with a smaller replacement of hydrogen by base.

Bradfield has prepared the acid clay in the laboratory and described its properties (see p. 147). Natural acid clay is formed from rocks initially poor in bases, especially in calcium, and exposed to high rainfall. It is also formed artificially in the field when sulphate of ammonia is frequently used as a fertiliser on soils containing little or no calcium carbonate; the ammonium displaces the calcium of the clay forming an ammonium clay from which the ammonia is taken by micro-organisms, but no other base is put in its place.

The power possessed by these clays of absorbing bases without giving up an equivalent amount of other base has caused them to be described by Ramann as "unsaturated" soils, and this term conveniently expresses a property of considerable importance in determining vegetation relationships.

Acid clays are unsuited to the normal flora and agricultural crops of the calcium clays. The unsuitability probably arises in part from the acid (p. 387), and in part from the circumstance that they compete for available bases with the plant. Further, they are more easily deflocculated than the calcium clays and have more affinity for water, so that in physical properties they are less suited to the growth of plants.

The Sodium Clay.

The sodium clay is formed when sodium salts come into contact with normal soil, and this happens in practice in either of two ways :—

1. In any climatic conditions when the sea breaks over and floods the land.

2. In arid or semi-arid conditions, whenever the drainage is not particularly good, and especially when the irrigation water contains sodium salts in solution, as it nearly always does.

Sodium clay is being prepared in various laboratories and its properties studied. When suspended in water it is more easily dispersed or deflocculated than the calcium clay and so is supposed to lose its sodium more easily, in other words to be more highly ionised and to carry a greater electric charge on its particles. It has more affinity for water, becomes more sticky and impervious when wet, and much harder when dry, than the calcium clay. It is, however, flocculated by salts.

Its most important chemical property is that in the presence of CO_2 it readily forms sodium carbonate, which intensifies its stickiness and imperviousness, and at the same time has a direct toxic effect on vegetation. The sodium is less firmly held by the clay than is calcium, magnesium, or potassium. These properties are discussed more fully on pages 210 *et seq.*

Organic Matter.

The distinguishing characteristic of soil is that it contains part of the complex material synthesised by plants. This material affords energy to numerous micro-organisms, and is gradually converted by them into simple substances appropriate for plant nutrition. We may look upon its constituents as taking part in a perpetual cycle: in one stage nourishing the growing plant and storing up the energy of sunlight, in the other stage nourishing micro-organisms and liberating energy. In addition, it has important physical effects on the soil.

Two great groups can be distinguished: one deposited with the soil during its formation, and therefore as old as the soil itself; the other furnished by recent generations of plants. No method of separation is known, but the amount and properties of the original organic matter can be surmised from a study of the subsoil at depths below the root-range of plants. Ten feet or more below the surface, sandy subsoils usually contain less than ·01 per cent. of nitrogen and clays less than ·05 per cent., but shales contain more than 0·1 per cent. The percentage of carbon fluctuates, but is usually five to ten times that of nitrogen (199*a*). Now these values are about one-tenth to one-fifth of those obtained in the surface soil, so that at the very outside, and assuming there has been no decomposition, not more than 10 to 20 per cent. of the surface organic matter is original.

The organic matter furnished by recent vegetation may roughly be classified as: (1) material as yet undecomposed and still retaining its definite cell structure; (2) partially decomposed and still decomposing material; (3) simple soluble decomposition products; (4) plant or animal constituents not decomposable in the soil.

The undecomposed material is important as the reserve supply for the entire chain of reactions to be considered later. It also has a certain mechanical effect in opening up the soil

and facilitating aeration and drainage, an effect useful on clays but often harmful on sands where these processes already tend to go too far.

The partially decomposed material forms a vague and indefinite group, containing all the non-volatile products of bacterial, fungal, enzymic, and other actions on the plant residues. It shades off in one direction into the simple soluble decomposition products, and in the other into undecomposed plant fragments, so that it cannot be sharply defined or accurately estimated. But it contains a substance or group of substances to which the name " humus " is given that has important physical effects on the soil, and possesses at least six properties not usually shown by the undecomposed plant residues.

1. It gives a dark brown or black colour to the soil.

2. It can withdraw various ions—NH_4, K, PO_4—from their solutions. The experiments of van Bemmelen (19, 21) indicate a complete parallelism with clay in this respect.

Baumann and Gully (11) and Odén (217*b*) show that undecomposed sphagnum can also absorb certain ions from solutions, but the phenomena differ in detail from those shown by humus.

3. It causes the soil to become puffed up, and so leads to an increase in the pore space (see p. 348). From this results a marked improvement in the tilth and general mechanical condition. The Rothamsted mangold plots receiving no organic manure, and therefore poor in partially decomposed organic matter, get into so sticky and " unkindly " a state that the young plants have some difficulty in surviving however much food is supplied, and may fail altogether in a dry spring; the dunged plots rich in humus are much more favourable to the plant and never fail to give a crop. But the puffing up or " lightening " may go too far, and sometimes causes much trouble in old gardens that have long been heavily dunged.

4. It increases the water-holding capacity of the soil. The

amounts of moisture present in adjacent plots at Rothamsted are shown in Fig. 20, from which it appears that the plot annually receiving farmyard manure contains normally 3 or 4

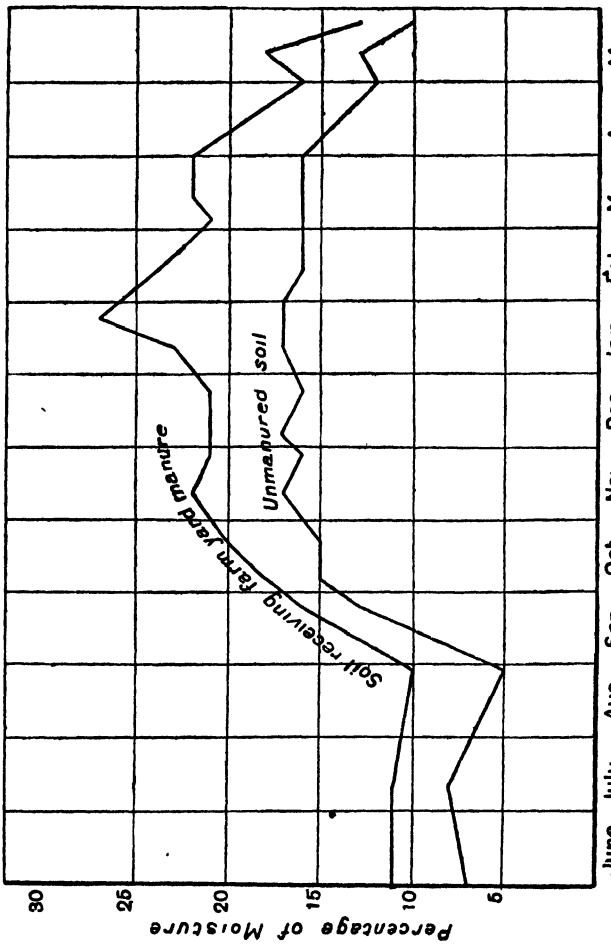


FIG. 20.—Curves showing the percentage of water in two soils on adjacent plots, one of which annually receives farmyard manure while the other does not. (Broadbalk field, Rothamsted.)

per cent. more water than the adjoining plot receiving no organic manure. The variations in water content of similar pairs of soils follow closely the differences in the amounts of organic matter present.

So marked are these physical effects that if 15 or 20 per cent. of organic matter is present in a soil the operation of other factors ceases to count for much, and the distinctions between sands, loams, and clays are obliterated. Thus, much of the famous Red River prairie soil of Manitoba is identical in mineral composition with certain poor infertile Wealden soils, but the presence of 26 per cent. of organic matter completely masks the harmful effect of the clay and fine silt. A similar pair of soils, owing their difference in agricultural properties to their different organic matter content, has been recorded by C. T. Gimingham[1] (Table XXXVIII.):—

TABLE XXXVIII.—EFFECT OF ORGANIC MATTER[2] ON THE TEXTURE OF SOILS.

	Good Texture.	Poor Texture.	Good Texture.	Poor Texture.
	Manitoban Prairies.	Weald Clay.	(Reported by C. T. Gimingham.)	
Fine gravel .	—	·5	—	—
Coarse sand .	1·6	1 to 2	·6	·5
Fine sand . .	3·8	10 ,, 12	4·3	8·4
Silt . . .	17·1	20 ,, 30	11·2	13·8
Fine silt . .	28·2	25 ,, 30	28·7	26·5
Clay . . .	23·3	20 ,, 25	23·8	25·0
Loss on ignition .	26·3	5 ,, 8	19·8	14·5

5. It swells when wetted.[3]

6. Although humus is essentially transitional it has a

[1] *Journ. Bd. Agric.*, 1910, **17**, 529-541, and *Journ. Agric. Sci.*, 1914, **6**, 328-336.

[2] Measured by the loss on ignition.

[3] Peat shows this phenomenon in a marked degree; indeed, after heavy rainfall inadequately-drained peat bogs may swell so much as to overflow into valleys with disastrous results. After drainage, however, drying and shrinkage set in, followed by a slow but steady erosion as air penetrates into the newly-formed spaces and starts the oxidation processes. When Whittlesey Mere was drained in 1851 a pillar was driven through the peat into the underlying gault, and the top of the pillar was made flush with the surface of the soil. So great has been the subsequent shrinkage that over 10 feet of the pillar is now out of the ground and the process has not yet reached its limit, for a perceptible further shrinkage took place during the dry season of 1911.

certain degree of permanency and only slowly disappears from the soil. It disappears more rapidly from chalky and sandy soils than from loams and clays.

These properties greatly enhance the fertility of the soil, and in most schemes of husbandry definite arrangements are made to keep up or even increase the supply of organic matter, while in forests the removal of leaves and other decomposable material has led to such bad effects that in all state forests of France, Belgium, Germany, etc., the practice is absolutely forbidden.

The properties of humus have been studied in two ways :—

1. By field observations.
2. In the laboratory.

Field Observations.

Most of the recorded field studies are on peats of various kinds, and in this country the work has been done largely by Dr. Moss and other members of the British Vegetation Committee (275). At least three great classes and another two that may be transition forms were recognised :—

1. Dry peat (the German *Trockentorf*) found on heaths in relatively dry regions and on poor sandy soils. It is often only a fraction of an inch in thickness, and is largely formed by lichens and mosses (*e.g. Cladonia rangiferina, Polytrichum piliferum*, and others). The dominant plant is *Calluna*. Much of the organic matter of heath soils, however, often consists of undecomposed vegetation, *e.g.* bracken fronds, etc.

1*a*. In wetter districts the layer of peat becomes thicker, and no doubt changes in composition, but it still carries essentially "heath" vegetation, although it shows resemblances to 2.

2. Wet peat (the German *Hochmoor*) formed in wet tracts or regions of high rainfall, and accumulating to so great a depth that it entirely determines the character of the vegetation whatever the underlying rock. It receives no supplies of

spring or underground water, and, therefore, no dissolved salts; the drainage water is acid and poor in soluble mineral matter. Two great divisions are recognised: *lowland moors* or mosses, formed in low-lying wet places largely from sphagnum, cotton grass (*Eriophorum*), and *Calluna;* and *upland moors*, formed mainly from *Eriophorum* spp. and *Scirpus cæspitosus* in elevated districts of high rainfall.

3. Fen (*Niedermoor* in German, see 299) formed from a calcicolous vegetation (*Phragmites*, *Cladium*, *Scirpus*, *Carex*, etc.), in presence of calcium carbonate and soluble mineral salts, showing no acid properties and giving neutral drainage waters.

3*a*. Carr, genetically related to the fen, containing much decaying tree residues, and formed in what at one time was a marshy wood.

Between fen and peat several transition forms have been described by Weber (299) and also recognised in England. Some of our moors are built up on older fens.

Forbes [1] recognises three classes of peat in Ireland:—

1. Mountain peat, corresponding with the wet peat lowland moss of the British Committee, which originates wherever the conditions are too sterile or the subsoil too impervious or water-logged to allow deep-rooted vegetation to flourish, and where, therefore, the plants are shallow rooted and, on dying, form a layer of organic matter on which sphagnum, cotton grass, etc., begin to develop. This occurs above the 800 feet level in most parts of Ireland, but in the west it often covers the entire surface down to the sea-level.

2. Marsh peat, corresponding with the British fen, which arises from reeds, sedges, rushes, etc., and which, so long as the water contains lime and nutrient salts, is as favourable a medium for plant growth as ordinary soil, though it affords no root-hold for trees, so that they are liable to be overturned in strong gales. This kind of peat forms the basis of all the low-

[1] A. C. Forbes, *Clare Island Survey*, 1914, 9 (*Proc. Roy. Irish Acad.*, 1914, 31).

land bogs in Ireland and of many of the small bogs in mountain districts.

3. This marsh peat finally becomes so consolidated with time and pressure that it loses connection with the water table, and a surface swamp forms on which a sphagnum bog of the "mountain type" arises. This, therefore, becomes similar in character to the first group: it differs, however, in its uniformity of growth, being higher in the centre than at the margins where soil water can get in and where, therefore, decomposition is more rapid.

The Scotch peats have been described by Lewis [1] and the Yorkshire moors by Elgee.[2]

Within each of the great classes described above several subdivisions are recognised, but how far they arise from differences in the organic matter, or from other differences is not yet ascertained.

Humus of Forest Soils.—The first investigations were made by P. E. Müller (206) on the types of humus occurring in the Danish forests.[3] In beech forests he found two types, which he called *mull* and *torf*, our nearest equivalents being mould and peat. On *mull* the characteristic plants were *Asperula odorata* with its associated *Mercurialis perennis*, *Milium effusum*, *Melica uniflora*, *Stellaria nemorum*, and others, moss being absent. The *mull* itself was only a few inches thick, and was underlain by 1 to 5 feet of loose soil, lighter in colour than *mull*, but almost equally rich in organic matter; still lower came a compact but porous layer of soil. The surface of the soil was covered by a layer of leaves, twigs, etc. Earthworms were numerous throughout; their potent influence in the soil had recently been shown by Darwin (76). Detailed

[1] *Trans. Roy. Soc., Edinburgh*, 1905, **41**, 699-724; 1906, **45**, 335-360; 1907, **46**, 33-70; 1911, **48**, 793-833. See also W. G. Smith, *Journ. Ecology*, 1918, **6**, 1-13.

[2] F. Elgee, *The Moorland of North-Eastern Yorkshire*, London, 1912; *Journ. Ecology*, 1914, **2**, 1-18.

[3] Other investigations on forest humus are dealt with by Ramann, *Forstliche Bodenkunde u. Standortslehre*, 1893, and H. Hesselmann, *Medd. Stat. Skogsförsöks Anstalt*, Stockholm, 1926, **22**, 169-552.

chemical examination was not made: it was shown, however, that *mull* was free from acid and contained about 5 to 10 per cent. of organic matter completely disintegrated and most intimately mingled with the mineral matter.

Torf differed completely. The characteristic plant was *Trientalis europæa* with the associated *Aira flexuosa* and moss, but surface vegetation was not very common. The loose layer of leaves was absent, and the *torf* itself was so tough and compact that rain water could not readily penetrate. Below it was a layer of loose, greyish sand (*bleisand*), and lower still a layer of reddish soil (*roterde*), or else a pan (*ortstein*). Practically no earthworms were found in the *torf*, but there were numerous moulds and fungi, *Cladosporium humifaciens* Rostrup and *Sorocybe Resinæ* Fr. being perhaps the commonest.

Torf was acid, contained about 30 per cent. of organic matter not completely disintegrated, nor well mixed with the mineral matter. It was not very favourable to the growth of young trees, and the forest tended to become an open heath as the old trees died.

The distribution of *mull* and *torf* did not seem to be determined by the nature of the soil, or by the amounts of soluble alkali salts or calcium carbonate present, but rather by the nature of the living organisms in the soil. Animals, especially earthworms, gave rise to *mull*, fungi produced *torf*. If the conditions were favourable to earthworms *mull* was therefore found, if not, *torf* was produced. The nature of the vegetation was also a factor: oak only rarely formed *torf* but commonly gave rise to *mull*, at least two varieties of which were observed; pine, like beech, could form either *torf* or *mull*, while *Calluna vulgaris* and *Vaccinium myrtillus* generally produced *torf*.

Humus of Field Soils.—The humus of field soils is divided into two great groups, differing greatly in vegetation characteristics: one neutral in reaction, commonly spoken of as neutral humus or "mild humus," and the other reacting like an acid and called "sour humus," acid humus, or by German writers, *Rohhumus*.

TABLE XXXIX.—ANALYSES OF THE ORGANIC MATERIAL EXTRACTED BY ALKALIS FROM SOIL (OFTEN CALLED HUMUS, SOLUBLE HUMUS, ACTIVE HUMUS, *MATIÈRE NOIRE*, ETC.).

Source.	Carbon.	Hydrogen.	Oxygen.	Nitrogen.	Ash.	Observer.
Arable land	56·3	4·4	36·0	3·3	Calculated ash-free	Mulder (205)
Garden soil	56·8	4·9	34·8	3·5		,,
Pasture land	56·1	5·3	32·5	6·1		,,
Peat	59·0	4·7	32·7	3·6		,,
,,	57·4	4·6	—	<1	—	F. Fuchs [1]
Rich prairie soil	45·1	3·7	28·6	10·4	12·2	Snyder (267)
Soil never cultivated	44·1	6·0	35·2	8·1	6·6	,,
Cultivated subsoil (*a*)	48·2	5·4	33·2	9·1	4·2	,,
,, ,, (*b*)	50·1	4·8	33·7	6·5	4·9	,,
"Humic acid" from sugar	66·4	4·6	29·0	—	—	Berthelot and André (30-31)
"Humic acid" from compost	53·3	5·6	37·5	3·6	—	Berthelot and André (30-31)
"Humic acid" from sugar through K salt	64·70	4·55	30·71	—	—	Robertson, Irvine and Dobson [2]
"Humic acid" from sugar through NH_4 salt	64·74	4·69	29·81	0·76	—	Robertson, Irvine and Dobson [2]
"Humic acid" from soil through K salt	56·67	5·16	35·68	2·49	—	Robertson, Irvine and Dobson [2]
"Humic acid" from soil through NH_4 salt	54·29	4·94	38·16	2·61	—	Robertson, Irvine and Dobson [2]

Chemical Studies of Humus.

It is commonly assumed by chemists that the humus of field soils is of the same nature as that of peat, fen, or forest. There are undoubtedly certain properties in common. Alway and Neller [3] find that the differences in moisture content of adjacent plots of varying organic matter content can be explained on the assumption that soil organic matter has the same water-holding capacity as the most absorbent peats, *i.e.* three to four times its own weight.

Two simple chemical properties of humus have always attracted the attention of chemists: its content of nitrogen,

[1] *Chem. Zeit.*, 1920, 44, 551. The molecular weight was about 680.

[2] *Biochemical Journ.*, 1907, 2, 458. For other studies see Mary Cunningham and Chas. Dorée, *Trans. Chem. Soc.*, 1917, 111, 589-608.

[3] *Journ. Agric. Res.*, 1919, 16, 263.

which caused it to be regarded as an important source of plant food; and the division of natural samples into two great groups, acid and neutral.

Typical analyses are given in Table XXXIX.; other analyses of peats are recorded by Tacke (274), Gully (117), and Michelet and Sebelien.[1] The nitrogen content of the peat is very variable: as a rule, though with many exceptions, it increases with the percentage of calcium, and is usually least in the high moors, greater in the low moor, and greatest in the fens (Table XL.):—

TABLE XL.—NITROGEN AND CALCIUM CONTENT OF VARIOUS PEATS.

		Nitrogen per cent. in Dry Matter.	CaO per cent. in Dry Matter.	Observer.
High moor	Bremen	1·14	0·44	Tacke
	Lancashire	0·85	0·11	Russell and Prescott
Low moor	Bremen	1·62	1·24	Tacke
	Cheshire	0·91	0·16	Russell and Prescott
Fen	Norfolk	2·85	7·5	,, ,,

The distinction between acid and neutral humus was from the outset explained by supposing that neutral humus is a calcium salt of the acid humus. This view still holds, though it has been much modified.

Chemical studies have been made of the soil organic matter as a whole, and of various constituents isolated therefrom.

In view of its complex and varying origin it might have been supposed that soil organic matter, taken as a whole, would have no constant properties. This supposition is not correct, however; the resulting complex mass has at least two characteristics which show curiously little variation from soil to soil.

1. The percentage of organic carbon is commonly ten to twelve times that of organic nitrogen, in other words the ratio $\frac{\text{carbon}}{\text{nitrogen}} = 10$ to 12, although in the original plant residues

[1] *Chem. Zeit.*, 1906, 356.

it may be as low as 25 [1] or as high as 40. The soils of Rothamsted, Woburn, and of parts of the United States have similar ratios in spite of considerable differences in conditions. But the ratio is not constant and changes under widely different climatic conditions, as shown by Sudan soils. Examples are given in Table XLI.:—

TABLE XLI.—CARBON-NITROGEN RATIO IN DIFFERENT SOILS.

Broadbalk wheat field, Rothamsted:—	
No manure since 1839	9·6
Farmyard manure every year since 1843	11·1
Barnefield mangold field, Rothamsted: Various fertiliser treatments	9·9 to 12·7
Woburn farm soils	10·0
Iowa (Brown and O'Niel)	12·13
Texas (Fraps)	9·0
Nebraska (Alway and Vail [2])	10·2 to 12·7
Various other states (J. W. Read [3])	4·5 to 10·7
Sudan (Joseph)	15·0

2. On soils of similar type the proportion of the organic nitrogen dissolved under standard conditions by alkalis shows but little variation whatever the manurial treatment of the soil. On the Broadbalk wheat field at Rothamsted one plot has received 14 tons per acre of farmyard manure each year since 1843; another has received artificial manures each year during the same period; while a third has been without manure of any kind since 1839. The differences in treatment could hardly be greater, yet the ratio of soluble to total nitrogen shows little change. On the other hand, differences in air supply or in climatic conditions cause considerable differences in the ratio (Table XLII.).

These studies of soil organic matter as a whole are useful for understanding the plant relationships, but the only way to ascertain the chemical nature of the soil organic matter is to

[1] In proteins it becomes much lower. This constant ratio was first recorded by Dyer in his examination of the Rothamsted soils (*U.S. Dept. Agric. Bull.*, 106, 1902).

[2] *Nebr. Expt. Stat.*, 25th Rept., 1912, p. 145.

[3] *Soil Sci.*, 1921, **12**, 491-495. Carbon determined by his special method.

TABLE XLII.—TOTAL AND SOLUBLE NITROGEN IN DIFFERENT SOILS.

	Old Arable Soil,[1] Rothamsted.			Old Grass Land,[2] Rothamsted.		Prairie Soil, Manitoba.
	No Manure since 1839.	Artificial Manure since 1843.	Farmyard Manure since 1843.	No Manure since 1856.	Artificial Manure since 1856.	No Manure.
Total N, per cent.	·0966	·115	·217	·260	·230	·618
Soluble N, per cent.	·050	·062	·114	·173	·149	·230
Ratio soluble to total when total = 100	51·8	53·8	52·5	66·3	65·0	37·2

isolate its various constituents. Wallerius (291) records some of the eighteenth century attempts, and Vauquelin, in 1797,[3] introduced a method which is still in use. He found that some of the organic matter was extracted by alkali after the soil had first been treated with dilute acid; the extracted material was precipitated apparently unchanged by adding an acid. The method formed the basis of an important investigation by Mulder,[4] who regarded the precipitate as an insoluble acid which formed soluble salts with potassium, sodium, and ammonium, but an insoluble one with calcium: the acid he called "humic acid," and its salts "humates." In neutral soils the acid was combined as insoluble calcium humate which had first to be decomposed by acids before alkalis could extract it, but in acid soils it existed uncombined with a base.

The part insoluble in alkalis was called humin and was almost entirely neglected by chemists.

Chemists long assumed (following Vauquelin's original suggestion) that the alkaline extract—"the humic acid"—was a

[1] Arable for at least 300 years.

[2] Grass for at least 300 years. The records show both to have been old in 1623.

[3] *Ann. Chim.*, 1797, **21**, 39.

[4] *Journ. Prakt. Chem.*, 1840, **21**, 203, 321; see also *Chemie der Ackerkrume*, Berlin, 1861-1862, and for later work, Detmer (85), and Ehrenberg and Bahr (94*d*).

single homogeneous body. Hoppe-Seyler [1] showed that it was not. Part dissolved in alcohol and part was insoluble. He regarded both fractions as single substances, and called the alcohol-soluble portion "hymato-melanic acid" and the insoluble part "humic acid." More recently Schreiner and Shorey (250) have shown that this view also is incorrect, both fractions containing numerous other substances, including the following :—

Substances Precipitated by Acids (the so-called *Humic* and *Ulmic* Acids).	Substances not Precipitated by Acids (the so-called *Crenic* and *Apocrenic* Acids).
Resin acids. *Resin esters.* *Glycerides.* *Paraffinic acid*, $C_{24}H_{48}O_2$, m.pt. 45°-48°, probably identical with the acid formed on treating paraffin with fuming nitric acid. *Lignoceric acid*, $C_{24}H_{48}O_2$, m.pt. 80°-81°, isomeric with above. *Agroceric acid*, $C_{21}H_{42}O_3$, m.pt. 72°-73°, a hydroxy fatty acid. *Agrosterol*, $C_{26}H_{44}O$, m.pt. 237°. *Phytosterol*, $C_{26}H_{44}O \cdot H_2O$, m.pt. 135°. Both of the cholesterol group.	*Dihydroxystearic acid*, $C_{18}H_{36}O_4$, m.pt. 98°-99°, identical with the acid formed on oxidising elaidic acid. *a-Picoline γ-carboxylic acid*, $C_7H_7O_2N$, m.pt 239°, identical with the acid formed on heating uvitonic acid to 274°. *Xanthine*, $C_5H_4O_2N_4$. *Hypoxanthine*, $C_5H_4ON_4$. *Cytosine*, $C_4H_5ON_3 \cdot H_2O$. *Histidine*, $C_6H_9O_2N_3$. *Arginine*, $C_6H_{14}O_2N_4$. *A pentosan.*

None of these, however, is the black substance characteristic of humus; until recently its sticky non-crystalline nature had baffled all chemical investigations. Within the last few years physical chemists have evolved methods for studying colloids, and these are now being applied to humus.[2]

Odén (217*d*) divides the alkali-soluble humic material—Mulder's humic acid—into three parts; a water-soluble portion which he calls fulvic acid; a portion insoluble in water, but soluble in alcohol, for which he retains Hoppe-Seyler's name, Hymatomelanic acid; and a portion insoluble in water, in alcohol, and in other organic solvents which is humic acid.

[1] Hoppe-Seyler, *Journ. Physiolog. Chem.*, 1889, 13, 66.

[2] The student will find good summaries of the voluminous work on humus and humic acid by S. Odén and by H. J. Page in *Trans. Faraday Soc.*, 1922, 17, 288-294, and 272-287.

From electrometric and conductrometric measurements [1] he concludes that humic acid is tetra basic and has the formula $C_{60}H_{52}O_{24}(COOH)_4$; its molecular weight is of the order 1350 and its equivalent weight 310 ± 10.[2] It is stronger than the clay acids giving *p*H values up to 4·5.[3] It is insoluble in water, but readily forms a suspension of very minute electronegative emulsoid particles (0·020 μ diameter, according to Odén), which can be coagulated by electrolytes forming the gel. The process resembles the flocculation of clay,[4] but it requires larger concentrations of the electrolytes. The gel is a good binding agent, binding the particles of sand together.[5]

As an emulsoid humic acid (but not calcium humate) can protect other colloids, including clay, from flocculation,[6] and this action is probably important in bringing about the washing down of fine particles into the subsoil in non-calcareous soils. At higher concentrations or when sufficient calcium carbonate is present the reverse effect is produced, and the clay and humus are both precipitated.

Humic acid readily combines with ammonia to form an easily dissociated salt having an almost black anion. It absorbs or combines also with other bases, and the resulting products show base exchange phenomena similar to those of

[1] The conductrometric method is based on the following principle: A solution of ammonia is added to pure water and also to a water suspension of the humic material and the conductivities are measured. If the suspension is unaffected by the NH_4OH there is no difference in the values. If it simply absorbs the ammonia the conductivity falls below that of the ammonia alone. If, however, it is an acid and forms a salt with ammonia, the conductivity rises above that of ammonia alone since NH_4OH, being but feebly hydrolised, has a smaller conductivity than that of an equivalent amount of its salt.

[2] Hissink, however, obtained the value 180 in conductrometric experiments (135).

[3] Notice this is weaker than peat soils; apparently some stronger acid must be present in them.

[4] Mattson (193); Gedroiz, *Journ. Expt. Agron.*, 1924, **22**, 29.

[5] For a comparison of humus and clay as binding agents see Mattson (193).

[6] Th. Schloesing, *Compt. Rend.*, 1872, **74**, 1408; 1874, **78**, 1279; 1902, **135**, 601, and later writers; Odén, *Journ. für Landw.*, 1919, 177-208.

clay;[1] Hissink, in fact, supposes the ultimate particles of both clay and humus to have the same kind of constitution, both being surrounded by a double electric layer. This absorption of bases by humic acid may explain the starved-looking xerophytic habit of many bog plants. Its high capacity for retaining water has been most clearly shown in the attempts to utilise peat and has indeed brought most of them to failure in the British Isles; natural deep-lying peat (the properties of which are largely dominated by humic acid) may contain 90 to 96 per cent. of water, only little of which is given up on air drying or by pressure, but it comes out much more readily when the peat is heated or subjected to the passage of an electric current.[2] When humic acid is thoroughly dried, it loses its colloidal properties, some of them for a long time, if not permanently. There is considerable difficulty in re-wetting this very dry humic acid.[3]

Odén considers humic acid to be free from nitrogen. He thus differs from many of his predecessors, who had regarded nitrogen as an essential constituent of soil humus. He prepared from peat a sample of humic acid containing only 0·7 per cent. of nitrogen, but no soil humus yet obtained has as low a content as this; indeed, the numerous specimens prepared by H. J. Page and his assistants at Rothamsted contain approximately 5 per cent. of nitrogen which cannot be removed by any fractionation process. The nature of the connection between the nitrogen and the humic acid is under investigation, but the facts at present known are consistent with the view that the nitrogen is in the form of protein combined or closely associated with the humic acid, but that the humic acid itself is free from nitrogen. The connection between the nitrogen and the humic acid is so close that it

[1] The base exchange phenomena have been studied by H. Heimann, *Zeit. Pflanz. Düng.*, 1922, A, 1, 345; also W. Hümmelchen and H. Kappen, *ibid.*, 1924, A, 3, 289.

[2] These properties have formed the basis of methods of utilising peat.

[3] See Devaux, *Compt. Rend.*, 1916, 162, 197, and E. Ramann, *Bodenkunde*, 1911, p. 345.

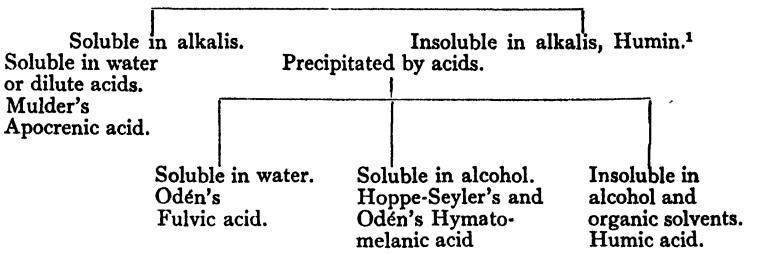
cannot be broken by solution in alkali and subsequent precipitation; so that the ratio of $\frac{\text{carbon}}{\text{nitrogen}}$ has approximately the same value for humic acid, whether prepared by cold or by hot alkali, as for the original soil.

The portion insoluble in alkali is called humin. It has not been much studied, though it might yield to methods of investigation such as have been used by Wheeler [1] in the study of coal. It appears to be closely related to humic acid, for on soils of similar type under similar climatic conditions there is a fairly constant relationship between the amount of humic acid and of humin, whatever the amounts of organic matter present. This idea is further supported by Arnold's [2] observations that hot alkali dissolves a considerable quantity of humin, extracting it as, or converting it into, a body indistinguishable from humic acid. Wheeler has shown that the corresponding insoluble substance found in coal is easily converted by mild oxidation into the soluble form. Conversely, humic acid, when heated, passes into an insoluble form which may be humin or something very like it. If one wishes for a chemical picture, one might think of humin as an anhydride or a condensation form of humic acid.

The fractions are shown in the following scheme :—

[1] Marie Stopes and R. V. Wheeler, *The Constitution of Coal*, H.M. Stationery Office, 1918; F. V. Tideswell and R. V. Wheeler, *On Dopplerite* (a black gelatinous substance found in layers at some distance, *e.g.* some 6 or 8 feet, below the surface of a bog), *Trans. Chem. Soc.*, 1922, **121**, 2345; W. Francis and R. V. Wheeler, *The Properties and Constitution of Coal Ulmins* (*Trans. Chem. Soc.*, 1925, **127**, 2236). The coal investigators use a somewhat different nomenclature from that of soil chemists, giving the name "Ulmin" both to the fraction soluble in alkalis and to that insoluble in alkalis; it is shown that the insoluble portion passes by slow oxidation into the soluble substance.

[2] Arnold, *Journ. Agric. Sci.*, 1927, **17**.



The influence of these various substances on plant growth is not definitely known. There is no evidence that humic acid plays any important part in plant nutrition, and if Odén's view be correct that it contains no nitrogen, the old idea of it as a source of nitrogen for plants falls to the ground. In Weir's and Crowther's pot experiments the crop yields were but little reduced when the humus was removed from the soil. These experiments, however, did not show how far the water or air supply to the roots was affected, and they gave no information as to the influence of humic acid on the physical properties of the soil. It is, however, on these physical properties that humus has its chief effect (p. 158).

Mechanism of the Formation of Humus.—The formation of humus has been studied in two ways. The older one was to attempt a synthesis, black sticky substances resembling humus being prepared from a variety of organic substances. The more recent method is to add known substances to the soil, and measure by analysis any increase in the quantity of humus present.

The synthetic method was for long confined to the action of acids on carbohydrates. Under suitable conditions condensation occurs and black sticky substances are formed. The investigations go back as far as 1835, when Malaguti prepared humic bodies by the action of nitric acid on sugar, a reaction further developed by Mulder. Berthelot and André (31) showed that the product of the action of acids on sugars is polybasic and readily loses water to form an

[1] Cold alkali.

anhydride having both acidic and alcoholic characteristics. Their product differed from natural humus, however, in its content of carbon; indeed, there was no real resemblance between the two. The difference in composition was emphasised by Robertson, Irvine, and Dobson,[1] who assigned the formula $C_{39}H_{32}O_{14}$ to the humic body prepared from sugar, and $C_{24}H_{24}O_{11}N$ to the soil humus obtained through the potassium salt. Maillard (189) showed that the reaction between acids and sugar is not confined to strong acids, but takes place also with amino acids and polypeptids, the condensing agent then being the NH_2 group: the product is much more like soil humus in elementary composition than anything previously prepared, containing, moreover, 4·4 to 6 per cent. of nitrogen. He put forward the most convincing view of humus formation given up to that time; he supposed a preliminary biological stage in which the proteins and polysaccharides, passing into the soil, break down to form amino-acids and sugars; the amino-group of the acids then condenses with the aldehydes and ketonic group of the sugar; the carboxyl group is disrupted forming CO_2; finally, water is lost. Subsequent slow changes occur in the soil and the ultimate products are anthracite and oil. On this view the formation of humus is a condensation of open-chain carbohydrates with amino-bodies; it is not an oxidation, and, moreover, nitrogen is an essential constituent of the molecule, although it might be split off in the extraction and purification processes.

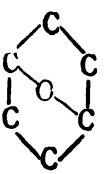
Greater precision is given to the course of the reaction by V. Beckley,[2] who showed that the carbohydrates yield first furfuraldehyde or methyl-hydroxy-furfuraldehyde which then condenses to form humus.

A second type of reaction gives rise to black sticky substances, physically resembling the humus obtained by the

[1] *Biochem. Journ.*, 1907, **2**, 458.
[2] *Journ. Agric. Sci.*, 1921, **11**, 69-77.

above condensations, but differing in chemical properties: the oxidation of phenols and their derivatives. This is primarily an oxidation, whereas the reaction described in the preceding paragraphs is primarily a condensation. The possibility that the phenolic humus might resemble soil humus was studied by Eller in 1920 (95*a*); he compared the humus prepared from phenols, carbohydrates, and soil, and also their nitro- and chlor-derivatives, and considered that the humus obtained from phenol more closely resembled soil humus than that obtained from carbohydrates. He therefore suggested that soil humus was formed by oxidation of phenolic substances.

More definite form is given to this hypothesis by Fisher and Schrader,[1] who show that lignin readily absorbs oxygen in the presence of weak alkali, giving humic matter. Now, lignin occurs to a considerable extent in the plant residues added to the soil, and it is built up from complex benzene ring groupings; it is therefore a feasible source of origin, both of soil humus and of coal. The lignin of the plant tissues is not necessarily the only source of humus. The benzenoid derivative may also be formed in the soil from open-chain compounds. Schrauth[2] suggests a formation of the fundamental unit of the lignin molecule by the condensation of three molecules of hydroxymethyl-furfuraldehyde; while Marcusson suggests that the carbohydrates in the plant residues may be converted into furfuraldehyde, and this through a paradifurane ring to a benzenoid grouping.[3]



Paradifurane Ring.

It would be easier to discriminate between these various possibilities if samples of humus prepared from the different sources could readily be compared. Unfortunately, purification is very difficult, and strict chemical methods, such as a

[1] *Brennstoff-Chem.*, 1921, **2**, 3.
[2] *Zeit. Angew. Chem.*, 1923, **36**, 149.
[3] *Ibid.*, 1922, **35**, 165; 1923, **36**, 42. See also Beijerinck (17).

comparison of the percentage of carbon and hydrogen in the different substances, cannot be applied. Du Toit's analytical results are given in Table XLIII. :—

TABLE XLIII.—PERCENTAGES OF CARBON, HYDROGEN, AND (WHERE PRESENT) NITROGEN IN "HUMUS" FROM VARIOUS SOURCES. DU TOIT, 91.

Source of Humus.	Carbon.	Hydrogen.	Nitrogen.
Soil	56·0	5·1	5·36
Rotted straw	56·2	5·5	2·56
Furfural	61·1	5·9	—
Lignin	60·2	5·9	—
Cane sugar	58·7	5·3	—
Cellulose	58·1	5·5	—
Hydroquinone	55·2	3·7	—
Maillard reaction	53·1	5·2	5·46
Dopplerite	50·8	5·4	2·37

Other investigators using conductrometric and electrometric methods have found that soil humus more closely resembles the oxidation product of the benzene ring derivatives, lignin, etc., than the condensation product of the aliphatic cellulose or furfuraldehyde. But the methods are not very rigid, and the results are consistent with the view that both types of humus are present in soil.[1]

Of recent years the problem has been studied by a different method. Various substances have been added to the soil, and their influence on its humus content has been ascertained. Addition of protein to the soil does not increase the humus; protein can, therefore, be ruled out as a possible parent substance.[2] Du Toit, at Rothamsted (91), approximated more nearly to natural conditions by mixing plant residues in soil, and after six months comparing the losses of their various constituents with the gains in the amounts of humus. His results are given in Table XLIV., all the figures

[1] For a discussion of the position in regard to coal see Marie Stopes and R. V. Wheeler, *The Constitution of Coal*, H.M. Stationery Office, 1918; and D. T. Jones and R. V. Wheeler, *Fuel* (*Colliery Guardian Supplement*), June, 1922, p. 91.

[2] Gortner, *Soil Science*, 1917, 3, 1-8.

being expressed as the percentages of the original ash-free organic matter.

TABLE XLIV.—LOSSES IN PLANT CONSTITUENTS AND GAINS IN HUMUS WHEN PLANT RESIDUES ARE DUG INTO SOIL. DU TOIT, 91.

Plant dug in.	Nitrogen Content.	Loss in Ash-free Organic Matter.[1]	Cellulose.		Furfuroids.		Lignin.		Humic Matter Produced.
			At Start.	Lost.	At Start.	Lost.	At Start.	Lost.	
Clover .	2·74	54	59·4	31·2	19·4	16·4	21·2	12·4	6·2
Straw .	0·53	49	45·2	10·3	35·5	32·7	19·2	9·2	3·2
Maize cobs	0·27	37	45·0	4·3	45·4	31·9	10·5	3·0	1·1
Sawdust .	0·05	21·4	54·7	9·0	12·5	8·5	32·8	3·9	0·9

The loss suffered by each constituent, *i.e.* the amount of decomposition, was in the order of the nitrogen content, as also was the amount of humic matter produced. The significance of this will be discussed more fully later when it will be shown that the nitrogen-supply determines the rate of most decompositions proceeding in the soil. Of the three constituents whose fate was followed, the furfuroids suffered more than any others, being almost completely decomposed, but their losses show no relation to the humus found. The figures for loss of cellulose are somewhat uncertain, since the estimation was by difference, but it seems clear that the sawdust lost as much cellulose as did the straw, yet it forms little more than one-quarter the amount of humus; further, the maize lost considerably less cellulose than did the sawdust, yet it gave rise to as much if not more humus. The clearest relationship is between the loss of lignin and the gain of humus, and from this circumstance Du Toit argues that soil humus is formed, not from cellulose or other open-chain compound, but from lignin, and he further shows that some 2·5 parts of lignin give rise in the soil to one part of humus, a figure almost

[1] *I.e.* amount of decomposition.

identical with that obtained by Schrader [1] in the purely chemical investigations. But it is possible that humus is really formed from both sources. Marcusson [2] shows that sphagnum peat contains over 40 per cent. of humic acid, though the original sphagnum contains but little lignin.

Wax-like Constituents.

Some of the soil organic matter is wax-like in properties, interfering very much with the wetting of the soil and the movement of the water. As it decomposes only slowly it tends to accumulate in rich soils and to become rather troublesome. It can be extracted by organic solvents, *e.g.* toluene, and obtained as a yellowish-brown mass containing appreciable quantities of nitrogen (a soil yielded ·003 per cent. of a substance containing 3 per cent. of nitrogen in one of the writer's analyses).

The Nitrogen Compounds in the Soil.

The nitrogen compounds in the soil are derived mainly from protein which, in turn, comes from residues of plants or soil organisms. They fall into two groups: inorganic, chiefly ammonia and nitrate, which, however, represents only a small fraction of the nitrogen: and organic, complex insoluble compounds of unknown constitution. Of these some date back to the time when the soil was first deposited, and although originally protein, have undergone considerable change, becoming highly resistant to chemical or biological action; the larger part, however, is of recent origin.

The nitrogen was long regarded as a constituent of the humus, and this view was supported by the fact that the percentage of nitrogen in humus remained unaltered (about 5)

[1] *Brennstoff-Chem.*, 1922, 11. Other evidence that lignin, and not cellulose, is the parent substance of humus is quoted by Page in Chemical Society's *Annual Reports*, 1924, p. 173.

[2] *Bied. Zentr.*, 1925, 54, 386.

throughout the various fractionations and precipitations (p. 171). The nitrogen is undoubtedly closely associated with the humus, but not apparently as a constituent of the humic acid molecule. According to present knowledge humic acid contains no nitrogen, but can enter into a firm union with protein which is not broken by any of the ordinary fractionation processes. On this view the soil nitrogen compounds are mainly protein derived from plants or soil organisms, but somewhat disguised by their association with the humic acid :[1] they are hydrolised by boiling HCl, giving soluble nitrogen compounds similar to those formed during hydrolysis of protein.[2]

The nitrogen compounds break down in the soil by reactions described later (p. 252) to form ammonia and nitrate. The decomposition, however, is never complete; at Rothamsted it practically stops when the soil nitrogen is reduced to about 0·09 per cent. To some extent, at present unknown, this represents the residue of the original nitrogen compounds deposited when the soil was formed. But the slowing down or cessation of the decomposition may also be a consequence of the relationship of the colloidal protein with the clay and the humic acid, and it is profoundly affected by the marked influence of the $\frac{\text{carbon}}{\text{nitrogen}}$ ratio of the soil on the reactions brought about by the soil organisms (p. 289).

The total nitrogen in arable soils is usually about 0·15 per cent., in pasture soils about 0·3 per cent.; higher amounts are present in chalk soils and still higher in fen, moorland, and black prairie soils. About half of the nitrogen in arable soils is contained in compounds soluble in alkalis, and a small proportion in unstable compounds readily breaking down to ammonia. About ·0001 per cent. (*i.e.* 1 part per 1,000,000) is present as free or combined ammonia in arable soils not

[1] This is being tested in the Rothamsted laboratories by R. P. Hobson.

[2] Jodidi, *Iowa Res. Bull.*, 1, 1911; Morrow, *Soil Sci.*, 1918, 5, 163.

rich in organic matter,[1] and some ten times this quantity in pasture or heavily dunged arable soils; much larger quantities occasionally occur as in heated soil, but abnormal growth

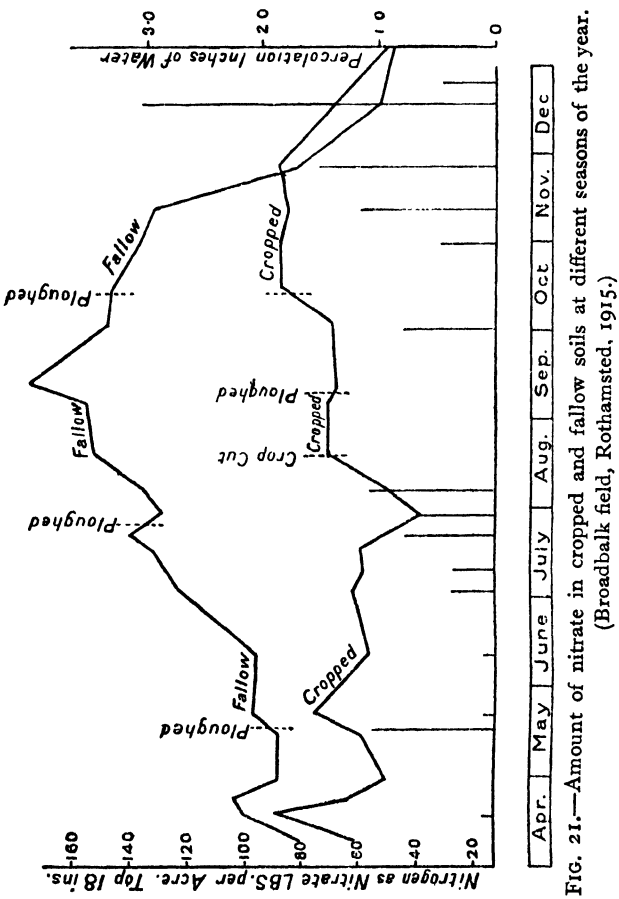


FIG. 21.—Amount of nitrate in cropped and fallow soils at different seasons of the year. (Broadbalk field, Rothamsted, 1915.)

effects are then produced.[2] The amount of nitrogen present as nitrate varies considerably; rich garden soils may contain 60 or more parts per 1,000,000 (·006 per cent.), arable soils

[1] André (*Compt. Rend.*, 1903, **136**, 820) obtained higher results in early spring which he attributed to the cessation of nitrification, but not of ammonification, during winter. See also Berthelot (33).

[2] See E. J. Russell and F. R. Petherbridge, *Journ. Agric. Sci.*, 1913, **5**, 248.

2 to 20 parts (·0002 to ·002 per cent.), pasture soils rather less and woodland soils still less.[1] The fluctuations are considerable; plants and rain rapidly remove nitrates and bacterial action rapidly forms them. The producing agencies are active in spring, and work throughout summer and autumn, while the removal agencies are active in summer and winter. Thus the amount of nitrate actually present in arable soil is usually highest in spring, falls in summer, often rises somewhat in autumn, and falls again in winter, as shown in Fig. 21 (see also p. 340).[2]

The nitrate and ammonia together rarely account for more that 1 per cent. of the nitrogen in the soil.

The Phosphorus Compounds of the Soil.

Part of the phosphorus in the soil is probably present in organic combinations derived from plant or animal residues: this has been investigated by Vincent,[3] by Potter and Snyder [4] and by Schollenberger; [5] none of whom, however, were able to identify the compounds. Part, however, is in inorganic combination and Bassett has shown [6] that it most probably occurs as hydroxyapatite—

$$(Ca_3P_2O_8)_3Ca(OH)_2,$$

this being the solid phase stable over a range extending from faintly acid to alkaline conditions: any phosphate such as superphosphate or basic slag added to the soil as fertiliser would tend to be converted into this substance.

[1] It is sometimes stated that woodland soils do not contain nitrates and are unsuited for nitrification, but Weis (301) has shown this to be incorrect.

[2] For American data see R. Stewart and J. E. Greaves, *Centr. Bakt. Par.*, 1917, 34, 115, and for Australian results: T. D. Hall, *Soil Sci.*, 1921, 12, 301, 363: the maximum here is in January and the minimum in June.

[3] *Compt. Rend.*, 1917, 164, 409.

[4] *Soil Sci.*, 1918, 6, 321-332.

[5] *Ibid.*, 365-395, 1920, 10, 127. About one-third of the phosphorus occurred in organic combination.

[6] *Trans. Chem. Soc.*, 1917, 111, 620-642.

Soil Acidity.

It has long been known that many soils are acid to litmus paper, but become neutral on addition of lime or calcium carbonate. The older chemists took the simple view that these soils contain an acid, which they assumed to be identical with that present in peat, and therefore organic, and formed in the decomposition of plant residues in badly aerated, undrained conditions.

Subsequent observations showed, however, that some acid soils were well drained, well aerated, and poor in organic matter; it seemed necessary here to assume a mineral acid such as a complex silicic or alumino-silicic acid.

No undeniable acid was ever isolated from soils, however, and when, some fifteen or twenty years ago, physical ideas dominated soil science, acidity was explained as a selective or preferential absorption common to many colloidal substances. It was assumed that the base was absorbed from salts or from blue litmus, thus leaving the acid or red litmus behind. Baumann and Gully (11, 117*b*) argued in favour of this view for peat, and Cameron (65*b* and *c*), Parker,[1] and Harris (125) for soil, the chief points being that the aqueous extracts of acid soils and peats are so slightly acid that the acid can be only weak, and hardly capable of liberating the acids from neutral salts, which is one of the characteristics of acid soils; further, it was alleged that this decomposition does not follow the ordinary stoichiometric laws.

The recent studies of base exchange, clay, and humus described earlier in this chapter, have caused chemists to revert to the older idea of true acids in the soil. Daikuhara, in 1914 (75*b*), showed that the puzzling reaction between an acid soil and neutral salts was simply an exchange of base, aluminium being given up from the soil in amount approximately equivalent to that of base absorbed, and making the

[1] E. G. Parker, *Journ. Agric. Res.*, 1913, 1, 179.

solution acid since its salts turn blue litmus red. Rice,[1] Hartwell and Pember (129), and Mirasol [2] adduced further evidence that acid soils owe their toxicity to soluble aluminium salts. Truog (281) showed, contrary to the older idea, that the interactions between soils and dissolved bases follow the ordinary stoichiometric laws when the conditions are controlled so as to avoid secondary reactions, and Bradfield (51) and other subsequent workers have confirmed this. All the old objections to the presence of definite acids in soils have thus been ruled out; further, there is no satisfactory direct evidence of preferential absorption beyond what is implied in base exchange. Positive evidence of the existence of clay and humus acids has now been obtained and quantitative studies of soil acidity have been made.

Modern investigations of soil acidity are largely based on Arrhenius' dissociation hypothesis, which assumes that an acid on solution in water dissociates into two parts called ions, one, the cation, being hydrogen, the other, the anion, being the rest of the molecule. Strong acids are highly dissociated, weak acids only slightly so. Recent elaborations of this hypothesis by physical chemists have hardly found their way into soil laboratories.

Using this hypothesis, chemists study acids in two general ways :—

1. By determining the titration value, *i.e.* the number of cubic centimetres of standard alkali solution which a given quantity of the acid will neutralise. In the language of the dissociation hypothesis this value measures the total quantity of hydrogen ions producible under the conditions of the experiment, supposing them to be neutralised or linked up with —OH ions as quickly as they are liberated.

The titration value measures the quantity of the acid but it makes no distinction between a strong acid, such as sulphuric, and a weak acid, like acetic; the great difference in action on

[1] Frank E. Rice, *Studies in Soils, I. Base Exchange* (*Journ. Phys. Chem.*, 1916, **20**, 214-227).

[2] *Soil Sci.*, 1920, **10**,

plant life exhibited by these two is missed altogether. Moreover, polybasic acids, which are by far the most numerous, have several titration values, according to whether one, two, or more of the hydrogen atoms are affected. Different indicators, therefore, give different numerical results. Again, a mixture of weak acids such as occurs in many biological fluids may show no sharp " end point " as titration, whatever indicator is used.

The old " lime requirement " methods were thought to give the titration values, but it is now known that the results are more complex (p. 214).

2. By measuring the " intensity " of the acidity, which is expressed by the concentration in the solution of hydrogen ions produced by the dissociation of the acid. The hydrogen ion concentration is measured electrometrically by means of a hydrogen electrode, or indirectly by indicators and standard solutions.[1]

In soil investigations the acids concerned are all weak. It can be shown that, for a weak acid, HX, and for water, H_2O,

$$\frac{[H^{\cdot}]\,[X']}{[HX]} = K_A$$

and

$$[H^{\cdot}]\,[OH'] = K_w$$

where $[H^{\cdot}]$ and $[X']$ represent the concentration of the hydrogen ions and anions respectively and $[HX]$ represents the concentration of the undissociated part of the acid.

In solutions of a strong acid the hydrogen ion concentration $[H^{\cdot}]$ is large, practically all the acid being dissociated : in solutions of a weak acid the concentration of the hydrogen ions is less, owing to incomplete dissociation of the acid.

The basis of the measurement is the concentration of the hydrogen ions in pure water. As this is neutral the hydrogen ions are exactly equal to the OH ions, *i.e.*

$$[H^{\cdot}] = [OH'].$$

[1] For a full discussion and description of experimental methods, see W. M. Clark, *Determination of Hydrogen Ions*, Baltimore, 2nd ed., 1922.

Physical determinations show that either is approximately equal to 10^{-7} gram-ions per litre.

In acid solutions the concentrations of hydrogen ions is greater than this, while in alkaline solutions the concentration of the hydroxyl ions is greater. The range of values is so large that the numbers cannot conveniently be plotted on curves, often the best way of dealing with them. The familiar device is therefore adopted of using the logarithm of the number, rather than the number itself, and omitting the negative sign. This notation was introduced by Sörensen,[1] and is designated by the symbol *p*H.

*p*H may thus be defined as the negative index of 10 which expresses the concentration of hydrogen ions in the solution of the acid; or, in other words, $pH = -\log [H^+] = \log \frac{1}{[H^+]}$. But it can be thought of simply as a notation for a scale of acidity and alkalinity, *p*H7 being neutral, successively lower numbers representing stronger and stronger acidity, and successively higher numbers stronger and stronger alkalinity. Acid solutions with concentrations of hydrogen ions, 1 N, 0·1 N, and 0·01 N respectively have *p*H values 0, 1, and 2, while alkaline solutions of concentrations of $-$ OH ions, 1 N, 0·1 N, and 0·01 N have *p*H values 14, 13, and 12 respectively.

The above equation for the dissociation of a weak acid can be re-written

$$\frac{1}{[H^+]} = \frac{1}{K_A}\frac{[X^-]}{[HX]}$$

or
$$pH = \log \frac{1}{[H^+]} = \log \frac{1}{K_A} + \log \frac{[X^-]}{[HX]}.$$

During the titration of the weak acid by a strong base, [HX], the concentration of the free, undissociated acid progressively decreases, and $[X^-]$, the concentration of the anion,

[1] S. P. L. Sörensen, *Biochem. Zeitsch.*, 1909, **12**, 130, and **22**, 352; see also *Ergebnisse d. Physiologie* (Asher and Spiro), 1912, **12**, 393.

i.e. of the salt, progressively increases; the ratio $\frac{[X^-]}{[HX]}$ however changes but slowly. Each 10 per cent. of the amount of base needed for neutralisation changes the *p*H value only by 0·2, yet the same amount of base added to pure water might have changed the *p*H by 4 or 5 units. This slowing down of the change of *p*H is called "buffer action," and solutions that show it are said to be highly "buffered." In more complex systems other factors may also operate, and the precise mechanism of the buffering is not always known, but its amount may be empirically measured.

The acid properties of soil are expressed by titration curves showing the *p*H values after successive additions of a base such as calcium hydrate. The curves are smooth and continuous, with no break at neutrality (*p*H7), and they resemble those given by mixtures of simple weak acids: some of E. M. Crowther and Martin's (72, VI.) are shown in Fig. 22. The curve for a strong acid would be an horizontal straight line suddenly swinging vertically when sufficient base has been added to effect neutralisation. These slopes of the soil curves are due to the buffering; usually sandy soils (*e.g.* Woburn, 5A) show much less buffering than clay soils (Harpenden common) or those containing much humus (Park, 11-1).

The interpretation of the soil curves is complicated by the peculiar constitution of the clay and humus acids of the soil; their insolubility and the circumstance that the "complex" which holds the hydrogen ions is not a simple anion but is enormously larger, being of the nature of the "acidoids" of Michaelis (p. 154).

Further, as the physical chemists had rightly emphasised, acidity is closely associated with absorption. A neutral soil interacts instantaneously with a solution of a neutral salt, exchanging bases in strictly equivalent proportions: the extent of the interchange being related to the concentration of the salt solution, as shown by Freundlich's equation. But an acid soil does not exchange bases in equivalent propor-

tions: there is an excess absorption of base and consequent liberation of titratable acidity. When account is taken of the hydrogen ions, however, the amount of base *plus* hydrogen ions given up from the soil is strictly equivalent to the amount of base absorbed from the salt. The extent of the action depends on the concentration of the salt and also on the

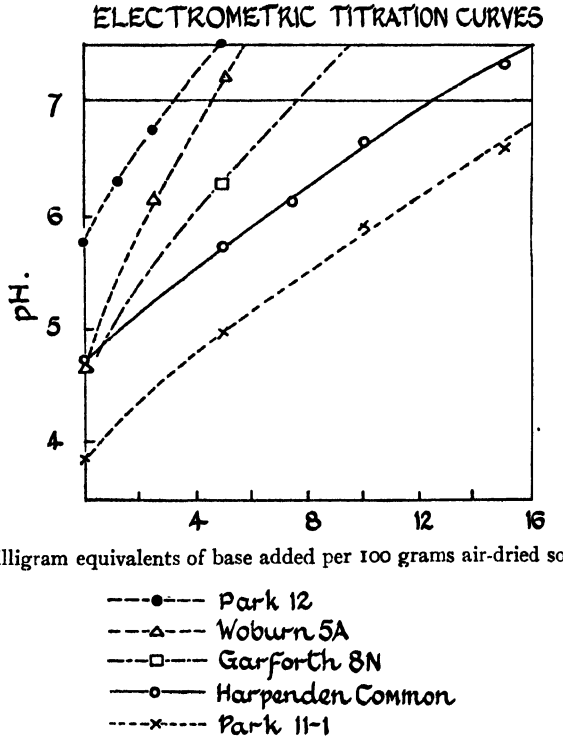


FIG. 22.—Changes in reaction (*p*H) of acid soils with successive additions of alkali.

strength of its acid radicle, a salt formed of a strong base and weak acid (*e.g.* sodium acetate) giving rise to more titratable acidity than one formed from a strong acid (*e.g.* sodium chloride). Moreover, aluminium, iron, and manganese are found among the bases given up by the soil (see p. 139). The range of equilibrium positions between acidity and complete

replacement of all the hydrogen ions may be expressed thus :—

$$\underset{\text{complex}}{\text{acid}}\ H'_n + nR'X \rightleftharpoons \underset{\text{complex}}{\text{acid}}\ H'_{n-y}R'_y \rightleftharpoons \underset{\text{complex}}{\text{acid}}\ R'_n + nHX$$

The final product may be called the " normal " salt of the acid complex and the intermediate products may be called the acid salts. The final product has no further power of absorbing bases excepting only by giving up a strictly equivalent amount. It is thus " saturated," to use the phrase of Ramann and Gedroiz. The intermediate products can still absorb more base then they give up ; they are therefore called " unsaturated." They are not, however, necessarily acid. Hissink finds that many soils are neutral, having a *p*H value of 7·07, when only 55 per cent. of their hydrogen has been replaced. A fully saturated soil has passed the neutral point, and may have a *p*H value of 10 or 11 (p. 219). It thus appears that the " acid complex " is a weak acid.

These considerations are found to explain most, if not all, of the facts, and they have therefore done away with the necessity for the various kinds of acidity assumed by some of the earlier workers.[1] It is simpler to assume the unbroken sequence indicated in the above equation.[2]

Estimates of the concentrations of hydrogen ions, *i.e.* the intensity of the acid in aqueous soil suspensions, made by colorimetric tests may be vitiated by the turbidity of the solution, absorption of the indicator, and other disturbing

[1] Such, for example, as the four types of acidity proposed by Kappen (*Landw. Versuchs.*, 1916, **88**, 13-104) : " Hydrolytic," where acidity is liberated from a hydrolysed salt of sodium acetate but not from a strongly dissociated salt, like sodium chloride ; " Exchange," where aluminium comes out from the soil and accounts for all of the acidity ; " Neutral salt decomposition," where there is a higher amount of titratable acidity than can be attributed to the aluminium ; and " Active acidity," where there seems to be no exchangeable bases. Other proposed distinctions were " Latent " or " Exchange " acidity, for acidity developing after addition of neutral salts, " Actual " or " Active " acidity, shown by the soil suspension in water, and " Total " acidity, measured by the amount of base needed to make the soil neutral.

[2] For a good presentation of modern views of soil acidity, see H. J. Page, *The Nature of Soil Acidity* (*Trans. Internat. Soc. Soil Sci.*, 1926, A, 232-244).

features,[1] and in any event do not show differences smaller than 0·1 *p*H. Bijlman's quinhydrone electrode[2] is more accurate, and is neither difficult nor tedious in use. The fundamental and most accurate is the electrometric method, using the hydrogen electrode: this gives direct readings of the hydrogen ion concentration, but it is both difficult and slow.

It would not at first be expected that the hydrogen ion concentration would show any relation to the titration values or "lime requirements," whether expressed by curves or by single numbers, nor can any be traced when soils of different types are compared; low intensity of acidity may be associated with considerable buffer action and high lime requirements or *vice versa*.

But for soils of the same type there is a fairly close correlation between *p*H values and lime requirements, and, where the organic matter content is approximately the same, there is also a relation between the "exchangeable CaO" and the *p*H values (see p. 217). The *p*H values for the acidity of peat may be as low as 3·0; for soils the extreme values recorded by Sharp and Hoagland are 3·7 to 9·7, and in Britain from 4·0[3] to 8·3, although it is unusual to obtain values less than 5·0. Normal fertile soils have *p*H values of 7 to 8 The range is much less than might be expected from the variations in amount of titratable acid in the soil, which, expressed as "lime requirement" values, go from 0 to more than 1 per cent.; the difference is attributed to buffer action.

We may now briefly sum up the current ideas of soil acidity.

[1] W. R. G. Atkins, *Proc. Roy. Dublin Soc.*, 1924, **17**, 341-347, R. M. Barnette, F. C. Gerretsen, D J. Hissink, and J. Van der Spek show that centrifuging the soil suspension at 8500 revolutions per minute gives a sufficiently clear liquid to be used safely for the colorimetric tests (*Chem. Weekblad.*, 1924, **21**, 145). See also *Rec. Trav. Chim.*, 1924, **43**, 434, for their studies of the electrometric method.

[2] *Journ. Agric. Sci.*, 1924, **14**, 232. See also H. R. Christensen and Jensen, *Internat. Mitt. Bodenkunde*, 1924, **14**, 1.

[3] On one of the Rothamsted grass plots (11-1) heavily manured year after year with sulphate of ammonia the value is 3·9.

The present position is that soil investigators have returned to the main outlines of the chemical views of sixty years ago, having found the purely physical view too indefinite and unsatisfactory. But the details are completely changed. The facts as at present understood are as follows :—

1. Soils contain two groups of acids :

   (*a*) Organic acids, mainly humic acid ;

   (*b*) Inorganic acids of the clay complex, probably alumino-silicic acids.

2. In neutral soils both of these are combined with bases, chiefly calcium, and to a less extent magnesium, sodium, and potassium, though not all of the hydrogen ions are replaced. In acid soils still more hydrogen ions are unreplaced ; there is a measurable excess of hydrogen ions over hydroxyl ions in the solution.

3. Acid soils react with alkalis or alkaline earths. The neutralisation follows the ordinary stoichiometric laws, apparent exceptions being explained by secondary reactions : the equilibrium phenomena can be represented by the Freundlich equation expressing surface actions.

4. Acid soils react with neutral salts, exchanging hydrogen ions for the cation of the salt. The hydrogen ions make the solution acid and also cause aluminium and iron ions to come into solution from the soil.

5. Acid soils are thus characterised by three properties :

   (*a*) Deficiency of replaceable calcium ;

   (*b*) Presence of hydrogen ions ;

   (*c*) Tendency to contain soluble aluminium and iron salts.

These reactions are dealt with in the next chapter (pp. 197 *et seq.*), and the influence of these various conditions on plants and on micro-organisms is discussed on pages 378 and 334.

The Soil Water or Soil Solution.

The soil retains by absorption and surface attractions some 10 to 20 per cent. of its weight of water distributed over its

particles. This water dissolves soluble substances in the soil, including carbon dioxide and various salts, forming a solution which is of obvious importance as the medium through which plants and micro-organisms receive their food. It is, in short, the culture solution of the plant.[1]

As has often happened in the history of agricultural science, the first investigation was made in France; Schloesing, in 1866 (245*e*), devised a method of collecting the soil solution based on displacement of water.

The importance of the soil solution was for many years not recognised by agricultural chemists. Whitney pointed it out in 1892 (303), but little was done till he was joined by Cameron, and issued the well-known bulletins of 1903 and 1904 which gave rise to considerable controversy, and led to many investigations in the United States and in Europe.

Whitney and the earlier workers adopted the simple method of stirring up the soil with water in such proportions as to make a 1 in 5 extract, and then rapidly filtering off. It was hoped that the added water would only dilute and not otherwise seriously alter the composition of the solution; this expectation, however, was not realised (p. 195). The method has, therefore, been discarded in favour of the original principle of displacement or of pressure.

Displacement Methods.—Schloesing placed 30 to 35 kgms. of freshly taken soil in a large inverted tubulated bell jar and poured on it water coloured with carmine, this being done to simulate the action of rain. The added water at once displaced the soil water and caused it to descend so that it could be collected: a sharp horizontal line of demarcation between the added and the original water persisted throughout the experiment even when eight days were occupied in the descent. A typical analysis of the displaced liquid in milligrams per litre was :—

[1] For a discussion of this assumption see D. R. Hoagland (136*d*); and for some vegetation tests see T. Saidel, *Bull. Agric.* (Roumania), 1925, vol. iv. (written in French).

SiO_2.	Nitric Acid.	Carbonic Acid.	CaO.	MgO.	K_2O.	Na_2O.	Sulphuric Acid.	Chlorine.	Organic Matter.
29·1	305	118	264	13·5	6·9	7·8	57·9	7·4	37·5

and in addition traces of phosphorus and of ammonia. This soil contained 19·1 per cent. of water.

The total concentration is seen to be about ·08 per cent.

Gola (110) also adopted the artificial rain device, and obtained solutions containing 2 to 0·2 or less per cent. of solid matter, the lower amounts being from agricultural soils.

The most convenient method is that of Burd and Martin (162*a*) in which 2 kilos of soil are packed into brass tubes 17 inches long and 3 inches in diameter; at the bottom is a brass screen covered with filter paper below which a tube leads out; the top is fitted with a screw cap and tube so that air pressure can be applied. 400 cc. of water are poured on the soil and the air pressure is increased, usually to 100 lb., till the liquid runs through. The solution is collected in 10 cc. fractions; the first lot are uniform in composition as shown by their electrical conductivity, and are assumed on good experimental grounds to represent the true soil solution.

Pressure methods have been devised but are not in common use.[1]

It was at first supposed (304*b*) that the soil solution was approximately constant in composition, being a saturated solution of the minerals common to all soils. This view is now discarded; the concentration and composition of the soil solution vary continuously, being modified by at least three factors: the amount of soil moisture; the action of the plant; and the action of the soil organisms.

Relation to Soil Moisture.—

(*a*) The concentration of *nitrate*, *chlorine*, and *calcium*

[1] See P. S. Burgess (64), F. W. Parker (223), and J. P. van Zyl, *J. für Landw*, 1916, **64**, 201-275.

varies inversely as the moisture content, indicating that the whole of the chlorine and the nitrate in the soil is in the soil solution along with an equivalent amount of calcium.

(*b*) The concentration of *phosphate*, though varying from soil to soil, is independent of the moisture content; the soil solution being presumably saturated with phosphate and dissolving more or throwing some out according as it is greater or less in amount; usually about 1 to 3 parts per million are present.

(*c*) The concentration of *potassium* increases as the soil solution becomes more concentrated, but not proportionally, as does that of chlorine and nitrate. This suggests an equilibrium between the potash in the liquid and in the solid phases resembling the adsorption equilibrium (p. 198).

Relation to Plant Growth.—The growing plant depletes the soil solution of much of its nutrient material, including almost the whole of the nitrate, but the solution is not absorbed as a whole; there is considerable selection. Some transfer of ions through the soil by movements of water or ionic diffusion [1] seems to go on as the root system, though extensive, does not range over every part of the soil. Fig. 23 and Table XLV.

TABLE XLV.—COMPOSITION OF SOIL SOLUTION. BURD AND MARTIN, CALIFORNIA (*Soil Sci.*, 1924, **18**, 151).

(Solutions displaced by water from cropped soils at beginning (April) and end (September) of growing season (1923) *and at the beginning of the next growing season* (1924).

Soil.	Date.	*p*H.	Parts per million of displaced solution.								
			NO_3.	HCO_3.	SO_4.	PO_4.	Ca.	Mg.	Na.	K.	Total Solids.
No. 7:	Apr. 30, 1923	7·4	149	83	561	1·1	242	91	42	21	1190
12·5 per cent.	Sept. 4, 1923	7·6	58	155	432	0·6	193	47	40	9	935
moisture	Apr. 28, 1924	7·6	252	142	699	0·6	336	76	59	12	1527
No. 11:	Apr. 30, 1923	8·2	173	160	671	3·3	222	97	87	41	1454
12·4 per cent.	Sept. 4, 1923	7·6	16	234	598	1·2	192	64	44	22	1171
moisture	Apr. 28, 1924	8·1	263	259	785	2·9	276	94	78	35	1793

[1] For studies of diffusion of salts in soil see Wheeting, *Soil Sci.*, 1925, **19**, 287-330, and 459-466.

show some of the California results: the effect of the crop is seen to persist for a long time (see p. 374).

Relation to Micro-organic Activity.—Micro-organisms restock the soil solution with the nutrients that the growing plant has taken. Their activity produces anions which bring an equivalent amount of cations into solution. Martin and Hoagland (136*d*) found that leached soils stored under sterile conditions (in contact with toluene) gained little or no soluble

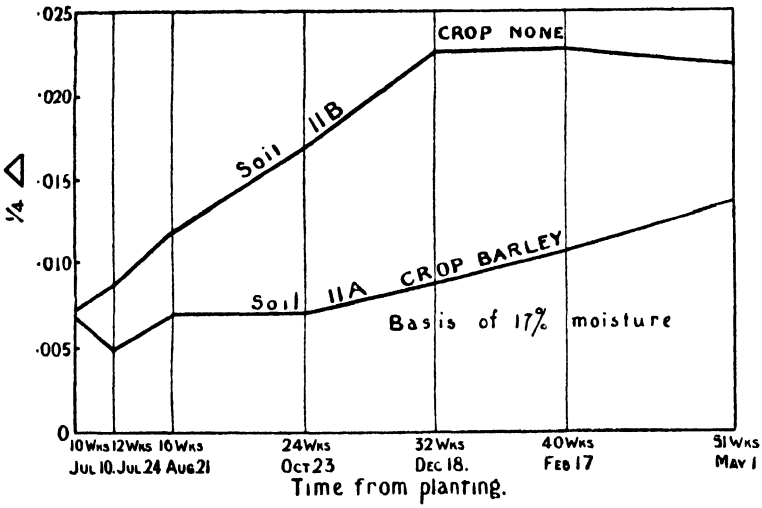


FIG. 23.—Variations in concentration of soil solution with crop and season, showing that the barley crop much lowers the concentration even after its removal in August. On the vertical axis one-quarter of each freezing-point depression is plotted: an approximate estimate of the corresponding osmotic pressure is obtained by multiplying the plotted value by 50. (Hoagland and Sharp, 136*b*, see alse Bouyoucos and McCool, 49*b*.)

material in a year, while the same soils without toluene, and therefore subject to micro-organic activity, gained considerably in soluble matter. Burd has studied the change in detail.[1] The anions produced are nitrate (chiefly), sulphate, and bicarbonate; the bases brought into solution depend on the colloidal constituents and the base exchange (p. 135), but they are usually calcium and magnesium.

[1] *Soil Sci.*, 1925, **20**, 269-283.

Rate of Renewal of the Soil Solution.—This is of obvious importance for the restoration of soil fertility. For those ions dependent on biological activity (nitrate and the equivalent cations) the rate of renewal is obviously limited by the rate of biological action. For the phosphate and potassium ions which are dependent on rate of solution, the rate of renewal is apparently very rapid. Thus the concentration of the phosphate ion is only 1 or 2 parts per million of the solution; if there were no renewal during its period of growth the crop would need impossibly large amounts of solution to furnish the 25 to 70 lb. per acre of PO_4 required. The rapidity of renewal is indicated by the circumstance that the 1 : 5 extract, though aiming at nothing more than the dilution of the solution, does, in fact, bring out much more phosphate and potassium.[1]

The general conclusion of these studies is that the solution in a normal agricultural soil contains mainly calcium nitrate and bicarbonate; with some organic matter, sodium, magnesium, silica, chlorine, sulphuric acid, less potassium, a trace of ammonia, and only little phosphate. In ordinarily moist soil it has a concentration of the order of 0·1 to 1·0 per cent., or some 0·5 to 5 atmospheres osmotic pressure; this varies however, with the rainfall, the vegetation, activity of micro-organisms, and the soil treatment, such as manuring. The proportions of the components also varies, changing with all the preceding factors. The nitrates are, perhaps, the most variable constituents, but the calcium and potassium also vary considerably. Since the soil solution is displaceable by water it might be expected to constitute, or at least appear in, the drainage water from field soils. Numerous analyses both at Rothamsted and on the Continent show a close similarity between the two. The drainage water varies in composition with the continuance of the rain, the first runnings being the most concentrated, and probably approximating to

[1] In Burgess' experiments (63*b*) about 30 times as much PO_4 and 3 to 5 times as much K.

the soil solution. It contains mere traces of NH_4 and PO_4, and only little K; but larger amounts of carbonic acid, SiO_4, Cl, SO_4, NO_3, Ca with some Fe, Mg, and Na. Typical analyses are given in Table XLVI.[1]:—

TABLE XLVI.—ANALYSES OF DRAINAGE WATERS FROM CULTIVATED FIELDS: PARTS PER MILLION OF SOLUTION.

	Rothamsted: Broadbalk Field.[2]			Field at Göttingen.[3]	
	No Manure.	Dung.	Complete Artificials.	Highest Result.	Lowest Result.
	Plots 3 and 4.	Plot 2.	Plot 6.		
CaO	98·1	147·4	143·9	184	157
MgO	5·1	4·9	7·9	46·4	31·3
K_2O	1·7	5·4	4·4	3·7	1·7
Na_2O	6·0	13·7	10·7	—	—
Fe_2O_3	5·7	2·6	2·7	—	—
Cl	10·7	20·7	20·7	—	—
SO_3	24·7	106·1	73·3	59·2	43·5
P_2O_5	·6	—	1·54	—	—
SiO_2	10·9	35·7	24·7	—	—
N as NH_3	·14	·20	·24	—	—
N as Nitrate	15·0	62·0	32·9	8·2	1·0
Organic matter, CO_2, etc.	67·7	77·3	84·6	—	—
Total solids	246·4	476·0	407·6	—	—

It will be observed that the total concentration of the Rothamsted drainage water varies from ·02 to ·05 per cent.

[1] A preliminary account of the data yielded by the Craibstone gauges is given by J. Hendrick, *Scottish Journ. Agric.*, 1924, 7, 1-11.

[2] A. Voelcker's analyses of five samples collected between 1866 and 1869 (285).

[3] Von Seelhorst's analyses of samples collected weekly, or fortnightly, from a field between August, 1899, and August, 1900 (257). For French data see Th. Schloesing (245*f*).

CHAPTER IV.

CHEMICAL AND PHYSICAL RELATIONSHIPS OF THE SOIL.

We have seen that soil contains two groups of colloidal materials, the clay and the humus; the humus contains a large proportion of a complex acid while the clay is built up somewhat on the model of a salt, able to exchange its bases, but differing from an ordinary simple salt in that the size of its smallest particle is vastly greater than that of a molecule. Its reactions are therefore much affected by surface forces.

Certain of the properties imposed by these colloids upon the soil are of great importance in its vegetation relationships. The chief are :—

1. The power of absorbing dissolved substances from their solutions.

2. The power of absorbing water in considerable amount and holding some of it rather loosely: parting with it again by evaporation in a continuous manner without any critical points or regions.

3. The change that can be brought about in some of the finer mineral particles from the flocculated to the deflocculated state, and *vice versa*. This is particularly shown by clay and has been discussed on pages 129 *et seq.*

4. The property whereby some of the soil components can enter into solution in pure water (not, however, a true solution) and be thrown out again on addition of small quantities of electrolytes. The soluble state is called a "sol," the precipitated state a "gel."

Absorption by Soil.

The discovery by Thompson of the fact of absorption of dissolved substances by soil and its first quantitative investigation by Way are dealt with on page 134. A great mass of subsequent work has shown that, whatever the substance absorbed, the equilibrium phenomena are usually expressible more readily by the Freundlich equation than by the ordinary chemical equations. The Freundlich equation is :

$$\frac{y}{m} = Kc^{\frac{1}{p}}$$

where

c = the concentration of the dissolved substance when equilibrium is attained ;

y = the amount absorbed by a quantity m of the absorbent ;

(this can be expressed as $(a - c)$ where a = the initial concentration) ;

K and p are constants depending on the nature of the solution and adsorbent.

This equation is applied to actions taking place at a surface where there are restraints on the movements of the molecules ; the ordinary equations, on the other hand, represent actions taking place in a free space and assume that all molecules are free to move equally in any direction. It was at first thought that the differences implied some fundamental distinction in the action itself, which was therefore put outside the range of ordinary chemical action and classed as a physical " adsorption." The present view is that the surface makes no fundamental distinction in the kind of action, but changes only its velocity and the position of equilibrium. The actions are shown to obey the ordinary stoichiometric laws and they can be thought of as simple chemical changes.[1]

[1] This view is held by many physical chemists, among them Irvine Langmuir, *Journ. Amer. Chem. Soc.*, 1916, **38**, 2221-2295 ; T. Svedberg, *Colloid Chemistry*, Wisconsin Lectures, 1924 ; G. N. Lewis, *Valency and the Structure of Atoms and Molecules*, 1923, but it is not universally adopted. Both J. N.

Nothing of interest to soil students has yet been deduced from the numerical values of the " constants " in the Freundlich equation. They are constant only for the particular experiment and vary with changes in experimental conditions. Some of the values collected by Wiegner are given in Table XLVII. :—

TABLE XLVII.—VALUE OF " CONSTANTS " OBTAINED IN ADSORPTIONS BY SOIL. WIEGNER (308*a*).

Absorbent.	Solute.	K.	$\frac{1}{P}$.	Worker.
Garden soil . . .	NH_4Cl	0·0948	0·039	Henneberg and Stohmann
" " . . .	NH_4Cl	0·131	0·424	
Nile sediment . .	NH_4Cl	0·489	0·399	Armsby
Permutite . . .	NH_4Cl	2·823	0·398	Wiegner
Sodium zeolite (artificial)	$CaCl_2$	2·487	0·317	Armsby
Zeolite (artificial)	LiCl	24·419	0·414	Campbell
Soil	NH_4OH	0·0994	0·434	Brustlein
"	NH_4OH	0·147	0·461	
"	NH_4OH	0·054	0·386	

Taken in detail, the numerous absorptions fall into three groups :—

1. Absorption of cations (bases).
2. Absorption of anions (acid radicles).
3. Absorption of colloidal sols, especially organic matter.

Absorption of Cations.—This has been much investigated, and is now regarded simply as an exchange of cations; it is described on pages 135 *et seq.*

Absorption of Anions.—There is no clear evidence of absorption. Precipitation of certain anions in the soil is well known, but it can readily be explained as a simple reaction with one of the bases. The absorption of the $-PO_4$ ion has been, perhaps, most studied; Russell and Prescott showed that it could be expressed by the Freundlich equation; they

Muckerjee (*Phil. Mag.*, 1922) and S. E. Mattson (*Koll. Chem. Beihefte*, 1922, 14, 2277) maintain alternative " adsorption " hypotheses. For a summary see E. A. Fisher, *Faraday Soc. Trans.*, 1922, 17, 305-316, and for the old views 65*a*.

regarded it as an "adsorption," but E. A. Fisher[1] and Comber (69*b*) have since shown that it is more easily explained as a purely chemical precipitation.

The anions that are not absorbed are $-HCO_3$, $-SO_4$, $-NO_3$, $-Cl$, and it is significant that these do not form insoluble salts with the soil bases at the concentrations at which they occur in the soil. They are therefore found in the drainage water (p. 196).

Various workers have assumed an absorption of the hydroxyl ion, because it offered a simple method of explaining some other phenomenon. Kappen assumes it to explain two of his types of acidity (p. 188), as also does Mattson to explain some of his flocculation results (p. 132).

Absorption of Colloidal Sols.—The absorption by soils of organic substances of high molecular weight has been much studied. The absorption of dyes has been used as a measure of the colloid material in the soil;[2] it can be regarded as similar to base exchange,[3] as also can the absorption of salts of organic bases.[4] For more complex organic substances a precipitation like the flocculation of clay may be brought about. This is of great importance in soil fertility; practically the whole of the organic matter added to the soil by plant residues or manure remains near the surface unless carried down mechanically by some agency such as earthworms. Even when heavy dressings of dung are annually applied at Rothamsted there is after fifty years no appreciable enrichment of the subsoil in nitrogen (Table XLVIII.). The purification of sewage by land treatment affords further illustrations of the absorptive power of soil for organic matter. In English experience a sewage farm on a good loam can deal with 30,000 to 40,000 gallons of sewage per acre per day (*i.e.* 1·3 to 1·8 inches per day).

[1] *Trans. Faraday Soc.*, 1922, **17**, 305-316.

[2] The earlier papers, beginning with one by Sjollema (*Journ. f. Landw.*, 1905, **53**, 67) are summarised by J. A. Hanley (*Journ. Agric. Sci.*, 1914, **6**, 58).

[3] J. A. Wilkinson and W. Hoff, *Journ. Phys. Chem.*, 1925, **29**, 808-815.

[4] E. Ungerer, *Kolloid Zeit.*, 1925, **36**, 228-235.

TABLE XLVIII.—NITROGEN IN BROADBALK WHEAT SOILS, 1893.

Per cent. of dry soil.

	Annual Dressing of Manure.					
	Unmanured.	Dung (200 lb. N).	Minerals only.	Minerals + 200 lb. Ammonium Salts (43 lb. N).	Minerals + 400 lb. Ammonium Salts (86 lb. N).	Minerals + 600 lb. Ammonium Salts (129 lb. N).
Top 9 in. .	·0992	·2207	·1013	·1107	·1222	·1188
9 to 18 in. .	·0730	·0767	·0739	·0720	·0681	·0752
18 to 27 in. .	·0651	·0656	·0645	·0628	·0583	·0630

Lb. per acre.

Top 9 in. .	2572	5150	2630	2870	3170	3080
9 to 18 in. .	1950	2050	1970	1920	1820	2010
18 to 27 in. .	1820	1830	1800	1750	1630	1760
Nitrogen supplied in manure in the 50 years .	None	10,000	None	2150	4300	6450

Some Consequences of Base Exchange.

If clay and humic acid alone were involved in base exchange, the phenomena would be sufficiently dealt with on pages 145 and 165. But the uncertainty whether clay and humus are the only soil constituents containing replaceable cations, and the certainty that the presence of the colloids introduces some complication, necessitates a discussion of the actions taking place when soil as a whole reacts with salts. Two cases commonly arise in field conditions :—

1. Nutrient salts or calcium carbonate are added to soils as fertilisers ;

2. Salts may be brought into the soil by seepage, irrigation, or flooding.

The actions in the main proceed as one would expect from a knowledge of the composition of the " exchangeable " bases (p. 139), but complications arise from : (*a*) the action of plants and micro-organisms ; (*b*) the circumstance that most soils contain calcium carbonate, which, coming into solution in the soil carbonic acid, participates in the reaction ; (*c*) the flocculating or deflocculation action that most substances have on the clay.

Action of Artificial Fertilisers and other Salts on Soils.

1. *Ammonium Sulphate.*—The changes here are of great technical importance because sulphate of ammonia is much used as a fertiliser. The first reaction seems to be with the exchangeable calcium :—

$$\underset{\text{insoluble}}{(\text{Clay complex})\,Ca} + \underset{\text{soluble}}{(NH_4)_2SO_4} = \underset{\text{insoluble}}{(\text{Clay complex})\,NH_4} + \underset{\text{soluble}}{CaSO_4}$$

The calcium sulphate is readily washed out in the drainage water. The further changes depend on whether calcium carbonate is or is not present.

(*a*) In presence of calcium carbonate the clay-ammonium compound rapidly nitrifies, giving calcium nitrate ; at the same time the calcium clay is reformed :—

$$\underset{\text{insoluble}}{(\text{Clay complex})\,NH_4} + \underset{\substack{\text{soluble}\\ \text{in presence}\\ \text{of } CO_2}}{2CaCO_3} + O_2 \rightarrow \underset{\text{insoluble}}{(\text{Clay complex})\,Ca} + \underset{\text{soluble}}{Ca(NO_3)}$$

Some of the calcium nitrate is washed out, but some is taken by growing plants, an action then occurs at the roots (p. 400), that regenerates calcium carbonate in the soil. Thus the final effect of sulphate of ammonia is to leave the clay complex unaltered, but to convert an equivalent amount of calcium into sulphates, which is lost from the soil ; the second equivalent converted into nitrate being regenerated. These results are collected in Table XLIX. :—

TABLE XLIX.—LOSSES OF CALCIUM CARBONATE FROM SOILS RECEIVING DIFFERENT FERTILISER TREATMENT. ROTHAMSTED. LB. PER ACRE.

	Broadbalk.				Hoos.		
	No Manure.	Sulphate of Ammonia.	Nitrate of Soda.	Farmyard Manure.	No Manure.	Sulphate of Ammonia.	Nitrate of Soda.
Content when first estimated . .	110,500	85,300	106,000	100,400	86,800	54,300	59,500
Content in 1904 .	90,200	61,800	92,700	85,100	63,900	37,500	42,500
Average annual loss	800	1,100	565	590	1,000[1]	775	595

(*b*) When there is no reserve of calcium carbonate the soil becomes acid. The fact was established by Wheeler in Rhode Island in 1891 (302); and quite independently, but a little later, by J. A. Voelcker at Woburn (286) where, the plots being permanent, the effect is continuously demonstrated. The course of this reaction has not been elucidated; Hall supposes that the ammonia is taken up by plants or micro-organisms, leaving the sulphuric acid in the soil.

2. *Superphosphate of Lime.*—Of all artificial manures this is used in largest quantity by farmers; it is made by adding sulphuric acid to mineral calcium phosphate, and thus contains more than half its weight of calcium sulphate; the rest is soluble mono-calcicphosphate, phosphoric acid, and water. As soon as the superphosphate reaches the soil it becomes insoluble. Two sets of actions may occur:—

(*a*) Where there is a reserve of calcium carbonate the soluble calcium mono-phosphate is converted into insoluble calcium phosphates such as the di-phosphate. The new combination is fully effective for increasing plant growth.

(*b*) The combination formed in absence of calcium carbonate appears to be less effective. The phosphate is therefore supposed to react with iron and aluminium compounds,

[1] Another plot which Hall thought more nearly comparable with the succeeding ones lost at the rate of 675 lb. per acre.

and thus becomes insoluble and unavailable. No critical investigation appears to have been made, but Fraps [1] has found some degree of relationship between the amounts of phosphoric acid absorbed by soils and of iron and aluminium oxides in the soil; there was no correlation, however, with calcium content. Superphosphate is sometimes, though incorrectly, regarded as an acid manure, but it has no effect on the *p*H value of the Rothamsted soils (Crowther, 72).

The effect of the calcium sulphate is to increase the quantity of exchangeable calcium in the soil but not to diminish the amounts of exchangeable magnesium or potassium. The amounts of the exchangeable bases (reckoned as oxides) in some of the air-dried soil of some of the plots of Broadbalk are :—

	Percentage of Dried Soils.			Milligram equivalents per 100 grams dry soil.		
	No Manure.	Sulphate of Ammonia only.	Sulphate of Ammonia and Super.	No Manure.	Sulphate of Ammonia only.	Sulphate of Ammonia and Super.
CaO	0·380	0·381	0·429	13·57	13·60	15·32
MgO	0·015	0·014	0·014	0·75	0·70	0·70
K_2O	0·020	0·014	0·015	0·42	0·30	0·32

Table L. shows that the calcium sulphate has not increased the availability of the potassium: it has led to no gain in weight of potassium in the crop. Briggs and Breazeale obtained a similar result on Californian soils.[2]

3. *Potassium Sulphate.*—This increases the amount of replaceable potassium, apparently at the cost of the calcium and magnesium. Some other action takes place for the increase is less than the amount added and retained by the soil: part goes into some other form, insoluble but not exchangeable. But this is not all: there are occasional instances

[1] G. S. Fraps, *Texas Bull.*, 304, 192
[2] *Journ. Agric. Res.*, 1917, 8, 21.

TABLE L.—EFFECT OF SODIUM AND MAGNESIUM SULPHATES IN INCREASING THE SUPPLY OF POTASSIUM TO THE PLANT. LAWES AND GILBERT (164*a*).

	Ammonium Salts only.	Ammonium Salts + Superphosphate.	Ammonium Salts + Super. + Sulphate of Sodium.	Ammonium Salts + Super. + Sulphate of Magnesium.	Ammonium Salts + Super. + Sulphate of Potassium.	Ammonium Salts + Super. + Sulphates of Sodium, Magnesium, and Potassium.
1852-1861.	Plot 10.	Plot 11.	Plot 12.	Plot 14.	Plot 13.	Plot 7.
K_2O in ash of straw, per cent. . .	18·8	14·8	20·1	22·0	24·1	23·7
K_2O in ash of grain, per cent. . .	33·9	31·7	32·8	32·6	32·9	32·9
Weight of K_2O in ten whole crops, lb. . . .	300	309	454	498	532	560
1862-1871.						
K_2O in ash of straw, per cent. . .	14·5	14·1	17·2	18·5	25·0	24·6
K_2O in ash of grain, per cent. . .	34·1	32·1	33·3	33·1	33·5	33·4
Weight of K_2O in ten whole crops, lb. . . .	240	260	378	391	552	530
Total amount of K_2O taken by crop during the twenty years, lb. . .	540	569	832	889	1084	1090

where sulphate of potash decreases the crop yield; whether the action is on the soil or on the plant is not known.[1] Both at Rothamsted and at Woburn sulphate of potash is without effect on the reaction of the surface soil, though it increases the acidity of the sub-soils on the acid plots (Crowther, 72), possibly through the washing down by rain of the acid liberated by cationic exchange. The effect on the exchangeable bases is shown in Page and Williams' analyses of the Broadbalk soil: the results in milligram equivalents per 100 grams of dry soil are:—

[1] For a discussion and summary of the literature see R. S. Smith, *Cornell Memoir*, 35, 1920.

	Unmanured.	Sulphate of Ammonia and Super.	Sulphate of Ammonia, Super. and Sulphate of Potash.	Sulphate of Ammonia, Super. and Sulphate of Soda.
CaO	13·57	15·32	14·89	16·29
MgO	0·75	0·70	0·50	0·70
K_2O	0·42	0·32	0·89	0·32

4. *Sodium Sulphate.*—On the Broadbalk wheat field sulphate of soda acts rather differently from sulphate of potash. It causes no diminution in the amount of replaceable calcium or potassium, but on the contrary an increase in the calcium. Apparently, therefore, the sodium has not replaced calcium or potassium, yet something has certainly happened, for more potassium is taken up by the crop. The Broadbalk wheat receiving sulphate of soda, but no sulphate of potash, contains more potassium than wheat on the adjoining plot receiving no sulphate of soda (Table L.).

5. *Magnesium Sulphate* has the same effect. From Table L. it appears that in the twenty-year period, 1852 to 1871, the sodium sulphate had enabled the plant to take up an additional 263 lb. of K_2O, whilst the magnesium sulphate has furnished it with an extra 320 lb. over and above what the crop on Plot 11 obtained. Calcium sulphate, on the other hand, has had no effect.

6. *Sodium Nitrate.*—This action has been studied in some detail by A. D. Hall[1] owing to its technical importance. When added in quantities of 5 to 10 cwts. per acre (not unusual for market garden crops or early potatoes), nitrate of soda is liable to spoil the texture of heavy soils: presumably it produces a sodium clay which is more readily deflocculated than the calcium clay. The evidence on Barnfield, Rothamsted, is clear; the surface soil shows the typical signs of deflocculation, being sticky when wet and hard when dry;

[1] *Trans. Chem. Soc.*, 1904, **85**, 964-971.

analysis indicates that much of the deflocculated clay is washed into the subsoil. On Broadbalk on the other hand, no visible effect has been produced; neither calcium nor potassium has been displaced nor has the tilth been recognisably affected. The dispersion and washing down into the subsoil of the clay, has, however, occurred, but only to the extent of some 5 per cent. of its total quantity, an amount that does not appreciably affect the values of the replaceable bases. On Barnfield for some unknown reason the difference in clay content is much greater, amounting to 25 per cent. of the whole (Table LI.):—

TABLE LI.—PERCENTAGE OF CLAY (< ·002 mm. DIAMETER) IN SOILS RECEIVING DIFFERENT FERTILISER TREATMENT. ROTHAMSTED.

Percentage of Clay.	Broadbalk.			Hoos Barley.			Hoos Potato.		Barnfield.			
		Minerals +			Super. +				Minerals +		Super. +	
	No Manure.	Sulphate of Ammonia.	Nitrate of Soda.	No Manure.	Sulphate of Ammonia.	Nitrate of Soda.	Sulphate of Ammonia.	Nitrate of Soda.	Sulphate of Ammonia.	Nitrate of Soda.	Sulphate of Ammonia.	Nitrate of Soda.
Top soil (0-9 ins.) .	14·9	14·9	13·6	15·5	16·4	14·5	17·7	16·5	19·9	15·2	20·5	15·2
2nd depth (9-18 ins.)	23·2	25·7	26·5	—	—	—	—	—	—	—	—	—
3rd depth (18-27 ins)	34·2	34·3	38·9	—	—	—	—	—	—	—	—	—
Soluble Silica[1] .	—	—	—	—	—	—	8·31	6·98	50·8	6·94	12·49	8·71

On the grass plots, however, nitrate of soda causes no reduction in the amount of clay in the surface soil, the percentages being:—

No Manure.	Minerals +	
	Sulphate of Ammonia.	Nitrate of Soda.
12·2	12·7	13·7

[1] Virtually a measure of van Bemmelen's "Silicate A," p. 136.

The difference in conditions is the very important one that the covering of grass by protecting the soil from the action of rain prevents the washing out of the dispersed clay. Hall was able to extract from the soil no less than 175 lb. sodium carbonate per acre, almost exactly equivalent to one-half the annual application of nitrate of soda.[1]

A further action of nitrate of soda on soil, for which no explanation is forthcoming, is that nitrate of soda in some way reduces the net loss of calcium carbonate from the soil by leaching. The losses in lb. per acre from some of the Rothamsted soils are given in Table XLIX. (p. 203).

Both at Rothamsted and at Woburn nitrate of soda has reduced the acidity of the soil. Crowther's values for *p*H are :—

	Woburn Stackyard Field.		Rothamsted Park Grass.	
	Nitrate of Soda.	No Nitrate of Soda.	Nitrate of Soda.	No Nitrate of Soda.
No other manure .	6·2	5·8	6·3	5·7
Mineral manures .	6·2	5·8	5·9 6·4	5·4

Effect of Sodium Chloride.—This does not differ in essentials from the action of sodium nitrate; it is, however, of great practical importance in places liable to be flooded by sea and because of its close connection with the formation of sodium carbonate in soils, especially in alkali soils.

Some interesting observations on the formation of a sodium clay by flooding with sea water were made by T. S. Dymond in 1897-1899.[2] The first effect of the flooding was to kill the vegetation by direct action of the salt. But when the flood subsided and the rain water began to wash away the salt, an interesting sequence of events was observed.

[1] This soil contains no calcium carbonate.

[2] Report on injury to agricultural land on the coast of Essex by the inundation of sea water on 29th November, 1897. Chelmsford, 1899.

The soil was at first " in remarkably good condition, ploughing well and forming a capital seed bed." But with further removal of the salt " this condition gradually altered until the soil became difficult to work and in dry weather hard and cindery." The clay became more deflocculated, and would remain suspended for weeks in water while that from the unflooded land settled in a few hours.[1]

Dymond proved that the effect of the salt was to displace calcium and magnesium from the clay, and he argued that sodium had taken their place. He attributed the initial favourable physical conditions to the flocculation brought about by the small quantity of salt still left; when this was gone the clay became highly deflocculated.

Dymond's observations are in full accordance with Dutch experience around the Zuyder Zee. The flooded soils of " Kweldergronden " remain open and porous so long as they are exposed to occasional floods, but after they are protected by dykes, they lose their salt through the action of the rain and gradually become sticky and impervious to air and water when wet, and very hard when dry.[2]

Agriculturists have used both of the general methods of treatment referred to on page 154; by preference they convert the sodium clay into a calcium clay which they understand; but they can also find special crops and special methods of treatment. Dymond noted that the crucifers, rape, mustard, charlock, all grew well on the sodium clay; it is also known that the soil remains porous if sodium salts are periodically added.

The conversion of the sodium clay into a calcium clay

[1] An interesting example can be seen at the present time at E. Halton in North Lincs. The land was formerly very productive, being especially suited for wheat and beans; it was flooded by the sea in 1921 and became infertile. It has not since been flooded, but it remains very sticky when wet and hard as concrete when dry, so that cultivation is impossible; even wild plants make but little growth. (H. J. Page and W. Williams, *Journ. Ag. Sci.*, 1926, **16**, 551-573.)

[2] For an account of these soils see Hissink's Report in *Verslagen Proefstations*, No. 29, 170-184. Abstract in *Bied. Zent.*, 1924, **53**, 306-311.

can be effected by adding considerable quantities of calcium sulphate (this being better than calcium carbonate, since it produces sodium sulphate and not sodium carbonate) or, more economically, by allowing any calcium carbonate present in the soil to interact with the sodium clay; this necessitates the presence of carbon dioxide to bring the calcium carbonate into solution. Adequate drainage is necessary to allow of the removal of the displaced sodium.

This latter method is adopted on the "Kweldergronden" already mentioned, and also on the Lincolnshire warp lands, which are artificially built up by allowing the brackish tidal rivers to flow at high tide over an enclosed area of low-lying land and there deposit their suspended mineral matter. A considerable amount of calcium carbonate is present, along with the sodium clay. When the water is finally drained off, the land must be left uncultivated for a time, but once a good crop of clover can be obtained (which evolves much CO_2 in the soil during the growth and after its residues are ploughed in) the success of the treatment is assured. Dymond noted that long hay (which readily produces great quantities of CO_2) ploughed into the flooded soil hastened its agricultural recovery.

Alkali Soils.

The sodium clays formed when arid soils are irrigated have been studied by Kelley (144). Arid soils usually contain sodium salts accumulated through lack of rain and arising either from decomposition of the rock minerals or from inland seas long since evaporated to dryness. When first irrigated these soils are very productive.[1] Usually the irrigation water contains a little dissolved sodium salt, which, as Mosseri has pointed out, does no harm if its amount is not too great, and, indeed, may do good by keeping the sodium clay flocculated

[1] It may be necessary to wash out most of the salt as was done when the Lake Aboukir was reclaimed in Egypt (*Proc. Inst. Civil Engineers*, 1890, 101, 189), and in many later reclamations.

and thus maintaining the soil in good physical condition for a considerable, if not indefinite, time. But when the sodium accumulates too much in the soil, difficulties begin to arise both from the sodium clay and from the sodium carbonate. From the problem of dealing with sodium it becomes the much worse one of dealing with alkali.

The Formation of Sodium Carbonate ("Black Alkali") in Soils.

It has long been known that irrigated soils in arid regions are liable to become alkaline through the formation of sodium carbonate, and, as stated above, this salt may be formed under English conditions where large quantities of nitrate of soda are used as a fertiliser on land not liable to much leaching action. The term "black alkali" is given in arid regions because of the black patches or puddles formed from the solution of the humus in the sodium carbonate when water is added to the soil.

The first investigations into the origin of sodium carbonate were made by the French chemists, the problem being brought to their notice when Napoleon, in the closing years of the eighteenth century, brought Egypt under French domination. Berthollet supposed that it was formed by the interaction of sodium chloride and calcium carbonate.[1] This hypothesis was generally adopted in Europe, and supported by Hilgard's school in California and by the physical chemists on the United States Bureau of Soils,[2] but it does not always

[1] C. Berthollet, *Observations sur le Natron, Journ. de Physique de chimie et d'Hist. Nat.*, 1800, 51, 1-9. An interesting study of the "Vallée des lacs de natron" in Egypt.

[2] Hilgard and Webber, *Amer. Soc. Promotion Agric. Sci.*, 1888; Hilgard and Jaffa, *Cal. Expt. Sta. Rept.*, 1890, 87-105; F. Cameron, *U.S. Div. of Soils, Bulls.* 17 and 18, 1901; W. P. Kelley, *The Effect of Nitrate of Soda on Soils, Cal. Expt. Sta. Rept.*, 1916, p. 59; J. F. Breazeale, *Formation of Black Alkali (Sodium Carbonate) in Calcareous Soils (Journ. Agric. Res.*, 1917, 10, 541).

explain the facts. Cameron [1] and Hall (120*b*) introduced two different biological explanations, both supposing that the carbonate may be formed by the growing plant, but Cameron assumed an excess absorption of alkali bases over acid by the plant, which excess, on decay, would remain in the soil as alkali carbonate, while Hall makes the reverse assumption, supposing an excess absorption of acid (*e.g.* the nitrate ion) over base, leaving alkali carbonate in the soil.

All three actions may, and probably do, occur in Nature. But they do not explain all the known facts, and a more usual method of formation is one first discovered in an ingenious investigation by Paul de Mondésir in 1888 (202).

Finding calcium chloride in the water extract of a soil near the sea, he argued that it must have been formed by sodium chloride. But where had the sodium gone? There was too much to have been taken by the crop, and he concluded it must have been absorbed by the soil. Direct laboratory experiment showed that soil reacted with sodium chloride to give calcium chloride and an insoluble sodium compound. After removal of the calcium chloride this sodium absorption compound readily broke down in the presence of CO_2 to give sodium carbonate, and by successive treatments of a soil first with sodium chloride, then with water, and finally with CO_2 and water, he was able to prepare 100 grams of sodium carbonate from 1 kilo of soil. His explanation, therefore, was that sodium chloride does not react with calcium carbonate, but with soil, forming a sodium absorption complex which, after removal of the calcium chloride, can be decomposed by CO_2 or calcium carbonate.

This paper was, unfortunately, overlooked, and the American workers continued to base their investigations on the old Berthollet hypothesis. Thirty-four years later (in 1912) the same explanation was put forward by Gedroiz

[1] Cameron was led to this investigation by a belief, popular in the Western States of America, that certain plants, notably the common Greasewood (*Sarcobatus vermiculatus*) converted harmless salts into sodium carbonate in the soil.

(107), who, as he does not mention Mondésir's work, w apparently unacquainted with it. By a curious fatality Gedroiz's work, in turn, passed unnoticed for twelve years, until it was translated from the Russian by the United States Department of Agriculture, and so made available for scientific workers.

In studying the alkali soils of Russia, Gedroiz had observed that the quantities of sodium carbonate extracted by water diminished in successive extractions, but less than if the sodium carbonate existed as such in the soil. He concluded, therefore, that the sodium carbonate is either held by absorption, or that it is continuously being produced in the soil.

He next showed that the amount of sodium carbonate washed out was lowered on adding sodium chloride or sulphate but increased after these salts were removed. This result does not allow of discrimination between the two possibilities, but it amplifies them; if the sodium carbonate is held by absorption, this is intensified by sodium chloride and sodium sulphate; alternatively, if it is being formed in the soil it cannot be direct from sodium chloride or sodium sulphate, as supposed in the old view.

He then added sodium chloride and calcium carbonate to soil and extracted with water; but he obtained only little sodium carbonate. Finally, he added sodium chloride alone, extracted with water, and then added calcium carbonate and again extracted, and obtained a great deal of sodium carbonate, much more than when no sodium chloride had been added.[1]

It appeared, then, that the formation of sodium carbonate proceeds in three stages: the first is the reaction between sodium chloride and the soil; the second is the leaching away of the soluble products; and the third is the

[1] A. B. Cummins and W. P. Kelley (*Univ. Cal. Tech. Paper*, No. 3, 1923), independently used this method to convert an acid soil first into a neutral and then into an alkaline one, and thus they demonstrated the simple relationship between acidity and alkalinity in soil.

reaction between the insoluble sodium product and a carbonate.

The simplest explanation was to suppose that the sodium chloride reacted on the "zeolitic silicates" to form a sodium clay which then reacted with the carbonate to form sodium carbonate and a calcium clay. The paralysing influence of sodium chloride and of sodium sulphate follows, naturally, as these salts interfere with the exchange between calcium carbonate and the sodium in the clay.

This explanation of the origin of sodium carbonate gives the clue to the treatment of "black alkali." Simple washing away of the carbonate with water is obviously insufficient so long as the clay remains a sodium clay; replacement of the sodium by calcium is a first necessity for a permanent cure; the next step is to prevent the reformation of the sodium clay.

Hilgard used calcium sulphate (gypsum or land plaster) with success in some instances where he was able to arrange for proper flooding and draining of the land, but in estimating the amount required he took into account only the sodium carbonate washed out from the soil by water. Kelley is now improving the method by taking into account the amount of replaceable sodium.

The fundamental trouble, not yet overcome, is that the irrigation water usually contains sodium salts so that the calcium clay is no sooner regenerated than it begins to revert to the sodium clay and the whole trouble starts afresh. Unless sodium salts can be kept down in quantity the difficulty seems to be insuperable.[1]

Action of Calcium Oxide or Calcium Carbonate on Soil: "Saturated" and "Unsaturated" Soils.

The action of calcium carbonate on the soil is, in principle, very like that of any other salt, but its results are of special importance to many plants and micro-organisms; chalk,

[1] For a good discussion of the alkali problem see *Soil Alkali, its Origin, Nature, and Treatment*," F S. Harris, Wiley & Sons, New York, 1920.

lime, and limestone are among the oldest of manures.[1] Part of the action is chemical: the calcium replaces hydrogen or sodium in the clay, thus converting an acid or alkaline clay into the more usual calcium clay; it also replaces acidic hydrogen in humic acid forming the so-called calcium humate or neutral humus: and it precipitates the soluble and toxic iron, manganese, and aluminium compounds from acid soils. Part of the effect is physical, the calcium flocculating the clay and bringing it to a better texture. In addition, both oxide and carbonate are often said to liberate potassium from the soil, but the extensive lysimeter experiments at Knoxville[2] afford no evidence for this. Calcium oxide decreases the loss of potassium and magnesium by drainage.[3]

There are certain differences in action between calcium oxide and calcium carbonate. The oxide is somewhat the more effective in bringing about some of the changes, though not apparently in stimulating the oxidation of soil organic matter; examination of the long-continued Pennsylvania plots[4] showed no significant difference in organic matter content whether oxide or carbonate had been applied. The oxide does not persist in the soil; it is slowly but quantitatively converted into the carbonate.[5]

These various calcium reactions have a great effect on vegetation, and soils in which they occur readily differ markedly from those in which they do not. Chemists call them "acid," agriculturists speak of them as "sour" in contradistinction to "sweet" soils, while Ramann (231*a*)

[1] Pliny describes with evident approbation the method in which the Belgæ used the chalk—and his description holds almost exactly for the traditional method followed till recently in the Home Counties (C. Plinii, *Secundi Naturalis Historiæ*, Lib. 17, Cap. 6. See also E. J. Russell, *Journ. Bd. Agric.*, 1916, 23, 625.)

[2] W. H. MacIntyre, W. M. Shaw, and J. B. Young, *Soil Sci.*, 1923, 16, 217.

[3] *Ibid.*, p. 449.

[4] J. W. White and F. G. Holben, *Soil Sci.*, 1924, 18, 201.

[5] Hutchinson and McLennan (140*c*); E. Blanck and W. Lohmann, *Zeit. Pflanz. Düng.*, 1924, 3, A. 91-110.

introduced the term " absorptively unsaturated " to describe them because they absorb the base from neutral salts leaving free acid in the solution.

The vegetation characteristics of " unsaturated " soils are discussed on pages 378 *et seq.*

Numerous attempts have been made to solve the important technical problem of discovering how much lime or chalk must be added to a " sour " or " unsaturated " soil to bring it to a fertile state.[1] So far there is no general agreement. The numerous methods in use by different workers fall into two groups, measuring respectively (1) the amount of lime needed to make the soil neutral (*i.e.* *p*H 7·0) or to bring it to a certain *p*H value; (2) the amount of lime or calcium carbonate which the soil will absorb from solutions; usually called its " lime requirement."

If the action were merely the neutralisation of a simple acid the two methods would give the same result, but they do not. Even the measurement of the amount of base needed to make the soil neutral is complex; it does not depend (as in the titration of a simple acid) merely on the amount of acid present, but also on the buffer action of the soil (p. 186). Further, it is affected by the hydrogen ion concentration in the soil (another difference from the titration of a simple acid), being usually higher for soils of low than for those of high *p*H value. The influence of the buffer action transcends that of *p*H value so that soils of equal *p*H values may require very different amounts of lime or other base to effect a given change in *p*H; loams require least, humus sandy soils more, and clays most.[2] Some of the causes are discussed later; it is clear, however, that single titration values have but little significance and titration curves have to be set up. Nor is the measurement of the amount of lime absorbable from a

[1] For a full discussion see *Trans. Internat. Soc. Soil Sci.*, 1926, **2**, A; the whole volume is devoted to this subject.

[2] For Danish experience see H. R. Christensen and S. T. Jensen, *Internat. Soc. Soil. Sci.*, 1926, A, 94-115; for Dutch experience, J. Hudig, *ibid.*, 116-125.

solution any simpler; the amount is not constant but varies with the conditions; single values have no definite significance, and for this also a curve is needed to express the results at all adequately.

For general agricultural and ecological purposes, however, it is convenient to have single values which allow rapid and easy comparisons between different soils. Three are in common use: the *p*H value; the lime requirement as ascertained by some accepted conventional method (in Britain by the Hutchinson-McLennan method); and the content of replaceable calcium as determined by the methods of Hissink, Gedroiz, Kelley, or others (in Britain that of Hissink). These values are all connected and usually vary in the same way for series of soils of similar character, but not soils differing in character. Table LII., showing some of G. W. Robinson's data for North Wales, is typical.[1]

Seven soils were studied; the lime requirement and *p*H values agree for five, but not for the remaining two. The

TABLE LII.—COMPARISON OF VALUES FOR LIME REQUIREMENT, *p*H, REPLACEABLE CALCIUM OXIDE ON SOILS OF VARYING DEGREES OF SOURNESS. G. W. ROBINSON AND RICE WILLIAMS (238).

Soil.	Response to Liming.	Lime requirement by Hutchinson and McLennan Method.	*p*H.	Percentage CaO Hissink Method.	Percentage CaO Soluble in N/25CO_2 Solution.[2]	Comber Test.
C 119 . .	+	0·43	5·2	0·057	0·028	red
C 134 . .	+	0·34	5·4	0·050	0·021	deep red
Bryn Odel .	+	0·20	6·0	0·165	0·013	red
Chwaen Goch	0	0·24	6·3	0·27	0·0325	red
Ab 16 .	0	0·20	6·4	0·215	0·029	red
Ab 1 . .	0	0·16	6·6	0·22	0·04	red
Wern, L. L.	0	0·40	6·7	0·43	0·031	deep red

[1] Examples showing relationship of lime requirement and *p*H values are given by E. M. Crowther (72) and H. J. Page and Williams (221), for Rothamsted and Woburn soils; E. A. Carlton, Quebec Soils, *Soil Sci.*, 1923, 16, 79; P. E. Karraker, *Soil Sci.*, 15, 473; A. M. Smith (*Journ. Agric. Sci.* 1925, 15, 466-475) found no relationship for Scottish soils.

[2] Fifty grains of soil shaken for sixteen hours with 500 c.c. of N/25 carbonic acid.

explanation lies in the fact that addition of lime to the soil does several things. In an acid, peat, or humus soil the chief need is to neutralise acidity, flocculation being less important. Humus is more sensitive than clay to changes in calcium content and more rapidly becomes neutral on the addition of successive doses of lime or, conversely, more readily develops acidity as the lime is washed out. It is enough, therefore, to add sufficient lime to make the soil neutral or as nearly neutral as the crops may require (p. 382). This is illustrated in some of Hissink's soils :—

*p*H values . . .	7·1	6·8	5·9	5·4	4·9	4·7	4·4
Replaceable CaO per 100 parts humus . .	5·0	4·5	3·3	2·4	2·5	2·1	1·5
Per cent. of humus in soil	35·3	22·5	20·4	7·8	41·9	46·5	52·7

When neutrality is reached the exchangeable lime is equal to 5 per cent. of the humus.

In a clay soil more is wanted from the lime. The extreme case is that of an acid clay containing no calcium carbonate and only small amounts of exchangeable calcium. The first successive additions of lime neutralise some of the acid, *i.e.* replace hydrogen ions by calcium. Neutrality is reached when the clay contains about 1·2 per cent. of replaceable calcium. There still remain, however, hydrogen and other ions which can be replaced by calcium so that absorption of calcium continues. During this stage, the clay, owing to its high content of sodium or other bases, may be deflocculated in spite of its neutrality. Some of Hissink's results afford illustrations :—

Physical State.	100 Parts of Replaceable Bases Contain.					
	Ca.	Mg.	Sum of Bi-valent.	K.	Na.	Sum of Univalent.
Good, normal clay	79·0	13·0	92·0	2·0	6·0	8·0
Fairly good . .	65·8	17·6	83·4	4·0	12·6	16·6
Bad . . .	42·1	25·0	67·1	6·5	26·4	32·9

Further additions of lime bring about more complete replacement and flocculation, while still further additions provide a reserve of calcium carbonate to ensure maintenance of the flocculated and neutral states.

An amount of lime ensuring neutrality may thus be more than enough on a humus soil but insufficient on a clay soil. On the other hand, absorption methods may indicate an unnecessarily high lime requirement, there being no point in replacing all the clay cations by calcium.

Hissink has introduced the useful idea of a ratio or " degree of saturation " [1] for the study of the clay problem. This ratio is :—

$$\frac{\text{quantity of bases actually held by the soil}}{\text{quantity of bases which the soil could hold}}.$$

No soil holds all, or nearly all, of the bases it might, usually not more than 53 to 56 per cent.; even when it is neutral and calcium carbonate is present some of the hydrogen ions remain.

Action of Water on the Soil.

Rain water dissolves out soluble substances from the soil, and certain important chemical and physical results follow :—

(1) The nitrates are rapidly lost, causing a temporary reduction in productiveness, seen particularly in early spring after a mild, wet winter (p. 180).

(2) The removal of certain ions, and especially of calcium, adversely affects the physical properties of the soil by deflocculating the clay and making it more sticky (p. 128).

(3) Of all bases calcium is the one most easily lost; this leads to an increased concentration of potassium, magnesium, iron, etc., relative to the remaining calcium (p. 411).

(4) The calcium carbonate goes first before the " replaceable " calcium or the " degree of saturation " is appreciably diminished. Longer exposure to rain causes a gradual loss of

[1] The same word as Ramann used (p. 215) but more clearly defined.

replaceable calcium and a lowering of the "degree of saturation"; presumably also an increase in the hydrogen ions associated with the clay.

This successive displacement of calcium in the first instance affects the physical properties. In contradistinction to humus soils change in reaction is not sharp and does not appear till a considerable quantity of base is removed [1] (Table LIII.); while the clay is neutral it may still be in a bad physical state.

TABLE LIII.—CHEMICAL CHANGES IN SOIL CAUSED BY SUCCESSIVE REMOVAL OF BASES (HISSINK).

Formation.	$CaCO_3$. Per Cent.	Degree of Saturation.	Exchangeable Lime per 100 parts of Clay.[2]	Total Quantity of Exchangeable Bases.[3]	*p*H.
Recent .	10·6	56·4	1·07	19·7	7·61
,, .	3·2	54·5	1·18	23·0	7·70
,, .	9·3	52·8	1·05	36·3	7·57
Older .	0·7	52·0	1·07	20·5	7·67
Very old .	Nil.	46·8	0·76	32·3	7·03
,, .	,,	44·7	0·83	33·0	6·25
,, .	,,	40·8	0·76	28·3	5·96
,, .	,,	38·8	0·73	27·1	5·89
,, .	,,	25·8	0·33	12·2	7·49

At a certain stage in the progression towards acidity aluminium and iron both become active and form part of the replaceable bases; how this happens is not clear.

(5) The clay gradually disappears under high rainfall, leaving fine silt as the chief fraction causing heaviness in the soil (p. 134).

River water has a different effect because it contains dissolved salts, usually sodium salts, which react with the clay

[1] J. Hendrick finds that large quantities of lime and other bases can be removed from the Craibstone soil without appreciably lowering the *p*H value (*p*H averages 5·9; lime requirement, 0·2 to 0·4 per cent. of calcium carbonate, average 0·25; replaceable lime, 0·2 per cent.).

[2] Calculated after assuming that the lime content of the humus at different *p*H values is as shown on p. 218.

[3] Mgm. equivalents in 100 grms. of dry soil.

producing a sodium clay and also sodium carbonate, both of which are unfavourable to plant growth.

These effects are cumulative, so that an increased water

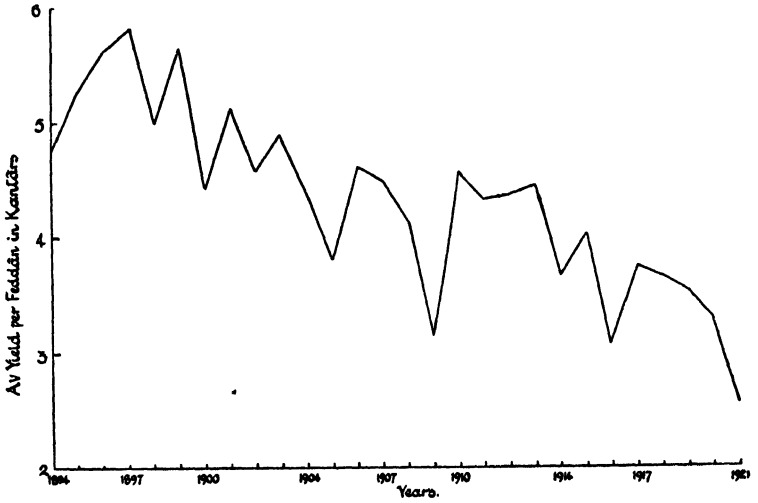


FIG. 24.—Yield of cotton, kantars per feddan, in Egypt in successive years after intensive irrigation began. (1 kantar = about 100 lb. lint; 1 feddan = 1·038 acres.)

supply beyond a certain point tends to progressive deterioration unless steps are taken to avoid it. Fig. 24 shows the falling yield of cotton on land in Egypt since it was brought under intensive irrigation.[1]

Prolonged Drying of Soil.

The soil colloids undergo some change on prolonged drying, resulting in a diminution of the clay properties and a marked increase in the amount of soluble matter and in productiveness. The soil of the Gezira (Sudan) is a very heavy clay which, in England, could not be cultivated, and yet in this hot, dry climate it falls down to a tilth resembling that of a light loam. Long storage of dry soils causes great increases in productiveness: Gedroiz's [2] experiments with oats grown in soils kept dry for a number of years are given in Table LIV.

[1] *First Annual Report Cotton Research Board*, Cairo, 1920; E. McKenzie Taylor and A. C. Burns, *Tech. Bull.*, 25, 1922, Egyptian Min. Agric.

[2] Gedroiz, *Bull. Internat. Instit. Agric.*, Rome, 1915, p. 37. For other results see Gustafson, *Soil Sci.*, 1922, 13, 173.

TABLE LIV.—EFFECT OF STORAGE IN A DRY STATE ON THE PRODUCTIVENESS OF SOILS. (OATS; GEDROIZ, 1908.)

Number of Years of Storage.	No Manure.	Complete Manure.	Without Nitrogen.	Without Phosphate.
0	10·3	83·5	13·5	11
1	17·8	83·9	32·3	19
3	24·6	90·9	23·6	35·4
5	25·0	102·8	32·2	42

The effect is not entirely physical, since important biological changes follow the resulting partial sterilisation. Prescott has taken account of these changes in his studies of the drying of Egyptian soils [1] and Lebjantzev, in studying Russian soils (see p. 342).

Soil Texture and Soil Tilth.

The components of the soil do not form a mere casual mixture; they are stuck together, almost brought into a loose combination, by the soil colloids, forming crumbs or compound particles which are far better suited to plant growth than a mixture of mineral fragments without colloids, such, for example, as a sand dune.

The ease of formation of these compound particles depends on the amount of colloid present. There is a continuous gradation from the blowing sands almost free from colloids and incapable of forming crumbs or compound particles, through the loams containing some 10 per cent. of colloidal material and readily forming good crumbs, to the heavy clays in which the colloidal properties are so pronounced that the soils are very sticky and impervious when wet, and, on drying, form hard clods or cakes through which young plants force their way only with difficulty.

The intensity of these properties depends, not only on

[1] The remarkable effect of drying ("Sharaqi") is described by Prescott (228*a*), and by V. Mosseri in *Int. Rome Bull.*, 1926.

the quantity, but also on the condition of the colloids; the flocculated condition is much more suited to the formation of the crumbs than the deflocculated condition (p. 127). Thus a soil may at one time be in a good crumbly state, very suitable for plant growth, and at another time be sticky, lumpy, and quite unsuitable for plants. The range within which its physical texture may alter is determined by the amount of colloids; it is almost nothing in a sand dune and very great in a clay soil. The fact of these variations puts out of the question any rigidly quantitative interpretation of mechanical analyses of soils. The properties of a soil are not the sums of the properties of the separate fractions; they are dependent also on the state of the colloid. The ultimate particles determine the limits within which the properties of the soil may vary, but the position of the soil within those limits at any time depends on the condition in which the colloids happen to be.

Agriculturists use the word "tilth" to denote the suitability of the soil texture to plant growth; a soil in the good crumbly state is described as being in good tilth while one that is sticky and lumpy is described as being in bad tilth. The art of cultivation consists in bringing soils into the best tilth of which they are capable, and it has been developed empirically to a high degree so that the skilled cultivator can often effect remarkable changes. The science of cultivation hardly exists, but a beginning has been made at Rothamsted and elsewhere in discovering the principles underlying these empirical methods. Broadly, they include the uniform mixing of the soil components, the conversion of deflocculated into flocculated colloids, and the maintenance of the flocculated state.

Four general methods are used by cultivators: (1) addition of lime or calcium carbonate; (2) addition of organic matter; (3) exposure of the soil to frost; also allowing it to dry and then become re-wetted; (4) mechanical movement of the soil, an operation requiring great skill because it has

to be properly combined with (3), and the appropriate operations done under the right weather conditions. Any other method of modifying the colloids might be expected to affect tilth and cultivation; both gypsum and alum have been used for this purpose.

These methods are fundamentally the same as the processes whereby good tilth arises naturally in uncultivated soils. Organic matter is added by the fall of leaves or the decay of roots. Earth-worms or other animals work the soil about, very gently, but almost continuously, making a complete mixture of the various constituents with the dead residues of plants.

Conversely, good tilth is destroyed and the compound particles are broken down by ploughing or digging the soil when wet; or allowing the stocks of organic matter or of calcium carbonate to fall too low; the soil then loses its fine crumbly state and becomes sticky when wet and lumpy when dry.

In the laboratory the compound particles can, to some extent, be formed by frequent freezing and thawing of the soil; they can be broken down by treating the soil successively with dilute acid to remove calcium carbonate, with hydrogen peroxide to oxidise the organic matter, and with an alkali, especially dilute ammonia, to deflocculate the clay (p. 461). Beyond this, however, very little is yet known about the compound particles, in spite of their great importance in soil fertility. The work on colloids, on flocculation, and on surface phenomena generally, will no doubt ultimately give the required information.

Until the nature of the compound particles is understood it is impossible to give a full definition of tilth, and what cannot be defined cannot be exactly measured. The force required to draw an implement through the soil is related to tilth, and it can be measured by the dynamometer, an elaborate spring balance inserted between the tractor and the implement, fitted with devices making a continuous record

of the pull exerted by the tractor: the so-called drawbar pull. From the records, contour lines of equal drawbar pulls or isodynes are mapped out and so the field is divided into areas of greater or less resistance to the passage of the implement (Fig. 25). On the Rothamsted fields these areas differ mainly in their content of clay, and there is a fairly close proportionality between clay content and drawbar pull. For one and the same soil the drawbar pull does not vary much with changes in water content within the limits between

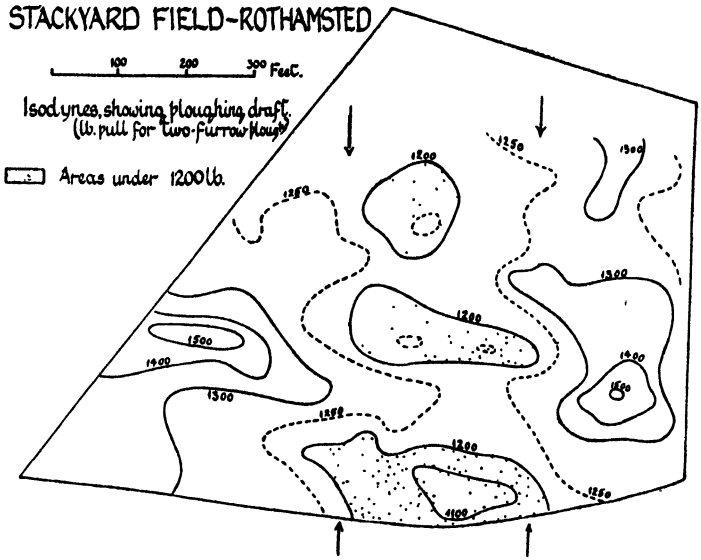


FIG. 25.—Isodynes showing also reduction effected by calcium carbonate applied to the strip between the arrows.

which a skilled cultivator will plough; the isodyne maps, therefore, do not differ greatly from year to year. The drawbar pull is permanently reduced by addition of calcium carbonate or of organic matter to the soil, but it is not much affected by the common artificial manures although these are electrolytes.

The values for drawbar pull promise to have considerable value in soil science. They afford a measure of tilth; they are of obvious importance to the implement maker; and they

give the best measure we have at present of the resistance of the soil to the movement of plant roots. They constitute an integration value for the clay properties; thus they are closely related to the rate of efflux of water from the drains laid 2 or 3 feet below the surface of the soil (Fig. 26). The relationship between these measurements and the vegetation characteristics is discussed on page 368.

W. B. Haines (118) has analysed the various factors concerned with drawbar pull; they are cohesion, plasticity, and

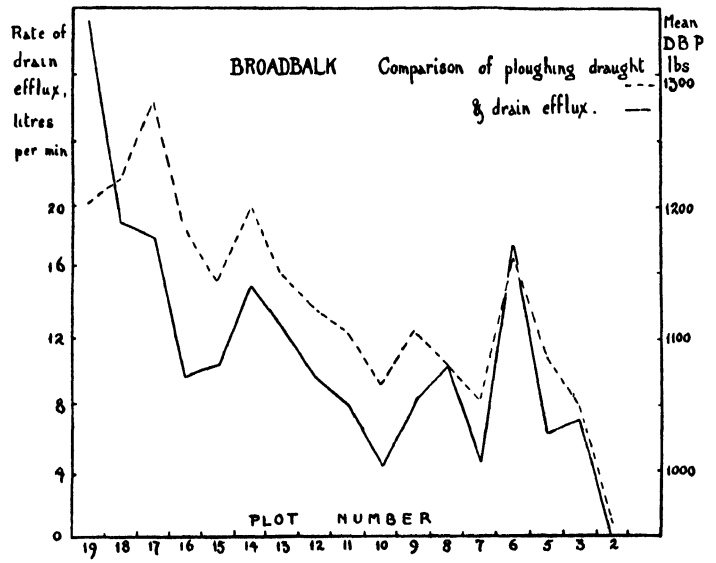


FIG. 26.—Rate of efflux of drains on plots on Broadbalk field (unbroken line) compared with drawbar pull (dotted line).

surface friction. These separate factors are profoundly affected by the water content of the soil, but in different ways; the cohesion decreases but the friction increases as the moisture content increases, so that within the limits where the soil is cultivated what is gained on one is lost on the other.[1] (Fig. 27).

The breaking down of the lumps of soil into fine crumbs is done by harrowing and rolling, but these operations are

[1] Beyond the cultivation limit the friction decreases with moisture.

strictly regulated by the moisture condition of the soil and not simply the moisture content. The skilled workman allows the soil to dry beyond the point when these operations are possible; then he waits for rain to re-wet the soil. Laboratory investigations show that the stability of a lump of soil depends, not only on its water content, but also in the direction in which the water is varying, *i.e.* whether the soil is becoming drier or wetter. The lump shrinks as it dries; at first by the exact volume of the water lost; afterwards by less than this volume. When the dry soil is re-wetted it expands [1]

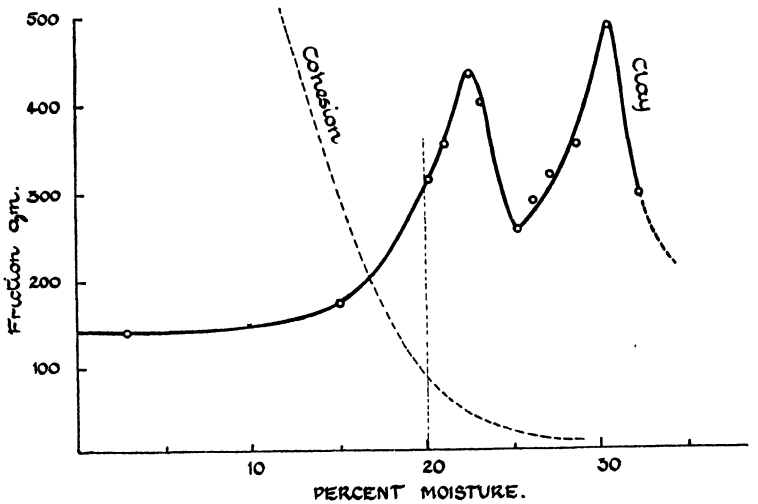


FIG. 27.—Relation between water content and (*a*) friction (unbroken line) and (*b*) cohesion (dotted line) of Rothamsted soil.

more than it shrank (Fig. 28). This phenomenon is common among colloids and is called hysteresis: it is explained by the fact that the original wet lump of soil contains no air in its innermost crevices, while the dry soil does contain air; on re-wetting, the imprisoned air helps to expand the lump. A soil containing a given amount of moisture may therefore occur in two states: the down grade when it is drying and the

[1] The expansion on wetting is confined to humus and clay soils; it does not take place in laterites where the colloids are mainly alumina and ferric oxide hydrogels. (F. Hardy, 123.)

up grade when it is becoming wetter; in the up grade it occupies a larger volume with a given moisture content than in the down grade because of the imprisoned air so that it is more unstable and easily shattered.

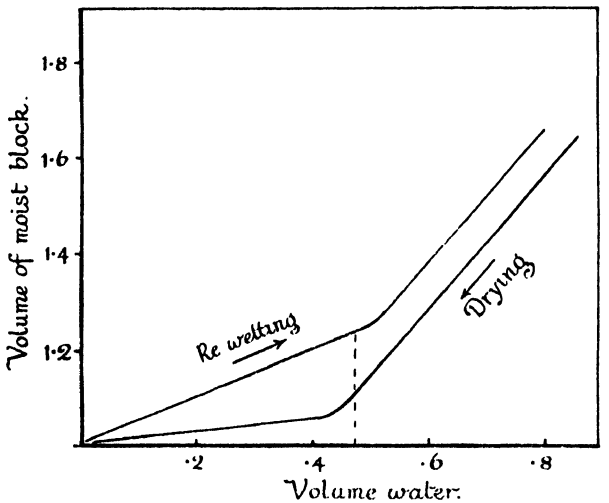


FIG. 28.—The volume of a given weight of moist soil depends not only on its water content but on whether it is drying down or being re-wetted.

The Constitution of the Soil.

The soil consists of mineral particles of varying shapes and sizes and of organic matter derived from plant residues. Part of its components are colloidal. In the preceding pages we have shown how many of the important soil properties are due to these colloids: the formation of the compound particles, the absorption of soluble manures, the retention of water (in part), the swelling of the soil when wet and its shrinkage when dry, are all colloidal phenomena. If we regard the mineral particles as the skeleton of the soil we must look upon the colloids as clothing it in many of its essential attributes. Dumont (89*a*), in 1909, put forward the view that the colloids form a coating round the mineral particles, and this is generally adopted [1] as being simple and

[1] See also P. Rohland, *Die Tone*, Vienna, 1910.

in accordance with the facts. The present view of the constitution of the soil is, then, that the mineral particles, though themselves hard and chemically inert, are coated with a gelatinous layer of chemically reactive material possessing colloidal properties, and partly organic and partly inorganic in composition; the organic matter includes the humus, and the inorganic includes the reactive alumino-silicic acids and their calcium and other compounds described in the last chapter. F. Hardy (123) argues that it is reticulate in structure. Both Comber (69*a*) and Haines (118) have shown how a colloidal coating alters the properties of mineral particles.

This system is moistened more or less continuously and the water dissolves all soluble substances present, making a solution the composition of which is determined largely by the amount of anions, especially of carbonate, nitrate, and sulphate: these are formed largely by micro-organisms, and they bring into the solution calcium, magnesium, potassium, and sodium. The properties of the solution are governed by the base exchanges and the colloidal properties of the solids.

Pan Formation.

A pan is a hard compact layer from 10 to 60 cms. in thickness which, under certain conditions, forms at a short distance —usually about 25 to 100 cms.—below the surface of the soil. Its effect is to separate the layers above it from the lower depths, and thus to impede the movement of water and therefore of air; the formation of the pan may lead to swamp conditions, and it is so detrimental to soil fertility that in agricultural practice it is always prevented as far as possible.

Pan formation seems to require three conditions: a sandy soil easily permeable to water and subject to sufficient rainfall; a low content of electrolytes and of exchangeable calcium; and a slow rate of decomposition of organic matter with resulting production of humic acids. It is invariably accompanied by a differentiation of the soil profile into three

or four layers; the top one is usually rich in organic matter and may be peaty; the second is white or light in colour, and may vary from 5 to 60 cms. in thickness; then comes the pan, darker in colour, ranging from yellow to black and 10 to 60 cms. thick, while lowest of all is the true sandy subsoil.[1]

The mineral particles of the bleached layer and the pan seem to be identical with those of the subsoil; the only difference is that those in the pan are cemented together to form a continuous layer.

Chemical analysis shows that the pan is richer in organic matter, iron, and aluminium oxides and other bases than either the bleached layer above or the subsoil below; the bleached layer is the poorest of all. It is inferred, therefore, and all available evidence supports the view, that these substances have been leached out from the upper layer and concentrated in the "pan" (see p. 440).

The leaching out of bases from acid soils exposed to sufficient rain is a general phenomenon not restricted to soils having a pan; it plays an important part in soil formation (p. 118).

The features that distinguish pan formation from normal soil formation are—

1. The leaching out of humus.

2. The precipitation of the various leached out substances in the narrow zone constituting the pan.

Various hypotheses have been put forward to explain these peculiarities.

The first, that of Mayer (194), extending the older work of Emeis,[2] assumed that the bases are washed out as humates. There was the difficulty, however, that iron exists in the soil as ferric oxide, and that ferric humate is insoluble in water.

[1] In German the pan is called "Ortstein" and the bleached sand "Bleisand," "Bleichsand," or occasionally "Grausand." When the formation, instead of being sand, is clay, the white soils are called "Molkenböden." Some of these are described in *Internat. Mitt. Bodenkunde*, 1914, 4, 105-137. See also (24).

[2] C. Emeis, *Waldbauliche Forschungen und Betrachtungen*, Berlin, 1875.

It was assumed, therefore, that humic acid reduced the iron and formed a soluble ferrous humate which then washed down and was deposited. In dry weather oxygen gained access to the deposit and stabilised it by converting it into insoluble ferric humate.

The explanation is unsatisfactory because, as Morison and Sothers (204) have shown, humic acid does not reduce ferric oxide in any conditions resembling those in the soil, though it rapidly reduces the chloride. Some reduction does seem to take place, however it may be brought about, because roots in acid, sandy soils are often surrounded by a bleached zone about an inch in width in which some of the iron has been changed to white ferrous carbonate. Once this salt is formed, it could, as Hall suggested, be leached out as it is somewhat soluble in carbonic acid. Other combinations of ferric oxide and organic compounds are soluble in water.

More recent investigators, Münst,[1] Ramann,[2] Morison and Sothers (203), and Hissink (135*b*), regard the process as one of dispersion rather than solution; no preliminary reduction of the iron need, therefore, be assumed. The humus, iron, aluminium, and other oxides are normally present in the soil as "gels," and remain in that form as long as sufficient electrolytes are present. But as these are washed out by the rain a critical concentration is reached when the "gels" change to "sols," and are readily dispersed in water and washed away: not in true solution, but in so finely divided a state that they readily pass through the soil. The phenomena are well established, and they satisfactorily explain the leaching out from the upper layer.

The precipitation lower down is less easily explained. The conditions necessary for precipitation are concentration of the sols beyond a certain point and presence of sufficient electrolytes. Once the process begins it might be expected to continue, since the clogging up of the soil with precipitated

[1] Münst, *Bied. Zentr. Agrik. Chem.*, 1912, 41, 3-10.
[2] Ramann, *Bodenkunde*, Berlin, 1911, p. 204.

gel would hold up the colloidal suspension in such a way as to make further precipitation almost inevitable.

The difficulty is to explain why the precipitation should begin in any particular part of the soil. The cause is something effective over a certain area, for a pan is more or less continuous, and is not infrequently approximately parallel to the surface of a fairly level soil. Mayer suggested that precipitation took place at the level of the water in the soil during winter—either of the free water or of the permanent moisture zone—where the downward flow of the leached out constituents would be checked. Ramann attributed it, not to checking of movement, but to presence of electrolytes; he supposed that it occurs in the zone intermediate between the surface soil and the subsoil, where weathering is still proceeding, and where, therefore, electrolytes are more abundant than in the layers above or below. There is the possibility of biological action, since ditches in soils liable to pan formation tend to accumulate deposits of ferric oxide formed by some of the iron oxidising micro-organisms.[1] The beginning of the process is still but little understood; measurements of contours of surface and of pan are highly desirable, along with attempts to discover why the deposition started.

The pan once formed would not necessarily remain permanent. It is, however, subjected to a certain amount of drying during the summer which so modifies the gel that it does not readily change back to the sol condition.

It is remarkable that pan formation is somewhat rare, seeing that two important parts of the process, the bringing into solution of the bases of the top layer of soil and the downward passage into the subsoil, are almost universal occurrences in the soil. Clearly the conditions causing even precipitation, whatever they may be, occur only rarely. Morison suggests that in normal soils there are oscillations of level of the soluble material unfavourable to uniform precipitation and

[1] See Harder (122).

tending to a much wider spread of the precipitate over the soil.

Calcareous pans are formed in dry regions, the cementing material being calcium carbonate instead of iron and aluminium oxides and organic matter. The soil solution penetrates only a certain distance into the soil and then evaporates, leaving its calcium carbonate.

A third type is more common and more readily explicable; it is found on clay arable soils that have been cultivated at uniform depths for many years with heavy implements. It is more correctly called a plough sole and it is formed by the heavy implement pressing the wet clay into a compact condition. In agricultural practice it is broken up by means of a subsoiler, and the operation much increases the productiveness of the land.[1]

[1] See *Journ. Min. Agric.*, 1923, **29**, 911-919.

CHAPTER V.

THE CARBON AND NITROGEN CYCLES IN THE SOIL.

THE organic matter added to the soil by plants rapidly undergoes changes. In presence of air, oxygen is slowly but continuously absorbed, and an almost equal volume of carbon dioxide is evolved, indicating that the main change is of the type :—

$$C_nH_{2m}O_m + nO_2 = nCO_2 + mH_2O$$

This absorption of oxygen was demonstrated by de Saussure about 1800, and proved by Schloesing to be due chiefly to the action of micro-organisms.[1] Wollny supported this view and showed that the evolution of carbon dioxide is much diminished by traces of antiseptics.

The actual amounts of oxygen absorbed and carbon dioxide evolved in field conditions have not been measured, but they can be estimated approximately from the Broadbalk data showing the losses of carbon from the soil. The soil receiving farmyard manure annually loses 3700 lb. of carbon per acre per annum, or 1·6 grams per kilo of soil, which corresponds to an absorption of 3 litres of oxygen per kilo of soil per annum, or 2 litres per square metre per day, without allowing for the stubble, which, however, is unlikely to increase the amount by more than about 20 per cent.

This value is probably above the normal for arable land, since annual dressings of farmyard manure are unusual. Other estimates by totally different methods have been made: one by Stoklasa and Ernest (271), another by Lars-Gunnar Romell

[1] *Leçons de Chimie Agricole*, 1883, p. 277 : " C'était là, pensait on alors, un fait purement chimique, c'est à dire que la combustion observée est le resultat de la vie de nombreux organisms, tel, par exemple, que le ferment nitrique, lequel est chargé de transporter l'oxygène sur l'azote."

(239), and a third by H. Lundegårdh (182*a*, p. 181). The results are :—

	CO_2 Evolved per sq. metre per day.	Oxygen Absorbed per sq. metre per day at 15° C.
	Grams.	Litres.
Broadbalk, dunged plot .	4·2 [1]	2
Stoklasa (Wheatfield) . .	7·5 [2]	4
Lars-Gunnar Romell (August)	13 to 20 [3]	7 to 10·5
Lundegårdh (August) . .	2·6 to 50	1·4 to 26

Of the various plant constituents the pentosans, sugars, and starches, are the first to break down and apparently their decomposition is complete on the lines of the equation set out above. The proteins also appear to break down completely, their carbon being oxidised to carbon dioxide, but an additional quantity of oxygen is required for the oxidation of the ammonia (p. 255). Two compounds may not be completely decomposed to CO_2 and water: cellulose, part of which, or an intermediate product, may undergo condensation, though not apparently oxidation, to form humus (it does in the laboratory, but has not been proved to do so in the soil), and lignin, which is oxidised to a somewhat different humus (p. 175). Thus, while most of the oxidations in the soil are of the type absorbing oxygen equal to the volume of CO_2 evolved, one, the oxidation of protein, absorbs more oxygen, and another, the oxidation of lignin, may absorb less, while the oxidation of cellulose is not sufficiently investigated.

The rate of oxygen absorption by a soil affords a convenient measure of the sum total of the oxidations occurring therein, and a less accurate measure of all the changes affecting the organic matter. Several of these contribute greatly to the fertility of the soil, particularly the conversion of the

[1] Annual evolution divided by 365. Stoklasa and Ernest assume only 200 "active" days: at which rate this value becomes 7·7, closely agreeing with theirs. But at Rothamsted there are more than 200 active days.

[2] Their total evolution is 13·5, but of this 6 is assumed to come from the roots of the wheat, leaving 7·5 to come from the soil.

[3] Forest soils: tree roots included. Summer values only.

useless structure material of the plant residues into valuable humus, the formation of nitrate, and the fixation of nitrogen. There is, therefore, a relationship between oxidation and fertility, and in a series of soils of similar physical and chemical composition, the rates of oxidation vary in the same way as the productiveness, being highest in the most fertile and lowest in the least fertile (Table LV.).

TABLE LV.—RATES OF OXIDATION, ORDER OF PRODUCTIVENESS, AND ANALYTICAL DATA FOR CERTAIN WOBURN SOILS. RUSSELL (240a).

Name of Field.	Agricultural History.	Order of Productiveness.	Oxygen Absorbed in 17 days (mm.).	Analytical Data.			
				Nitrogen.	Carbon.	Loss on Ignition.	Calcium Carbonate.
Stiff Oxford clay	Wheat stubble	1	23·2	·252	2·53	8·73	·021
Road Piece	Wheat stubble preceded by mangolds fed on the land . . .	2	18·7	·172	1·76	5·31	·072
Lansome field	Barley following mustard ploughed in; mineral manure . . .	3	14·1	·122	1·19	4·17	·027
Lansome field	Barley following tares ploughed in; mineral manure . . .	4	10·2	·132	1·24	3·22	·051
Lansome field	Barley following tares ploughed in; no mineral manure . . .	5	8·2	·109	1·18	3·46	·008
Stackyard field	Wheat unmanured . . .	6	8·2	·060	1·39	4·07	·004
Stackyard field	Wheat, ammonium salts only .	7	7·8	·102	1·29	4·58	nil

The oxidation proceeds with evolution of energy. It is the complete reversal of the process whereby plants build up their complex constituents by means of energy fixed from sunlight by their chlorophyl apparatus; carbon dioxide and water, the original starting points, are reformed, and the stored-up energy is liberated. In part the oxidation is brought about by micro-organisms, and it furnishes them with food and energy. Differences might be expected according as it can proceed quickly or slowly; *i.e.* as the oxidation potential is high or low,[1] but these have not been adequately explored. Rapidly, easily effected oxidations, such as those of protein,

[1] Gillespie, *Soil Sci.*, 1920, 9, 199.

pentosans, sugars, and starch are accompanied by rapid multiplication of micro-organisms that require considerable quantities of ammonia and nitrate for their nutrition; non-nitrogenous compounds may thus bring about the depletion of the soil of nitrate and adversely affect plant growth (p. 287). There is some indication worth pursuing that slow oxidation may be favourable to nitrogen fixation in the soil (p. 273). The numbers of the soil population are limited by the energy supply as also are certain of their activities, notably the fixation of nitrogen by Azotobacter and Clostridium, and the assimilation of carbon dioxide by the nitrifying organisms; for the former action the energy is derived from oxidation of carbon compounds, and for the latter from the oxidation of ammonia. These energy relationships will be dealt with more fully under the separate headings.

The Decomposition of the Non-Nitrogenous Compounds in Soil. Production of Humus.

The Simpler Carbohydrates: Sugars and Starches.—Among the first of the plant constituents to be decomposed in the soil are the sugars, starches, and pentosans. Under normal aerobic conditions these substances can be attacked by a large number of organisms, and either assimilated or fermented, but in either case ultimately broken down to CO_2 and water according to the general reaction on page 234; aliphatic acids may be formed as intermediate products, but they react with calcium carbonate forming calcium salts, which are re-converted by micro-organisms into calcium carbonate.[1] Sugars and starch, however, occur only to a small extent in plant residues, and their oxidation is but a minor part of the soil processes. The pentosans occur in greater amount; little is known of their decomposition, but an organism has been isolated that is capable of oxidising xylose, a pentose sugar closely associated with them.[2]

[1] See A. D. Hall and Miller (*120b*).

[2] E. B. Fred, W. H. Peterson, and S. Davenport, *Journ. Biol. Chem.*, 1919, 39, 347.

More Complex Compounds: Cellulose and Lignin.—These two substances form the major part of the organic matter added to the soil and their decomposition is the chief reaction taking place therein. The decomposition differs in two important respects from that of the starches, sugars, and pentosans. It is effected only by a limited number of organisms and it may, and in soil usually does, have a well-marked stage, the production of humus. As already pointed out (p. 175), lignin and cellulose give different humic products, the colloidal properties of which, however (and it is these which are of importance in the soil), appear to be identical. The lignin humus seems to predominate in the soil according to the usual chemical tests, but considerable quantities of cellulose humus may also be present, though this is not definitely proved.

The humus is not a permanent soil constituent, but continuously decomposes; with the shifting conditions it may accumulate at one time and disappear at another. It accumulates whenever, for any reason, the decomposition processes are slowed down, and it disappears whenever they are hastened.[1] Breaking up of virgin land or grass land for cultivation is followed by a great reduction in amount of humus, the result, no doubt, of greater aeration. Laying down of arable land to grass or slowing down of decomposition, however caused, increases the amount of humus.

Cellulose.—Hitherto the biological work has been entirely confined to cellulose, the decomposition of lignin not having been studied in spite of its great interest. The cellulose used in some investigations has been filter paper, in others sulphite pulp, and in others again straw.

[1] It is sometimes assumed that peat is formed only at rather low temperatures. This is not true; the essential conditions for formation is the absence of one or more factors necessary to the decomposition of plant residues. Absence of air, presence of acidity, or lack of nutrients for the organisms may all reduce the rate of decomposition and thus lead to accumulation of peat even in good temperature conditions. Tropical peats have been described in Sumatra, Ceylon, and Tanganyika. For a summary of the descriptions see F. E. Weiss, *Journ. Ecology*, 1925, **13**, p. 311.

It decomposes in two distinct ways, according as air is or is not present.

Anaerobic Decomposition.—This occurs naturally in swamps, marshes, etc., and is characterised by the production of methane, which thus derived its old name marsh gas. It was first systematically investigated by Déhérain in 1884,[1] and shown to be brought about by bacteria which, however, are dependent on the presence of nitrogen compounds. It can proceed in either of two ways, giving respectively marsh gas and hydrogen: the latter, however, being always associated with the formation of butyric acid. He suggested that there were two distinct micro-organisms, one producing marsh gas and the other hydrogen, or alternatively, one organism capable of producing either gas as the conditions varied. Eleven years later, when bacteriology had advanced considerably, Omeliansky was able to show that there are, in fact, two separate organisms. Both organisms require the same general conditions of air exclusion, ample supply of water and nitrogen compounds. They differ in their reaction requirements; the hydrogen organism requires an acid and the marsh gas organism a neutral medium. The fermentation can therefore be changed over to either direction by controlling the acidity.

In neutral conditions considerable quantities of gas are obtained by fermentation of straw or other plant tissues. E. H. Richards and R. L. Amoore have obtained at Rothamsted quantities of gas corresponding to 10,000 cubic feet per ton of vegetable material (Nile Sudd was used); the gas contained 38 per cent. CO_2, 56 per cent. methane, and 6 per cent. other combustible gas, mainly hydrogen, representing about one-third of the energy (calorific power) of the fermented material. In acid conditions evolution of gas is much slower, but it contains up to 55 per cent. hydrogen, the rest being chiefly carbon dioxide.

[1] *Annales Agronomiques*, 1884, 10, 385; see also 1888, [14, 97, where he discusses the decompositions in a manure heap.

Aerobic Decomposition.—Under aerobic conditions cellulose may be decomposed both by fungi and bacteria. Van Iterson, in 1904,[1] made the first investigations, and since then a number of bacteria have been picked out which are said to possess this power.[2] Many of them act only slowly, but a few are known which can rapidly break down considerable quantities of cellulose under favourable conditions. The first to be studied in detail was *Spirochæta cytophaga* (Hutchinson and Clayton, 140*f*). This organism is distributed in soils; it is aerobic and very selective in its action, cellulose being the only compound on which it will grow: it is indeed inhibited by many carbohydrates, especially those containing reducing groups. Its nitrogen requirements are met by simple compounds, such as ammonium salts, nitrates, amino-acids, but not by higher compounds, such as peptone (except in weak solution), gelatine, etc. The products of decomposition of cellulose include small quantities of volatile acids; mucilage soluble in ammonia but insoluble in acids, and yielding no optically active compounds on hydrolysis; and a pigment apparently related to the carotin group: there is no obvious gas in the cultures. Like many other soil organisms, it passes through a life cycle, the stages of which show considerable morphological differences.

A second organism possessing remarkable powers of decomposing cellulose aerobically is *Microspira agar-liquefaciens*, described by P. H. H. Gray and C. H. Chalmers (113). It differs from the spirochæte, both morphologically and in the important property of being more tolerant of other carbohydrates, its power of destroying cellulose being, indeed, enhanced by small quantities of dextrin, xylose, arabinose, and certain other sugars, and also of lignin; unlike most other organisms, it liquefies agar. It resembles *Spirochæta*

[1] *Centr. Bakt. Par.*, 1904, 11, 689-698.

[2] See, for example, Kellerman and McBeth, *ibid.*, 1912, ii., 34, 485-494; I. G. McBeth, *Soil Sci.*, 1916, i., 437-487; and McBeth and F. M. Scales, *U.S. Bur. Plant Ind. Bull.*, 266, 1913.

cytophaga in utilising ammonia and nitrate as nitrogenous nutrients.

Among other organisms studied,[1] the *Clostridium thermocellum* of Viljoen, Fred, and Peterson,[2] like some of the fungi effecting cellulose decomposition, shows remarkable tolerance of high temperatures. Its range of fermentation is from 43° C. to 65° C.; it continues to live at 72° C., though it no longer decomposes cellulose at that temperature. Since it ceases to act below 40° C. it is not likely to be important in the soil, though it may operate in manure heaps, the temperatures of which are not infrequently sustained about 50 or 60° C., and may rise to 70° C.

None of these organisms produces humus from cellulose in artificial media, though whether either *Spirochæta cytophaga* or *Microspira agar-liquefaciens* do so in the soil is unknown.

The commonest cellulose decomposers under aerobic conditions are the actinomyces and the fungi, and it is generally assumed as the result of Waksman's work (289) that these are more active in the soil than the bacteria, and further that they produce humus. The first investigations were again by Van Iterson and McBeth, but the subject deserves re-examination, in view of the possibility, suggested by some of the more recent work, that cellulose may not be the source of humus in the soil, but may completely disappear, all its carbon being changed into carbon dioxide in accordance with the equation given on page 234.[3]

Rege has isolated and studied certain thermophilic species of Coprinus, Aspergillus, and Acremoniella, which decompose cellulose at high temperatures, and apparently play an important part in manure heaps. It is not certain how far they are likely to act in soils.

[1] A descriptive list is given by K. F. Kellerman, I. G. McBeth, F. M. Scales, and N. R. Smith, in *Centr. Bakt. Par.*, 1914, **39**, 502-523. It is not clear that all these organisms are true cellulose dissolvers. See also McBeth, *Soil Sci.*, 1916, **1**, 437-481.

[2] *Journ. Agric. Sci.*, 1926, **16**, 1-17.

[3] H. Heukelekian and S. A. Waksman, *Journ. Biol. Chem.*, 1925, **66**, 323.

E. H. Richards and his colleagues at Rothamsted [1] have emphasised the close relationship between supply of nitrogen and amount of decomposition of the cellulose material. Some 0·7 parts of nitrogen are assimilated by the micro-organisms for every 100 parts of straw decomposed, and if less is supplied decomposition is proportionately restricted. They have based on this relationship an ingenious method for making a humus manure direct from straw by micro-organic activity: it closely resembles farmyard manure.

Some of the protozoa may take part in the decomposition of cellulose or of lignin. L. R. Cleveland [2] maintains that termites depend for the digestion of their food—woody tissue—on the protozoa present in their intestines and they are unable to feed after they are freed from protozoa by partial sterilisation.

It also seems possible that some of the cellulose may change to humus by purely chemical processes without the intervention of micro-organisms.[3]

Benzene Ring Compounds.

Lignin.—It has already been shown that lignin is, in all probability, the source of much of the humus of the soil (p. 175), and while something is known of the chemical changes involved, nothing is known of the means by which they are effected. H. Pringsheim and W. Fuchs [4] have discussed the possibility of bacterial action, and [illegible] under investigation in the Rothamsted labor[illegible]

Aromatic Plant Constituents and Decompos[illegible]
Certain plant constituents and some of th[illegible] products of proteins are poisonous to plants [illegible]

[1] See E. H. Richards and H. B Hutchinson, *Journ. A.* 398-411.

[2] *Biolog. Bull.*, 1924, 46, 177-225; *Physiological and Symbiotic Relations between the Intestinal Protozoa of Termites and Their Host.*

[3] A. C. Thaysen, W. E. Baker, and H. J. Bunker, *Biochem. Journ.*, 1926, 20, 210-216.

[4] *Ber. Deutsch. Gesell.*, 1923, 56, 2095.

serious injury if they should accumulate in the soil.[1] Fortunately they do not; those capable of oxidation with evolution of energy are decomposed by micro-organisms. The commonest occurring in nature are the phenols and their derivatives, and certain aromatic aldehydes, vanillin, etc. Fowler, Ardern, and Lockett [2] were the first to show that phenol could be decomposed by bacteria and to isolate and describe the organisms. In the course of an investigation on sewage they had observed a disappearance of phenol from effluents in circumstances strongly suggesting biological activity. R. Wagner [3] found many organisms in soil capable of oxidising and utilising as sources of energy phenol, benzene, toluene, xylene, catechol, phloroglucinol, and similar compounds: this has been confirmed by various workers at Rothamsted. Owing to its technical importance (p. 399), the decomposition of phenol has been studied in detail by N. N. Sen Gupta (259). The action is complex, including a chemical change brought about apparently by the manganese dioxide in the soil and an oxidation effected by bacteria. H. G. Thornton and P. H. H. Gray found several kinds of bacteria in English soils that can oxidise phenol, some of them showing remarkably interesting properties; they occur but rarely, however, in unmanured land.

The oxidation of vanillin by bacteria in the soil is of some interest as this substance occurs in certain plant residues and would be toxic if it accumulated.[4] Numerous aromatic compounds were found by Mrs. A. Matthews to cause great increases in bacterial numbers in the soil [5] and presumably, therefore, served as food or energy material.

[1] Thus Liechti and Mooser (*Landw. Jahrb. Schweiz.*, 1906, 1) estimate that from 34 to 83 kilos per hectare (= 30 to 74 lb. per acre) of phenol are added to the land with an ordinary dressing of liquid manure. These figures are far higher than we can obtain at Rothamsted.

[2] *Proc. Roy. Soc.*, 1911, **83**, 149-156.

[3] *Zeit. f. Gärungsphysiol*, 1914, **4**, Heft. 4.

[4] See W. J. Robbins and E Lathrop, *Soil Sci.*, 1919, **7**, 475; W. J. Robbins and A. B. Massey, *ibid.*, 1920, **10**, 237; and M. J. Funchess, *Ala. Expt. Sta. Bulls.*, 195 and 196, 1917.

[5] *Journ. Agric. Sci.*, 1924, **14**, 1-57. See also W. Buddin (60).

The Decomposition of the Nitrogen Compounds.

The decomposition of the nitrogen compounds in soil has been studied mainly by determining the changes in the total quantity of nitrogen and of nitrate. Four cases have been investigated.

1. The simplest is that of an ordinary arable loam kept moist, aerated, and at 10° to 15° C.—these being normal conditions—free from vegetation and from the washing action of rain—this being an abnormal condition. A considerable formation of nitrate then takes place, about 3 per cent. per annum of the nitrogen being converted, and generally there is a small loss of nitrogen, presumably in the free state. How far the accumulation of nitrate would go under these circumstances has never been ascertained, because the experiment is necessarily very slow. Boussingault (48) stated that in eleven years one-third of the nitrogen of a rich soil changed to nitrate, and about one-half of the carbon to carbon dioxide.

2. If the conditions are made more normal by exposing the soil (still kept free from vegetation) out-of-doors to the action of rain and weather generally, the nitrates do not accumulate but wash out, and can be detected in the drainage water. The soil thus loses nitrogen compounds, and in course of time the loss becomes very considerable. At Rothamsted a little plot of arable land $\frac{1}{1000}$ acre in extent has been kept free from vegetation by hoeing, but not otherwise disturbed, since 1870; it has now lost one-third of its original stock of nitrogen. The plot has been converted into a lysimeter by isolating it from the surrounding ground by cement partitions and then underdraining: the drainage water is all collected and analysed. At the end of forty-seven years the amounts of nitrogen found as nitrate in the drainage waters were added up and found approximately to equal the total loss of nitrogen from the soil (Table LVI.). The experiment is not fine enough to justify any discussion of the small balance, but it shows that the loss of nitrogen is *mainly* due to leaching out of nitrates.

The obvious uncertainty attaching to so prolonged an experiment is reduced in this case by the fact that the determinations were for the last twenty-eight years of the period made by the same analyst. Miller found that the rate of loss of nitrogen (estimated by the quantities of nitrates in the drainage water) was about 40 lb. per annum in the earlier years, and fell below 30 lb. and finally below 25 lb. per annum in the later years.

TABLE LVI.—CHANGES IN NITROGEN CONTENT OF A SOIL KEPT FREE FROM VEGETATION FOR FORTY-SEVEN YEARS, BUT EXPOSED TO RAIN AND WEATHER. MILLER (199*b*), RUSSELL AND RICHARDS (241*h*).

Per Cent. of Nitrogen in Soil, top 9 inches.		Lb. of Nitrogen per Acre, top 9 inches.			Nitrogen Recovered as Nitrate, 1870-1917.
In 1870.	In 1917.	In 1870.	In 1917.	Loss in 35 Years.	Lb. per Acre.
·146	·099 ·097	3500	2376 2328	1124 1172	1247 [1] 1200

It is unfortunate that this highly important experiment has not been repeated with other types of soil, because there is evidence that a richer soil would lose *more* nitrogen than is accounted for by the nitrates formed, the rest presumably escaping as gas.

Consideration of the curves for the rate of washing out of nitrate led Russell and Richards (241*h*) to suppose that there must be a nitrate immobiliser, probably certain organisms, functioning in soils even when uncropped, taking up a part of the nitrate formed and only slowly liberating it.

3. When the conditions are made wholly normal by allowing vegetation to grow, some of the nitrate is taken up by the plant and only a part is washed away, the division depending on the favourableness of the conditions for plant growth. The absorption of nitrate by the plant is much greater, and the amount of nitrate in the drainage water is therefore much

[1] After deduction of the amount brought down in the rain. The upper line of figures refers to the 20 inch and the lower to the 60 inch gauge. Some nitrate is no doubt contributed by the sub-soil.

less, on the Rothamsted wheat plots where ample supplies of potassium salts and phosphates are present, than on the plots where these nutrients are less abundant and the crops smaller (Table LVII.) :—

TABLE LVII.—EFFECT OF PHOSPHATES AND POTASSIUM SALTS ON THE UTILISATION OF NITRATES BY PLANTS.

Treatment.	Crop Yield per Acre per Annum.		Nitrogen, Recovered in Crop, lb. per Annum.	Nitrogen Present as Nitrate in Drainage Water during Autumn, Parts per Million.	Per Cent. of N in Soil.	N lost from Soil, lb. per Annum.
	Grain, Bushels.	Straw, Cwts.				
Ammonium salts containing 86 lb. N + No P or K salts .	16·0	14·75	33·5	17·8	·106	67·5
Abundant supplies of P and K salts .	26·7	30·75	45	8·5	·116	51

4. There is no reason to suppose that the amount of nitrogen in an uncultivated soil alters appreciably from year to year so long as the land is untouched. But directly ploughing and cultivation operations begin great losses of nitrogen set in, as shown by Shutt's analyses of the Indian Head soil, Saskatchewan (Table LVIII.). In this particular case there is practically no drainage water, and therefore little or no washing away of nitrates, yet only one-third of the lost nitrogen is recovered in the crop. Snyder (*267b*) has given similar results for Minnesota soils, and Swanson for Kansas soils.[1]

TABLE LVIII.—LOSSES OF NITROGEN CONSEQUENT ON BREAKING UP OF PRAIRIE LAND, TOP 8 INCHES. SHUTT (265).

	Per Cent.	Lb. per Acre.
Nitrogen present in unbroken prairie . .	·371	6940
,, ,, after 22 years' cultivation .	·254	4750
Loss from soil		2190
Recovered in crop		700
Deficit, being dead loss		1490
Annual dead loss		68

[1] Kansas *Bulls.*, 199, 1914; 220, 1918. See also *Journ. Ind. Eng. Chem.*, 1915, 7, 529. Summaries of other results are given by A. W. Blair and H. C. McLean, *Soil Sci.*, 1917, 4, 283-293.

The exhaustion of the soil is due, therefore, not to the removal of the crop, but to the cultivation.

Similar losses take place when heavy dressings of farmyard manure are repeatedly applied to land. One of the Broadbalk wheat plots receives annually 14 tons of farmyard manure per acre, containing 200 lb. of nitrogen. Only little drainage can be detected though considerable leaching out of nitrates may occur, but the loss of nitrogen is enormous, amounting to nearly 70 per cent. of the added quantity. Alongside is a plot receiving no farmyard manure, from which, in spite of drainage, there is no apparent loss (Table LIX.) :—

TABLE LIX.—LOSSES OF NITROGEN FROM CULTIVATED SOILS, BROADBALK WHEAT FIELD, ROTHAMSTED, FORTY-NINE YEARS, 1865-1914.

	Rich Soil, Plot 2, lb. per Acre.	Poor Soil, Plot 3, lb. per Acre.
Nitrogen in soil in 1865 .	·175 per cent. = 4,340	·105 per cent. = 2,720
Nitrogen added in manure, rain (5 lb. per annum) and seed (2 lb. per annum) . . .	10,140	340
Nitrogen expected in 1914 .	14,480	3,060
Nitrogen found in 1914 . .	·259 per cent. = 5,950	·095 per cent. = 2,590
Loss from soil . .	8,530	470
Nitrogen accounted for in crops	2,500	750
Balance, being dead loss .	6,030	−280[1]
Annual dead loss . .	123	−6[1]

Experiments of this kind have led to the conclusion that some gaseous product is formed in addition to nitrates, and, as no sufficient amount of ammonia can be detected, it is supposed that gaseous nitrogen is given off. The conditions for this decomposition appear to be copious aeration, such as is produced by cultivation, and the presence of large quantities of easily decomposable organic matter. Now these are precisely the conditions of intense farming in old countries and of pioneer farming in new lands, and the result is that the reserves of soil and manurial nitrogen are everywhere being depleted at an appalling rate.

[1] Gains.

It is evident that there must be some recuperative agency or the stock of soil nitrogen, which is never very great, would long ago have disappeared in old countries. Experiment has shown that soil *gains* nitrogen and organic matter when it is allowed to remain undisturbed and covered with unharvested vegetation as in natural conditions. On the Broadbalk field a third plot adjacent to the two already mentioned was, in 1882, allowed to go out of cultivation and has not been touched since; it soon covered itself with vegetation, the leaves and stems of which enriched it in organic matter. The gain in nitrogen is very marked, as shown in Table LX. The gain is much influenced by the amount of calcium carbonate in the soil, and is considerably less on another plot in Geescroft field, where only little calcium carbonate is present;

TABLE LX.—GAINS IN NITROGEN IN SOILS PERMANENTLY COVERED WITH VEGETATION—ROTHAMSTED SOILS LEFT TO RUN WILD FOR 22-24 YEARS. HALL (120e).

	Broadbalk: $CaCO_3$, 3·32 per Cent.				Geescroft: $CaCO_3$, 0·16 per Cent.			
	Carbon, per Cent.		Nitrogen, per Cent.		Carbon, per Cent.		Nitrogen, per Cent.	
	1881.	1904.	1881.	1904.	1883.	1904.	1883.	1904.
1st 9 inches	1·14	1·23	·108	·145	1·11	1·49	·108	·131
2nd 9 inches	·62	·70	·070	·095	·60	·63	·074	·083
3rd 9 inches	·46	·55	·058	·084	·45	·44	·060	·065
Approximate gain in nitrogen, lb. per acre				2200				1400
Lb. per acre per annum				91·7				60

LAND LAID DOWN TO GRASS IN 1856 AND MOWN ANNUALLY (DR. GILBERT'S MEADOW, ROTHAMSTED).

	1856.	1879.	1888.	1912.
Per cent. of N in top 9 inches	[·152][1]	·205	·235	·338

whether this is due to any specific action, or to the changed physical conditions brought out by decalcifying a soil, is not clear. Gains of nitrogen also take place on land covered with

[1] Estimated.

perennial grasses and clovers even when the crop is mown or grazed. On clay pastures dressings of basic slag, by improving the growth of herbage, have been found to increase the nitrogen content of the soil, whilst potassium salts, such as kainit, have had the same effect on sandy soil.

This effect of wild vegetation, sown grasses and clovers, in increasing the organic matter and nitrogen content of the soil has long been known to soil cultivators. The old method of replenishing soil fertility was to alternate the periods of arable cultivation with a year's " rest " when the plant was left to cover itself with wild or self-sown plants which were then ploughed under; this so-called fallow was prescribed one year in seven in the Mosaic law [1] and one year in three in mediæval England.[2] One of the greatest improvements in agriculture was the substitution of a definite sown crop of selected grasses and clovers for the indefinite mixture of self-sown plants of the mediæval fallow. In the Norfolk rotation introduced in the eighteenth century one year in four was given up to clover. In more recent rotations the clover or " seeds " mixture is sometimes left for two or three years before it is ploughed up, so that the enrichment may become more marked.

In humid climates the gains in nitrogen are greatest where leguminous plants are most abundant, and the increase after a clover crop is so marked that it can be measured after one year only (p. 283). Mr. Mason, at Eynsham Hall,[3] considerably enriched in nitrogen some poor Oxford clay by the growth of lucerne. The added nitrogen compounds are readily attacked by soil bacteria and converted into nitrates, so that the fertility of the land increases. Theophrastus [4] (about 300 B.C.) and Virgil [5] (about 40 B.C.) both record the excellent

[1] *Leviticus*, xxv. 1-7.

[2] T. Tusser, *Five Hundreth* (*sic*) *Points of Good Husbandry*, 1573.

[3] A. D. Hall, *Journ. Roy. Agric. Soc.*, 1904, lxv., 106-124. For a reclamation of sand see Schultz-Lupitz (255).

[4] *Enquiry Into Plants*, Bk. VIII., 2; and Bk. IX., 1; trs. Arthur Hort, Loeb's Classical Library.

[5] *Georgics*, Bk. I., line 73, *et seq.*

results obtained by growing vetches as preparation for wheat, while the advantage of clover has been known all through the ages.

The residues of non-leguminous plants when brought into the soil by natural agencies or by ploughing also add to the supplies of nitrogen and of organic matter. The extent of the action depends very much on the conditions (p. 287).

It is impossible in natural field conditions to discriminate between the two actions as leguminous plants are usually present, but the distinction has been made under carefully controlled conditions and will be fully discussed later on (pp. 267 *et seq.*).

The accumulation of nitrogen thus brought about does not go on indefinitely; in course of time a point of equilibrium is reached, higher or lower according to the soil conditions, where further gains are balanced by losses, so that the nitrogen content remains constant.

Thus there is an upper as well as a lower limit to the nitrogen content of the soil, the actual values depending on the soil conditions. Between these limits the nitrogen content may be maintained at any desired level, high when the ground is left in grass and leguminous crops, low when the ground is continuously cultivated. Unfortunately, on our present knowledge it is impossible to maintain a high content of nitrogen on cultivated land except at a wasteful expenditure of nitrogenous manure.

Some of these limits are :—

	Black Organic Soils (containing more than 10 per Cent. of Organic Matter).	Chalk Soils.[1]	Loams.[1]	Sands.[1]
Upper limit . .	1	·42	·25	·20
Lower limit . .	·25	·13	·09	·03

But the nitrogen cannot be increased by itself alone; increases are possible only when the carbon is increased; and the gain

[1] Containing less than 10 per cent. of organic matter.

in nitrogen is only about one-tenth that of the carbon. Purely nitrogenous fertilisers, such as nitrate of soda, sulphate of ammonia, dried blood, etc., add no nitrogen to the soil beyond what corresponds with any carbon added by the stubble. On the Broadbalk plots to which sulphate of ammonia has been given annually since 1844 and nitrate of soda since 1852 the percentages of nitrogen and of carbon were, in 1914 :—

		As Sulphate of Ammonia.			As Nitrate of Soda.	
Nitrogen added, lb. per acre .	None	43	86	129	43	86
Nitrogen in soil, per cent. . .	0·104	0·111	0·119	0·129	0·116	0·115
Carbon in soil, per cent. . .	1·15	1·14	1·41	1·35	1·52	1·73

J. G. Lipman and A. W. Blair (172) record losses of nitrogen from cropped soils in spite of added nitrogenous fertilisers.

The foregoing discussion applies only to soils in humid climates. In arid conditions different relationships appear. Cultivation is followed by no loss of nitrogen; indeed, many instances occur where cultivated land is richer in nitrogen than the original virgin land. Moreover, lucerne is singularly ineffective in raising the nitrogen content of the soil, while wheat stubble appreciably raises it. Some of the results are given in Table LXI.

This curious reversal of effects when compared with humid regions is probably not due to any new factors but to differences in relative importance of factors present in both conditions (p. 336).

Under hot, dry conditions the accumulative processes almost cease to function, and soils become very poor in nitrogen. The Gezira soil of the Sudan, a heavy clay, contains only 0·015 per cent.[1]

The reactions involved in all these changes are obviously complex, but they have been partially disentangled, and we can now pass on to a more detailed consideration of the separate changes.

[1] A. F. Joseph, *Khartoum Repts., Chem. Pub.*, No. 22, 1921.

TABLE LXI.—PERCENTAGE OF NITROGEN IN SOILS IN ARID REGIONS.

	E. Oregon. Bradley.[1]			Cache Valley, Utah. Stewart.[2]
	(*a*)	(*b*)	(*c*)	
Virgin soil .	0·114	0·101	0·098	0·198
Cultivated land	0·107	0·102	0·102	0·203
Land mainly under wheat,	—	—	—	0·206
Lucerne .	—	—	—	0·201

The Formation of Ammonia.

Ammonia is in all probability an intermediate product in the formation of nitrates. It is formed in the soil from the proteins of plant residues or manures, and the process is effected mainly by micro-organisms, but not entirely, for it still continues at a diminished rate in presence of antiseptics. The reaction has not yet been completely elucidated.

There is evidence of the production of amino acids which subsequently hydrolyse, or oxidise.[3] Although amino acids are in general fairly stable, several reactions are known

[1] *Journ. Ind. Engin. Chem.*, 1910, **2**, 138. In cultivation for (*a*) 25-30 years, (*b*) 17 years, (*c*) 25 years. The carbon had decreased in (*a*) from 1·53 to 1·17 per cent. and in (*b*) from 1·41 to 1·11 per cent. There had been no change in nitrogen in subsoil in (*a*) (0·081), and in (*b*) a fall from 0·094 to 0·090. The carbon had fallen in the subsoil of (*a*) from 0·986 to 0·754 and of (*b*) from 0·973 to 0·735. For further data on this interesting question see: J. E. Greaves, "A Study of the Bacterial Activities of Virgin and Cultivated Soils," *Centr. f. Bakt.*, Abt. II., Bd. 41 (1914), pp. 443-459; J. E. Greaves, "Does Crop Rotation Maintain the Fertility of the Soil?" *Scien. Mo.*, May, 1918, pp. 458-466; Alway and Bishop, "Some Notes on Alfalfa and Clover Residues as Sources of Nitrogen," *Nebr. Agric. Expt. Sta.*, 25th Ann. Report, 1912; Swanson, "The Effect of Prolonged Growing of Alfalfa on the Nitrogen Content of the Soil," *Journ. Amer. Soc. Agron.*, 1917, **9**, 305; Swanson and Latshaw, "The Effect of Alfalfa on Fertility Elements of the Soil in Comparison with Grain Crops." *Soil Sci.*, 1919, **8**, 1; Brown and Stallings, "Inoculated Legumes as Nitrogen Fertilisers," *Soil Sci.*, 1921, **12**, 365.

[2] *Utah Bull.*, 109, 1910. In the second foot depth the cultivated soil had lost nitrogen relative to the virgin soil, the loss under lucerne being greater than that under wheat.

[3] See R. H. Robinson and H. V. Tartar, *Journ. Biol. Chem.*, 1917, **30**, 135-144.

whereby they may be decomposed with production of ammonia :—

$$R{\cdot}CH{\cdot}NH_2{\cdot}COOH + H_2 = R{\cdot}CH_2COOH + NH_3.$$
$$R{\cdot}CH{\cdot}NH_2{\cdot}COOH + O_2 = RCOOH + CO_2 + NH_3.^{1}$$
$$R{\cdot}CH{\cdot}NH_2{\cdot}COOH + H_2O = RCH{\cdot}OH{\cdot}COOH + NH_3.$$
$$R{\cdot}CH{\cdot}NH_2{\cdot}COOH + H_2O = RCH_2{\cdot}OH + CO_2 + NH_3.^{2}$$

It is not, however, known how they break down in the soil.

Miyake (201) showed that the rate of production of ammonia can be expressed by the equation for autocatalytic reactions,

$$\log \frac{x}{A - x} = K(t - t_1)$$

where x = the amount of ammonia and nitrate produced at time t,

A = the total amount produced during the whole course of the reaction,

t_1 = time in which half of A is produced.

The whole of the added nitrogen did not appear as ammonia and nitrate; some was lost or assimilated by the organisms. The percentages converted depended on the compound added and on the soils; some of his values are :—

Soil.	Arlington.	Caribou.	Indiana.	Superior.	Washburn.
Leucine .	78·5	78·1	84·5	82·8	82·7
Tyrosine .	64·0	71·6	43·0	58·4	79·6

Acetamide was more completely ammonified, but acetanilide, benzamide, and benzanilide produced only little ammonia.[3]

Results of the same order can be deduced from the

[1] Dakin, *Journ. Biol. Chem.*, 1908, iv., 63; *Oxidation and Reduction in the Animal Body* (Longmans, 1912).

[2] Ehrlich, *Zeitsch. Verein. Rübenzucker Ind.*, 1905, 539-567.

[3] *Journ. Amer. Chem. Soc.*, 1917, 39, 2378.

extensive series of vegetation experiments recorded by J. G. Lipman and A. W. Blair (172) at New Jersey, where the recovery of nitrogen in dried blood is 90 and that in fresh farmyard manure is 75, compared with sulphate of ammonia as 100.

The investigations by Marchal (190) in 1893 of the method of ammonia production in the soil are so complete that little has since been added to the facts he ascertained. Müntz and Coudon (207*b*) had established the micro-organic nature of the process by showing that it was stopped by sterilisation. Marchal, therefore, made systematic bacteriological and mycological analyses of soils, and studied the action of the organisms thus obtained on solutions of albumin. Of the dozen or so varieties that invariably occurred, practically all decomposed the albumin and formed ammonia. One of the *mycoides* group proved very vigorous and was studied in some detail. The process was considered to be a simple oxidation necessary to the life of the organism; oxygen was absorbed and carbon dioxide evolved, the ratio $NH_3 : CO_2$ produced being 1 : 8·9. For complete oxidation of the carbon, hydrogen, and sulphur of the albumin molecule the ratio would be 1 : 10·3; but the change was known to be incomplete, and small quantities of leucine, tyrosine, and fatty acids could also be detected. Free oxygen, however, was not essential. When grown in a culture solution containing sugar and nitrate the organism took its oxygen from the nitrate, but it still produced ammonia.

The energy relationships thus indicated were wholly overlooked by investigators for nearly a quarter of a century: it was not till 1916 that Doryland (87) showed their significance. The organism produces ammonia, not because it must, but because it thereby obtains its prime requirements, nutrients, and energy, and can still leave ammonia in excess of its needs. If sources of energy other than proteins are supplied, *e.g.* carbohydrates, ammonia production may fall to nothing or become negative: the ammonia producers then become ammonia

absorbers just like the higher plants, and indeed they compete with growing crops.[1]

Of the few attempts to study the individual species of organisms concerned in ammonification H. J. Conn's is perhaps the most notable. Contrary to the older view, he claims that ammonia formation is mainly brought about by non-spore formers: *B. mycoides*,[2] generally regarded as one of the most common ammonia producers in the soil, he dismisses as ineffective. He maintains that of the eight ammonifiers studied by Marchal only one, *B. fluorescens liquifaciens* (a non-spore former), is a typical soil organism. He describes in detail two organisms, *Ps. fluorescens and Ps. caudatus*, which, while not very numerous in unmanured soil, multiply vigorously on addition of farmyard manure and also produce ammonia (70*c*). Waksman has argued from their numbers in the soil that fungi, and especially actinomycetes, are active ammonia producers, but it is very desirable to obtain more direct evidence.

Nitrification.

The ammonia formed by the action of soil bacteria, or added in manures, is changed to carbonate, which is then rapidly converted by *Nitrosomonas* into nitrite, and this by *Nitrobacter* into nitrate, the changes proceeding so rapidly that only traces of ammonia or nitrite are ever found in normal arable soils (241*i*). We may, therefore, infer that the production of nitrates is the quickest of the three reactions, the production of nitrites is slower, while the formation of ammonia is the slowest of all and sets a limit to the speed at which they

[1] For other experiments on the effect of carbohydrate in reducing ammonia production see H. M. Jones, *Journ. Infect. Dis.*, 1919, 19, 33, showing that *Bac. proteus* produces no proteolytic enzyme in presence of available carbohydrate; J. G. Lipman and Blair, *New Jersey Bull.*, 247, 1912, and *Annual Rept.*, 1914, p. 220, ammonia-producing power of soil is diminished by carbohydrates; S. A. Waksman, *Journ. Amer. Chem. Soc.*, 1917, 39, 1503, similar effects are produced in cultures of aspergillus; I. J. Kliger, *Journ. Bact.*, 1, 663, and Berman and Rettger, *ibid.*, 1918, 3, 389.

[2] Really a group, not a single organism.

can take place. Thus a measure of the speed at which nitrates are formed in soil does not measure the rate of nitrification, as is sometimes assumed, but the rate of ammonia production.[1]

The essential facts of nitrification are readily demonstrated by putting a small quantity of soil—·2 to ·5 grm.—into 50 c.c. of a dilute solution of ammonium sulphate containing nutrient inorganic salts and some calcium or magnesium carbonate, but no other carbon compound.[2] After three or four weeks at 25° the ammonia has all gone and its place is taken by nitrates. The conversion is almost quantitative, only an insignificant quantity of nitrogen being retained by the organisms.

The story of the discovery that nitrification is brought about by micro-organisms has been told on page 23. The organisms themselves are among the most remarkable in the soil. They alone are known to produce nitrites and nitrates,[3] and each one is narrowly specific in its action; nitrosomonas oxidises ammonium carbonate and nothing else; it will not touch nitrites, urea, or the substituted ammonias or even other ammonium salts, except in presence of a carbonate (295 and 219*a*); while nitrobacter oxidises nitrites and not ammonia. The differences between them are small; nothing has been discovered to account for the mutual exclusiveness of their activities. There is some evidence that nitrobacter, besides being more rapid in action, is also somewhat more sensitive than nitrosomonas, with the result that nitrites can be detected in soils where conditions are unfavourable for

[1] See also P. L. Gainey, *Soil Sci.*, 1917, 3, 399-416.

[2] Omeliansky (219*b*) used 2 grms. each $(NH_4)_2SO_4$ and NaCl, 1 grm. KH_2PO_4, ·5 $MgSO_4$, ·4 $FeSO_4$ in 1 litre of water, and added ·5 grm. $MgCO_3$ for each 50 c.c. of solution used. Nitrite formation goes on in this solution. For nitrate production he used 1 grm. each $NaNO_2$ and Na_2CO_3, ·5 each KH_2PO_4 and NaCl, ·4 $FeSO_4$ and ·3 $MgSO_4$ in 1 litre of water. S. F. Ashby (*Trans. Chim. Soc.*, 1904, 85, 1158, and *J. Ag. Sci.*, 1907, 2, 52) found that both processes went on simultaneously when he diluted the first of these solutions to one quarter the strength.

[3] Unless T. Sack's organism turns out to have this power (*Centr. Bakt. Par.*, 1925, 62, 15-24, and 64, 32-39). See also N. V. Joshi, *Mem. Dept. of Ind.*, 1915, 1, 85.

bacterial action. Certain morphological differences exist. Nitrosomonas occurs in several forms, mostly oval in shape 0·5 to 1μ wide and up to 2μ long, but whether these are distinct varieties is not known; it has a zoogloea stage. Nitrobacter is rod-shaped, 1μ long and about 0·3μ thick; only one variety is recognised.

It has already been stated that neither organism tolerates gelatine, hence Warington's failures to isolate them. Glucose, peptone, and other organic substances are also harmful (311*b*). Winogradsky recognised that the organisms obtain their carbon from carbon dioxide, and prepared a silica jelly free from organic matter on which they could grow sufficiently well to enable him to isolate and study them. The proof that carbon dioxide is the source of their carbon was made more rigid by Godlewsky, who showed that nitrification proceeds in solutions free from organic matter so long as the air supplied contained carbon dioxide, but stops as soon as the carbon dioxide is removed by passage over caustic potash.[1] But the synthesis of complex cell substances from carbon dioxide is an endothermic process requiring a supply of energy. In the case of the green plant, the energy comes from light, the transformer being chlorophyll. Here, however, light is out of the question, and is even fatal to the organism. Winogradsky (311*a*) suggested that the necessary energy is afforded by the oxidation of ammonia and of the nitrite, and he traced a definite relationship between the amount of ammonia oxidised and the carbon assimilated.

	Experiment 1.	Experiment 2.	Experiment 3.	Experiment 4.
Ammonia oxidised (expressed as nitrogen) .	722·0 mg.	506·1 mg.	928·3 mg.	815·4 mg.
Carbon assimilated .	19·7 ,,	15·2 ,,	26·4 ,,	22·4 ,,
Ratio $\frac{N}{C}$ . . .	36·6 ,,	33·3 ,,	35·2 ,,	36·4 ,,

[1] Quoted in Lafar, *Tech. Mykologie*, 1906, Bd 3, 165.

In these experiments mixed cultures were used, the nitrate producers predominating. Later on Coleman,[1] using pure cultures of nitrate producers, obtained ratios varying from 40 to 44 for the second stage of the process.

It was somewhat hastily inferred that organic matter would have a retarding effect in the soil just as it has in culture solutions. From the outset, however, certain facts were known to be against this view: thus, there was a good deal of organic matter in the old nitre beds (233) and also in rich garden soils, and yet nitrification went on vigorously in both. An exception was therefore made in favour of "humus" (208). Later on Adeney (1), and again Miss Chick,[2] found another exception: the organic matter of the filter beds used in sewage purification. Richards finds that nitrification proceeds very vigorously during the activation of sludge by aeration. Coleman has shown,[3] and Stevens and Withers (269) have confirmed it, that *only in culture solutions* is organic matter injurious: in the soil it does no harm, and may even help the process. Thus quantities of dextrose that stopped nitrification entirely in Winogradsky and Omeliansky's culture solutions were found to act beneficially in soil under normal conditions of temperature and moisture content. The discrepancy cannot yet be explained. Sucrose, lactose, and certain other non-nitrogenous compounds had no effect, but nitrogenous compounds were distinctly injurious.

The organisms will not tolerate an acid medium; a sufficient excess of calcium carbonate is therefore necessary both in culture solutions and in soils. Nor will they tolerate free ammonia. In culture solutions the nitrate producer is somewhat sensitive even to ammonium salts, indeed, both Warington (295) and Omeliansky (219*b*) suppressed it by maintaining a sufficient concentration of ammonium sulphate.

But against ammonia, as against organic matter, soil seems to exert a protective effect. Löhnis proved this in

[1] *Centr. Bakt. Par.*, II., 1908, **20**, 401-420 and 484-513.
[2] *Proc. Roy. Soc.*, 1906, **77**, 241-266.
[3] *Centr. Bakt. Par.*, 1908, **20**, 401-420 and 484-513.

laboratory investigations (178*a*), and Müntz and Lainé (208*b*) applied the knowledge in developing an arrangement of nitre beds on peat by which considerably higher concentrations of ammonium salts (7·5 grams ammonium sulphate per litre) can be nitrified on a larger scale than would be possible in solutions.[1] N. V. Joshi [2] has succeeded in setting up beds to nitrify cattle urine, converting it into a manure that can be conveniently handled.

In like manner soil protects the organisms against drought. They die at once in pure cultures in absence of moisture, but they are more resistant in the soil, though they are not known to form spores. But soil does not protect them against heat or antiseptics; they are killed when the soil is heated to 45° C. or treated with toluene, carbon disulphide, and other antiseptics (241*a*). They do not tolerate certain products formed when soil is heated to 90° C. or more, though they will grow after these products disappear; also they are less tolerant than other organisms of the salts in alkali soils.[3] Calcium or magnesium carbonates are essential to their activity.

The chemical course of the oxidation is unknown. Beesley showed that the ammonia disappears before it is converted into nitrite so that the sum of ammonia + nitrite first falls considerably below the amount of ammonia originally present and then rises to about 90 per cent. of the original quantity.[4] Whether the ammonia is first assimilated by the organism or converted direct into hydroxylamine has never been rigidly proved; Beesley, and also Mazé,[5] incline to the latter view. The rate of nitrate production is expressed by the equation for an autocatalytic action [6] (p. 253).

Nothing is known of the mechanism of the oxidation.

[1] For a discussion of the large scale tests see E. Boullanger, *Annales de l'Institut Pasteur*, 1921, **35**, 575-602; and 1922, **36**, 305.

[2] *Agric. Journ. Ind.*, 1925, **20**, 20-36.

[3] J. E. Greaves, E. G. Carter, and Yeppa Lund, *Soil Sci.*, 1922, **13**, 481-499.

[4] R. M. Beesley, *Trans. Chem. Soc.*, 1914, **105**, 1014-1024.

[5] *Compt. Rend.*, 1921, **172**, 173.

[6] Miyake (201); see also Beesley's curve.

Neither Omeliansky nor Bonazzi could find any evidence of an oxidase or peroxidase in nitrosomonas (219*a* and *b*) or the culture solution. Bonazzi (41*b*) has shown that the oxygen absorbed during the oxidation of ammonia is 2·89 ± 0·08, instead of three times the nitrogen oxidised as expected by the equation $NH_3 + 3O = HNO_2 + H_2O$, and Page [1] suggests that part of the remainder may come from the CO_2 taken up by the organism. Bonazzi shows also that the trace of iron salt essential to the process is reduced from the ferric to the ferrous state, and he suggests that it acts as the carrier of oxygen on lines similar to those assumed by Bach and Chodat for green plants.

The oxidation of ammonia to nitrate obviously needs a base since the organisms are very sensitive to acidity. Normally, this need is met by calcium carbonate, so that calcium goes into solution as nitrification proceeds. In absence of calcium carbonate, magnesium carbonate or mineral calcium phosphate also serve. There is, however, no evidence that insoluble phosphates are brought into solution as the result of nitrification where calcium carbonate is present.[2]

I.—Microbiological Activities removing Nitrates and Nitrogen from Soils.

Denitrification.

If the air supply of the soil is cut off by water-logging, or in the laboratory by means of an air-pump, the nitrates rapidly disappear, whilst nitrites, ammonia, or gaseous nitrogen are formed. The conditions can be so arranged that the decomposition of nitrate-bouillon by soil shall give rise to notable quantities of gaseous nitrogen, nitrous oxide (18), or nitric oxide.[3]

The reduction of nitrates to nitrite has long been known.

[1] *Chem. Soc. Repts.*, 1923, 20, 213.

[2] See Kelley, *Journ. Agric. Res.*, 1918, 12, 682; and C. Hopkins and Whiting, *Ill. Bull.*, 190, 1916.

[3] S. Suzuki, *Centr. Bakt. Par.*, 1911, 31, 27-49.

As early as 1867 Schönbein [1] stated that it could be brought about by "frische Conferven, wie sie so häufig in stehendem Wasser vorkommen"; after ten to fifteen minutes' boiling, however, the property was lost. Meusel, in 1875 (198), showed that it was bacterial, and could be stopped by antiseptics. The property appears to be generally possessed by bacteria, and was shown by no fewer than 85 out of 109 kinds investigated by Maassen (184).

The formation of gaseous products is effected by a smaller but still considerable number of organisms; these were first investigated by Gayon and Dupetit (106), and by Déhérain and Maquenne (81*a*).

The physiological significance of the reduction is to supply oxygen to the organisms when free gaseous oxygen is no longer available. The reaction is not, however, a simple transfer of oxygen from the nitrate to the organism; a supply of easily oxidisable organic matter, sugar, cellulose, etc., must be present, humus is less effective. Beijerinck and Minkman (18) supposed that N_2O was an essential intermediate product, being formed by direct action between the nitrate and the organic compound. Stoklasa and Vitek [2] and also Mazé [3] attributed the reduction to nascent hydrogen formed by anaerobic fermentation of the carbon compound (see p. 239): on this view, which is supported by W. Hulme's experiments [4] the organism obtains its oxygen from the organic compound or possibly the water, and part of the hydrogen thus set free reduces the nitrate, the remainder appearing as gas.

There is a very sharp contrast between the bacterial production and the bacterial destruction of nitrates. Nitrate production is confined to one or two organisms only at each stage, and the end result is a single product quantitatively

[1] C. F. Schönbein, *Beit. zur Phys. Chem. Zeitsch. f. Biol.*, 1867, 3, 325-340.
[2] *Centr. Bakt. Par.*, 1905, 14, 102 and 183.
[3] *Ann. Inst. Pasteur*, 1911, 25, 289.
[4] *Trans. Chem. Soc.*, 1914, 105, 623-632.

equivalent to the original ammonia; no single chemical process oxidises ammonia in this complete manner. The bacterial reduction of nitrates, on the other hand, gives no single product, but a number of products not in any simple ratio, whilst the chemical reduction can readily be made to go quantitatively to ammonia.

Whether denitrification goes on to any extent in properly drained agricultural soils is doubtful, because the three essential conditions, lack of air, presence of much easily decomposable organic matter and of nitrate are rarely obtained. In 1895 Wagner and Maercker startled the agricultural world by announcing that unrotted dung destroys the nitrates in the soil and reduces the crop yield (287). Their experiments were criticised by Warington (296) who pointed out that their dressings of dung were enormous and their results would not apply to ordinary farm practice. In summing up a long-continued experiment in cylinders at New Jersey,[1] J. G. Lipman and A. W. Blair were unable to find evidence of denitrification in normal soil conditions. But it may occur in rich soils and it goes on to a marked extent in wet soils. Nagaoka (211*b*, see also 75) has shown that nitrate of soda frequently depresses, instead of increasing, the yield of rice, sagittaria, and juncus on the swamp soils of Japan, an action which he attributes to the formation of poisonous nitrites. Organic manures or sulphate of ammonia are always used on such soils. Kelley has obtained similar results in Hawaii.[2]

Denitrification will also take place in peaty soils, and this has led to a very interesting observation as to the effect of lime. So long as these soils are left in their natural acid state nitrification cannot take place and therefore there is no denitrification. But as soon as lime is added in sufficient quantities to give a neutral reaction nitrification begins: part of the nitrate is then reduced to nitrite by microbic activity, then a chemical reaction sets in between the nitrite and the peat whereby some nitrogen is lost and some transformed into in-

[1] (172). [2] *Hawaii Bull.*, No. 24.

soluble compounds. Thus large doses of lime may produce injurious effects on peat soils (Arnd (4*a*)).

Nitrates disappear sometimes completely from dry tropical soils during bare fallow. F. J. Martin and R. E. Massey [1] found the following amounts of nitric nitrogen in parts per million during the dry period :—

Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March.
8	2	2	1	2	trace	nil

The samples were taken from the first foot, but by March the depletion of nitrate had extended to four feet. The reason for this remarkable loss is not known, but it is not a washing out, there being neither rain nor irrigation water, and it is hardly likely to be assimilation by micro-organisms.

The Evolution of Gaseous Nitrogen.

It has long been known that losses of nitrogen may occur during the bacterial decomposition of organic matter which cannot be attributed to the volatilisation of ammonia, and which, therefore, are put down to an evolution of gaseous nitrogen: instances are afforded by manure heaps, by rich soils, and by sewage beds. The observations go back to the time when the sources of nitrogen for vegetation were being investigated, and attempts were made to set up a balance sheet showing the relation between the amounts of nitrogen in the plant and the soil at the beginning and at the end of its growth respectively. Reiset,[2] Ville (284*b*), and Boussingault (44) sometimes found less nitrogen in soil + plant at the end of an experiment than in soil + seed at the beginning, and attributed the difference to an evolution of free nitrogen. Some of these early observations were probably faulty by reason of the crudeness of the analytical methods, but Lawes, Gilbert, and Pugh (163) showed that losses of nitrogen undoubtedly took place sometimes, though not always, when

[1] See Wellcome Research Laboratories, Khartoum, *Chem. Publ.*, 29, 1923.
[2] Reiset, *Jahresbericht der Chemie*, 1856.

nitrogenous organic matter, wheat-meal, barley-meal, or bone-meal, was made into an "agglutinated condition" with water, and allowed to decompose in presence of air. Practically no ammonia could be detected. Lawes and Gilbert suggested three possible reactions, a suggestion that still holds the field.

1. An oxidation analogous to that of the action of chlorine on ammonia, by which free nitrogen is evolved.

2. A reduction similar to that of a great number of substances upon the oxygen compounds of nitrogen, by which the oxygen is appropriated and the nitrogen set free.

3. These two actions may operate in succession the one to the other.

Little attention was paid to these results at the time, but later on losses of nitrogen were found to occur in the purification of water and of sewage. Angus Smith [1] in 1863 observed an evolution of gaseous nitrogen from a dilute solution of putrefying blood, and showed that nitrates gave off nitrogen under certain circumstances. The earlier sewage workers, Frankland,[2] and others, did not actually mention any loss of nitrogen during sewage purification though the published results show that it occurred. Later sewage workers recognised the loss, and Letts, indeed, made measurements of the evolved nitrogen, special gasometric methods being devised for the purpose.[3]

A serious attempt to grapple with the problem was made in 1896 and 1897 at some of the German Experiment Stations, notably Jena, in consequence of the request made by the German Agricultural Society for an investigation into the losses of nitrogen from farmyard manure. The first hypothesis, set up by Wagner, was that nitrates are present in the manure, and in absence of air are reduced to nitrogen. This

[1] Angus Smith, *Memoirs Manchester Lit. and Phil. Soc.*, 1863, 1867-1868, vol. iv.; also *Report to the Local Govt. Board*, 1882.

[2] Frankland, Denison, and Chalmers Morton, *Royal Commission, Pollution of Rivers*, 1868, vols. i.-iv.

[3] Letts, *Fifth Report, Sewage Commission*, Appendix 6, 171-194; also *Report to the Corporation of Belfast on the Purification of Belfast Sewage.*

view, however, soon proved to be erroneous, for it supposed that the loss occurred only in absence of air, whereas, in point of fact, it occurs only in presence of air.

Immendorf [1] attributed the evolution of nitrogen to direct oxidation or combustion of the nitrogen compounds. Pfeiffer and his assistants at Jena (225*a*) began on the reduction hypothesis, and supposed that nitrates were formed on the outside of the heap and then diffused inside, where they were denitrified. But during the course of their experiments they changed their view, and ended by accepting the direct oxidation hypothesis.

Two lots of cow manure (made with peat) were put up: air was blown through one, and over the other. The losses of nitrogen were :—

	Grams.	Per Cent.
Air blown through	4·26	42·6
,, ,, over	2·76	27·6

They argued that blowing air over the dung would be favourable to their supposed nitrification and denitrification process, while blowing air through would be unfavourable. Yet it had caused the greater loss.

On the other hand, the sewage investigators Müntz and Lainé (208*c*) and Adeney (1) obtained results inconsistent with the direct oxidation hypothesis. Albuminose, asparagin, etc., evolved no nitrogen during bacterial decomposition in dilute solutions saturated with oxygen, nor did urine and fæces in Russell and Richard's experiments (241*g*).

It appears, therefore, that the loss of nitrogen does not occur under purely aerobic nor purely anaerobic conditions, but only in a combination of the two such as is found in manure heaps, rich soils, and sewage beds.[2] Neither the direct reduction nor the direct oxidation hypothesis explains the facts. Alternate nitrification and denitrification explains much but not all; Russell and Richards suggest that molecular groupings formed in the anaerobic period become unstable and

[1] *Landw. Jahrb.*, 1892, 21, 281-339.

[2] Note, however, that moisture is always present.

evolve nitrogen as soon as oxidation begins: an action parallel to the shortening of the propionic acid chain with formation of an acetic acid derivative which takes place in these conditions.[1] The investigations set out in the preceding paragraphs were all made in moist conditions. In hot dry conditions such as obtain in tropical regions of low rainfall, there is the possibility of decompositions brought about by the sun's heat.

II.—Microbiological Activities Saving Nitrogen from Loss. Assimilation of Ammonia and Nitrate by Bacteria and other Micro-organisms.

Most of the micro-organisms of the soil, excepting the protozoa, obtain their nitrogen by assimilating ammonia and nitrate. The nitrate is not permanently lost from the soil, being reformed when they die and are decomposed, but it is temporarily withdrawn.

The withdrawal and formation processes balance each other in normal soils so long as there has been no recent addition of organic matter; added ammonium compounds are quantitatively converted into nitrate.[2] The equilibrium seems to be mobile and the nitrate apparently fluctuates, but always within certain limits.

But when organic matter has been recently added, the numbers of micro-organisms greatly increase and make a corresponding demand on ammonia and nitrate for their nutrition. If the organic matter contains enough nitrogen to satisfy their needs there is no net change in the amount of nitrate in the soil; for ordinary vegetation residues this "null point" is reached when about 1·8 per cent. of nitrogen is present. A higher content of nitrogen allows accumulation of ammonia and nitrate in the soil, there being more than the

[1] See G. Barger, *The Simple Natural Bases* (Longmans).

[2] At any rate 98 per cent. or more; the methods are not fine enough to attach significance to the remaining 2 per cent. See Schloesing *père* (245*c*); also Russell and Hutchinson. In peats, however, much ammonia is assimilated and not nitrified (Lemmermann, 166).

organisms require in multiplying up to the limit set by the energy content of the added organic matter. A lower content of nitrogen or absence of nitrogen necessitates an absorption of nitrate from the soil which may become complete ;[1] indeed, there is no surer way of removing all nitrate from the soil than by adding sugar. The various possibilities are illustrated by Lyon, Bizzell, and Wilson's experiments (183*b*) (Table LXII.).

TABLE LXII.—NITRATE CONTENT OF SOIL, TO WHICH ROOTS HAD BEEN ADDED, AND LEFT FOR THREE MONTHS. LYON, BIZZELL, AND WILSON.

Material.	Nitrogen per Cent.	Weight of Roots added in Grams.	Nitrogen as Nitrate. Milligrams.
Control . .	—	—	946·6
Oat roots . .	0·45	133·3	207·3
Timothy roots .	0·62	96·8	398·4
Maize roots .	0·79	75·9	510·6
Clover roots .	1·71	35·1	924·4
Dried blood .	10·71	5·6	1751·1

0·6 grm. nitrogen added to 28 lb. soil in each experiment.

III.—MICROBIOLOGICAL ACTIVITIES INCREASING THE AMOUNT OF NITROGEN IN SOILS.

The Fixation of Nitrogen.

The first systematic search for a recuperative agency to make good the losses of nitrogen from the soil was started forty years ago by Berthelot. He found that certain organic compounds could absorb free nitrogen under the influence of silent electric discharges, and at first attributed the natural recuperation to this cause. He also examined the possibility of bacterial action, as micro-organisms at that time were playing a large part in French science under Pasteur's influence. Accordingly he exposed sterilised and unsterilised sands and clays poor in nitrogen (·01 per cent. or less) to air in large closed flasks for five months, and found distinct gains in nitrogen in the unsterilised, but not in the sterilised soils. Fixation is, therefore, not due to any external physical cause,

[1] Other factors also come in: see Y. L. Starkey, *Soil Sci.*, 1924, **17**, 293.

which would operate equally in both cases, but to micro-organisms (26). There seems to have been an element of good fortune in this experiment, for when Gautier and Drouin [1] repeated it they obtained fixation of nitrogen only when sufficient organic matter was present in the soil. But the research was at once fruitful of results because it gave Hellreigel and Wilfarth the key to the clover problem (p. 24), and led Winogradsky (312) to search for the actual organism.

No investigator of our subject has shown greater ingenuity than Winogradsky in devising methods at once simple, direct, and effective. In looking for the nitrogen-fixing organisms he inoculated soil into a medium containing every nutrient except nitrogen compounds: only bacteria capable of assimilating gaseous nitrogen could therefore develop, and these had a clear field. But he further recognised that the process was endothermic and required some source of energy, hence he added sugar to the solution. The method (known as the elective method) thus consists in making the conditions as favourable as possible for the group of organisms under investigation, and as unfavourable as possible for all others; it has proved extremely valuable in the subsequent development of soil bacteriology.

Winogradsky's solution contained 2 to 4 per cent. dextrose, a little freshly washed chalk, 0·1 per cent. K_2HPO_4, 0·05 of $MgSO_4$, and traces of NaCl, $FeSO_4$, and $MnSO_4$, together with a little soil. Under aerobic conditions nitrogen was assimilated and the sugar was decomposed with evolution of carbon dioxide and hydrogen and formation of *n*-butyric and acetic acids in the proportion of three or four molecules of the former to one molecule of the latter, the two acids together accounting for nearly half the sugar. A little alcohol was found, but practically no non-volatile acid. There was a distinct relationship between the amount of nitrogen assimilation and the sugar decomposed, each milligram of nitrogen fixed requiring the oxidation of about 500 mgms. of sugar.

[1] *Compt. Rend.*, 1888, **106**, 754-863.

Three organisms were present, a clostridium and two bacteria, and they obstinately refused to be separated by the method of successive cultures. Not until recourse was had to anaerobic conditions were the two bacteria suppressed and the clostridium obtained pure. The bacteria having been isolated, it appeared that the clostridium alone possessed the power of fixing nitrogen, but a fresh difficulty now arose because in pure cultures the organism would *work only under anaerobic conditions*. Only when the protective bacteria were simultaneously present did fixation go on in presence of air. The organism was called *Clostridium pasteurianum*:[1] it formed rods 1·2 μ thick and 1·5 to 2 μ long and also spores (312).

In order to simplify the bacterial flora Winogradsky had heated his soil to 75°, thereby killing non-spore formers, but later on Beijerinck (14 and 15), working with unheated soil, discovered three other nitrogen-fixing organisms; Azotobacter chroococcum (so called because it produces a dark brown pigment), Granulobacter and Radiobacter.[2] Of these, azotobacter is the most active; in cultures it usually forms large cocci, or rods, 4 to 6 μ in thickness, but Löhnis and Smith (181*e*) have shown that it passes through a complex life cycle. It differs in two important respects from clostridium; (1) it is aerobic; (2) it produces practically no butyric acid. Its effects can be studied by inoculating 0·1 to 0·2 grm. of soil into 100 c.c. of tap water containing 2 per cent. mannitol, ·02 per cent. K_2HPO_4, and sufficient $CaCO_3$, and keeping for some weeks at 27° to 30° C. in a thin, well-aerated layer[3] in an Erlenmeyer flask. Azotobacter fixed more nitrogen than clostridium per grm. of sugar decomposed. Other organisms have since been described as fixers of

[1] For further investigation of the clostridium see Omeliansky, *Internat. Rev. Sci. and Pract. of Agric.*, Rome, 1917, 8, 1190.

[2] Since shown by Stoklasa and others (*Centr. Bakt. Par.*, Abt. II., 1908, 21, 484 and 626) to possess only slight nitrogen-fixing power.

[3] Later on Beijerinck used calcium malate in place of sugar, and showed also how to make plate cultures of the organisms (16).

nitrogen, particularly amylobacter,[1] Bondorff's *Planobacillus*,[2] and phoma, one of the mycorrhiza,[3] but none is so effective as azotobacter, and to this most of the investigations have been confined.

Beijerinck's solution works satisfactorily for crude cultures but not for pure cultures. Various hypotheses have been put forward in explanation; it was supposed that azotobacter required the presence of some other organism, or that it lost its efficiency on cultivation. Krzemieniewsky (157) showed that an important factor is the presence of a little soil; so long as this is added pure cultures retain their effectiveness. The active agent is the humus, but its effect is not to furnish carbon or nitrogen to the organism, and it loses its power after treatment with hydrochloric acid. Remy and Rösing (235*b*) attribute the action to the iron invariably present.[4] Allen,[5] on the other hand, supposes that the colloids of the humus prevent complete precipitation of the phosphate and thus facilitate phosphorus nutrition of the organism.

Soil acidity is particularly harmful (p. 277), but salts of the alkalis are not: azotobacter is indeed, of all organisms, the most tolerant of the conditions of alkali soils (p. 336). Small quantities of nitrates or other nitrogen compounds are beneficial in the early stages, particularly for growth of the organisms, also, though to a less extent, for fixation.[6] Larger quantities of nitrate are favourable for growth, but beyond a certain point suppress fixation altogether,[7] the organism apparently assimilating nitrate in preference to free nitrogen.

The nitrogen-fixing power of azotobacter is greatly increased by the presence of other organisms, whether algæ,

[1] G. Bredemann, *Centr. Bakt. Par.*, 1909, **23**, 385-568.
[2] *Kg. Veter. Landbo. Aarsscrift.*, 1918, 365.
[3] B. M. Duggar and Davis, *Ann. Miss. Bot. Gard.*, 1916, **3**, 413-437.
[4] But see also Reed and Williams, *Centr. Bakt. Par.*, 1915, **43**, 166.
[5] E. R. Allen, *Ann. Mis. Bot. Gard.*, 1919, **6**, 1.
[6] T. L. Hills, *Journ. Ag. Res.*, 1918, **12**, 183-230.
[7] Bonazzi (41*a*).

bacteria, or protozoa. Beijerinck and van Delden (15) recognised that mixed cultures fixed more nitrogen than pure cultures, while Hanzawa showed that two strains of azotobacter growing together fixed more nitrogen than either separately.[1] Omeliansky explained the increased fixation brought about by a mixture of clostridium and azotobacter by supposing that azotobacter, being vigorously aerobic, maintained local anaerobic conditions for the clostridium, so that both were able to work. Kossowitsch (153*a*) studied a mixture of azotobacter and nostoc, Bouillac (42 and 43) used various algæ, and C. B. Lipman and L. J. H. Teakle used chlorella : [2] the increased effectiveness is attributed to the provision by the algæ of the necessary carbon compounds. The mixture with protozoa has been studied at Rothamsted by S. M. Nasir,[3] and by Bal : the enhanced fixation is attributed to the protozoa feeding on the azotobacter, and so preventing the population becoming dense enough to cause the well-known staleing effects.

Whether all these actions are as different as the explanations is not clear ; it is possible that the main cause of the increased fixation is the local nitrogen starvation brought about by the presence of the other organisms. It is interesting that the other vigorous nitrogen-fixing organism, Bacillus radicocola, also fixes most nitrogen when associated with another organism, in this case a leguminous plant (p. 279).

Little is known of the chemistry of the fixation. The sugar or other carbon compound is completely oxidised to CO_2 and water, the volume of CO_2 being equal to that of oxygen absorbed.[4] There is no indication of acid or alcohol production, though this might happen if the solutions were not fully aerobic.

[1] *Centr. Bakt. Par.*, Abt. II., 1914, 41, 573.

[2] *Soil Sci.*, 1925, 7, 509.

[3] *Ann. Appl. Biol.*, 1923, 10, 122. See also Moler, *Botaniska Notiser*, 1915, 163, quoted by Bonazzi (41*a*, 1924).

[4] The oxidation is so vigorous in culture solution that 1 grm. weight has evolved no less than 1·3 grms. CO_2 in twenty-four hours (271).

Nothing is known of the nitrogen changes; not even whether the first step is a reduction to ammonia or an amide, or oxidation to a nitrite or nitrate; the latter possibility is sometimes ruled out on the grounds that neither nitrates nor nitrites are found in the culture solution,[1] though in view of the ease with which azotobacter assimilates nitrate the argument is not conclusive. On the other hand, ammonia is found in the culture liquid (15).

There is some connection between the amount of nitrogen fixed and the chemical nature of the carbon compound supplied, some being more effective than others (Table LXIII.).

TABLE LXIII.—MGMS. OF NITROGEN FIXED BY AZOTOBACTER PER GRM. OF SUBSTANCE DECOMPOSED.[2] LÖHNIS AND PILLAI (179).

Mg. of Nitrogen Fixed.	
7·5 to 10	Mannitol, xylose, lactose, lævulose, inulin, galactose, maltose, dextrin, sucrose + calcium carbonate.
5 to 7·5	Sucrose alone, dextrose, sodium tartrate + calcium carbonate, glycerol + calcium carbonate.
2·5 to 5	Starch, sodium tartrate, sodium succinate, calcium lactate.
1 to 2·5	Sodium propionate, sodium citrate, glycerol alone.
Nil	Calcium butyrate, potassium oxalate.

GERLACH AND VOGEL.[3]

Glucose decomposed mgs.	1,000	2,000	3,000	4,000	5,000	6,000	7,000	10,000	12,000	15,000[4]
Nitrogen fixed, mgs.	7·4	13·5	17·8	31·4	39·4	45·9	59·9	91·4	127·9	62·9
Nitrogen fixed, per grm. of sugar	7·4	6·8	5·8	7·8	7·9	7·6	8·5	9·1	10·7	—

Mean 8·9 mgs. nitrogen fixed for 1 grm. sugar.

But there is no close relationship; the ratios vary with the condition and the age of the culture; the most efficient condi-

[1] Kellerman, *Centr. Bakt. Par.*, Abt. II., 1914, 40, 479-482.

[2] For list of other substances see F. A. Mockeridge, *Biochem. Journ.*, 1915, 9, 272-283.

[3] *Mitt. d. Kaiser Wilhelm Inst.*, Bromberg, 1902, 9, 817-821 and 1903, 10, 636.

[4] The sugar was not all used up in this experiment.

tions are with young cultures[1] in soil extracts.[2] If the oxidation of the carbon compound is solely for the purpose of obtaining energy for the nitrogen fixation, the process might strike an engineer as very inefficient, since only about 1 per cent. of the energy is utilised.[3]

Because, however, we happen to be most interested in the power of these organisms to fix gaseous nitrogen, it by no means follows that this is the central process of their lives. Bonazzi (41*a*), indeed, regards the process as one to which they have recourse only if they are starved of nitrogen.

It is difficult to obtain clear evidence showing how much nitrogen is fixed in natural soils by free living nitrogen-fixing organisms. Wherever a gain in nitrogen has been recorded in natural conditions in humid climates, there have also been leguminous plants growing to which it might be attributed (p. 249). Laboratory investigations in humid climates suffer from the difficulty that the soils already contain so much nitrogen that small changes are difficult to measure accurately, and there are losses of nitrogen which counterbalance any fixation. Investigation would be easier in some of the soils very poor in nitrogen found in hot, arid conditions. Rigid incontestable proof could be furnished only by a demonstrated gain in nitrogen effected by azotobacter, all other possibilities being ruled out. This proof has not yet been forthcoming.

However, the evidence is clear that soils free from leguminous vegetation have gained in nitrogen when all the conditions necessary for the action of azotobacter are satisfied. Usually sugar or other non-nitrogenous organic matter is added to the soil, and the changes in nitrogen content studied. The sugar has the double effect of removing all nitrate from the soil (p.), and of supplying energy for the fixation, both of which are essential to the activity of the organism. Generally, there is a gain of nitrogen; losses are, however,

[1] A. Koch and S. Seydel, *Centr. Bakt. Par.*, Abt. II., 1912, 31, 570.
[2] C. B. Lipman and L. J. H. Teakle, *Soil Sci.*, 1925, 19, 99-103.
[3] G. A. Linhart, *Journ. Gen. Phys.*, 1920, 2, 247-251.

often recorded (248), whilst a certain loss of nitrate invariably occurs. A. Koch (151*b*) added successive small doses of dextrose to 500 grms. of loam, mixed with sand and spread on plates to secure copious aeration, kept uniformly moist and at 20° C. Nitrogen fixation began very soon and reached its maximum after eighteen weeks, when losses set in; the results are given in Table LXIV.

TABLE LXIV.—NITROGEN FIXED IN SOIL BY BACTERIAL ACTION IN PRESENCE OF DEXTROSE. KOCH (151*b*).

Increments of Dextrose per 100 grms. of Soil.	Total Dextrose Supplied in grms. per 100 grms. of Soil after				Mgs. N fixed per 100 grms. of Soil after			
	5 Weeks.	8 Weeks.	18 Weeks.	26 Weeks.	5 Weeks.	8 Weeks.	18 Weeks.	26 Weeks.
	June 26.	July 20.	Oct. 3.	Nov. 30.	June 26.	July 20.	Oct. 3.	Nov. 30.
·2	1·0	1·6	3·6	5·2	8·3	14·9	17·8	18·9
·5	2·5	4·0	9·0	13·0	20·1	32·5	36·8	31·6
1·0	5·0	8·0	18·0	26·0	35·8	57·2	58·7	52·7
1·5	7·5	12·0	27·0	37·5	40·5	66·7	68·5	66·8
2·0	8·0	14·0	26·0	36·0	43·9	78·8	80·0	78·8

For each gram of dextrose supplied in the small doses about 8 mgms. of nitrogen were fixed during the first eight weeks; but only 4 or 5 mgms. later on. In larger doses the sugar was less effective, only 5 to 6 mgms. of nitrogen being fixed per gram of sugar at first and 3 mgms. later.

Pot experiments showed that the nitrogen thus added to the soil became available for plant food. Dextrose and sucrose first depressed the crop, then caused an increase, and finally left the soil richer in nitrogen at the end of the experiment than at the beginning (Table LXV.).

But if the soil temperature fell too low nitrogen fixation ceased: it was not observed at 7° C. although it appeared to go on at 15° C. The optimum temperature lies between 25° and 30° C.

Pfeiffer and Blank (225*b*), however, were unable to obtain any beneficial results from sugar. The Rothamsted trials showed increases for autumn applications but decreases for spring dressings (140*e*).

TABLE LXV.—EFFECT OF DEXTROSE AND SUCROSE ON THE PRODUCTIVENESS AND NITROGEN CONTENT OF THE SOIL. KOCH (151*b*).

Sugar added per 100 grms. of Soil.	Crops Obtained.				Total N Removed in Crop.	Nitrogen Left in Soil, Spring, 1906.	
	Oats, 1905.		Sugar Beets, 1906.				
	Dry Matter.	Yield of N.	Dry Matter.	Yield of N.	Grms.	Total N per Cent.	N as Nitrates, Parts per Million.
None	100	100	100	100	0·5014	·093	10
2 per cent. dextrose .	32·8	62·5	186	190	0·6814	·105	17
2 ,, ,, cane sugar	33·3	58·7	179	195	0·680	·105	15
4 ,, ,, ,, ,,	37·7	78·1	283	339	1·0092	·119	37

Increased yields of sugar cane have followed the application of molasses to soils at the Station Agronomique and on Mr. Ebbels' estate [1] in Mauritius, where the residual effect is well shown, and also in Antigua.[2] Peck in Hawaii, on the other hand, observed marked losses of nitrate, as also did Harrison in British Guiana.[3]

An increase in crop following the application of sugar or starch to the soil is not evidence of nitrogen fixation, but might equally well be adduced to show that sugar and its decomposition products are direct plant nutrients. Only when an actual gain in nitrogen is demonstrated by analysis does the proof become satisfactory. As a practicable scheme the addition of sugar to the soil would be out of the question for field work. Beijerinck (15) has shown, however, that certain compounds producible in the decomposition of cellulose also serve as sources of energy to azotobacter, and Pringsheim [4] found that the same holds true for clostridium also.

Hutchinson (140*e*) has shown that leaves, stubble, etc.,

[1] See *The Agricultural News*, 1908, vii., 227; 1910, ix., 339; and 1911, x., 179.

[2] See *Manurial Experiments with Sugar Cane in the Leeward Islands*, 1908-1909 and 1909-1910. (Pamphlets 64 and 68, West Indian Department of Agriculture.)

[3] *West India Bull.*, 1913, 13, 136. This contains an interesting discussion on the losses of nitrogen from soil.

[4] *Biol. Centr.*, 1911, 31, 65-81.

serve to increase nitrogen fixation, though under other conditions they can, like sugar, depress the nitrate content of the soil.[1] Doryland[2] has discussed the possibility of using various waste substances as energy supply, and Emerson[3] has discussed the prospect of soil inoculation with azotobacter.

Richards (236) has made the interesting observation that animal fæces also serve for the organism both in culture and in more natural conditions, but there is a sharp connection between the diet and the effect. Horses fed on oats gave fæces which induced the greatest fixation: horses in grass came next: cattle receiving cake were next, while the fæces from cattle fed on grass proved unsuitable.

The difficulty of material might therefore be overcome because large quantities of cellulose are available on the farm in the form of straw. But there still remains the question of temperature. Azotobacter, as we have seen, requires more warmth than many other organisms, and according to Koch's experiments ceases to work at 7° C. Thiele read temperatures daily for three years of arable and grass soils at different depths at Breslau (277), and concluded that only rarely were they favourable for azotobacter. But it is impossible to argue from a culture solution to the soil, and, indeed, Löhnis has shown that the mixed cultures of the soil are almost as effective at 10° as at 20°.[4]

It seems legitimate to conclude that in humid climates azotobacter fixes nitrogen in well-aerated soils sufficiently provided with calcium carbonate, potassium salts, and phosphates, carbonaceous material of the right kind and moisture, so long as the temperature is high enough. The nitrate content of soils varies considerably at different seasons (p. 180),

[1] For Dvorak's work published earlier, see *Zeit. Landw. Versuchs. Osterreich.*, 1912, 25, 1077-1121.

[2] *Sci. Proc. Soc. Amer. Bacteriologists*, 1918.

[3] *Iowa Research Bull.*, 45, 1918.

[4] *Mitt. Landw. Inst.*, Leipzig, 1905, vii., 94.

10°-12° C.	20°-22° C.	30°-32° C.
3·15 mgs.	4·55 mgs.	4·27 mgs. nitrogen fixed.

and may often be too small to interfere with nitrogen fixation. Where the air supply is diminished owing to the close texture of the soil there is still the possibility of fixation by clostridium. Ashby[1] found that the relative distribution of azotobacter and clostridium at Rothamsted depended on the amount of calcium carbonate in the soil; wherever any notable quantity was present, azotobacter invariably occurred: otherwise clostridium alone was found. This result appears to be general.[2] Remy suggested in 1906 that azotobacter was a good organism for the bacterial diagnosis of soils—absence showing some harmful factors and a rich development showing favourable conditions. Christensen (*67a*), and afterwards Winogradsky,[3] gave definite form by designing workable methods, while Gainey[4] has ascertained that azotobacter occurs in soils with a *p*H value 6·0 or more, but not in those with *p*H value 5·9 or less. In arid climates the evidence for activity of azotobacter in the soil seem stronger. Wheat growing increases rather than decreases the nitrogen content of the soil (p. 251). The heads are stripped off with the header and most of the straw ploughed in; nitrogen fixation apparently proceeds actively, the temperature conditions being eminently suitable.[5]

Nitrogen Fixation by Bacteria in Symbiosis with Leguminosæ.

After Hellriegel and Wilfarth's great discovery of the relationship between bacteria and leguminosæ (p. 24) many unsuccessful attempts were made to isolate and study the

[1] *Journ. Agric. Sci.*, 1907, **2**, 35-51.

[2] Hugo Fischer (1905) found azotobacter on the limed plots at Bonn-Poppelsdorf but not on the unlimed. Burri (1904) found it in only one-third of the Swiss soils examined.

[3] *Annals Inst. Pasteur*, 1926, **40**, 455.

[4] *Journ. Agric. Res.*, 1918, **14**, 265. E. B. Fred and A. Davenport found the limits in culture solutions to lie between 6·5 and 8·6 (*Journ. Agric. Res.*, 1918, **14**, 317).

[5] J. E. Greaves, *Centr. Bakt. Par.*, 1914, Abt. II., **41**, 444-459.

organisms by the methods then in vogue. In 1888 Beijerinck (13) broke away from the ordinary meat-bouillon-gelatin plate and substituted a slightly acid medium made up of infusion of pea leaves, gelatine (7 per cent.), asparagine (·25 per cent.) and sucrose (·5 per cent.). Growth readily took place and the colonies yielded rods 1 μ wide and 4 to 5 μ long, some of which showed signs of bacteroid formation, and " swarmers " 0·9 μ long and 0·18 μ wide, these being among the smallest soil organisms known.[1]

The organisms pass through a definite life cycle. This was worked out by W. F. Bewley and Hutchinson (35) for culture solutions, but the same changes occur both in the nodule [2] and in the soil.

Beginning with the non-motile cocci: these swell, develop flagella, and become motile (the " swarmers " of the older workers); next they elongate and develop more flagella, becoming motile rods; finally they lose their flagella, become non-motile and vacuolated, taking on a banded appearance; they may be straight or branched. These then break up, releasing the cocci and so the cycle starts again (Fig. 29).

The branched T or Y forms are the bacteroids commonly seen in the nodule; their formation in culture media is stimulated by sugars or small quantities of organic acids such as occur in the sap of the host plant (Stützer, 272). On the other hand, the formation of the cocci, which quickly become the motile swarmers, is much stimulated by addition of phosphates or of milk (279); as many as 80 per cent. of the organisms in a culture can be brought into this form.

Unlike most other soil organisms, *Bacillus radicicola* does not occur in all regions; it is found only in places where its host plant lives, thus having the unusual property of a discontinuous geographical distribution. But although apparently tied to the host plant, it is not confined to the nodule but occurs independently in soil; it has, indeed, been isolated

[1] Golding has shown that they will even pass through a porcelain filter and has prepared pure cultures in this way.

[2] E. Wallin, *Journ. Bact.*, 1922, 7, 471.

from soil by various workers.[1] It has even been supposed to fix nitrogen during this independent existence, but the evidence is not very good.[2]

Nothing was known of the life of the organism in the soil till H. G. Thornton and N. Gangulee (279) ingeniously overcame the difficulties of the investigation. Using a modification of Winogradsky's direct staining method (p. 296), they were able to show that the organism goes through the same cycle in the soil as in culture solution, and that the development of motility is stimulated by addition of phos-

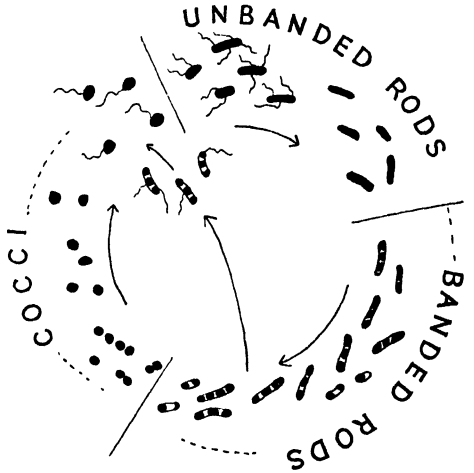


FIG. 29.—The life cycle of *Bacillus radicicola*.

phates. Under favourable conditions of moisture, temperature, and soil packing the motile forms can travel through the soil at the rate of 1 inch in twenty-four hours; in normal conditions the rate is probably slower. The older estimates of 1 inch in forty-eight to seventy-two hours may not be far out,[3] while in drier or more compact conditions spreading may be exceedingly slow.[4]

[1] See C. B. Lipman and L. W. Fowler, *Science*, 1915, 256 and 725, for the methods used.

[2] N. V. Joshi, *Pusa Memoirs Bacteriology*, 1920, 1, No. 9.

[3] K. F. Kellerman and E. H. Faucett, *Science*, N.S., 25, 806.

[4] See W. C. Frazier and E. B. Fred, *Soil Sci.*, 1922, 14, 29.

Multiplication occurs at two stages in the cycle but in different ways; the motile rods divide by binary fission and the banded rods by multiple fission, this being the more important. In consequence of these differences, the total

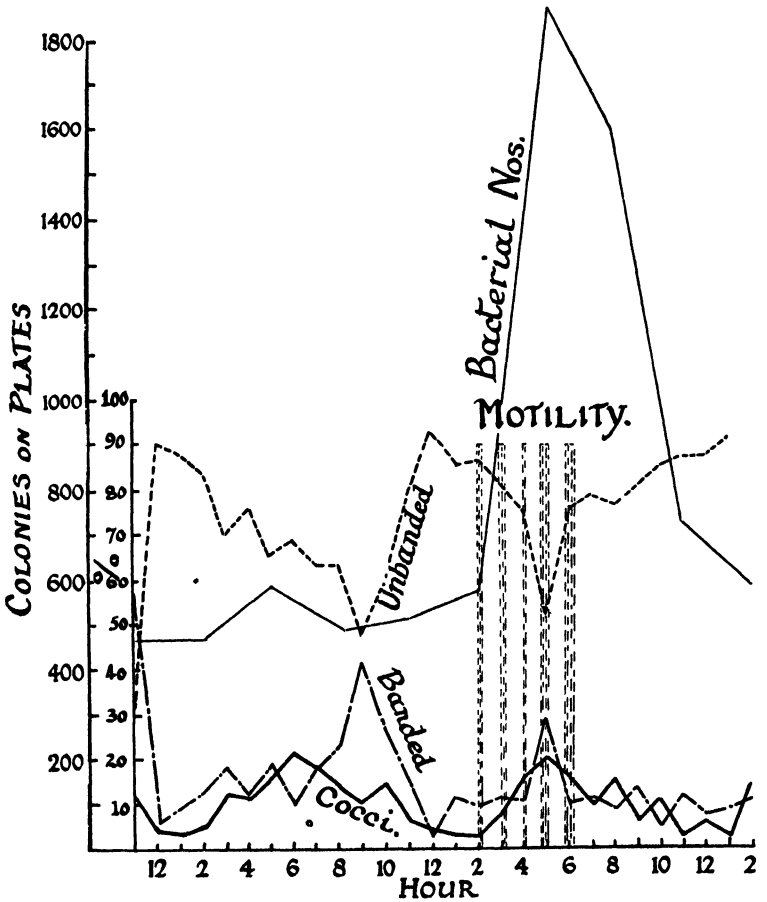


FIG. 30.—Total number of organisms, and percentages as cocci, banded and unbanded rods, at two-hourly intervals in a culture. (Thornton and Gangulee, 279.)

number of organisms in a soil does not remain constant, even under constant external conditions such as temperature, moisture supply, etc.; it continually varies (Fig. 30).

Some eleven or twelve varieties of the organism are known,

each of which can attack and enter certain leguminous crops, but not others.[1] They also respond differently to serological tests.[2] The varieties further differ in their tolerance of acidity, the limits ranging from *p*H 3·15 to *p*H 4·9; all, however, are more tolerant of acidity than azotobacter. Within the varieties there are strains, which, though capable of infecting the same plants, differ serologically and in their efficiency for nitrogen fixation,[3] usually also they show some difference in appearance on the plates or in their relative distribution on tap root and laterals.

The mode of entry of the organism into the plant was studied, first by Prazmowsky[4] for the pea, afterwards by Nobbe and Hiltner (214, 215), Marshall Ward (292), and Miss Dawson (80), who described the morphological changes; there is also much later work. The first step is that the organism attaches itself to a root hair near the tip and multiplies rapidly, softening the cell walls (shown by the curling over of the end of the hair) and thereby facilitating the entry of the organisms. But the bacteria cannot wander at will through the plant; they are confined by some mechanism not yet known to a slimy filament which grows down the interior of the root hair, penetrating the cell walls by some unknown means, till they reach the inner layer of the cortex of the root. The adjacent cells at first multiply rapidly to form a mass of small cells which constitutes the nodule; but these small cells, once they are entered by the bacteria, cease to divide and instead they enlarge considerably. Only at the distal end do the cells remain uninfected, and these continue division so that the nodule elongates.

The organisms are not yet, however, in connection with the circulating system of the plant, and until they are the symbiosis is not effective. Connection is established by

[1] T. J. Burrell and R. Hansen, *Ill. Bull.*, 202, 1917.
[2] Zippel, M. Klimmer, and R. Kruger, *Centr. Bakt. Par.*, 1914, 40, 256-265.
[3] J. W. Stevens, *Soil Sci.*, 1925, xx., 45-62.
[4] *Landw. Versuchs-Stat.*, 1890, 37, 161-238, and 1893, 38, 5-62.

vascular strands which grow out from the stele and surround the swollen cell tissue. Along these new vessels pass sugars and other nutrients and sources of energy from the plant to the organism, and the synthesised nitrogen compounds from the organism to the plant.

During the process the organisms have passed through their life cycle. They were non-motile cocci or pre-swarmers in the soil; they enter the root hair as swarmers; they become rods and multiply rapidly in the slime filament;[1] and branched banded rods or "bacteroids" in the nodule.

Infection proceeds most rapidly in plants weakened by nitrogen starvation; it scarcely occurs in plants growing vigorously on rich soils. Hiltner (134*a* and *b*), therefore, regarded the relationship as a parasitism, a view which has been confirmed by later workers. In a striking investigation W. E. Brenchley and H. G. Thornton (54) showed that the proper linking up of the bacteria with the plant is dependent on the presence of a trace of boron. In its absence there is little or no development of strands from the vascular system to the nodule; the bacteria, though in the root, are unable to draw sugar from the plant or to transmit to the plant the nitrogen compounds they have synthesised; instead they begin to attack the root tissues and cause considerable injury.

J. Golding (110*a*) was able to reproduce the nitrogen-fixing process artificially by growing the organisms in a suitable medium and continuously filtering off the products of metabolism. He thus succeeded in fixing considerable quantities of nitrogen. He has also shown that the reaction of the medium during actual fixation is alkaline, but changes to acid when fixation is stopped by the accumulation of nitrogen compounds. An actual loss then seems to set in.

The chemistry of the process is unknown; even the changes in the carbohydrates of the culture medium have not been worked out. Nitrogen fixation is known to take place in the nodule, which thus becomes richer in nitrogen than the

[1] Hiltner's "infection thread."

rest of the root,[1] and its final product is supposed to be a soluble protein which is passed on to the plant. Phosphates, calcium compounds, and carbon compounds, such as sugars, organic acids, the decomposition products of straw, etc., and according to Olaru,[2] manganese compounds, have a marked effect in stimulating nodule formation in soil cultures.[3]

The amount of nitrogen fixed in this way is so large that it is easily measured on the field. When the host plant dies, or is ploughed into the ground, the nitrogen compounds speedily change into nitrates. A uniform piece of ground at Rothamsted was divided into two parts; on one a crop of clover was taken, on the other barley was grown. After the crops were removed samples of soil were taken for analysis, and then barley was grown in both plots. The analytical results were :—

	Plot where Clover was Grown.	Plot where no Clover was Grown.
Nitrogen in crop (1873), lb. per acre	151·3 (in clover)	37·3 (in barley)
Nitrogen left in soil after crop was removed (1873), per cent. . .	·1566	·1416
Nitrogen in crop (1874), lb. per acre .	69·4 (in barley)	39·1 (in barley)

These facts are well known to the practical man, and are

[1] Stoklasa's analytical results with yellow lupines (*Landw. Jahrb.*, 1895, xxiv., 827) are :—

	Blossom Formed.	Seed Beginning to Form.	Seed Ripe.
Nitrogen in nodule, per cent. .	5·2	2·6	1·7
,, in rest of root, per cent. .	1·6	1·8	1·4

Whiting (*Ill. Bull.*, 179, 1915) has discussed this question also.

[2] *Compt. Rend.*, 1915, **160**, 280.

[3] J. K. Wilson, *Cornell Agric. Expt. Sta. Bull.*, 386, 1917. W. A. Albrecht, *Soil Sci.*, 1920, **9**, 275, and various papers from A. L. Whiting's laboratory, Illinois. This may explain the action of farmyard manure on the clover crop. (E. J. Russell, *Journ. Bd. Agric.*, 1919, **26**, 124.)

utilised for increasing the nitrogen supply of cultivated soils and for reclaiming barren sands and clays (p. 249).

The organisms are not invariably present in the soil, being restricted both by the geographical distribution of the host plants and by their own intolerance of acid conditions, and it may happen that a leguminous crop grown for the first time does not find its appropriate organism. The possibility of introducing cultures of the necessary organism into soils from which they are absent was first studied by Hiltner (134*a* and *b*, 215*b* and *c*), whose pioneering investigations have opened up various fruitful fields of work. Sufficient success was obtained to show the feasibility of the method, but the failures showed that all the conditions for success were not fully known. Gradually the difficulties have been overcome, particularly by C. Bartel (9) in Sweden, H. Christensen in Denmark, F. C. Harrison[1] in Canada, the Bureau of Plant Industry in the United States, and H. G. Thornton in England.[2] Inoculation is now a practicable process which has proved very useful in the growth of leguminous crops, particularly of lucerne.

Oxidation of Sulphur and its Compounds.

Sulphur enters into the composition of certain plant constituents, and it appears in the decomposition products in the soil as sulphate in which form it is readily assimilated by plants. The process was first studied by Brown and his co-workers (57*b*), and since by many others. Interest has centred round certain organisms that can oxidise elementary sulphur, apparently for the purpose of obtaining energy. Two studied by Waksman and Joffe[3] are remarkably interesting; one can live in purely inorganic solution, obtaining its carbon from carbon dioxide (like the nitrifying organism); another, *Thiobacillus thio-oxidans*, has an amazing tolerance for acidity and is said to continue growth till the *p*H of the

[1] F. C. Harrison and B. Barlow, *Centr. Bakt. Par.*, 1907, 19, 264, 426.
[2] *Rothamsted Ann. Rept.*, 1924, p. 24. [3] *Journ. Bact.*, 1922, 7, 239.

medium has fallen to 0·8, probably the record for living organisms. Advantage is taken of these properties in the United States to make the soil acid when needed, as, for example, in controlling potato scab (p. 386).

The reverse process, reduction of sulphates to sulphides, takes place in anaerobic conditions.

Oxidation of Ferrous and Manganous Carbonates.

Certain bacteria are able to oxidise ferrous and manganous carbonates and thus to obtain their energy. Winogradsky [1] studied *Leptothrix* and Lieske [2] a *Spirophyllum;* both organisms can live without organic matter, deriving their carbon from carbon dioxide. How far they are important in the soil is not known, most of the technical studies having been in connection with waters.

Effect of Micro-organisms on Soil Phosphorus and Potassium Compounds.

The organic phosphorus compounds in plant residues gradually break down in the soil and become converted into phosphates. The bacteria decomposing nucleo-proteins have been studied by A. Koch and A. Oelsner,[3] but it is not known what other organisms may take part. From time to time it has been suggested that insoluble mineral phosphates are dissolved by certain micro-organisms in the soil. This action certainly goes on in culture solutions under appropriate conditions, and it is effected in the soil to some extent by carbonic acid liberated by micro-organisms. Hopkins and Whiting [4] maintained that the nitrifying organisms could act direct on mineral phosphate in absence of calcium carbonate, but it is doubtful whether this is a normal occurrence

[1] Winogradsky, *Ueber Eisenbakterien, Botanischer Zeitung*, 1888, 46, 262.

[2] Lieske, R., "Physiologie von *Spirophyllum ferrugineum*, Ellis," *Jahrb. wiss. Botanik*, 1911, 49, 91-127; *Zur Ernahrungsphysiologie der Eisenbakterien* (*Centr. Bakt. Par.*, Abt. II., 1919, 49, 413-425).

[3] *Biochem. Zeit.*, 1922, 134, 76. [4] *Ill. Bull.*, 90, 1916.

in the soil. On the whole the evidence is against any action of soil organisms on mineral phosphates apart from that incidental to the decomposition of organic matter.

The decomposition of plant residues in the soil increases the amount of potassium available for plant growth. But there is no evidence of any direct action of micro-organisms; the breakdown of the complex organic compounds in itself liberates the potassium from the tissues, while any effect on the insoluble minerals of the soil is more simply attributable to chemical actions.

Swamp and Paddy Soils.

In the East—in India, Japan, etc.—considerable quantities of rice are grown on swamp soils, and the biochemical changes differ considerably from those in normal soils. Brizi has shown that algæ play an important part in aerating these soils by taking up CO_2 from the swamp water and converting it into oxygen which is liberated (p. 298).

As already pointed out, nitrification does not go on but the converse process, denitrification occurs, so that if nitrogenous artificial manures are to be used nitrates are out of the question, and organic manures and ammonium salts only are possible (p. 260).

Green manuring is, however, commonly adopted and considerably benefits the crop: the decompositions taking place when the green crop is ploughed in are effected by bacteria, the fungi being apparently wholly inactive.[2] Some of the changes have been studied by W. H. Harrison and Aiyer (127). In the body of the soil marsh gas, hydrogen, and CO_2 are evolved as would be expected from the anaerobic decomposition of cellulose. But at the surface of the soil the change is entirely different and the gases consist of oxygen and nitrogen only. The difference was traced to a film of organisms which have

[1] W. P. Kelley, *Journ. Agric. Res.*, 1918, **12**, 682.

[2] Thaysen, Baker, and Bunker, *Biochem. Journ.*, 1926, **20**, 210-216.

the power of converting the marsh gas into CO_2[1] and this into oxygen. The oxygen is directly beneficial to the plant by providing for the aeration of the root. The production of oxygen was suppressed when the film was killed by adding copper sulphate: marsh gas and hydrogen then appeared at the surface.

It is only so long as the film is working that green manuring is beneficial to the crop. The plant roots must have oxygen and the film supplies it. The green manure, therefore, supplies not only ammonia, but also dissolved oxygen.

It would be interesting to have studies of the conditions obtaining in water-cress beds.

The Effect of Adding Plant Residues to the Soil.

The addition of plant residues to the soil is a normal occurrence and a recognised method of manuring land. The effects produced depend on the proportions of carbohydrate and protein present in the residues.[2]

If the conditions are favourable to the activity of micro-organisms the result of the addition is to cause an increase in numbers and in activity of the micro-organisms: this is shown by increases in oxygen absorption and CO_2 evolution. The increase is rapid if the material is easily decomposed (*e.g.* clover residues), but it is soon followed by a fall; it is slower but longer sustained if the material is less easily decomposed (*e.g.* timothy residues).[3] The increased numbers may have any of the following effects:—

1. If the material is rich in energy supply but not in nitrogen (*e.g.* carbohydrates) the organisms may assimilate

[1] The biological oxidation of marsh gas has been described by Kaserer and Söhngen and by I. Giglioli and G. Masoni (Pisa: *Chim. Agric. Stud. e. Ricerche*, 1909-1914, part 22, 76-108). For the effect of algæ see p. 298.

[2] For further discussion see H. B. Hutchinson (140*e*); P. E. Brown and F. E. Allison (58); P. Felber, *Mitt. Landw. Hochschule f. Bodenkulture in Wien*, 1916, 3, 23; S. A. Waksman (289*c*).

[3] B. D. Wilson and J. K. Wilson, *Cornell Memoir*, 95, 1925.

nitrates or ammonia already existing in the soil and thus reduce the amounts of these substances present (p. 266). These circumstances are favourable to the nitrogen-fixing bacteria, and if the temperature is sufficiently high there may be an increase in the amount of nitrogen fixed (p. 274). The assimilation effects are temporarily harmful, but the fixation is ultimately beneficial to the growing plant. Fig. 31 shows the various changes when straw is added to the soil.

2. If the material is rich in nitrogen (*e.g.* protein), the

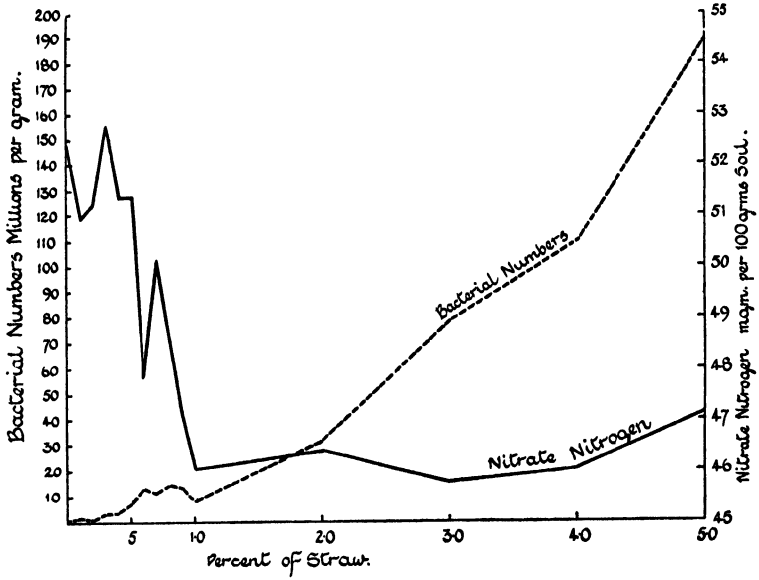


FIG. 31.—Effect of straw on soil biological processes after twelve weeks. (T. J. Murray, *Soil Sci.*, 1921, **12**, 233.)

organisms will produce considerable quantities of ammonia in obtaining their energy supplies. The ammonia is then converted into nitrate. This effect is wholly beneficial to the plant.

The nitrate is the most easily lost of all the nitrogen compounds in the soil. It is liable to be leached out, absorbed by plants or decomposed. Further, losses of gaseous nitrogen are liable to occur when much nitrogenous organic matter is present (p. 263).

The net result of these various activities is that the ratio of carbon to nitrogen in a soil is not easily disturbed; in humid conditions it is about 10. Addition of non-nitrogenous organic matter, such as starch, cellulose or straw (which is poor in nitrogen) sets in train the process of nitrogen fixation which increases the amount of nitrogen at the expense of a much larger amount of carbon, and also the microbiological assimilation of nitrates, which, while reducing the amount of carbon, protects the nitrogen already present against loss. Both sets of processes decrease the carbon and increase the nitrogen, thus restoring the original ratio.

Addition of nitrogenous organic matter would increase the proportion of nitrogen, but it sets going a loss of gaseous nitrogen, and also nitrification which produces nitrates easily lost. These losses of nitrogen proportionately exceed those of carbon, so that again the original ratio is restored.

3. If the air supply is insufficient—either generally or locally—but other conditions are favourable, the organisms will obtain some of their oxygen from the nitrates present in the soil, and gaseous nitrogen will be evolved. This effect is wholly harmful to the plant (p. 260).

4. If, however, conditions are unfavourable (*e.g.* if there is acidity or too low a temperature) the organisms will not act; the material will only partly decompose and it will accumulate as peat (p. 238).

Summary of the Changes Taking Place and of the Agencies Involved.

1. Decomposition of plant residues, animal remains, etc., with production of—

(*a*) Nitrates essential for plant nutrition;

(*b*) CO_2 which effects various changes in the soil;

(*c*) Mineral residues: phosphates, potassium, calcium, and other salts left after the plant tissue is decomposed;

(*d*) Humus, which has important physical effects on the soil.

2. Decomposition of plant constituents or of by-products from the above reactions, which, if they remained in the soil, would be harmful to the growing plant.

3. A cycle of changes affecting the nitrogen compounds, in some of which they are decomposed with formation of nitrate or evolution of gaseous nitrogen, in others the gaseous nitrogen is fixed and converted into protein. The quantitative effect of these changes is to maintain the relative proportions of carbon and nitrogen fairly uniform; in humid conditions the ratio $\frac{C}{N}$ is roughly between 10 and 12. The absolute amounts vary between certain limits. In humid conditions the lower limit is reached in cultivated land and the upper limit in land covered with grass or other vegetation not removed from the soil. In arid conditions the limits are narrower, and the position is reversed, there being a tendency for the upper limit to be reached on the cultivated land.

These changes are represented diagrammatically in Fig. 32. Many of the changes closely resemble those occurring during sewage purification, as worked out by Adeney (1) and Fowler,[1] one of the main differences being that they proceed more quickly in sewage than in soil.

There is good reason to suppose that the changes are in the main brought about by micro-organisms, but the evidence is indirect, since no satisfactory experiments have been made in sterilised soil, the methods hitherto adopted for sterilisation having always themselves produced considerable changes in the soil.

The conclusion is based on two general lines of evidence :—

1. Many of the changes are diminished or stopped altogether when an antiseptic is added to the soil.

2. The various changes are known to be normal activities of organisms commonly occurring in soil.

Neither of these is wholly convincing. The action of antiseptics is not conclusive proof of biological activity, since

[1] *Bacteriological and Enzyme Chemistry*, London, 1911.

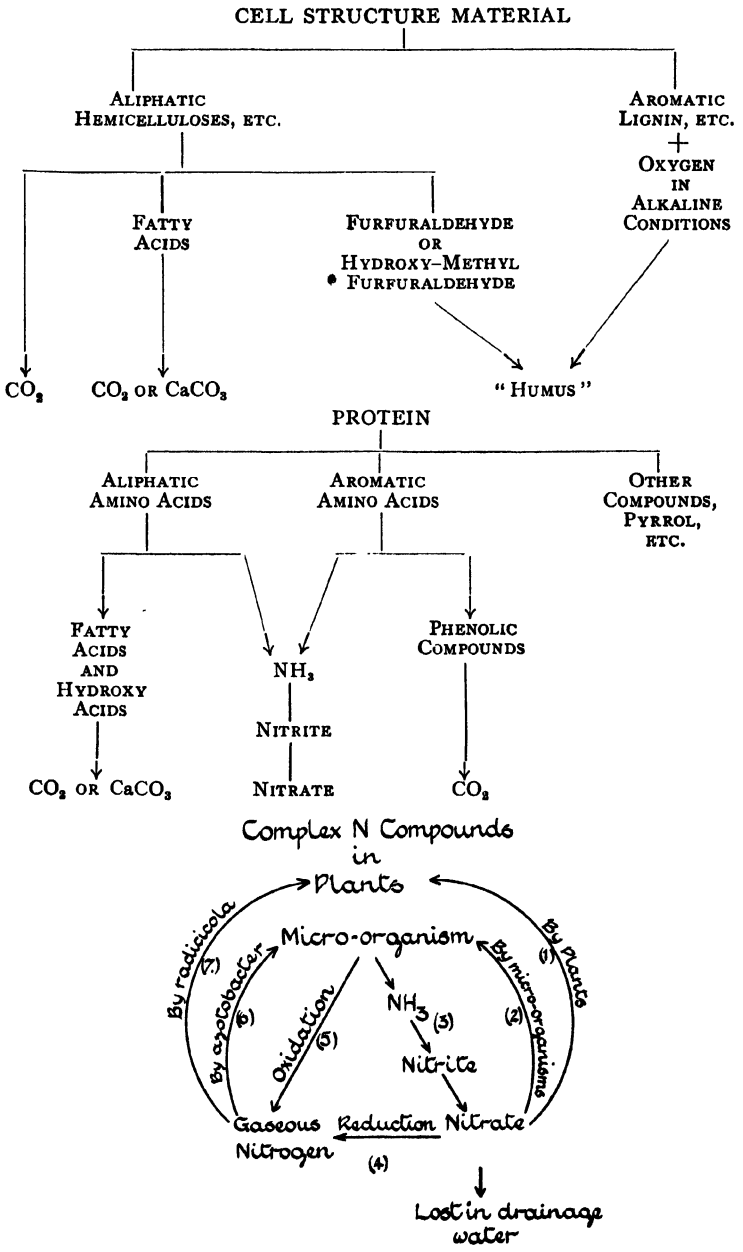


FIG. 32.—Scheme showing decomposition of plant residues in soil, so far as is at present known

many catalysts are "poisoned" by the same agents. But, on the whole, the biological explanation is simpler than any other. In so far as the organisms are leading a trophic existence in the soil, they must effect changes to furnish themselves with nutrients and energy; only if they were there merely as resting forms would alternative chemical explanations be necessary.

CHAPTER VI.

THE MICRO-ORGANIC POPULATION OF THE SOIL AND ITS RELATION TO THE GROWTH OF PLANTS.

THE investigations described in the last chapter have shown that the soil contains many micro-organisms capable of effecting changes of great importance to the living plant. The organisms first discovered were bacteria, and for some long time these were regarded as the only living microscopic occupants of the soil. Later work has revealed many other forms including fungi and actinomycetes, algæ, protozoa, and nematodes. These have usually been picked out from the soil by cultural methods and studied in the laboratory; little is yet known of the way in which they live in natural conditions in the soil.

The older conception of the soil population arose quite naturally from the way in which it first came into prominence. It was supposed to be engaged in producing plant food and to be made up of groups of specialised organisms, each capable of effecting certain changes. The following were recognised :—

1. Ammonifying.
2. Nitrifying.
3. Nitrogen fixing.
4. Denitrifying.
5. Pectin fermenters.

Their actions in the soil were deduced from the results of laboratory culture experiments, and values were assigned to the "ammonifying power," "nitrifying power," etc., which were used in comparing different soils and manures. This method of investigation was introduced by Remy (235*a*), and developed by Löhnis (178*b*), and J. G. Lipman (171, 172); it

achieved considerable popularity because of the ease and simplicity of its manipulation.

The " nitrifying power " was measured by putting a definite weight of the soil into Omeliansky's or Ashby's medium (p. 256), incubating under definite conditions and determining the amount of nitrate formed. For measuring " ammonifying power " 1 per cent. peptone solution was used and for the " nitrogen fixing power " Beijerinck's or some similar solution.

The method had a certain value for the testing of soils, and there was usually some relationship between the various " powers " and the productiveness. On the whole, for a reason given later (p. 295), the " nitrifying power " was most nearly related to productiveness and " ammonifying power " least.[1] But the indications were never very certain, the exceptions could not usually be explained and little useful information emerged. The determination of " nitrogen fixing power " has alone survived as an analytical method, but even this is used more for estimating the degree of acidity of soil than as a measure of biological activity.

In addition to these attempts at finding an integration or summation value of the activities of the soil population, bacteriologists attempted to study the members themselves. Methods for isolating the organisms forming the various groups were devised, usually on the lines of Winogradsky's " elective " method (p. 268), and they led to some striking discoveries, particularly of organisms limited in their range of activities (like the nitrifying organisms) or possessing some special property, such as the power of fixing nitrogen or oxidising phenol, that enables them to survive when others perish. Further investigations showed, however, that these cultural methods do not give a true picture of the population of organisms as they live and work in natural soil. In the first place many of the organisms exist in two states, one

[1] For recent critical studies see S. A. Waksman, *Soil Sci.*, 1923, 16, 55-67. Of the older papers see P. E. Brown (57*a*), P. S. Burgess (63), Stevens and Withers (269), Ehrenberg (94*b*). The position is reversed on alkali soils.

active or trophic, and the other resting or comparatively inert. The line between them may not be sharp, and there may be constant change from one to the other as the conditions in the soil vary. But it is not possible to discover by culture methods whether any particular organism found in the soil is active or simply resting.

Further, it was found that only few of the soil organisms are limited to one type of activity; most of them have considerable powers of changing their actions when the conditions alter. The grouping into ammonifiers, nitrogen fixers, etc., therefore had no significance in the soil, and meant nothing more than that the organisms could, in the particular conditions of the experiment, bring about the particular changes observed. The method had a certain validity when applied to the specialised nitrifying organisms, and its indications showed some relation to the facts of soil fertility. But it did not hold well for ammonia production, this being a property shared by many organisms.

A new conception of the activities of the soil population has therefore grown up. The organisms are now studied, not merely as producers of plant food, but as independent forms of life seeking food and energy material and possessing a range of choice in their quest. They may effect one change under one set of circumstances, but another change under other circumstances. Some of the organisms have a very wide choice, others are more limited. The action most conspicuous in culture media is not necessarily the customary action in the soil. The proper use of culture studies is to discover the morphology and general physiology of the organisms and so indicate the limits within which their activities may vary. Nothing but studies in the soil itself can show which particular phases of activity are usual in the soil. The outcome of the development of this idea is that investigators are devising methods for work in the soil in addition to the work (which must necessarily always continue) in culture media in the laboratory.

Two general methods have been introduced :—

1. The statistical method used at Rothamsted in which the organisms are counted daily or at shorter intervals in a natural soil in the field, the counts being sufficiently replicated, and sufficiently long continued, to allow statistical examination of the significance of the results. The data are then correlated, under proper statistical control, with other quantities.

2. The direct method of microscopic examination of the soil for active forms, which has been often tried and given up in the past, but is now on a better basis since Winogradsky developed his staining technique, using an acid stain, *e.g.* erythrosine, which shows up the active forms of bacteria but not the spores or minute soil particles (313).

The application of these methods has shown the invariable presence of living organisms, not only in surface soils, but also in subsoils. Even freshly won coal was found to contain bacteria [1] which had probably travelled down with the water. So far as the writer can discover, the only record of soil or dust absolutely free from living organisms is the dust from a newly-opened 18th dynasty Egyptian tomb which had been left dry and undisturbed for over three thousand years.[2]

We shall now proceed to study the different groups of organisms present.

The Algæ.

The soil has a characteristic algal flora which appears to be substantially the same in general type all over the world so far as investigation has gone. B. M. Bristol Roach (56) finds that the central group of almost universal occurrence includes *Hantzschia amphioxys*, *Trochiscia aspera*, *Chlorococcum humicola*, *Bumilleria exilis*, and rather less frequently, *Ulothrix subtilis* or types similar to these.[3]

[1] H. Schroeder, *Centr. Bakt. Par.*, Abt. II., 1914, 41, 460.
[2] A. C. Thaysen, Private Communication.
[3] See also F. E. Fritsch, *Journ. Ecology*, 1922, 10, 220.

Algæ grow and multiply in two very different conditions in the soil.

1. On the surface exposed to light, where, by means of their chlorophyll, they fix the energy of sunlight and assimilate carbon dioxide thus producing complex organic matter. In these conditions the algæ are suppliers of energy material to the soil, and they assimilate nitrates and other nutrients from the soil just as green plants would do.

2. In the depths of the soil beyond the reach of light, where the chlorophyll ceases to function (though it may still remain in being) and the organisms obtain their energy and carbon from preformed organic matter; *i.e.* they live saprophytically. They now become consumers of the soil stock of energy material. In Dr. Bristol Roach's experiments the soil algæ always retained this property of assimilating complex organic matter, even when living in light, as on the surface of the soil. The chlorophyll apparatus may, therefore, be regarded as supplementary, coming into play when light is available, but not otherwise.

Of the organic substances tested, the hexose sugars were the most suitable nutrients. The nitrogen is usually assimilated as nitrate, but some soil algæ can assimilate ammonia and a few can attack protein (gelatin) direct.

Although its general types persist, the algal flora varies somewhat in different soil conditions. These ecological aspects were studied by Esmarch (96) in his pioneering investigation of the blue-green algæ of certain African and German soils; other workers are quoted by Dr. Bristol Roach in the Rothamsted Monograph.[1] The blue-green algæ are more in evidence in warmer, and the green algæ in cooler, conditions; both, however, require sufficient moisture. On the Rothamsted arable fields the floral type is not obviously affected by the manuring, but the numbers of organisms are smallest on the unmanured plot and largest on the one receiving farmyard manure; this holds also for surface growth. The

[1] *The Micro-organisms of the Soil*, Longmans, 1923.

Rothamsted grass fields have not been examined, but Esmarch found more species in grassland than on arable; blue-green algæ, however, appear to be commoner on arable land than on grass land, while diatoms—usually very small ones—occur in numbers in old gardens. The influence of soil reaction was examined by J. B. Petersen in Denmark; he showed that the flora of acid soils was dominated by *Mesotænium violascens*, *Zygnema ericetorum*, and two species of *Coccomyxa*, while the flora of neutral soils was largely *Mesotænium macrococcum*, *Hormidium* and *Vaucheria*.

The activities of soil algæ important to plant growth appear to be :—

1. The addition of organic matter to the soil. This action is confined to the surface growth and is dependent on light. It is valuable in most circumstances, but on newly-formed soils it is of the greatest importance. After the complete destruction of the soil and vegetation of Krakatoa by volcanic eruption in 1883 the first colonists of the barren mineral layer were six species of blue-green algæ, viz. *Tolypothrix*, *Symploca*, *Anabaena*, and three species of *Lyngbya*, which gradually spread over the whole surface, and made the beginning of a soil on which seeds brought by birds could grow.[1] Fritsch has also given examples of colonisation of new ground in Ceylon.

2. The assimilation of nitrate (p. 266).[2]

3. Symbiosis with azotobacter leading to an increase in the amount of gaseous nitrogen fixed (p. 270).

4. The assimilation of easily oxidisable organic matter, *e.g.* sugars.

5. In swamp soils algæ facilitate aeration of the roots by decomposing the CO_2 dissolved in the water and liberating oxygen, which still remains in solution. Brizi[3] observed

[1] Treub, *Ann. Jard. Bot. Buitenzorg*, 1888, 7, 221-223.

[2] Discussed long ago by Gautier and Drouin, *Compt. Rend.*, 1888, 106, 754 *et seq.*

[3] *Ann Instit. Agrar.*, Milan, 1905, 6, 84-89. See also Harrison and Aiyer (127).

that the "Brusone" disease of marsh rice, which he attributed to inadequate aeration of the roots, did not appear when algæ developed plentifully on the surface of the marsh.

In addition some of the algæ have been credited with the power of fixing gaseous nitrogen, but this is now known to be incorrect.[1]

The numbers of the green algæ in the soil can be roughly estimated by an appropriate dilution method, but the blue-green forms cannot be counted. The estimate is not sufficiently trustworthy to allow of the application of statistical methods, but minimum values of the order of 100,000 green algæ per gram of soil have been recorded by Dr. Bristol Roach, and the blue-green forms may be equally numerous. Treating the cells as if they were spheres of radius 10μ (which is not far out), the mass of algal protoplasm for a population of this size would fall intermediate between that of bacteria countable by the plate method and of protozoa, being roughly three times that of the former and one-third that of the latter.

Francé (102) claims that the numbers of algæ in the soil reach a maximum in the spring, which, if true, would accord with the behaviour of bacteria and protozoa.

Fungi.

It has long been known that fungi occur in the soil, and as long ago as 1886 no less than eleven different species were isolated by Adametz.[2] Subsequent workers have greatly enlarged the list and more than 200 species have now been described as soil fungi.

The investigations have fallen into several groups. Some workers, as Butler[3] in India, Hagem[4] in Norway, and

[1] B. Muriel Bristol (now Bristol Roach) and H. J. Page, *Ann. App. Biol.*, 1923, 10, 1-30.

[2] L. Adametz, *Untersuchungen über die niederen Pilze der Ackerkrume* (*Inaug. Diss.*, Leipzig, 1886).

[3] E. J. Butler, *An Account of the Genus Pythium and some Chytridiaceæ* (*Mem. Dept. Agric.*, India, *Bot. Ser.*, 5, 1, 1-160, 1907).

[4] O. Hagem, *Untersuchungen über norwegische Mucorineen* (*Videns Skrift*, I., *Math. Nat. Kl.*, 1907, No. 7; Part II., 1910, No. 4).

Lendner [1] in Switzerland, have confined themselves mainly to particular types, and have not attempted a comprehensive survey of the whole field. Others have tried to ascertain how far disease-producing fungi could live saprophytically in the soil: apparently certain species of Fusarium, Pythium and others can do this. Pratt [2] has isolated fungi which cause disease in potatoes from virgin desert lands and also from Idaho soils that have never been cropped with potatoes.

The more serious problem of studying the fungus flora of the soil as a whole has been attempted in Holland by Oudemans and Koning,[3] in the United States by Waksman (288*b*) and P. E. Brown, and in England by Miss E. Dale.[4] It is now under investigation at Rothamsted by W. B. Brierley.

The great difficulty is the lack of suitable methods of investigation: neither the morphologists nor the physiologists have yet developed precise, simple methods. The fungi are invariably isolated from the soil by means of cultural media, but there is no means of ensuring that the medium used is suitable for the development of all forms that may be present: many of the parasitic forms and others in addition are doubtless missed. Further, the morphological characters may vary with different media: [5] hence it is impossible to describe the organisms as they exist in the soil. Nor are the physiological properties entirely satisfactory as criteria: they may vary with the physiological condition of the organisms and in any case are not sharply distinct for the different strains. Rigid identification is, therefore, very difficult.

Again, there is no very satisfactory method of estimating the numbers of various fungi in the soil. When used for fungi, the plating methods devised for bacteria and for pro-

[1] A. Lendner, *Les Mucorinées de la Suisse*, Berne, 1908.

[2] O. A. Pratt, *Journ. Agric. Res.*, 1918, **13**, 73-100.

[3] *Arch. Neerland. Sci. Exact et Nat.*, 1902 [2], **7**, 266-298.

[4] *Ann. Mycol.*, 1912, **10**, 452-477, and 1914, **12**, 32-62.

[5] For a discussion of the phenomena see W. B. Brierley, *Some Concepts in Mycology—An Attempt at Synthesis* (*Trans. Brit. Mycol. Soc.*, VI., Part II., 1919).

tozoa suffer from the drawback that they involve the breaking up of pieces of mycelium and the scattering of clusters of spores, with the result that a single fragment of fungus in the soil might appear as hundreds, or even thousands, of individuals on the plates. The methods can, however, be standardised to give relatively satisfactory results.

Up to the present neither the statistical nor the direct method has been found applicable to the study of soil fungi; our present knowledge is based on the pioneering methods.

It is generally assumed by the investigators that there is a central group of fungi in the soil so characteristic as to constitute a soil flora, though the evidence is not yet very convincing. But it is not known whether the species forming the flora show anything like a geographical distribution, or whether, as happens for other organisms, the flora comprises substantially the same members in all parts of the world. The types most commonly found in temperate regions, and therefore presumed to be the commonest, are the *Penicillia* and *Mucors;* in addition, *Fusarium*, *Aspergillus*, *Trichoderma* and *Cladosporium* are common. In the warmer Southern States, however (*e.g.* Texas), Waksman found *Aspergillus* more frequently than *Penicillium.*

The ecological studies have not yet clearly shown whether or how far the fungus flora is affected by soil conditions. The older workers held simple and definite views to which modern workers are unwilling to commit themselves. It was formerly supposed, and the view was emphasised by Ramann (231*a*), that fungi predominate in acid soils and bacteria in neutral soils. This generalisation drew support from the known fact that fungi tolerate acid media better than do bacteria, and, indeed, they are separated from bacteria by growing them on a carefully regulated acid medium. Beyond its inherent probability, however, there is little direct proof. Hagem concluded that the differences in soil conditions affected the proponderance of the various species of *Mucor* in the soil flora; he found, for instance, that the species in forest soils

differed from those in cultivated soils; indeed, there were suggestions of ecological communities of fungi like those of higher plants. But neither F. C. Werkenthin,[1] H. M. Goddard, nor W. B. Brierley [2] could find any consistent differences in the fungus floras of different soils; there are minor differences, however, which may be significant.

In spite of the difficulties of estimating the numbers of fungi in the soil, certain general results seem to emerge from the data already accumulated. Waksman found more individuals and more species in fertile soils rich in organic matter than in infertile ones. On the other hand, neither the temperature nor the moisture content of the soil seem markedly to affect the numbers of fungi on the six plots at Iowa studied by Brown and Halversen (59). Aeration appears to be very important; fungi are more numerous in the surface layers than lower down. It is said that they cannot act in water-logged soils; indeed, Snell [3] recommends immersion in water as an infallible means of preserving from timber rot.

It cannot be said as yet whether there are seasonal fluctuations in numbers or activity, such as are shown by bacteria and protozoa.

All species of fungi can utilise carbohydrates for both energy and tissue formation. Taken generally, they are among the most economical of soil organisms in their metabolic processes, dissipating less carbon as CO_2 and assimilating more (sometimes as much as 60 per cent.) for the formation of tissue than any other organisms.

The ability to decompose cellulose is more common among fungi than among bacteria. It was first studied in detail by van Iterson (143), and afterwards by McBeth and Scales (185*b*), who found the most active cellulose decomposers to be the *Penicillia*, *Aspergilli*, *Trichodermæ*, and *Verticillia*; on the

[1] F. C. Werkenthin, *Fungus Flora of Texas Soils*, Phytopath, 1916, **6**; H. M. Goddard, *Bot. Gaz.*, 1913, **56**.

[2] Rothamsted Monograph, *Micro-organisms of the Soil* (Longmans), p. 120.

[3] *Paper*, 1921, **28**, 22. See also Thaysen, *Biochem. Journ.* 1926, **20**, 210-216.

other hand, the *Mucorales* apparently effect little or no decomposition of cellulose.[1] The chemical changes involved are unknown, but it is unlikely that the reaction would proceed by itself in the soil; in all probability the soil bacteria would participate.

When ample supplies of carbohydrate (including cellulose) are present, the most economical nitrogen nutrients are the amino-acids (Czapek).[2] In absence of sufficient supplies of carbohydrate, Waksman shows that the fungi can obtain both energy and nitrogen from soil protein compounds, but in this case more degradation occurs than is necessary to supply the nitrogen required, and consequently ammonia remains over (289*c*). Under suitable conditions certain fungi (*e.g. Trichoderma Koningi*) can produce ammonia more rapidly than bacteria (McLean and Wilson, 188). Fungi have no power of oxidising ammonia to nitrates. They can, however, readily assimilate both ammonia and nitrates, and they have been supposed by Ehrenberg (94*c*) to cause considerable locking up of these compounds in the soil.

It was at one time thought that fungi could fix gaseous nitrogen, but Duggar and Davis,[3] in a careful series of experiments, were unable to obtain evidence that any fungus excepting *Phoma betæ* possessed this property.[4] E. V. Abbott's experiments indicate that fungi probably have less effect on the inorganic than on the organic constituents of the soil.[5]

It is impossible on present knowledge to assess the importance of fungi in soil fertility. The decomposition of cellulosic material is undoubtedly beneficial and may yet justify the old view that fungi are the humus formers of the soil

[1] Waksman, *Soil Sci.*, 1918, **6**, 137.

[2] *Beit. Chem. Physiol. u. Path.*, 1901-1902, **1**, 538; **2**, 557; **3**, 47.

[3] *Ann. Mo. Bot. Gard.*, 1916, **3**, 413-437.

[4] According to Ternetz (*Jahrb. f. wiss. Bot.*, 1907, **44**, 353-408) *Phoma radicis* can also assimilate gaseous nitrogen. See also M. C. Rayner, *New Phytologist*, 1926, **25**, 171-190.

[5] *Soil Sci.*, 1923, **16**, 207-216.

(Ramann, 231): on the other hand, the locking up of nitrogen compounds is a disadvantage which, however, would be considerably counterbalanced if the substance of the mycelium were readily decomposable by bacteria on the death of the organism. Many of the fungi are closely associated with growing plants; some are, or can, become parasitic and cause disease; others enter into more beneficial relationships as mycorrhiza. The heaths, birch, hazel, and beech among common British plants, and orchids in the tropics, all form associations of this kind.[1] One fungus (*Pyronema confluens*) seems specially favoured by something produced when soil is heated above 100° C. and grows strongly on sterilised or burnt soils.[2]

Actinomycetes.

This group of organisms, sometimes included in the fungi and sometimes in the bacteria, is of frequent occurrence in the soil. Conn (70*b*) estimated that they were one-quarter as numerous as the bacteria in arable soil and one-half as numerous in grassland. It is very doubtful, however, whether any counting method is reliable. Waksman and Curtis (289*a*) have made an extensive study of this group and have described thirty or forty soil species. Apparently the actinomycetes decompose cellulose though they do not readily produce ammonia from protein. It is said also that they can reduce nitrates to nitrites. Certain forms are associated with disease.[3]

Bacteria.

Historically, bacteria are by far the most important group of organisms in the soil. They were the first to be isolated, and for long were regarded as the only organisms important in normal conditions; they therefore had laboratories and de-

[1] For the trees see E. Melin, *Untersuchungen über die Bedeutung der Baummykorrhyza*, Gustav Fischer, 1926. For orchids, N. Bernard, *Ann. Sci. Nat.* (*Bot. Ser.*), 9, 1909. For heaths, M. C. Rayner, *Ann. Bot.*, 1915, 29, 97-133, and *New Phytologist*, 1926, 25, 1, 65, 171.

[2] For a study of this organism see W. Robinson, *Ann. Bot.*, 1926, 40, 245-272.

[3] W. A. Millard and S. Burr, *Ann. App. Biol.*, 1926, 13, 580.

partments set up for their study in most of the agricultural research institutions.

The Bacterial Flora of the Soil.—Unfortunately for ease of identification, bacteria change their appearance so easily with slight variations in conditions, and many of them can effect so wide a range of chemical reactions, that it is difficult to characterise them exactly. The individual species of the flora arising on the plates have, therefore, not been fully catalogued. Conn [1] found that about 5 to 10 per cent. of the colonies on gelatine plates consisted of large spore-forming bacteria related to *Bacillus subtilis;* about 10 per cent. were non-sporing organisms related to *Pseudomonas fluorescens*, rapidly liquefying gelatine; while 40 to 75 per cent. were short rods with much less, if any, power of liquefying gelatine. No more definite description has been given, though with the increasing efforts to standardise the diagnosis, such as those of the American Society of Bacteriologists and others, more precision may be expected in the future.

We are not, therefore, in a position to describe the soil bacteria in any detail. But there seems little doubt that they are not a fortuitous assemblage of all the possible forms, but represent a definite central flora, with, however, an admixture of stray and casual organisms.

The common soil bacteria seem to be the same all the world over so far as it is possible to judge; any identifiable organism common in one place usually occurs in any other region where it is sought. Only two or three forms show clear signs of discontinuous geographical distribution, viz. :—

1. Certain of the nodule organisms, such as those associated with lucerne, soy bean, crotalaria, etc., which seem to be confined in their distribution to the districts occupied by the host plant.

2. Certain of the phenol decomposing organisms.[2]

[1] *Centr. Bakt. Par.*, ii., 1910, **28**, 422, and *Journ. Bact.*, 1917, **2**, 35.

[2] Rothamsted Monograph, *Micro-organisms of the Soil*, p. 24. These, however, are the organisms most closely studied. It is possible that fuller search might reveal many others.

From time to time local forms of widely distributed organisms have been described, *e.g.* the Nitrosomonas found by Omeliansky in Java and *Azotobacter Vinelandii* found by J. G. Lipman in New Jersey, but whether these are truly local or simply rare forms that might be found elsewhere with systematic search, or stages in a complex cycle, is not known. Nor is it known whether, as happens with algæ and protozoa, the number of species increases as the conditions become more favourable to micro-organic life.

Some, if not all, of the bacteria pass through a complex life cycle in the soil (pp. 240, 269 and 278).

The Number of Bacteria in the Soil.—It has not yet been possible to estimate the total number of bacteria in a soil because of the impossibility of finding any one medium on which they will all grow. Bacteriologists have, for the present, ceased to attempt estimates of the total numbers, but confine themselves to estimates made by rigidly standardised methods which give comparable though not absolute results. The numbers given by the Rothamsted standard method devised by H. G. Thornton (p. 464) are commonly of the order of twenty to forty millions per gram in arable soil (p. 315).

The numbers of bacteria in the soil, however, do not remain constant, even under apparently constant external conditions. The fluctuations were observed by King and Doryland in 1909 (148); they are well seen in the Rothamsted investigations; by themselves they show no uniformity, but they are inversely related to the fluctuations in numbers of amœbæ discussed on page 318. The fluctuations of some of the organisms may be attributed to differences in rates of reproduction in the different stages of the life cycle, such as those worked out by Thornton and Gangulee for *Bacillus radicicola* (p. 278). But they may not all be so caused, for Cutler has shown that they can quite simply be explained by the fluctuations in numbers of amœbæ (which might themselves be reproduction phenomena). When bacteria alone are present in the soil their numbers remain much more steady (p. 331).

Superimposed on these daily fluctuations are the seasonal fluctuations which are well seen by plotting ten-day averages of daily counts (Fig. 33). The numbers are high in spring and autumn and low in summer and winter. Conn observed similar fluctuations. N. R. Smith and S. Warden [1] claim that their

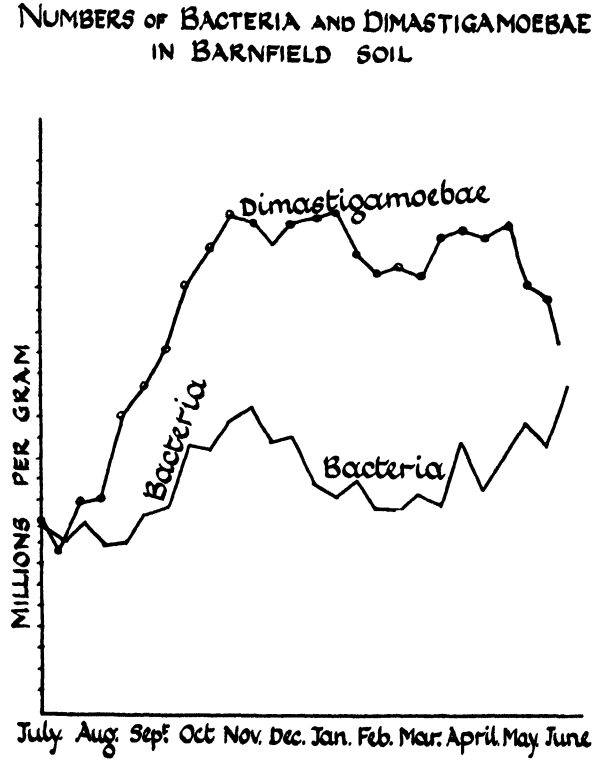


FIG. 33.—Seasonal fluctuations in numbers of bacteria and of protozoa (plotted on logarithmic scale) in Barnfield soil, Rothamsted. (Cutler, Crump and Sandon (74).)

medium shows no fluctuations in numbers. If this be correct, and in view of the fact that the medium gives higher numbers than Thornton's, it might mean that some organisms fluctuate in a different direction from others.

Effect of External Conditions on Bacterial Numbers.—The existence of these fluctuations makes it very difficult to trace

[1] *Journ. Agric. Res.*, 1925, 31, 501-517.

the effect of external conditions on the numbers of bacteria in the soil. Small numbers of counts are of little use; it is necessary to have sufficiently extensive data to justify the application of statistical methods. Unfortunately, many investigations had been made before this was recognised. But in several directions their results are fairly concordant, and the cumulative evidence justifies certain conclusions.

The chief factor influencing bacterial numbers in the soil is the amount of energy material available, the numbers rapidly rising when the energy material increases. There appears also to be a close connection between bacterial numbers and nutrient supplies, especially of nitrogen and phosphate, though this has been established more clearly for bacterial activity than for numbers.[1]

Soil bacteria are much affected by the reaction of the medium. Fig. 34A shows the numbers present in an acid soil to portions of which calcium carbonate has been added.[2] In the original soil the numbers are low. Addition of small amounts of calcium carbonate have but little effect, nor have larger ones till the soil is neutral according to the Veitch method; then a marked rise occurs. Further additions of calcium carbonate, however, cause a gradual fall; both rise and fall are intensified when phosphate is added. Similar results were obtained by Fabricius and von Feilitzen (99*b*); 0·1 million bacteria occurred per gram in raw moorland soil, but 7 millions per gram in adjoining soil that had been cultivated and manured.[3]

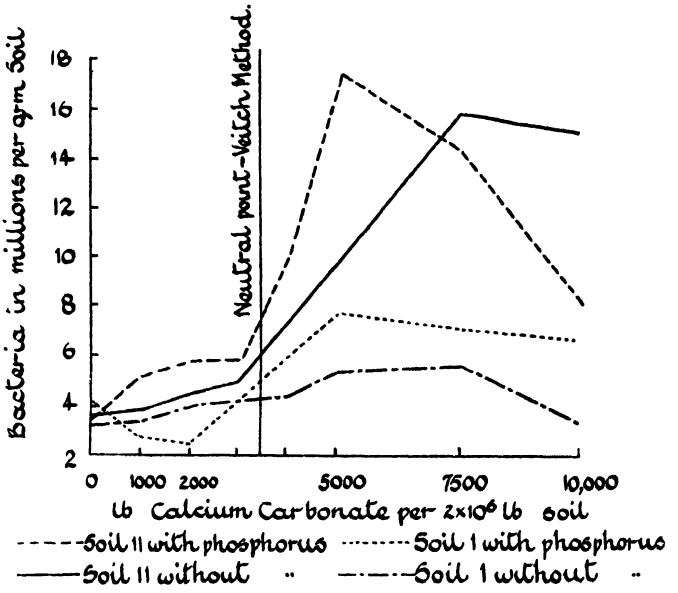
These results are compared in Fig. 34B with those Thornton obtained with his medium (279*b*): the numbers are small for low *p*H values: they rise suddenly between *p*H 6·8 and 7·0, and gradually fall at higher values.

The different kinds of bacteria are not equally affected,

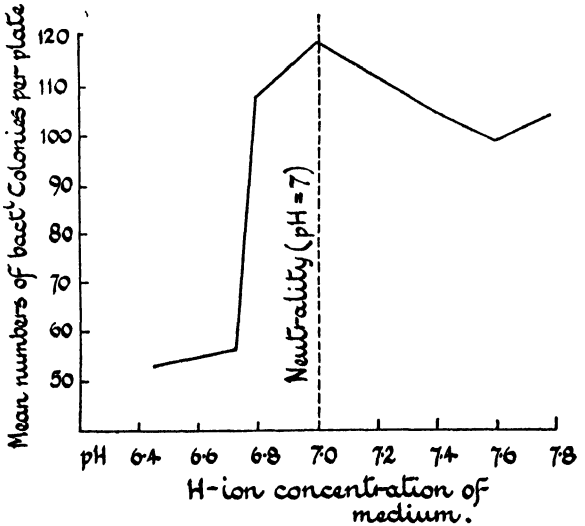
[1] For influence of energy supply, see pp. 288 and 341; for nitrogen, see p. 242; for potassium, see J. Dumont, *Compt. Rend.*, 1897, 125, 469-472.

[2] F. E. Bear, *Soil Sci.*, 1917, 4, 433.

[3] See also Th. Arnd (4*b*).



A. Effect of successive additions of calcium carbonate to an acid soil (F. E. Bear, *Soil Sci.*, 1917, 4, 433).



B. Effect of change in reaction in a liquid medium (H. G. Thornton [279*b*]).

FIG. 34.—The effect of soil reaction on numbers of bacteria.

however, by the changes in *p*H. The nitrogen fixing organisms (*Azotobacter* and some varieties of *B. radicicola*) show the sharpest response, occurring in quantity only under a narrow reaction range: nitrifying organisms apparently increase more continuously as the reaction moves from acidity to neutrality; some of the other organisms are less affected.

The soil bacteria appear to be very unresponsive to changes in temperature or moisture supply within the limits favourable to trophic life: this is all the more remarkable in view of the fact that both water and temperature exert their expected effects on bacterial numbers in partially sterilised soils (Table LXVI.). Temperature variations from 40° C. to

TABLE LXVI.—EFFECT OF TEMPERATURE OF STORAGE ON BACTERIAL NUMBERS IN SOILS, MILLIONS PER GRAM.

Temperature of Storage °C.	Untreated Soil.				Soil Treated with Toluene.			
	At Start.	After 13 Days.	After 25 Days.	After 70 Days.	At Start.	After 13 Days.	After 25 Days.	After 70 Days.
5°-12°	65	63	41	32	8·5	73	101	137
20°	65	41	22	23	8·5	187	128	182
30°	65	27	50	16	8·5	197	145	51
40°	65	14	9	33	8·5	148	52	100

25° C. have no consistent effect on the numbers. This is indicated by the older data discussed in the earlier editions,[1] and is convincingly shown by the 365 consecutive daily studies of the Barnfield soil at Rothamsted (p. 318).

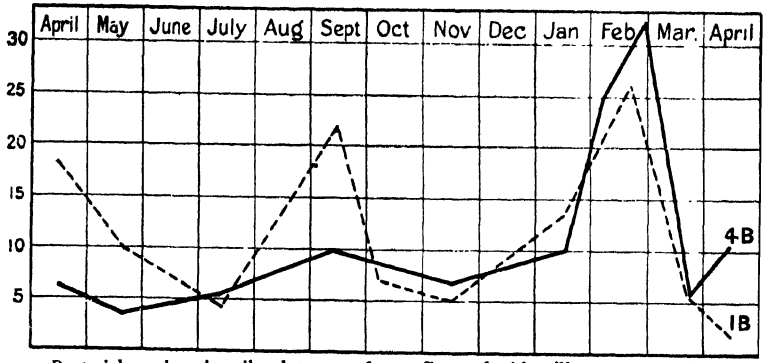
But when the soil is exposed to temperatures outside the limits of trophic life, some remarkable results appear. Freezing the soil, so far from depressing bacterial numbers, greatly increases them. Conn (*70a*) found considerably higher numbers of bacteria in frozen soils kept at −12° C. than at ordinary temperatures;[2] indeed, his results suggest an almost inverse

[1] *E.g.* Hiltner and Störmer (*134c*); Engberding (95); W. E. King and Doryland, *Kansas Bull.*, 161, 1909; S. A. Waksman, *Soil Sci.*, 1916, 1, 363-380.

[2] Confirmed by P. E. Brown and R. E. Smith at Iowa (*57c*), but not by Wojtkiewicz, *Centr. Bakt. Par.*, 1914, 42, 254-261, who obtained low numbers in winter and no high ones till spring. Lochhead, 1924, found a slight rise in numbers in frozen Canadian soils but a much bigger rise on thawing.

relationship (Fig. 35). Exposure to temperature above the normal causes, as one might expect, a drop in the numbers of organisms; but if the temperature has risen above a certain critical value (about 45° C.) this drop is followed by a considerable and permanent rise in numbers when the soil regains its normal temperature (p. 342).

Similar effects are produced by changes in the moisture content of soils. Within the range suitable to active life, moisture variations produce singularly little effect on bacterial numbers. But outside these variations the same peculiarity is seen as with temperature. Drying the soil in



Bacterial numbers in soil: plots 1B and 4B. Cropped with millet; unmanured. (The curve showing moisture content is very similar to that for 4B.) (Conn.)

FIG. 35.—Bacterial activity in soils at different seasons of the year.

air at first lowers the bacterial numbers, but on re-wetting they may rise considerably, though not for long. Water-logging, however, alters the flora.

These curious facts are discussed on page 342. They are probably consequences of the fact that bacteria are not the only organisms present in the soil, and between them and the other members of the soil population there is a mobile equilibrium, which, however, is disturbed by changes in temperature and water supply.

The soil bacteria participate in most of the chemical changes going on in the soil. In the decomposition of plant residues many of them, in common with other organisms, can

attack the simpler carbohydrates; a few can attack cellulose (p. 240); but it is unknown whether any can attack lignin, or produce humus. The oxidation of ammonia to nitrite or nitrate and the fixing of gaseous nitrogen are restricted to bacteria with the possible exception of Phoma.

An interesting distinction has been observed, however, between bacteria and fungi. Fungi reassimilate 20 to 60 per cent. (more usually 30 to 40) of the carbon of the substratum they have decomposed, while bacteria reassimilate much less, only 1 to 30 per cent., usually 5 to 10 per cent.[1] But for one part of carbon assimilated, bacteria assimilate considerably more nitrogen than do fungi, containing in their dry substances 10 to 12 per cent. of nitrogen against 5 to 8 per cent. in the dry matter of fungi.

Of the other changes affecting the nitrogen compounds, the decomposition of protein, the formation of ammonia, and the assimilation of ammonia and nitrate are brought about by many bacteria, but also by fungi and other organisms.

Soil Protozoa.

The suggestion that protozoa form a normal part of the soil population influencing the growth of plants was made by Russell and Hutchinson as the result of the investigations on partial sterilisation of the soil described later on pages 342-343, 344.

Protozoa had been found in the soil, and the earlier workers, Ehrenberg and Dujardin (1841), thought of them as active, but, after the discovery of cyst forms by Stein in 1878, the idea had grown up that they occurred in soil only accidentally and as cysts, and this was widely accepted at the time of the work on partial sterilisation.[2] Extended in-

[1] S. A. Waksman (289*c*); W. Kruse, *Allgemeine Mikrobiologie*, Leipzig, 1910, 1.

[2] See Sherman (261); G. P. Koch, *Soil Sci.*, 1916, **2**, 163; G. T. Moore, *Science*, 12 Nov., 1912: C. R. Fellers and F. E. Allison, *Soil Sci.*, 1920, **9**, 1, and for a general review to 1917, N. Kopeloff and D. A. Coleman, *Soil Sci.*, 1917, **3**, 197-269. See also E. J. Russell, *Science*, 4 April, 1913. Waksman (288*a*), was one of the first of the American workers to recognise a trophic protozoan fauna.

vestigations were organised at Rothamsted to ascertain whether there is an active protozoan fauna in the soil, and if so what are its relations to other members of the soil population and to the growing plant. The first experiments by Goodey (111) dealt mainly with ciliates and indicated that they occur only as cysts. Subsequently, Martin and Lewin (191) by ingenious separation methods showed that a trophic population of amœbæ and flagellates exists normally in soils, and that it differs from the population developing in hay infusions. This view was confirmed by later work, and has been considerably extended by D. W. Cutler, L. M. Crump, and H. Sandon.

The methods developed at Rothamsted for studying the soil protozoa are :—

1. The organisms in the soil are counted by a dilution method, each soil sample being tested (*a*) in its original fresh form, (*b*) after treatment with dilute acid to kill trophic forms and leave only cysts.

2. Cultures are set up to discover the range of properties of each of the organisms studied.

Numerous attempts have been made to develop a direct method of detecting protozoa in the soil. Lewin and Martin met with partial success by stirring soil into a solution of picric acid and then picking up the organisms floating on the surface. But the method is tedious and not very effective. Direct microscopic examination of the soil reveals little or nothing, a fact that caused considerable difficulty in accepting the idea of a protozoan fauna till Cutler found the explanation (73*a*). He showed that the organisms rigidly adhere to the soil particles, and indeed up to a certain limit they can be completely removed from a suspension by shaking for a few minutes with soil. The saturation capacity of the soil is high ; at Rothamsted it is 1,500,000 or 2,000,000 per grm., a figure considerably in excess of the numbers present. Only in exceptional cases can organisms be dislodged sufficiently readily to be recognised under the microscope.

The most detailed investigations have been those on the Rothamsted soils, but numerous surveys have been made of soils from other countries.[1] Many species of protozoa are found, but there is a central group of almost universal occurrence forming a soil fauna, which, like the flora of bacteria and algæ, persists all over the world with remarkably little variation; Sandon's examinations now range from Gough Island, in the Antarctic, to Spitzbergen, in the Arctic regions. The predominant members of this soil fauna are :—

Amœbæ.—Nægleria (*Dimastigamœba*) *gruberi*,[2] *Hartmanella hyalina* (one or other, but not both together).

Flagellates.—Heteromita lens and *globosa*, *Cercomonas*, *Oicomonas termo*.

Ciliates.—Colpoda cucullus and *steinii*.

In addition, there are generally some Shelled or *Thœcamœbæ*, among them *Chlamydophrys stercorea*, *Difflugia constricta* and *Trinema enchalys*.

It is not yet possible to explain why these forms should be so widespread in the soil, and others, not apparently very different, should be so rare. It is, perhaps, significant that all the common soil forms are small; there are few, if any, of the larger forms, such as occur with some of the soil species in other habitats, *e.g.* in stagnant water. The wide persistence of the soil forms is all the more remarkable in view of the fact that, apart from the *Thœcamœbæ*, which are relatively insignificant in numbers, the various members of the population are simply masses of naked protoplasm having no protection against heat, cold, or drought, nor can they get away from adverse conditions by sinking to lower depths as can the plankton in the sea. They can form cysts, but investigations at Rothamsted make it doubtful whether cyst formation is induced by adverse conditions.

[1] Among recent papers are: M. Francois Perey (224), for French soils; H. Sandon, *Journ. Linn. Soc.* (Zoology), Spitzbergen soils, 1924, 35, 449-475; *Quest* Expedition, *ibid.*, 1924, 36, 1-12. See also his *Monograph*; R. V. Allison, *Soil Sci.*, 1924, 18, 339-352, United States soils.

[2] This form is called *Vahlkampfia Soli*, in Martin and Lewin's paper (191).

The organisms go through a cycle of changes in the soil, some of the flagellates have an amœboid stage, and at least one of the amœbæ (*Nægleria*) has a flagellated stage.

There is no evidence of geographical distribution nor of clear-cut ecological associations of protozoa corresponding with those of plants. There are, however, certain distributions which cannot yet be explained; the two common amœbæ, *Dimastigamœba* and *Hartmanella*, appear to be mutually exclusive and rarely occur together in any quantity; one or other dominates, but not both. The number of varieties is usually highest in those soils containing the greatest numbers of individual protozoa.

The numbers of protozoa in the soil, as shown by Cutler's method, are given in Table LXVII. The figures are incom-

TABLE LXVII.—NUMBERS AND ESTIMATE OF APPROXIMATE WEIGHTS OF PROTOZOA AND OF BACTERIA IN ARABLE SOIL RECEIVING FARMYARD MANURE, ROTHAMSTED.

	Numbers per Gram of Soil.	Approximate Weight, lb. per Acre.
Amœbæ—high activity .	280,000	320
,, low activity	150,000	170
Flagellates—high activity	770,000	190
,, low activity .	350,000	85
Ciliates—high activity .	1,000	—
,, low activity .	100	—
Bacteria—high activity .	45,000,000	50
,, low activity .	22,500,000 [1]	25
Algæ (excluding blue-green) . . .	> 100,000	> 125

USING MODIFIED METHOD.

	Broadbalk Dunged Plot.		Broadbalk Continuously Unmanured.		Active Forms.	Approximate Diameter.
	Low Level.	High Level.	Low Level.	High Level.		
Flagellates .	150,000	600,000	5,500	15,000	15 to 95 per cent. of total in all cases.	7·5-15 μ
Amœbæ .	5,000	15,000	40	2,000		8-22 μ
Thecamœbæ	—	1,000	—	—		15 μ
Ciliates .	50	200	—	—		20-40 μ
Bacteria .	10,000,000	24,000,000	4,000,000	5,000,000		1-4 μ

[1] Numbers developing on the plates. The actual numbers are higher (p. 306).

plete, since some forms are almost certainly missed, but they are probably nearer the true value than is yet possible for bacteria or any other of the soil forms.

The flagellates are the most numerous, the amœbæ come next, and the ciliates are by far the fewest. Owing to the difference in sizes it is difficult to visualise the population from these figures alone; making certain assumptions as to the volume of the organisms and taking Allison's [1] value (1·04-1·06; for algal cells, 1·1) for their density it is possible to calculate their approximate weights per acre. The figures given in Table LXVII. show that the weight or volume per acre of the amœbæ is almost double that of the flagellates, and both far exceed the bacteria.

The whole of the organisms, however, are not active at any one time; the proportion of active forms varies considerably, but on most days they constitute more than half of the total numbers.

The numbers of protozoa in the soil, however, do not remain even approximately constant, but change continuously from day to day. This is particularly true of the individual species: it is not uncommon for the numbers of any one species to vary from a few hundreds to 400,000 or more within twenty-four hours; moreover, in the same period the percentage of individuals in the active form may jump from 0 to 100.

Two kinds of change occur :—

1. A definite two-day periodicity is shown by the active *Oicomonas termo* (Fig. 36), the numbers being high one day and low the next.

2. A continuous fluctuation, shown by the amœbæ, which, if it be a periodicity, does not correspond with our days (Fig. 37).

The causes of these phenomena are not known, but they are being studied at Rothamsted.

These fluctuations make it difficult to study the effect of

[1] R. V. Allison, *Ann. App. Biol.*, 1924, 11, 153-168.

external conditions on the protozoan fauna, only two or three factors being sufficiently potent to over-ride them. Of these, the most important are :—

The amount of organic matter (*i.e.* energy material) in the soil, there being an increase in the general level of numbers of individual protozoa and also in the number of varieties with increases in the organic matter of the soil.

The effect of season is also marked, the numbers of all forms being high in spring and autumn and low in summer and winter.

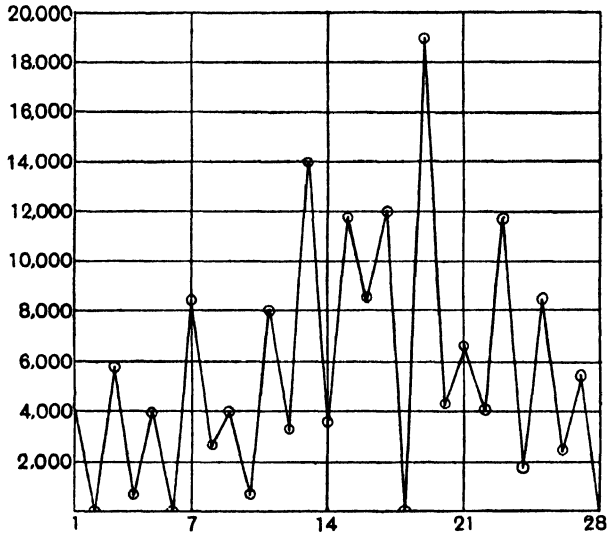


FIG. 36.—Daily counts of active flagellates (three species) in Broadbalk Plot 2 (dunged) (Cutler and Crump).[1] The numbers are in thousands per grm., and show a remarkable periodicity.

Aeration probably has a potent influence in determining the numbers of organisms.

But other external conditions have no consistent effect on protozoan numbers; neither the reaction (*p*H value) within limits, the moisture content, the rainfall, or the temperature.[2]

The relationships of the ciliates and amœbæ to the other

[1] *Ann. Applied Biology*, 1920, 7, 11-24.

[2] See Cutler, Crump and Sandon (74).

members of the soil population are under investigation at Rothamsted. Both groups of protozoa feed on bacteria: most of the species feed on nothing else so far as is known, so that the forms active in the soil are detrimental to bacteria and keep down their numbers. There is a sharp inverse relationship between numbers of bacteria and those of active

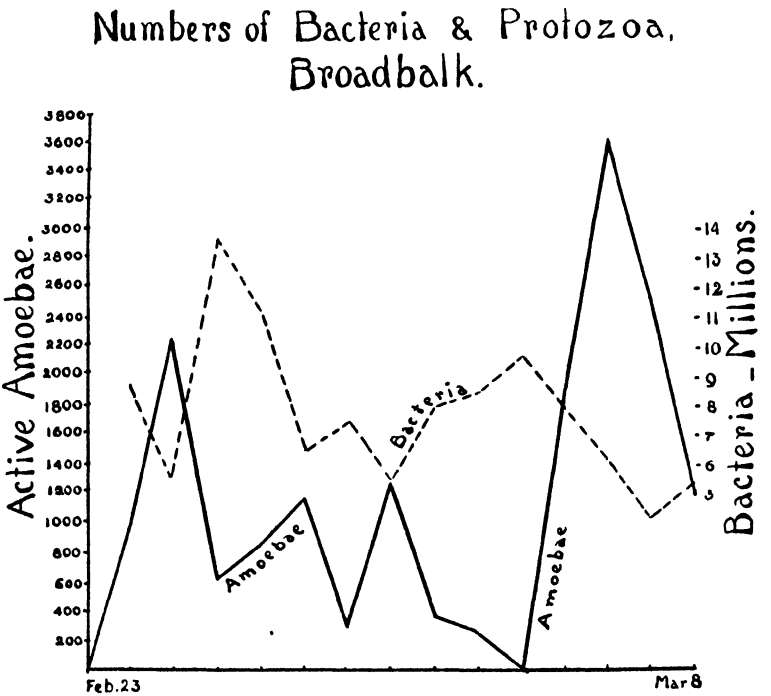


FIG. 37.—Daily counts of active amœbæ and of bacteria in Broadbalk Plot 2 (dunged) (Cutler and Crump). The active amœbæ are given in thousands, and the bacteria in millions, per grm. of soil.

amœbæ; when the numbers of amœbæ fall, those of bacteria rise and conversely when the numbers of amœbæ rise, those of bacteria fall. So far as can be ascertained, it is the amœbæ that are responsible for the fluctuations in bacterial numbers; apparently the bacteria when alone do not fluctuate as much as in normal soil (see p. 331).

Some of the flagellates resemble amœbæ in feeding on

bacteria and their relationships to soil bacteria are, therefore, presumably very similar. But others are different. They feed on soluble organic and inorganic substances, which they absorb by diffusion through their body surface, *i.e.* they feed saprophytically;[1] they do not directly affect the bacterial numbers except by competing for food supplies. One of the most urgent problems in soil microbiology is to study the life of the flagellates in the soil.

The relationship of protozoa to plant growth is not yet definitely established. The effect of the flagellates, by far the largest group of all the active, non-bacterial organisms in the soil (with the possible exception of fungi) is entirely unknown. The effect of the amœbæ, and so far as they are active, the ciliates, by feeding on the bacteria and so keeping down their numbers, might be expected to keep down the production of nitrates and other plant nutrients and thus to reduce soil fertility. Rigid proof is difficult, but it is shown that any method of treatment which kills amœbæ enhances soil fertility (p. 343).

Like other organisms, when added to cultures of Azotobacter, they stimulate the fixation of nitrogen.

The Remaining Invertebrate Fauna of the Soil.

Quantitative faunistic studies of the invertebrates other than protozoa have been made under A. D. Imms' direction on two groups of field soils, one in Cheshire by A. E. Cameron,[2] and the other at Rothamsted by H. M. Morris,[3] the method being to collect a large sample of the soil, wash it through a series of sieves graded to retain animals of various sizes, and finally through a bag of bolting silk to keep back the smallest. The animals are then identified and counted. They include

[1] H. G. Thornton and Geoffrey Smith, *On Certain Soil Flagellates* (*Proc. Roy. Soc.*, 1914, 88B, 151-165).

[2] A. E. Cameron, *Journ. Econ. Biol.*, 1913, 8, and *Trans. Roy. Soc. Edin.*, 1917, 52. See also H. M. Morris, *Ann. App. Biol.*, 1921, 7.

[3] H. M. Morris, *ibid.*, 1922, 9, 281-305. For other work see P. Buckle, *Ecology of Soil Insects on Agricultural Land* (*Journ. Ecology*, 1923, 11, 93).

many species. Some are only temporary inhabitants, using the soil as a convenient place for breeding or pupation; the permanent inhabitants include phytophagous forms feeding on plants, predaceous forms feeding on other animals, and saprophagous forms feeding on organic matter (Table LXVIII.). The most numerous are the insects, but the most important as soil makers are the worms of various kinds, and particularly the earthworms; these alone will be dealt with here, though reference to parasitic forms is made on page 323.

TABLE LXVIII.—NUMBERS OF INVERTEBRATES IN ONE ACRE OF SOIL TO A DEPTH OF NINE INCHES: AVERAGE FOR TWELVE MONTHS. BROADBALK WHEATFIELD. MORRIS.

	Unmanured Plot.	Plot receiving Farmyard Manure.
Insects	2,474,700	7,727,300
Larger Nematoda and Oligochæta limicolæ	794,600	3,600,400
Myriapoda—		
Diplopoda (Millipedes)	596,000	1,367,000
Chilopoda (Centipedes)	215,400	208,700
Symphyla (very minute)	64,000	215.500
Total	875,400	1,791,200
Oligochæta (Terricolæ) (earthworms)	457,900	1,010,100
Arachnida—		
Acarina (mites and ticks)	215,400	531,900
Araneida (spiders)	20,200	20,200
Total	235,600	552,100
Crustacea (Isopoda) (woodlice)	33,700	80,800
Mollusca (Pulmonata) (slugs and snails)	13,500	33,700
Total invertebrata	4,885,400	14,795,600

Unlike the micro-organisms, the invertebrates show very marked response to geographical factors so that there is a well-marked geographical distribution. Within the geographical regions there are, no doubt, ecological communities, but these have hardly been studied as yet.

The small worms, particularly minute free living eel-worms, occur in considerable number in the soil, but their mode of life and the part they play in the decomposition of plant residues is unknown. There is some evidence that they assist in the disintegration of roots and leaves, entering the tissues after the fungi have forced a way in.

The earthworms have been studied in detail as a result of the classical investigation by Darwin described in *Earthworms and Vegetable Mould*, one of the most interesting books on soil ever written. Earthworms produce two important effects in the soil; aerating it and mixing its constituents, they pass large quantities of material through their bodies and eject it on the surface as "worm casts," which Darwin estimated would form a layer 0·2 inches thick in the course of a year. They are thus perpetually turning the soil over to the depth to which they operate, mingling the various soil constituents, dragging in leaves and other plant residues from the surface, and thus facilitating decomposition by the micro-organisms. The results are very striking, and are well seen in comparing soils well stocked with earthworms with those containing only small numbers. Where earthworms are active in the soil, organic matter is distributed throughout the layer in which they operate. But where earthworms are few or absent, there is much less mixing; the dead vegetable matter accumulates on the surface, becoming a partly decomposed, acid, peaty mass, in which the normal soil decompositions are not completed. The surface vegetation becomes profoundly modified, only few plants being able to force their way through the mass of dead material; as they die their remains also lie on the surface, and may, if the rate of decomposition be sufficiently slow, accumulate to form a bed of peat.

The second great effect of earthworms is to facilitate aeration and drainage. They honeycomb the soil with their burrows, leaving channels along which air and water easily pass.

A third action, formerly attributed to earthworms, but on

insufficient grounds, is that they increase the amount of decomposition of organic matter in the soil. No evidence for this could be found by the writer or in the more recent studies of Heymons ; [1] grass cuttings mixed with the soil decomposed as readily in the absence of earthworms as in their presence. But in these experiments the aerating and mingling actions of the earthworms were excluded.

As happens with other organisms, the number of earthworms in a given weight of soil is governed by the amount of organic matter present. But earthworms are peculiarly sensitive to soil acidity and in their absence a mass of dead vegetation tends to accumulate on the surface of acid soils and changes into peat. The acid grass plots at Rothamsted contain no earthworms,[2] although the adjoining nearly neutral plots contain many. Hanley records that the presence or absence of worm casts on pastures is one of the surest ways of showing whether the land is " sweet " or " sour." It is not certain whether the cause of the suppression of worms is a positive injury by acidity or a consequence of the calcium starvation from which everything growing on acid soils is liable to suffer [3] (p. 390).

One of the most difficult problems in the garden is to deal with the crude mixture of clay, sand, and small stones that often forms a considerable part of the soil. An effective method used by the writer with considerable success is to dig grass cuttings and other vegetable matter into the soil, burying much of it to a depth of about 8 inches, and to apply frequent dressings of grass cuttings and also of finely powdered calcium carbonate (chalk or limestone) to the surface. Earth-

[1] E. J. Russell, *Journ. Agric. Sci.*, 1910, 3, 246-257 ; R. Heymons, *Zeit. Pflanz. Düng.*, 1923, 2, 97-129.

[2] They have also, perhaps consequently, no moles. Farmers in the north of England regard mole-hills as a good sign in grass land.

[3] Earthworms are largely dependent for their nutrition on calcareous glands which presumably cannot be maintained, and are liable to dissolution, in soil with much capacity for absorbing calcium. See also E. J. Salisbury, *Journ. Linn. Soc. Botany*, 1924, 46, 415-425.

worms multiply rapidly and wander from the upper to the lower layers of vegetable matter, thoroughly blending and aerating the soil.

Atkins and Lebour have found that the numbers of snails in different districts are closely related to the reaction of the soil, being greatest when the *p*H is about 7.[1]

Organisms Acting Directly on the Plant.

(1) *Parasitic and Disease Organisms.*

The study of these organisms has developed into a special branch of Economic Biology, and we need therefore only briefly refer to them here. The commonest are the eel-worms, the myxomycete *Plasmodiophora*, some of the "wilts," and certain organisms that attack potatoes.

Of the numerous kinds of eel-worms occurring in the soil, about six are known to attack and enter the plant, and do considerable direct injury, besides opening the way for the entrance of fungi, bacteria, etc. The commonest are *Heterodera radicicola*, which causes swellings or "knots" on the roots of tomatoes, cucumbers, and other plants, and *Tylenchus dipsaci* (*syn. devastatrix*) which attacks oats, causing tulip root, and clover, bringing on one form of clover sickness. In some soils, especially those short of lime, another pest is common: the myxomycete *Plasmodiophora*, which enters the roots of swedes, turnips, and other plants of the *Brassica* tribe, causing the disease known as finger-and-toe.

(2) *Symbiotic Organisms.*

These have already been dealt with: the nodule organisms on page 277, and the mycorrhiza on page 304.

General Microbiology of the Soil.

The investigations recorded in the preceding pages show the invariable presence of organisms in the soil leading their

[1] W. R. G. Atkins and M. V. Lebour, *Sci. Proc. Roy. Dublin Soc.*, 1923, 17, 233-240.

lives there and bringing about changes of vital importance in soil fertility.

The groups of organisms present include algæ, fungi, actinomycetes, bacteria, protozoa, and larger forms. In spite of great differences among these organisms, they have certain properties in common in their lives in the soil, and they show certain relationships which appear to be of wide application.

For each of these organisms, except, perhaps, the fungi, there is a group occurring so commonly in a trophic form in the soil that it can be regarded as a definite soil flora or fauna. The whole of these groups make up the soil population.

So far as is known, the composition of the soil population shows remarkably little variation in different parts of the world. The characteristic groups of algæ, bacteria, and especially protozoa, are the same in the Arctic as in temperate and tropical climates; there is nothing corresponding with the geographical distribution of plant and animal groups. The reasons for this constancy of the soil population are to be sought, partly in the nature of the organisms themselves, partly in the soil as a habitat. It is possible, and indeed probable, that micro-organisms are less susceptible to environmental conditions than are the larger forms. It is certain that the biological conditions at a depth from 2 to 7 or 8 inches below the soil surface vary much less than on the surface itself; the temperature is more even (p. 364), and the atmosphere is almost always humid and nearly saturated; there are no marked differences in degree of humidity such as Shelford [1] supposes to influence the distribution of land animals, and ecological workers know to affect profoundly the distribution of plants.

While the general groups remain the same, the relative numbers probably vary, making new combinations, recalling the ecological associations of higher plants, such as Hagem's

[1] V. E. Shelford, *Animal Communities in Temperate America*, Chicago, 1904; also *Journ. Econ. Entomol.*, 1912, 7.

associations of fungi, assuming these to be well founded (p. 301), and the mutual exclusiveness of *Dimastigamœba* and *Hartmanella* (p. 314). Some forms tend to be restricted to certain soil conditions; those intolerant of acidity may occur only on neutral soils and may be absent from acid soils, *e.g.* azotobacter and certain varieties of radicicola, while other soil conditions determine a regional distribution of the phenol decomposing organisms. But all these are essential minor changes, mere variations within the great uniformity of the soil population.

The identification of the members of the soil population is carried out by the ordinary laboratory methods.

It is much more difficult to form an idea of what the soil population is like and how it lives; to construct the impression one would gain if one could shrink down to the size of a micro-organism and wander about in the soil. The staining method promises to give the direct picture. The statistical method, however, gives the quantitative information, but except for the protozoa, it fails to show the stage in the life cycle in which any particular organism occurs. The bacteria are by far the most numerous, but they are the smallest; the amœbæ are fewer, but a single one may be a thousand times the size of a bacillus. A better view of the soil population is obtained, therefore, if instead of the numbers only, we calculate the masses of the organisms. Certain assumptions as to shape are necessary, and hence the data are somewhat uncertain, but the figures given in Table LXVII. (p. 315) are perhaps not far out; they show that fungi are probably the chief constituents, in point of weight protozoa come next, followed by algæ, and finally bacteria. Our conception of the population would be improved if it were possible to take into account the mobility of the organisms and so allow for the speed with which they can get about in the soil to effect their various changes. None of these methods show the relative importance of the organisms as active agents in the soil, which, after all, is the property of chief interest so far as

plant growth is concerned. So far as can be seen, the only way to achieve this end would be to compare the energy transformed, or, alternatively, and perhaps more simply, though it is a less fundamental quantity, the amount of CO_2 evolved or of oxygen absorbed by each group with that of the total population. Investigations on these lines are now being carried out at Rothamsted.

The general requirements of the soil organisms are the same as those of plants; *viz.* energy, nutrients, water, temperature, air, and absence of harmful conditions. The great difference is in the source of energy. Plants derive their energy from sunlight, fixing it by means of chlorophyll, while the soil population derives it from preformed plant tissues brought into the soil by natural, or, on cultivated land, artificial agencies. It is this dependence on soil organic matter derived from plant residues that makes the common link between all members of the soil population. A few members, such as the algæ and green flagellates (*Euglena*, etc.), have a chlorophyl apparatus and can utilise the energy of sunlight, but they are not dependent on this method and retain always their habit of utilising the energy of soil organic matter.

The organisms do not all derive their energy in the same way from the organic matter. There is a chain of decomposition processes; some organisms effect one part and some another; for example, in breaking down protein some organisms can carry the nitrogen only to the stage of ammonia while others can oxidise the ammonia. With a few exceptions the reactions are not rigidly restricted to one group of organisms; there is considerable interchangeability. But the chain of actions is governed by one inexorable law; there is a certain amount of energy to be got by oxidation of a given weight of organic matter, and no more than this amount can be extracted whatever the organisms, however they act, and whether there are one or many stages in the reaction. Further, no action is known that gives out more energy than the oxidation.

The nutrient requirements are the same for all members of

the soil population as for plants, though they are not always satisfied in the same way. All of the soil organisms require nitrogen, and most of them—apart from protozoa and other animals—can take it in the form of ammonia or of nitrate. A few, however, azotobacter and *Bacteria radicicola*, are able to fix gaseous nitrogen when neither nitrate nor ammonia is to be had. Phosphate and potassium nutrition appears to follow closely on the same lines as for plants.

So far as present knowledge goes, the soil organisms are living right up to their income in the matter of nutrients and energy supply. Any increase in available organic matter capable of supplying energy leads at once to a great increase in activity of the whole population and also in numbers of the individual groups of organisms; this is accompanied by an absorption of ammonia and nitrate from the soil to supply them with nitrogen. Of two plots, one supplied with farm-yard manure and the other not, the unmanured plot always contains fewer organisms, not only a smaller total population, but fewer kinds and fewer of every kind yet enumerated. The supply of energy and nutrients thus becomes the chief factor determining the numbers of organisms in the soil. An exact measure of the amount of energy available to micro-organisms in a given weight of soil would be one of the most important quantities in soil microbiology. Unfortunately, no method is yet known for its determination. Combustion in a calorimeter gives the total quantity but does not show how much is available. An estimate of the amount of energy transformed in a given period can, however, be obtained by determining the total quantities at the beginning and at the end; the values for two of the Broadbalk plots are given in Table LXIX.

A second factor of equal importance with the total quantity is the rate at which the energy can be made available for the organisms when all conditions are favourable. For this, however, no method of estimation is yet possible.

There is a vital distinction between nutrients and energy. utrients can be used over and over again by an unending

TABLE LXIX.—ANNUAL ENERGY CHANGES IN SOIL: BROADBALK. APPROXIMATE VALUES ONLY.

Millions of Kilo Calories per Acre per Annum.

	Farmyard Manure Added.	No Manure Added.
Added in manure	14	Nil
„ in stubble	2	0·3
Total added	16	0·3
Net loss from soil	Nil	0·5-1
Stored in soil	0·5-1	Nil
Dissipated per annum . . .	15	1
Per day: Calories	41,000	2,700
Equivalent to the requirements of .	12 men	¼ man
The human food grown provides for .	2 men	½ man

succession of micro-organisms; an atom of nitrogen never loses its value and might in the course of a single day form part of a fungus, a bacillus that decomposed it, an amœba that ate the bacillus, and a bacterium that decomposed the dead amœba; for all these organisms one and the same atom of nitrogen would be a perfectly good nutrient.

But energy cannot be used in this way. It is as indestructible as matter, but once transformed to heat, it cannot be used by micro-organisms or any other living things. There is a certain definite amount of energy to be got by the oxidation of a definite weight of organic matter, but no more, and it can be got only once. The soil organic matter is attacked by a great multitude of organisms, but whatever energy is dissipated by one organism becomes thereby for ever out of the reach of the others. It follows, therefore, that no factor, either internal or external, that affects the trophic life in the soil without adding to the stock of energy material or nutrients can permanently increase the numbers of all the groups; if one increases, others necessarily decrease.

We can think of the various groups of soil organisms as being in a state of mobile equilibrium which is perpetually changing as a result of changes in the organisms themselves, such as their passage through the life cycle, and by the opera-

tion of any factor that favours one organism or life cycle stage more than another, but governed rigidly by the inexorable law that energy cannot be used twice ; what one organism has taken another cannot have.

The increase in numbers resulting from addition of energy material is not uniform for all organisms but depends on the nature of the added substance. This is shown by the appearance of the plates ; the new colonies arising from the increased numbers appear to belong to one or two kinds of organisms only. The same conclusion is reached by Winogradsky. In the poor, unmanured soil of the Institut de Bric-Comte-Robert he found only a few active organisms ; three or four species of cocci, a few azotobacter, a little mycelium of actinomyces, and an occasional yeast, but no bacilli and no moulds. These were all the living things ; he calls them the normal population for that particular soil.

Addition of an artificial preparation of humus gave an increase in numbers but no new forms ; the flora still remained as restricted as before. Addition of carbohydrate or protein, however, led to a rapid change in the type of population ; with peptone after incubation at 30° for one night the original population disappeared and was replaced by two kinds of bacilli in enormous numbers. Addition of starch was followed by a great increase in numbers, but the organisms were of two kinds only, a bacillus and a mycelium of actinomyces. After a short time, however, the population reverts to the normal type.

It is significant that humus alone gave the general uplift to all the normal inhabitants such as happens with increases in organic matter content of normal soils.

Organic substances in the soil appear to be decomposed in two ways. They may be wholly or in part assimilated by the organisms, simpler products being excreted or left untouched. Or they may be decomposed as sugar is fermented by yeast : by a process external to the cell, the purpose of which, in the physiology of the organism, is not known.

One of the most promising lines of investigation in soil microbiology would be to study these various changes thermodynamically. An interesting beginning was made by Gillespie,[1] who introduced the idea of oxidation-reduction potentials, and by G. A. Linhart (169), using the methods devised for a purely chemical system by G. N. Lewis. Both these investigations might well be followed up.

The organisms in the soil do not work independently of each other. They interact in two different ways. Competition is severe, a fact that sometimes makes plate cultures difficult, media having to be modified so as to restrict growth after it has proceeded sufficiently far. But as against this, joint action and symbiosis are common. Winogradsky and Beyerinck have both discovered instances of symbiosis of an aerobic with an anaerobic organism to the mutual advantage of both. Joint action—perhaps one should more strictly say consecutive action—is the normal occurrence in the soil. The by-products or metabolic products of one organism, if they are anything more complex than CO_2 and water, are the standing point for activity of other organisms; and this activity is continued by one or other of the population so long as there is any potential energy of oxidation in the products, but no longer. There is no evidence whatsoever of the slowing down of micro-organic activity in normal soils by accumulation of oxidisable products corresponding to the slowing down in cultures; no "bacterio-toxins" can be detected, and nothing to show that the "auto-intoxication" of pure cultures ever occurs in the soil (140*g*). The products that might have these effects are quickly attacked by other organisms; the final products are CO_2 and nitrates, and both these are easily removed from soil.

A remarkable property of the soil population, common to all groups, is that as the numbers of individuals increase so do the numbers of species. This is in marked contrast with the

[1] *Soil Sci.*, 1920, **9**, 199.

surface vegetation. On the Rothamsted grass plots the unmanured land carries the highest number of species, but none of them makes vigorous growth; doubtless the poor growth of all allows the chance of life to many not well suited to the conditions. Any scheme of manuring that increases plant growth acts differentially; some species flourish more than others, and, in growing, crowd out their less vigorous neighbours; the manured plots, while carrying more and larger individuals, have therefore fewer species. The difference may lie in the circumstance that the plants, being restricted to a surface of two dimensions, necessarily compete more drastically with each other than the soil micro-organisms which can wander about in three dimensions. There is, however, another and possibly more nearly parallel case. In the Polar regions the numbers of plankton organisms in the sea water are unusually large, but the numbers of species few. It is possible, however, that the absence of other forms is due to external conditions and has nothing to do with the large numbers of those already present. In frozen soils Conn found great numbers of bacteria, but only few varieties (p. 311).

One of the most striking properties of the soil population shown by all groups for which examination is possible, is that the numbers do not remain constant, even under apparently constant conditions, but fluctuate continuously in number. There is some uncertainty whether this happens for the individual groups separated from the soil or only when all the groups are together in the soil. Cutler has shown that the amœbæ and flagellates fluctuate in numbers in culture conditions. Bacteria, however, were always present, these being the only foods of the organisms studied; the cause is internal, and may be related to reproduction. Bacteria, on the other hand, did not fluctuate in numbers when grown by themselves in sterilised soil; they rose to high numbers and remained at approximately a constant level. Their numbers fell, however, as soon as the soil amœbæ were introduced, but no

constant level was reached; instead there were continuous fluctuations as in the normal soils (Table LXX.).

TABLE LXX.—NUMBERS OF BACTERIA IN SOIL WHEN LIVING ALONE, AND IN PRESENCE OF AMŒBÆ. CUTLER (73*b*).

Number of Days after Inoculation.	Bacteria alone.	Bacteria + Amœbæ.
0	13·0	12·2
1	48·6	35·4
2	97·6	117·2
3	127·0	178·4
4	154·8	154·4
5	196·8	177·0
6	214 8	151·8
7	193·4	75·6
8	165·2	65·8
15	169·2	72·8
16	174·8	30·2
17	175·6	53·2
18	168·4	82·8
19	160·4	43·8
20	171·2	70·8
21	176·2	28·2

But some bacteria fluctuate in numbers even when alone. Thornton and Gangulee (279) show that the numbers of *Bacillus radicicola* fluctuate continuously in sterilised soil, and they traced the changes to the circumstance that, during one part of the life cycle reproduction is by binary fission, and during another part of the cycle it is by multiple fission (Fig. 30, p. 280). These results are at first sight at variance with Cutler's, but there is no necessary inconsistency between them. Cutler's medium would not allow *Bacillus radicicola* to develop, and this is, as yet, the only organism tested by Thornton and Gangulee: moreover, the separate varieties of bacteria in his mixed culture might each be fluctuating within small limits, and the total numbers might still remain fairly constant.

Whether the majority of the soil bacteria would by themselves behave like *Bacillus radicicola*, or like the forms present in Cutler's experiments, they undoubtedly fluctuate in field soils, and their fluctuations are closely but inversely related

to those of the amœbæ, being presumably caused by the amœbæ feeding on them (p. 318). If we may assume that the soil organisms are all the while living right up to the energy and nutrient supplies, it follows that any increase in one group, not accompanied by an increase in energy material, must depress the numbers of near competitors, but this again may allow a third group to multiply.

Superimposed upon these daily fluctuations are the great seasonal changes; for all groups so far studied there is a tendency to greater numbers and higher activity in spring and autumn, and lower numbers and lower activity in winter and summer.

Hitherto no satisfactory explanation of these variations has been found. Variations in water supply and in temperature have no consistent effect on the numbers of any group yet studied (pp. 302, 310 and 317).

The only factor known to raise the numbers of all alike is energy supply, and the phenomena seem to be precisely as if additional energy supplies were brought into the soil during spring and autumn and not during summer and winter. But the cause may be much more deep-seated; algæ in lakes and rivers fluctuate in much the same way, being most numerous in spring and autumn, and the phenomena may be related.[1] Atkins and Harris [6] show that in the ponds the *p*H of the water also varies with the season, being high (*i.e.* alkaline) in spring and autumn and lower in winter and summer; whether similar changes occur in soil is not known.

Although variations in water supply and in temperature do not alter the numbers of soil micro-organisms in any predictable way, the total activity of the population so far as it can be estimated by the rates of oxygen absorption of CO_2 evolution, or nitrate production, is increased by increases in water supply or temperature up to the optimum range as

[1] See W. H. Pearsall, *Journ. Ecology*, 1923, **11**, 165.

would *a priori* be expected.[1] Thus, for a chalky loam, the following results were obtained :—[2]

Moisture present . . .	Air dry (7·4 per cent.)	20 per cent. added	25 per cent. added
Oxygen absorbed in 23 days, mm.	6·5	21·67	27·7

The effect on nitrate production is shown in Table LXXI. and Fig. 38.

TABLE LXXI.—EFFECT OF TEMPERATURE OF STORAGE ON BACTERIAL NUMBERS AND NITRATE PRODUCTION. RUSSELL AND HUTCHINSON (241*a*).

Temperature of Storage.	Bacteria, Millions per Grm. of Dry Soil.			Nitrate and Ammonia, Parts per Million of Dry Soil.		
	At Start.	After 10 Days.	After 50 Days.	At Start.	After 10 Days.	After 50 Days.
7°-12°	16	16	16	17	18	22
20°		12	21		16	30
30°		15	14		24	36
40°		9	14		55	76

It would be interesting to study the relationships of the changed equilibrium between the members of the soil population with changes in external conditions and the amount of energy transformed.

If the changes in temperature or moisture supply overstep the degree of tolerance of any group of organisms, that group is put out of action, and the remainder find a new equilibrium, at higher numbers if the energy supply allows. These phenomena are discussed more fully on page 342.

The effect of the soil reaction on the soil population differs with the different members. Bacteria and some of the larger animals, especially earthworms and snails, are most influenced by soil acidity, fungi and protozoa apparently less so. Within each group the members are differently affected ; there seems

[1] E. M. Delf, *New Phytol*, 1915, 14, 63 (Hampstead ponds) ; W. and G. S. West, *Journ. Linn. Soc. Bot.*, 1912, 40, 395 (English lakes) ; C. A. Koford, *Bull. Ill. State Lab. Nat. Hist.*, 1903 and 1908 (Illinois River) ; W. R. G. Atkins and G. T. Harris, *Proc. Roy. Soc.*, Dublin, 1924, 18, 1-21.

[2] E. J. Russell, *Journ. Agric. Sci.*, 1906, 1, 266.

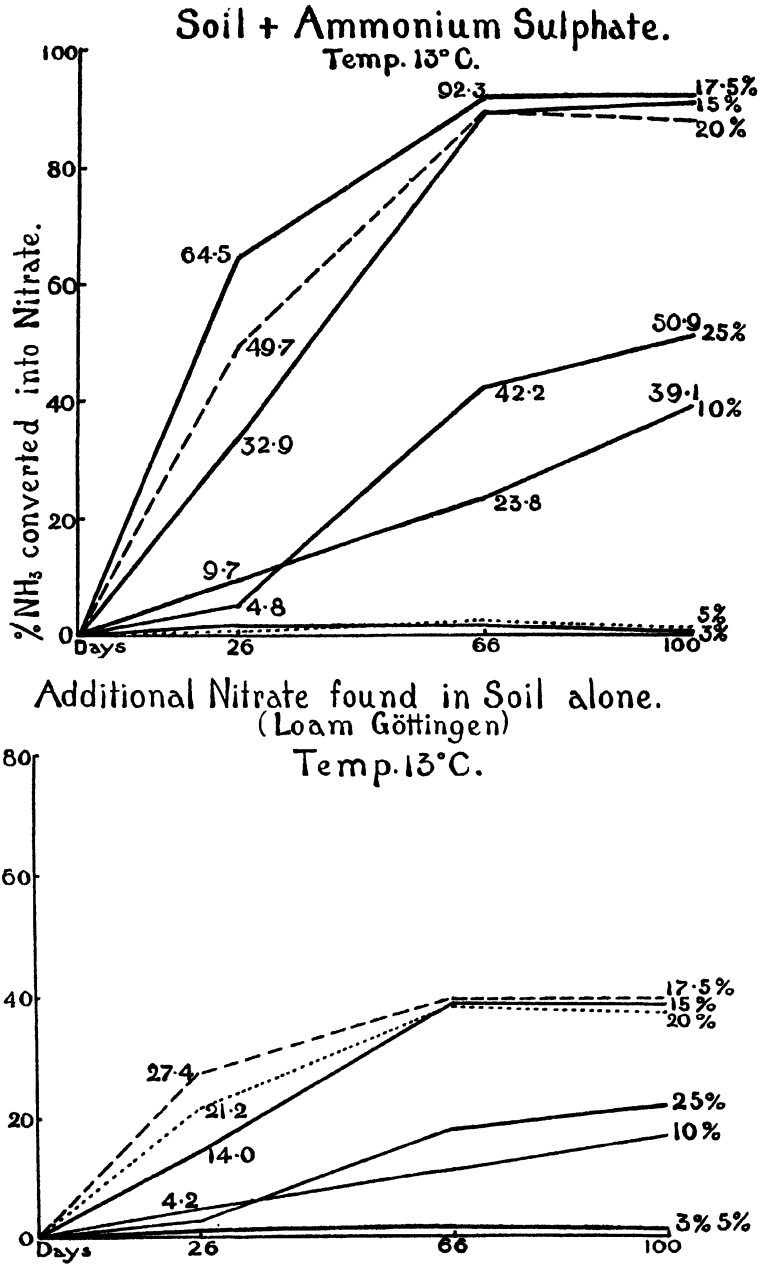


FIG. 38.—Effect of moisture on nitrification process in the soil (Traaen).

to be a tendency to floristic and faunistic differences corresponding to different *p*H values, but many more observations are needed before any definite statement could be made.

The activity of the soil population is greatest at about a neutral reaction (*p*H 7), but some of the actions are further increased by adding more calcium carbonate. Nitrification in particular is increased, but not, apparently, ammonification. The numbers of organisms are also greatest about *p*H 7. In consequence, addition of lime to an acid soil does not necessarily increase the amount of nitrate; both in Stephenson's [1] and Hall's [2] experiments the limed soil usually contained less than the unlimed, presumably because of the reduced ammonification and increased assimilation of nitrate by the additional organisms.

The effect of soluble salts and of soil alkali on the micro-organisms of the soil have been much studied in the Western United States, especially by C. B. Lipman in California (170*b*), J. E. Greaves and his co-workers in Utah (114), and W. G. Sackett and Collins in Colorado. Beyond a certain concentration soluble salts are harmful; indeed, it is possible by measuring the reduction in activity of the micro-organisms (using CO_2 production, ammonification, etc., as the measure) to form an estimate of the wheat-yielding power of an alkali soil.[3] But lower concentrations decidedly stimulate the action of all the micro-organisms yet studied. The extent of stimulation and the critical concentration beyond which further increases produce injury vary with different organisms. Azotobacter is most tolerant; the various ammonia-producing organisms come next, and the nitrifying organisms are least tolerant; wheat seedlings are intermediate in tolerance between ammonia producers and nitrifiers. The different salts vary in their effects; in general chlorides are the most

[1] R. E. Stephenson (Kentucky), *Soil. Sci.*, 1921, **12**, 133-144.

[2] T. D. Hall (Potchefstroom), *ibid.*, 301-363. For difference in action between calcium oxide and carbonate see Hutchinson and McLennan (140*c*).

[3] J. H. Barnes and Barket Ali, *Agric. Journ. India*, 1917, **12**, 368. See also S. M. Nasir, *Pusa Bull.*, 145, 1923.

toxic, while nitrates, sulphates, and carbonates are successively less toxic to the ammonifying organisms: the order is almost reversed, however, for the nitrifiers, being: CO_3 (most toxic) > NO_3 > SO_4 > Cl.[1] Usually the more toxic the salt, the greater its power of stimulation at low concentrations. Table LXXII. shows typical results obtained by J. E. Greaves and his colleagues; the effects, however, are not constant, but vary with the soil and other conditions:—

TABLE LXXII.—PERCENTAGES OF VARIOUS SALTS IN LOAM SOIL WHICH ARE NECESSARY TO REDUCE AMMONIFICATION, GERMINATION, AND DRY MATTER PRODUCED IN WHEAT TO ABOUT HALF NORMAL. J. E. GREAVES, E. G. CARTER, AND H. C. GOLDTHORPE (1146).

	Wheat Seedling to Half Normal.	Ammonification to Half Normal.	Nitrification to Half Normal.
Sodium chloride .	0·20	0·117	0·234
Calcium ,, . .	·30	·222	—
Potassium ,, . .	·25	·298	·298
Magnesium ,, . .	·40	·381	·006
Potassium nitrate . .	·40	·607	·101
Sodium ,, . .	·30	·850	·170
,, sulphate . .	·55	·852	·568
Magnesium ,, . .	·70	·963	·361
Sodium carbonate . .	·30	1·166	·212
Magnesium nitrate . .	·45	1·187	·074
Potassium sulphate . .	·60	1·394	·349
,, carbonate .	·70	1·520	·138

From the fact that the soil organisms cannot be seen by direct microscopic examination in any number approaching those revealed by the counting methods, it may be inferred that they live on the surface of the particles of soil from which they are not readily detached. There is good reason to suppose (p. 228) that the surface of the particle is coated with a gelatinous layer of colloidal alumino-silicates, oxides of iron, aluminium and silicon, organic matter, nutrient salts, etc. Cutler has shown that protozoa firmly adhere to the soil particles and will not be washed off; a gram of the Rothamsted soil will hold tenaciously as many as one-and-a-half or

[1] For discussion of relation to osmotic pressure, see J. E. Greaves, *Bot. Gaz.*, 1922, 73, 161-180.

two million protozoa—a number far in excess of that naturally present. But a very curious thing happens when larger numbers of protozoa are brought into the soil or when soil is shaken with a suspension of protozoa. Up to a certain point they are firmly absorbed; beyond that point the rest are all left unabsorbed; the phenomena are as sharp as those of titration and quite different from those of ordinary absorption where there is no definite end point. At saturation the protozoa still appear to have plenty of room. The surface of a gram of Rothamsted soil cannot be closely estimated, but it probably exceeds 2000 square centimetres. But the amœbæ and flagellates retained by it would occupy little more than 4 square centimetres if set down regularly on a flat surface in close formation. Why they cannot sit closer in the soil is difficult to understand.

It is not known whether similar sharp " saturation points " exist for other organisms also, the experimental difficulties not having been overcome.

Thornton and Gangulee (279) have successfully adapted Winogradsky's method to study the rate of movement of micro-organisms in the soil. *Bacillus radicicola*, with which alone they experimented, moved in favourable conditions at the rate of 1 inch in twenty-four hours, a value which lends support to the older estimates of 1 inch in forty-eight hours in natural soils. It is desirable to study other organisms to find their rates of movement also.

Relationship of the Soil Population to Plant Growth.

The fundamental relationship between the soil population and plant growth is that the soil population decomposes the plant residues in the soil for the purpose of obtaining nutrients and energy, and the process taken as a whole is advantageous to the plant.

The plant benefits in three ways :—

1. Certain decomposition products, nitrates, and the ash constituents, are direct plant nutrients;

2. Other products, including the colloid complex humus, greatly improve the physical conditions of the soil for the plant, while the unaltered structure material may injure the physical conditions;

3. Some of the intermediate products of decomposition would be harmful if they accumulated, *e.g.* certain phenolic substances, but they are speedily oxidised and rendered inocuous by micro-organisms.

These actions might be grouped as nutritive and scavenging.

The soil population has also certain effects on the soil which improve it as a medium for plant growth.

1. Certain bacteria fix gaseous nitrogen;

2. Algæ may increase the store of organic matter.

The plant, however, may suffer in two ways:—

1. The soil organisms take up nitrates, phosphates, and other mineral nutrients from the soil, and appear to be able to get them more readily than the plant.

2. Certain of the soil organisms may directly injure the plant, *e.g.* the parasitic forms.

The micro-organisms benefit by the growth of plants because the greater the growth the more energy material will be brought into the soil.

But the benefit is not immediate; the growing plant may, indeed, depress the growth of micro-organisms.

These various actions are all concurrent; their resultant represents the effect of the soil population on fertility. Increases in nutrient supplies lead to increased activity of the micro-organisms. Hendrick,[1] in lysimeter experiments, finds that the amount of nitrate derived from the soil (which measures the amount of ammonia produced) is greater on soils receiving large quantities of artificial fertilisers than in unmanured soils. The quantities in lb. per acre over a period of fifteen months are:—

[1] *Scottish Journ. Agric.*, 1924, 7, 1, 8-18. The differences are usually less than these.

	No Manure Added.	Sulphate of Ammonia added.	Sulphate of Ammonia and Superphosphate.	Sulphate of Ammonia, Superphosphate and Muriate of Potash.
Total nitrate in crop and drainage water .	193	774	792	776
Nitrate supplied by manure .	—	475	475	475
Nitrate from soil	193	299	317	301

The seasonal fluctuations which are a marked feature of the numbers of organisms show up equally clearly for the products of their activity. The production of CO_2 and of nitrate is most rapid in spring and autumn, least rapid in summer and winter. There are consequential changes in the bases which, however, have not been fully worked out. The spring activity is specially well marked; it has been a tradition among gardeners and farmers from time immemorial.[1] It was studied by Löhnis and Sabachnikoff at Leipzig (180*a*) and under the picturesque title of *Le Réveil de la Terre*, by Müntz and Gaudechon (209). Fig. 21 shows the Rothamsted results. Leather in India (165*b*) and Jenson [2] in South Dakota obtained similar results.

The change in nitrate content of the soil is important in view of the fact (pp. 47, 377) that plants assimilate most of their nitrogen in the early days of their growth.

But when one gets away from the great simple outlines, the details of the relationships are very complex. Among the most interesting results are the curious reversals of activity sometimes observed, which make the path of the dogmatist in soil microbiology peculiarly treacherous. Thus,

[1] Cf. Virgil, *Georgics*, Bk. II., 11, 324-327 :—

vere tument terrae et genitalia semina poscunt.
tum pater omnipotens fecundis imbribus aether
coniugis in gremium laetae descendit et omnis
magnus alit magno commixtus corpore fetus.

[2] C. A. Jenson, *U.S. Dept. of Agric. Bureau Plant Indust. Bull.*, 173, 1910.

addition of organic matter containing 4 or 5 per cent. of nitrogen is commonly followed by an increased production of nitrate and enhanced fertility. But should the organic matter contain only 1 or 2 per cent. there may be an absorption of existing nitrate and a decrease in fertility; the decrease is only temporary but it is quite clear. Again: in neutral soils of cool climates, *Bacillus radicicola* is the most active fixer of nitrogen and azotobacter is relatively inactive; lucerne, therefore, enriches the soil in nitrogen while wheat stubble does not. In alkaline soils of warm climates, on the other hand, azotobacter is greatly stimulated; *Bacillus radicicola* is not; wheat stubble, therefore, enriches the soil in nitrogen while lucerne has hardly any effect (p. 251).

Still more remarkable are the strikingly unexpected results of treating the soil in ways calculated to injure the trophic life; drying, treating with poisons, heating, etc. Instead of decreasing the activity of micro-organisms these treatments tend to increase it at any rate for certain groups (p. 342).

The relative simplicity of the effects of moisture and temperature on the amount of decomposition when studied only in broad outlines, and the difficulties encountered when one comes down to details, account for the measure of partial success attained in the attempts to trace simple relationships between specific activities of the micro-organisms and soil fertility. Soils differing only in their content of organic matter present the simplest case; if they are otherwise comparable the differences in numbers of micro-organisms or in the amounts of their products run fairly closely with differences in fertility.[1] Soils differing in reaction also show relationships between activity of micro-organisms and fertility if the difference is sufficiently marked, but not otherwise, the fungi being apparently less sensitive than the

[1] Out of many instances in the literature we may quote Stoklasa and Ernest (271), who found only one to two million organisms in their barley land, three to five millions on the better treated sugar beet land, and seven to eight millions on the clover land. See also P. E. Brown, *Iowa Res. Bull.*, No. 13, 1913; Heinze, *Landw. Jahrb.*, 1910, 39; Ergänz. Bd., 3, 314-343; and Arnd (4*b*).

plant (p. 301). But where the fertility is determined by some other factor the relationships are more complex and cannot be expressed simply. Microbiological methods are of only limited value in soil analysis except in special cases (p. 294).

The Effect of Simplifying the Soil Population: Partial Sterilisation.

In the preceding pages several instances have been given of treatments detrimental to trophic life increasing the activity of the surviving members of the soil population and particularly of the bacteria.

Relatively mild treatments, such as drying the soil, heating to 45° C., treatment with poisons which are not too strong,[1] cause a fall in numbers of bacteria, but when the conditions are again made suitable, the numbers rise considerably. They do not remain high, but sooner or later fall to the normal range of values.

More drastic treatment, such as heating the soil to 50° C. (at which temperature most of the trophic forms are killed), or treatment with certain stronger poisons, also causes a fall and subsequent rise in bacterial numbers when favourable conditions are restored, but the high numbers are permanently maintained. The phenomena are not confined to soil but are shown also by sewage beds.[2] According to Waksman and Starkey (290), the fungi also are first much depressed, but increase greatly in numbers soon after the conditions again become favourable. Russell and Hutchinson showed that the numbers of bacteria in partially sterilised soils, unlike those in normal soils, reacted in accordance with expectation towards changes in temperature and water content.

[1] The effect of poisons was first observed in Alsace (216) and has been much studied in France by M. Truffaut, Rivière and Pritchard (*Ann. Sci. Agron.*, 1922, 39, 366), Miège and others.

[2] The disinfection of sand filters leads to increases in the numbers of bacteria. This was observed in the typhoid epidemic at Lincoln in 1904, and also in the experimental sewage filter at Guildford in 1907 (Houston and McGowan, *Fifth Report, Sewage Commission*, Appendix IV., Cd. 4282, 1910, p. 111.

As a general explanation the writer suggests that the treatment, by curtailing or eliminating (according to its severity) one or more of the groups of the soil population, leaves the others more free from competition, and, therefore, able to increase to higher numbers than before and also to react normally to changes in external conditions. This view was put in more concrete form in conjunction with H. B. Hutchinson (241*a*) and evidence was adduced that bacteria, at that time regarded as the only living organisms in the soil, were not so in fact, but that other organisms were normally present keeping down their numbers. It was shown that these organisms were probably protozoa, a view that Cutler has since substantiated (p. 318).

The organisms surviving partial sterilisation produce more ammonia and nitrate than did the original population, so that soils treated by methods calculated to injure trophic life gain in fertility, an apparently paradoxical result in view of the importance of trophic life to soil fertility (Table LXXIII.).

The fact has long been known to cultivators of the soil. Heating the soil has been practised from time immemorial in India; the process is called "rab," and is mentioned in the Vedas;[1] the burning of stubble was known by the Romans to increase the fertility of the soil, and various possible explanations were shrewdly put forward by Virgil.[2] Exposure of the soil to the baking heat of the sun is an ancient practice

[1] Like to a tender plant whose roots are fed,
On soil o'er which devouring flames have spread.

Stories of the Buddha's Former Births. Trans. H. L. Francis.

[2] *Georgics*, Bk. I., 11, 84-93:—

saepe etiam steriles incendere profuit agros,
atque levem stipulam crepitantibus urere flammis;
sive inde occultas vires et pabula terrae
pinguia concipiunt, sive illis omne per ignem
excoquitur vitium atque exsudat inutilis umor,
seu plures calor ille vias et caeca relaxat
spiramenta, novas veniat qua sucus in herbas;
seu durat magis, et venas adstringit hiantis,
ne tenues pluviae rapidive potentia solis
acrior aut Boraea penetrabile frigus adurat.

TABLE LXXIII.—CHANGES PRODUCED IN SOIL BY PARTIAL STERILISATION. WEIGHT AND COMPOSITION OF CROPS GROWN ON PARTIALLY STERILISED SOILS. RUSSELL AND DARBISHIRE (240*b*).

	Dry Weight of Crop.	Percentage Composition of Dry Matter.			Weight of Nutrients Taken by the Plant from Soil, grms.		
	Grms.	N	P_2O_5.	K_2O.	N.	P_2O_5	K_2O.
Buckwheat.							
Untreated soil .	18 14	2·75	1·87	5·62	·499	·339	1·019
Soil treated with carbon disulphide	23·27	3·15	2·34	5·97	·733	·544	1·389
Mustard.							
Untreated soil .	15·88	2·30	1·00	4·20	·367	·159	·668
Heated soil . .	24·33	4·43	2·08	5·02	1·077	·506	1·221

AMMONIA AND NITRATE ACCUMULATING IN A SOIL KEPT TWENTY-THREE DAYS AT ABOUT 15° C. IN A MOIST CONDITION, PARTS PER MILLION OF DRY SOIL. RUSSELL AND HUTCHINSON.

	Nitrogen Present as Ammonia.		Nitrogen Present as Nitrates.		Total Nitrogen Present as Ammonia and Nitrate.		
	At Beginning.	After 23 Days.	At Beginning.	After 23 Days.	At Beginning.	After 23 Days.	Gain in 23 Days.
Untreated soil . .	1·8	1·7	12	16	13·8	17·7	3·9
Soil heated 2 hours to 98° C.	6·5	43·8	13	12	19·5	55·8	36·3
Soil treated with toluene, which was then evaporated	5·0	27·8	12	12	17·0	30·8	22·8
Soil treated with toluene, which was not removed	7·2	14·5	11	10	18·2	24·5	6·3

still common in India [1] and in Egypt, where it is known as *sheraqui*, and has been studied by J. A. Prescott (228), and by Victor Mosseri (204), and shown to be due partly to microbiological, and partly to physical, causes. Lebediantzev [2] considers that this repeated drying and heating of the soil plays no small part in maintaining its fertility in hot countries. The effects on the plant are in all cases described as resembling those of nitrogenous manure.

[1] H. and A. G. L. Howard, *Nature*, 1910, p. 456.
[2] *Soil Sci.*, 1924, 18, 419-447.

This increased production of ammonia and nitrate is not a necessary consequence of the higher numbers of organisms; on the contrary higher numbers, *e.g.* those induced by adding non-nitrogenous organic matter to the soil, might depress the ammonia and nitrate content (p. 287) by taking up these substances for their own nutrition. The increased production of ammonia and nitrate is a distinct phenomenon, and several explanations have been put forward to account for it.

Hiltner and Störmer (134*c*), who were the first to associate the beneficial effects of partial sterilisation with bacteria,[1] considered that the new bacterial flora set up after the treatment was more potent in decomposing protein than the old one. This view was shown to be inaccurate by Russell and Hutchinson, who replaced the old flora by inoculating untreated soil into partially sterilised soil, and showed that the bacterial numbers rose even higher, and produced even more ammonia and nitrate, than did the new flora by itself.

The idea has recently been modified by S. A. Waksman and E. L. Starkey (290), who suggest that in the normal soil much of the decomposition of the protein is effected by fungi, which assimilate a good deal of the carbon and a corresponding amount of nitrogen; after partial sterilisation, however, the fungi are for a time suppressed and the decomposition passes to the bacteria which assimilate much less of the carbon and nitrogen, and, therefore, produce a larger amount of ammonia. While this assumption has not been proved, it has the support of probability.

Russell and Hutchinson connected the increased ammonia production with the increased numbers of bacteria, supposing that the new bacterial flora was not widely different from the old, and might therefore be expected to behave like the old, except that, being more numerous, it would accomplish more decomposition. The close relationship between bacterial numbers and ammonia (or nitrate) production in their experiments supported this view. Störmer suggested that the

[1] The earlier investigator, A. Koch, attributed the increased productiveness to a direct stimulation of the plant.

additional ammonia and nitrate came from the decomposition by bacteria of the organisms killed by the partial sterilisation process. The amounts formed, however, are much larger than correspond with our present estimates of the soil population; in the Rothamsted soil they are of the order of 20 to 50 parts of nitrogen per million of soil, while the whole protozoan and bacterial population represents only 4 parts: estimates of the nitrogen in soil fungi are, however, only rough.

The phenomena are complicated by the circumstance that partial sterilisation, however it is done, affects the colloids and the organic matter of the soil. The effect of heat has been much studied; [1] it is shown to bring about considerable decomposition of the organic matter, and thus to go some way towards the production of ammonia and nitrate. S. U. Pickering (*226b*) showed that antiseptics had the same kind of effects but to a less degree. R. Greig-Smith [2] supposed the soil particles to be coated with a waxy material "agricere," which is removed in partial sterilisation; for this, however, there is no clear evidence.[3] The consequences of the changes in the colloids and the organic matter are likely to remain unknown until more has been discovered about these substances in the soil.

There has been a great amount of controversy as to the reasons for the increased bacterial numbers and the increased production of ammonia and nitrate in partially sterilised soils.[4] The two phenomena, though closely related, are probably distinct, and they are probably influenced by all of the changes brought about by partial sterilisation. It is desirable to have a thorough investigation of the chemical changes brought about by partial sterilisation, and of the way in which these affect the activities of the micro-organisms.

[1] *241a*; also S. U. Pickering, *Journ. Ag. Sci.*, 3, 171; Seaver and Clark, *Biochem. Bull.*, 1912, 1, 413; Schreiner and Lathrop, *U. S. Bureau Soils Bull.*, 89, 1912.

[2] *Centr. Bakt. Par.*, 1911, Abt. II., 30, 154-156; *Proc. Linn. Soc.*, New South Wales, 1918, 43, 142-190.

[3] See Russell and Hutchinson: also J. P. du Buisson, *Soil Sci.*, 3, 353-392.

[4] For a summary complete up to 1925 see 290.

CHAPTER VII.

THE BIOTIC CONDITIONS IN THE SOIL.

In the preceding chapters we have dealt separately with the plant and the soil; we shall now deal with them jointly and discuss the relationships between the soil properties and the growth of the plant. The conditions directly and markedly influencing the life of the plant, which may be called the chief biotic conditions in the soil, are air supply, water supply, temperature, supplies of nutrients, tilth, reaction, and possible toxins.

Air Supply: the Gas Phase of the Soil.

The soil being a porous mass, air can enter and pass out both by direct streaming and by diffusion. The amount that enters, and the rate of entry, depend on the pore spaces which in turn are determined by the sizes, shapes, and modes of arrangement of the soil particles. But the pore space has also to hold the soil water, so that a knowledge of its amount gives only the maximum space available for air. The space actually occupied by air at any time is this maximum less the space occupied by the water present.

If the soil particles were all spherical, the pore space could be studied mathematically. C. S. Schlichter [1] has shown that it would constitute 47 per cent. of the total volume if the particles were arranged in the most open fashion, and 26 per cent. if they were packed as closely as possible.

[1] *U.S. Geol. Survey*, 19th Ann. Rept., 1899. For further developments see W. B. Haines, *Journ. Agric. Sci.*, 1925, 15, 529-535.

For natural soils, however, no suitable mathematical treatment has been devised, and an experimental estimate is therefore made. A known volume of the soil, taken *in situ* with a rectangular sampling tool, is dried and weighed. The true specific gravity of the particles is then determined, and the volume of the solid matter is calculated. The pore space is the difference between this volume and that of the whole soil.

Table LXXIV. shows the pore spaces for certain Rothamsted

TABLE LXXIV.—PORE SPACE, WATER CONTENT, AND AIR CONTENT OF CERTAIN SOILS. RUSSELL.

	Specific Gravity of Dry Soil.		Volume Occupied in Natural State by		Volume of Water.		Volume of Air	
	Apparent.	True.	Solid Matter.	Air and Water (Pore Space).	In Normal Moist State.	After Period of Drought.[1]	In Normal Moist State.	After Period of Drought.[1]
Poor heavy loam (Rothamsted), loss on ignition, 4·3 per cent. . . .	1·57	2·36	65·9	34·1	23·2	17·0	10·9	17·1
Heavily dunged arable soil (Rothamsted), loss on ignition, 10·0 per cent.	1·46	2·31	61·8	38·2	30·3	20·0	7·9	18·2
Pasture soil, loss on ignition, 13·0 per cent. . . .	1·17	2·22	52·7	47·3	40·0	22·3	7·3	25·0

soils: it varies from 34 to 47 per cent., figures within the range of Schlicher's theoretical values. The pore space is increased by the presence of clay [2] and of organic matter, and it is higher in grass-land than in arable, partly as a result of the actions of living organisms.

The space occupied by air at any time is calculated by deducting the volume of the water present from the total pore

[1] Driest periods of 1909 and 1910. During the abnormal drought of 1911 the numbers fell to 6 and 8 for the first two soils.

[2] For illustrations see B. A. Keen and H. Raczkowski, *Journ. Agric. Sci.*, 1921, 11, 441-449.

space, it being assumed that the volume of moist soil is the sum of the volumes of the solid particles and the water, an assumption which, while not strictly true, is probably not far wrong. About 7 to 10 per cent. of the total volume of the Rothamsted soil is usually filled with air, the values ranging from about 25 per cent. down to very little.

In humid climates (Europe, North America, etc.) the air in the soil to the depth penetrated by plant roots (6 or 9 inches) is almost identical with that of the atmosphere, the two important differences being in the carbon dioxide and moisture content (Table LXXV.).

TABLE LXXV.—COMPOSITION OF THE AIR OF SOILS, PER CENT. BY VOLUME.

Soil.	Usual Composition.		Extreme Limits Observed.		Analyst.
	Oxygen.	Carbon-dioxide.	Oxygen.	Carbon-dioxide.	
Arable, no dung for 12 months	19·20	0·9	—	—	Boussingault and Lévy (47).
Pasture land . .	18·20	·5-1·5	10-20	·5-11·5	Schloesing *fils* (246).
Arable, uncropped, no manure, sandy soil	20·6	·16	20·4-20·8	·05- ·30	Lau (159), mean of determinations made frequently during a period of 12 months. Values at depths of 15 cm., 30 cm., and 60 cm., not widely different. (30 cm. values given here.)
Arable, uncropped, no manure, loam soil	20·6	·23	20·0-20·9	·07- ·55	
Arable, uncropped, no manure, moor soil	20·0	·65	19·2-20·5	·28-1·40	
Sandy soil, dunged and cropped (potatoes), 15 cm. . . .	20·3	·61	19·8-21·0	·09- ·94	
Seradella, 15 cm. .	20·7	·18	20·4-20·9	·12- ·38	
Arable land unmanured	20·4	0·2	18·0-22·3	0·01-1·4	Russell and Appleyard (241*e*).
„ „ dunged .	20·3	0·4	15·7-21·2	0·03-3·2	
Grass land . .	18·4	1·6	16·7-20·5	0·3-3·3	

(Atmospheric air contains 21 per cent. of oxygen and ·03 per cent. of CO_2.)

In arable soils the percentage by volume of oxygen usually exceeds 20·3, that of nitrogen is usually about 79, while the carbon dioxide varies from about 0·15 to 0·65 : the values for

atmospheric air are respectively 20·96, 79·01, and 0·03. The chief variable, the CO_2, increases with the amount of organic matter in the soil and with temperature and moisture content; it is higher in summer than in winter. It increases also when the crop is growing: H. W. Turpin[1] found in pot experiments 0·3 to 0·95 per cent. of CO_2 in the air of uncropped soils, but 0·3 to 2·0 per cent. in the air of cropped soils. In soils covered with grass the air contains more CO_2 (usually about 1·6 per cent. at Rothamsted), and appreciably less oxygen, usually about 18·4 per cent., but sometimes less than 17 per cent. at Rothamsted.

Comparison of these values with the rates of production of CO_2 in soils shows that there must be a rapid exchange between the soil and the atmosphere. According to Romell's calculations, the air must be completely renewed every hour to a depth of 20 cms. when CO_2 is being generated at the recorded rate of 7 litres per square metre per day, or it could not remain at its normal composition. The cessation of the exchange for one and a half hours would double the amount of CO_2, while for fourteen hours it would increase the amount fourfold (Romell, 239). This rapid exchange is brought about partly by direct movement or streaming and partly by diffusion of the air.

Several agencies cause a certain amount of direct movement. Changes in the atmospheric pressure traverse the soil as if it were not there; they are exactly the same and are felt at exactly the same time 10 feet below ground as on the surface;[2] the exchange of air thus effected must be considerable. Changes in temperature, movements of wind across the surface or of rain water through the soil also cause streaming of air in and out of the soil. E. H. Richards has shown[3] that rain brings down an appreciable amount of dissolved oxygen:—

[1] *Cornell Memoir*, 1920, 32.

[2] G. J. Bouyoucos and M. M. McCool, *Soil Sci.*, 1924, 18, 53-63. The records were taken on barographs buried in the soil.

[3] *Journ. Agric. Sci.*, 1917, 8, 331-337.

DISSOLVED OXYGEN BROUGHT DOWN IN RAIN. RICHARDS.

	Average Rainfall (Inches) at Rothamsted (28 Years).	Dissolved Oxygen.	
		Parts per Million.	Lb. per Acre.
Summer .	13·32	9·0	27·12
Winter . .	15·50	11·2	39·27
Year . .	28·82	—	66·39

The aggregate effect of these weather conditions is sometimes sufficient to account for the hourly exchange; indeed, the older workers [1] attributed the whole effect to them. But the CO_2 content of the soil air shows no clear connection with barometric pressure or velocity of wind (241*e*), and Romell's investigations show that in general these agents are insufficient to produce the observed effects; some continuously acting mechanism is necessary. Diffusion is therefore now regarded as being in all probability the chief factor in bringing about the exchange. The diameters of the soil pores are small, but, as H. T. Brown and F. Escombe have shown,[2] the rate of diffusion through small pores is not much less than through larger ones.[3]

The importance of the soil air to the growing plant has led agriculturists to seek for methods of control. The most effective is to ensure a free passage to water capable of draining away, so that the pore spaces shall not be blocked; this is done by various drainage devices.

Cultivation is commonly supposed to exert a great effect on soil aeration, but experiments have shown nothing very

[1] Ramann (231), Mitscherlich (200*c*), Hann, and others.

[2] *Phil. Trans.*, 1900, 193B, 223-292.

[3] L. M. Hutchins and B. E. Livingstone (*Journ. Agric. Res.*, 1923, 25, 133-140) have proposed a method for direct measurement of the rate at which equilibrium is restored once it is disturbed, their purpose being to study the rate at which the soil supplies oxygen to plant roots. A porous porcelain cylinder, having walls 1 to 2 mm. thick impregnated with paraffin oil, was sunk in the soil and the air diffusing in was swept out by a current of illuminating gas and then analysed.

striking: there is a reduction in the amount of CO_2 but not much. Clearly if the air of an arable soil already contains as much as 20·3 per cent. of oxygen and as little as 0·3 per cent. of CO_2, there is little margin for improvement by cultivation, even by breaking the cap which forms after rain on a heavy soil. Yet the effect of tillage operations on plant growth is very marked, leading to a firm belief among farmers and gardeners that the soil aeration has been thereby perceptibly improved—a belief that deserves careful and unprejudiced examination by scientific workers.

In natural conditions earthworms play an important part in aeration; their burrows make passages down which air and water can easily pass.

In spite of the rapidity of diffusion there appear to be local variations in composition of the soil atmosphere. Leather obtained evidence that the amount of CO_2 is higher near plant roots than further away. Localised activities of soil micro-organisms are probably accompanied by variations in CO_2 output, which, however, are difficult to demonstrate as the taking of even a small sample of soil air means extensive evacuation of the pores.

The carbon dioxide in the soil atmosphere is not all that is present in the soil. Some is dissolved in the soil water, the exact amount depending on the other dissolved substances and the way in which the equilibrium with the soil air is affected by the presence of the soil colloids. Leather's calculations suggested large amounts of dissolved CO_2, but direct determinations would be desirable.

Below the dried mulch soil air is always saturated with moisture, a property of obvious importance for the micro-organic life in the soil, since it excludes the factors of varying humidity and evaporating power known to exert marked effects on life above ground.

Russell and Appleyard obtained evidence of a dissolved atmosphere in soil composed mainly of CO_2 and some nitrogen; presumably this is held by colloidal envelopes of the soil

particles. Its significance is that organisms needing anaerobic conditions can find them in normal soil provided they can tolerate CO_2.

In water-logged soils the air may contain much more CO_2 than in aerated soils and much less oxygen. A great change sets in when the oxygen disappears altogether. Marsh gas and hydrogen are then formed (p. 239) neither of which is present in normal soil air to any greater extent than in the atmosphere (241*e*).

So far we have been dealing with conditions in temperate and humid climates only. Leather's determinations at Pusa (165*c*) suggest that the CO_2 in the soil air may be much higher, some of his values varying from 1 to 5 per cent., while the oxygen fell considerably; during the hot, dry season of April and May it was sometimes only 16 to 18 per cent., and during the rains (monsoon) of June and July it fell to 8 to 12 per cent. Others of his values, however, are not unlike those of temperate climates.

The Water Supply.

Of the water reaching the soil from the rain part runs straight through the surface layers into the subsoil where it either remains or drains away; while the rest is held near the surface till it evaporates or is transpired by plants. In regions of low rainfall the water does not penetrate far into the subsoil, and there is a lower depth sometimes called the dead layer which no water ever reaches. In humid regions there is normally drainage: the amount is greater in winter than in summer, and is higher on uncropped land than where vegetation is growing. At Rothamsted the figures for uncropped land are given in Table LXXVI. :—[1]

[1] For Pusa results see H. N. Batham, *Chem. Mem. Dept. Agric.*, India, 1926, 8, 127-152.

TABLE LXXVI.—RAINFALL, DRAINAGE AND EVAPORATION FROM UNCROPPED LAND 20 INCHES DEEP. ROTHAMSTED, MONTHLY MEANS FOR 54 YEARS, 1870-1924.

Month.	Rainfall.	Drainage.	Drainage per Cent. of Rainfall.	Evaporation.
	Ins.	Ins.		Ins.
September .	2·348	0·762	32·5	1·586
October . .	3·143	1·793	57·0	1·350
November .	2·724	2·053	75·4	0·671
December .	2·851	2·426	85·1	0·425
January . .	2·374	1·922	81·0	0·452
February .	1·995	1·468	73·6	0·527
March . .	2·076	1·125	54·2	0·951
April . .	2·043	0·666	32·6	1·377
May . .	2·048	0·488	23·8	1·560
June . .	2·270	0·564	24·8	1·706
July . .	2·713	0·718	26·5	1·995
August . .	2·683	0·706	26·3	1·977
Year . .	29·268	14·691	50·2	14·577

The water retained in the surface layers, like the soil air, is held in the pores, and the volume of pore space sets the limit beyond which its amount cannot increase, and which, indeed, in nature it rarely attains. The quantities usually present vary with the different types of soil, as shown in Table LXXVII.:—

TABLE LXXVII.—MOISTURE CONTENT [1] OF SANDY, LOAMY, AND CLAY SOILS AT WOBURN, LYING NOT FAR APART, AND UNDER APPROXIMATELY EQUAL RAINFALL CONDITIONS. RUSSELL.

	Sandy Soil (Clay=5·0 per Cent.).	Loamy Soil (Clay=9·3 per Cent.).	Clay Soil (Clay=43·0 per Cent.).
Highest observed . .	14·0	16·5	35·0
Lowest observed . .	1·1	6·0	15·8
Mean of all observations .	9·0	12·0	27·0

They are highest and least liable to fluctuations in clay and peaty soils, and lowest and most liable to fluctuations in sandy

[1] This determination was made by drying at 40° C.

and chalky soils. The determining factor appears to be the amount of colloid present.

The water relationships of the soil are considerably more complex than the air relationships. Unlike the molecules of air, water molecules are not free to move in any direction within the pores of the soil. The force of gravity causes some of the liquid water to sink in the soil; surface attractions of various kinds hold some of it to the soil particles; and the soluble salts hold it by other forces. The operation of these actions makes it impossible for the plant to obtain all the water in the soil, any that is held by forces more powerful than it can exert being out of its reach; in effect, therefore, some of the water is not available for the plant. This is in sharp contradistinction to the soil air, all of which may be regarded as available.

The older investigators regarded the soil as a collection of mineral grains on which the water was spread in thin films; the chief factor determining the water relationships was supposed to be the force of capillarity.[1] It is now recognised, however, that the soil colloids also play a great part; indeed most investigators attach more importance to them than to capillary actions.

The physical forces acting on the soil water and against which the plant must successfully compete are :—

1. Gravity, which acts on all the water and which is equivalent to a pressure of about 1 atmosphere.

2. Surface forces, falling into two groups: (*a*) capillarity, which holds water on the surface of the particles or in pores or interstices of less than a certain size: (*b*) imbibition,[2] the force with which the colloids hold water. These forces vary with the amount of water and with the conditions;

[1] See L. J. Briggs (55*a*), 1897, for an interesting discussion from this point of view.

[2] Apparently the same as the "vesicular" water of Wilsdon (*Pusa Mem. (Chemical)*, 1921, 6, 155-186), and F. Hardy, *Journ. Agric. Sci.*, 1923, 13, 340-351.

they may range from one up to several hundred atmospheres.[1] But how far this division affects the relationships between the soil water and the growing plant is not yet known.

3. More intimate surface forces of high magnitude equivalent to several hundred or a thousand atmospheres, affecting only a small proportion of water.

These forces overlap in their operation, and the state of the soil water is continuous, at any rate until the extreme condition when the vapour pressure falls off considerably. This was deduced by Keen from studies of the rate of evaporation of water from soil (145*a*) and by G. A. Shull (264) in measuring the absorption of water from soil by seeds. In neither investigation was there any sign of a break. Later work shows that the proof is not rigid since the rate of evaporation is the complex resultant of soil water relationships and environmental factors, and absorption of water by seeds in a solution does not necessarily follow the same course as in soil. But the evidence is sufficiently good to justify the abandonment of the old divisions of the soil into sharp groups of "gravitational water," "capillary water," "imbibitional water," and "hygroscopic water." We must think of the water as being held by forces which vary smoothly and continuously with its amount, being very small when the water content is large and very great when the water content is small (Fig. 39). The variation is much affected by the size of the particles and the amount of colloidal material. In a sand almost all the water is held by forces of low magnitude, while in a loam some 5 to 10 per cent. may be held by forces of high magnitude, and in a clay or peat as much as 20 per cent. or more may be so held. But there are no sharp divisions.

[1] For discussions of the different points of view see Green and Ampt, *Journ. Agric. Sci.*, 1911, 4, 1; E. A. Fisher, *ibid.*, 1923, 13, 121-143; *Proc. Roy. Soc.*, 1923, 103A., 139, 664; B. A. Keen, *Trans. Far. Soc.*, 1922, 17, 228-243, other papers follow this; B. A. Keen, E. M. Crowther and J. R. H. Coutts, *Journ. Agric. Sci.*, 1926, 16, 105-122; Wilsdon, *Pusa Mem.*, 1921, 6, 155.

The result of the inverse relationship between the magnitude of the force holding the water to the soil and the quantity of water present is to narrow the fluctuations in water content. For each soil in a humid climate there is a range of values beyond which the water content does not readily pass. Any excess relatively easily drains away (assuming there is no

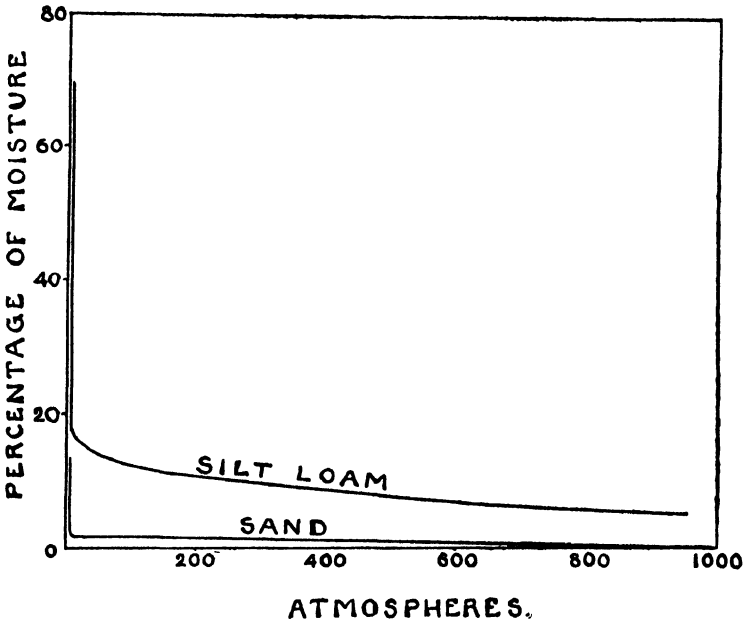


FIG. 39.—Magnitude of force with which water is held by soil, showing change with decreasing water content. (C. A. Shull, 264.)

mechanical obstacle); while losses beyond a certain amount become increasingly difficult. No sharp distinction exists at either end. Fig. 20 (p. 159) shows typical results; the winter and summer values both remain fairly steady; deviations in either season are slow to set in.

The plant growing in the soil exerts a certain pull on the water and can therefore obtain all water held by less potent forces. The pull is exerted by virtue of the osmotic pressure of the root sap which varies with the plant and the conditions

but ranges from about 7 to 20 atmospheres;[1] this then may be regarded as the critical region on the curve of Fig. 38; water held by stronger forces being unavailable to the plant, but water held by less force being available. Experiment shows, however, that the plant does not obtain all the water thus expected; it wilts and dies soon after 4 atmospheres is passed.[2] The discrepancy is readily explained; wilting occurs when the loss of water from the leaves exceeds the intake by the roots; and it is therefore affected by the rate at which water travels in the soil to replace any taken by the plant, and the rate at which new rootlets grow out to fresh regions of moist soil. A complete account of the soil water in relation to the growing plant involves a knowledge not only of the curves showing the pull on the water, but also of its rate of movement.

It is hopeless to seek for sharp equilibrium points between the growing plant and the soil in their respective pulls on the water. In a general way, however, one can distinguish—

1. Excess water, which by filling up the pore spaces of the soil excludes air and therefore injures the roots.

2. Available water.

3. Unavailable water, beyond the power of the plant to absorb.

This grouping is useful for ecological and agricultural studies, and it is unobjectionable if it is recognised as having no precise quantitative significance.

There is an obvious similarity between this and the physical divisions; in the main indeed they are more or less the same, for water capable of being drawn off by gravitation would be

[1] See E. Hannig, *Ber. Deut. bot. Gesell.*, 1912, 30, 194-204 (7 to 8 atmospheres); Dixon and Atkins, *Proc. Roy. Dublin Soc.*, 1912, 13, 229. Some of their results are: Roots of *Beta vulgaris* up to 21·8 atmospheres; of *Ilex aquifolium*, 7·64-10·38 atmospheres; of *Helianthus tuberosus*, 12·76-18·67 atmospheres.

[2] Shull. Many wilting coefficients (*i.e.* the percentage of water left in the soil when the plant just begins to wilt) have been determined by L. J. Briggs (55*b*, *c*). For further discussion see Shull, *Trans. Farady Soc.*, 1922, 17, 255-259.

harmful if it were mechanically prevented, and the water held by the surface forces of high magnitude is unavailable for the plant.

Several attempts have been made to estimate by simple laboratory tests how much of the water in a given soil is available to plants. There is unfortunately no easy way of setting up curves like that of Fig. 39, which, with the osmotic pressure of the root sap, would give valuable information. For rapid survey work some convention as to what shall be regarded as unavailable water is usually adopted. The simplest, though very crude, is to assume that all water left in the soil after air drying at 15° C. is unavailable; this has been used to some extent in ecological and agricultural surveys.[1] A more definite quantity is the amount of water which the dry soil has absorbed from a saturated atmosphere at a constant temperature when equilibrium is finally attained. This has been much used in field work by Hilgard (133*a*), Alway (2*a*), and more recently by L. D. Batchelor and H. S. Reed;[2] the values generally fall between 3 and 14 per cent. of the weight of the dry soil and are called the hygroscopic coefficients.

Another and rather different division has been proposed by Bouyoucos. As the soil dries the freezing-point of the soil water changes in such a way as to suggest that part of the water is, in his own word "unfree"; this can be calculated. The division has, however, been criticised on physical grounds by Keen[3] and by E. A. Fisher.[4]

Briggs and McLane (55*b*) endeavoured to make a better division by basing it on the force of attraction; all water held by forces of less than a certain magnitude is thrown out by means of a powerful centrifuge, working under rigidly controlled conditions. The water still retained by the soil is

[1] *E.g.* W. B. Crump, *Journ. Ecology*, 1913, 1, 96-100; *New Phytologist*, 1913, 12, 125-147.

[2] *Univ. Cal. Publ.*, Tech. Paper No. 10, 1923.

[3] *Journ. Agric. Sci.*, 1919, 9, 400-415.

[4] *Journ. Phys. Chem.*, 1924, 28, 360-367.

called the *moisture equivalent.* This division has the advantage that it is obviously conventional, and yet it represents something definite; it is a point on the curve of Fig. 34, and Joseph and Martin have found the method useful in studying the Sudan clays.[1]

Any of these divisions could be criticised as arbitrary and conventional, but so far as they have proved useful in the field, they have justified themselves. Much effort has been devoted to the tracing of cross relationships between these and other pseudo-equilibrium points that have from time to time been proposed, but as these are of physical rather than of ecological or plant physiological interest they need not be discussed here. Briggs' moisture equivalent has, as might have been expected, the highest numerical value, being nearly double (1·8 times) the wilting coefficient, which in turn is somewhat greater (1·4 times) than the hygroscopic coefficient. But, as the values are all conventional, there is no advantage in pursuing their cross relationships too closely except for the purpose of lightening the labour of determining them.[2]

As pointed out above, the relationships between the growing plant and the soil water are not determined wholly by the amount of water but also by the rate at which it can travel in the soil to replace any taken by the plant, or, what in the end comes to the same thing, the rate at which the plant roots can develop in the soil to reach fresh supplies of water. Both processes are easy in medium loams, so that plants growing on them suffer less from drought or heavy rainfall than those growing on other soils. On the other hand, roots develop and water moves with greater difficulty in heavier soils: a sharp line usually separates the dried-out upper layer of soil from the moister one below; indeed in hot, rainless weather, a clay soil may be cracking with drought only a few feet away from

[1] *Journ. Agric. Sci.*, 1923, 13, 49-59.

[2] For summary see B. A. Keen, *Trans. Far. Soc.*, 1922, 17, 228-243, and a more detailed discussion in *Journ. Agric. Sci.*, 1924, 14, 170-177. See also Pratolongo (227) and Alway and McDole (26). The "water content at maximum plasticity," familiarly known as the "sticky point" of the best Indian workers, is promising (Hardy, 123).

a stream. Capillarity was formerly regarded as the chief cause of water movements in soil; nowadays it is considered less important; lysimeter experiments indicate that water which has once passed into the sub-soil rarely comes back again sufficiently quickly to be a factor in plant growth.[1] E. A. Fisher suggests that "imbibition" is a powerful moving force. New methods of investigation have been devised, including the "soil point" method for field studies used by Livingstone and Koketsu [2] and by F. Hardy,[3] and the water level movements in the cylinders set up by B. A. Keen at Rothamsted: fuller information will doubtless be forthcoming.

Farmers and gardeners have discovered empirically that soil moisture may be increased by adding organic matter to the soil, and they have developed effective methods of doing this, including—

(*a*) The application of farmyard manure.

(*b*) Growing mustard, vetches, lupins, and other bulky crops, then ploughing them in while still green.

(*c*) Penning sheep in fields where the crops are growing in order that they may eat the crops and tread the residues together with their excrements into the soil.

(*d*) Leaving the land in grass for a period.

These methods increase the colloidal matter in the soil and therefore increase the amount of water held by imbibition.

Farmers have also discovered that losses of water are much diminished by keeping on the surface a fine layer of soil obtained by shallow cultivation. It rapidly dries, and, as will be shown later, it then constitutes a good non-conducting layer protecting the soil below from the sun's heat and therefore diminishing the loss of water by evaporation. This is

[1] For a review of the literature see F. J. Alway and G. R. McDole, *Journ. Agric. Res.*, 1917, 9, 27; and for a calculation of the theoretical maximum height of rise see B. A. Keen, *Journ. Agric. Sci.*, 1919, 9, 396. Leather (165*a*) obtained but little evidence of capillary movement at Pusa.

[2] *Soil Sci.*, 1920, 9, 469.

[3] *Journ. Agric. Sci.*, 1923, 13, 355-360.

the basis of the so-called "dry farming" practised with success in many parts of the world and well studied in the State of Utah.[1]

The Temperature of the Soil.

The soil derives its heat almost entirely from the sun, the small amount due to radio-activity being negligible in influencing plant growth. The temperature of the soil depends therefore on the amount of heat received by the surface and the way in which this heat is used.

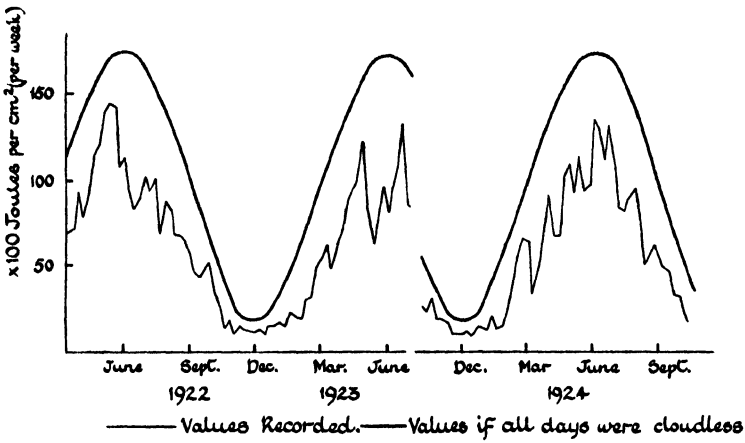


FIG. 40.—Solar radiation received at Rothamsted, 100 Joules per sq. cm. per week. Lower line: actual values; upper line: smoothed curve for cloudless days.

The amount of heat sent out from the sun, more strictly the total radiation, is not constant but varies from time to time. Not all the radiation reaching the earth's atmosphere penetrates to the soil surface; part is absorbed by the atmosphere, and this also is inconstant, because the most powerful absorbers, the CO_2, ozone, and particularly the water vapour, vary in amount.

Fig. 40 shows the amount of energy received on a horizontal surface at Rothamsted; it averages per square centi-

[1] For full descriptions see *Dry Farming*, J. A. Widtsoe, Macmillan, 1913. See also *Utah Expt. Stat. Bull.*, 175, 1920; *New Mexico Bull.*, 130, 1922; *Washington State Coll. Bull.*, 164, 1921.

metre per week about 250 small calories or 1000 Joules in the winter time; about 3500 calories or 15,000 Joules in the summer time; and about 2500 calories or 10,000 Joules over the growing period, March to September. The variations from season to season are mainly due to cloud, for when the data for cloudless days are collected and joined up the curve is seen to be substantially the same each year.[1] Broadly speaking, the total radiation received on each acre of land at Rothamsted during the growing period, March to September, is about $2{\cdot}5 \times 10^{12}$ calories or 10^{10} British thermal units.[2]

These values are for a horizontal surface; for inclined surfaces they would be different by amounts easily calculated. A surface at right angles to the sun's rays at midday receives more heat than an equal area sloping any other way; a south slope in our latitude is warmer than a north slope, often by several degrees, sufficient to produce marked vegetation differences.

In natural conditions the rays reaching the surface do not all penetrate the soil. Many of the rays may be intercepted by vegetation, consequently land densely covered by plants is cooler than bare land; advantage is often taken of this fact in tropical countries to protect soil from intense evaporation by the growth of "shade" crops. Of the rays that do finally reach the surface not all are absorbed, an unknown fraction being reflected back again into space: although no actual measurements have been made, the loss from this cause is probably greater on a white chalky soil than on a black humus soil.

The extent to which a given quantity of absorbed heat

[1] W. B. Haines, *A Comparison of the Radiation Recorders at Rothamsted* (*Journ. Roy. Met. Soc.*, 1925, 51, 95-100); the relations with hours of sunshine are discussed. The surface is enclosed in an evacuated glass bulb and the record is made by the Callendar Recorder of the Cambridge Scientific Instrument Company: 1 calorie (small calorie) = 4·2 Joules and 1 Joule = 10^7 ergs.

[2] This equals nearly 3 million Board of Trade electrical units, or 4 million H.P. hours: it is equivalent to the heat developed by burning some 350 tons of coal and would bring 25,000 tons of water from the freezing to the boiling point (only about 0·5 per cent. of this is recovered in the crop).

raises the temperature of a soil depends on its specific heat and this again on its water content. Dry soil has a specific heat of 0·2, while wet soil has a specific heat approximating more closely to 1; hence under equal sunshine conditions a dry soil will attain at its surface a higher temperature than a moist one. Not infrequently the surface layer of the soil is hotter than the air, especially on a sunny day.[1]

The temperature of the body of the soil depends on two factors—the specific heat of the various layers of soil, and the rate of propagation of the heat wave. At Rothamsted the maximum temperature is commonly attained about 2.15 p.m. in the air, but at 5.30 p.m. at 6 inches depth in the soil. The ease of propagation is not constant, *e.g.* it is much increased by an increase in moisture content. This, however, much increases the specific heat; and the result of the two factors is a considerable damping of the temperature wave as it progresses through the soil. In consequence, fluctuations in air temperature of less than 2° C. are often inappreciable at 6 inches depth.

The temperature curve of the soil at a depth of 6 inches below the surface somewhat resembles that of the air in summer, but it lacks the sharp peaks and depressions. The soil minimum is always greater than that of the air, especially in summer; the maximum is also usually greater in winter, although it is sometimes below in summer. In winter time, however, the curve is often flat all the twenty-four hours and sometimes shows practically no variation for two or three days together (145*d*, Fig. 41).

[1] This is especially true of hot climates. Leather (*Pusa Chem. Mem.*, 1914, 3, 1-49) states that the maximum temperature at Pusa (India) may rise to 70° C. at the soil surface and to 50° at the depth of 1 to 2 inches, the air temperature also being about 50° C. E. McKenzie Taylor and A. C. Burns recorded 65° C. at the surface, and over 56° at a 2-inch depth at Giza, near Cairo (*Min. Agric. Egypt. Bull.*, 31, 1924). P. A. Buxton describes a simple device for recording surface temperatures in hot climates: a set of waxes differing each about 2° in melting-point from its neighbour is used: shavings are dropped on to the soil (*Journ. Ecology*, 1924, 12, 127-134).

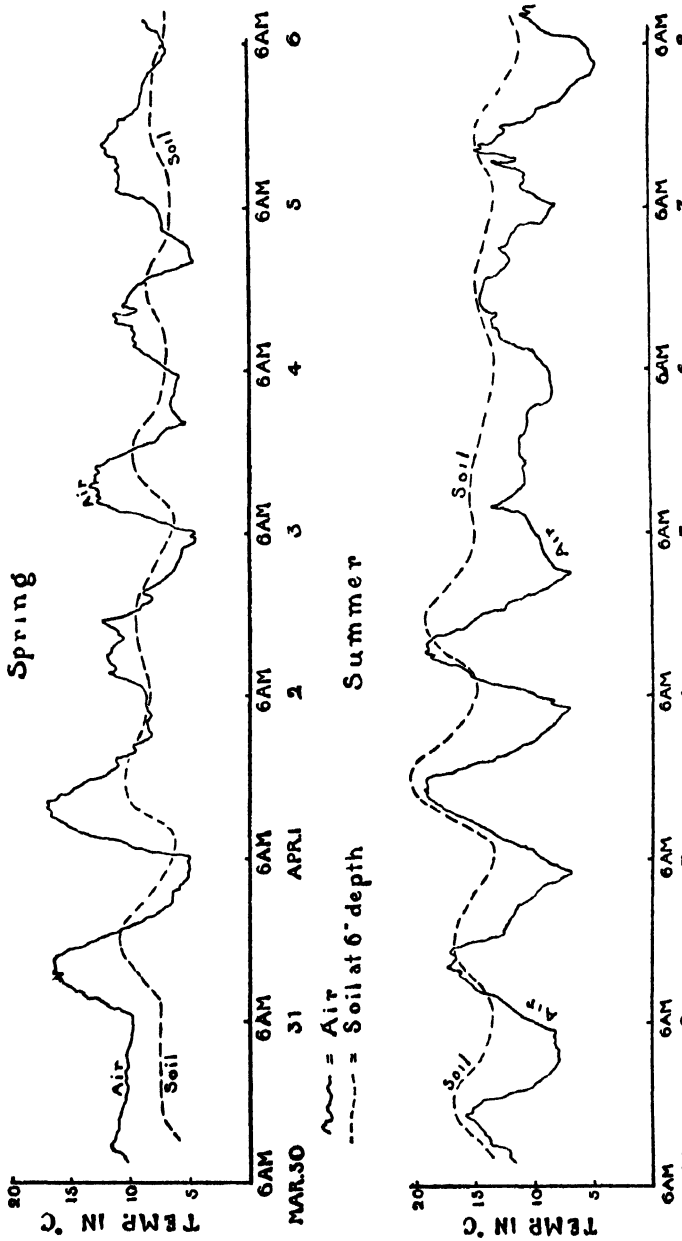


FIG. 41.—Soil temperatures in spring and summer taken by a continuous recording thermometer embedded 6 inches in bare ground at Rothamsted. (Keen and Russell, 1925.)

The general result of all these interactions is that—

1. A south slope is warmer than a north slope.

2. Bare land is warmer than land covered with vegetation, excepting during winter months.

3. Soil exposed to the sun's rays is often hotter at the surface than the air, and is subject to considerable temperature variations.

4. These variations, however, only slowly affect layers three or more inches deep; they also become rapidly narrower. At a depth of 6 inches they are much less than those of the air temperature.

5. Moist soil, being a better conductor than dry soil, is more uniform in temperature.

6. The top 6 inches of soil has a higher mean temperature than the air both in summer and in winter. At 6 inches the warmer part of the day centres round 5.30 p.m., and the cooler part round 9.30 a.m.

7. The warming of the soil in spring is facilitated by drying; the cooling in autumn is increased by clear nights and diminished by rain (Keen and Russell, 145*d*).

Records extending over periods of some months have been published by Wollny (315) and by Thiele (277). British data generally refer only to 6-inch or 12-inch readings; they have been collected and worked up by Mawley, by Mellish,[1] and by Franklin.[2] Systematic readings are taken at the Radcliffe Observatory, Oxford,[3] at Kew, and also at Rothamsted, where a continuous self-recording thermometer is installed. Detailed records of soil temperatures at East Lansing, Mich., have been taken by Bouyoucos (49*a*), who has also discussed their effect on the physical properties of the soil.

Some degree of control of soil temperature[4] is exercised by farmers and cultivators. The most effective way of raising

[1] See *Quart. Journ. Roy. Meteor. Soc.*, 1899, xxv., 238-265.

[2] *Proc. Roy. Soc.*, Edin., 1920, **40**, 10-22, 56-79.

[3] See A. A. Rambaut, *Radcliffe Observations*, 1901, **48**, 1-245, and 1911, **51**, 103-204; also *Phil. Trans.*, 1901, **195** A, 235-258.

[4] For discussion of the ecological significance of soil temperature variations see H. Lundgårdh (182*a*).

the temperature is to remove some of the water; draining a waterlogged soil often leads to striking increases. A second method, more frequently applicable, is to lay the soil in ridges, if possible running east and west; the south face of the ridge thus becomes warmed. The total heat received by the field is of course not increased, but it is concentrated on part of the land.

Lowering of the soil temperature, often desirable in hot countries or during dry summers, is accomplished by maintaining on the surface a layer of loose dry earth which, being a non-conductor, shields the soil from the sun's rays (Table LXXVIII.):—

TABLE LXXVIII.—TEMPERATURES OF SOIL AT DIFFERENT DEPTHS UNDER VARYING CONDITIONS. RUSSELL.

Effect of Weather.

	Air Temp.	Temperature of Bare Soil.					
		Untouched.			Surface Stirred by Hoes.		
		½ inch.	3 inch.	6 inch.	½ inch.	3 inch	6 inch.
Hot sunny day, 20th June, 1910	30°	35°	30·5°	27°	31·5°	29·8	26·5°
Cold cloudy day, 27th June, 1910	18°	17·5°	16·7°	15·8°	17°	16·3°	15·5°

Effect of Vegetation.

	Warm Weather, 5th Oct., 1910, Air Temperature, 17°.			Cold Weather, 4th Jan., 1911, Air Temperature, 3·5°.		
	½ inch.	3 inch.	6 inch.	½ inch.	3 inch.	6 inch.
Bare soil	17°	16·7°	15·5°	3°	2·5°	2·5°
Soil covered with living vegetation (grass land)	15·5°	15°	14·5°	3°	3°	3°
Soil covered with dead vegetation (mulched land)	15·5°	15°	14·5°	2·5°	2·0°	2·0°

Soil Tilth.

The fine crumbly soil texture known as a good tilth is the best suited for plants; it is associated with good water and air supply and easy travel for the roots. The sticky lumpy state is unsuited for plants; the air supply to the roots is

inadequate; so, often, is the water supply; while the roots themselves are unable to travel into the soil, so that the natural vegetation is restricted to plants like Agrostis possessing a surface habit of growth or others such as coltsfoot with large thick roots of great penetrating power. On cultivated land the relationships between early plant growth and drawbar pull or the percentage of clay (p. 226) is fairly close whether the growth be measured by the number of plants surviving the winter (Fig. 42) or the number of tillers of the cereal crop.

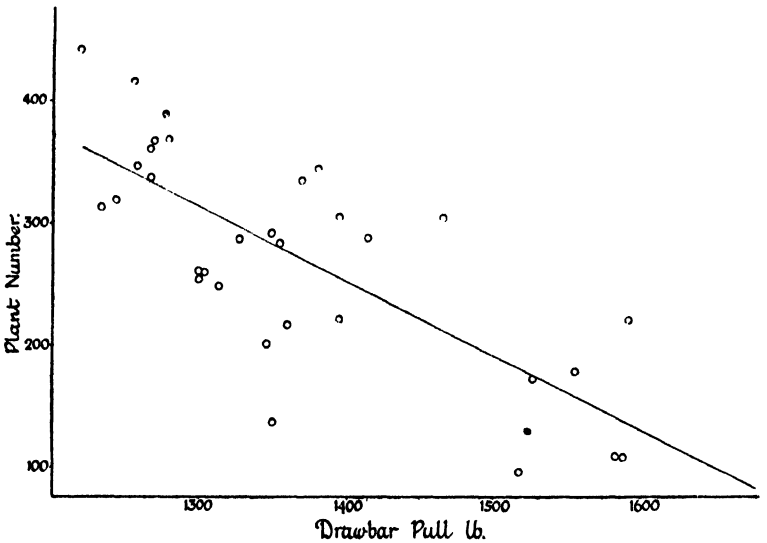


FIG. 42.—Relation between drawbar pull and numbers per row (22 yards) of wheat plants surviving the winter.

The later growth may not show this relationship; the extra moisture held by the clay and the freedom of competition from weeds and from adjoining plants enable the survivors to make considerable growth so that their lack of number is counterbalanced by their greater size. On these soils additional phosphate supply is particularly beneficial to the plant.

The relationships between plant growth and tilth are now being studied at Rothamsted.

The Supply of Plant Nutrients and the Soil Solution.

The relationships of plant nutrients in the soil to the growth of plants are considerably more complex than the water relationships. In addition to the incomplete absorption of nutrients by the plant, due to the strong pull exerted by certain other soil constituents and the competition of micro-organisms, there is the fact that the nutrient elements are present in a variety of combinations of widely different value to the plant. So far no method of completely overcoming the resulting complexity has been devised and the subject has been dealt with empirically.

The nitrogen compounds present the simplest problems. Plants growing in cultivated land probably obtain all their nitrogen as nitrate while those in wild or undisturbed conditions may take up ammonia as well. The amounts of nitrate and ammonia in soil at any moment are readily determined, but both are being formed continuously and there is no method of ascertaining how much more can be produced. Some nitrogen occurs in compounds very resistant to the action of micro-organisms, but some of it is circulating in the tissues of micro-organisms, being in the form of protein while the cell is living, then of ammonia or nitrate when the cell is dead and decomposed, but being again taken up by other organisms or by the plant only to pass through the same cycle of changes later on. There is no means of distinguishing analytically between the fractions passing through the cycle and the stable portion which is undergoing no change. Only the net result can be measured, *i.e.* the amount of ammonia and nitrate present at any time and available for the plant to absorb or for rain water to dissolve out. The cycle of changes is very complex (Chap. V.), and there are approximate limits below which this net production of nitrate does not usually fall and above which it does not usually rise. At Rothamsted even the poorest soil rarely contains less than 5 parts of nitric nitrogen per million, corresponding to about one-half per cent.

of the total nitrogen present. Nitrates are not absorbed by the soil and not completely assimilated by micro-organisms unless additional energy material is supplied (p. 266). They are always present in fallow soil where they can be readily estimated, and though they may be absent from cropped soils a minimum value for the amount that has been produced is given by the amount of nitrogen taken up by the crop.

The entire stock of nitrate in the soil at any time appears to occur in the soil solution, and it is liable to be washed out completely by heavy rain; in any case little if any survives the winter. In favourable conditions fresh supplies are soon produced (Fig. 21, p. 180), but after a wet winter when the soil is cold and poorly aerated nitrification may be slow. Crops then show a marked response to dressings of sulphate of ammonia, nitrate of soda or nitrate of lime. Very little ammonia appears in neutral soil, it being readily absorbed by the colloids and assimilated or oxidised by micro-organisms.

It was formerly supposed first by Grandeau (112) and afterwards by Hilgard (133) that the "soluble humus" of the soil (*i.e.* the material extracted by alkalis after preliminary treatment with acid) played an important part in nitrogen and phosphorus nutrition, but this view is no longer held. There is no reason to suppose that the soluble humus is inherently more available than some of the insoluble nitrogen compounds.

The phosphorus occurs in three types of combination: as organic substances, as insoluble mineral phosphates, and as somewhat soluble phosphates. Of these, the organic substances, nucleic acids, lecithin, and similar compounds, are presumably—though it is not yet proved—broken down by the micro-organisms and ultimately appear as somewhat soluble phosphates; there is no evidence that in their undecomposed state they directly influence plant growth. It is from the mineral phosphates that plants obtain their phosphorus, but all are not equally effective. Chemists have generally assumed that only the more soluble are likely to

serve as nutrients, and they have therefore devised methods for dividing up the phosphates into a more and a less soluble fraction. Němec uses water as the solvent,[1] but most methods are based on extraction of the soil with dilute acids under definitely specified conditions. Dyer's 1 per cent. citric acid (92) has been and is still much used in Great Britain: if it extracts less than 0·01 per cent. of P_2O_5 [2] the plant usually responds to phosphatic manuring. Continental workers have used other solutions, but American workers do not usually attempt the distinction. No two acids give the same results,[3] and even the same acid gives different results if the conditions are altered. Russell and Prescott (241*f*) found that two actions are proceeding simultaneously: the acid rapidly dissolves the P_2O_5; but the P_2O_5 then reacts with some of the soil constituents and is again precipitated. The dissolving action was the same for dilute hydrochloric, nitric and citric acids of equivalent strengths; the reverse action was different, hence the net amount of P_2O_5 determined by the analyst differed for all these acids. Russell and Prescott regarded the reverse reaction as an adsorption, but E. A. Fisher and N. Comber have both shown that it is more probably a chemical precipitation.

Only part of the phosphate is normally dissolved in the soil solution owing to the presence of reactive bases, calcium in neutral soils and iron and aluminium in acid soils. The concentration of the $-PO_4$ ion in the soil solution is usually approximately constant at about 1 to 2 parts P_2O_5 per million, independent of changes in soil moisture content, indicating that the solution is saturated with $-PO_4$ ion.

The various compounds of potassium, calcium, and other bases occurring in the soil vary so much in solubility that they can hardly be of equal value as plant nutrients. By common consent the insoluble resistant minerals are entirely disregarded and only easily soluble compounds are considered

[1] *Compt. Rend.*, 1926, 183, 314; see also Burd, 61*a*.

[2] The amount dissolved is usually called the available P_2O_5.

[3] See Hall and Plymen (120*a*) for a comparison of a number of acids.

as important. The discriminating agent used in this country has generally been Dyer's 1 per cent. citric acid, anything dissolved in this being called available; but there is now a tendency to regard the exchangeable bases (p. 139) as the more probable nutrients seeing that they are a natural division and not an arbitrary grouping of soil constituents. This view was put forward by Knop (150) in 1871 in place of the older view of Liebig, that only the bases physically retained by the soil were directly effective as nutrients.[1] Knop regarded the absorption of bases by the soil as being in the first instance physical, followed by a chemical process in which the bases combined with silica or aluminium silicate. They could, however, easily be displaced and therefore were readily taken up by plants. Soils of high fertility contained large quantities of easily displaced bases; he measured the amount by determining the ammonia absorbed from a 0·5 per cent. solution of ammonium chloride, assuming that, as absorption was only a substitution, the greater the amount of replaceable base the greater would be the absorption of ammonia. The method was applied to a number of soils and gave results in fair agreement with their agricultural history. It was somewhat modified by Kellner [2] who measured the quantities of potassium and calcium displaced and found they agreed exactly with the amounts taken up by plants in pot culture.

For some years, however, the replaceable bases of the soil were rather neglected by chemists and the view that they constituted the plant nutrients fell into abeyance. It has again come to the front with the renewed interest in base exchange. Ramann in 1914 suggested that the best measure

[1] "The power of the soil to nourish cultivated plants," Liebig wrote, "is, therefore, in exact proportion to the quantity of nutritive substances which it contains in a state of physical saturation. The quantity of other elements in a state of chemical combination distributed through the ground is also highly important, as serving to restore the state of saturation, when the nutritive substances in physical combination have been withdrawn from the soil by a series of crops reaped from it" (168*d*).

[2] O. Kellner, *Landw. Versuchs. Stat.*, 1886, **33**, 349-392.

of the bases available to the plant would be the amount of exchangeable bases, which he estimated by extraction with a 5 per cent. ammonium nitrate solution percolating through the soil. Modern methods of determining the exchangeable bases in the soil give concordant results, indicating that they are a definite group, and from their properties they may reasonably be regarded as plant nutrients. Indeed A. von Nostitz [1] has even gone further, and maintains that calcium, magnesium, and potassium applied in permutit complexes to sand cultures were more effective nutrients than when given as soluble salts.

The amount of potassium in the soil solution varies with the water content; the figures indicate a division between the solid and the liquid phases entirely consistent with the idea that the exchangeable potassium is the part most concerned.

Any of these nutrients, nitrogen, phosphorus, basic elements, and possibly also those needed only in small amounts, may be present in insufficient quantities to allow of maximum development of the plant. Not only is growth then restricted, but characteristic physiological symptoms appear which, as shown in Chapter II., help in diagnosing the conditions.

In spite of much investigation it is not yet certain what part is taken by the organic substances of the soil in plant nutrition. There is no doubt that the plant can grow satisfactorily and attain full development with inorganic nutrients only. But numerous field observations suggest that in the soil some of the organic matter may play a direct part. No combination of artificial fertilisers is as effective as farmyard manure in maintaining a high uniform level of crop production from year to year (p. 82). Some crops, notably clover and certain fruits,[2] seem to respond particularly well to farmyard manure. When soil is heated to 100° C. something is formed

[1] *Landw. Versuchs. Stat.*, 1925, 103, 159-177.

[2] Bush Fruits at Woburn (S. U. Pickering, *Science and Fruitgrowing*, p. 101; *Woburn Ann. Rept.*); Citrus Fruits at Riverside, California.

which stimulates root development to a remarkable extent (Russell and Pethcrbridge, 241*c*): possibly it is present in unheated soils also. Schreiner and Shorey (250, 252) showed that certain organic constituents of the soil stimulated plant growth in artificial cultures. The general conclusion to which the evidence points is that while not essential some of the soil organic matter may be distinctly helpful to the plant.[1]

The Absorption of Nutrients by the Plant: the Soil Solution.

Tull's old idea that plant roots took up solid particles of soil (p. 5) gradually gave place to the view that they absorbed only dissolved substances. Comber has indeed shown [2] that there may be no fundamental necessity for the preliminary solution, colloidal substances being probably absorbable by the plant: but the facts are all consistent with the idea that the dissolved nutrients are the chief if not the only source of plant food.

It was long thought that the plant exercised some direct effect on the soil constituents, dissolving them by means of acid excretions from its roots, and thus preparing its own food solution. This idea formed the basis of the acid extraction methods long used in soil analysis: Dyer (92) arrived at his 1 per cent. citric acid solution by finding that it more closely resembled root sap in its action than any other acid he tested. Later physiological work by Czapek and others [3] has put this view out of court and it has been generally abandoned; there is no direct evidence of acid excretions other than CO_2. Undoubtedly CO_2 assists in dissolving the inorganic substances, but its action is only slight and is not perceptibly increased by such additions to its amount as are

[1] See N. A. Clark, *The Soil Organic Matter and Growth-Promoting Accessory Substances* (*Journ. Ind. Eng. Chem.*, 1924, **16**, 249-250); N. A. Clark and E. M. Roller, *Soil Sci.*, 1924, **17**, 193, and A. Saeger, *J. Gen. Physiol.*, 1925, **7**, 517-526.

[2] *Journ. Agric. Sci.*, 1922, **12**, 363-369.

[3] *Biochemie der Pflanzen*, especially Bd. 2, pp. 872 *et seq.*

made by plant roots.[1] Plants exert direct effects on the soil (p. 399) but so far as is known they do not dissolve significant quantities of nutrients which would otherwise remain undissolved.

Whitney and Cameron in 1903 (304*a*) put forward the view that the plant obtains its nutrients from the solution already present in the soil; it is a passive absorber of pre-existing substances rather than a preparer of its own food. After much controversy and modification this view is now generally adopted; it has been elaborated and brought into conformity with modern physical ideas by D. R. Hoagland, J. S. Burd, J. C. Martin, and their colleagues at the Californian University.[2]

The composition of the soil solution has been discussed on p. 191. It contains all the soil nitrate, of which there is no solid phase; it is constantly saturated with phosphate, being in simple equilibrium with the solid phase so that the concentration in the solution is constant for a given soil; but its content of potassium, calcium, and magnesium varies with the moisture content, indicating a complex equilibrium between the solution and some absorbing substance in the soil.

Whitney first thought that the soil solution was constant in composition for all soils (apart from dilution by rain water), being in simple equilibrium with the soil-forming minerals which are the same over large tracts of country. But with the growing recognition of the properties of the soil micro-organisms and of the soil colloids this view became untenable; it was indeed shown to be improbable by Russell [3] and to be incorrect by Hall, Brenchley, and Underwood (121*d*). The solution is now known to be constantly changing in concentration and in composition. The action of micro-organisms continuously alters the amount of nitrate which in turn affects

[1] See F. W. Parker, *Soil Sci.*, 1925, **20**, 39-44.
[2] See 136*d* for a summary of the present position.
[3] *Journ. Agric. Sci.*, 1905, **1**, 327.

the amount of dissolved bases. Plants and micro-organisms are continuously taking something out, rainwater dilutes it, evaporation concentrates it. The soil solution is very dilute, its concentration being of the order of 0·05 to 0·2 per cent., and its osmotic pressure about 0·2 to 1 atmosphere in ordinary agricultural soils. The root sap is much more concentrated, its osmotic pressure amounting to some 7 to 20 atmospheres. In these circumstances it is not at all clear how the ions pass from the soil solution to the root. As Hoagland has pointed out, the process obviously requires a source of energy.[1]

In spite of its dilution the soil solution appears to suffice for plant nutrition. This caused no difficulty to the older workers who maintained that variations in concentration had but little effect on the plant,[2] but their view was disproved by Hall, Brenchley, and Underwood, and by Hoagland and Sharp (136*c*) who find that growth increases with the concentration in solutions as dilute as the soil solution.

It is, however, remarkable that the soil solution of even a poor soil contains sufficient nutrients for the needs of the crop judging by the amounts actually taken up from the solution in fertile soils.[3]

There is no clear evidence that variations in composition of the soil solution such as occur in normal soils have any important effect on plant growth. Hoagland finds that the solutions in Californian soils of equal fertility may differ considerably in composition.[4]

During its growth the plant greatly alters the composition of the solution, removing most if not all of the nitrate and

[1] L. Casala suggests that the ectoplasm of the absorbing plant cells has a slightly smaller negative charge than the soil colloids, thus causing a difference of potential between the plant and soil which results in a migration of ions (*Staz. Sperim. Agrar. Ital.*, 1921, **54**, 65-113).

[2] *E.g.* Breazeale (52*a*), Whitney and Cameron (304), W. Stiles, *Ann. Botany*, 1915, **29**, 89-96.

[3] J. S. Burd, *Journ. Agric. Res.*, 1918, **12**, 297-309.

[4] *Trans. Far. Soc.*, 1922, **17**, 249-254.

much of the potassium, calcium, and magnesium, though it has little effect on the phosphate, this being renewed as fast as it is absorbed by the plant. In natural conditions the plant is thus supplied with a stronger solution of nutrients in its early days than later on. The physiological consequences have been studied in culture solutions by J. S. Burd who shows that the barley plant normally absorbs its nutrients before the time of heading out; it needs but little afterwards. Gericke suggests that nutrients given later may even be harmful (p. 83). The plant also changes the reaction of the solution, moving it towards neutrality if it is acid (p. 400).

The amount of nutrients which the plant obtains depends not only on the amount present in the soil solution but on the rate at which the absorbed nutrients are replaced. As with air and water the "supplying power" of the soil, to use a phrase of the United States workers, is of great importance.

Replacement of nutrients may be effected in three ways:—

1. Ions may diffuse from other parts of the soil.

2. The composition of its solution may be restored *in situ* as a result of interactions with the solid phase.

3. There may be a drift of the soil solution to the roots from the surrounding soil.

Little diffusion of ions appears to occur in the soil. A grass field at Rothamsted, originally uniform in its herbage, was in 1856 divided into plots each of which actually touches its neighbours: certain manurial treatments have been given annually to each and continued without change (on most plots) ever since. Marked differences in herbage have resulted. But the edges bounding the plots are fairly sharp; there is no evidence of much lateral diffusion in the period of seventy years. Renewal *in situ* is more probable though it does not necessarily restore the soil solution to its original composition. Any absorption of phosphate or of bases from the solution brings fresh supplies into solution by mere disturbance of the equilibrium. The activity of micro-organisms in producing anions—particularly $—NO_3$, $—SO_4$, $—HCO_3$—

constantly tends to add more bases to the solution, but the proportions actually appearing are determined by the base exchange relationships of the soil.

Direct drift of the soil solution to the roots is quite possible, governed by the factors regulating the mass movement of water in the soil; it has, however, not been investigated.

A more important factor may be, as Hoagland suggests, the growth of the plant roots outwards. The new rootlets form the absorbing surfaces for nutrients, and as they spread into fresh portions of the soil, they absorb what they want from the soil solution. Indeed the whole phenomena of supply of nutrients may be simply a case of root spread, in which case the "supplying power" of the soil is the same as the power to encourage root development. In all probability, however, the matter is more complex, involving both root development and replacement of ions.

The view that the plant is a purely passive agent in soil nutrition, taking its nutrients from a pre-existing solution, has undergone some modification since it was first introduced. Plants of different species growing side by side in the soil obtain from it very different quantities of the various nutrients,[1] indicating that they possess different "feeding powers." Differences in root spread would account for many of the observed facts [2] and would be quite consistent with the idea of passive absorption. Truog, however, considers that the reaction of the cell sap influences the absorption and thus causes the plant to play a direct part in the process.[3]

Soil Reaction: "Sourness of Soil."

It has long been known that some infertile soils are much benefited by addition of lime or calcium carbonate, and

[1] For data see Lawes' and Gilbert's tables of the composition of the leguminous, gramineous, and miscellaneous herbage on the Rothamsted grass plots (*Phil. Trans.*, 1900, **192**, B, p. 154).

[2] See A. R. Davis, D. R. Hoagland, and C. B. Lipman, *Science*, 1923, **57**, 299.

[3] *Wisconsin Res. Bull.*, 41, 1916; *Science*, 1922, **56**, 294.

chemists explained the results by supposing that soils were acid and the lime had made them neutral. Agriculturists apply the term "sour" to such soils and it has the advantage that it simply labels them without offering an explanation. Not all crops, however, respond to lime treatment; the numerous Danish experiments have been summarised by Olaf Arrhenius (5) in Table LXXIX. :—

TABLE LXXIX.—PERCENTAGE OF EXPERIMENTS WHERE LIMING INCREASED CROP YIELD.

Arrhenius' Analysis of Danish Experiments.

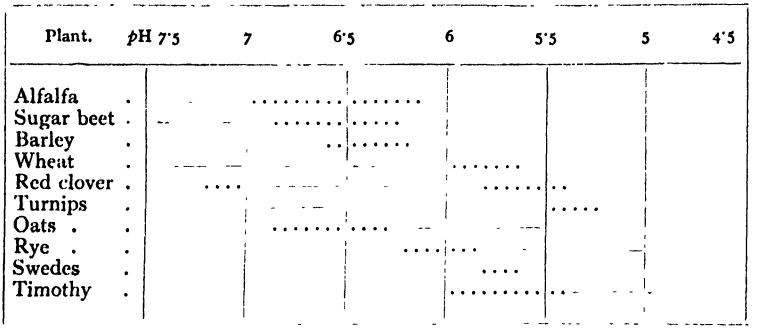
Plant.	Acid Soil.	Neutral Soil.	Alkaline Soil.
Wheat	100	—	—
Sugar beets	100	100	66
Fodder beets	92	66	—
Turnips	85	62	—
Barley	80	75	50
Oats	64	87	28
Rye	53	50	—
Potatoes	50	—	—
Swedes	25	100	—

The reaction of the soil can be measured either by its *p*H or its "lime requirement" values (they are not the same, though usually they run in much the same order for a series of comparable soils) (p. 189). When the results of liming experiments and of farmers' general experience are examined they point to certain ranges of soil reaction as being more favourable than others for the growth of particular plants. Arrhenius has made a survey of some 200 Swedish farms on these lines, with the results recorded in Table LXXX.

There are, however, no sharp limits and the reaction range varies with the conditions and with the plants; some can tolerate a wide range, others only a narrow one. Nearly all plants include the neutral region (*p*H 7) in their favourable range. Oats, rye, and swedes appear as exceptions, but they are not; the table shows only their tolerance towards acidity. Their absence from neutral soils arises not from intolerance,

TABLE LXXX.—SOIL REACTION AND PLANT GROWTH: SURVEY OF ABOUT 200 FARMS. ARRHENIUS.

The unbroken lines indicate frequent cultivation and good yields: the dotted lines poor yields and less common occurrence.



but from the fact that farmers having soils of *p*H 7 grow barley, wheat, and sugar beet by preference. Some of the Ericaceæ, however, thrive only in acid conditions. *Calluna vulgaris* is very rarely found on limestone or chalk: even when it occurs the surface soil is usually devoid of calcium carbonate, though the subsoil into which the roots penetrate may not be. Dr. Rayner [1] has shown that the determining factor is neither the physical conditions nor an adverse effect on the Mycorrhiza on which the plant is dependent. The action may be on the Calluna in view of M. Hinchliff and J. H. Priestley's [2] observation that its metabolism, like that of other plants commonly occurring on badly aerated peat moors, characteristically produces exceptionally large quantities of fatty substances in the form of fat deposits, cuticle, secondary endodermis, etc., which no doubt are of great advantage in peat conditions. It is suggested that calcium would tend to form insoluble soaps with these fats thus choking up the tissues just behind the growing point.

When the soil reaction is unsuitable the plant may fail to grow, and if it survives it shows certain characteristic appear-

[1] M. C. Rayner, *Ann. of Botany*, 1915, **29**, 97-133.
[2] *Naturalist*, July, 1924, p. 201.

ances. The young plant is most affected and it may die, or just survive but fail to develop, or it may become a fully grown plant; if it successfully passes the seedling stage it attains normal size, indeed in absence of competition it may become larger. The total yield per acre is smaller than on land of suitable reaction, but the reduction is due to bare patches where the seedlings failed rather than to the uniformly poor growth characteristic of nitrogen starvation. Success or failure of the seedling turns on very slight differences, for adjacent plants under apparently identical conditions may ultimately come to very different ends.

The young leaves are at first dark green. Some of the grasses, notably sheep's fescue and anthoxanthum, retain this colour, but most other plants lose it and become yellowish.[1] Pastures containing these two grasses thus take on a curious mottled appearance, but in arable crops the yellowish-green predominates; there is still the patchy appearance because some plants are growing well. The roots are yellowish-brown and stunted with short branches and abrupt ends; they lack the clean white rootlets of normal plants.

The effects are less pronounced when organic manure (*e.g.* farmyard manure) or superphosphate is supplied, and as a rule they are less in dry than in wet seasons.

The phenomena are simplest where the vegetation consists of a single crop on cultivated land; the only factor concerned is the degree of tolerance of the plant to the conditions. So far as this can be gathered from observation and agricultural experience it is set out in Table LXXXI.

In English conditions the less tolerant crops are liable to fail on light soils when the "lime requirement" exceeds 0·2 per cent. of calcium carbonate.

The value of the list in advisory work lies in the obvious

[1] The most striking colour change is that produced in the flowers of hydrangeas. Atkins (*Proc. Roy. Dublin Soc.*, 1923, 17, 201-210) states that the flowers are blue when the soil *p*H is 6 or less; pink when it is 7·5 or more; and blue and pink on the same plant when the *p*H is between 6 and 7·5.

TABLE LXXXI.—DEGREE OF TOLERANCE OF SINGLE CROPS TO SOURNESS OR ACIDITY.

England.		Rhode Island (Hartwell and Damon, 128*b*).	
Less Tolerant.	More Tolerant.	Less Tolerant.	More Tolerant.
Red clover	Cabbage and kale	Red clover	Beans
Foxtail (*Alopecurus pratensis*)	Lupines [1]	*Alopecurus prat.*	Maize
Barley	Alsyke	Lucerne	Potatoes
Peas, beans, and vetches	Swedes	*Poa pratensis*	Tomato
Wheat	Oats	*Dactylis glomerata*	*Agrostis canina*
Mangolds	Cocksfoot	Barley	*Agrostis vulgaris*
Mustard	Potatoes		
Rye grass	Rye		
White clover	Sweet vernal grass (*Anthoxanthum*)		
	Sheep's fescue		
	Yorkshire fog (*Holcus lanatus*)		
	Sorrel (*Rumex acetosa*)		
	Rhubarb		

advantage of growing crops suited to existing soil conditions rather than attempting costly changes over a large area. Thus on certain sour soils in Yorkshire farmers tend to confine themselves to oats, potatoes, and rye, and do not attempt barley or red clover. Near Leeds, where even the rain water is acid, rhubarb is extensively grown.[2]

The weakening of the crops on sour land allows the growth of weeds which tolerate the sourness, but would not tolerate the competition of a full crop. Thus farmers commonly regard mayweed (*Matricaria*) among the wheat on heavy land, spurry (*Spergula arvensis*) among the barley and roots on lighter land, sorrel and bent grass (*Agrostis*) on grass-land as indications of sourness.

The phenomena are more complex in natural conditions where there is a mixed flora. The element of competition, one of the most important factors affecting plant growth, now comes in. Plants that can tolerate sourness somewhat

[1] See p. 414.

[2] For American experience see F. V. Coville, *U.S. Dept. Agric. Bull.* 6, 1913; Hartwell and Damon (129*b*); E. Truog (281*b*).

better than their competitors survive while the others die; they dominate the flora of sour soils, but it must not be supposed that sourness is necessarily their optimum condition. Any adverse factor has this effect; it alters the balance in competition in favour of these plants that can tolerate it and against others which are therefore eliminated.

A second factor frequently restricts the flora on sour land undisturbed by cultivation. Owing to the diminished activities of earthworms [1] and micro-organisms (pp. 308, 334) the dead vegetation lying on the surface of the soil is not decomposed during autumn and winter, but persists through spring and summer, forming a mat through which only few kinds of plants can penetrate, all others dying as seedlings.

A third factor is that certain disease organisms are very tolerant of sour conditions and may do much injury to the growing plant.

The operation of these factors is, as might be expected, much influenced by other conditions, so that it is not possible to arrange plants in absolute order of dominance in the floras of sour soils. But where the general conditions are in other respects similar certain floristic differences are commonly associated with different degrees of "sourness." Ecologists have studied many of these communities.[2] The Wiltshire Downs contain areas of sour "bake" land surrounded by neutral or chalky soils; the "bake" land carries sheep's sorrel (*Rumex acetosella*), scarlet pimpernel (*Anagallis*), and knawel (*Scleranthus annuus*), but not toadflax (*Linaria vulgaris*) or white and bladder campion (*Lychnis vespertina* and *Silene inflata*), which, however, are common on the adjoining chalk soils.[3]

E. J. Salisbury finds *Quercus sessiliflora*, *Holcus* and *Anemone* more common on the sourer soils and *Quercus robur*

[1] Absence of worm-casts on grass-land is a common sign of sourness (p. 322.)

[2] For an interesting study of the Swiss ecological communities corresponding to different ranges of *p*H values see F. Chodat, *Bull. Soc. Bot. Genève*, 1924, 16, 36-143.

[3] W. E. Brenchley, *Annals of Botany*, 1912, 26, 95-109.

and *Mercurialis* on the less sour soils of Hertfordshire woodlands (242*a*). Hutchinson and McLennan's studies of Harpenden Common [1] are shown in Table LXXXII. :—

TABLE LXXXII.—LIME REQUIREMENT AS RELATED TO VEGETATION.

Harpenden Common. Hutchinson and McLennan (140*d*).		Woods. Salisbury (242*a*).	
Average Lime Requirement of Soil.	Dominant Flora.	Lime Reqt.	
Approx. 0·22 per cent. $CaCO_3$	Wild white clover (*Trifolium repens*)	0·24	*Mercurialis*
,, 0·26 ,, ,,	Fescues (*F. ovina and rubra*)		
,, 0·31 ,, ,,	Mixed Yarrow, wood-rush and moss		
,, 0·39 ,, ,,	Gorse		
,, 0·43 ,, ,,	Yorkshire fog	0·52	*Holcus*, *Anthoxanthum*, *Cnicus*
,, 0·53 ,, ,,	Sorrel	0·62	*Holcus* *Anemone*

Striking examples are found on undisturbed grass-land. The Rothamsted grass plots are of varying degrees of sourness; some have been made strongly acid by long manuring with ammonium sulphate, while most of them have had lime applied to one half but not to the other. The resulting differences in the herbage have been recorded in the Monograph by W. E. Brenchley; [2] they vary in detail according to the treatment of the plots. Some are quoted in Table LXXXIII.

Bent grass (*Agrostis vulgaris*), *Holcus*, *Anthoxanthum*, *Rumex*, *Plantago* and *Conopodium* are all common on the sour land; after addition of lime they are partly replaced by *Alopecurus*, *Avena pubescens*, and *Poa pratensis*; *Lathyrus* also increases.

The floristic differences of the Garforth grass plots (York-

[1] See also T. Eden, *Journ. Ecology*, 1924, **12**, 267-286.

[2] *Manuring of Grass-land for Hay*, by W. E. Brenchley, Rothamsted Monographs (Longmans, 1924). The figures are percentages of the air-dried hay. The mark — indicates absence of the species. Some minor species are omitted from the table.

TABLE LXXXIII.—INFLUENCE OF LIME ON *p*H VALUE AND HERBAGE OF ROTHAMSTED GRASS PLOTS: 1919 RESULTS.

	Plot 3.		Plot 7.		Plot 11′.	
	No Manure.		Potassic and Phosphatic Fertilisers. No Nitrogen.		Complete Fertilisers. Heavy Dressings of Sulphate of Ammonia.	
	No Lime.	Lime.	No Lime.	Lime.	No Lime.	Lime.
*p*H of surface soil	5·72	6·88	5·43	6·68	3·79	4·13
,, subsoil	6·16	6·58	5·90	6·24	4·35	4·71
Vegetation.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Agrostis vulgaris	8·34	1·53	5·38	2·01	1·65	0·94
Alopecurus pratensis	0·29	0·61	1·73	15·20	0·77	63·91
Anthoxanthum odoratum	6·97	3·06	3·55	0·45	0·02	0·14
Arrhenatherum avenaceum	0·29	0·51	3·05	2·62	31·34	15·51
Avena flavescens	0·88	2·76	0·71	0·96	—	—
Avena pubescens	4·12	19·10	2·84	8·81	—	—
Briza media	1·95	8·89	—	—	—	—
Bromus mollis	—	—	0·05	0·60	—	—
Dactylis glomerata	8·34	7·35	21·52	18·57	0·19	5·66
Festuca ovina	6·68	5·01	7·11	5·39	0·08	0·01
Holcus lanatus	9·13	7·66	4·26	1·56	64·80	11·63
Poa pratensis	0·15	1·94	1·17	1·61	—	1·95
Poa trivialis	—	0·10	0·36	1·21	—	—
Lotus corniculatus	1·57	2·45	0·46	0·03	—	—
Lathyrus pratensis	0·88	1·23	7·11	19·53	—	—
Trifolium pratense	2·06	1·74	1·02	0·03	—	—
Achillea millefolium	1·57	1·84	6·30	0·96	—	—
Centaurea nigra	5·70	6·13	2·54	1·11	—	—
Conopodium denudatum	4·61	0·61	9·44	3·67	—	—
Heracleum sphondylium	—	—	4·16	1·56	—	0·05
Leontodon hispidus	6·87	1·53	—	—	—	—
Plantago lanceolata	18·93	11·95	1·32	0·50	—	—
Ranunculus spp.	0·39	2·55	1·93	3·98	—	—
Rumex acetosa	1·96	4·19	10·55	7·10	1·15	0·11
Poterium sanguisorba	5·70	3·06	—	—	—	—

shire) have been summarised by Crowther and Ruston,[1] and observations on the Yorkshire grass-lands (West Riding) have been published by Mr. and Mrs. Lynn.[2] Generally in Yorkshire the most striking result of correcting sourness by lime

[1] C. Crowther and A. G. Ruston, *Journ. Agric. Sci.*, 1915, 7, 197-218.

[2] J. C. and D. A. Lynn, *Ann. of Applied Biology*, 1924, 11, 135-152.

is to replace *Nardus* and *Luzula*, or on the better pastures, *Agrostis*, by *Festuca ovina*, *Trifolium repens*, and *Lotus corniculata*. Perennial rye grass is not common on land with lime requirement exceeding 0·3 per cent. Wild white clover is less sensitive to acidity; it is often improved by addition of lime in Yorkshire but not at Cockle Park (Northumberland). The difference in behaviour is attributed to the mat of dead vegetation in the Yorkshire fields which effectively prevents the growth of the clover, but which is removed by lime (see p. 308); while at Cockle Park there is no mat, but bare soil simply awaiting basic slag to become colonised with clover: lime here has no function to fulfil.

The influence of disease organisms in determining the vegetation characteristics of sour soils is well seen on cultivated land. *Plasmodiophora brassicæ* (finger-and-toe organism) tolerates " sourness " better than its host plants the cultivated brassicas (swedes, turnips, cabbage, etc.); it is therefore injurious on sour soils. Addition of lime improves the soil for the crop but makes it less suited to the parasite[1] (Table LXXXIV.). On the other hand, *Actinomyces chromogenus* (*Oospora*, potato scab) is less tolerant of sourness than its host, and over a certain range potatoes can be grown well without

TABLE LXXXIV.—*p*H VALUES FOR PAIRS OF COMPARABLE SOILS DIFFERING AS HABITATS FOR PLANTS OR MICRO-ORGANISMS. CROWTHER (72).

Centre.	Crop.	Condition.	*p*H.	Condition.	*p*H.
(1) Rothamsted	Swedes	Finger and toe	5·85	No finger and toe	7·90
,,	,,	,, ,,	6·05	,, ,, ,,	7·87
(2) Garforth .	,,	,, ,,	5·66	,, ,, ,,	6·13
(3) Aberdeen .	Turnips	Much finger and toe	6·21	Little finger and toe	7·13
(4) Somerset .	Barley	Failure	4·41	Good	5·77
(5) Ipswich .	Lucerne	,,	6·15	,,	7·86
(6) Carrington[2]	—	Uncultivated	3·01	Cultivated	5·52
Moss .	—	Bad field	4·88	Good field	5·14
(7) Pusey .	Potatoes	Much scab	7·40	Little scab	6·13
	,,	,,	7·65	,,	6·75

[1] For field trials see J. Hendrick, *Trans. Highland Agric. Soc.*, 1918, 30, 137-145.

[2] These soils have been discussed by E. Price-Evans, *Journ. of Ecology*, 1923, 11, 64-77.

fear of attack. Even though their soils need lime for other crops, Cheshire farmers do not add it until after the potatoes are lifted, otherwise "scab" may develop. More acid soils need lime for potatoes, but great judgment is exercised in applying it or "scab" results. At Selby (Yorkshire) one ton of lime per acre benefited the potatoes and not the "scab" organism, but 5 tons per acre caused so much "scab" that the potatoes were unsaleable.[1]

The effect on the general soil population is discussed on page 334.

It is difficult to get behind these effects and to discover which of the various properties of sour soils is the main cause. The older view that soil acids are responsible has been much controverted.

In addition to their acid reaction these soils are liable to contain soluble aluminium compounds (p. 140); they produce but little nitrate, so that plants have to obtain their nitrogen from some other source, such as ammonia; they have but little replaceable calcium; the ratio of easily soluble calcium to aluminium or to potassium is lower than in normal soils; and the clay is likely to be in a sticky unsuitable state (p. 156). Laboratory investigations into these separate factors are necessarily somewhat artificial, while field observations give indefinite results because the properties are so closely associated that they stand in nearly the same order for each of the soils in any comparable series. The soluble aluminium compounds were regarded as the chief agents by Hartwell and Pember of Rhode Island (*129a*) on the grounds that they closely resembled acid soil extracts in their qualitative effects on plant growth.[2] This view is accepted at the New

[1] J. A. Hanley, private communication. In the Kilmarnock trials lasting over eight years potatoes were injured by lime though oats benefited (*West of Scotland Agric. Coll. Bull.*, 55, 1911, pp. 193-222). For other examples see E. J. Salisbury, *Journ. Ecology*, 1920, 3, 205.

[2] J. B. Abbott, S. D. Conner, and H. R. Smalley had previously attributed the infertility of an Indiana soil to the presence of aluminium salts (*Ind. Expt. Sta. Bull.*, 170, 1913). See also Mirasol, *Soil Sci.*, 1920, 10, 153-193.

Jersey Experiment Station,[1] at other centres in the United States, in Hawaii, and by some of the Indian tea experts.[2] But the explanation does not always suffice. In one of the most exhaustive investigations yet made, C. Olsen [3] concluded that barley alone out of all the plants tested is injured by soluble aluminium salts in the quantities in which they occur in sour soils. O. C. Magistad, at Wisconsin, showed that soy bean and maize also suffer, but clover, lucerne, oats, and rye are insufficiently affected to account for the improvement brought about by liming.[4] Olaf Arrhenius in his surveys of Swedish acid soils also rules out soluble aluminium compounds as a general cause of sourness except for barley.[5]

Acidity if sufficiently intense would account for the infertility and the cure effected by lime. There are, however, one or two difficulties, but they are more apparent than real. The *p*H values recorded for sour soils are not particularly high—rarely falling below 5—indeed they indicate far less acidity than is common in good water culture solutions. The solution successfully used for barley at Rothamsted has a *p*H 3·8; on the field plots at Woburn barley fails when the *p*H has fallen only to 4·5. The two cases are not strictly comparable, however; the soil is highly buffered while the solution is not; in absorbing its nutrients the plant brings about certain changes which lower the acidity of the solution, changing it to neutrality or even alkalinity, but the same effect may not be produced in the highly buffered soil.

Further, there are no constant *p*H values for soils just

[1] A. W. Blair and A. L. Prince, *Soil Sci.*, 1923, 15, 109-129.

[2] W. T. McGeorge, *Hawaiian Sugar Planters Expt. Sta. Bull.*, 49, 1925; P. H. Carpenter and C. R. Harler, *Indian Tea Assoc. Scientif. Journ.*, 1921, 2, 43. See also N. Comber, *Trans. Far. Soc.*, 1924, 537-572; K. Miyake and J. Tamachi, *Journ. Biochem.*, 1924, 3, 305.

[3] *Compt. Rend. Lab. Carlsberg*, 1923, 15, 1.

[4] *Soil Sci.*, 1925, 20, 181-225.

[5] *Zeit. Pflanz. Düng.*, 1925, 4, A, 348-358. See also his *Kalkfrage, Bodenreaktion and Pflanzenwachstum*, Leipzig, 1926.

tolerated by a given plant or organism.[1] Tolerance of plants and micro-organisms to acidity, and the susceptibilities of the host plant to attack by parasites are affected by the other soil conditions. Millard finds that potatoes take scab less easily, and Howard finds indigo less affected by *Psylla*, after green manure has been ploughed in.[2]

Olsen, in the investigation to which reference has just been made, after ruling out soluble aluminium compounds and non-nitric nutrition, shows that the hydrogen ion concentration is the most probable cause of injury on the sour soils he was studying. His field work was accurately done and the results analysed statistically—the only satisfactory treatment of masses of field data. Some of his figures are given in Table LXXXV. :—

TABLE LXXXV.—AVERAGE FREQUENCY[3] OF MEADOW SPECIES ON SOILS OF DIFFERENT *p*H VALUES. OLSEN.

*p*H Class.	3·5-3·9.	4-4·4.	4·5-4·9.	5-5·4.	5·5-5·9.	6-6·4.	6·5-6·9.	7-7·4.	7·5-7·9.	No. of Localities.
Deschampsia flexuosa.	86	68	40	—	—	—	—	—	—	13
Calluna vulgaris .	20	47	10	20	—	—	—	—	—	13
Gallium hercynicum .	94	77	40	20	15	—	—	—	—	18
Potentilla erectum .	67	99	63	73	48	45	10	20	—	39
Agrostis canina .	—	100	100	73	63	100	—	—	—	12
Festuca ovina . .	—	100	47	35	20	20	50	—	—	12
Anthoxanthum odoratum . . .	33	47	79	80	83	76	27	30	30	46
Deschampsia cæspitosa	—	—	—	40	67	62	33	52	23	33
Circium oleraceum .	—	—	—	—	—	—	50	100	80	8
Angelica sylvestris .	—	—	—	—	—	35	33	48	30	14
Tussilago farfara .	—	—	—	—	—	10	10	55	80	9
Agrostis alba . .	—	—	—	—	—	—	30	65	60	7

[1] In Crowther's tests potato scab was rarely found on soils with *p*H below 6·1, while Gillespie and Hurst (108*b*) found it commonly on the Washburn loams of North Maine having *p*H values about 5·9, though rarely on the Caribou loams where the value is 5·2.

[2] Millard, *Leeds Bull.*, 118, 1920; A. Howard, *Ann. App. Biol.*, 1921, 7, 373-389.

[3] The frequency is determined on ten trial areas (0·1 sq metre) at each centre chosen. If a plant is found on eight of these areas at one centre, the frequency is 80 per cent. The figures in the table are the average of the frequencies at all the centres.

Of other species the distribution is as follows :—

*p*H 4·5 or less : *Vaccinium myrtillus, Deschampsia flexuosa, Carex pilulifera, Luzula pilosa, Convallaria majalis, Maianthemum bifolium, Trientalis europæa.*

*p*H 4·5 to 6·0 : *Melica uniflora, Milium effusum, Asperula odorata.*

*p*H 6·0 to 7·4 : *Hordeum europæum, Mercurialis perennis, Allium ursinum, Ægopodium podagraria, Brachypodium sylvaticum, Ficaria verna, Geum urbanum, Anemone hepatica, Sanicula europæa.*

Direct experiment in soil culture showed that *Deschampia flexuosa* and *Senecio sylvaticus* made their best growth at *p*H 5·2. In water cultures also plants made better growth at some values than at others, corresponding with their order of occurrence in natural soils.

The acidity of humus is apparently less harmful than that of clay; humic acid may be more easily detected by indicators as used in field tests, but in any event the physical properties of acid clay are detrimental to the plant.

Lack of calcium available to the plant probably causes much of the harm done by " sourness," low absolute amounts being probably more important than the ratios discussed by Pearsall.[1] Perhaps as the result of the shortage of calcium, plant juices are more acid on unlimed than on limed soils,[2] which may affect the oxidase and other activities in the plant. G. W. Robinson considers calcium starvation the chief factor in North Wales. The parent rock contains no calcium except as silicate. The upland acid soils are poor (usually less than 0·05 per cent.) in exchangeable calcium, this being thoroughly leached out by the heavy rainfall together with the carbon dioxide coming from the rather high amount of organic matter; they respond to lime. In the valley bottoms, how-

[1] *Journ. Ecol.*, 1926, 14, 154-163. See also E. J. Salisbury, *ibid.*, 1925, 13, 149-160. These two papers, written from very different standpoints, give an interesting account of soil acidity and sourness. See also p. 104.

[2] E. Truog and M. R. Meacham, *Soil Sci.*, 1919, 7, 469-474. See also A. R. C. Haas, *ibid.*, 9, 341-368.

ever, soils while also containing much organic matter and free from calcium carbonate, do not respond to lime. In contradistinction to the upland soils they contain from 0·2 to 1 per cent. or even more replaceable calcium oxide.[1]

Reviewing the whole of the evidence it seems probable that all the factors may operate, and while the plant may escape injury from any one factor if all other conditions are favourable, in natural conditions this does not commonly happen. Which of the factors is the most important in any given conditions can be found only by direct investigation.

Alkalinity of Soils.—Alkalinity is not a common occurrence in humid conditions; occasionally too much lime is added and crops suffer in consequence.[2] In natural conditions alkalinity is confined to arid regions (p. 211). The effect of a slight alkaline reaction is much more damaging to the plant than slight acidity [3] (p. 103).

Control of "Sourness" and Soil Reaction.—Sourness is remedied by dressings of lime or calcium carbonate in quantities which have to be determined empirically in the first instance though useful guidance is subsequently obtained from the various lime requirement methods which enable the experimenter to compare soils with the standard on which field tests have been made (p. 456).

It is more difficult to shift the reaction towards acidity. J. G. Lipman has suggested the use of sulphur; good results have been obtained in the United States.[4]

Are Toxins Present in the Soil?

A persistent idea that one crop may poison another is current among practical men. Early in the last century De

[1] See also E. Truog, *Soil Sci.*, 1918, 5, 169-195, and D. R. Hoagland, *Hilgardia*, 1925, 1, 246.

[2] Bobko, Golubev and Tülin show that the ammonia produced is one factor in causing injury (*Journ. Pflanz. Düng*, 1926, 6, A, 128).

[3] C. Olsen, *Compt. Rend. Trav. Lab. Carlsberg*, 1925, 16 (2), 1-21; M. Trénel, *Journ. Pflanz. Düng.*, 1925, 4, B, 340-353.

[4] *Soil Sci.*, 1919, 7, 181; 1921, 11, 75 and 87.

Candolle formulated the hypothesis that plants excrete from their roots toxins that remain in the soil for some time and injure other plants of the same species, but not necessarily plants of different species. He thus explained the well-known fact that a rotation of crops is more effective than a system of continuous cropping; in a rotation the toxin excreted by a particular crop is innocuous to the succeeding crop and disappears from the soil before the same plant is sown again.

The hypothesis was tested in a classical research by Daubeny at Oxford (78), but could not be justified. Eighteen different crops were grown continuously on the same plots, and the yields compared with those obtained when the same crops were shifted from one plot to another, so that no crop ever followed another of the same kind. No manure was supplied. The results showed a gradual decrease in the yield in almost every instance, and the decrease was generally greater when the crop was repeated year after year on the same plot than where it was shifted from one to another. Nevertheless the difference between the yields in the two cases was not sufficient to justify any assumption of the existence of a toxin, except perhaps in the case of *Euphorbia lathyris;* in the other seventeen cases it was attributed to the more rapid removal from the continuous plots of the mineral nutrients required by the plant. This explanation was supported by analyses of the plant ash and of the soil—analyses which led to the important distinction between " available " and " unavailable " plant food.

Pot experiments made by the writer at Rothamsted have led to the same conclusions. Six crops of rye were grown in succession in sand to which only nutrient salts were added so as to maintain the food material at a constant amount. A seventh crop was then taken and at the same time a crop was grown on perfectly fresh sand, on which no crop had ever grown before, but which was supplied with an equal amount of the same nutrient salts. There was no significant difference in the two crop yields. A similar experiment was made with

buckwheat, another with spinach, and a parallel series was made in soil cultures. In all cases but one the result was the same; the 1910 weights were as follows :—

	Sand Cultures.			Soil Cultures.		
	Weight of dry matter found, grams (mean of 4 pots).			Weight of dry matter found, grams (mean of 4 pots).		
	Rye.	Buckwheat.	Spinach.	Rye.	Buckwheat.	Spinach.
Cropped six times previously . .	30·4	5·4	33·3	26·4	23·9	20·0
Fresh sand or soil .	31·3	13·5	29·5	27·1	25·2	20·8

Both sand and soil contained 2 per cent. of calcium carbonate.

If either the rye, buckwheat, or spinach excreted any toxin the amount accumulating during the growth of six successive crops was insufficient to cause any appreciable depression in yield in the next crop; the exceptional result given by buckwheat in sand could not be confirmed.

These and similar experiments show that no lasting toxic effect is produced by any of the crops studied, and they rule out any toxin hypothesis as an explanation of the advantages of rotations [1] where there is always a lengthy interval between the crops. They do not, however, show that there is no transient effect, and they are thus quite consistent with some remarkable observations by Pickering on the effect of grass on apple-trees (*226a*). It was found at Woburn—and the observation has since been confirmed elsewhere—that the effect of growing grass round apple-trees is to arrest all healthy growth and absolutely stunt the tree. The leaves become unhealthy and light coloured, the bark also becomes light coloured, while the fruit loses its green matter and becomes waxy yellow, or brilliant red. Where the grassing was done gradually the trees accommodated themselves somewhat to the altering conditions, but never grew so well as when grass was absent.

[1] Some curious problems are thus left unsolved, some of which are discussed more fully by the author in *Science Progress*, July, 1911, p. 135. Gericke (*Bot. Gaz.*, 1924, 78, 440-445) considers that there was a falling off in yield in water-culture experiments made on somewhat similar lines.

This effect might have been due to various causes: changes in aeration, temperature, water supply, food supply, or physical condition of the soil, but careful experiments failed to show that any of these factors came into play. Covering the soil with cement excluded air at least as thoroughly as grass, and yet did not produce the grass effect, nor was it suppressed by wet seasons, liberal watering, or a supply (in pot experiments) of sufficient water or nutrient solution to keep the soils of grassed and ungrassed trees equally moist, or equally well supplied with food. On the other hand, the grass effect was produced when perforated trays of sand containing growing grass were placed on the surface of the soil in which trees were growing, so that the washings from the grass went straight down to the tree roots. There seemed no possibility of the grass roots in the trays abstracting anything from the soil, and the only explanation appears to be that a toxin is excreted by the grass.

Other plants behave in the same way. Pickering therefore concluded that toxins are produced by all growing plants. He was unable to discover their chemical properties, except that they must be very unstable because no toxic properties could be detected either in soil that had been removed from the grass roots or in the washings from the above-mentioned trays. Further there was no recognisable difference between one plant toxin and another: injury resulted whatever crops were grown in the pots and trays [1] and it was not confined to plants of the same kind as supposed by de Candolle.

On Pickering's view one growing plant may, and usually does, injure others growing alongside of it, but injury is only during its lifetime and ceases with its death. The toxin is transient and not permanent; it is produced by the plant in any soil whether fertile or not.

The idea of permanent or stable toxins in soil was put

[1] Mitscherlich also concluded that the root excretions of clover must be the same as those of oats (*Landw. Versuchs. Stat.*, 1913, 81, 469-474, *Zur frage der Wurzelauscheidungen der Pflanze*).

forward by Whitney, Cameron, and Schreiner (305, 65*b*, 249), restricting it, however, to infertile soils. These toxins may arise from the growing plant or from its decomposition products, but, unlike Pickering's toxin, can be extracted by water and are stable in the solution. Whitney and Cameron (305) selected two Cecil clays of very different productiveness but of identical chemical and physical constitution, prepared aqueous extracts, and used them as culture solutions for wheat seedlings. The extracts contained in parts per million :—

	NO_3.	PO_4.	K.	Ca.
Good soil .	3·2	1·6	3·6	3·2
Poor soil .	3·5	1·6	2·0	2·8

and were thus identical in their content of plant nutrients; they were also both neutral. Yet they produced very different effects on the wheat seedlings : the " good soil " extract caused a larger and healthier development of root and a somewhat better development of leaves. In other cases it has been found that growth in extracts of poor soils is even worse than in distilled water. The productiveness of the extract could be raised, according to Livingstone (175), by dilution, shaking with calcium carbonate, precipitated ferric or aluminium oxide, animal charcoal, or soil; results which are explained by supposing that these agents precipitate a toxin. Addition of fertilisers, and especially of an aqueous extract of farmyard manure, improved the solution; these substances also were supposed to precipitate the toxin.

A double set of experiments was therefore begun by Schreiner and his colleagues; a careful search was made in the soil for such organic compounds as could be identified (see p. 169); and the effect of these and similar compounds on plant growth was studied by elaborate water cultures. Considerable attention has been devoted to dihydroxy-stearic acid. This substance is toxic to plants in water culture, and is almost invariably present in infertile soils, especially such

as are badly drained, badly aerated, too compact, and deficient in lime (251); soils, in short, that in England are called "sour." On these soils intermediate decomposition products harmful to the plant may accumulate through the slowing down of micro-organic activity. In special cases this accumulation may occur on fertile soils. In the United States sorghum injures the succeeding crop; in the semi-arid regions on the west it also causes deflocculation of the soil. J. F. Breazeale [1] shows that a toxic substance is formed during the decomposition of its stubble after being ploughed under, which not only injures the crop but checks bacterial action, reduces the production of CO_2 and alters the equilibrium between the sodium and calcium in the soil, bringing about deflocculation.

The present position may briefly be summed up as follows:—

There is no evidence of the presence of soluble toxins in normally aerated soils sufficiently supplied with plant food and with calcium carbonate.

Toxins, including hydrogen ions, soluble aluminium, iron and manganese compounds, and organic substances, may occur on "sour" soils badly aerated and lacking in calcium carbonate, or on other exhausted soils.

There is no evidence of plant excretions conferring toxic properties on the soil, but the Woburn fruit-tree results show that a growing plant may poison its neighbour. The effect does not appear to be specific; any plant will be injured by any other within its range, but it may suffer more from one of its own kind than from one of another kind.[2]

Bacterio-toxins.—Several observers, including Greig-Smith,[3] Bottomley [4] and others, have claimed to find soluble bacterio-

[1] *Journ. Amer. Soc. Agron.*, 1924, 16, 689-700.

[2] Thus Burmeister (*Fühl. Landw. Zeit.*, 1914, 63, 547-556; see *Rome Bull.*, 1914, 1691) claimed that couch (*Triticum* or *Agropyron repens*) increased the yield of oats, and Dr. Brenchley found that certain weeds had the same effect on the yield of wheat *per plant* (*New Phytologist*, 1917, 16, 53-76).

[3] *Centr. Bakt. Par.*, 1911, 30, 154: *Proc. Linn. Soc. New South Wales*, 1918, 43, 142.

[4] *Brit. Ass. Rpts.*, 1911.

toxins in soils. Hutchinson and Thaysen (140g), on the other hand, obtained wholly negative results, and concluded that soluble bacterio-toxins are not normal constituents of soils, but must represent unusual conditions wherever they occur. But the possibility of the existence of toxins insoluble in water still remains.

Continuous Cropping: Rotations: Soil Sickness.

The fact that any crop grows better in rotation with others than when following one of the same kind is still to be explained. The magnitude of the effect is shown in Table LXXXVI. which gives the yields of wheat grown at Rothamsted without manure under the three distinct conditions of continuous cropping with wheat; cropping in alternate years only, the land lying fallow during the intervening time; and cropping in a four-course rotation.

TABLE LXXXVI.—WHEAT GROWN WITHOUT MANURE AT ROTHAMSTED: (1) GROWN CONTINUOUSLY; (2) IN ALTERNATION WITH FALLOW; (3) IN FOUR-COURSE ROTATION. AVERAGE FOR THE YEARS 1851 AND EVERY FOUR YEARS THEREAFTER UNTIL 1923.

Dressed Grain per Acre.		
Continuous Wheat (Broadbalk, Plot 3).	Wheat after Fallow (Hoos Field, Plot 0).	Rotation Wheat (Agdell Field, Plot 5, formerly 21-22).
Bushels	Bushels	Bushels
11·7	14·7	24·2

The practical man, naturally anthropocentric in his outlook, speaks of land becoming "sick" and supposes that soil, like ourselves, benefits by a change. The Rothamsted field experiments afford the best data on the subject, and show that continuous cropping with the same crop is attended by many difficulties.

1. It is usually accompanied by uniformity in cultivation operations which may have harmful effects on the soil. Repeated ploughing to the same depth may form a hard layer

or plough sole which interferes with root action; in a rotation this is less likely to happen as the depth of ploughing is varied at least once in three or four years.

2. It favours the persistence of weeds specially adapted to live among the crop. The Broadbalk wheat-field at Rothamsted is badly infested with Slender Foxtail (*Alopecurus agrestis*), poppies (*Papaver rhœas*) and in places colts-foot (*Tussilago farfara*). The rotation fields are much less affected by weeds as the intervening year in root crops affords opportunities for their extermination.

3. It favours also the persistence of diseases and pests, especially those that can survive only a short time in the soil or that can find alternative hosts in close proximity.[1]

4. It allows no opportunity of maintaining the organic matter in the soil such as is given by the clover or "seeds mixture" of a normal rotation. The effect of this is well shown in the Agdell rotation field half of which carries clover once in four years while the other half does not (Table LXXXVII.):—

TABLE LXXXVII.—CROPS GROWN UNDER TWO ROTATIONS, ONE INCLUDING CLOVER EACH FOUR YEARS, THE OTHER NOT. AGDELL FIELD, ROTHAMSTED.

Produce per Acre.

Manuring.	Clover Hay.	Wheat, Total Produce.		Roots.		Barley Grain.	
		After Clover.	After Fallow.	After Clover.	After Fallow.	After Clover.	After Fallow.
	cwt.	lb.	lb.	cwt.	cwt.	bu.	bu.
None . .	14·0	3696	4028	8·2	19·5	14·7	16·5
Minerals only .	47·0	6052	5147	216·0	167·5	26·3	18·9
Minerals + nitrogen . .	50·1	6093	5493	342·6	386·7	34·5	26·5

5. When the cultural system involves some special condition, as on sewage farms or glasshouses maintained at high temperature and humidity, the micro-organic population alters and may produce less plant food.

[1] See A. Koch (151*a*) and H. L. Bolley, *North Dakota Bull.*, 107, 1913.

These five effects appear to explain the differences between the yields of rotation and of continuous crops, and the general phenomena of " sickness " in soils.

The glasshouse problem is of such technical importance that it has been investigated in detail by Russell and Petherbridge (241*c*), and methods of treatment worked out based on partial sterilisation of the soil. These have proved so effective that heating by steam or treatment with poisons (usually cresol) has become a recognised practice in the Lea Valley; the investigation is being continued at Rothamsted and at the Cheshunt Experiment Station,[1] where also the effect of the disappearance of the turf residues is studied.

The Action of the Growing Plant on the Soil and on the Soil Organisms.

Although the growing plant apparently produces no persistent toxin it has several direct effects on the soil. It considerably alters the soil solution by absorbing the nitrate, phosphate, and other nutrients [2] (p. 193), but the action differs at different periods of the plant's life. Burd (61*b*) recognises three periods in the growth of barley: up to the time of formation of the head the rate of absorption progressively increases till finally the amounts of nitrogen and potassium in the plant reach a maximum. During the period of translocation of material into the developing heads, however, there is not only a decreased rate of absorption from the soil but a substantial loss of nitrogen and potassium from the aerial parts of the plant. Towards the end of this period some of the lost materials are regained. In the third period ripening is completed, absorption ceases, and loses are resumed. These losses are experimentally traced from the aerial parts alone, and it is impossible to assert that they take place from the whole plant owing to the difficulty of completely extracting

[1] *Cheshunt 11th Ann. Rept.*, 1925, also W. F. Bewley, *Journ. Min. Agric.*, 1926, 33, 297-311.

[2] For the total quantities taken up see p. 401.

the roots from the soil. The presumption is, however, that such losses do take place.[1]

In natural conditions the elements taken up by the plant from the soil are ultimately returned to the surface layer of the soil. In bringing material from the lower depths to the surface the plant thus counteracts to some extent the effect of rain in washing soluble substances down from the surface.

Different plants vary greatly in the relative amounts of nutrients they absorb even when grown under similar conditions. English data assembled by Warington are set out in Table LXXXVIII.; extensive German data giving not only the final amounts but also the amounts taken at the various stages of growth are published by Wilfarth, Römer, and Wimmer (309*b*). Cereals absorb less nutrients than any of the crops studied; as shown in the Table their total production of dry matter is approximately the same as that of red clover hay and swedes, and greater than that of meadow hay and beans, yet they take from the soil only half the nitrogen and potassium and only one-third of the calcium. Clover takes up large amounts of potassium, calcium, and magnesium, while mangolds take much greater quantities of nitrogen, potassium, sodium, magnesium, phosphoric acid, and chlorine than any other crop. The figures for potatoes are incomplete, no recent data for haulms being available.

Another effect of the growing plant on the soil is to alter its reaction. The plant roots are continually giving off carbonic acid. It might be supposed that this would cause the surrounding medium to become acid, but this does not happen: as a matter of fact, water cultures tend to become alkaline because the plant takes up the acid radicle of the sodium nitrate and leaves behind the base, which immediately appears as the carbonate. Hall and Miller (120*b*), and subsequently

[1] Le Clerc, *U.S. Dept. of Agric Year Book*, 1908, 389-402; also André, *Compt. Rend.*, 1910, 151, 1378-82, support the view that the losses occur by washing from the leaf rather than from the root. For a mass of data suggesting root losses see Wilfarth, Römer, and Wimmer (309*b*).

TABLE LXXXVIII.—AMOUNTS OF VARIOUS SUBSTANCES ABSORBED FROM THE SOIL BY THE COMMON AGRICULTURAL CROPS OF ENGLAND. WARINGTON.[1]

	Weight of Crop.		Total Pure Ash.	Nitrogen.	Sulphur.	Potash.	Soda.	Lime.	Magnesia.	Phosphoric Acid.	Chlorine.	Silica.
	At Harvest.	Dry.										
	lb.	lb.	lb.	lb.	lb.	lb.	lb.	lb.	lb.	lb.	lb.	lb.
Wheat, grain, 30 bush.	1,800	1,530	30	34	2·7	9·3	0·6	1·0	3·6	14·2	0·1	0·6
,, straw . .	3,158	2,653	142	16	5·1	19·5	2·0	8·2	3·5	6·9	2·4	96·3
Total crop . .	4,958	4,183	172	50	7·8	28·8	2·6	9·2	7·1	21·1	2·5	96·9
Barley, grain, 40 bush.	2,080	1,747	46	35	2·9	9·8	1·1	1·2	4·0	16·0	0·5	11·8
,, straw . .	2,447	2,080	111	14	3·2	25·9	3·9	8·0	2·9	4·7	3·6	56·8
Total crop . .	4,527	3,827	157	49	6·1	35·7	5·0	9·2	6·9	20·7	4·1	68·6
Oats, grain, 45 bush. .	1,890	1,625	51	34	3·2	9·1	0·8	1·8	3·6	13·0	0·5	19·9
,, straw . .	2,835	2,353	140	18	4·8	37·0	4·6	9·8	5·1	6·4	6·1	65·4
Total crop . .	4,725	3,978	191	52	8·0	46·1	5·4	11·6	8·7	19·4	6·6	85·3
Meadow hay, 1½ tons .	3,360	2,822	203	49	5·7	50·9	9·2	32·1	14·4	12·3	14·6	56·9
Red clover hay, 2 tons	4,480	3,763	258	98	9·4	83·4	5·1	90·1	28·2	24·9	9·8	7·0
Beans, grain, 30 bush. .	1,920	1,613	58	78	4·4	24·3	0·6	2·9	4·2	22·8	1·1	0·4
,, straw . .	2,240	1,848	99	29	4·9	42·8	1·7	26·3	5·7	6·3	4·3	6·9
Total crop . .	4,160	3,461	157	107	9·3	67·1	2·3	29·2	9·9	29·1	5·4	7·3
Turnips, roots, 17 tons .	38,080	3,126	218	61	15·2	108·6	17·0	25·5	5·7	22·4	10·9	2·6
,, leaf . .	11,424	1,531	146	49	5·7	40·2	7·5	48·5	3·8	10·7	11·2	5·1
Total crop . .	49,504	4,657	364	110	20·9	148·8	24·5	74·0	9·5	33·1	22·1	7·7
Swedes, roots, 14 tons .	31,360	3,349	163	70	14·6	63·3	22·8	19·7	6·8	16·9	6·8	3·1
,, leaf . .	4,704	706	75	28	3·2	16·4	9·2	22·7	2·4	4·8	8·3	3·6
Total crop . .	36,064	4,055	238	98	17·8	79·7	32·0	42·4	9·2	21·7	15·1	6·7
Mangolds, roots, 22 tons	49,280	5,914	426	98	4·9	222·8	69·4	15·9	18·3	36·4	42·5	8·7
,, leaf . .	18,233	1,654	254	51	9·1	77·9	49·3	27·0	24·2	16·5	40·6	9·2
Total crop . .	67,513	7,568	680	149	14·0	300·7	118·7	42·9	42·5	52·9	83·1	17·9
Potatoes, tubers, 6 tons	13,440	3,360	127	46	2·7	76·5	3·8	3·4	6·3	21·5	4·4	2·6

[1] The yields quoted are not averages, though they are commonly obtained on farms.

Maschhaupt (192), have obtained evidence of a similar action in the soil, the calcium nitrate formed during nitrification being converted into calcium carbonate while the nitrate radicle is taken by the plant. This tends to increase the amount of calcium in the surface soil.

The CO_2 evolved from plant roots cannot be distinguished from that given off by micro-organisms, and it is impossible to allocate the part played by each in its production. Russell and Appleyard found soil carrying ripening cereals contained much CO_2 (241*e*) which might be a result of plant activity.

The growing plant has considerable influence on the soil micro-organisms. It is not known how far the numbers are affected but the activities are certainly changed, particularly the accumulation of nitrate. Cropped soils contain less nitrate than adjoining fallow soils even when allowance is made for the quantity absorbed by the plant. The fact has been observed at Rothamsted[1] (Table LXXXIX.), at Grignon,[2] at Ithaca, New York (183), in Europe, India,[2] and Egypt.[3] Under these widely varying climatic conditions it can hardly be attributed to the minor differences in temperature and moisture content between cropped and uncropped soils. The fact of crop interference with nitrate accumulation was first observed in 1905 by Warington; the Broadbalk drainage waters contained less nitrate than was expected from the manure applied and the crop reaped, a result he attributed partly to dentrification and partly to some obscure interaction between the plant and the nitrate. Lyon and Bizzell (183) found that potatoes and oats interfered with nitrate accumulation, but maize somehow stimulated it so that there was more nitrate on land cropped with maize than on the adjoining fallow—a reversal of action which is not uncommon among soil micro-organisms.

The causes of this interaction between plant and organisms are not known. The CO_2 given off by the plant root or the removal of nutrients and the change of reaction in its immediate

[1] Deherain (81*b*). [2] Leather (165*b*). [3] Prescott (228).

TABLE LXXXIX.—NITROGEN AS NITRATES IN CROPPED AND UNCROPPED SOILS. (*a*) AT ROTHAMSTED. RUSSELL (241*d*).

	June, 1911.		July, 1912.	
	Fallow Land.	Cropped Land.	Fallow Land.	Cropped Land.
N. as nitrate in top 18 in. of soil (June)	54	15	46	13
Nitrogen in crop, lb. per acre .	—	23	—	6
Total lb. per acre . .	54	38	46	19
Deficit in cropped land, lb. per acre	—	16	—	27
Expressed as N., parts per million.				
N. as nitrate 0 to 9 in. depth . .	12	4	8	2
9 to 18 in. depth . . .	9	2	10	3

TABLE (*b*) AT ITHACA, N.Y. (LYON AND BIZZELL) PARTS PER MILLION.

1908.	Fallow Land.	Land Carrying Maize.	1909.	Fallow Land.	Land Carrying Oats.
May 19 .	4·9	3·9	April 22 .	19·0	10·9
June 22 .	10·9	9·3	June 24 .	12·6	2·5
July 6 .	14·5	14·2	July 12 .	12·5	1·0
July 27 .	42·1	43·2	August 7	18·4	0·8
August 10	40·3	37·3	—	—	—

vicinity may depress the activity of the micro-organisms. On the other hand, the shedding of dead rootlets may provide the organisms with energy material causing them to multiply locally and so assimilate nitrate. This latter possibility is supported by McBeth and Smith's observations that cropped irrigated soils of Utah (185*a*) have higher nitrifying power (p. 294) than fallow soils: also by the higher bacterial numbers found by Le Clair under cow peas than in the fallow plots,[1] and by some of Joshi's experiments.[2] On the other hand, Harrison and Aiyer (127) conclude that the crop on the paddy land had somehow reduced the bacterial action.

[1] *Journ. Agric. Res.*, 1916, 5, 439-477.
[2] *Pusa Mem. Bact.*, 1920, 1, 247-276.

Field observations alone are insufficient for the solution of the problem.

Normal Conditions on a Heavy Soil.

Table XC. summarises many of the Rothamsted results and shows the conditions normally obtaining on a heavy soil in Hertfordshire under a rainfall of 28 to 30 inches.

TABLE XC.—CONDITIONS NORMALLY OBTAINING IN THE SOIL AT ROTHAMSTED.

Manurial Treatment of Soil.		Soil Moisture.* Per Cent. by Volume.	Soil Moisture.* Per Cent. by Weight.	Total Nitrogen. Parts per Million.	Total Nitrogen. Lb. per Acre.	Nitrogen as Nitrate. Parts per Million.	Nitrogen as Nitrate. Lb. per Acre.	Numbers of Bacteria, Millions per grm.	CO_2 in Soil Air.
							(top 9")		
No manure .	Cropped	23·12	15·8	990	2500	5·12	12·30	7·12	0·2-0·6
Condition poor .	Fallow	23	15			8·15	20·36	7·12	0·2-0·4
Farmyard manure	Cropped	30·15	17·8	2200	5000	10·20	25·50	22·45	0·5-1·0
Condition good .	Fallow	30	17			20·35	50·84	22·45	0·2-0·6
Ordinary arable field . .	Cropped	25·12	15·8	1500	3700	10·15	25·36	15·25	0·5-1·0

[1] Running on occasions up to 1·8.

[2] Occasionally up to 2·3.

[3] Occasionally up to 2·5.

* The concentration of the dissolved matter is of the order of 0·2 per cent. and the osmotic pressure about 1 atmosphere.

For other micro-organisms see pp. 315 and 320.

CHAPTER VIII.

THE SOIL IN RELATION TO PLANT GROWTH.

THE vegetation relationships of a soil are determined by the extent to which it can supply water, air, temperature, nutrients, and other conditions of plant growth, and this in turn is governed by—

1. The composition of the soil.
2. The climate.
3. The position of the soil.
4. The soil profile.

The influence of the soil constituents has already been discussed.

The effect of the climate is three-fold. Acting through geological time it has largely determined the composition of the mineral constituents of the soil through its influence on the disintegration and decomposition of the original rock (p. 114). In shorter periods of time it greatly affects the organic matter of the soil through its influence on the plants from which the organic matter arose. Moisture, warmth, and aeration favour the development of a succulent vegetation which sheds easily decomposable leaves and stems on to the soil; earthworms and bacteria flourish and produce the normal decomposition products that make up "mild humus" and a fertile soil. Dryness necessitates a narrow-leaved xerophytic vegetation, the leathery fragments of which mingle with the soil, but afford a very indifferent medium for the growth of earthworms and bacteria, so that little decomposition goes on. Wetness and lack of aeration necessitate other

kinds of vegetation and decomposition forming " mild humus " or " acid humus " according to the amount of calcium carbonate present.

Finally the rainfall determines the amount of water reaching the soil, while the temperature, wind, etc., determines the amount evaporating from the surface.

The position of the soil—its aspect and elevation—affects its temperature, its water supply, and its composition, especially its reaction and its content of soluble matter.

Effect of Slope on Temperature Water Supply and Soluble Matter.

The temperature on sloping land is affected in two different ways. As a general rule the higher land is cooler than the lower, being more exposed to wind. But on clear nights, when heat lost by radiation from the earth's surface is not again returned by the clouds, the air near the surface cools considerably and rolls down the slope to the lowest level it can reach, being replaced by warmer air. Thus the low-lying ground suffers from cold nights or even frost which the higher ground escapes. This fact is of considerable importance in fruit-growing districts; plantations are made above the low levels liable to these frosts though not so high up as to suffer from exposure to wind. For ordinary farm crops this factor is of less importance but it operates in modifying the vegetation of wild land. Bracken suffers more from frost than heather and is therefore less likely to survive at levels where late frosts are common.

The movement of rain water in the soil tends to be vertically downwards, but it is always liable to disturbance by impervious layers in the subsoil. In general low-lying soils receive from higher ground a considerable amount of water which they lose only with difficulty by drainage. They are therefore moister than the higher soils and may indeed be waterlogged. Man has often intervened, drained the lower levels of their excess

of water so that while they remain moist (no human effort can prevent this) they are no longer marshy. Drainage has extended rapidly in all civilised countries during the past two or three generations, and it has much affected natural floras and faunas. In an interesting survey of the changes in the flora of Hertfordshire, E. J. Salisbury showed that nearly two-thirds of the eighty species that have decreased or become extinct since records began are natives of wet or moist habitats; the rest are mainly natives of waste land.[1]

The water soaking through the soil is charged with carbonic acid and it dissolves whatever it can from the higher

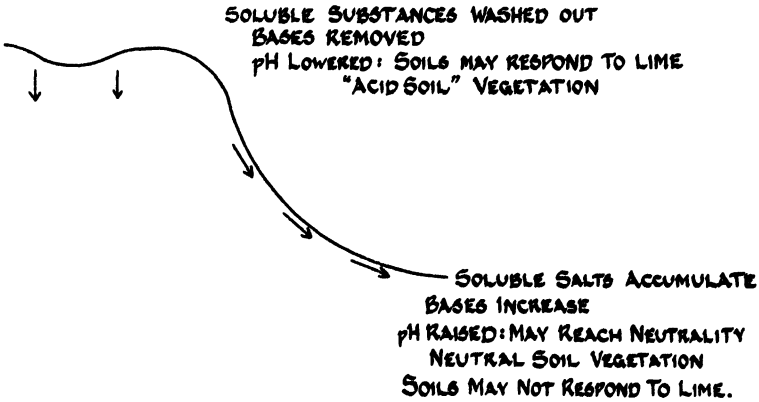


FIG. 43.—Diagram showing movements of water and soluble salts from the upland to the valley.

ground; in course of time it may remove much of the replaceable calcium and other bases, leaving the higher ground poorer in soluble matter and acid in reaction responding to dressings of lime. This soluble matter accumulates at the lower levels; there is therefore a tendency for the lower land to contain more soluble matter, more exchangeable bases, and to be more nearly neutral in reaction than the higher land, and not responding to dressings of lime (see p. 390). These differences are summarised in Fig. 43.

The aggregate effect on vegetation of these various actions

[1] *Trans. Herts. Nat. Hist. Soc.*, 1924, 18, 51-68.

is very marked. E. J. Salisbury [1] has studied a number of slopes in England that have been undisturbed by recent cultivation, and finds a strong tendency for a calcifugous flora to develop on the higher land, and a calcicolous flora on the lower. In the extreme case the upper land carried *Vaccinium* or *Calluna* and various species associated with them on acid soils, while the lower land carried *Mercurialis perennis*, *Allium ursinum* and the associated plants found on neutral soils. In less sharply contrasted conditions the sequence still holds. On Hudnall Common, one of the calcareous heaths of Hertfordshire, he observed the following :—

	Vegetation.	Inches.	Soil Data.	
			$CaCO_3$.	*p*H.
Summit	*Pteris* dominant	0·1	Nil-0·02	5·1-5·4
		2-4	0·01-0·04	5·3-6·0
Half-way down	Chalk pasture	0·1	0·68-1·0	7·3
		2-4	1·1-3·2	7·3
Floor of dry valley	Chalk pasture with scrub	0·1	12·5	7·5
		2-4	20	7·5

On the cultivated land the same characteristics are brought out in a different way; the land at the bottom of a slope tends to be wet though not necessarily acid; it may be a marsh, wet grass-land or moist arable land according to the ease with which the water can move; on the slope it is moist but not necessarily wet, and it is commonly in cultivation in England; the highest land, however, may be infertile through leaching and acidity and is besides much exposed to wind, etc. These factors combined may make it unsuited to cultivation so that it is left for rough grazing, wood, etc.

Effect of Profile.

The soil profile, like its position, considerably influences

[1] *Journ. Ecology*, 1922, 9, 220; see also A. G. Tansley and E. J. Salisbury, *ibid.*, p. 19.

the moisture relationships and the reaction of the soil. A layer of impervious rock or soil prevents excess of water from draining away and may considerably restrict root development. On the other hand a layer of gravel or stones may facilitate too much the removal of water. In good cultivated soils, the lower layer is usually somewhat, but not much, richer in clay and fine particles than the upper layer. Typical profiles are shown on pp. 439 and 440. One and the same soil may thus be fertile, well-cultivated land suitable to a great number of plants, or waste land carrying a very restricted flora, according as the underlying material allows or prevents penetration of roots and water.

Even where there is no obvious rock or gravel layer under the surface and where the material seems essentially the same for some depth and probably was the same when the soil was first formed, there are characteristic differences brought about by the combined influence of climatic factors and vegetation. These have been studied by the Russian investigators. Glinka calls the surface soil or upper layer the "A horizon"; the lower layer the "B horizon" and the parent material the "C horizon."[1] The basis of the distinction is that the "A horizon" loses soluble and easily dispersed colloidal material by downward movement of the soil water; the "B horizon" gains them. Thus in the silicate soils of cold or temperate humid climates (p. 119), the calcium carbonate passes right out from the soil[2] while some of the iron and aluminium oxides and clay are carried from the A horizon down to the B horizon, where they can be detected by chemical and mechanical analysis (Table XCIII.). Sometimes the effect is so clear as to be distinctly visible. Where a layer of peat covers the soil the drainage water is acid and the A horizon may be bleached; the B horizon then becomes

[1] Not necessarily the original geological formation; it may have undergone metamorphosis.

[2] Only in arid regions is it redeposited in the zone where the downward percolating water finally evaporates.

pronounced because it culminates in the pan (p. 229).[1] In agricultural land, however, the frequent cultivation of the soil to a depth of 6 to 9 inches much disturbs the natural horizons and makes a characteristic surface layer fairly uniform in character to the depth of the ploughing.

In addition to this slow continuous downward drift of soluble material there is an upward movement brought about by vegetation. Plants growing in the soil remove from the lower depths phosphorus, calcium, magnesium, potassium, and other bases, and bring them up to their leaves, stems, etc. When these die and fall back on the surface the elements are returned to the soil, but they are now concentrated in the upper layers, being distributed in the first instance only so far as earthworms or other animals will carry them. The amounts brought up depend on the plant. Salisbury shows that beech and birch, having a high calcium content in their leaves, are more effective in maintaining the supply of bases in the top soil than pine, bracken, and heather, which contain much less. In course of time the plant structure decomposes and the mineral matter is left exposed to leaching once more. The calcium carbonate tends to go first and the potassium and magnesium more slowly; it depends on the amount of rain and the ease of drainage whether the calcium carbonate permanently remains higher in the surface layer than lower down. But there is always the tendency to accumulation in the surface layer of soil. This is shown in the data of Table XCI. obtained by Salisbury and Tansley.[2]

[1] P.Edginton and J. R. Adams have found a striking distribution of nitrogen in the horizons of this "Podzol" type in New Hampshire; the percentages are:—

	A 1 Dark Upper Layer.	A 2 Leached Layer. Lighter Colour.	B Deposition Layer—Brown.	C Parent Rock.
N	1·62	0·05	0·43	0·20
*p*H	4·3	4·4	5·0	4·6

[2] *Journ. Ecology*, 1922, 9, p. 23. For other data see Salisbury, *ibid.*, p. 221.

TABLE XCI.—DISTRIBUTION OF BASES, P_2O_5 AND N IN SUCCESSIVE LAYERS OF SOIL.

Aymestry Limestone: Rowburrow Wood.

Depth of Sample.	Humus.	$CaCO_3$.	K_2O.	MgO.	Fe_2O_3.	P_2O_5.	N.
0- 4 cms . .	18·6	1·43	0·83	1·01	2·06	0·16	0·35
4-10 ,, . .	9·3	0·65	0·20	0·84	1·42	0·11	0·30
10-25 ,, . .	6·2	0·64	0·65	0·82	1·30	0·11	0·20

Further, when the roots die they are decomposed, leaving organic residues in the form of humus. The layer of soil normally permeated by plant roots—in this country about 6 inches (15 cms.) deep—is thus rich in organic matter.

The relationships between soil profile and vegetation are well illustrated by the successions of plant communities observed in growing sand dunes at Blakeney where detailed observations have been annually made on the vegetation and environmental conditions. E. J. Salisbury (242*c*) has recorded the successions. In their early stages the sand dunes contain calcium carbonate and are neutral. As they grow older some or all of the calcium carbonate is washed out and the organic matter increases so that the dune becomes markedly acid and moister.[1]

The embryo dunes have on the whole a calcicolous flora, the older ones a calcifugous flora.

	$CaCO_3$.	Organic Mat ter per Cent.	Maximum Water Content, per Cent. Weight.	*p*H.
Embryo dunes .	0·4	0·4	25	6·9-7·4 (Av. 7·2)
Older dunes .	0·01	1·1	36	6·1-7·3 (Av. 6·4)

Soils and their Vegetation Characteristics.

Within zones of similar climatic conditions soils of similar

[1] At Blakeney and at Southport the acid condition is attained in about 150-200 years; after this, organic matter rapidly accumulates (*Journ. Ecology*, 1925, 322).

constitution are found to have certain vegetation characteristics in common. In regions wholly undisturbed by man these characteristics operating over vast periods of time have produced a stable flora determined by tolerance of the conditions. As soon as man disturbs things the floras change, but only slowly: woodland plants survive long after the forest has gone. The return is apparently quicker. A piece of a well-cultivated wheat-field was enclosed at Rothamsted with its corn growing in 1882, and has not since been touched; it is now a thick wood.[1]

Agriculture involves a more or less complete displacement of the native flora by a new one which, however, is still dominated by the soil conditions. Usually also the soil conditions are altered somewhat, particularly by drainage, additions of lime and of organic matter. Additions of clay have in the past also been made to alter the soil. Nowadays, however, there is a tendency to avoid costly changes and to produce new varieties of crops better suited to existing conditions than those at present grown.

We shall now proceed to set out some of the more prominent of these common characteristics. For more detailed accounts the reader is referred to the treatises on Ecology and the Agricultural Surveys (p. 450). The description applies only to British soils; the soils of North Wales and of Scotland formed from palæozoic rocks since the glacial period show certain differences (p. 120).

Calcareous Soils.—On these soils calcium carbonate is the controlling factor in determining the soil properties. The conditions here seem to be extraordinarily well suited to plant and animal life. Bacteria are numerous and active, rapidly oxidising organic matter. Hosts of animals, wireworms, earthworms, and others live in the grass-land, and even get into the arable land, honeycombing the soil with their passages, puffing it up or "lightening" it considerably, and encouraging

[1] See W. E. Brenchley and Helen Adam, *Journ. Ecology*, 1915, 3, 193-210.

the multiplication of moles. Rabbits abound in dry places. Vegetation is restricted on thin exposed soils, but becomes astonishingly varied where there is sufficient depth of soil and shelter to maintain an adequate water supply. Ash is the characteristic tree in the north and west, and beech in the south of England, and there is a great profusion of shrubs—buckthorn, spindle, guelder rose, dogwood, hawthorn, hazel, maple; and especially of flowering plants—scabious (*S. Columbaria*), the bedstraws, vetches, ragwort, yellow wort (*Chlora perfoliata*), salad burnet (*Poterium sanguisorba*), lady's fingers (*Anthyllis*), *Linum carthariticum*, *Lotus corniculatus*, *Cirsium acaule*, *Helianthemum vulgare*. Of the grasses on the chalk downs and pastures the commonest include *Festuca ovina* and *rubra*, *Avena pratensis*, *Trisetum flavescens*, *Briza media*, *Bromus erectus*, *Kœleria gracilis* (*cristata*). *Carex flacca* (*glauca*) is also common.[1] Still more remarkable than the existence of a chalk or "calcicolous" flora is the fact that a few plants, the so-called calcifuges, do not occur; they are found only in pockets of acid soil.

Of the other plants many will grow but are liable to nutritional disturbances, particularly to chlorosis, if the proportion of calcium carbonate in the soil becomes too high. In France Chauzit showed that vines suffered badly when 35 per cent. or more was present, but not when the amounts fell to 3 per cent.[2] In Porto Rico bush beans (*Phaseolus nanus*) and radishes are unaffected by even 35 per cent. of $CaCO_3$; sunflowers, soy beans, and sugar canes are somewhat depressed; while sweet cassava (*Manihot palmata*), rice, and pine-apples were considerably depressed by this amount. The amounts of nitrogen, potash, and phosphoric acid in the various crops were apparently unaffected by the carbonate, but the iron was notably depressed.[3]

[1] The vegetation of English chalk has been studied in detail by A. G. Tansley and R. S. Adamson, *Journ. Ecology*, 1922, 9, 114; 10, 168; 1925, 13, 177.

[2] See *Revue de Viticulture*, 1902, xviii., 15, and also Molz, *Centr. Bakt. Par.*, Abt. ii., 1907, xix., 475.

[3] P. L. Gile and C. N. Ageton, *Porto Rico Agric. Expt. Sta. Bull.*, 16, 1914.

With rare exceptions (*e.g. Calluna*, p. 380) neither the calcicolous nor the calcifugous habits are constant properties of the plant, but are affected by climate or other external conditions. W. E. Brenchley finds that the calcifuges of the West of England are not all calcifuges in the Eastern Counties.[1] Mazé (197) attributes part of the harmful action of calcium carbonate to the rendering insoluble of manganese, iron, and other elements necessary for plant growth. Salisbury suggests that the calcifuges have special need for potassium which they might have some difficulty in obtaining on a chalk soil.[2] When there is no competition from other plants many calcifuges will grow in presence of calcium carbonate. The lupin has been studied in Germany where it is much grown and is known to suffer on calcareous soils (*Kalkempfindlichkeit*): Hiltner proposed to use ferrous sulphate to counteract this trouble. But in experimental plots Pfeiffer and Blanck[3] obtained even better growth in presence of chalk than in its absence; possibly the beneficial effect was on the nodule organism rather than on the plant. In a prolonged investigation near Karlstadt, Kraus (154) found no plant occurring exclusively on soils with even approximately equal content of calcium carbonate, although some preferred more, *e.g. Festuca glauca*, *Teucrium montanum*, and *Melica ciliata*, while others preferred less, *e.g. Brachypodium pinnatum*, *Kœleria cristata*, and *Hieracium pilosella*. True chalk plants were found on the adjoining sand, especially when some calcium carbonate was present, although the true sand plants did not wander on to the chalk. In such cases of displacement or "heterotopy" it was shown that the general physical conditions of the two locations were similar in spite of their wide difference in chemical composition. Kraus, therefore, argues that the true chalk plants inhabit chalk soils not because they need much calcium carbonate, but because they find there the general

[1] *Ann. of Botany*, 1912, **26**, 95-109.

[2] The significance of the calcicolous habit., *Journ. Ecology*, 1920, **8**, 202.

[3] *Mitt. Land. Inst.*, Breslau, 1914, **7**.

physical and chemical conditions they require. Dr. Salisbury expands this view and shows that plants come on to the chalk for two reasons: for the general physical conditions, aeration and moderate water supply; and for chemical reasons, especially the absence of acidity and the abundant supply of calcium. But if these conditions are satisfied on other soils they will grow there quite well. Thus the beech thrives best in a somewhat dry, well-aerated soil. In England it finds this conditions as a rule only on the chalk soils. But in southern warmer parts of the Continent it finds them on other soils so that the plant is not calcicolous. On the other hand, *Solanum dulcamara, Fraxinus excelsior, Cornus sanguinea* and others come on to the chalk to avoid acidity. They tolerate wet conditions quite well, and are indeed found in wet places where there is a tendency for the surrounding soil to be acid. It is, however, remarkable, as Dr. Rayner has pointed out, that calcifugous and calcicolous plants form symbiotic relationships with micro-organisms, *e.g.* the *Ericacæa, Orchidacæa,* and *Leguminosæ.*

The agricultural value of chalk soils depends very largely on their depth, and is much greater in valleys where the soil and water collect than on the higher ground where the soil is thinner. The two defects most in need of remedy are the lack of organic matter and the tendency to become light: these are met by additions of dung or other organic manures, by rolling and cultivating with heavy instruments, and above all by feeding animals on the land with the crops actually growing there and with purchased food, a process known as "folding." Heavy wooden ploughs are still in use, and until recently were worked in many places by large teams of heavy oxen. Sheep are by far the most suitable animals to be fed on the land, and they form the centre round which the husbandry of chalk districts has developed; indeed, so important are they that each chalk region has evolved its own breed of sheep —South Downs, Hampshires, etc. As fertilisers potassic manures, especially kainit, are generally profitable; super-

phosphate is needed for turnips, and in wet districts basic slag is useful on the grass-land. Skilful cultivation is always necessary, or the soil dries into hard, steely lumps that will not break down. And, lastly, the pre-eminent suitability of the chalk to plant and animal life has its disadvantages; no soils are more prone to carry weeds, turnip "fly," or wireworm. Skilful management is the keynote of success and it generally obtains, the bad farmers not usually surviving many seasons.

The fact that a calcareous rock lies beneath is no proof that the soil itself is calcareous: on the contrary, the soil may often contain practically no calcium carbonate, either because it has become decalcified by rain, or because it really represents some deposit of wholly extraneous origin.

Black Soils or Humus Soils.—In these the organic matter dominates all other factors.

There is a sharp distinction between:—

1. True peat, such as is found in moorlands, acid in nature, and commonly occurring in wet districts and regions of high rainfall or low temperature. This again is subdivided into high moor and low moor. The organic matter shows definite structure.

2. Fen, neutral in nature, occurring more locally: in England mainly in the Eastern counties. The organic matter usually shows no structure.

Fen land when drained has a high agricultural value, being worth some £2 per acre annual rent and producing considerable crops of potatoes, celery, and wheat.

True peat, on the other hand, has little agricultural value in its natural state and where high-lying is largely waste land, being unsuited to the growth of many plants and micro-organisms [1]. In this country it may have a certain sporting value, but elsewhere it lacks even this.

[1] For studies of nitrification and other bacterial actions in moorland soils see E. Gully, *Das Nitritzerstörungs und Nitritbildungvermögen der Moorboden*

Peat Soils.—The characteristics of peat soils are—

1. Wetness.

2. Deficient aeration: the vegetation has to be specially adapted to meet this.

3. Acidity.

4. Low content of calcium and other bases.

5. Absence of nitrate and low power of nitrification so that plants must usually obtain their nitrogen from ammonia or other sources.

The various peats recognised by ecologists in this country are described on p. 161. Numerous schemes have been projected for utilising the great peat areas, and they may roughly be grouped into two classes :—

1. Ameliorating substances (such as lime, artificial manures, etc.) are added, and the peat is cultivated as if it were normal soil. This is possible only when the deposits do not lie too high.

2. The peat is removed and sold, and if the climate allows the underlying formation is—

(*a*) Ploughed up, if it is clay or sand.

(*b*) Covered with town refuse and then cultivated, as at Chat Moss.

(*c*) Warped, *i.e.* systematically flooded with tidal water carrying silt till several feet of soil have been formed; this is only possible in a few areas, *e.g.* in Lincolnshire, lying below high water-level.

The first of these methods is in use in Ireland [1] and on the Continent; it is much investigated at the experiment stations at Jonköping (Sweden) by H. von Feilitzen, at Bremen (Prussia), Munich, and Arnheim (Holland). The second has been the subject of many experiments in England.

(*Landw. Jahrb. Bayern*, 1916, **6**, 1-81); Th. Arnd (4c), *Zur Kenntnis der Nitrification in Moorboden* (*Centr. Bakt. Par.*, ii., 1919, **49**, 1-51). For nitrification in forest soils see H. Hesselman, *Studien over Saltpeterbildningen*, Stockholm, 1917, and F. Weis (301).

[1] For experiments in Ireland, see *Journ. Dept. Agric., Ireland*, 1915, **16**, 229-236.

The removal and sale of peat is perfectly sound in principle. Peat is an asset of considerable value, but it is essentially a wasting asset; it disappears at a measurable rate after the drainage that is nowadays necessary. Under modern conditions peat cannot be conserved for future generations, and we are therefore fully justified in using it ourselves, even if the process be somewhat wasteful.

Peat may be made to serve three purposes :—

(*a*) Fuel, after it has been cut and dried.

(*b*) Litter, if it is sufficiently fibrous.

(*c*) It may be decomposed by heat, and made to yield valuable products, such as sulphate of ammonia, power gas, tar, etc.[1]

Fen Soils.—The fen soils form an interesting group in the low-lying areas adjoining the river Ouse and its tributaries in Norfolk, Cambridge, etc. As already stated, the soil water is not acid but contains calcium carbonate : the vegetation is not of the acid-soil type and crops do not respond to lime. The main characteristics of these soils are their richness in lime and their very high content of nitrogen, of which no less than 3 per cent, is sometimes found (see p 166).

The region was not much in cultivation till the great reclamation schemes of the seventeenth century, when Vermuyden, the engineer, and the Duke of Bedford and other enterprising capitalists took the matter in hand and erected the great dykes, drains, and pumps that alone keep the land dry and usable.

When drained these soils proved extraordinarily fertile, and they would be completely in cultivation but for the deliberate saving of Wicken Fen as a wild life sanctuary. Their high fertility is due to :—

1. Their high content of organic matter and of bases.

2. The absence of acidity.

3. The presence of a water table near the surface yet sufficiently far down to allow of copious root aeration.

[1] See F. M. Perkin, *Recent Progress in the Peat Problem*, 1925 (Brit. Assoc. paper, privately published).

Farmers distinguish two types of fen: the clay fen on the western side and the sandy fen on the eastern side of the region; the difference lies probably in the subjacent material, there being little evidence of any difference in the actual fen. The Kimeridge clay on the west lies about 5 feet below, but occasionally it comes above the surface and forms the rising ground on which alone dwellings could be built before the reclamation—the "eys" or islands of the old days. On the east the fen is underlain by sand.

The most suitable crops are oats, wheat, and above all potatoes, the introduction of which some thirty years ago completely revolutionised fen husbandry. In smaller quantities mangolds, celery, mustard seed, cole seed, rye grass seed, buckwheat, and other seeds are grown. Corn crops, however, do not finish well: they start well but do not "corn out." Where clay lies underneath a complete remedy lies in bringing up the clay and spreading it: this is done about once in twenty years. The soils shrink very much on drying, forming large cracks dangerous to animals and sometimes destructive to cart wheels. Oxidation is continually proceeding at a rapid rate and within living memory the fen has shrunk several feet: in many cases it only has another 5 or 6 feet to fall before disappearing altogether.

Fen soils do not require lime or nitrogenous manures, or, as a rule, potash. But they do respond in a marked degree to superphosphate, as shown by the following experiments made by the Cambridge Department of Agriculture:— [1]

With Mangolds.			With Potatoes.		
	Tons.	Cwts.		Tons.	Cwts.
No manure . .	11	2½	No manure . .	5	12
3 cwts. superphosphate	16	2	4 cwts. superphosphate	7	15
6 „ „ . .	21	13	8 „ „	8	10

[1] *Cambridge Farmers' Bull.* No. 6. Two of the soils overlay clay, the third was over gravel.

Bones also give good results, but basic slag appears to be without effect. Summer fallow has been observed to have a bad effect on fen soils.

In practice the clay fen soils after their periodical claying receive nothing but superphosphate: they are extraordinarily fertile, commonly yielding 10 tons of potatoes, 90 bushels of oats, and 56 bushels of wheat per acre. The sandy fen soils are less fertile because they cannot be clayed except at great expense: the chief need again is for phosphate, but potassium also is wanted.

The wonderful black earths of Russia, Canada, etc., are probably akin to the fen soils. The black soils of the Canadian prairies have been described by Shutt (265): under wheat cultivation they require no fertiliser; the similar Tchernozem of Russia and Hungary also carry practically nothing but wheat and receive little or no manure (86, 153*b*).

The "muck land" of the United States appears to be of the same type: it is underlain by shell deposits containing lime, and no structure can be detected in the organic matter: it responds, however, to lime and potassic fertilisers.

Clay Soils.—Clay soils are characterised by the presence of 20 to 50 per cent. of "clay" and similar quantities of silt and fine silt; in consequence of this excess of fine particles the size of the pores is so diminished that neither air nor water can move freely. Clay soils, therefore, readily become water-logged and in time of drought may not sufficiently quickly supply the plant with water; in our climate, however, they are usually moist or wet. The high content of colloidal matter impresses marked colloidal properties: (1) the soil shrinks on drying and forms large gaping cracks which may be several inches wide and more than a foot deep; (2) it absorbs much water, a good deal still being held even when the soil appears to be dry; (3) the water, however, moves only slowly, and it is not uncommon to find a fairly sharp line of demarcation between moist and dry soil, and for land to crack badly within a few feet of a ditch full of water; (4) the soil readily

absorbs certain soluble salts and organic substances. In addition the special clay properties are shown: plasticity and adhesiveness when wet, and a tendency to form very hard clods when dry. All these properties are much modified by calcium carbonate and calcium hydroxide; the chalky boulder clay is usually fertile: on the other hand, liquid manure (which contains ammonium carbonate) and nitrate of soda (which gives rise to sodium carbonate in the soil) may in certain conditions have unfavourable physical effects.

Clay soils have had rather a chequered agricultural history. Originally covered with oak forest and hazel undergrowth they were early reclaimed for agriculture purposes by draining, applications of lime,[1] and, later, of ground bones. Wheat and beans were the great clay crops, and in the early part of the last century, under the combined influence of high prices, large drainage schemes and artificial stimulus to enclosure, great areas came into cultivation so that now only little unreclaimed clay remains, excepting where the forest was preserved for hunting. Crops grew well but ripened late; a wet harvest was a terrible calamity. Bare fallowing was always necessary once in four years, and any of the intervening years might, if wet, be lost by the difficulty of getting on the land to sow the crop. When the price of wheat fell in the 'eighties many of these soils went out of cultivation and became covered with a mixed growth of grass and weed, which was grazed by stock and gradually deteriorated as the old drains choked up and the land became more and more waterlogged. *Aira cæspitosa*, "bent" grass (*Agrostis vulgaris*), yellow rattle (*Rhinanthus Crista-galli*), and in drier places the quaking grass (*Briza media*) and ox-eyed daisy (*Chrysanthemum leucanthemum*) are among the more obvious plants on these neglected fields; the only relics of the past are the field names and the high ridges or "lands" made years ago to facilitate drainage. But recently marked improvement has set in. Drainage is

[1] *E.g.*, see *Inrichment of the Weald of Kent*, by R. I., 1625 (attributed in the 1636 and later editions to Gervase Markham).

gradually being attended to, improved implements allow of better cultivation : mangolds, kohlrabi, and other fodder crops suitable for heavy soils have been grown, whilst additions of lime and phosphates (as basic slag) have markedly improved the herbage, favouring the development of white clover (*Trifolium repens*), the pasture grasses, also thistles, and crowding out such weed grasses as *Aira cæspitosa*, bent (*Agrostis*) and others. Figs. 44*a* and *b* shows specimens of herbage from some of Robertson's plots at Horndon-on-the-hill, Essex (London clay). Potassic fertilisers are not usually needed. Only in the dry eastern counties has the old arable cultivation survived.

It is commonly observed that plants growing on clay soils tend to have larger leaves, and to make shorter-jointed growth, than plants on sandy soils.

In ecological and agricultural surveys it is necessary to distinguish between the silty clays and the true clays. The former owe their heaviness to the presence of much fine silt which differs in colloidal properties from clay (p. 127), and is not flocculated by lime, frost, etc. Indeed, no way is known for ameliorating these soils and they are generally left as rather poor pasture. The true clays are often indistinguishable on casual inspection, but they behave differently on cultivation and respond to lime and good treatment whenever it is deemed worth while to improve them.

Sandy soils are formed of large silica particles deficient in colloidal matter, and therefore possessing little power of cohesion, or of retaining water or soluble salts. Hence they tend to be dry, loose, and poor in soluble substances—"hungry," the practical man calls them. Their behaviour towards vegetation depends very largely on their position, their depth, and the nature of the subsoil, these being the factors determining the water supply to the plant.

Absence of much clay, presence of much gravel and coarse sand and location on gravel or coarse sand tend to irregularities in the water supply which is fatal to plant growth. Extensive



FIG. 44A.—Poor grass pasture, untreated plot, Horndon-on-the-hill, Essex (London clay) (G. Scott Robertson).



FIG. 44B.—Adjoining plot, but treated with Gafsa phosphate, Feb. 27th, 1918. Photographed Aug., 1919.

areas of such soils exist in the western parts of Norfolk and Suffolk and are left wild as "brekland"; they have been studied ecologically by E. P. Farrow.[1] Surrey also furnishes examples in the Bagshot Lower Greensand formations; in places the general dryness is broken by ponds formed by saucer-shaped layers of clay which hold up the water.

Small modifications in the soil composition—an additional percentage of clay and silt, less coarse sand, a somewhat more compact subsoil or frequent rainfall (as, for example, in North Wales) enables these soils to be cultivated. When this is possible they are so attractive to cultivators that none are left uncultivated.[2] They yield early crops of high quality rather than heavy crops, the tendency to drought inducing early maturation, while the absence of stickiness makes sowing an easy matter at any time. Fruit, nursery stocks, potatoes, and market-garden produce are often raised, and high quality barley is also grown. The winter feeding of sheep on the land is a common way of fertilising, but crops must be sown early, or the fertilising material is washed out unused, and the young roots have no time to strike into the subsoil before the surface layer dries out. High farming is the only profitable way of dealing with these soils; any carelessness in cultivation lets in hosts of weeds, such as poppies, knot-weed (*Polygonum aviculare*), spurrey (*Spergula arvensis*), sorrel, horsetail, convolvulus, creeping buttercup, and others. Crops should follow each other in rapid succession, any interval being a period of loss; under good management two or even three market-garden crops can be secured in the year, while in purely farming districts catch crops should always be taken. Organic manures are necessary to increase the water-holding capacity: sheep-folding or green-manuring are, therefore, very desirable. Frequent repetition is necessary, as the organic matter speedily disappears. Calcium carbonate is

[1] *Plant Life in East Anglian Heaths*, Camb. Univ. Press.

[2] For fuller information as to the agricultural history of these and other soils, see E. J. Russell, *Fertility of the Soil*, Camb. Univ. Press.

often needed and is better applied as ground chalk or limestone than as lime. Potassium salts are beneficial and may be added as kainit; nitrates often give remarkable results, but phosphates are not usually needed because the soil conditions already tend to promote good root development. Only small quantities of manure must be added at the time, as the soil has little retentive power. Above all, no very costly scheme of manuring should be recommended till preliminary trials have shown its profitableness.

In reclaiming or fixing sand dunes the first step is to grow grass, *e.g.* Marram grass (Psamma), which will stabilise the form and then allow a more varied vegetation, *e.g.* sand binders (*Carex arenaria*, *Festuca rubra*, *var. arenaria*), and ephemerals, to stabilise the surface, thus leading to the development of a festuca sward or, in other conditions, to heath and scrub.[1]

A soil underlain at a short distance below the surface by a bed of gravel, a layer of rock, or a "pan," is liable to be either parched or waterlogged, and its water supply is usually so unsatisfactory that cultivation is unprofitable. Under low rainfall the land becomes a steppe, under rather higher rainfall a heath, but the vegetation is always xerophytic, consisting of heather, ragwort, broom, etc., the trees being birch and conifers—the latter often planted in recent times. No method of cultivating these soils has ever been devised, and most of them still remain barren wastes, defying all attempts at reclamation. Two special cases have, however, yielded to treatment:—

1. When the layer of rock or the pan is only thin and is, in turn, underlain by a rather fine-grained sand, its removal brings about continuity in the soil mass and thus effects a great improvement in the water supply. The soil now resembles the fertile sands, and should be treated in the same

[1] See F. W. Oliver and E. J. Salisbury, *Topography and Vegetation of Blakeney Point* (*Trans. Norfolk and Norwich Nat. Soc.*, 1913, 9, 485-543).

way. A good example is afforded by Cox Heath, Maidstone (p. 448).

2. Where the gravel or rock is not too near the surface, systematic green manuring with lupines and other crops fertilised by potassium salts and calcium carbonate will often effect sufficient improvement to make cultivation profitable. Examples are afforded by the Schultz-Lupitz estate, Germany (255), and Dr. Edwards' experiments at Capel St. Andrews, Suffolk, and at Methwold. On such land an industrious cultivator may make a living but not a fortune.

Under favourable conditions recourse may be had to dressings of clay (as in Lincolnshire) or to warping (in the Fens).

Barren conditions also result when, by reason of a thin parting of clay or its low situation, water cannot run away but accumulates and forms a marsh. Reclamation in such cases is possible as soon as a way out has been found for the water.[1]

Loams.—As the proportion of fine material in the soil increases and that of coarse material falls off, a gradual change in the character of the soil sets in, till finally, but without any sharp transition, a new type is reached known as a loam. The increase of fine material somewhat retards the movements both of air and of water, so that loams are characterised by a more uniform water content throughout the mass than sands. On the other hand, loams show less tendency to become waterlogged or to allow plants to become parched in very dry weather than clays. The soil decompositions proceed normally, rapidly producing plant food, with little tendency to " sour " [2] or other abnormal conditions so long as sufficient calcium carbonate is present. In consequence, most plants will grow on loams, even some of those supposed to be specially associated with some other soil type. Thus, where a chalk and a loam soil meet, it is not uncommon to find the chalk

[1] For a fuller discussion of land reclamation see E. J. Russell, *Journ. Roy. Agric. Soc.*, 1919, 80, 112-133.

[2] See pp. 378 *et seq.*

plants, *e.g.* traveller's joy (*Clematis Vitalba*), guelder rose, etc., wandering on to the loam, and it is much more difficult to find the line of separation of the soils than where the chalk abuts on to a sand or a clay. For the same reason loams allow of very wide choice in the systems of husbandry, and, as they become very fertile under good management, they are usually in this country all cultivated. Closer observation over a limited area shows, however, that a given class of loam is more suited to one crop than to another; the ecologist recognises differences in the sub-associations or facies, and the practical man will distinguish between a potato soil, a barley soil, a wheat soil, etc.: distinctions due, no doubt, to water and air relationships, and arising from differences in the compound particles. Unfortunately no method of investigating the compound particles has yet been devised, and a study of the ultimate particles by a mechanical analysis is alone possible. But even though the differences are thus attenuated they can still be traced, as shown by the analysis in Table XCII. of soils in Kent, Surrey, and Sussex, known to be well suited to the particular crops.

Low amounts of clay and fine silt, and high amounts of coarse sand, whenever the clay begins to approach 12 per cent., characterise the potato soils; these are the most porous of the series, allowing free drainage and aeration. Barley tolerates heavier and shallower soils. Fruit and hops both require deep soils, and seem to find their most favourable cir-

TABLE XCII.—MECHANICAL ANALYSES OF SOILS WELL SUITED TO CERTAIN CROPS IN THE SOUTH-EASTERN COUNTIES; LIMITS OF VARIATION. HALL AND RUSSELL (1218).

	Potatoes.	Barley.	Fruit.	Hops.	Wheat.	Waste Land.
Fine gravel .	0·1-3	0·2-2·5	0·3-2·3	0·3-2·3	0·4-6	1-7
Coarse sand .	2-47	1-53	0·8-9·5	0·7-9·5	0-13	16-69
Fine sand .	23-68	20-45	30-55	25-39	15-31	18-64
Silt . .	3·5-21·4	5-33	13-44	20-45	11-35·5	2-7
Fine silt .	5-9	3·5-16·4	6-11	6-11	9·5-24	2
Clay . .	5·5-12·6	4-19	10·5-14·6	11·5-15	13-24	1 or less

cumstances only in a restricted class of soils: the fruit soils generally contain rather more sand and less silt than the hop soils. But the fruits differ among themselves; the best nursery stock is raised on soils of the potato class, where the conditions are for some unknown reason very favourable to fibrous root development; strawberries prefer the lighter and apples the heavier kinds of fruit soil. Even different varieties of the same plant show distinct preferences for one class of soil over another: the finest varieties of hops are found only on the typical hop soils, and have to be replaced by coarser varieties directly it is desired to grow hops on heavier soils. Preference for certain soil conditions are also shown by varieties of the common crops, oats, barley, wheat, etc.; unfortunately these can only be discovered by direct field trials, and even then the results hold only so long as similar conditions prevail and may often be reversed in a different climate or season.

Between the lighter and the heavier loams the difference lies partly in the balance between air and water supply. For as the loams become heavier the water supply becomes greater and the air supply correspondingly less. Plants that require much oxygen for root growth but only moderate amounts of water are therefore less likely to flourish on the heavier loam than those that can tolerate less oxygen and respond to the extra water. Examples from wild vegetation are given by Cannon [1] (66). The stickiness of a heavier soil and its greater resistance to the movement of plant roots also considerably affect the growth of plants. In this country there are some interesting agricultural examples which have not yet, however, been fully analysed. At Rothamsted, early plant growth and especially tillering are closely related to

[1] For a further discussion see: Weaver, *Ecologial Relations of Roots*, Pub. Carnegie Inst., 286, 1919; Noyes, Trost and Yoder, *Bot. Gaz.*, p. 364, 1918; Haasis, *Relation Between Soil Type and Root*, from *Ecology*, **2**, 292, 1921; Waterman, *Development of Root Systems under Dune Conditions* (*Bot. Gaz.*, 1919, **68**, 22-53); Oswald, *Fühlings Landw. Zeit.*, **68**, 321-340, and 370-386, 1919.

heaviness of soil as measured by the drawbar pull needed to move the plough through it.[1] Wheat growing on entirely suitable loams tillers well, produces stiff straw and ears copiously set with corn, so that a crop of 50 or 60 bushels per acre may be raised without difficulty; on soil rather different in type, and especially under somewhat different climatic conditions, only 30 or 40 bushels can be raised, because the ears are less thickly set and the straw is too weak to carry a heavier crop, becoming "laid" directly an attempt is made to increase production by increased manuring.[2] Whether some unknown nutrient is absent from these soils, or whether the adjustment of the air and water supply is wrong, is not known; but the limitation of yield arising from this unsuitability of soil conditions is a serious problem.

Not only is the amount of growth altered, but the composition and character of the plant. Barley grown on some soils produces much better malt than on others.[3] Potatoes grown in the Dunbar district are remarkable for their quality, they will stand boiling and subsequent warming-up without going black. The same varieties of potatoes grown in the same way in the Fens blacken badly under the same treatment, and consequently command a lower price in the market.[4]

Grass is considerably affected.[5]

In Romney Marsh pastures commonly occur carrying a vegetation of rye grass and white clover, with crested dog's-tail and agrostis, easily capable of fattening sheep in summer without any other food. All round these pastures are others, with *the same type of vegetation*, but the plants grow more slowly, produce more stem and less leaf, are less nutritious and

[1] B. A. Keen, *Journ. Roy. Agric. Soc.*, 1925, **86**, 20-42.

[2] Further illustrations are given by the author in *Science Progress*, 1910, v., 286.

[3] For full discussion see E. J. Russell, *Journ. Inst. Brewing*, 1924, **30**, 818-837.

[4] S. F. Ashby, *Journ. Agric. Sci.*, 1905, **1**, 347-357.

[5] 121*c*, also Rowett Institution publications: *Journ. Agric. Sci.*, 1926, **16**, 59-104.

incapable of fattening sheep. The soils are identical in mechanical analysis and in general water and temperature relationships, although certain differences have been detected. Grass grown on Lower Lias pastures in Somersetshire and Warwickshire causes acute diarrhœa (" scouring ") in cattle, whilst grass on adjoining alluvial pastures does not.[1] Harmful effects of a wholly different nature are recorded from certain Swiss pastures.[2] Some of the South African grazing lands tend to give the animals a serious disease, Lamziekte, which is attributed to a harmful quality in the herbage and not to any particular plant or organism.[3] Instances might be multiplied to show how greatly the plant responds to variations in soil conditions.

The agricultural treatment of loams, as already indicated, admits of considerable variety. The old plan was to apply a good dressing of dung every third or fourth year and a smaller intermediate dressing; clover was also grown every fourth year, and, on light loams, the root crop was eaten by animals on the land. At long intervals lime was applied and sometimes bones. The modern movement is towards specialisation, each man producing the crops he can best grow and managing them in the way he finds most profitable, but the system usually involves feeding a good deal of imported food to sheep and cattle, either on the land, or in yards, and utilising the excretions as manure, buying nitrate of soda, sulphate of ammonia, and manufacturers' waste products (generally those derived from imported animal or vegetable products) to supply more nitrogen, and buying also imported phosphates and potassium salts. Thus the fertility of highly-farmed countries like England tends to increase at the expense of new countries that export large amounts of animal and vegetable produce. But the transfer is prodigiously wasteful;

[1] C. T. Gimingham, *Journ. Bd. Agric.*, 1910, **17**, 529-541, and *Journ. Agric. Sci.*, 1914, **6**, 328-336.

[2] *Jahrb. Schweiz.*, 1898, 104-105.

[3] See Ingle, *Journ. Agric. Sci.*, 1908, **3**, 22-31; A. Theiler, also H. H. Green, *5th and 6th Veterinary Reports, Union of South Africa*, 1918.

enormous losses arise in virgin countries through continuous cultivation (p. 246), and at this end in making dung (p. 264), and especially through our methods of sewage disposal. It seems inevitable that these losses must make themselves felt some day, unless the movement for the conservation of natural resources ever becomes a potent factor in international life.

Soil Fertility and Soil Exhaustion.

We can now summarise the various properties that make up soil fertility.

1. Sufficient water, air, and nutrients must be present in the soil to ensure the fullest growth permitted by the temperature.

The air and water are complementary quantities; both have to fit into the pore space of the soil, and any increase in one automatically reduces the other. The amount of pore space is determined by the size and arrangement of the soil particles. The water is held near the surface by the soil colloids.

2. Further, the plant must obtain the air, water, and nutrients sufficiently quickly to allow it to grow continuously and without check. This has been spoken of as a "supplying power" of the soil, and it might be brought about by a drift of soil water or nutrient solution to the plant roots to replace the material taken up. On the other hand, it is at least equally probable that the soil system is purely passive, the plant roots growing out to new supplies of water and nutrients.

3. Whichever view is adopted easy root growth is essential to soil fertility. For most plants this necessitates sufficient air and therefore not too much colloid in the soil—yet also not too little or the moisture supply may become inadequate. But the state of the colloid is equally important; the deflocculated condition is not as well suited to root growth as a proper flocculated condition.

4. Of all clays the calcium clay is most favourable for the growth of plants; magnesium, sodium, and acid clays

occur in nature and permit of plant growth, but, with some rare exceptions, not of full growth. This gives calcium a unique position among chemical elements in determining soil fertility.

5. Dead plant residues falling back on the soil and carried into it by earthworms, ants, etc., add to the soil quantities of organic matter containing energy and plant nutrients. These residues permit the growth of a large population of micro-organisms which, in obtaining their energy, convert the organic into simple inorganic combinations, especially the anions $-HCO_3$, $-SO_4$, $-NO_3$, $-PO_4$. The micro-organisms vary in their activity at different seasons and even from day to day. The anions bring an equivalent amount of cations into solution. Thus the amount and composition of the plant nutrients in the soil and soil solution both fluctuate, probably continuously. Some of the nutrients are assimilated or decomposed by micro-organisms. In a fertile soil the net rate of production of nutrients available for the plant completely satisfies plant requirements.

6. Rain-water falling on the surface displaces the soil solution and dissolves fresh material; in soaking through the soil it carries away considerable amounts of bases and plant nutrients. This tends to lower the fertility. On the other hand the plant roots take up nutrients, bases, etc., from the lower depths of the soil, deposit them in their leaves and stems, and ultimately return them to the surface of the soil. There is thus a constant circulation of bases and nutrients, the rain washing them out from the surface, and the plant bringing them back again. In humid regions the return is not complete, and if the soil is exposed to high rainfall and situated at the top of a slope or on a porous subsoil allowing easy drainage, it may lose so much base and nutrients as to become acid and infertile while the soil lower down gains in fertility. In fertile soils there is either a gain from higher soils or a net loss so small as to be counteracted by the action of micro-organisms.

7. The effect of the three factors: micro-organisms, rain,

and the growing plant, is that inorganic salts—bicarbonates, nitrates, sulphates, phosphates—are continuously being made in the soil at inconstant rates; that the soluble substances continuously tend to be washed downwards by the rain, interacting as they go with the reactive clay alumino-silicates; they are brought back again by the plant. The soil thus alters continuously; there is no constancy about any of the factors determining fertility.

8. In a fertile soil these variations fit in with the necessities of the plant.

9. It follows that fertility cannot be simply expressed either by chemical analysis or in any other way. The factors determining fertility are constantly changing; fertility is the resultant of all these changes. It is not an absolute property, but is closely related to climate.

Infertility is on the whole easier to investigate than fertility because it is generally presented as a specific problem. It arises when one or more essential conditions is not fully satisfied; it may come from lack of air, of water, of nutrients —especially nitrogen, phosphorus, potassium, and calcium. Lack of calcium has far-reaching effects and leads to development of acidity in the soil which aggravates any harmful effects already being produced. Frequently one factor dominates the situation; the problem is to discover which it is and then to suggest methods of amelioration or crops or systems of husbandry tolerant of the conditions.

Cultivators wishing to improve the productiveness of their soils usually adopt one or other of the following methods:—

1. Increasing the water supply by increasing the colloid material, deepening the soil, *e.g.* by breaking a "pan," by enriching the lower spit, or other device; increasing the air supply by drainage.

2. Building up the compound particles by proper cultivation, by addition of organic matter (*e.g.* dung, green manuring, etc.), and of calcium carbonate.

3. Addition of sufficient calcium carbonate to ensure a reaction suitable for the crop and the micro-organisms.

4. Increasing the supply of plant nutrients by the addition of fertilisers, the ploughing-in of green leguminous crops, feeding cake on the land, etc.

The reduction of fertility brought about by cropping is called " exhaustion " of the soil. It results from the circumstance that the nutrients and bases absorbed from the soil by plants are not returned to the surface but carried away more or less completely so that the restorative part of the cycle is broken. In humid climates soil exhaustion is limited to the removal of calcium carbonate, plant nutrients (often nitrogen and phosphorus) and some of the organic matter, and the destruction of tilth or of the proper compound particles. Further than this it is hardly possible for a cultivator, however neglectful, to go; the mineral particles and the greater part of the soil colloids remain unaffected. A distinction is therefore made between the temporary fertility or " condition " within the cultivator's control, and the " inherent " fertility that depends on the unalterable ultimate particles. The distinction is very indefinite, and, in practice, wholly empirical, no proper methods of estimation having yet been worked out, but it is of importance in compensation and valuation cases.

Serious soil exhaustion did not arise under the old agricultural conditions where the people practically lived on the land and no great amount of material had to be sold away from the farm. Phosphate exhaustion was the most serious occurrence because there was no way of meeting it, and as the original supplies were not as a rule very great, it must have become acute by the end of the eighteenth century in England, for remarkable improvements were, and still are, effected all over the country by adding phosphates. Then began a process, which has gone on to an increasing extent ever since, of ransacking the whole world for phosphates; at first the search was for bones, even the old battle-fields not being spared, if we may believe some of the accounts that

have come down; later on (in 1842) Henslow discovered large deposits of mineral phosphates, to which more and more attention has been paid. Phosphate supplies may yet become the factor that will determine the course of history.

The crowding of the population into cities, and the enormous cheapening of transport rates, led during the nineteenth century to the adoption in new countries, particularly in North America, of what is perhaps the most wasteful method of farming known: continuous arable cultivation without periodical spells of leguminous and grass crops. The organic matter was rapidly oxidised away, leaching and erosion increased considerably when the cover of vegetation was removed, while the compound particles that had slowly been forming through the ages soon broke down. Nothing was returned to the soil, the grain and other portable products were sold, and the straw burnt. The result has been a rate of exhaustion unparalleled in older countries, and wholly beyond the farmer's power to remedy, consequently he left the land and moved on. The excellent experimental studies of Hopkins (138) at the Illinois Experimental Station, of Whitson at Wisconsin,[1] and other American investigators, have shown that additions of lime, of phosphates, and sometimes of potassium salts, with the introduction of rotations including grass and leguminous crops, and proper cultivations will slowly bring about a very marked improvement.

[1] *Wisconsin Bulls.*, 174, 202, 204, 205, 1911.

CHAPTER IX.

METHODS OF SOIL EXAMINATION.

Soil analysis is used for two purposes :—

1. For enabling soil investigators, ecologists, and others to characterise soils and explain their vegetation relationships.

2. For aiding agricultural experts to advise farmers.

The first methods of soil analysis were purely chemical; they were based on Liebig's "mineral hypothesis" (p. 15) and on the idea that acid excretions from plant roots dissolved potassium and phosphates in the soil (p. 374); they necessarily lost their value when these ideas became untenable. Later on mechanical analysis was brought into prominence by Milton Whitney; it has proved very useful in characterising the physical properties of soils and it is therefore retained.

More recently there has been a reversion to chemical methods, which, however, are wholly distinct from the older ones; they include estimations of the amount and composition of the colloidal matter and the exchangeable bases, of the reaction of the soil, its hydrogen ion concentration and lime requirement.

The data thus obtained give information about the properties of the soil, but these are not always clearly related to the phenomena of plant growth. Climate plays so important a part that direct correlations of soil analytical data with plant growth can be sought only in regions of comparable climatic conditions; the data are insufficient for a statistical study of the relationship between soil analysis, climate, and plant growth, though certain general results will be indicated later.

The safest procedure is to use soil analysis for comparing

soils rather than attempting absolute descriptions. In ecological studies the comparisons must depend upon the particular investigation. For agricultural advisory purposes the soils of an experimental station or other land on which detailed studies are made of plant growth become standards with which other soils are compared by the various analytical processes. This general method has been elaborated into Soil Surveys.

Two methods have been used in making soil surveys. The geological survey formed the basis of the older. This answers very well for soils derived from the underlying rock so long as the various formations show characteristic chemical and physical properties as in Kent, Surrey, and Sussex (121*a*).

The method cannot so well be applied where the soil is derived from drift material, or where the geological formations do not differ sufficiently in physical and chemical properties to yield different kinds of soil. The grouping of the soils can then be effected by dividing the region into districts of similar vegetation characteristics, and, as the plant is a sensitive indicator of soil conditions, these districts are taken as the units for soil examination.

In regions of high rainfall or other extremes of climate there is little direct relationship between soil and geological formation. Soil types can still be mapped [1] but the basis is not geological. Geological classification breaks down altogether where applied to large areas (*e.g.* whole countries or to continents; its basis is age and method of formation, not lithological character, and one and the same geological formation may vary widely in character over a wide stretch of country. In addition where areas are large, the climate alters, and this causes changes in soil even when the rock was originally the same and gave rise to the same kind of mineral particles. The effect of these geological and climatic variations is that a formation may produce one type of soil in one district and a totally different type elsewhere.

In the American Soil Survey the geological basis is there-

[1] *E.g.* G. W. Robinson, see p. 451.

fore discarded. The survey is based solely on the soil properties. The soil is regarded as a separate entity and studied independently of its geological history, its vegetation, or the climate. The principle is unimpeachable. In practice it is not possible to study fully the properties of the undisturbed soils; no field methods have been devised for measuring *in situ* such important quantities as the power of transmitting air and water. It therefore becomes necessary to select certain properties as the bases of comparison and classification in practice. The profiles as studied by the Russian investigators, Glinka and others, are used. C. F. Marbut's instructions to the surveyors show how the work is done in the field.[1] The normal soil is sought on smooth uplands, in undulating (not flat) areas at least 6 feet above the level of permanent ground water. A section is dug to show the profile of the soil and the characters of the A, B, and C horizons (p. 409). Mature soils have well-developed profiles with sharply distinguished horizons from the upper of which all calcium carbonate and other readily soluble alkali or alkaline earth salts have been leached out. Associated with them may be immature soils with ill-developed profiles, but different kinds of mature soils do not occur in the same region.

The surveyor first determines the "texture profile." In the United States the A is usually relatively light textured, the B is heavier, while the C is often lighter and looser. B is usually distinguished from C by complete decomposition and oxidation which causes a marked colour change. The "colour profile" is determined by noting the colours of the separate layers in each of the three horizons. Usually in virgin soils the A horizon has two colour layers, the A_1 and the A_2 (the material lying on the top of the soil is not taken into account). The "structure profile" is also recorded. The soil must be

[1] I am indebted to Dr. C. F. Marbut for help with this section. Fuller accounts are given in his *Reports to the International Society of Soil Science*, while examples are found in the recent soil surveys of the United States.

moderately dry and examined either at a natural outcrop or in masses lifted with a spade or pick; the augur sample is unsatisfactory and cultivated soil is entirely useless. Several structures are distinguished:—

1. Single grain silty or floury structure, the particles not being grouped at all.

2. Granular structure, the granules being roughly spherical and fine, about the size of a bird shot, or coarse, about the size of small nuts.

3. Buck-shot structure, in which the soil on drying breaks up into angular fragments; this is seen in heavy clays having a large percentage of lime.

4. Plate structure, horizontal plates usually recognisable in outcrop, but sometimes seen only after the soil has been dug up and allowed to disintegrate by gentle shaking.

A columnar structure is found in some regions, *e.g.* the Western States: the upper part of the soil profile after exposure breaks into vertical columns.

The "chemical profile" is studied by estimating calcium carbonate (often found as a "horizon of accumulation" where the rainfall is less than 17 inches a year in cool climates or 30 inches a year in hot ones), calcium sulphate, iron oxide, alkali, etc.; the "reaction profile" by applying the B.D.H. soil-testing outfit, Soiltex, or other simple test (p. 456). The "consistency profile" relates to friability, plasticity, stickiness, compactness, cementation, etc.

Having thus examined the standard profile others are made by digging or samples are taken out with an augur. Soils of similar profiles (judged according to these tests) are grouped together and shown on the map by some scheme of numbering, hatching, or colouring. Soils of dissimilar profiles are mapped differently, even although the surface layer may be the same; the relationship would be indicated in a note.

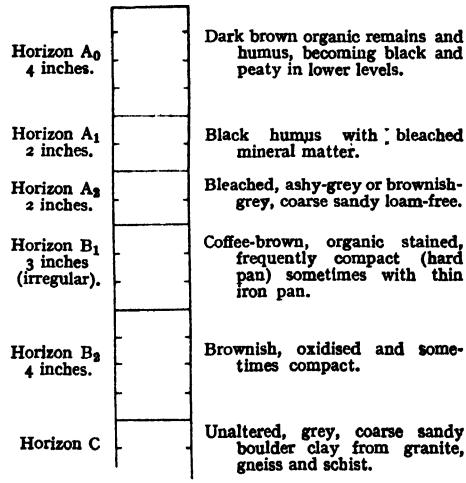
Frequently, however, the profiles are imperfectly developed; there may be little or no difference between the A and B horizons, either because the whole soil is new or because it has

always been very moist or water-logged (Fig. 45; Table XCIII.).

The C horizons are grouped according to the geological formation.

Chemical and mechanical analyses are then made of typical samples from the various horizons and sub-horizons.

In England virgin soils no longer remain to give the



Area—East Aberdeenshire.
Usual vegetation—*Pinus sylvestris, Calluna vulgaris, Vaccinium myrtilus, Descampsia flexuosa.*
Rainfall—32 inches.
Height above sea level—400-500 ft.
Reaction throughout profile—acid.
(G. Newlands, Agric. Dept., Aberdeen.)

FIG. 45.—Profile of undisturbed soil, Aberdeenshire.

necessary standard profiles. Most of the soil has been turned over many times and anything capable of bearing crops is under arable or grass cultivation. The natural profiles have therefore become obliterated, and the striking distinction in colour, texture, and composition between the upper layer of soil as far as the usual depth of cultivation, and the soil below, completely obscures any distinction between the A and B horizons. Moreover, although many of the soils are " mature "

TABLE XCIII.—PROFILES OF UNCULTIVATED SOILS, NORTH WALES.

"Podzol" Profile, Rhos Hirwaen (Carnarvon). (C Horizon is Boulder Clay.)

Vegetation: *Ulex gallii, Erica cinerea, Molinia cærulea* and *Salix aurita.* (H. T. Jones and G. W. Robinson.[1])

B. 153.	A Horizon.		B Horizon.		C Horizon.	
	0-2".	2-5".	5-12".	12-18".	18-24".	24-32".
Fine gravel	—	7·9	10·2	12·1	11·7	13·6
Coarse sand	—	8·5	17·1	14·9	17·6	17·9
Fine sand	—	18·5	22·0	21·2	22·9	21·6
Silt	—	10·3	10·8	12·3	12·5	10·5
Fine silt	—	15·0	16·2	15·5	15·2	17·2
Clay	—	11·0	14·8	15·0	14·3	13·3
Hyg. moisture	9·2	3·4	1·5	2·0	1·4	1·4
Ignition loss	46·0	23·9	6·3	6·0	3·8	3·7
Soluble in 20% HCl SiO_2	—	5·4	5·8	4·9	5·4	5·5
Soluble in 20% HCl R_2O_3 (*i.e.* Al_2O_3, Fe_2O_3, etc.)	—	6·2	5·8	13·7	13·1	10·6
Colour	Dark brown.	Greyish-black.	Grey.	Light brown.	Greyish-brown.	Light grey.

"Immature" Profile, Not Differentiated into Horizons, Penlan, Llangollen, (Denbigh).

C Horizon is Silurian Shale.

Vegetation · Poor Upland Grass. (G. W. Robinson and J. O. Jones.[2])

	0-3".	3-6".	6-9".	9-12".	12-15".	15-18".
Fine gravel	1·9	3·6	3·3	3·3	5·8	15·9
Coarse sand	0·6	0·9	0·7	0·7	1·0	6·3
Fine sand	7·6	9·4	9·6	13·0	14·3	15·1
Silt	18·7	22·8	27·0	27·3	27·5	21·3
Fine silt	18·5	23·5	25·0	24·9	22·9	21·1
Clay	21·0	22·3	20·3	17·7	15·7	9·9
Hyg. moisture	4·4	3·0	3·4	2·6	2·5	2·5
Ignition	21·6	12·8	10·5	9·3	7·7	6·9
Soluble in 20% HCl SiO_2	8·2	6·6	5·5	5·7	6·3	6·2
Soluble in 20% HCl R_2O_3	11·7	12·3	13·0	13·3	13·1	14·3
Colour	Dark brown.	Brown.	Light brown.	Yellowish-brown.	Yellowish-brown.	Light yellowish-brown.

[1] *Welsh Journ. Agric.*, 1925, 1, 142-147.

[2] *Agric. Progress*, 1926, 3, 39-42.

in the sense that they have long been exposed to weather and to a high rainfall, they contain calcium carbonate which has been added artificially by long generations of farmers.[1] It seems improbable, therefore, that surveying by profile would prove as helpful to ecologists and agricultural advisers in England as it is expected to prove in Continental areas. But it is clear that the profiles must be studied and that the samples for detailed chemical and physical examination should be chosen in relation to them.

Mechanical analysis has proved the most useful means for characterising soils, but the grouping of the soils presents difficulties where there is no close relationship with the geological formation.

In making a soil survey in England, the first step is to go over the region with the Ordinance Survey contour map, a rainfall map constructed from the data in *British Rainfall*, and the Geological Survey drift map about which the memoirs give fuller information. Areas shown as approximately uniform on all these maps are taken as units for the survey unless differences in agricultural or vegetation characteristics are sufficiently marked to necessitate further sub-division. Samples are then drawn for analysis from either grass or corn land, but avoiding steep slopes and disturbed ground. Full inquiries must be made on the spot as to the agricultural value of the land, the crops and manures most suitable, its behaviour during drought and wet weather, and any special points to be observed during cultivation. Information is also wanted about the most troublesome weeds, the native vegetation, hedgerow and other timber, etc., and note must be taken of the position of the soil in regard to water supply, the nature of the strata down to the permanent water table, etc. The most reliable information is obtained only by properly conducted manurial trials.

[1] Pliny describes the method by which the Belgæ chalked their land; this was still used by the "chalk drawers" of Hertfordshire until the time before the War (*Journ. Board of Agric.*, 1916, 23, 625).

If there is no break in the soil continuity the sample of surface soil is taken to a depth of 9 inches, and of subsoil from 9 to 18 inches.

The vegetation areas correspond with the geological formations only so long as the lithological characters remain constant. Some formations are very uniform, *e.g.* the Folkestone beds of the Lower Greensand, but, in general, certain changes are observed. Where the formation has been laid down in an estuary of no great size, the coarser particles are deposited near the old shore and the finer particles farther out, so that a gradual change from finer to coarser soil is observed in travelling along the formation, necessitating a soil division into two or three vegetation areas; the Hythe beds of the Lower Greensand and the London clay afford illustrations. Drift soils and formations like the Lower Wealden present more difficulty because the uniform areas are so small. Probably the best plan is to group into districts of soil variation between an upper and a lower limit.

Table XCIV. shows the kind of variation that occurs within short distances in the South-Eastern counties on the heavier soils:—

TABLE XCIV.—VARIATION IN SOIL DUE TO WASHING OR FLOODING.

Formation	London Clay.				Clay-with-Flints.				Weald.			
Locality	Merton, Surrey.				Hamsey Green, Surrey.				Woodchurch, Kent.			
	Lower Ground.		On the Hill.		Soil 109.		Soil 110, 200 yards away.		Soil 69.		Soil 70.	
	Surface.	Subsoil.	Surface.	Subsoil.	Surface.	Subsoil.	Surface.	Subsoil.	Surface.	Subsoil.	Surface.	Subsoil.
Fine gravel	1·7	1·3	1·5	0·3	1·6	3·1	1·7	1·4	0·5	0·6	0·9	0·7
Coarse sand	18·4	23·6	16·9	8·4	9·5	6·7	5·3	7·1	2·5	1·9	1·1	1·1
Fine sand	12·7	11·3	12·4	12·7	22·3	28·0	28·7	25·1	14·7	13·0	9·3	9·0
Silt	16·6	18·0	16·6	13·4	25·4	22·5	26·3	17·6	24·2	27·8	25·9	18·8
Fine silt	11·1	11·4	10·1	9·8	9·9	12·6	10·2	9·5	23·7	23·3	24·4	26·5
Clay	24·6	24·9	26·7	41·7	16·0	16·4	16·4	28·3	20·1	28·9	28·6	37·8

The Interpretation of Mechanical Analysis.[1]

The following illustrations of the interpretation of an analysis are taken from Hall and Russell's survey of Kent, Surrey, and Sussex (121*a*) :—

The Chilworth soil (Table XCV.) contains so little clay and fine silt and so much coarse sand that it has very little power of retaining water. As it lies too high to obtain seepage water from the neighbouring formations it is dependent on the immediate rainfall, and is therefore not in cultivation but has always been heath land. Owing to its bad constitution and its high situation it could not by any known method be made suitable for farming.

TABLE XCV.—MECHANICAL ANALYSES OF SOILS AND THEIR INTERPRETATIONS.

Formation . .	Folkestone Beds.		Thanet Beds.		Brick Earth.		London Clay.	Weald Clay.	Alluvium.	
Locality . . .	Chilworth.	Shalford.	Goldstone.	Barton.	Ickham.	Oving.	Tolworth.	Shaddoxhurst.	Ewhurst.	
Gravel . .	1·2	2·5	0·2	0·2	0·3	0·9	0·4	0·2	0·7	0·1
Coarse sand .	65·9	52·6	15·3	2·3	0·7	1·3	12·8	1·5	1·0	0·5
Fine sand .	23·7	26·2	44·9	34·7	24·7	16·0	25·5	11·0	19·8	19·3
Silt . .	2·4	4·8	17·3	36·2	44·8	35·5	11·3	19·6	28·4	13·0
Fine silt . .	2·0	3·5	6·3	6·3	8·6	13·3	11·1	26·8	12·1	20·0
Clay . .	0·9	3·8	8·9	11·5	14·7	15·9	23·7	22·1	19·7	26·9
Calcium carbonate .	nil	0·3	0·08	0·18	0·4	0·75	2·0	0·16	0·05	0·28
Loss on ignition	2·6	3·3	3·1	4·3	4·6	6·5	5·6	9·8	10·2	11·3

The Shalford soil lies lower down and has a better water-supply, less coarse sand, and more clay and fine silt. But its water-holding capacity and its retentive power for manures are low; artificial manures are of less value than organic manures, and the best treatment of the land is to grow green crops and fold them off to sheep. It is better suited to special purposes

[1] See Appendix (p. 460) for Methods of Analysis, and pp. 120 *et seq.* for dimensions and composition of fractions.

like the production of malting barley or market-garden crops than to ordinary mixed farming.

The Goldstone soil contains more clay and fine silt, and has therefore better power of retaining water and manures; it is more productive and more generally useful. But as the coarse sand exceeds the clay in amount it is still distinctly light; it responds better to organic than to artificial manures and suffers rather in droughty weather in spite of lying not far above the marshes. It contains 45 per cent. of fine sand and therefore tends to cake on the surface after rain and to form steely lumps if worked when wet. Under proper management, however, it produces good crops and is equally suited for ordinary arable and for fruit[1] or potato cultivation.

The next three soils may be taken as illustrations of the best loams in the three counties. Silt forms the largest fraction and therefore the soils possess sufficient, but not too great, a power of retaining water. The fine silt is always lower than the clay; the latter varies between 12 and 16 per cent., a satisfactory amount where the rainfall is not too high. As there is a considerable amount of fine sand and no excess of fine silt and clay, the absence of coarse sand is no disadvantage.

The Tolworth soil is productive arable land but almost too heavy for profitable cultivation; only by dressings of lime and dung can it be kept workable. But for its coarse sand it would have gone down to grass.

The Shaddoxhurst soil is bad. It contains much clay and still more fine silt, and its texture is not improved as much as might be expected by liming. There is practically no coarse sand and not much fine sand to keep it open, it has always and deservedly been in bad repute. It is best as pasture land, and, after drainage and treatment with basic slag, it may be made useful but never very good.

[1] Mr. T. Wallace of Long Ashton informs me that in the West Country also some of the good fruit soils (*e.g.* the Keuper and Mitford beds) contain about 50 per cent. of fine sand. Where the soil contains 50 per cent. coarse sand it is less suitable.

The Ewhurst soils are both in pasture, being too heavy for arable cultivation on account of their high clay and low coarse sand content. The first has the better constitution; silt is the predominant feature, the clay is not too high, nor is the fine silt. It has all the characteristics of a good, heavy, soil, and is indeed known to be an excellent bullock pasture. The second is not so good; it contains too much clay and fine silt, and too little silt and coarse sand. It has no great agricultural value.

Factors Modifying the Interpretation of a Mechanical Analysis.

The Amount of Organic Matter.—Organic matter at the proper stage of decomposition has the effect of binding a loose soil and lightening a heavy one; thus it reduces the difference between a light sand and a heavy clay, bringing them both closer to the loams. When 10 to 15 per cent. of organic matter is present it so impresses its properties on the soil that the mechanical analysis loses much of its significance, and all the analyst can do is to point out what the soil would become if by persistence in certain methods of management the organic matter were reduced below a certain point.

It is, however, essential that the organic matter should be properly decomposed. Barren sandy wastes not infrequently contain 5 to 10 or even 15 per cent. of organic matter, but much of it is simply dried bracken or other vegetation that has not broken down and has no value, but rather the reverse, in improving the physical conditions. If the drainage is bad a good deal of peat may form; further, the water fills up the soil, making its condition bad whatever its composition may be.

The Amount of Calcium Carbonate.—Calcium carbonate may greatly modify the clay properties and give a considerable degree of friability to a soil which otherwise would be very intractable. When the percentage rises much above 5, the soil becomes very chalky and the mechanical analysis loses its meaning, just as when much organic matter is present.

Rainfall.—Under high rainfall the coarse fractions of the soil lose much of their disadvantage. The finer fractions lose much of their value, their water-holding capacity becomes unnecessary and the disadvantage of their "stickiness" is intensified; fortunately large percentages of clay are found only in dry and not in wet regions.[1] For example, the Stedham soil (Table XCVI.) is rather lighter than the Swanley soil, and yet in virtue of its extra rainfall is more useful for farming purposes;[2] indeed, the Swanley soil is essentially a market-garden soil, requiring large dressings of dung for successful cultivation. The North Chapel soil is physically as good as the East Farleigh soil but agriculturally much inferior; owing to the higher rainfall it becomes somewhat too sticky to cultivate profitably and so is in rather poor grass; the East Farleigh soil, on the other hand, is from a highly fertile hop garden.

TABLE XCVI.—WATER-SUPPLY AND INTERPRETATION OF MECHANICAL ANALYSIS.

	Swanley.	Stedham.	North Chapel.	East Farleigh.	Tolworth.	Nutfield.	Dunbar.	
Fine gravel .	1·2	1·4	0·9	2·3	0·6	2·9	3·0	1·0
Coarse sand .	10·2	9·3	11·4	9·5	37·8	46·6	33·8	23·7
Fine sand . .	58·6	68·5	43·2	30·6	33·1	22·9	28·0	38·2
Silt . . .	13·3	3·6	13·0	19·7	7·7	3·5	5·5	6·8
Fine silt . .	5·1	5·6	10·2	11·1	4·7	8·8	10·8	11·8
Clay . . .	5·5	5·5	10·9	13·3	7·6	6·9	6·6	9·5
Loss on ignition .	2·9	3·4	5·1	5·6	3·6	3·6	6·9	6·2
Calcium carbonate	·02	·03	·80	1·0	·27	·21	·15	·31
Rainfall in inches (approximate) .	24	33	30	24	28	27·5	25	25

Coolness of Climate.—Soils containing so much coarse sand or fine sand that they would scorch or burn in a dry warm district may prove very suitable for cultivation in a cooler

[1] See p. 134.

[2] An example is given by G. W. Robinson, *Journ. Agric. Sci.*, 1917, 8, 370.

district of lower evaporation. Potatoes grow best on light soils, cool and moist. The Nutfield soil (Table XCVI.) is on a slope facing northwards not far above a stream, and therefore does not quickly dry out, hence it is good for main crop potatoes. The Tolworth soil, on the other hand, although similar in composition, is so placed that it quickly dries and is of much less value. Both resemble the famous potato soils of Dunbar.

Effect of Underground Water.—When the underground water is near the surface, but sufficiently far below to allow of proper root development, the clay and fine silt are less necessary. The Weybridge soil (Table XCVII.), at about 3 feet below its surface, has a current of underground water and therefore grows excellent wheat crops. The Bagshot sands, although similar in physical type, have in general no such water-supplies and are sterile because they lack the clay which, in their circumstances, could alone confer an adequate power of holding water from one shower to the next.

TABLE XCVII.—UNDERGROUND WATER AND MECHANICAL ANALYSIS.

	Weybridge.	Bagshot Beds.	Shalford.	Lydd.
Fine gravel . .	1·3	·1 to ·6	2·5	0·1
Coarse sand . .	38·4	20 „ 30	52·6	0·9
Fine sand . .	39·9	45 „ 65	26·2	66·7
Silt . . .	5·6	5 „ 10	4·8	7·2
Fine silt . .	5·1	5 „ 10	3·5	11·4
Clay . . .	3·8	3 „ 7	3·8	3·9

The Shalford soil is a light sand with little power of retaining water, consequently the grass land, except near the brooks, is parched and scorched. The Lydd soil produces one of the best pastures in Romney Marsh. It has, however, a constant supply of water, 3 or 4 feet below the surface, while at Shalford the water level is much lower down.

This underground flow is one of the factors concerned in the proverbial fertility of valleys. Soils lying towards the bottom of a long slope receive not only the rainfall but also

the water steadily drifting downwards to the stream or marsh at the bottom, and this advantage is further enhanced by the continuous transport of soil, soluble matter, bases, etc.

Effect of the Subsoil.—In general the subsoil is rather heavier in type than the surface soil, especially in the case of clays; examples are given in Table XCVIII. The exceptions to this rule may arise through periodical flooding with water containing much clay in suspension, or through the occurrence of a bed of sand just below the surface.

TABLE XCVIII.—NATURE OF THE SUBSOIL.

	Loddington.		Harting.		Dicker.		Shopwyke.		Wye.	
	Surface.	Subsoil.	Surface.	Subsoil.	Surface.	Subsoil.	Surface.	Subsoil.	Surface.	Subsoil.
Fine gravel .	3·5	2·6	0·6	0·2	1·0	0·6	0·6	0·1	1·0	0·2
Coarse sand .	10·2	9·8	3·3	3·2	2·0	1·1	0·8	0·4	3·0	1·9
Fine sand .	33·5	30·2	31·6	33·9	26·6	23·2	25·0	21·9	27·2	25·3
Silt . .	14·6	17·5	17·3	21·3	23·0	15·1	27·3	38·0	40·0	41·4
Fine silt . .	14·9	15·5	14·5	13·4	17·8	21·9	16·4	15·2	8·9	9·6
Clay . .	12·2	15·3	12·3	16·0	17·9	25·7	11·1	15·7	11·2	14·5

The bad effect of a layer of impermeable material near the surface is shown by the Loddington soil (Table XCVIII.), typical of a fertile area near Maidstone (Cox Heath) much of which was waste land. Its sterility was due to no fault in the soil, but to a thin layer of rock lying near the surface; when this was removed good crops could be grown. The Dicker soil is not inherently bad, but it lies on a deep bed of stiff clay which keeps it wet in winter and parched in summer.

The Shopwyke soil suffers from over-drainage, being spoiled by lying on a deep bed of gravel only 9 inches or a foot below the surface—the subsoil sample could be taken only in one or two places. Consequently it dries out badly in summer and does not repay much expenditure on manures.

The Wye soil illustrates more fertile conditions It becomes rather heavier in its lower depths, with the result that the movement of water is somewhat impeded but not stopped.

Thus the subsoil furnishes a reserve of water for the surface, yet it does not hold too much even in wet weather.

Chemical Analysis.

For rapid comparisons, determinations of loss on ignition —mainly organic matter—and of nitrogen are useful; note should be taken whether the organic matter is well decomposed or whether it shows much definite structure. In the South-Eastern counties the nitrogen is generally about 3 per cent. of the loss on ignition except on waste land when it is less. High nitrogen content is not necessarily a sign of high fertility; some of the best loams contain but little, and some of the waste lands contain a good deal (Table XCIX.). Soils containing

TABLE XCIX.—NITROGEN AND LOSS ON IGNITION.

	Fertile Arable Soils.				Poor Arable Soils.				Barren Wastes.		
Loss on ignition	4·65	6·58	3·70	4·65	4·13	6·23	3·60	5·14	5·94	7·00	5·81
Nitrogen . .	·120	·220	·133	·141	·128	·143	·182	·152	·130	·195	·167
Loss on ignition in subsoil .	3·00	4·94	2·81	3·29	3·74	5·50	2·58	4·14	—	—	2·70
Nitrogen in subsoil . .	·078	·139	·081	·097	·112	·104	·061	·096	—	—	·058

much calcium carbonate are usually richer in nitrogen than other mineral soils both in the upper and the lower layers.

The presence of calcium carbonate indicates that the soil is not acid. Heavy arable soils containing 0·25 or even 0·5 per cent. may, however, respond to further dressings because of the importance of ensuring flocculation; grassland is less responsive and lighter soils may need but little.

The soil reaction is discussed on page 378.

Various relationships usually exist between the amount of clay and the proportion of certain bases extracted by strong HCl, also between the ratios of some of these bases and the soil acidity. In the much weathered soils of the South of England the amount of alumina is approximately one-third that of the clay fraction (except where much fine silt is present

when it is less); iron oxide, however, shows no such relationship. The amount of potash soluble in strong HCl is about one-tenth of the alumina or one-thirtieth of the clay. The relationship between base ratios and acidity is discussed on page 219.[1]

Little information can be derived from values for phosphoric acid in the soil. Unlike the potassium it is not associated with any one fraction and the values show no relation to fertility. The figures for "available" phosphoric acid and potash are of some value in comparing the soils where comparison is legitimate with a standard soil on which field trials have been made. Increases in water supply diminish the response of the crop to potash and an increased lightness of the soil may diminish the response to phosphates.

SOIL SURVEYS.

Soil surveys of the following counties have been published:—

ENGLAND.

BEDFORD.—

Rigg, Th. *The Soils and Crops of the Market-garden District of Biggleswade. Journ Agric. Sci.*, 1916, vii., 385.

CAMBRIDGE.—

Foreman, F. W. *Soils of Cambridgeshire. Journ. Agric. Sci.*, 1907, ii., 161.

DORSET.—

Gilchrist, D. A., and Luxmoore, C. M. *The Soils of Dorset. Reading Coll. Dorset C. Council*, 1907.

KENT, SURREY, AND SUSSEX.—

Hall, A. D., and Russell, E. J. *Agriculture and Soils of Kent, Surrey, and Sussex. Bd. Agric. and Fisheries*, 1911.

NOTTINGHAM.—

Goodwin, Wm. *The Soils of Nottinghamshire. Mid. Agric. and Dairy Coll. Kingston, Derby.*

[1] See also K. K. Gedroiz, *Zhur. Opet. Agron.*, 1925.

NORFOLK.—

Newman, L. F. *Soils and Agriculture of Norfolk. Trans. Norfolk and Norwich Nat. Soc.*, 1912, ix., 349-393.

SHROPSHIRE.—

Robinson, G. W. *A Survey of the Soils and Agriculture of Shropshire. County of Salop Higher Education Com.*, n.d.

WALES.

Robinson, G. W. *Studies on the Paleozoic Soils of North Wales. Journ. Agric. Sci.*, 1917, viii., 338.

Robinson, G. W., and Hill, C. F. *Further Studies on the Soils of North Wales. Journ. Agric. Sci.*, 1919, ix., 259.

Griffith, J. J. *Influence of Mines upon Land and Livestock in Cardiganshire. Journ. Agric. Sci.*, 1919, ix., 366.

SCOTLAND.

Hendrick, James, and Ogg, W. G. *Studies of a Scottish Drift Soil.* I. *The Composition of the Soil and of the Mineral Particles which compose it. Journ. Agric. Sci.*, 1916, vii., 458.

IRELAND.

Kilroe, J. R. *Soil Geology of Ireland. Dept. Agric. and Tech. Instruction for Ireland*, 1907.

See also publications of *Dept. of Agric. and Tech. Inst. for Ireland.*

In France the surveys have been made on a petrogeological basis as initiated by M. Risler in 1856. The work is particularly associated with the Station Agronomique de l'Aisne et Laon. Many of the maps are beautifully drawn: for an example see *Journ. Min. Agric.*, 1920, **27**, 57. In the United States an extensive soil survey is organised by the Dept. of Agriculture and in many of the individual States by the Colleges or Agricultural Experiment Stations. For the soil map of Germany see *Int. Mitt. Bodenkunde*, 1917, **7**, 1.

APPENDIX I.

THE METHODS OF SOIL ANALYSIS

How to take the Sample of Soil.—Owing to the variation in composition of the soil at different depths it is particularly necessary that the sample should always be taken to the same depth and with a tool making a clean vertical cut. The spade is unsuitable. The American sampling tool is light and can be obtained of apparatus dealers. The British tool can be made by a blacksmith : it consists of a steel tube 2 ins. in diameter and 12 ins. long, with a $\frac{3}{4}$-in. slit cut lengthwise and all its edges sharpened and fixed on to a vertical steel rod, bent at the end to a ring 2 ins. in diameter, through which passes a stout wooden handle (Fig. 46). A mark is made 9 ins. from the bottom so that the boring process can be stopped as soon as this depth is reached. On withdrawing the tool the core of soil is removed by a pointed iron rod. Five or six samples should be taken along lines crossing the field so as to get as representative a sample as possible; the whole bulk must then be sent to the laboratory. Samples should not be taken from freshly ploughed or recently manured land.

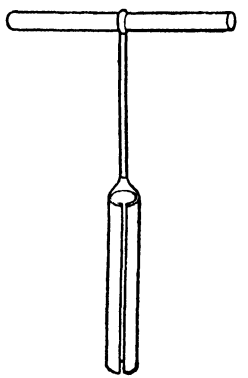


FIG. 46.—Tool for taking soil samples.

In very stony soils it is easier to use a 2-in auger, but this does not, in our experience, yield as satisfactory a sample as the tool shown here.

A spud is useful for rapid preliminary inspection of waste land to ensure that the sample is normal; much disturbance of these soils is sometimes caused by rabbits.

For precautions to be taken in drawing the sample see Russell, *Journ. Bd. of Agric.*, 1916, **23**, 342, and for a discussion of the

magnitude of the experimental error see Robinson and Lloyd, *Journ. Agric. Sci.*, 1915, **7**, 144-153, and Leather, *Trans. Chem. Soc.*, 1902, **81**, 883-886.

For American methods of sampling see *Bot. Gazette*, Feb., 1919, p. 173. C. B. Lipman and D. E. Martin [1] show that no further or unusual precautions need be taken when the sample is required for bacteriological purposes.

The Analysis.—On arrival at the laboratory the soil is spread out to dry, and is then pounded with a wooden pestle and passed through a 3 mm. sieve. The stones that do not pass through, and the fine earth that does, are separately weighed, and the proportion of stones to 100 of fine earth is calculated. Subsequent analytical operations are made on the fine earth.

Moisture.—Four or five grms. of the soil are dried at 100° C. till there is no further change in weight. See also Keen and others, *Journ. Agric. Sci.*, 1925, **15**, 68, 272.

Organic Matter.—No accurate method of estimation has yet been devised. It is usual to ignite at low redness the sample dried as above. The loss includes organic matter, water not given off at 100° C., and carbon dioxide from the carbonates; allowance may be made for the latter, but not for the combined water. For purposes of preliminary examinations the loss on ignition is often taken as organic matter. For more accurate work the carbon is determined either by the ordinary combustion or by some wet combustion method. A convenient colorimetric method for estimating "humus" in mineral soils is described by T. Eden (*Journ. Agric. Sci.*, 1924, **14**, 469).

Total Nitrogen.—Kjeldahl's method is almost invariably adopted. About 25 to 30 grms. of soil are ground up finely in an iron mortar; 10 to 15 grms. are heated in a Kjeldahl flask with 20 to 25 c.c. of strong sulphuric acid for three-quarters of an hour; 5 grms. of potassium sulphate are added, and then a crystal of copper sulphate. The heating is continued till all the black colour has gone. Then cool and dilute the mixture, transfer the fluid part to a distillation flask, but leave as much as possible of the sand behind, wash well to remove all the adhering liquid. Add saturated soda solution till the liquid is strongly alkaline, distil, and collect the ammonia in standard acid.

[1] *Soil Sci.*, 1918, **6**, 131-136.

Nitrates must be determined in a sample taken direct from the field and extracted at once or dried without any delay at 55° C. 200 to 500 grms. of the dried soil are pressed firmly on to a Buchner funnel fitted to a filter flask, and hot distilled water is poured on. The first 300 c.c. of water passing contains practically all the nitrates, but it is safer to wash more fully. The solution is made up to 500 c.c. and two portions of 200 c.c. taken for duplicate determinations. The solution is poured into a flask covered by an inverted porcelain crucible-lid, 10 c.c. of 8 per cent. caustic soda and 10 c.c. of 3 per cent. potassium permanganate are added, and the whole is then boiled down to some 75 c.c. and kept just boiling for about six hours. If the permanganate is completely decolorised a little more is added until there is no appreciable change in half an hour. The solution is diluted to 300 c.c. and distilled down to 50 c.c. with the addition of 3 grms. powdered Devarda alloy, 20 c.c. of 40 per cent. caustic soda and 5 c.c. of alcohol. The condenser should be of pure tin with a short length of hard glass tubing at its lower end to dip into the N/50 sulphuric acid in the receiver. Shortly before the end of the distillation the cooling water is emptied out so that steam passes through. A large volume of hydrogen and spray is given off at the beginning of the operation, so special attention must be given to trapping. The titration is carried out as for *Ammonia.*

In the United States the more rapid phenol sulphonic acid method is used. (See C. B. Lipman and L. T. Sharp, *Univ. Cal. Pub. Agric. Sci.*, 1912, **1**, 23-37.)

For statistical discussion of errors see D. D. Waynick, *Univ. Cal. Pub. Agric. Sci.*, 1918, **3**, 243-270. For a critical test see F. Hansen, *Tidsskrift for Planteœvl*, 1926, **32**, 69-120.

Ammonia may be estimated by distilling with magnesia and water under reduced pressure (Russell, *Journ. Agric. Sci.*, 1910, **3**, 233), but more accurate results are given by the aeration method of Matthews, which, however, requires special apparatus (*Journ. Agric. Sci.*, 1920, **10**, 72).

Results agreeing closely with those given by the latter method are obtained by leaching the soil with sodium chloride solution, followed by distillation of the extract with magnesia (Maclean and Robinson, *Journ. Agric. Sci.*, 1924, **14**, 548).

For older methods see Potter and Snyder (*Iowa Research Bull.*, No. 17, 1914).

Carbonates are determined by treating a weighed quantity of the soil with dilute sulphuric acid and estimating the carbon dioxide evolved. Collins' calcimeter is a satisfactory instrument.[1]

Lime Requirement.—Hutchinson and McLennan's method for the determination of the lime requirement of the soil is as follows: 10 to 20 grms. of the soil are placed in a bottle of 500 to 1000 c.c. capacity, together with 200 to 300 c.c. of approximately N/50 solution of calcium bicarbonate, and the air in the bottle is displaced by a current of carbon dioxide in order to avoid possible precipitation of calcium carbonate during the period of the determination. The bottle is then placed in a shaking machine for three hours, after which time the solution is filtered and an aliquot portion of the filtrate is titrated against M/10 acid, using methyl orange as indicator. The difference in strength of this filtrate and that of the initial solution represents the amount of calcium carbonate absorbed, each cubic centimetre of N/10 acid being equal to 5 mgs. calcium carbonate.

For a discussion of the method, see E. M. Crowther and W. S. Martin, *Journ. Agric. Sci.*, 1925, **15**, 237. For an account of the biological and other methods, see H. R. Christensen (67*a*).

Hydrogen Ion Concentration, pH value, or Soil Reaction.—The indicator method of determining *p*H (E. A. Fisher, *Journ. Agric. Sci.*, 1921, **11**, 10, and 45) is not universally applicable, owing to the disturbing effect of the clay fraction. The electrometric method is more reliable and accurate, but requires complex apparatus (E. M. Crowther, *Journ. Agric. Sci.*, 1925, **15**, 201). For the quinhydrone electrode, see Bijlman (*Journ. Agric. Sci.*, 1924, **14**, 232). Comber's test for acid soils is simple (*Journ. Agric. Sci.*, 1920, **10**, 420): 2 or 3 grms. of air-dried soil are shaken vigorously in a test-tube with 5 c.c. of a saturated alcoholic solution of potassium thiocyanate. A pink or red colour develops at once, or on standing, if the soil is acid. The liquid may be filtered if the colour is faint. The degree of acidity of similar soils is roughly indicated by the intensity of the red colour. A simplified form of this test, involving the use of aqueous potassium salicylate instead of alcholic potassium thiocyanate, can be applied directly to the moist soil (Comber, *Journ. Agric. Sci.*, 1922, **12**, 370). Other useful tests

[1] *Journ. Chem. Soc. Ind.*, 1906, **25**, 518. The apparatus is made by Messrs. Brady & Martin, Newcastle-on-Tyne.

for detecting soil acidity and for roughly gauging the "lime requirement," are those of Truog (*Wisconsin Agric. Exp. Sta. Bull.*, 321, 1921) and of Spurway ("Soiltex" method, *Michigan Quart. Bull.*, 1924, 16, 93, and U.S. Pat. 1,520,891), not suitable for heavy clay or peaty soils. British Drug Houses Ltd. make a "Soil Testing Outfit," in which the indicator gives a variety of colours corresponding with various *p*H values.

Mineral Substances.—Complete analysis of a soil after the silicates have been decomposed and the silica volatilised by treatment with hydrofluoric acid is only rarely attempted. The British method, adopted by the Agricultural Education Association, is thus described by Hall: "20 grms. of the powdered soil are placed in a flask of Jena glass, covered with about 70 c.c. of strong hydrochloric acid, and boiled for a short time over a naked flame to bring it to constant strength. The acid will now contain about 20·2 per cent. of pure hydrogen chloride. The flask is loosely stoppered, placed on the water bath, and the contents allowed to digest for about forty-eight hours. The solution is then cooled, diluted, and filtered. The washed residue is dried and weighed as the material insoluble in acids. The solution is made up to 250 c.c., and aliquot portions are taken for the various determinations. The analytical operations are carried out in the usual manner, but special care must be taken to free the solution from silica or organic matter" (*The Soil*). As a rule only potash and phosphoric acid are determined, but where necessary other bases are estimated in the usual way.

Hissink [1] has discussed the value of strong HCl as a solvent in soil analysis. American methods are described by F. E. Bear and R. M. Salter,[2] and Continental methods by von Sigmond (266).

Potassium.—50 to 100 c.c. of the solution are evaporated to dryness, after addition of 0·5 grm. of pure $CaCO_3$ if the original soil did not effervesce on addition of HCl.

Add 10 c.c. of 5 per cent. baryta solution, evaporate to dryness, *gently* ignite over a Bunsen burner until completely charred, and then extract with water until all the potassium chloride has dissolved (Neubauer's method [3] (212)). Add 2·5 c.c. perchloric acid

[1] *Internat. Mitt. Bodenkunde*, 1915, 5, 1-24. For determination of iron see Morison and Doyne, *Journ. Agric. Sci.*, 1914, 6, 97.

[2] *West Virginia Bull.*, 159, 1916.

[3] The older method due to Tatlock is still sometimes used. It is described by Dyer (92).

(sp. gr. 1·12), concentrate until dense fumes are given off, dilute, add a few drops more of perchloric acid, concentrate again, allow to cool, add 20 c.c. 95 per cent. alcohol, and stir. Decant off the clear alcohol, add 40 c.c. alcohol containing 0·2 per cent. perchloric acid, transfer to a weighed Gooch crucible, suck away the acid alcohol, wash with 50 to 100 c.c. of 95 per cent. alcohol saturated with $KClO_4$ till the runnings are no longer acid, dry at 100° and weigh as $KClO_4$ (see H. J. Page, *Journ. Agric. Sci.*, 1924, **14**, 133).

Phosphoric Acid.—The charred residue from which the potassium chloride has been removed is digested for half an hour on a sand bath with 50 c.c. of 10 per cent. H_2SO_4 and filtered; the filtrate is treated with 25 c.c. conc. NH_4NO_3 solution and warmed to 55° C.; 25 c.c. ammonium molybdate, previously warmed to 55° C., is added and the whole allowed to stand for two hours. Two methods are then available.

(*a*) Filter, wash with 2 per cent. $NaNO_3$ till the washings are neutral, transfer the precipitate and filter paper to the beaker used for the precipitation, and add a known volume of standard alkali so that the precipitate completely dissolves. Measure the excess by titration, using phenolphthalein as indicator. 1 c.c. of $\frac{N}{10}$ alkali = ·0003004 grm. P_2O_5.[1]

(*b*) Filter on a Gooch crucible, weigh as $(NH_4)_3PO_4 . 12MoO_3$ (factor for P_2O_5=0·03753) after drying at 160° to 180° C., *or*, more conveniently, ignite gently (inside a nickel crucible lined at the bottom with asbestos paper), to the bluish-black phosphomolybdic anhydride, $24MoO_3$, P_2O_5 (containing 3·946 per cent. P_2O_5), and weigh.

Available Potash and Phosphoric Acid.—Dyer's directions are as follows: 200 grms. dry soil are placed in a Winchester quart bottle with 2 litres of distilled water, in which are dissolved 20 grms. of pure citric acid. The soil is allowed to remain in contact with the

[1] This volumetric method was originally described in *Bull.* 46 (revised), *United States Division of Chemistry* (Washington, 1898). A careful examination has been made by Prescott and the conditions laid down under which it gives satisfactory results (*Journ. Agric. Sci.*, 1914, 6, 111-120). Prescott's modification is given here. The method is applicable for the "available" P_2O_5, but in this case the residue from the citric acid extraction has first to be heated two hours at 120° to 160° to render the silica insoluble. The older method is described by Dyer (92).

solution at ordinary temperatures for seven days, and is shaken a number of times each day. The solution is then filtered, and 500 c.c. taken for each determination; this is evaporated to dryness, and gently incinerated at a low temperature. The residue is dissolved in hydrochloric acid, evaporated to dryness, redissolved, and filtered; in the filtrate the potash is determined. For the phosphoric acid determination the last solution is made, as before, with nitric acid.

Exchangeable Bases.—Hissink's method (*Internat. Mitt. Bodenkunde*, 1922, **12**, 81): to 25 grms. of air-dried soil add 100 c.c. of a normal salt solution, heat on a sandbath to about 80° C. for an hour, and occasionally stir. Cool and allow to stand overnight, decant the supernatant liquid through a filter paper; then transfer the soil to the filter by a jet of the salt solution. Wash with the same solution till the required volume is obtained. Leach to 500 c.c. with N. ammonium chloride for all determinations except that of exchangeable calcium in soils containing calcium carbonate; for these ammonium chloride is not suitable owing to its solvent action on calcium carbonate; normal sodium chloride is used instead and leaching is continued until two successive litres of extract are obtained. The difference between the calcium content of the first and second litres represents the amount of exchangeable calcium.

After suitable concentration of the extract, calcium, magnesium, potassium and sodium (and if necessary iron, aluminium, and silica) are determined by the usual methods. The volumetric method for calcium (titration with permanganate after solution of the precipitated calcium oxalate in sulphuric acid) is accurate and obviates the necessity of removing the hydroxides of iron and aluminium, and silica, from the calcium oxalate precipitate. Double precipitation is usually necessary if magnesium is to be determined, or some is lost in the calcium oxalate precipitate. If the soil is acid, some silica may remain in solution after removal of calcium, and must be removed before precipitation of the magnesium. Sodium is determined by weighing the mixed chlorides or sulphates of magnesium, potassium, and sodium, and subtracting the values found separately for the first two. It is usually most convenient and rapid to determine calcium, magnesium and potassium on separate extracts. For further discussion of chemical

analysis of soils, see K. K. Gedroiz, *Chemische Bodenanalyse*, Borntraeger, Berlin, 1926.

Mechanical Analysis.—The object is to obtain information about the size of the ultimate particles of which the soil is composed; the compound particles are therefore broken down by treatment with hydrochloric acid, and afterwards with ammonia. Direct measurement of the ultimate particles is found to be impracticable; indirect methods have to be adopted, depending on the time taken to fall through a column of water of given height. When a body falls through a vacuum the time taken is independent of its size or weight, but if air or any other fluid is present the case becomes more complicated and the proper mathematical relationship for spherical particles has been found by Stokes to be $v = \frac{2ga^2(\sigma - \rho)}{9\eta}$, where v = velocity of the falling particle, σ its density, a its radius, and ρ the density and η the coefficient of viscosity of the medium (*Trans. Camb. Phil. Soc.*, 1851, vol. ix., p. 8).

The numerical values at 16° C. are: $g = 981$, $\sigma = 2{\cdot}7$, $\rho = 1$, $\eta = {\cdot}011$, and the equation therefore reduces to $v = a^2 \times 33690$, or $a = \frac{\sqrt{v}}{184}$ cm.

The calculated and observed values agree fairly well for the sand and silt fractions, differences being due to the fact that the particles are not true spheres, and to the existence of convection currents produced by changes of temperature. The effect of variations in temperature is discussed by Robinson in *Journ. Agric. Sci.*, 1914, **7**, 142.

The equation ceases to hold, however, for the finest clay fraction where the colloidal coating and the Brownian motion both cause complications.

The method adopted by the Agricultural Education Association (*Journ. Agric. Sci.*, 1926, **16**, 123, and *Agricultural Progress*, 1926, vol. 3) is as follows:—

On arrival at the laboratory the soil is spread out to dry at room temperature, and is then passed through a 1-mm. round-hole sieve, any lumps being previously gently disintegrated in a mortar with a wooden pestle. The residue on the sieve, consisting of stones and fine gravel, before being discarded, is weighed and expressed as a percentage of the total weight of the air-dry soil. The

material passing the sieve is the bulk sample from which separate sub-samples are carefully and uniformly taken for the following analyses :—

I. Grading into fractions.
II. Determination of carbonates (p. 456).
III. Moisture content, and loss on ignition (p. 454).

I. *Grading into Fractions.*

This section consists of two distinct operations, (*a*) dispersion, and (*b*) the actual mechanical analysis.

(*a*) *Method of Dispersion.*—Weigh out 20 grms. of air-dry soil into a tall 600 c.c. beaker. Add about 60 c.c. of 6 per cent. (20 vol.) hydrogen peroxide (free from barium, chloride, phosphate, and sulphate) and place in a boiling water bath, on a hot plate, or over a rose burner. A vigorous reaction with organic matter soon takes place. The contents are stirred from time to time, and watched to avoid frothing over. After the reaction has subsided a further addition of peroxide should be made and the beaker again heated. There is usually no great degree of frothing with the second addition of peroxide, unless the soil contains much organic matter, when further additions of peroxide must be made. The humified organic matter is rendered soluble or destroyed by the peroxide treatment, and the soil loses its dark humic colour. After cooling, enough water and HCl is added to give 150 to 200 c.c. of N/5 HCl, allowance being made for the acid necessary to decompose carbonates. The contents are allowed to stand, with frequent stirring, for about an hour (or left overnight) and then filtered through an 18-cm. hard filter paper. If Whatman No. 1 be used, the first runnings may be turbid, but by pouring them back on to the filter, a clear filtrate may be obtained. The soil is then thrice washed on the filter with 100 c.c. of distilled water each time. No attempt should be made to wash down the soil to the bottom of the filter, as not only does this considerably decrease the rate of filtering, but fine material may pass through. After washing is complete, the filter paper is spread out on a large watch glass, and the soil washed with a jet of hot water on to a 100-mesh sieve held over the mouth of a beaker. When no more can be removed, the paper is rolled into a loose ball, thoroughly wetted, and squeezed like a sponge.

This process is repeated as long as any turbid liquid can be obtained. The material that cannot be removed in this way does not exceed 0·2 to 0·4 per cent. of the whole sample.

The filtrate collected after the peroxide-HCl treatment contains, in addition to calcium from calcium carbonate, a small quantity of dissolved material, amounting usually to about 2 to 3 per cent. of the total weight of soil, and consisting principally of mixed sesquioxides and a small amount of silica. For routine purposes it is sufficient to determine this loss of sesquioxides and silica by weighing, after gentle ignition, the percipitate obtained by the addition of ammonium hydroxide and ammonium chloride to the filtrate. It should be reported as " loss in solution."

(*b*) *Mechanical Analysis of Dispersed Sample by Pipette Method.* —The material on the 100-mesh sieve is rubbed with a rubber pestle under a jet of water, until no more will pass through. The residue on the sieve is the " coarse sand " fraction which is dried, ignited and weighed.

The material passing the sieve is transferred to a litre shaking bottle, and is made up to about 500 c.c. with distilled water, to which is then added 50 c.c. of dilute (10 per cent.) ammonia, made by diluting 0·88 ammonia with twice its volume of distilled water. The contents are shaken in an end-over-end shaker at a speed of 30 to 40 revolutions per minute. For sandy soils overnight shaking is sufficient; very heavy soils may require forty hours. The shaking concluded, the suspension is made up to 1 litre in a measuring cylinder. The contents are thoroughly shaken by repeated inversion of the cylinder for about one minute, making certain that any sediment which has settled to the bottom is thoroughly mixed up with the liquid. The cylinder of suspension (equivalent to a 2 per cent. suspension of the original soil) is then allowed to stand for 5 minutes.

Meanwhile a 20 c.c. pipette is fixed in a cork so that when the cork rests on the top of the cylinder the point of the pipette will be 30 cm. below the surface of the suspension. At the end of the 5-minute period the pipette, with the top closed by the finger, is carefully lowered into position (this operation being begun about twenty seconds before the time is up), and 20 c.c. of the suspension is withdrawn, care being taken to avoid

too rapid ingress of the liquid with consequent eddying. In lowering the pipette into the column of suspension care must be taken to avoid any considerable inflow of the more dilute suspension at the top of the column. Even when the top of the pipette is closed by the finger a certain amount of suspension from above the point of sampling may be forced in by hydrostatic pressure. With a pipette having a reasonably fine aperture, this ingress should be inconsiderable if the pipette is lowered fairly rapidly through the upper part of the column. The error from this cause will also be minimised by using a pipette with a slender stem. With the pipette and cylinders ordinarily in use, sampling at 30 cm. is carried out without the need for suction since the graduation mark is just below the surface of the suspension.

The contents are rapidly adjusted to the mark and delivered into an ignited weighed flat porcelain or vitrosil dish. We have used and recommend the ordinary type of dish, 72 mm. diameter, commonly employed for the determination of dry matter in milk. The dish is then taken to dryness on a water bath, or more conveniently, on an electric hot plate. It is then ignited at red heat in a muffle for thirty minutes and, after cooling in a desiccator, weighed. The weight of material multiplied by five gives the concentration of the suspension at the point sampled. Let this be X. Then, the original concentration being 2 per cent., the percentage of material having settling velocity less than $30/300 = 0{\cdot}1$ cm./sec. is given by $100\ X/2$. Actually, the calculation given here in full reduces in practice to dividing the number of milligrams of the ignited material by four. This represents as a percentage the sum of the clay, fine silt and silt.

The contents of the cylinder are again shaken up for one minute, and sampled in the same way, this time at a depth of 12 cm., after a settling period of twenty minutes. From this sampling the precentage of fine silt plus clay is obtained. The cylinder is again shaken up and allowed to settle for twenty-four hours and sampled at a depth of 8·6 cm., from which the percentage of clay is obtained. We have thus obtained the percentage of

silt + fine silt + clay,
fine silt + clay,
clay,

and from these the percentages of silt and fine silt are obtained by subtraction.

The remaining fraction, the fine sand, can be obtained by difference, but it is preferable to determine it directly as a check on the other determinations. After the clay sampling, the bulk of the supernatant liquid is poured away and the sediment in the cylinder is transferred to a 400 c.c. beaker and made up with water to a height of 10 cm. above the base. It is well stirred up and allowed to settle for 100 seconds, when the turbid suspension is poured away. The beaker is again filled to the mark with water and the process repeated until the liquid is no longer turbid at the end of the 100-second period. The residue is the fine sand, which is collected, ignited and weighed as above. As an appreciable time is occupied in each pouring, matters should be so arranged that the 100-second period elapses at about the middle of the pouring.

Method of Stating Results.—The results are usually expressed as percentages of material of given particle size (p. 120 and the Tables in Chap. IX.). Odén adopts mass distribution curves as more effective for investigation. G. W. Robinson (*Journ. Agric. Sci.*, 1924, **14**, 626) suggests plotting weights of the fractions against logarithms of settling velocities in cms. per second; these curves are purely experimental and do not involve Stokes' law.

Methods of Sand and Soil Cultures.—See Hellriegel (130*b*); A. G. McCall, *Journ. Amer. Soc. Agron.*, 1915, **7**, 249-282; *Soil Sci.*, 1916, **2**, 207-253; *Journ. Amer. Soc. Agron.*, 1918, **10**, 127-134; D. R. Hoagland, *Journ. Agric. Res.*, 1919, **18**, 177.

Comparison of Sand and Water Cultures.—D. R. Hoagland, *Journ. Agric. Res.*, 1919, **18**, 11.

Bacteriological Examination.—The method used at Rothamsted for counting the number of bacteria in soils is as follows:—

The freshly sampled soil is passed through a 3-mm. sieve and thoroughly mixed (aseptic technique is needed only if qualitative examination for species is to be made). 10 grms. are transferred to 250 c.c. of sterile saline (5 grms. NaCl, 1 grm. $MgSO_4 . 7H_2O$, 1 litre H_2O), and the flask shaken for four minutes, the cotton wool plug being replaced by a sterile cork. 1 c.c. of the resulting suspension is transferred by means of a sterile pipette into 99 c.c. of sterile saline and shaken for one minute. 1 c.c. of this suspension

is similarly transferred to a second 99 c.c. of sterile saline and shaken for one minute. (In making these transfers it is best to wash out the pipette once with the liquid to which the suspension has just been added, so as to minimise loss of organisms due to adherence to the pipette walls.) Five sterile petri dishes are taken, and to each is transferred with a sterile pipette 1 c.c. of the final suspension (equals 1/250,000 grms. of soil). Before each transfer the flask should be shaken to ensure an even suspension.

Into each dish is then poured about 10 c.c. of sterile count medium (see below) previously melted and cooled to 42° C., and the dish at once carefully oscillated so as to mix the medium well with the soil suspension and give a uniform mixture before the medium sets. The plates are allowed to stand till the medium is quite firm, then they are incubated in an inverted position at 20° C. for ten days. The number of colonies on each plate is counted (some practice is needed to distinguish bacterial colonies from those of moulds and the acetomycetes) and the mean value for the five plates, divided by four, gives the number of bacteria in the fresh soil in millions per gramme that can develop on the medium. The total number of organisms cannot be determined since no medium allows all the soil bacteria to develop, but comparable values are obtained by the above method.

Agar count medium (Thornton, *Ann. Appl. Biol.*, 1922, **9**, 241). K_2HPO_4 1 grm., $MgSO_4 . 7H_2O$ 0·2 grm., $CaCl_2$ 0·1 grm., NaCl 0·1 grm., KNO_3 0·5 grm., $FeCl_3$ 0·002 grm., asparagine 0·5 grm., mannitol 1 grm., agar 15 grms., water to 1000 c.c. The phosphate, nitrate and asparagine are first added, followed by the other salts, previously dissolved in water, and finally the agar. The water is heated in the steamer until the agar is dissolved, and then filtered in the steamer at 100° C., being passed twice through a ½-in. layer of absorbent cotton wool. The mannitol is added to the filtrate, and the reaction of the medium adjusted to *p*H 7·4 with caustic soda (see Gillespie, *Soil Sci.*, 1920, **9**, 115, for simple method of adjusting *p*H).

It is filled into tubes in 10 c.c. lots and sterilised in the autoclave at 15 lb. pressure for fifteen minutes.

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