UNIVERSAL
LIBRARY

OU_164285

UNIVERSAL
LIBRARY

THIS BOOK IS A PART
OF THE LIBRARY OF =



THE TRVE VNIVERSITY IS A
COLLECTION OF BOOKS. CARLYLE

THEORY AND PRACTICE IN THE USE OF FERTILIZERS

THE WILEY AGRICULTURAL SERIES

EDITED BY

J. G. LIPMAN

Food Preservation.
By W. W. CHENOWETH, Massachusetts State College. 344 pages; 76 figures.

Dairy Farming.
By WILBER J. FRASER, University of Illinois. 333 pages. Ill.

Animal Breeding.
By LAURENCE M. WINTERS, University of Minnesota. Second Edition, Rewritten and Reset. 389 pages. Ill.

Theory and Practice in the Use of Fertilizers.
By FIRMAN E. BEAR, Science Editor, *Country Home Magazine*. Second Edition. 360 pages. Ill.

Cooperation in Agriculture.
By HORACE C. FILLEY, University of Nebraska. Describes cooperative marketing. 468 pages. Ill.

Dairy Bacteriology.
By BERNARD W. HAMMER, Iowa State College. 473 pages. Ill.

Sugar Cane and Its Culture.
By the Late F. S. EARLE. 355 pages. Ill.

Condensed Milk.
By ATSUSHI MIYAWAKI, Hokkaido Imperial University. 380 pages. Ill.

Green Manuring.
Principles and Practice. By ADRIAN J. PIETERS, Bureau of Plant Industry, U. S. Dept. of Agriculture. 356 pages. Ill.

The Commerce of Agriculture.
A Survey of Agricultural Resources. By FREDERICK A. BUECHEL, Bureau of Business Research, University of Texas. 439 pages. Ill.

Potash.
A Review, Estimate, and Forecast. By J. W. TURRENTINE, American Potash Institute. 188 pages. Ill.

Laboratory Experiments in Dairy Chemistry.
By LEROY S. PALMER, University of Minnesota. 84 pages.

Soil Management.
By FIRMAN E. BEAR. Second Edition, Rewritten. 412 pages. Ill.

Principles of Dairying—Testing and Manufactures.
By H. F. JUDKINS, Vice-President, Sealtest System Laboratories, Inc., New York, N. Y. Second Edition, Revised by the late RICHARD W. SMITH, JR. 322 pages. Ill.

The Soil and the Microbe.
An Introduction to the Study of the Microscopic Population of the Soil and Its Rôle in Soil Processes and Plant Growth. By SELMAN A. WAKSMAN and ROBERT L. STARKEY, Rutgers University. 260 pages. Ill.

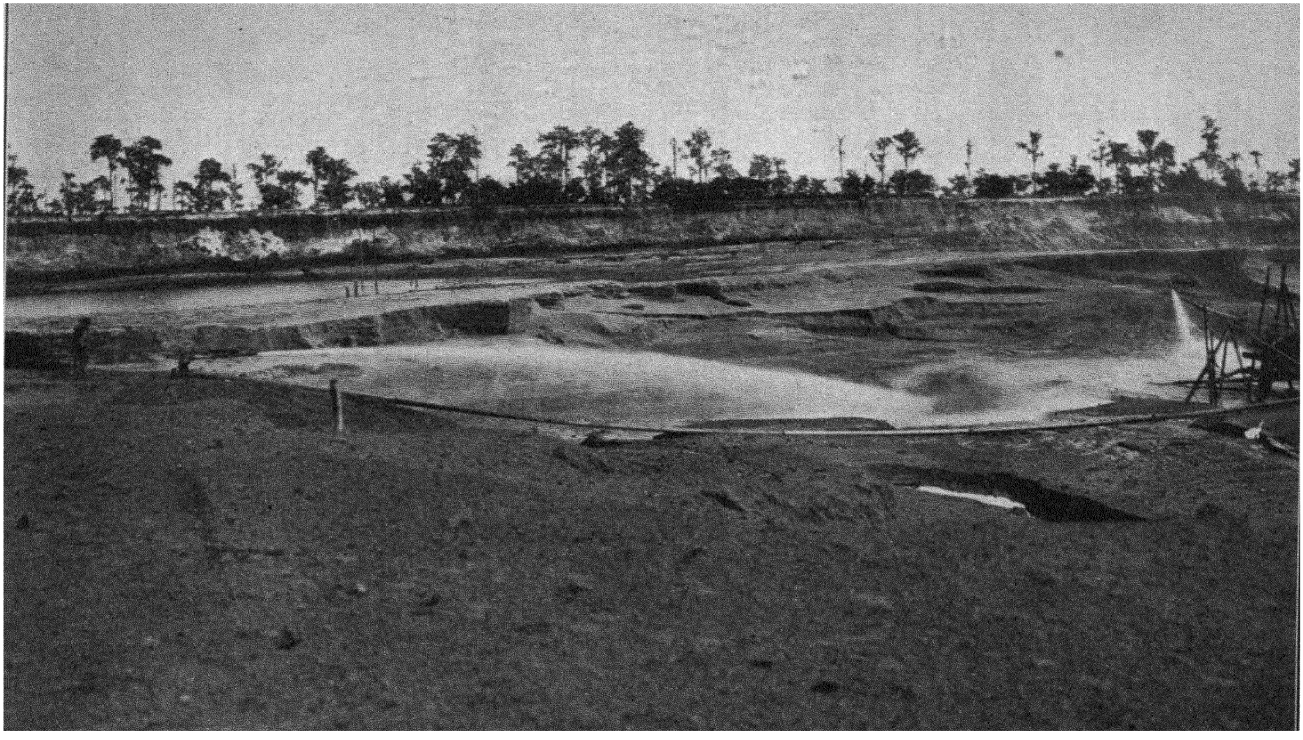
Agricultural Marketing.
By JOHN T. HORNER, Michigan Milk Producers Association. 249 pages. Ill.

Beef Cattle.
By ROSCOE R. SNAPP, University of Illinois. Second Edition. 494 pages. Ill.

Essentials of Systematic Pomology.
By BROOKS D. DRAIN, Tennessee Agricultural Experiment Station. 284 pages. Ill.

The Production of Cotton.
By GILBERT H. COLLINGS, Ph.D., Clemson Agricultural College. 256 pages. Ill.

Uniformly bound in cloth. 6 by 9 inches.



HYDRAULIC MINING OF PEBBLE-PHOSPHATE ROCK AT BREWSTER, FLORIDA:

THEORY AND PRACTICE IN THE USE OF FERTILIZERS

BY

FIRMAN E. BEAR, PH.D.

Science Editor, The Country Home Magazine
Formerly Professor of Agricultural Chemistry
and Soils, The Ohio State University

SECOND EDITION

NEW YORK
JOHN WILEY & SONS, INC.
LONDON: CHAPMAN & HALL, LIMITED
1938

COPYRIGHT, 1929, 1938
BY FIRMAN E. BEAR

PRINTED IN U. S. A.

PRESS OF
BRAUNWORTH & CO., INC
BUILDERS OF BOOKS
BRIDGEPORT, CONN.

PREFACE TO SECOND EDITION

PROGRESS in the manufacture and use of fertilizers has been very rapid during the period that has elapsed since the first edition of this book was published. Accordingly, it became necessary to make a number of changes throughout the text, to rewrite several chapters entirely, and to add a chapter on "trace" elements. It is hoped that, with these changes, the book may continue to serve a useful purpose to those interested in the growing of higher acre yields of the standard crops.

FIRMAN E. BEAR

NEW YORK CITY
October 1, 1938

PREFACE

THIS book has been written for the purpose of bringing together in one volume the various points of view concerning fertilizer practice that have been developed by the many workers in this field since the time of Liebig and of Lawes and Gilbert of Rothamsted fame.

It is apparent that much remains to be done before a really scientific use of fertilizers will be possible. We need to know much more about the specific requirements of plants, the interrelationships of plants and soils and the interactions between soils and fertilizers.

The author is indebted to a host of workers in this and related fields for many of the points of view that are expressed. The problem is so large that no one man can hope to have more than a rather superficial knowledge of many of the various phases of it.

The men, reproductions of whose photographs are shown in the various chapters, were chosen by reason of specific contributions which each man has made on the subject with which that particular chapter deals. Many other men whose work is equally important might well have been included.

The author is especially indebted for illustrations and otherwise to the Soil Improvement Committee of the National Fertilizer Association, the several producers of fertilizer materials, producers of fertilizer distributing machinery, and the agronomists of the various experiment stations whose work has been reviewed.

FIRMAN E. BEAR

OHIO STATE UNIVERSITY
January 19, 1929

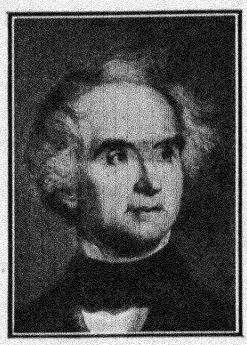
CONTENTS

CHAPTER		PAGE
I.	Early Soil Science	1
II.	The Nitrogen Controversy	12
III.	Biological Fixation of Nitrogen	25
IV.	Nitrification	36
V.	Nitrogen Economy in Soils	54
VI.	The Mineral Theory	75
VII.	Ash Analyses of Plants	96
VIII.	Mineral Constituents of the Soil Solution	108
IX.	Mineral Economy in Soils	126
X.	Development of the Fertilizer Industry	151
XI.	Nitrogen Fertilizers	165
XII.	Phosphoric Acid Fertilizers	189
XIII.	Potash Fertilizers	211
XIV.	Mixed Fertilizers	225
XV.	Principles of Fertilizer Practice	239
XVI.	The Selection of Fertilizers	262
XVII.	The Application of Fertilizers	276
XVIII.	Controlling the Soil Reaction	298
XIX.	Supplying Organic Matter	314
XX.	Trace Elements in Soils and Crops	325
	Index	341

THEORY AND PRACTICE IN THE USE OF FERTILIZERS

CHAPTER I

EARLY SOIL SCIENCE



Justus von Liebig.

THERE is an art and a science of agriculture. The art dates from prehistoric man. The science did not have its beginning until the early years of the seventeenth century. Previous to that time experience guided practice. During the last three hundred years science has gradually assumed the leadership. In soil management it has pointed the way to improved practices by which it is now readily possible to transform even the most barren soil into one that is suitable for a garden. But the art of agriculture still flourishes. Many well-established practices are as yet unexplained. They challenge science to the best it has to offer.

In the literature of every civilization which has left a record there are frequent references to the problem of soil improvement and crop production. These are of considerable historic interest but have little scientific value. Not until the introduction of the experimental method was rapid progress made. Of these earliest experiments a few have been selected because of their interest in connection with certain phases of the soil problem which are still under investigation.

SOME EARLY SOIL EXPERIMENTS

Three hundred years have passed since Johan Baptista van Helmont, a citizen of Brussels, conducted his classic experiment the report of which has been translated as follows:

"I took an earthen vessel into 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 3 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 autumn. In the end I dried the soil once more and got the same 200 pounds of soil that I started with, less about 2 ounces. Therefore, the 164 pounds of wood, bark and root arose from the water alone."

The loss in weight of two ounces from the original 200 pounds of soil was considered by Helmont to be within the limits of accuracy of the experiment. Since nothing but water had been added to the soil and the air which surrounded the tree had no apparent weight, it was inconceivable to him that the 164 pounds of material contained in the increased weight of the tree had any other source than that of the water applied to the soil during the five-year period covered by the test.

That the necessity for experimental inquiry was becoming recognized is evidenced by the organization of the "Society for Promoting Philosophical Knowledge by Experiments" about this time. In 1660 Digby, in an address before this society, called attention to the value of potassium nitrate in stimulating the growth of plants. He said:

"By the help of plain saltpeter, diluted in water and mingled with some other fit earthy substance that may familiarize it a little with the corn into which I endeavored to introduce it, I have made the barrenest ground far outgo the richest in giving a prodigious plentiful harvest."

The actual contribution of the soil in the nutrition of plants was not recognized until 1699, when Woodward reported his tests with spearmint grown in sewer and river waters in comparison with rain water. In concluding his discussion he writes:

"Vegetables 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 and 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."

SOIL AS THE FOOD OF PLANTS

In 1733 Jethro Tull, an English land owner and a graduate of Oxford, published his "Horse Hoeing Husbandry" in which he summarizes the conclusions of earlier writers and presents a somewhat more advanced point of view as to the source of the material entering into the composition of plants. He writes:

"Water from Van Helmont's experiment was by some great philosophers thought to be it (the true food of plants). But these were deceived in not observing that water has always in its intervals a charge of earth, from which no art can free it.

"Air could be no part of it (the tree) because air has no greater specific gravity than the incumbent atmosphere and could not be of any weight in it.

"Nitre is useful to divide and prepare the food and may be said to nourish vegetables in much the same manner as my knife nourishes me, by cutting and dividing my meat. But when nitre is applied to the root of a plant it will kill it as certainly as a knife misapplied will kill a man; which proves that nitre is just as much food of plants as white arsenic is the food of rats.

"Heat warms but fire burns; the first helps to cherish, the latter destroys plants." (According to Aristotle, who lived in the fourth century B.C., all matter could be divided into four principal elements; earth, air, fire and water.)

"Every plant is earth and the growth and true increase of a plant is the addition of more earth.

"Too much nitre corrodes a plant; too much water drowns it; too much air dries the roots of it; too much heat (or fire) burns it; but too much earth a plant can never have unless it be therein wholly buried."

Acting on the theory that earth is the true food of plants Tull, in preparing his fields for crops, made an especial effort to thoroughly pulverize the soil. A considerable amount of his time was devoted to the improvement of plows and other tillage implements. From his point of view, cultivation is effective because it pulverizes the soil and makes the particles fine enough to be taken in by plant roots. Unless these particles were no larger "than those on which the colors of bodies depend" they could not be "insumed" by the roots.

According to Tull, tillage can be used as a substitute for manure. The effect of both was believed to be the same. Tillage was said to pulverize the soil by "attrition" and dung by "fermentation." He argues:

"The quantity of dung is limited but by tillage we can enlarge our field of subterranean pasture without limitation though the external surface of it be confined within narrow bounds."

THE BEGINNING OF CHEMICAL SCIENCE

The latter half of the eighteenth century brought with it a very considerable interest in the science of chemistry, the development of which was fundamental to an understanding of the processes of plant and animal growth. Unfortunately the phlogistic theory, proposed by Stahl, so dominated the point of view of chemists that the correct interpretations of chemical phenomena were delayed. Priestly, Helmont, Cavendish and Rutherford had separated the gases which we now know as oxygen, carbon dioxide, hydrogen and nitrogen and which make up such a large percentage of the plant structure. But these had all been discovered in the search for phlogiston, the unknown substance which escaped during combustion.

It remained for Antoine Laurent Lavoisier, the brilliant French chemist, who lived during the latter half of the eighteenth century, to determine the true nature of combustion and to overthrow the phlogistic theory. He showed that combustion is a process of oxidation and that carbon dioxide is composed of carbon and oxygen in the proportions now known to obtain in this gas. It had long been known that plants give off bubbles of gas when immersed in water. Priestly had observed that growing plants purify the air when it has become foul from the presence of animals. In 1779 Ingen-Hausz published a book entitled "Experiments on Vegetables" in which were reported his researches which prove that the absorption of carbon dioxide and the giving off of oxygen is a plant function which takes place only in the presence of light.

THE EMPIRICAL METHOD OF EXPERIMENTING

Meanwhile facts were being accumulated which show that the rate of growth of vegetation is augmented by the use of materials of various kinds when applied to the soil. Manure, compost, bones, lime, chalk, ashes, saltpetre and many other substances were known to be effective in increasing crop yields. Pot and field experiments were conducted to determine the influence of

these materials on plant growth. The effects could be measured, but the causes of their effectiveness were not so readily determined. For example, while it was recognized that bones are very beneficial on grass, the credit was given to the oil contained in them. For that reason the bones of fat cattle were especially prized. The good results obtained from the use of rape cake and from the residues of seeds of various plants were thought likewise to be due to their content of oil.

One of the most prolific agricultural writers of this period was Arthur Young, whose "Annals of Agriculture" contains accounts of some of his own "experiments to determine how far and in what form phlogiston is the food of plants." In these pot tests he grew barley in sand to which had been added such widely different substances as "train oil, spirit of wine, poultry dung, charcoal, gunpowder, nitre, pitch, oyster shells, sea coal, flour of brimstone, citrolated tartar, ashes, common salt, spirit of salt, turpentine and tallow."

The difficulties which beset Young in the interpretation of his experimental data may be inferred from the following comment concerning manure:

> "Without a certain degree of putrefaction (of dung) the phlogiston will not be volatile. Continued too long it will be volatile. Consistent with this theory is an observation I make every year in my own farm yard; I have a standing sheepfold partly covered and closed and part of it uncovered. The whole is littered equally but one load of dung in the covered is worth two in the uncovered. When the carts go by to be unloaded it stinks much more offensively and makes the men's eyes water that move it. This shows that the volatile alkali and phlogiston are retained and the action of the sun and atmosphere is to carry them off."

EARLY AGRICULTURAL CHEMISTS

Modern agricultural chemistry had its foundation in the work of Theodore de Saussure, of Switzerland, in the beginning of the nineteenth century. He was interested in the quantitative study of the constituents in air in relation to plant growth and of the salts found in the ash of plants. He succeeded in measuring the amount of oxygen liberated by plants and the increase in the carbon content of these plants during the same period. The conclusion was reached that the most important constituents of

plants are carbon, hydrogen and oxygen and that these materials are derived for the most part from carbon dioxide and water. The importance of the soil as a source of plant material was also pointed out by de Saussure, who discovered that the ash of plants is derived from this source. To this man, probably more than any other, we owe the first definite statement, verified by quantitative experiments, of the source and nature of the materials entering into the composition of plants.

In 1813 Sir Humphry Davy published his "Elements of Agricultural Chemistry," which is composed of a series of lectures on the principles concerned in vegetable growth. The chief value



FIG. 2.—Broadbalk Field, Rothamsted, England, on which Lawes began his fertilizer tests on wheat in 1844 and on which wheat has been grown continuously ever since. Note pieces of chert in soil in foreground.

of these lectures is his interpretation of the then known facts in chemical terms. He writes concerning the constitution of plants:

"It is evident that the most essential vegetable substances consist of hydrogen, carbon and oxygen in different proportions, generally alone; but in some few cases combined with nitrogen. The acids, alkalies, earths, oxides and saline compounds, though necessary in the vegetable economy, must be considered as of less importance, particularly in their relation to agriculture, than the other principles. Water and the decomposing animal and vegetable matter existing in the soil constitute the true nourishment of plant. The earthy parts of the soil are useful in retaining water, so as to supply it in the proper proportion to the roots of vegetables."

Davy's reputation as a scientist was such that his statements concerning the nutrition of plants were rather generally accepted. They added weight to a theory that had already gained some prominence which credited the decaying organic matter in soils as being the universal nutrient of plants. This theory, "the

humus theory," had found its most prominent exponent in Albrecht Thaer of Germany. From the work of de Saussure and others it was known that plants are composed of carbon, hydrogen, oxygen and mineral constituents. In the opinion of Thaer the inorganic elements acted merely as plant stimulants while the true food of plants is identical with that of animals, viz., organic matter.

THE HUMUS THEORY

In 1840 Justus von Liebig, a German chemist then only thirty-seven years of age, addressed the British Association for the Advancement of Science on the subject of plant nutrition. These lectures were subsequently published in book form under the title, when translated, "Organic Chemistry in Its Application to Agriculture and Physiology." In the preface to this book is written:

"Perfect agriculture is the true foundation of all trade and industry—it is the foundation of the riches of states. But a rational system of agriculture cannot be formed without the application of scientific principles; for such a system must be based on an exact acquaintance with the means of nutrition of vegetables and with the influence of soils and the action of manure upon them. This knowledge we must seek from chemistry, which teaches the mode of investigating the composition and of studying the characters of the different substances from which plants derive their nourishment."

The key to the content of Liebig's lectures is found in these statements taken from the preface of his book:

"The primary source whence man and animals derive the means of their growth and support is the vegetable kingdom.

"Plants, on the other hand, find new nutritive material only in inorganic substances."

Liebig was convinced that the humus theory was no longer tenable. In discussing the organic matter in plants and the source of their carbon, he states that while the "difference in growth of plants according to the known abundance or scarcity of humus in the soil seems to afford incontestable proof of its (the humus theory) correctness" the facts are in opposition to this belief. The explanation of the good effects of animal manures lies in some other direction. The amount of carbon which can be secured by plants from the humic acid in the soil is "extremely

trifling in comparison with that actually produced in vegetation." This is on the assumption that the plant takes up its humus in the form of humate of lime which, according to Liebig, has a solubility of one part in 2500 parts of water. In spite of the fact that carbon is removed yearly from the field in crops, the soil often becomes richer in this element. This can not be explained on the assumption that the source of the carbon is the humus in the soil. The question also arose as to the origin of the primitive humus. "Plants must have preceded the humus."

Liebig argues that since the quantities of oxygen and carbon dioxide in the atmosphere remain unchanged, they must have some fixed relation to each other. This can be explained only on the assumption that some agency is responsible for removing from the air the carbon dioxide which is given off during combustion and respiration, and that through this agency the oxygen is again liberated. "Both of these causes are united in the process of vegetable life." He, therefore, concludes: "The carbon of plants must be derived exclusively from the atmosphere."

The opinion that the carbon dioxide of the air is the source of the carbon of plants was not new. It had been "admitted, defended and argued for by the soundest and most intelligent natural philosophers, namely, by Priestly, Senebier, de Saussure and even by Ingen-Hausz himself." The publication of Liebig's lectures in book form and their translation into English by Playfair permitted of their being very generally read. The arguments were so logical and so well fortified by experimental evidence, partly from his own laboratory and in part from the laboratories of other investigators, that the "humus theory" was very effectively disposed of. That the carbon derived from the atmosphere may be supplemented by organic compounds derived from the decaying plant and animal residues in the soil was not to receive any very serious consideration again for three-quarters of a century.

Having disposed of the "humus theory," Liebig's attention was next directed to the source of the nitrogen used by plants. Analyses had shown that vegetable matter contains, in addition to carbon, hydrogen and oxygen, a certain amount of nitrogen. Careful analyses in his laboratory had demonstrated that this

element is invariably present in plants. Having been able to satisfy both himself and his critics that the source of the carbon of plants is the carbon dioxide of the atmosphere and that their hydrogen and oxygen comes largely from water, Liebig looked toward the simplest rational explanation of the source of their nitrogen.

Since the nitrogen of the air is so inert and does not enter into "combination with any element except oxygen, even by the employment of the most powerful chemical means," plants must secure this element from some other source. It was known that ammonia is formed during the process of vegetable and animal



FIG. 3.—Effect of nitrogen fertilizer on high-yielding strain of wheat in Germany, the home of Liebig, who believed that all of the necessary nitrogen could be gotten by plants from the ammonia of the air. (Courtesy Synthetic Nitrogen Products Corporation.)

decay and Liebig concluded that this is the form in which plants secure their nitrogen. Since for the most part the crops and animals are sold and a portion of the supply of this element is, therefore, lost from the farm, there should be a gradual reduction in the amount of combined nitrogen that is available for crop use. Analyses show, however, "after a given number of years, the quantity of nitrogen will be found to have increased." Evidently "plants, and consequently animals, must, therefore, derive their nitrogen from the atmosphere" in the form of ammonia.

Examination of the rain water shows that combined nitrogen is always present. In fact, since the ammonia from putrefaction of animals escapes into the air, it can "never be absent." Calculations of the quantity which could be expected from the rain falling on a given area of ground indicated to Liebig that "a field of 40,000 square feet must receive annually upwards of 60 pounds of ammonia." This is sufficient to supply the needs of the crops to be grown and the conclusion was, therefore, drawn: "It is ammonia which yields nitrogen to vegetable albumen."

THE ROTHAMSTED EXPERIMENT STATION

The source of the nitrogen of plants and the means of insuring an adequate supply of this element for their use were destined to be subjects of controversy for another half century. Foremost among those who were interested in these problems was John Bennett Lawes. In the year 1837 Lawes took charge of Rothamsted, his father's estate, at Harpenden, twenty-five miles out from London, England. Being interested in chemistry, he immediately thought of its application to agriculture on assuming the active management of Rothamsted. Some experimental work with fertilizers had been undertaken by Lawes previous to the appearance of Liebig before the British Association for the Advancement of Science. Returning from listening to Liebig's lectures, he enlarged his experimental work and began a series of somewhat extensive field tests with fertilizers. Records of the crops grown on the Broadbalk Field of the Rothamsted Experimental Farms are available since 1839, with data as to yields from 1844 to date.

In 1843 Lawes employed Dr. Henry Gilbert, a chemist who had been trained under Liebig, to work with him. These two men were associated in their investigations of soil and plant problems until their deaths in 1900 and 1901, respectively. From the beginning their experimental work was carried out with painstaking care and the records of crop treatments and resulting yields, together with the analytical data secured in a laboratory study of problems related to the soil, are invaluable.

Among other things, Lawes and Gilbert were not able to agree with Liebig as to the source of the nitrogen in plants. By carefully catching the rainwater which fell on a definite area and

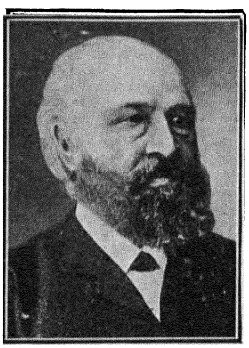
determining its content of combined nitrogen, they were able to show that this amounted to not more than five pounds per acre annually, a quantity entirely inadequate to satisfy the requirements of agricultural crops. Their field tests also showed that nitrate of soda, as well as the sulfate and chloride of ammonia, produced marked effects when used as fertilizers on wheat. The publication of their conclusions in 1847 was the beginning of a controversy which continued for nearly forty years before it was apparently finally settled.

SELECTED REFERENCES

1. Aikman, C. M. Manures and Manuring, London, pp. 3–20, 1902.
2. Davy, Humphry. Elements of Agricultural Chemistry. London, 1813.
3. Digby, Kenelm. A Discourse Concerning the Vegetation of Plants. London, 1669.
4 Grey, Edwin. Rothamsted Experimental Station, Reminiscences, Tales and Anecdotes. 1872–1922.
5. Ingen-Hausz, Jan. Experiments upon Vegetables. London, 1779.
6. Liebig, Justus von. Organic Chemistry in Its Application to Agriculture and Physiology. Translation by Lyon Playfair, London, 1840.
7. Meyer, Ernst von. History of Chemistry. Translation by George McGowan, The Macmillan Company, pp. 108–110, 1891.
8. Russell, E. J. Soil Conditions and Plant Growth, Longmans, Green and Co., pp. 1–21, 1927.
9. Saussure, Theodore de. Recherches Chimiques sur la Vegetation. Paris, 1804.
10. Shenstone, W. A. Justus von Liebig; His Life and Work, Cassell and Co., pp. 110–104, 1901.
11. Tull, Jethro. Horse Hoeing Husbandry. London, 1733.
12. Woodward, J. Thoughts and Experiments on Vegetation. Phil. Trans., Vol. 21, pp. 382–392, 1699.
13. Young, Arthur. Annals of Agriculture, Vol. 1, pp. 254–279, 1784.

CHAPTER II

THE NITROGEN CONTROVERSY



H. Hellriegel

WHILE Liebig, in his remarks in 1840 before the British Association for the Advancement of Science, stated that the source of the nitrogen in plants is the ammonia of the atmosphere, he was also of the opinion that the ammonia in dung and in mineral manures is of considerable additional value as an aid in maintaining a sufficient supply for agricultural crops, although not necessary for ordinary vegetation. In the revised edition of his book, issued in 1843, Liebig lays more stress on the sufficiency of the ammonia in the atmosphere. In his opinion, the quantity of nitrogen added in manure is too small to be of any particular importance for crops, considering the amount of ammonia produced in the soil and that which is returned in the rain from the atmosphere.

LIEBIG'S CONCLUSIONS QUESTIONED

Lawes, in his first contribution to the Journal of the Royal Agricultural Society of England, in 1847, calls attention to what he considers to be an error in Liebig's point of view that certain substances are of little value as manures because plants and shrubs in their natural state are capable of obtaining them in sufficient quantities for their use. Lawes says:

"Many of the errors into which Liebig has fallen have, I think, arisen from his not sufficiently considering what agriculture really is. Practical agriculture consists in the artificial accumulation of certain constituents to be employed either as food for men or other animals upon a space of ground incapable of supporting them in its natural state.

"Agricultural plants possess widely differing powers of reliance upon the

atmosphere for the constituents which it is known to supply in a greater or less degree. If grain crops held the same relation to the natural and artificial supply of their organic constituents as the leguminous crops and turnips, the farmer would not require the assistance of the latter crops. But since, compared with these, the grain crops are in some important respects far more dependent upon artificial supply to the soil of certain organic constituents, of which the price is high and the supply limited, it becomes necessary to employ certain plants which possess the power of collecting these ingredients from the atmosphere and such procedure constitutes a rotation of crops."

EARLY WORK AT ROTHAMSTED

Lawes then outlined in detail the experiments which had been carried on at Rothamsted for some years and in which he placed "great reliance" since they had been conducted "under the eye of Dr. Gilbert, a gentleman who received his scientific education in the best British and continental laboratories." His description of the soil and the history of the Broadbalk Field is interesting in this connection:

"The soil upon which my experiments were tried consists of rather a heavy loam resting upon chalk, capable of producing good wheat when well manured, not sufficiently heavy for beans, but too heavy for good turnips or barley. The average produce of wheat in the neighborhood is said to be less than 22 bushels per acre, wheat being grown once in five years. The field selected for purposes of experiment had been reduced to the lowest state of fertility by removing a certain number of corn (grain) crops without applying any manure, and wheat and turnips were chosen for the subjects of investigation. The wheat field consists of 14 acres, the crops removed since it was manured being barley, peas, wheat and oats. In 1844 the first experimental wheat crop was harvested and the fourth is now growing. The wheat field was divided into a certain number of equal spaces of which one has been left unmanured, and one received 14 tons of dung every year. The remainder of the plots received different descriptions and quantities of artificial manures."

The yields of wheat produced under conditions of continuous culture were quite variable, depending upon the fertilizing materials applied. The unfertilized yield, in 1844, was 16 bushels per acre as compared with $16\frac{3}{4}$ bushels on the plot receiving acid phosphate and $21\frac{1}{4}$ bushels on the plot receiving sulfate of ammonia in addition to the phosphate. "The value of the ammonia salts was so evident that the application of mineral manures (fertilizer salts other than carriers of nitrogen) alone was discontinued the second and third years." Lawes concludes

that to produce "agricultural crops of corn, nitrogen must be supplied in some form or other." It seemed apparent to him that answers were needed to two questions, viz.: "What amount of nitrogen must the farmer accumulate in his soil to obtain each bushel of corn beyond the natural produce; and what are the most economical means at his disposal for securing the necessary supply?" In answer to the first question, he was inclined to believe that every additional bushel of wheat would require about 5 pounds of ammonia. Answering the second he writes:

> "Besides being expensive, this ammonia cannot be procured in the market in any large quantities, but by cultivating turnips and the leguminous plants, a large amount of this substance is collected by them from the atmosphere. A rotation of crops may in one sense, therefore, be considered as an economical process for obtaining ammonia."

In June, 1860, Lawes, Gilbert and Pugh presented a paper before the Royal Society of London, of which only an abstract was published, the title of which is "The Sources of the Nitrogen of Vegetation." In this paper consideration was given to the question of the assimilation of atmospheric nitrogen by plants. From analyses of crops produced continuously on the same land without the use of nitrogenous fertilizers it was shown that there is considerable variation in their capacity to secure nitrogen. Cereal crops, when grown year after year on the same land, contained an average of about 30 pounds of nitrogen per acre per annum. Clover had secured, as an average of three years, 120 pounds of nitrogen per acre. The cereal crops were nearly doubled when preceded by a legume. It was further shown that the legumes were little benefited by nitrogenous fertilizers.

EXPERIMENTS ON NITROGEN FIXATION AT ROTHAMSTED

In order to test the matter of the assimilation of free nitrogen by plants elaborate experiments were planned and carried out in detail at Rothamsted. The soil employed in the tests was "ignited with free access of air, well washed with distilled water and re-ignited." In order to insure the presence of the proper amounts of mineral constituents, plants of the kind to be grown were incinerated and the ash added to the soil. The ordinary

distilled water was redistilled over phosphoric acid. "Before use, the red-hot matrix and the freshly ignited ash were mixed in the red-hot pot, and the whole allowed to cool over sulphuric acid." After several days well-selected seeds were planted, other similar specimens being analyzed for their nitrogen content.

The whole apparatus was enclosed in a large glass case which was made air tight by a mercury seal. The air entering the chamber passed through sulfuric acid to free it of ammonia. The carbon dioxide that was supplied to the growing plants was prepared by the action of acid on marble. Members of both the Graminaceæ and the Leguminosæ were grown. In the two



FIG. 5.—Soybeans, one of the legume crops which secure part of their nitrogen from the air.

years, 1857–58, thirteen experiments were conducted in which the plants were supplied with no nitrogen except that contained in the seed. "In no one of these cases was there more nitrogen in the plants themselves than in the seeds sown." Lawes and his co-workers conclude that there is in these experiments no indication that plants can assimilate free nitrogen.

EFFECT OF NITROGENOUS FERTILIZERS ON GRASS LAND

In the year 1856 a tract of land was set aside for experiments on the use of various fertilizers on permanent grass land on the

tract now known as the Park Field. Data were accumulated on the acre yield of hay and its chemical composition. In 1862 it was decided to make a detailed study of the nature of the vegetation on these plots, a previous preliminary study in 1858 having shown that the use of the several fertilizers developed differences in the predominating species of plants. The percentages of each of three plant groups of plants that were found on these plots are shown in the following table.

TABLE I

EFFECT OF FERTILIZER TREATMENT ON PLANT GROUPS, PARK FIELD, ROTHAMSTED

Percentages of Plants of Various Groups

Plot	Treatment	Graminaceous	Leguminous	Miscellaneous
1	Unmanured	74.20	7.61	18.19
3*a*	Superphosphate	78.72	2.60	18.67
6	Nitrate of soda	84.22	0.32	15.46
4	Ammonia salts	88.34	0.15	11.51
8	Mixed minerals	66.40	24.09	9.51
16	Manure	79.07	1.72	19.21
3*b*	Same as 4 plus 3*a*	83.48	0.11	16.41
13*b*	Same as 4 plus 8	95.02	0.00	4.98

The use of nitrogen, in any form, as a fertilizer had a marked tendency to reduce the percentage of leguminous plants in the permanent meadow, where the grass was cut for hay.

FRENCH INVESTIGATIONS IN NITROGEN FIXATION

In 1802 Jean Baptiste Boussingault, who has been designated "the founder of modern agricultural chemistry," was born in Paris. He was brought up under conditions of poverty and in a section of the city inhabited by rag pickers, parchment makers and wine merchants of the petty type. He records in his memoirs that the house in which he lived as a youth was dark but that it was the only one on the street which received an hour of sunlight per day. Yet this boy became interested in chemistry, later in agriculture and finally, in 1837, began his famous investigations on the farm of his father-in-law in Alsace, where he earned for himself the title of "The Farmer of Bechelbronne." For a

period of over twenty years Boussingault had been studying the economy of the mineral elements and nitrogen in soils and plants. These investigations involved both field and laboratory studies. His experiments on nitrogen fixation by plants, originally reported in 1838, were outlined in detail in his book which was published, in revised form, in 1865 under the title, when translated, of "Rural Economy in its Relation with Chemistry, Physics and Meteorology, or Chemistry Applied to Agriculture."

Commenting on the subject of nitrogen fixation, Boussingault writes:

"There is reason for believing that the plowing in of certain green crops and fallowing, are not effectual merely by introducing carbon, hydrogen and oxygen, but nitrogen also into the soil."

The experiments on which Boussingault based these conclusions were conducted as follows:

"For soil, I made use of burned clay or siliceous sand freed from all organic matter by proper calcination. In this soil moistened with distilled water were sown the seeds whose weight was known. The porcelain vessels, in which the experiment was conducted, were placed in a glass house at the end of a large garden. During the whole term, the windows were kept closed; but the sun shone on the house all day."

Five experiments were conducted in this manner. The crops grown were clover, peas, wheat and oats. The results are shown in the following table.

TABLE II

BOUSSINGAULT'S EXPERIMENTS ON NITROGEN FIXATION

Crop	Beginning Weight of Seed or Plants	End Weight of Plants	Beginning Nitrogen in Seeds or Plants	End Nitrogen in Plants	Total Nitrogen Gain or Loss
	Grs.	Grs.	Grs.	Grs.	Gr.
Clover	24.48	63.38	1.759	2.408	+0.649
Peas	16.55	68.56	0.710	1.559	+0.849
Wheat	25.38	46.65	0.870	0.920	+0.050
Clover*	13.64	34.96	0.500	0.864	+0.364
Oats*	.....	221.84	0.910	0.818	−0.092

* Transplanted.

In recapitulating the conclusions obtained from these experiments we find:

"First, the clover and peas grown in a soil absolutely without manure, acquires a very appreciable quantity of nitrogen in addition to a large quantity of carbon, hydrogen and oxygen.

"Second, that wheat and oats, grown in the same circumstances, took carbon, hydrogen and oxygen from the air and water around them; but that analysis showed no increase of nitrogen in these plants after their maturity."

Continuing his investigations further, Boussingault secured conflicting results. After forty years of the most laborious effort he wrote Lawes, in 1876, as follows:

"If there is any fact perfectly demonstrated in physiology, it is this of the non-assimilation of free nitrogen by plants."

During the period of 1849–56 Georges Ville, of Paris, had also been investigating this problem. In his experiments Ville had made use of washed and ignited sand, sand and brick, or sand and charcoal as soil, adding plant ash as the source of the mineral plant food materials. Washed and unwashed air was supplied. In the latter case the content of ammonia in the atmosphere was taken into consideration. A variety of plants, both legumes and non-legumes, were grown. In his later experiments a small amount of nitrate of soda was supplied as a means of giving the plants a more vigorous start. Ville's conclusions were that nitrogen fixation is a property that is common to many plants including among others in this list wheat, rye, tobacco and sunflowers.

The conflicting results obtained by Ville and Boussingault served to make the Rothamsted workers more desirous than ever of finding the explanation of the phenomena observed. While their own experiments had not indicated any fixation of free nitrogen by any plants, yet they were at a loss to know why it was that "leguminous crops assimilate, from some source, so very much more nitrogen than the graminaceous ones."

In 1882 Lawes and Gilbert prepared a paper which was read before the Chemical Section of the American Association for the Advancement of Science at Montreal, Canada. The subject of this paper was "Determinations of Nitrogen in the Soils of Some of the Experimental Fields at Rothamsted and the Bearing of the Results on the Question of the Sources of the Nitrogen of Our Crops." In summary they write:

"It has been concluded that the balance of direct experimental evidence is decidedly against the supposition that plants assimilate the free nitrogen of the atmosphere. Indeed, the strongest argument that we know of in favor of such a supposition is that, in defect of other conclusive evidence, some such explanation of the facts of production would seem to be needed."

THE INFLUENCE OF SOIL MICROÖRGANISMS SUGGESTED

Berthelot, the famous French chemist, in 1876, questioned the accuracy of the conclusion that plants do not assimilate the free nitrogen of the air. His objections were first on the grounds



FIG. 6.—Peanuts, a nitrogen-fixing legume of great importance in the southern states.

that the plants were grown in enclosed vessels which excluded the possibility of electrical fixation. According to Berthelot nitrogen fixation takes place when moistened filter paper or dextrin is placed under the influence of the silent electric discharge and he believed the same might be true in the case of plants.

Later Berthelot objected to Lawes and Gilberts' experiments on the ground that by heating the soils to drive off the nitrogen the soil microörganisms had been destroyed. His experiments had been conducted with argillaceous sands and crude clays. From his earlier tests he concluded that the nitrogen fixation which occurred was due to electrical fixation, but in his fifth

series of experiments, in 1885, in which the soils were sterilized by heat, he found instead of a gain that a slight loss of nitrogen occurred when the soils were left standing after the sterilization. Berthelot concluded that there was a fixation of free nitrogen due to living organisms in the soil.

AMERICAN CONTRIBUTIONS

In February, 1885, an article written by W. O. Atwater of the Connecticut Agricultural Experiment Station "On the Acquisition of Atmospheric Nitrogen by Plants" appeared in the American Chemical Journal. This article contains the results of his attempts at the solution of the problem which had been the subject of controversy for the preceding forty years. In these investigations peas were grown "in sand which had been purified by washing and igniting and to which were applied nutritive solutions containing known quantities of nitrogen." The record of one set of these experiments is shown in the following table.

TABLE III

ATWATER'S EXPERIMENTS ON NITROGEN FIXATION

Experiment	Nitrogen Supplied at Beginning of Experiment			Nitrogen Found at End of Experiment			Gain of Nitrogen
	In Seed	In Nutritive Solution	Total	In Residual Solution	In Plants	Total	
	Mgs.	Mgs.	Mgs.	Mgs.	Mgs.	Mgs.	Mgs.
A	49.5	61.4	110.9	7.2	167.2	174.4	63.5
B	36.4	92.2	128.6	8.0	133.8	141.8	13.2
C	35.6	61.4	97.0	1.3	108.7	110.0	13.0

The outcome of these experiments may be concisely stated thus:

"The plants, peas, grown in nutritive solutions exposed to the air, but protected from rain and dew, contained at maturity much more nitrogen than was supplied them in nutritive solution and seed. Such were the results of a first series of trials confirmed even more strikingly by a second series the succeeding year. For this excess of nitrogen there is but one possible source, namely, the atmosphere."

In a later article (1886) Atwater presents some further evidence on the fixation of nitrogen by peas and discusses the status of the problem at that time. In this article he refers to the work of Berthelot as follows:

"I do not see how they (microörganisms) can explain the acquisition of nitrogen in my own experiments, however. It would seem that if the nitrogen in my own experiments was due to the agency of microbes, the plants themselves must have had a share in the operation since neither purified sand alone, nor an aqueous solution of salts, nor both together, so far as I am aware have ever been shown to have any power of gathering nitrogen, except in so far as solutions may take nitrogen compounds from the air."

Commenting further on this subject he writes:

"Unless further research should bring evidence directly opposed to the best now at hand, it must be allowed that the great part of the nitrogen which the plants obtain from the air comes through the foliage."

FIXATION OF NITROGEN BY LEGUMES PROVEN

In September, 1886, a meeting of German Agricultural Research Chemists was held in Berlin. At this meeting H. Hellriegel read a paper the title of which, when translated, reads: "What Nitrogen Sources Do Plants Have at Their Command." His experiments consisted in growing barley, oats and peas in pots having a depth of 20 centimeters and containing 4 kilograms of pure washed sand. Nutritive solutions containing no nitrogen were added to all of the pots. Certain of the pots received, in addition to the nutrient solution, varying amounts of nitrate of soda. The growth of the barley and oats was proportional to the amounts of nitrogen added but the peas grew remarkably well in the pots to which no nitrogen had been supplied. No determinations of the nitrogen content of the plants grown or of the soil are recorded. Hellriegel drew his conclusions from the evident differences in growth of the cereals and the peas. His conclusions were that the Leguminoseæ are distinguished from the Graminaceæ in not being dependent on the soil for their nitrogeneous food. In order to determine whether the ammonia in the air was being utilized by the peas Hellriegel passed the air through sulfuric acid and found that the growth was equally good whether the air had been washed or not. Therefore, the peas must have been able to use the free nitrogen of the atmosphere.

Hellriegel observed that when peas are planted in nitrogen-free soil the growth is normal and the color of the leaves quite green until the reserve food in the seed has been used up. At this period the plants become yellow and cease growing. After a time they again recover their natural color and grow to maturity. An occasional plant, however, never recovers from the yellow color and fails to mature. In all such cases the plants have no nodules, or only very small ones, on their roots. Those plants which develop normally have nodules in abundance. The larger the nodules and the greater their number the better the growth of the plants.

His next experiment was that of determining the definiteness of the relationship of the nodules and normal development of peas. Forty experimental pots were filled with nitrogen-free soil. To each of ten of these pots 25 cubic centimeters of an extract of a fertile soil were added and peas were planted. The peas developed normally in each of these ten pots but in only two of the remaining thirty to which no soil extract had been added. A study of the root systems showed that there was a close connection between the development of nodules and the growth of the plants. Hellriegel concluded that the root nodules and the microörganisms which they contain stand in very close relationship to the nourishment and nitrogen assimilation of the Leguminosæ.

DIFFERENCES IN NODULE ORGANISMS NOTED

In experimenting with lupines, this relationship was not so successfully shown and, although the conditions were exactly similar, the lupines failed to take on the second growth. Hellriegel, therefore, conducted some tests wherein the soil in which the lupines were to be planted was treated with an extract of soil from a field in which they had previously been grown successfully. The lupines in those pots to which no soil extract had been supplied and also those in the pots to which an extract of the ordinary garden loam had been added did not recover from their starvation period, while the plants in the pots receiving the extract from the lupine soil showed the normal period of starvation but later recovered and developed satisfactorily. Only one nodule was found on the roots of the plants in the first two series of pots

while every plant in the series where normal growth occurred had its roots covered with nodules.

The conclusion reached from these experiments was that the organisms in the nodules on the roots of lupines differ from those in the nodules on the roots of peas. Serradella, vetches, beans and red clover were also studied. Serradella behaved as the lupines. The peas, vetches and beans grew well in soil treated with extract of the garden loam. The clover showed no special results. Hellriegel also proved that legumes do take up nitrogen from the soil, especially if supplied as nitrates, but he was doubtful whether they could attain to normal development in the absence of the microörganisms.

QUANTITATIVE RESULTS

In September, 1887, Wilfarth, who was associated with Hellriegel, discussed some subsequent experiments before certain prominent agricultural chemists assembled at Wiesbaden. The results corresponded so well to those previously reported that it did not seem necessary to any longer doubt their accuracy. Wilfarth pointed out that while it seems natural to attribute the results to the action of bacteria and to connect it with the organisms of the nodules, yet the experiments did not settle the question. In his mind it was doubtful whether the root nodules had any connection with the taking up of the nitrogen. Wilfarth presented the following record of produce and its nitrogen content

TABLE IV

NITROGEN FIXATION WITH LUPINES—HELLRIEGEL AND WILFARTH'S EXPERIMENTS

Pot Number	Dry Substance	Nitrogen Content	Treatment
	Grs.	Grs.	
3	44.73	1.099	Soil solution
4	45.63	1.156	Soil solution
5	44.68	1.194	Soil solution
6	42.45	1.337	Soil solution
9	0.938	0.0146	Distilled water
10	0.800	0.0136	Distilled water
11	0.921	0.0132	Distilled water
12	1.021	0.0133	Distilled water

to show the extent of the nitrogen fixation. The experiment consisted in growing lupines in nitrogen-free sand in two series of pots. In one of these series the sand was watered with soil solution and in the other series distilled water was used.

This was the final proof that legumes, which had long been known to have a beneficial effect on the crops following, were able to add to the content of nitrogen in the soil. From this time on the investigations along this line have been devoted largely to the study of the morphology of the organisms responsible for fixation, the quantity of nitrogen so fixed and the nature of the processes involved.

SELECTED REFERENCES

1. Atwater, W. O. On the acquisition of atmospheric nitrogen by plants. American Chemical Journal, Vol. 6, p. 365, 1884.
2. —— On the liberation of nitrogen from its compounds and the acquisition of atmospheric nitrogen by plants. American Chemical Journal, Vol. 8, pp. 398–420, 1886.
3. Berthelot, Marcellin. Fixation directe de l'azote atmosphérique libre per certains terrains argileux. Compt. Rend., pp. 775–84, 1885. See also Compt. Rend., pp. 205–209 and 625–630, 1887.
4. Boussingault, J. B. Rural Economy in its Relations with Chemistry, Physics and Meteorology. Translation by Law, Orange Judd Co., pp. 33–51, 1865.
5. Hellriegel, H. Welche Stickstoffquellen stehen der Pflanze zu Gebote? Tageblatt der 59 Versamml. deutscher Naturf. u. Aerzte, Berlin, p. 290, 1886.
6. Lawes, J. B., and Gilbert, J. H. On the growth of wheat by the Lois Weedon System on the Rothamsted Soil and on the combined nitrogen in the soil. Jour. Roy. Agr. Soc. Eng., Vol. 17, p. 582, 1856. (Rothamsted Memoirs, Vol. 1, No. 9.)
7. —— On the sources of the nitrogen of vegetation; with special reference to the question whether plants assimilate free or uncombined nitrogen. Abstract Proc. Roy. Soc. Lond., Vol. 10, p. 544, 1860. (Rothamsted Memoirs, Vol. 1, No. 14.)
8. —— The effect of different manures on the mixed herbage of grass land. Jour. Roy. Agr Soc. Eng., Vol. 24, p. 131, 1863. (Rothamsted Memoirs, Vol. 1, No. 18.)
9. —— On the sources of the nitrogen of vegetation with special reference to the question whether plants assimilate free or uncombined nitrogen. Jour. Chem. Soc. Lond., New Ser., Vol. 1, Entire, Ser., Vol. 16, p. 100, 1863. (Rothamsted Memoirs, Vol. 3, No. 1.)
10. —— On the present position of the question of the sources of the nitrogen of vegetation, with some new results, and preliminary notice of new lines of investigation. Philosophical Transactions, Vol. 180, pp. 1–107, 1889.
11. Ville, Georges. Recherches Experimentales sur la Vegetation, 1857.
12. Wilfarth, H. Über Stickstoffaufnahme der Pflanzen. Land. Vers. Stat., Vol. 34, pp. 460–61, 1887.

CHAPTER III

BIOLOGICAL FIXATION OF NITROGEN



E. B. Fred

It will be remembered that Berthelot (1885) called attention to the fact that soil appears to have the power of absorbing atmospheric nitrogen. It was his opinion that this nitrogen is brought into combination with other elements, presumably oxygen and hydrogen, through the agency of "silent electrical discharges." Later observations caused him to modify his point of view when it was found that if the soil is heated, the nitrogen accumulation ceases. This made it appear that the fixation process is biological in its nature and Berthelot questioned, therefore, the conclusions of Lawes and Gilbert as to the inability of legumes to secure atmospheric nitrogen since their experiments had been conducted on soils that had previously been ignited.

NITROGEN FIXATION BY NODULE BACTERIA

The discoveries of Hellriegel and Wilfarth showed that nitrogen fixation accompanies the growth of legumes only in unsterilized soils and indicated that the process is related in some manner to the presence of root nodules. Further investigations resulted in confirming the belief that the nodule bacteria are responsible for the nitrogen accumulation. As a result the significance of Berthelot's researches were overshadowed for a time. It was later found, however, that soils that are left standing, under suitable conditions as to temperature and moisture, seem to accumulate nitrogen even though they are not planted to legumes. This raised the question as to whether the nodule bacteria are able to fix atmospheric nitrogen in the absence of their host.

In answering this question a considerable amount of investigational work was undertaken. Some very interesting results were reported as, for example, by Maze, who grew the nodule bacteria in a liquid medium and found, on analysis of 100 cubic centimeters of this medium at the end of a sixteen-day period, an increase of 23.4 milligrams of nitrogen. However, other workers who were perhaps somewhat more careful in their methods of analysis failed to find any such large amounts of accumulated nitrogen. Considerable doubt arose as to whether the increases that were noted were in reality more than could be accounted for in the errors of experiment.

In a further study of this problem Fred has more recently grown bacillus radicicola of sweet peas, garden peas, serradella and alfalfa in liquid media and on agar containing maltose or cane sugar as their source of carbohydrate. Analyses of the resulting cultures after a period of one month showed the following gains in nitrogen.

TABLE V

NITROGEN FIXATION BY NODULE BACTERIA IN ABSENCE OF HOST—FRED

Variety of Bacteria	Milligrams Nitrogen Gained per 100 cc.	
	Liquid Media	Solid Media
Sweet pea	1.29	
Serradella	1.53	
Alfalfa	1.58	1.27
Garden pea	....	1.17

The average gain in all of the experiments was 1.20 milligrams of nitrogen per 100 cubic centimeters of media. Although the gain is small, it appears to be positive in every case and Fred concludes that legume bacteria, in a suitable culture medium, are able to fix small amounts of atmospheric nitrogen independently of the host plant. Similar experiments, conducted with sterilized soils, also showed some increase but not sufficient to be sure that it might not be accounted for in the analytical error.

THE FUNCTION OF THE HOST IN FIXATION PROCESSES

It seems illogical to expect any considerable accumulation of nitrogen beyond that required by the nodule bacteria themselves in growth and reproduction except as some agency is operating to remove this nitrogen as it accumulates. Other bacteria and higher plants serve in this capacity. Golding reasoned that the legume plant plays an important rôle in this connection in addition to that of supplying soluble carbohydrate food for the nodule bacteria. Accordingly he devised a scheme by which this function of the legume plant could be taken over by mechanical means in the laboratory. A porous Chamberlain filter candle was placed in the vessel in which the nodule bacteria were being grown in a culture medium and from time to time the solution was withdrawn through the filter and new solution was supplied to the bacteria which were left behind on the outside of the candle. As a result of this method of experimentation, Golding obtained a much greater fixation of nitrogen than had previously been reported from other studies of this problem.

It seems probable, from these investigations, that when the nodule bacteria are grown in symbiosis with a legume, the removal of the soluble nitrogen is an important function of the legume. In the absence of the legume, this function might be performed by non-legume plants or by other bacteria. It would appear, therefore, that the nodule bacteria may fix atmospheric nitrogen in the soil under field conditions in the absence of the legume, if conditions are favorable for their growth and reproduction. The presence of available carbohydrate and mineral foods is essential. There is one important difference in that, in the soil, other bacteria are active competitors for carbohydrate food while in the nodules this is not the case.

FIXATION OF NITROGEN AS A FUNCTION OF LEGUME LEAVES

Reference has already been made to the fact that Wilfarth was doubtful whether the nodule bacteria have anything to do with the accumulation of nitrogen by legumes. The investigations of Hellriegel and himself had shown that nitrogen fixation is accomplished by legumes and that nodule formation on the roots accompanies the successful growth of legumes in a nitrogen-

free medium. Atwater just missed being honored with the discovery of the importance of the symbiotic relationship of legumes and their associated nodule bacteria when he drew the conclusion that the nitrogen fixation which his experiments proved takes place should be credited to the foliage of the legumes.

There continues to be considerable interest in the question as to the capacity of legume leaves to take nitrogen from the air. A recent investigation of this is reported by Whiting. Cowpeas and soybeans were grown in white sand until two leaves were developed and small nodules were present on their roots. The plants were then transferred to bottles and the sand was supplied with a nutrient solution containing all the essential mineral elements with the exception of nitrogen. The stems and leaves were permitted to extend above the bottles but roots were sealed in by the use of rubber tissue. A gas mixture containing 96 to 98 per cent of oxygen and from 2 to 4 per cent of carbon dioxide was admitted to the roots. A typical example of the results obtained is given in Table VI.

Control experiments showed that the plants and bacteria are not injured by an atmosphere of carbon dioxide and oxygen. The results indicate that nitrogen fixation is not a function of the leaves but that it is carried on through the agency of the bacteria in the nodules.

FIXATION OF NITROGEN BY NON-LEGUME PLANTS

It will be recalled that Ville reached the conclusion that nitrogen fixation is a function of many plants and that it is not confined to the legume species. His researches were made the subject of an investigation by a special committee of the French Academy of Science who reported in favor of his conclusions. Recently Lipman has again raised the question, after having carefully studied the work of Mameli and Pollacci which indicates rather conclusively that a considerable variety of green plants are able to secure supplemental nitrogen from the air.

Mameli and Pollacci's experiments consisted in growing green plants in air which had been deprived of ammonia and also of nitrate and nitrate nitrogen by being passed through sulfuric acid and caustic potash tubes. The amount of nitrogen secured by these plants from the air was determined both by analyses

TABLE VI

CAPACITY OF COWPEA LEAVES TO ABSORB NITROGEN—WHITING

Plant	Root Supplied with	Nitrogen in Plant End of 83 Days	Nitrogen in Check Seedlings	Nitrogen Fixed
		Mgs.	Mgs.	Mgs.
1	CO_2 plus O_2.....	9.48	7.90	1.58
2	CO_2 plus O_2.....	7.49	7.90	0.41
3	CO_2 plus O_2.....	8.49	7.90	0.59
4	Air.....	186.86	7.90	177.96
5	Air.....	238.02	7.90	230.12
6	Air.....	187.22	7.90	179.32

of the plants and by measuring the loss of nitrogen gas from the air supplied to them. The plants were grown under sterile conditions. Altogether it would seem that all the requirements for accuracy had been met. Their conclusions, as a result of these investigations are as follows:

"From our experiments it results then that the power of absorbing the free nitrogen of the atmosphere is a property much more widespread than has been admitted heretofore, and that in general all chlorophyllous vegetables, from algae to phanerogama, may, according to the conditions of their existence, make use, to a greater or less degree, of this power.

"It is a natural thing, nevertheless, that many species cannot refrain from using the combined nitrogen which they have found for a long period of time and in great quantities in the earth. But it is likewise natural that plants should exist which are endowed with a special power of assimilating free nitrogen which are in a true sense accumulators of nitrogen, and the cultivation of which perhaps, in time, and with proper means, we shall be able to render remunerative.

"Thus this question, studied in its details, may have great importance, not only in the purely scientific field, but also in the field of practical agriculture."

DISCOVERIES OF OTHER NITROGEN-FIXING BACTERIA

The experiments of Berthelot, in which he demonstrated that bare soil, free of all vegetation, when kept at suitable temperatures and moisture conditions accumulates much more nitrogen than can be accounted for by that known to be contained in the rain, were of considerable greater significance than has been noted above. They lead to further careful studies of this problem by

S. Winogradsky of Russia and Martinus W. Beijerinck of Holland which resulted in the isolation, in pure culture, of two species of nitrogen-fixing bacteria that are able to accumulate atmospheric nitrogen in considerable amounts when grown in nitrogen-free media. The first of these discoveries, that of Clostridium pastorianum, was reported by Winogradsky in 1895. Beijerinck gave the name Azotobacter chroöcoccum to the organisms which he isolated, when his investigations were published in 1901.

EFFICIENCY OF NON-SYMBIOTIC NITROGEN-FIXING BACTERIA

Further investigations have shown that both groups of bacteria are rather generally distributed and play important parts in the nitrogen economy of soils. The amount of nitrogen fixed by them has been the subject of a considerable amount of research. Winogradsky found that for every gram of carbohydrate supplied (as a source of energy), approximately 2 milligrams of nitrogen were accumulated by Clostridium pastorianum when grown in liquid media under suitable temperature conditions. Beijerinck's researches indicated that Azotobacter are more abundant and more active in nitrogen fixation than the Clostridia, the quantity fixed per gram of carbohydrate supplied being as much as 7 milligrams. (Considerably larger amounts of nitrogen per gram of carbohydrate have been reported by other workers.) Ashby studied in detail the distribution and the requirements of Azotobacter. His and subsequent investigations have shown that the relative abundance

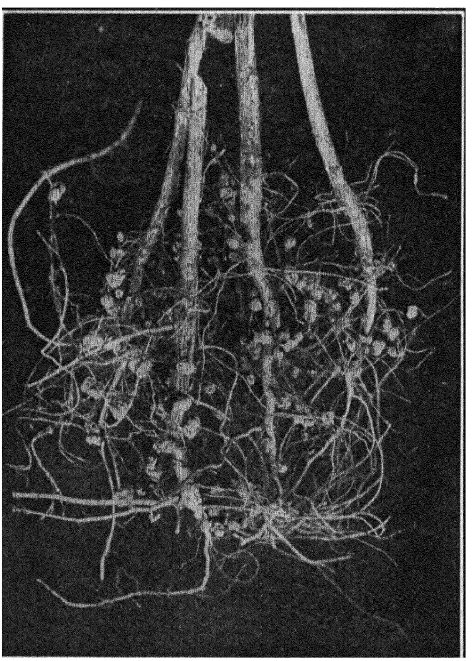


FIG. 8.—Nodules on roots of soybean plant in which the nitrogen-fixing bacteria live.

of the two groups is determined largely by the basicity of the soil. In soils containing a considerable amount of calcium carbonate, the Azotobacter predominate. In acid soils, only Clostridia may be found.

More recently Omelianski and his associates have shown that the nitrogen-fixing Clostridia are more universally distributed than the Azotobacter. This is in part due to the fact, previously mentioned, that the former are less sensitive to acid soil conditions. Their work indicates that the combined activities of the two groups of bacteria may be considerably greater than when either occurs alone, a well-coördinated relationship of the two being the apparent explanation. The Azotobacter consume the free oxygen and destroy the butyric acid produced by the Clostridia. Unfortunately, according to Gainey, the Azotobacter disappear from soils having a *p*H of less than 6. Fred and Davenport placed the critical *p*H of two strains of Azotobacter at 6.5.

It seems probable that further study will show that the non-symbiotic nitrogen-fixing bacteria are of equal or greater significance in the economy of nitrogen in soils than are the legume bacteria. This is not necessarily because of their greater efficiency but because of the time factor. The legume bacteria function to best advantage in the presence of the host. The non-symbiotic groups are assumed to be more or less continuously at work. This, of course, presupposes that their necessary requirements, such as a fairly high temperature, and the presence of available carbohydrate and soluble mineral elements (in the case of Azotobacter, also carbonate of lime) have been met.

OTHER NON-SYMBIOTIC NITROGEN-FIXING BACTERIA

Beijerinck isolated two species of Azotobacter, viz.: A. chroöcoccum and A. agilis. Later Lipman discovered three other species, or strains of the above species. Nitrogen fixation has also been shown to be a function of several other species of bacteria found in soils. Of these, Waksman enumerates Bact. pyocyaneum, Bact. pneumoniæ, B. lactis viscosum, Bact. radiobacter, Bact. aerogenes, Bact. prodigiosum, Bact. malabarensis, Bact. danicus and B. mesentericus. There is also considerable evidence which indicates that certain fungi have the power of

securing nitrogen from the air. More recently Emerson has reached the conclusion that most of the bacteria living in the soil are able to grow on nitrogen-free media and to assimilate atmospheric nitrogen. Whether or not this is the case remains to be verified by further experimentation. In any event, it would appear that the Azotobacter and Clostridia groups are the most important of these non-symbiotic nitrogen-fixing bacteria.

The importance of algæ merits consideration in this connection. By reason of their being chlorophyllaceous plants they are able to manufacture sugar and starch with the aid of sunlight and thus provide a source of carbohydrate for the nitrogen-fixing bacteria. It is possible that a considerable amount of available carbohydrate in the soil may be from this source. A symbiotic relationship between these plants and the nitrogen-fixing bacteria in the soil has been postulated and there is evidence in favor of this assumption.

"NITRE SPOTS" OF COLORADO

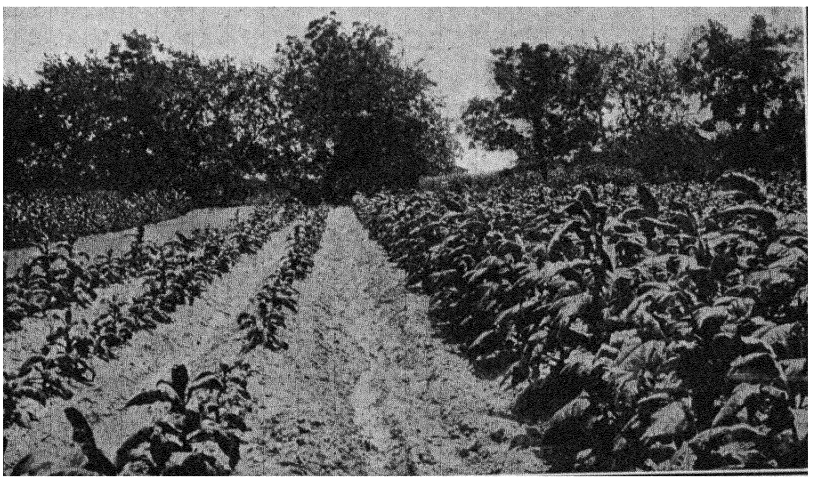
The discovery that nitrogen fixation is a function of a number of soil organisms and that it takes place readily under suitable conditions gave rise to some speculation as to their probable relationship to the nitrate deposits of Chile. What appears to be a similar accumulation of nitrates in Colorado in the "nitre spots" was reported by Headden who found that Azotobacter are present in abundance in the soil from these areas. Without the addition of any carbohydrate material, fixation processes are quite rapid in these soils when placed under control conditions in the laboratory. The quantity of nitrogen that has accumulated in these spots amounts to as much as 100 tons per acre to plow depth. It is present in the form of sodium nitrate. The accumulations are such that all of the vegetation has been destroyed and complaints have been sent in to the Colorado Experiment Station from many sources, particularly from the orchardists whose trees are located in the affected areas.

There is some doubt as to the accuracy of Headden's conclusions that the Azotobacter are responsible for the accumulations. Stewart and Peterson believe, from a study of similarly affected areas, that the accumulation of nitrates is the result of their being leached from the surrounding country rock and their

concentration in these areas from seepage with the later evaporation of the water.

INOCULATION OF SOILS WITH PURE CULTURES OF BACTERIA

There is no longer any question as to the effectiveness of inoculation with nodule bacteria when a given legume is newly introduced. It is effective in producing larger yields of the legume and in increasing its nitrogen-accumulating capacity. There is, however, some doubt about the practicability of inoculating the



No fertilizer. 800 pounds of 3-8-6

FIG. 9.—Effect of fertilizers on growth of tobacco at Edgecomb Test Farm, North Carolina.

soil with non-symbiotic nitrogen-fixing bacteria. Some years ago a firm in Eberfield, Germany, put on the market a commercial culture of Bacillus ellenbachensis under the trade name of "Alinit." For some time this created considerable interest but later its sale was discontinued when it was found that the results secured from its use were insignificant. Similar attempts have been made to interest the farmers of America in cultures of Azotobacter but as yet with little success. In general, it is believed that little can be expected from such inoculation by reason of the almost universal distribution of these bacteria in the soil. Investigations by Emerson with pure cultures of several

species of Azotobacter led him to believe that A. beyerincki and A. vinelandii might be used to advantage for inoculating purposes under some circumstances. Since Azotobacter appear to be especially sensitive to acid soil conditions, it is possible that reinoculation following liming might be productive of good results on soils in which the lack of carbonate of lime had long been a limiting factor.

PEAT AS A CULTURE MEDIUM

In conducting some experiments to determine the most satisfactory medium for soil inoculating bacteria, including both the symbiotic and the Azotobacter groups, Bottomley selected peat as best satisfying the requirements because of its high potential energy. In order to make it a more satisfactory medium he first treated the peat with "humifying" bacteria and kept it at a temperature of 26° C. under optimum conditions for one week. At the end of this period steam was forced through the mass until all of the organisms were killed. The resulting material was sterile and neutral or slightly alkaline in reaction. It was then inoculated with pure cultures of B. radicicola and Azotobacter chroöcoccum and put on the English market under the name of "humogen."

It was reported that when this material is added to the soil there is a rapid accumulation of nitrogen and a rather remarkable growth of crops. On adding the bacterized peat in amounts too dilute to effect any decided improvement in the soil, beneficial results out of all proportion to the quantity of material added were reported. After further investigation Bottomley formulated the hypothesis that accessory food bodies are present which function in plant nutrition in a manner analogous to vitamines in human nutrition. These substances were given the name "auximones" and are supposed to be a product of the bacterial decomposition of organic matter.

In commenting on the subject Russell writes:

> "It would be attractive to think that some of the vague physiological conditions that trouble the grower are to the plant what beri-beri and similar diseases are to the animal—the result of withholding some essential or useful 'accessory substance.'"

Russell's investigations with "humogen" did not confirm the

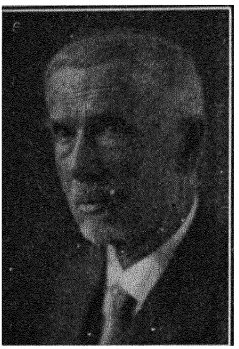
reported findings of Bottomley and the conclusion was reached that it possesses no special agricultural value beyond that of any other organic fertilizer containing the same amount of nitrogen.

SELECTED REFERENCES

1. Ashby, S. F. Some observations on the assimilation of atmospheric nitrogen by a free living soil organism Azotobacter chroöcoccum. Beyerinck, Jour. Agr. Sci., Vol. 2, pp. 34–51, 1907.
2. Beijerinck, M. W., and van Delden, A. Ueber die Assimilation des freien Stickstoffs durch Bakterien. Centr. Bakt. Par. Abt., II, Vol. IX, pp. 3–43, 1902.
3. Berthelot, M. Nouvelles recherches sur la fixation de l'azote atmosphérique par les microbes. Compt. Rend., Vol. 101, p. 775, 1885.
4. Bottomley, W. B. Some effects of organic growth promoting substances (auximones) on the growth of Lemna minor in mineral culture solutions. Proc. Roy. Soc., Lond., Ser. B, pp. 481–503, 1917.
5. Emerson, Paul. Soil inoculation with azotobacter. Iowa Agr. Exp. Sta. Res. Bul. 45, p. 64, 1918.
6. Fred, E. B. A physiological study of legume bacteria. Virginia Agr. Exp. Sta. Annual Rep., p. 145, 1911–12.
7. Gainey, P. L. Influence of the absolute reaction of a soil upon its Azotobacter flora and nitrogen-fixing ability. Jour. Agr. Res., v. 24, pp. 907–938, 1923.
8. Golding, John. Importance of removal of products of growth in assimilation of nitrogen by organisms of the root nodules of leguminous plants. Jour. Agr. Sc., Vol. 1, p. 59, 1905.
9. Headden, W. P. The fixation of nitrogen in some Colorado soils. Colorado Agr. Exp. Sta. Bul. 186, 1913.
10. Lipman, C. B., and Taylor, J. K. Do green plants have the power of fixing elementary nitrogen from the atmosphere? Jour. Frank. Inst., pp. 475–506, 1924.
11. Mameli, E., and Pollacci, G. Sull' assimilazione diretta dell' azoto atmosferico libero nei vegatali. Atti dell' Ist. Bot. dell' Universita di Pavia, Serie II, Vol. XIV.
12. Omelianski, V. L. Fixation of atmospheric nitrogen by mixed cultures. Arch. Sci. Biol. Petrograd 18, 1–40, Abst. in Chem. Abs., Vol. 18, p. 2018, 1924.
13. Russell, E. J. Report on humogen. Jour. Bd. Agr., Vol. 24, p. 20, 1917.
14. Stewart, R., and Peterson, W. Further studies of the nitric nitrogen content of the county rock. Utah Agr. Exp. Sta. Bul. 150, 1917.
15. Waksman, S. A. Principles of Soil Microbiology, Williams & Wilkins Co., pp. 103–140, 1927.
16. Whiting, A. L. A biochemical study of nitrogen in certain legumes. Ill. Agr. Exp. Sta. Bul. 179, 1915.
17. Winogradsky, S. Clostridium pastorianum, seine Morphologie und seine Eigenschaften als Butter Säureferment. Cent. Bakt. Par. Abt. II, Vol. IX, s. 43–54 und 107–12, 1902.

CHAPTER IV

NITRIFICATION



S. Winogradsky.

BECAUSE of the demand for potassium nitrate in the manufacture of gunpowder, knowledge of the means by which it could be produced had long been eagerly sought by the rulers of Europe and Asia. Consideration of the sources of the nitrates that were available soon led to the discovery that most of the deposits apparently had their origin in decomposing animal and vegetable matter. "Saltpeter plantations," subsidized by the various governments, became the recognized source of nitrates. A description of these is given by Aikman in the following statement:

"These generally consisted of heaps of mould, rich in nitrogen, mixed with decomposing animal matter, rubbish of various kinds, manurial substances, ashes, road scrapings, and lime salts. The heap was underlaid with brushwood, and was watered from time to time with liquid manure from stables, consisting chiefly of dilute urine. In forming the heap, care was taken to keep the mass porous, so as to admit of the free access of air. The heap was further protected from rain by covering it with a roof."

EARLY STUDIES OF NITRIFICATION

As early as 1862 Louis Pasteur, the brilliant French bacteriologist, had expressed the opinion that nitrification is due to an organized ferment. In 1878 Schloesing and Muntz, while attempting to effect the purification of Paris sewage by the use of soil, discovered that the process is a biological one as evidenced by the fact that it can be stopped by the use of volatile antiseptics and again started by reseeding with new soil.

Their experiment consisted in taking a glass tube one meter in length and filling this with a mixture of 5 kilos of quartz sand

and 100 grains of powdered limestone. Sewage was then supplied to the tube and allowed to pass through slowly. For some time no change was noted, but at the expiration of twenty days it was found that nitrates were present in the filtrate. In time all of the ammonia in the filtrate disappeared. The question arose as to why a delay of twenty days occurred before nitrification set in.

In order to determine whether the process is due to living organisms Schloesing and Muntz placed a small vessel of chloroform at the top of the tube and allowed the vapors to pour continuously upon the soil. Within ten days after the beginning application of chloroform, the formation of nitrates ceased. The process was not resumed, after the use of chloroform was discontinued, until the sand had been reseeded with soil from a vegetable garden.

Robert Warington, at Rothamsted, became interested in these investigations and conducted some experiments which confirmed those of Schloesing and Muntz. By passing moist air, either alone or laden with volatile antiseptics, through soil he was able to show that chloroform, phenol and carbon bisulfide are effective in preventing nitrification. The following table shows the results obtained.

TABLE VII

EFFECT OF VOLATILE ANTISEPTICS ON NITRIFICATION—WARINGTON
Nitrogen as Nitrites and Nitrates in Parts per Million

History of Soil	Experiment I	Experiment II
Original soil	6.12	8.91
Air passed through	40.87	50.86
Air with phenol	17.20	40.77
Air with carbon bisulfide	6.70	9.75
Air with chloroform	9.48	7.86

Warington also succeeded in bringing about the nitrification of a weak solution of ammonium chloride by seeding it with an extract from a soil containing nitrates, but he was unable to isolate the causal organisms even after years of exhaustive research.

ISOLATION OF NITRIFYING BACTERIA

In 1890 Winogradsky reported that the nitrifying bacteria do not thrive when grown in media containing organic matter. This accounted for the previous inability to grow them on gelatin and agar. Winogradsky prepared solutions containing only inorganic substances and found that when these solutions were seeded with small quantities of soil containing nitrifying organisms, nitrate formation proceeded rapidly. It was found that the carbon of ammonium carbonate could be utilized by the nitrate formers, the ratio of nitrogen oxidized to carbon assimilated being about 35 to 1. This was the first evidence that any organism which does not contain chlorophyll can secure the necessary carbon required for the synthesis of organic matter from inorganic sources.

The fact that nitrifying bacteria would not grow on media containing soluble organic matter made their isolation and identification difficult. Frankland and Winogradsky seeded inorganic ammoniacal solutions with soil and by continued transfer to new sterile solutions succeeded in getting practically pure cultures. Winogradsky carried this further and by spreading the cultures on gelatin and selecting from areas on the gelatin which showed no growth was able to secure pure cultures which were capable of nitrifying ammonia. In 1891 he succeeded in growing the nitrate bacteria in pure culture on gelatinous silica containing only inorganic food materials.

Warington discovered that both nitrites and nitrates are produced in the process of nitrification. By the use of solutions containing ammonia and others containing nitrites it was found possible to isolate two groups of bacteria one of which produced only nitrites and the other nitrates. Winogradsky, after further investigation, confirmed Warington's conclusions. He found that the production of nitrous acid is a function of two species of bacteria which were named Nitrosomonas and Nitrosococcus. Nitrates are produced as a result of the activities of a third species of bacteria to which were given the name Nitrobacter. Later investigations have resulted in the isolation of other species of bacteria that are also capable of producing nitrite and nitrate, respectively, from ammonia.

CONDITIONS FAVORING NITRIFICATION

Following the discovery that nitrification is caused by biological agencies Warington, realizing the significance of the process in agriculture, investigated in considerable detail the conditions affecting it. He showed that nitrification takes place only in the presence of a base such as calcium carbonate although the element calcium does not seem to be essential to the process. The formation of nitrates is hindered by light but increases with rising temperatures, the optimum being between 25° and 30° C. The process ceases entirely at a temperature of 40° C.

Studies of the drainage water from the plots of Broadbalk Field, at Rothamsted, showed that nitrates are present in them throughout the ordinary winter. Cultivation increases the rate of nitrification as does also applications of chalk. The final nitrogen product resulting from the action of the soil bacteria upon ammonium salts or nitrogenous organic matter is the nitrate.

Subsequent investigations have shown that good drainage, frequent cultivation, adequate quantities of water, warm temperatures and the presence of carbonate of lime are essential to the rapid production of nitrates in the soil. Excessive water, or the absence of oxygen from any other cause, tends to favor an anaërobic flora and may result in stopping the nitrification process entirely and in the reduction of such nitrates as may have been previously formed under more favorable conditions. Nitrification is an oxidation process.

INFLUENCE OF ORGANIC MATTER ON NITRIFICATION

It was apparently shown in earlier investigations that the presence of soluble organic matter is detrimental to the nitrifying bacteria when grown in pure cultures. Their isolation was made possible only after the discovery that they are able to utilize inorganic forms of carbon and nitrogen. When use was made of gelatinous silica media the bacteria were then isolated and subsequently grown in pure cultures. The fact that nitrification proceeds rapidly in soils which contain large amounts of organic matter makes it seem probable that the above conclusions do

not apply, at least to mixed cultures, under the conditions which obtain in the soil.

Recently Fred and Davenport isolated pure cultures of Nitrobacter and grew them on slants of organic media both in the absence and in the presence of nitrite. The Nitrobacter grew satisfactorily and retained the power of oxidizing nitrites to nitrates when transferred later to an inorganic medium containing them. However, an infusion of beef was shown to be toxic to the nitrate formers. This is explained as probably being due to the presence of some type of organic toxin in too great concentration. A number of other soluble organic substances not only had no injurious effect on the nitrate formers but some of them appeared to be beneficial.

THE NITROGEN-CARBON RATIO IN ORGANIC MATTER

Of particular significance is the fact that nitrate formation and accumulation in a soil is very definitely related to the nature of the crop residues in that soil. Thus it has been found that the quantity of nitrate nitrogen that may be produced in the soil in the decomposition of organic materials is not directly related to the quantity of nitrogen that they contain but rather to the ratio of this nitrogen to the carbohydrate content of the materials. The presence of considerable amounts of available carbohydrates tends to result in an increase in bacterial numbers with a minimum of nitrate nitrogen. Materials that are high in carbohydrates, therefore, yield up little nitrate for crop use when they are added to the soil. Other substances that contain higher ratios of protein are much more useful as sources of nitrate nitrogen to crop plants.

C. J. T. Doryland, in 1916, was the first to offer an explanation of this phenomenon. He pointed out that the soil organisms use the carbohydrate material as a source of energy while the protein material is of value largely as a source of nitrogen. In proportion as the material contains a large percentage of carbohydrate, the multiplication of soil organisms is so rapid that their nitrogen requirements may be equal to or even greater than the supply of nitrogen that is liberated as ammonia in the decay process. This results not only in there being no accumulation of

nitrates but also in a using up of any previous supply of nitrat in the soil to the end that none remains for the use of the crop In other words, there is a direct competition between the micro örganisms and the crop plants for any nitrogen that is yielde up in the process of decay of materials that are high in available carbon.

Clover residues and well rotted manure, materials that ar relatively high in nitrogen as compared to their content of carbo hydrates, yield an excess of ammonia. This is nitrified and unless leached out by water or utilized by the crop, accumulate as nitrates in the soil. On the other hand, timothy sods, straw cornstalks, strawy manure and similar materials may have negative effect on the crop that follows their being plowed unde or being cultivated into the soil. In this case the decomposin bacteria utilize all of the available nitrogen including both tha liberated in the process of decay and that already in the soil Applications of commercial nitrogen, to be effective, must b sufficiently large to meet the requirements of the microörganism and of the crop as well.

The evidence indicates that when the ratio of carbon to nitro gen in organic materials exceeds about 15 to 1, nitrification prac tically ceases. Much, of course, depends upon the nature of th organic materials and upon the quantity and form of nitroge that may already be present in the soil or may be added i fertilizer form. In the event of a yellowing of the crop as result of the plowing under of organic materials, an applicatio of nitrate nitrogen suggests itself.

SOIL REACTION IN RELATION TO NITRIFICATION

It has been repeatedly shown that applications of neutralizin agents to soils are frequently followed by marked increases in th rate of formation of nitrates in them. Thus in the following tes an acid Dekalb soil, having a lime requirement by the Veitc method of 3500 pounds of calcium carbonate, showed additiona benefit as to nitrate accumulation from much larger application of the carbonate than were required to neutralize the acid in th soil and to effect an alkaline reaction to the soil solution. I fact the optimum *p*H for nitrite and nitrate bacteria lies betwee 7 and 8.

TABLE VIII

RELATION BETWEEN CALCIUM CARBONATE USED AND NITRATE ACCUMULATED*—BEAR

Calcium Carbonate Applied per 2,000,000 Pounds of Soil	Nitrate Nitrogen after 21 Days in 100 Grams of Soil
Lbs.	Mgs.
0	7.2
1,000	9.5
2,000	12.4
4,000†	17.5
10,000	20.0
20,000	20.9
40,000	23.3

* Acid Dekalb soil—nitrogen supplied as ammonium carbonate.
† Neutral point, Veitch method.

It has usually been assumed that one of the factors limiting crop yields in acid soils is the absence of sufficient nitrates to satisfy the requirements of the growing crops. White found, however, that considerable amounts of nitrate nitrogen are present in the very acid soils of the plots receiving heavy sulfate of ammonia treatments on the Pennsylvania Experiment Station Farm at State College. It is questionable whether sufficient nitrates would be produced under such conditions to satisfy the requirements of large crop yields although it was shown that whereas the corn on these plots was an absolute failure, sufficient nitrate nitrogen was present in the soil to supply the needs of a 40-bushel crop.

NITRATE REDUCTION

As has been previously mentioned, the presence of oxygen is essential to nitrification since this is an oxidizing process. If for any reason the air is excluded, the anaërobes gain the ascendency and secure the oxygen which is needed in their life processes from that which is present in combined form in such substances as nitrates. Not only does the oxidation of nitrogen cease under such conditions but the nitrates already present are reduced to nitrites, or to ammonia. An example of the effect of an excessive amount of water, presumably to be explained in the development of anaërobic conditions, is given in the following table. In this

test 20 milligrams of nitrogen in the form of ammonium sulfate were added to 100-gram portions of soil which were incubated at room temperature for a period of three weeks.

TABLE IX

EFFECT OF EXCESS WATER ON NITRATE ACCUMULATION

Water Added in Cubic Centimeters per 100 Grams Soil	Nitrates Present after 21 Days' Incubation. Milligrams per 100 Grams Soil
16	6.5
20	8.9
24	12.3
28	14.4
32	17.3
36	1.9

DENITRIFICATION

Some reducing bacteria are able to carry the reduction only to the nitrite stage. With many of them the process continues to the formation of ammonia. Denitrification, strictly speaking, results in the production of free nitrogen from nitrates. The original discovery of this process, and of the bacteria responsible for it, may be credited to Gayon and Depetit, who isolated B. denitrificans in 1886. It was subsequently discovered that the denitrifiers are rather generally distributed. They were found in large numbers on straw and in raw manure. This caused Paul Wagner, in 1895, to reach the conclusion that the use of manure might not be advisable on soils containing available nitrates or to which fertilizer nitrogen was to be applied. Subsequent investigations by the German Agricultural Association indicated that Wagner's conclusions were not well founded although some loss of elemental nitrogen was found to take place. It is probable that the bad effects of heavy dressings of manure reported by Wagner may be accounted for in the utilization of soluble nitrogen by the bacteria which decompose cellulose in the soil. In the event of the development of large numbers of these bacteria, due to the use of liberal amounts of raw manure, they would undoubtedly compete with plants for soluble nitrogen. This would not mean

a loss of nitrogen as such but a change from the nitrate or ammonia forms to that of protein. On the other hand, the principle employed in sewage disposal plants is that of alternate oxidation and reduction with final volatilization of the nitrogen in the elemental state. Such a process may also take place in virgin soils containing large amounts of organic matter when they are first cultivated. It may also occur in soils to which very heavy applications of manure have been made.

EFFECT OF NITRIFICATION ON THE SOIL CONSTITUENTS

The effect of the nitrous acid produced during nitrification on the availability of other soil constituents has been considered by



FIG. 11.—Outlets for tile drains under plots in Broadbalk Field, Rothamsted, for purpose of studying losses of nitrates and other nutrients in drainage water of cropped soil.

some investigators to be worthy of study. Hopkins and Whiting seeded a solution, to which had been added an ammonium salt and some phosphate rock, with nitrate bacteria and set the flasks aside to incubate at 82° F. for twenty weeks. At the end of that period the amounts of soluble phosphorus and calcium were determined. On the average, it was found that for every 100 pounds of nitrogen oxidized to the nitrite form approximately 200 pounds of phosphorus were dissolved and practically twice

that quantity of calcium went into solution. If all the nitrous acid produced in the soil reacted with apatite, the phosphate mineral in soils, very much larger amounts of phosphorus would be made available than are required to satisfy the requirements of the maximum growth of plants possible from the nitrogen made available. It is evident, however, that much of this acid effect is spent in other ways in the soil.

AMMONIFICATION PRECEDES NITRIFICATION

As a precedent to the formation of nitrous acid and nitrates, the protein substances in plant and animal residues in the soil must undergo hydrolysis and ammonification. While it has been suggested that the nitrifying bacteria might be able to utilize protein nitrogen directly, it is known that the process, as ordinarily carried out in the soil, is preceded by the formation of ammonia and that under control conditions in the laboratory the use of ammonia in some form, such as the sulfate or the chloride, is essential. The discovery that nitrification is a bacterial process paved the way for additional investigations relating to the complete nitrogen cycle. As a result Muntz and Coudon showed in 1893 that between protein nitrogen and nitrous nitrogen the formation of ammonia is an essential step and that it also is the result of bacterial action.

AMMONIFYING ORGANISMS

The number of organisms which play a part in the production of ammonia from protein nitrogen is quite large. As a precedent to ammonia, amino acids and related cleavage products are formed through bacterial action, the predominating groups of bacteria being determined by the nature of the protein or other nitrogenous material and its content of other elements such as sulfur or phosphorus. One of the end products, however, is always ammonia which is present in the soil probably as the carbonate, unless it has had opportunity to combine with some stronger acid or to displace some cation in the mineral complex.

Among the bacteria most frequently mentioned as being related to this process are B. proteus, B. fluorescens, B. pro-

with these, particularly in acid soils, are certain ammonia-producing molds. Whether the soil be acid or alkaline in reaction, or whether anaërobic or aërobic conditions obtain, readily decomposable nitrogenous compounds yield up their nitrogen as ammonia and their oxygen and carbon as water and carbon dioxide. Associated with these compounds under anaërobic conditions are such gases as methane or hydrogen sulfide.

CONDITIONS FAVORING AMMONIFICATION

While ammonia is produced in soils under a great variety of conditions and by a very large number of species of organisms, the conditions which give the largest production of ammonia are as a rule quite similar to those favoring nitrification. The maximum ammonia formation is ordinarily reported to be at a temperature of about 30° C. The optimum moisture content is about two-thirds saturation. Soils which are well supplied with carbonate of lime are usually high in their ammonifying capacity. In general, that condition of the soil which is most favorable to ordinary crops and to nitrification also favors the formation of ammonia. The difference between the two processes lies in the greater range of conditions under which ammonification may proceed, undoubtedly related to the number of organisms which are capable of producing ammonia as one of their end products.

ACCUMULATION OF SOLUBLE NITROGEN IN SOILS

The quantity of ammonia found in soils is not large under normal conditions since it is usually changed to nitrates as rapidly as produced, after which it is largely either taken up by plants or leached from the soil in the drainage. The amount of nitrate nitrogen present in the soil may be considerable following periods of favorable weather and in the absence of a growing crop. With the next heavy rain, however, the nitrates present in the soil are likely to be carried to lower levels or entirely removed in the drainage water, since it has been found that the soil has little absorptive capacity for nitrogen in this form. Under ordinary conditions and with a growing crop in the soil, the total acre content of nitrate nitrogen to plow depth would probably not be in excess of 25 pounds and oftentimes much less,

while on the same soil, after a season of fallow with not too abundant rainfall, the amount of nitrate nitrogen might exceed 150 pounds per acre.

On soils which contain no carbonate of lime and in which the nitrification process has been slowed down or has practically ceased, there is some tendency for ammonia to accumulate. Ammonia is retained by soils in considerable quantities against the action of gravitational water. It has been shown that, on leaching a soil to which sulfate of ammonia has been applied, the drainage water will contain practically the equivalent of the ammonium sulfate as calcium sulfate. The original study of this problem by Way showed conclusively that soils have a very considerable capacity to remove ammonia from solutions containing it.

AMMONIA AS A NEUTRALIZING AGENT IN ACID SOILS

The explanation of the presence of nitrates in acid soils may lie in the previous production of ammonia, which serves to neutralize the nitrous acid produced with the result that nitrate formation may proceed. Under these conditions the toxic substances which occur in acid soils and which are known to be injurious to plants, particularly to certain species, may also be the limiting factors which prevent the activities of nitrifying bacteria.

Temple, in working with acid soils, came to the conclusion that ammonia is produced in such soils in excess of the nitrous acid and acts in the capacity of a base satisfying the acids present and permitting the nitrifying bacteria to function normally. Organic substances containing nitrogen are therefore believed to be preferable on acid soils. Ammonium salts of inorganic acids, such as ammonium sulfate, cannot be utilized to advantage under such conditions, since the ammonia is already combined with an acid which retains its power to combine with bases after the ammonia has been changed to nitrous acid.

FORMS OF NITROGEN USED BY NON-LEGUME PLANTS

It will be remembered that Liebig was of the opinion that plants secure their nitrogen as ammonia from the air. Later investigations showed that additional supplies of this element

are taken from the air by legumes and left behind in the soil in their residues. Finally it was found that ammonia is formed in the process of decomposition of protein compounds in the soil. The final nitrogen product of the activities of the soil organisms in productive soils was shown, however, to be nitrates. Applications of nitrate of soda were found to be effective in increasing crop yields. It has, therefore, come to be generally believed that nitrates are the direct source of the nitrogen utilized by all non-legume plants. Even though ammonia salts are applied to the soil, the change to nitrates is sufficiently rapid, assuming that the soil contains adequate amounts of carbonate of lime to neutralize the nitrous acid produced, to explain the good effects noted as a result of supplying the plant with additional quantities of nitrate. The tendency, therefore, is to consider that nitrate nitrogen is the only form used by non-legume plants.

It is apparent, however, that certain plants are found growing under conditions in which nitrate production is retarded or entirely stopped. An interesting discussion and investigation of paddy rice, as related to the problem of nitrogen assimilation, is given by Nagaoka, who showed that the nitrates were only about 40 per cent as effective as ammonia salts as sources of this element in rice fertilizers. He suggests that the nitrates are probably reduced to nitrites under the conditions in which paddy rice is grown and that these are toxic to plants when present in any considerable concentration.

Nitrification is known to proceed best in soils containing sufficient carbonate of lime to neutralize the nitrous acid produced. It is a well-known fact that many plants grow on soils which are distinctly acid in reaction and contain no basic carbonates. Some plants, for example, cranberry, sorrel, rhododendron and broomsedge, grow on strongly acid soils, while many other plants are not particularly sensitive to the lack of bases in the soil.

Hall believes that plants growing on acid soils are able to utilize ammonia. Experiments on soils which had become acid as a result of the use of liberal amounts of sulfate of ammonia indicated that those plants which fail to thrive are those which require nitrates. This point of view is also expressed by Coville. White, as previously mentioned, questions the accuracy of the conclusion that nitrates are not produced in acid soils and believes

that the limiting factor in the growth of certain crops under such conditions is something else.

A considerable amount of investigational work has been carried on in which plants were supplied with various forms of nitrogen in an attempt to determine their specific requirements in this regard. Summarizing these investigations Hutchinson and Miller write:

"As regards ammonium salts, the results obtained by Griffiths and Maze seem to prove conclusively that beans and maize assimilate nitrogen in this form as readily as nitrates. The same may be said of Kossowitsch's experiments with peas. Breal's results may also be considered to establish the

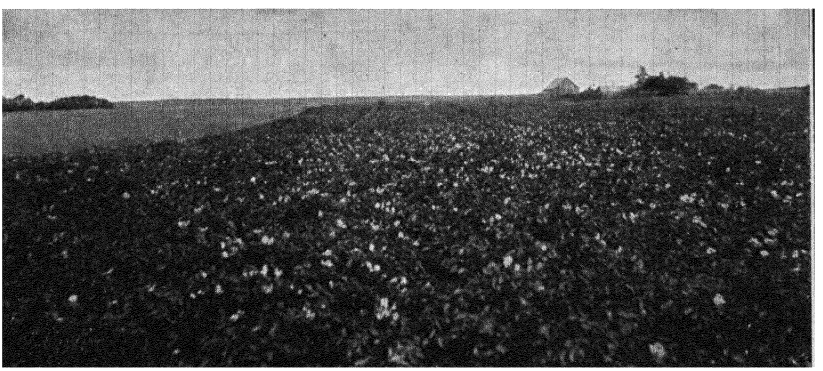


FIG. 12.—Field of potatoes in Aroostook County, Maine, which received 1500 pounds per acre of a 5–8–7 analysis.

utilization of ammonia by Poa annua. The results obtained by Pitsch, Muntz, Gerlach and Vogel, and Kruger indicate that the various plants employed are able to grow in the absence of nitrates, but fail to prove that ammonia was the sole source of nitrogen.

"As regards organic compounds, the great majority have been negative, if not uncertain results. More or less satisfactory evidence of assimilation has been obtained with the following compounds—methyl, amyl, and allyl amines, dimethylamine, acetamide, choline, betaine, leucine, urea, dicyanodiamide, aspartic acid, asparagine, glutamine, allatoin, uric acid, hippuric acid, tyrosine and humic acid. The gains in nitrogen have, however, generally been very small and in many cases negative results have been obtained by other investigators."

In many of the tests referred to there is some question as to whether the possibility of nitrification had been precluded.

Hutchinson and Miller conducted a number of experiments with wheat and peas to determine the forms in which nitrogen could be assimilated by these plants. The seeds were sterilized by treating them with a warm mercuric chloride solution after the removal of any air bubbles by means of a vacuum pump. They were then washed with sterile water and transferred to Petri dishes and a sterilized 1.25 per cent agar solution was added. The seeds were incubated at 20° C. After they had germinated and formed roots 1 to $1\frac{1}{2}$ inches long, they were transferred to sterile test tubes for a few days and then to Woulff's bottles.

As a result of their investigations, Hutchinson and Miller state that peas are able to assimilate ammonia, acetamide, urea, barbituric acid, alloxan and humates. Certain other plants appeared able to utilize formamide, glycine, amino propionic acid, oxamide and peptones.

Most of the experiments on feeding plants with the several forms of nitrogen have consisted in supplying one nitrogenous substance at a time. In considering the complex protein molecule as a condensation product of amino acids, it would seem more logical in every case to add the several units which are known to be present in the proteins of the plant under experiment. In the presence of one unit and the absence of others, the plant must be able to tear apart the one supplied and reconstruct the other units from it.

Comparative field trials have been frequently made between nitrate of soda, sulphate of ammonia and organic sources of nitrogen. As a rule the crop yields have been increased most by the nitrates, with sulphate of ammonia a close second. The process of nitrification proceeds without delay in normal soils and therefore the plant has had little opportunity for choice as to the form of nitrogen to be used. Many times the differences in yield of crops accompanying the use of these materials can be accounted for from the effect of the residues left behind in the soil. Nitrate of soda is physiologically alkaline and sulphate of ammonia leaves an acid residue.

"HUMUS THEORY" MODIFIED

It will be recalled that Liebig disposed of the old "humus theory" as being absurd and said that humus was of no direct

value to plants. Knudson who worked on the food value of carbohydrates to plants has the following to say on this subject:

"It is, of course, recognized that plants may grow and mature in the absence of organic material from the substratum. However, the fact that in many soils a rich microbial flora exists, postulates the presence of directly available organic substances or of substances made available by extracellular digestion. Since there is no reason to assume that permeability or metabolism in fungi and bacteria differs from that in higher plants, it is logical to conclude that, in general, what is available for the fungus is likewise available for the higher plant. In this connection it is significant that there exists among the phanerogams, plants devoid of chlorophyll, which necessarily derive all of their organic material from the soil."

Knudson's research consisted in supplying plants with carbohydrates under sterile conditions and determining as to whether the plants were able to use them directly. It was found that corn was able to assimilate the sugars and that increased growth resulted. This was particularly true with glucose and fructose but also with sucrose and maltose. This would make it appear that it was not illogical to expect similar results from the use of amino acids and other products of protein decomposition.

In the process of decomposition of plant and animal residues in the soil the proteins are hydrolyzed to form amino acids, which are acted on by bacteria with the resulting formation of ammonia, nitrous acid and nitrates. While it is evident that many plants seem to utilize nitrates to best advantage, it would appear logical that they would also be able to use some of the intermediate soluble products of protein decomposition.

There is sufficient evidence to justify the belief that organic decomposition products in the soil represent a supplemental source of partially synthesized compounds for plant use. The known good effects of organic matter in the soil may be due in part to its being a source of these substances. As to how important this is in the production of large crop yields is not known. It has been demonstrated, however, that the presence of organic compounds is not essential to crop growth since it has been found possible to grow plants successfully in purely inorganic media both in water and in pure quartz sand.

The relative amounts of ammonia and nitrates present in the soil are quite likely to vary with the reaction of the soil. It is

altogether probable that plants which tolerate acid soils are able to utilize ammonia to better advantage than those which grow best on neutral or alkaline soils. The requirements of different species of plants may be quite variable also. The presence of nitrates, ammonia and a variety of partially synthesized nitrogenous compounds may satisfy the requirements better than the presence of any one compound by itself. This is the condition which obtains in the most productive soils.

FORMS OF NITROGEN USED BY LEGUMES

It is known that legumes make use of nitrate nitrogen when it is supplied to them. The application of small quantities of nitrate to young alfalfa has been shown to have a marked effect in getting it started. Apparently, in the absence of nodules, legume plants utilize the nitrogen in the soil in the same way and in the same form or forms as do other plants. When the nodule bacteria begin to function, the free nitrogen from the soil air is made available to the legume through their help. The form in which the nitrogen is accumulated by the bacteria and the form in which it is transferred to the legume are not definitely known. Ammonia has been separated from the nodules but it is thought possible that this may have been derived from asparagin, which has been shown to be present, in the process of distillation in the laboratory.

Strowd found that nodules from Ito San soybeans contained 5 per cent of nitrogen when air dry. Of this, 30 to 40 per cent was soluble in water while from 40 to 55 per cent was soluble in 10 per cent salt solutions or in dilute alkali. About 3 per cent of the water-soluble nitrogen was in the form of protein or proteose. Approximately 16 per cent of the total water-soluble nitrogen was in the form of primary amino nitrogen and 19.3 per cent as amide nitrogen. In so far as the legume itself is concerned, it is apparent that it does not differ radically from other plants as to the form of nitrogen required. It is probable, however, that a part of the synthetic process is carried on by the nodule bacteria which are able to start with elemental nitrogen instead of the usual nitrate form.

SELECTED REFERENCES

1. Bear, F. E. A correlation between bacterial activity and lime requirement of soils. Soil Sci., Vol. IV, p. 445, 1917.
2. Coville, F. V. The agricultural utilization of açid lands by means of acid tolerant crops. U. S. D. A. Dept. Bul. 6, 1913.
3. Doryland, C. J. T. The influence of energy material upon the relation of soil microörganisms to soluble plant food. North Dakota Agr. Exp. Sta. Bul. 116, 1916.
4. Fred, E. B., and Davenport, A. The effect of nitrogenous compounds on the nitrate-forming organism. Soil Sci., Vol. XI, pp. 389–404, 1921.
5. Gayon, V., and Dupetit, G. Recherches sur la réduction des nitrates par les infiniment petits. Mémoirs de la Société des Sciences physiques et naturelles de Bordeaux, p. 107, 1886.
6. Gibbs, W. M. The isolation and study of nitrifying bacteria. Soil Sci., Vol. 8, pp. 427–481, 1919.
7. Hall, A. D. Fertilizers and Manures, Dutton & Co., pp. 62–64, 1910.
8. Hopkins, C. G., and Whiting, A. L. Soil bacteria and phosphates. Illinois Agr. Exp. Sta. Bul. 190, 1916.
9. Hutchinson, H. B., and Miller, N. H. J. The direct assimilation of inorganic and organic forms of nitrogen by higher plants. Cent. F. Bakt. Abt. 2 Bd. 30, pp. 513–547, 1910.
10. Knudson, Lewis. Influence of certain carbohydrates on green plants. Cornell Agr. Exp. Sta. Mem. 9, 1916.
11. Müntz, A., and Caudon, H. La fermentation ammoniacale de la terre. Compt. Rend., Vol. 116, pp. 395–398, 1893.
12. Nagoaka, M. On the behavior of the rice plant to nitrates and ammonium salts. Bul. Col. Agr. Tokio Imp. University, Vol. II, pp. 285–334, 1904.
13. Schloesing, T., and Müntz, A. Sur la nitrification pour les ferments organises. Compt. Rend., Vol. 84, pp. 301–303, 1877.
14. Strowd, W. H. The forms of nitrogen in soybean nodules. Soil Sci., Vol. XI, pp. 123–130, 1921.
15. Temple, J. C. Nitrification in acid or non-basic soils. Georgia Agr. Exp. Sta. Bul. 103, 1914.
16. Vorhees, E. B., and Lipman, J. G. A review of investigations in soil bacteriology. U. S. D. A. office of Experiment Stations, Bul. 194, 1907.
17. Warington, Robert. On nitrification. Jour. Chem. Soc., Vol. 33, pp. 429–456.
18. —— On nitrification. U. S. D. A. Office of Experiment Stations, Bul. 8, pp. 42–94, 1892.
19. Way, J. T. On the power of soils to absorb manure. Jour. Roy. Agr. Soc., England, Vol. II, pp. 313–379, 1850.
20. Wagner, P. Die geringe Ausnutzung des Stallmiststickstoffs und ihre Ursachen. Deut. Landw. Presse, Vol. 92, p. 98, 1895.
21. Waksman, S. A. Principles of Soil Microbiology, Williams & Wilkins Co., pp. 504–519, 1927.
22. White, J. W. Nitrification in relation to the reaction of the soil. Penn. Agr. Exp. Sta. Annual Report, pp. 70–84, 1913–14.
23. Winogradski, S. Recherches sur les organismes de la nitrification. Ann. Inst. Pasteur, Vol. 4, pp. 213–257 and 760–771, 1890.

CHAPTER V

NITROGEN ECONOMY IN SOILS



J. G. Lipman

EARLY in the history of the study of soils consideration was given to their content of nitrogen and to the quantities of this element that are removed from them by crops. Boussingault kept the first "bank account" of nitrogen income and outgo from the soil under field conditions, records of which were published in 1841. These studies, as well as those of Liebig and of Lawes and Gilbert, were designed to solve the problem of the source of the nitrogen required to replace that sold in crops or livestock from the farm and not returned in the form of manures. When it was later discovered that the soil nitrogen becomes available through biological agencies and that nitrogen fixation is a function of several groups of soil bacteria, there still remained the problem of determining the relation to each other of all the factors involved in the nitrogen economy in the soil.

NITROGEN CONTENT OF SOILS

The content of nitrogen in soils varies between wide extremes, being dependent upon the quantity of organic matter which they contain. The original igneous rocks contained no nitrogen. That which is accumulated in soils in the form of plant and animal residues had its origin in the atmosphere from which it was fixed by chemical and biological means. The ratio of the quantity of organic matter to that of nitrogen is fairly constant, being normally about 20 : 1. A somewhat more constant ratio is that of organic carbon and nitrogen which is usually about 10 : 1.

As would be anticipated from what is known about the

variations in the quantity of organic matter in soils, some soils are very rich in nitrogen while others are very deficient in this element. The following table gives the average nitrogen content of a number of different types of soils and of their subsoils as reported by Hopkins for the state of Illinois.

TABLE X

POUNDS OF NITROGEN IN AN ACRE OF SOIL—HOPKINS

Soil Type*	0–6⅔ ins.†	6⅔–20 ins.	20–40 ins.	0–40 ins.
Deep peats	34,880	64,980	97,730	197,590
Black clay loams	7,230	7,470	3,210	17,910
Brown silt loams	5,035	5,920	3,570	14,520
Brown loams	4,720	6,660	4,150	15,530
Deep-gray silt loams	3,620	2,250	2,280	8,150
Brown sandy loams	3,070	3,920	4,160	11,150
Yellow-gray silt loams	2,890	2,710	3,240	8,840
Gray silt loams	2,880	3,210	3,240	9,330
Drab silt loams	2,800	3,160	3,400	9,360
Yellow fine sandy loams	2,170	2,610	2,730	7,510
Yellow silt loams	2,020	2,050	2,410	6,490
Light-gray silt loams	1,890	1,920	2,100	5,910
Sands	1,440	2,070	3,100	6,610

* These soil types are found in considerable areas in the North Central States.

† This is on the assumption that there are two million pounds of soil in an acre for each depth of 6⅔ inches.

Ordinarily the percentage content of nitrogen decreases with the depth until a certain point is reached at which it remains practically constant. The entire quantity present in the soil and subsoil is often quite large and would be sufficient to supply large yields of crops for many years, assuming that it could be made available as required. When soils are first placed under cultivation the rate at which their nitrogen becomes available is usually fairly rapid. As time goes on and that part of the organic matter which undergoes decomposition quite readily has yielded up its nitrogen in available forms, the residues which remain become largely those that for some unknown reason are very resistant to decay and their nitrogen is, therefore, of little value for crop-producing purposes. Fresh crop residues and animal manures are of greater importance than these humus

materials as sources of organic matter and nitrogen, particularly if their nitrogen content is sufficiently high to permit of their yielding up more of this element in available form than is required by the bacteria of decomposition.

FACTORS INFLUENCING NITROGEN ECONOMY IN SOILS

The farmer has the problem of maintaining the supply of nitrogen in the soil at a point which will prevent its lack or its excess from being a limiting factor in crop growth. As the nitrogen of plant and animal residues in the soil is changed to ammonia in the process of decomposition and that which is not consumed by microörganisms is oxidized to the nitrate form, this latter part may either be utilized by crop plants or carried off in the drainage water. In either case it is removed from the soil. To compensate for such losses, there are to be considered the nitrogen that is carried to the soil in combined form in the rainwater, that secured from the soil air by nitrogen-fixing bacteria, and that which may be supplied in the form of manures or fertilizers.

The point of equilibrium between nitrogen income and outgo is determined by a variety of factors among which may be mentioned the conditions as to drainage and aëration in the soil, the temperature, the rainfall, the texture of the soil, the soil reaction, the cropping system and the manurial and fertilizer treatments which the soil receives. The data presented in the following tables must be interpreted with these factors in mind.

NITROGEN REMOVED IN CROPS

The quantity of nitrogen that is removed from the field in crops depends upon the species or variety to which they belong, their age, the part of the plants harvested, the composition of the soil and the favorableness of the conditions of growth. The total amount of nitrogen removed from the soil will vary from as much as 150 pounds per acre in a 100-bushel crop of corn to perhaps very little in the case of legumes, which are assumed to secure a large portion of their nitrogen from the soil air through the agency of the nodule bacteria. From averages of all analyses on record Morrison gives the percentage of nitrogen in the four

common farm crops as indicated below from which calculations are made that give some indication of the acre requirements of those crops.

TABLE XI

NITROGEN REQUIREMENTS OF CROPS *—MORRISON

Crops	Percentage Nitrogen	Possible Acre Yields, Weights	Nitrogen Content, Pounds
Corn:			
Grain	1.61	100 Bu.	90
Stover	0.96	3 T.	58
Cobs	0.32	½ T.	3
Oats:			
Grain	1.97	100 Bu.	63
Straw	0.58	2½ T.	29
Wheat:			
Grain	1.97	50 Bu.	59
Straw	0.50	2½ T.	25
Clover:			
Hay	2.00	4 T.	160

† The percentage content of nitrogen and other nutrients for a number of other plants and parts of plants is given on page 102.

It is not safe to assume that since 100 bushels of average corn contain 90 pounds of nitrogen that this is the quantity of nitrogen that has been removed by the crop from an acre of soil from which 100 bushels of corn have been harvested. As the yield of a crop increases the percentage content of nitrogen usually decreases. This is in part because of a greater relative accumulation of carbohydrate material with increasing yields and in part because the supply of nitrogen in the soil is usually so limited that a large yield of any crop does not have as much of this element at its disposal as could be utilized in the construction of proteins.

The ratio of grain to stalk or of root to top of plants also varies within rather wide limits. For example, in the above table the ratios given as to grain, stover and cobs are probably fairly good averages for the corn crop. But with weather and soil conditions that favor vegetative growth, or for the silage varieties of corn, very different figures would be expected.

DRAINAGE LOSSES OF NITROGEN

Some interesting data on drainage losses are available in the lysimeter experiments at Cornell. In these studies use was made of a Dunkirk clay loam soil, having a nitrogen content in the first foot of 0.134 per cent. In their investigations with this soil, Lyon and Bizzell found that the rate of loss of nitrogen in the drainage from this soil was correlated rather definitely with the quantity of drainage water. The rather surprising feature of these investigations thus far has been the relatively small amount of nitrogen that is in the drainage from cropped lysimeters. Excluding the first year, in which the loss was abnormally high due to the fact that the soil had been disturbed in moving and oxidation had probably been considerably increased as a result, the average annual loss from well-manured, cropped soil amounted to only 3.4 pounds per acre. It was shown that the nitrogen losses in drainage were least in the presence of mixed grasses although the nitrogen removed by them from the soil, as shown by analysis, was the smallest of any of the crops under observation. In the absence of vegetation, the nitrogen losses averaged nearly 100 pounds per acre annually, equal to half of the quantity that was applied in the form of manure.

The texture of the soil is a very important factor in determining the rate of nitrification and the subsequent loss of the nitrates in the drainage water. For this reason the problem is most serious in sandy soils, especially if they happen to be in a warm, moist climate. The possibilities of losses of nitrate fertilizers under such conditions are shown in the lysimeter tests with citrus fruit trees in Florida, as reported by Collison and Walker, where a large part of the nitrate was found in the drainage water. However, as this experiment progressed and the trees in the tanks grew larger, the losses were very considerably curtailed for the reasons that a larger part of the soil water was returned to the air by transpiration and that more nitrate was utilized by the trees.

From data reported by Dole and Stabler and by Clarke it is possible to check the accuracy of the lysimeter test as applied to large areas of land. For example, the amount of nitrogen in the Miami River above Dayton, in the limestone area of Ohio, as

determined for the year 1906–07, indicated an annual acre loss from the soil of that watershed amounting to 4.4 pounds per acre. Similarly in the Muskingum River above Zanesville, in the sandstone and shale area of Ohio, the nitrate nitrogen amounted to 1.13 pounds per acre as applied to the entire watershed. The percentage of cultivated land is considerably higher in the watershed of the Miami. This is also true of the nitrogen content of the soil. The results of the calculation indicate that, on the whole, the soil is rather economical with its nitrogen supply, as the lysimeter tests indicate, and that the loss in this manner has probably not been any greater than the gain in the rainfall.

It may be well to add that the nitrogen found in river water is only a part of that removed from the soil either as dissolved or suspended material. Nitrate nitrogen, under some circumstances, may be transformed into nitrogen gas. There is also the possibility of the transfer of colloidal organic matter from the surface to the subsoil where it is beyond the reach of the bacteria of decomposition.

LOSS OF NITROGEN BY DENITRIFICATION

The extent of the loss of nitrogen through denitrification is not so definitely known. The denitrifying bacteria, when grown under laboratory control and under anaërobic conditions, are able to decompose nitrates in the soil with the liberation of free nitrogen. The conditions which favor denitrification are those in which the soil is excessively wet for a considerable length of time. This was shown by Warington who found that soils saturated with water decompose applied nitrates with the evolution of nitrogen gas. The data are not sufficient to permit of any very definite statement as to the losses which occur under field conditions. It is probable, however, that any nitrate nitrogen which may have previously accumulated or may have been supplied to a soil will be lost to the atmosphere under conditions in which the soil is not sufficiently drained and remains saturated for considerable periods of time following heavy rains. As previously mentioned, denitrification must be considered in connection with the use of nitrogenous fertilizers on paddy rice and on other crops grown under similar conditions. Heavy applica-

tions of raw manure or of coarse organic matter may also cause some loss of nitrogen by denitrification.

NITROGEN CONTENT OF WEEDS

Of interest also is the nitrogen content of weeds. These serve in the capacity of competitors with crop plants, but they may also have a function in connection with the economy of nitrogen and other elements in the soil by reason of their competition with the drainage water for the salts in solution. Analyses reported by Millspaugh and others by Ince of a few of the common weeds are given below.

TABLE XII

NITROGEN CONTENT OF SOME COMMON WEEDS—MILLSPAUGH

Common Name	Scientific Name	Per Cent Nitrogen *	Pounds per Ton
Sorrel	Rumex acetosella	1.38	28
Ox-eye daisy	Chrysanthemum levcan	2.12	42
Broomsedge	Andropogon scoparius	0.78	16
Rag weed	Ambrosia artemisifolia	1.36	27
Pigweed	Amaranthus retroflexus	2.60	62
Mustard	Porassica juricea	3.75	75

* Air dry basis.

The Amaranthus is reported to be very high in its content of nitrate nitrogen. It is possible that such plants could be employed as an agent for the removal of nitrates from the soil where for any reason this might seem desirable.

COMBINED NITROGEN IN RAINWATER

It will be recalled that Lawes and Gilbert tested Liebig's conclusions as to the sufficiency of the ammonia in rainwater as a source of the nitrogen of plants and concluded that the quantity present was by no means adequate, the amount thus secured being estimated at from 6 to 7 pounds per acre. Later, more exact determinations, summarized by Russell and Richards and covering the period from 1888 to 1916, showed an average acre content of ammoniacal and nitric nitrogen in the rainfall at

Rothamsted amounting to 3.97 pounds. To this may be added that recorded as being in organic forms and estimated at 1.35 pounds per acre, making a total of 5.32 pounds from an average rainfall of 28.8 inches.

A review of the literature on this phase of the subject, by Wilson, shows that the nitrogen content of rainwater has usually been found to be from 5 to 8 pounds per acre annually. Occasional reports have indicated much larger quantities amounting to as much as 15 to 20 pounds. In his investigations at Ithaca, New York, covering the period from 1915 to 1920, Wilson found an average of 12.51 pounds per acre of ammoniacal and nitric nitrogen with a rainfall of 29.3 inches. There is some question as to how correctly this figure may represent the nitrogen in the rainfall of that locality. It is possible that the high quantities noted for three years may be related to the enlarged industrial activities associated with the World War. For the two-year period from May, 1918, to May, 1920, the average was slightly less than 4 pounds per acre. Ames reports the nitrogen content of the rainwater at Wooster, Ohio, at from 6 to 7 pounds per acre, with an average rainfall of 37.9 inches.

No very definite correlation is apparent between the amount of combined nitrogen in the rainwater and any contributing agent. In general it may be said that the amount tends to be larger with increased rainfall and perhaps also with the nearness to industrial centers. Probably the quantity that is added in rainwater over much of the agricultural areas of the humid sections of America would not amount to more than 5 or 6 pounds per acre annually.

NITROGEN FIXATION BY NODULE BACTERIA

The experiments designed to determine the quantities of nitrogen that are secured from the air through the agency of legume bacteria may be classified into three groups:

1. Comparisons of the nitrogen content of legumes and non-legumes grown on equal areas of similar soil.

2. Comparisons of the nitrogen content of inoculated and uninoculated legume crops grown on equal areas of similar soil.

3. Analytical records of the nitrogen content of the soil of a

given area before and after the growth of the legume, together with records of the nitrogen in the seed and water added and that removed in the crop and drainage water.

NITROGEN CONTENT OF LEGUMES AND NON-LEGUMES

As early as 1860 Lawes and Gilbert pointed out that legume plants contain much larger amounts of nitrogen than do non-legumes when grown on the same soil. As an average of three years data they had found the nitrogen content of the cereal crops at Rothamsted to be approximately 30 pounds per acre as compared to 120 pounds contained in an acre of clover. However, the difference in nitrogen content of a legume and any given non-legume grown on the same land may not represent the nitrogen gained through the agency of the legume and its associated bacteria, since the several non-legumes also differ markedly in their capacity to take nitrogen from the soil. Hiltner classifies the non-legumes into two groups, the "nitrogen wasters" and the "nitrogen conservers." Of the latter group he mentions in particular the rape plant. Analysis shows that this plant in common with several well-known weeds such as purslane and field daisies may contain percentages of nitrogen equal to or greater than those of the clovers.

In this connection the conclusion of Lyon and Bizzell that the rate of nitrification in soils is influenced by the growing crop is pertinent. Maize and clover were shown to have markedly stimulating effects on nitrate formation. Timothy and some of the grasses were found to depress nitrification. Of particular interest is the possibility that legumes, by reason of their favorable effect on nitrification, may thereby be enabled to secure larger amounts of nitrogen from that stored in the soil organic matter than is ordinarily supposed. If the comparison is to be between a legume and a non-legume perhaps a member of the "nitrogen conserver" group should be selected.

NITROGEN IN INOCULATED AND UNINOCULATED LEGUMES

Numerous examples of this type of investigation are found in the literature. Among the more recent may be mentioned the data reported by Arny and Thatcher on first crop, second season,

sweet clover and alfalfa grown on moderately productive soil. In their tests it was shown that the nitrogen content of the former, calculated from the tops and roots produced on plots of three square yards, was increased by inoculation on limed soil at the rate of 133 pounds per acre. Similarly, 118 more pounds of nitrogen per acre were found in inoculated than in uninoculated alfalfa. Fred found an increase from inoculation in the nitrogen content of the tops, roots and nodules of soybeans, calculated from the crops grown on an area of 137.5 square feet of sandy soil amounting to 57 pounds per acre.

Such a method of calculation would apparently not exaggerate the nitrogen-fixing capacity of the nodule bacteria, since it is difficult to find an area of the legume crop which is not at least partially inoculated. However, the foraging power of the legume plant for soil constituents must be considerably increased as a result of the better growth following inoculation. The work of Arny and Thatcher shows that not only are the quantities of the mineral constituents in legumes thus increased, but that the actual percentages may be larger. The increase in the nitrogen content of legumes may, therefore, represent a saving as well as a fixation. Taken in connection with the fact that legumes stimulate nitrification, this would throw considerable doubt on the validity of the argument that differences in nitrogen content due to inoculation represent the fixation by the nodule bacteria of legumes.

The following conclusion of Hopkins, drawn from this type of investigation, is interesting in this connection:

"On normally productive soils, one-third of the nitrogen contained in legumes is taken from the soil, not more than two-thirds being secured from the air. This proportion would apply to the nitrogen content of the roots as well as to the tops; so that, if one-third of the nitrogen of the entire plant is in the roots and stubble and two-thirds in the crop harvested, the soil would neither gain nor lose in nitrogen because of the legume crop having been grown, the soil having furnished as much nitrogen to the plant as remains in the roots and stubble."

ANALYTICAL RECORD OF NITROGEN IN SOIL AND CROP

Of the more exact methods involving analyses of the soil, seed, and water, and of the crops removed, the pot tests of Hartwell and Pember merit particular mention. These inves-

tigators studied the nitrogen economy in Warwick sandy loam soil accompanying the growth of cowpeas, soybeans, crimson clover and adzuki beans, using vetch as a winter cover crop. Most satisfactory growth was reported for the first two. Summarizing their investigations they wrote:

"The approximate five-year net gain of nitrogen in the presence of these two crops (cowpeas and soybeans) and the vetch which was grown alternately with each, was a ton of nitrogen per acre, about seven-tenths of which was contained in the twenty-five tons of moisture free summer crop removed, and the remainder in the soil itself."



FIG. 14.—Cylinders used in nitrogen economy studies at New Jersey Agricultural Experiment Station.

This indicates that the fixation processes may be quite rapid where the conditions are kept at or near the optimum. The original soil contained 0.150 per cent of nitrogen. That in the soybeans pots had a nitrogen content of 0.1981 per cent and of the cowpea pots of 0.194 per cent at the end of the five-year period. A point would probably soon have been reached at which the legume would have made larger use of the nitrogen previously fixed and made available through nitrification.

Another interesting test which not only shows a complete record of the nitrogen in the soil and crop but also permits a comparison of inoculated and uninoculated legumes is given below. In this test three successive crops of soybeans were grown in pots

in an acid sandy soil after which nitrogen determinations were made both of the soil and of the crops that had been harvested.

TABLE XIII

POUNDS * NITROGEN FIXED BY SOYBEAN BACTERIA—FRED

	Limed Soil		Unlimed Soil	
	U	I	U	I
Soil at beginning	1165	1165	1165	1165
Soil at end of three years	1016	1034	1003	1042
Crop, leaves and stems	139	453	333	511
Taken from soil	148	130	161	122
Taken from air	−9	323	172	389

U = Uninoculated; I = Inoculated.
* Per acre of soil and crop.

This test is of considerable interest by reason of the fact that it shows that the nitrogen content of the soil is not necessarily increased by growing legumes, if the legumes are harvested and removed from the field. The test also indicates that inoculation, even without the use of lime, may be very effective for soybeans when they are grown on quite acid soil as was used in this experiment. Under the most favorable circumstances, that is, when the soil was both limed and inoculated, the average annual fixation of nitrogen associated with the growing of soybeans amounted to nearly 130 pounds per acre.

The sweet clover crop is of especial importance in this connection by reason of its usefulness as a catch crop in general farming. Some very significant data are presented below which give an idea of the value of this crop for green manuring purposes both by reason of its content of nitrogen and of the inorganic nutrients as well. In this test the crop was harvested May 10 at the time when it might have been plowed under previous to planting corn. While one cannot say that all of the nitrogen that was contained in the crop had been secured from the free nitrogen of the soil air, it seems safe to assume that a large portion of it was fixed by the nodule bacteria.

TABLE XIV

POUNDS OF PLANT NUTRIENTS IN AN ACRE OF SWEET CLOVER *—WHITING

Elements	2600 Pounds Tops	3100 Pounds Roots	5700 Pounds Total	Elements Required by	
				100 Bu. Corn	50 Bu. Wheat
Nitrogen	108.7	110.7	219.4	150.0	96.0
Phosphorus	7.3	5.7	13.0	23.0	16.0
Sulfur	13.3	13.2	26.5	15.3	11.8
Potassium	36.0	17.8	53.8	71.0	58.0
Calcium	40.4	14.4	54.8	22.0	11.0
Magnesium	12.3	12.2	24.5	17.0	8.0

* Crop harvested May 10.

NITROGEN FIXATION BY NON-SYMBIOTIC BACTERIA

In most of the investigational work on nitrogen fixation no attempt has been made to differentiate between the work of the bacteria growing in the nodules on the roots of legumes, the activities of the nodule bacteria when living in the soil in the absence of legumes, and the contributions of the Azotobacter and other free-living, non-symbiotic, nitrogen-fixing bacteria in soils. Laboratory studies have shown that under controlled laboratory conditions and when suitable amounts of carbohydrate, soluble phosphate and calcium carbonate are added to bare soil, a rapid accumulation of nitrogen takes place. A rate of fixation of more than 200 pounds per two million pounds of soil in from two to three weeks time has frequently been noted. The rate at which nitrogen is fixed in bare soil under field conditions is undoubtedly not so rapid, as a rule. However, a part of the responses of crops to applications of acid phosphate, limestone and molasses that have been noted in experimental tests of these materials may safely be credited to their stimulating effects on bacterial activities in soils of which those of the non-symbiotic nitrogen-fixing bacteria may be an important part.

Some interesting figures are presented by Hall which have a bearing on this subject. In 1904 some analyses were made of the soils in the Broadbalk and Geescroft fields of the Rothamsted

Experiment Station in England which had been allowed to run wild since 1881 and 1883, respectively. During this period of undisturbed vegetation the following species of plants in the percentages noted took up their residences on these areas.

TABLE XV

HERBAGE PERCENTAGES ON AREAS LEFT UNDISTURBED FOR TWENTY YEARS—HALL

Plant Groups	Broadbalk	Geescroft
Graminæ	59.64	95.26
Leguminosæ	25.31	0.43
Miscellaneæ	15.05	4.31
	100.00	100.00

Analyses of the soils to a depth of 27 inches had been made previous to the time the areas were turned wild. The following figures show the nitrogen content of these soils before and after this period.

TABLE XVI

NITROGEN ACCUMULATIONS IN SOILS OF UNDISTURBED AREAS—HALL

	1881–83	1904
Broadbalk:	Per Cent	Per Cent
First 9 inches	0.1083	0.1450
Second 9 inches	0.0701	0.0955
Third 9 inches	0.0581	0.0839
Geescroft:		
First 9 inches	0.1081	0.1310
Second 9 inches	0.0739	0.0829
Third 9 inches	0.0597	0.0652

It was Hall's opinion that the nitrogen accumulation on the Geescroft field would have to be accounted for on the basis of the activities of such organisms as Azotobacter. In this field, in the almost entire absence of legumes, the nitrogen increase amounted

to more than 60 pounds per acre per year. In the Broadbalk field the accumulation averaged 92 pounds per acre annually.

It is evident that a part of the accumulation of extra nitrogen in the soil of these undisturbed areas may be due to the fact that insects and small animals harbor and die in such areas. There are also the droppings of birds to be considered.

Of interest in connection with the consideration of this problem is Lipman's statement that "from the data at present available different investigators have estimated the quantity of nitrogen fixed by Azotobacter at 15 to 40 pounds per acre per annum." This would apparently be somewhat high for ordinary field conditions but perhaps not too high if the statement were made to include all of the non-symbiotic, nitrogen-fixing bacteria.

NITROGEN FIXATION AS RELATED TO NITROGEN CONTENT OF SOILS

The growing of a leguminous crop may not always result in accumulating additional stores of nitrogen. Swanson reports that soils on which alfalfa had been grown continuously for periods of from twelve to thirty-three years did not contain as large amounts of nitrogen as did nearby native sod land, although both the alfalfa soil and the native sod soils contained more nitrogen than did the cropped soils. As an average of all the analyses reported, the nitrogen content of the alfalfa soils was 3650, of the native sods 3735, and of the cropped soils 2705 pounds per acre to plow depth.

An interesting comment on this phase of the subject is given by Bonazzi in a study of carbohydrate utilization by Azotobacter in the presence of nitrates. As a result of his investigations, the conclusion was reached that as long as available nitrates are present the Azotobacter serve as nitrate conservers. Only after the nitrates have been utilized does "a second physiological phase set in, in which the cells assimilate atmospheric nitrogen." He writes:

> "It appears that 'all' organisms choose the line of least resistance for obtaining and assimilating their food; and microörganisms are not an exception to the rule."

From this it appears logical to believe that the rate of nitrogen fixation in the soil is quite definitely related to the nitrogen con-

tent of the soil and particularly to the quantity of nitrate nitrogen at the disposal of the bacteria concerned in the fixation process.

As Swanson points out:

"On the whole the growing of alfalfa has not added to the amount present in the soil. . . . All that the alfalfa has done has been to prevent further losses or, in other words, to maintain an equilibrium."

An interesting phase of this problem is presented in the records of the vegetation on the permanent grass plots at Rothamsted. In a comparison of the vegetation on two plots, one of which received phosphate and potash only and the other nitrate of soda in addition, Hall shows that, while the legumes amounted to 25 per cent of the total vegetation on the former plot, they constituted only 4 per cent of the latter. Apparently the net effect of nitrogenous fertilizers is to discourage the growth of legumes.

GROWING LEGUMES AND NON-LEGUMES IN ASSOCIATION

Such results would indicate the desirability of not growing legumes in succession but rather with intervening non-legumes. Another means by which any excessive amounts of nitrogen could be prevented from affecting the nitrogen-fixing capacity of legumes would be to grow a mixture of legumes and non-legumes. This is what occurs in hay fields of timothy and clover and in pastures of white clover and bluegrass. The question of the associated growth of soybeans and corn is related to this problem. Can a non-legume secure nitrogen from the legume while growing in association with it?

Lipman devised an ingenious experiment to determine whether non-legumes secured any nitrogen from association with legumes. Two pots, one of which was smaller than the other, were fitted into each other. The inside pot was in some cases porous and in others glazed. A non-legume was planted in the inner pot and a legume in the outer one. The non-legumes were oats and rye. The legumes were peas and vetch. The lack of agreement between the duplicates interferes with drawing too definite conclusions but the indications were that nitrogen secured from the air by the nodule bacteria was supplied to the non-legume through the unglazed wall of the pot.

Ellett and his associates grew timothy and red clover, bluegrass and white clover, and corn and soybeans together in the greenhouse. The results were negative with the first two but in the last case the corn appeared to benefit from the association. Lyon and Bizzell found that timothy grown with clover or alfalfa contained more nitrogen than timothy grown alone. The same was true with oats when grown in combination with peas. They were inclined to believe, however, that this increase in nitrogen came from a more rapid nitrification in the soil in some way related to the presence of the legume rather than to the taking up of nitrogen secured in the nitrogen-fixing processes.

A review of the data on this point, together with supplementary investigations, by Wright, indicates that it is not safe to assume that the association of legumes and non-legumes always guarantees a greater nitrogen content of the non-legumes or an increased rate of fixation of the nodule bacteria.

THE SOIL REACTION AS RELATED TO NITROGEN ECONOMY

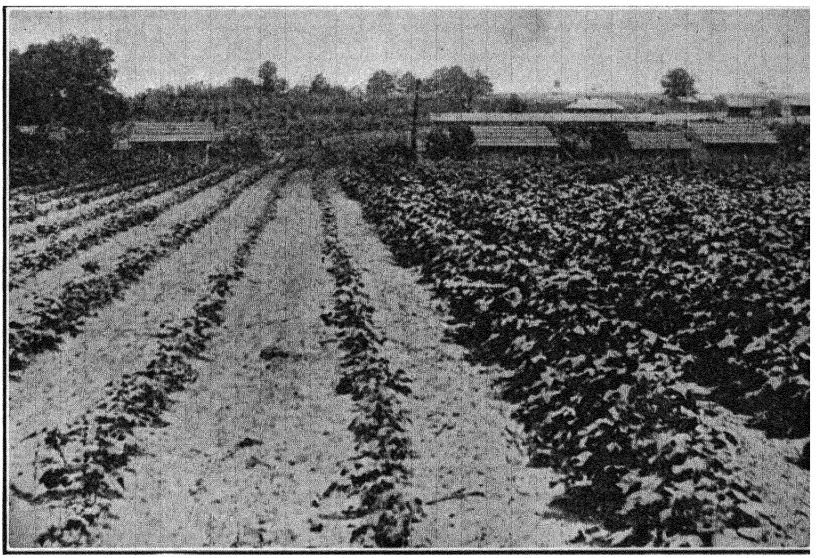
Both nitrogen fixation and nitrification are known to be stimulated by the addition of carbonate of lime to acid soils. In the absence of lime, nitrogen fixation may be slow but the nitrification processes are likely to be correspondingly slow. To accumulate nitrogen in a soil, nitrification need not necessarily be stopped, but both conserving and fixation processes must be in operation.

It may be possible to grow acid-tolerant legumes on soils in which nitrification has been retarded because of the acidity and thereby to accumulate nitrogen. The critical *p*H of the nodule bacteria of the soybean, for example, was found by Fred and Davenport to be 3.4 as compared to a *p*H of 4.3 for those of red clover and 5 for those of sweet clover and alfalfa. The critical point in the soil is approximately 1 *p*H higher than would be expected from culture solutions, due probably to the toxicity of the soluble aluminum. This would place the critical *p*H for nodule bacteria of soybeans at 4.4. Nitrification in an acid soil is found not to be accelerated to any considerable extent until the *p*H had been raised to 6, with a maximum between 7 and 8. Apparently Azotobacter are more seriously disturbed by acidity

than are most of the nodule bacteria. Under acid soil conditions, their functions may be taken over by the Clostridia. It is possible, therefore, that a degree of acidity could be selected at which nitrogen accumulation could continue with a minimum loss of nitrate. This would seem to be of little practical significance, however, since nothing is gained by accumulating nitrogen unless this nitrogen is readily nitrified for crop use.

TEMPERATURE AS RELATED TO NITROGEN ECONOMY

In regions of warm temperatures and heavy rainfall, such as the Southern States, land under cultivation tends to become



No fertilizer 500 pounds of 6–8–4

FIG. 15.—Effect of fertilizers on cotton at the Alabama Agricultural Experiment Station.

depleted of its organic matter and nitrogen at a very rapid rate. With suitable attention to the growing of leguminous crops and to the use of phosphate-potash fertilizers and liming materials, the nitrogen-fixing processes may be sufficiently rapid to compensate for the losses from excessive nitrification. Ordinarily, with somewhat indifferent cropping systems, the lack of available nitrogen in the soil of such regions is soon evidenced by marked decreases in yields of crops.

In regions of cool and moist climates no such exhaustion of the organic matter and nitrogen of farmed soils takes place since nitrification is very much retarded during a large portion of the year. At the same time fixation processes are probably not so rapid. In so far as available nitrogen is concerned there may be little difference between soils of moist, cool climates and those of warm regions of heavy rainfall. In fact, nitrogen fertilizers have been shown to be almost equally effective in both but for entirely different reasons.

PHOSPHORUS IN RELATION TO NITROGEN ECONOMY

In connection with a study of the residual effects of fertilizers on the soils of some tests plots on the West Virginia Agricultural Experiment Station Farm, it was shown that there was a very evident relationship between the nitrogen and phosphorus content of these soils. Arranging them in the order of the quantities of phosphorus found in the surface two million pounds of soil at the expiration of fifteen years of the experimental use of liberal amounts of fertilizers, the ratios of nitrogen to phosphorus on the plots to which the latter element had been applied, either in the form of manure or acid phosphate, were found to be as indicated below:

TABLE XVII

NITROGEN-PHOSPHORUS RATIOS IN WEST VIRGINIA DEKALB SOILS—BEAR

After Fifteen Years of Experimentation—All Crops Removed

Plot	Fertilizer Treatment	Hundredweight Produce per Acre in Fifteen Years	Pounds per Two Million of Soil		N–P Ratio
			Phosphorus	Nitrogen	
25	M	1396	1220	3240	2.65
20	M–Ca	1524	1050	2700	2.57
26	N–P–K	1179	900	2660	2.95
31	N–P	959	880	2400	2.72
34	P	634	880	2300	2.61
28	P–K	769	860	2280	2.65
19	N–P–K–Ca	1206	740	2130	2.88

M = Manure; Ca = Burned lime; N = Nitrate of soda; P = Superphosphate; K = Sulfate of potash.

It is evident that the nitrogen-phosphorus ratio in the soil remained fairly constant irrespective of differences in fertilizer treatments or in the amounts of crops removed. Phosphorus apparently is related to nitrogen fixation or to nitrogen conservation, one or both. Consideration of the nitrogen content of the crops removed led to the conclusion that nitrogen fixation estimated at from 20 to 78 pounds per acre per year had taken place in the soil of these plots, the higher amount having been calculated in the case of the plot receiving both superphosphate and sulfate of potash.

EQUILIBRIUM BETWEEN NITROGEN INCOME AND OUTGO

Under what might be considered average cropping systems, the nitrogen gains and losses in the average soil in the Central States apparently come to equilibrium at a nitrogen content of about 2000 to 3000 pounds per two million of surface soil. Fluctuations above or below this quantity are dependent largely upon the climate and upon the attention which the problem receives at the hand of the farmer. The use of phosphate and potash fertilizers apparently enables the nitrogen-fixing bacteria to satisfy the nitrogen requirements of larger crop yields, but if the crops are removed the point of equilibrium in the soil is disturbed but little. If there is an accumulation of phosphorus either as a result of its application or for any other reason, the point of equilibrium is apparently raised to correspond to the increased content of this element. The only correlations with the nitrogen content which have been established are those of the content of phosphorus and of organic matter in soils of the same type and under similar climatic and cultural conditions. The accumulation of nitrogen is not so important, however, as that it be usable. The conditions for crop growth are usually satisfactorily met when both fixation and nitrification processes are rapid and properly balanced.

SELECTED REFERENCES

1. Ames, J. W. Supply of nitrogen in the soil. Ohio Agr. Exp. Sta. Mo. Bul., Vol. 5, pp. 174–178, 1920.
2. Arny, A. C., and Thatcher, R. W. The effect of different methods of inoculation on the yield and protein content of alfalfa and sweet clover. Jour Amer. Soc. Agron., Vol. 9, pp. 135–136, 1917.

3. Bear, F. E., and Salter, R. M. The residual effects of fertilizers. West Virginia Agr. Exp. Sta. Bul. 160, 1916.
4. Bonazzi. A. Studies on Azotobacter chroöcoccum Beij. Jour. Bact., Vol. 6, pp. 331–369, 1921.
5. Collison, S. E., and Walker, S. S. Losses of fertilizers by leaching. Fla. Agr. Exp. Sta. Bul. 132, pp. 10–13, 1916.
6. Dole, R. B., and Stabler, H. Water supply paper No. 234, U. S. G. S., p. 78, 1919.
7. Dyer, B. Results of investigations on the Rothamsted soils. U. S. D. A. Off. Exp. Sta. Bul. 106, 1902.
8. Ellett, W. B., Hill, H. H., and Harris, W. G. The effect of association of legumes and non-legumes. Virginia Agr. Exp. Sta. Tech. Bul. 1, pp. 28–36, 1915.
9. Fred, E. B. The fixation of atmospheric nitrogen by inoculated soybeans. Soil Sci., Vol. II, p. 470, 1921.
10. Fred, E. B., and Davenport, Aubrey. Influence of reaction on nitrogen-assimilating bacteria. Jour. Agric. Res., Vol. 14, p. 331, 1918.
11. Fred, E. B., and Associates. Root nodule bacteria of Leguminosæ. Wisconsin Agr. Exp. Sta. Res. Bul. 72, 1926.
12. Giobel, Gunnar. The relation of soil nitrogen to nodule development and fixation of nitrogen by certain legumes. New Jersey Agr. Exp. Sta. Bul. 436, 125 pp., 1926.
13. Hall, A. D. On the accumulation of fertility by land allowed to run wild. Jour. Agr. Sci., Vol. 1, pp. 241–249, 1905.
14. Hartwell, B. L., and Pember, F. R. The gain in nitrogen during a five-year pot experiment with different legumes. R. I. Agr. Exp. Sta. Bul. 147, p. 14, 1911.
15. Hiltner, L. Stickstoffmehrer und Stickstoffzehrer. Lafar Handbuch der Technischen Mykologie, Jena, p. 24, 1906.
16. Hopkins, G. G. Soil Fertility and Permanent Agriculture, Ginn & Co., Boston, p. 217, 1910.
17. Ince, J. W. Fertility and weeds. North Dakota Agr. Exp. Sta. Bul. 112, 1913.
18. Lipman, J. G. The associative growth of legumes and non-legumes. New Jersey Agr. Exp. Sta. Bul. 253, 1912.
19. Lyon, T. L., and Bizzell, J. A. Some relations of certain higher plants to the formation of nitrates in soils. Cornell Agr. Exp. Sta. Mem. 1, p. 111, 1913.
20. —— Lysimeter experiments. Cornell Agr. Exp. Sta. Mem. 12, p. 36, 1918.
21. Millspaugh, C. F. Weeds as fertilizers. West Virginia Agr. Exp. Sta. Bul. 19, 1891.
22. Swanson, C. O. The effect of prolonged growing of alfalfa on the nitrogen content of the soil. Jour. Amer. Soc. Agron., Vol. 9, pp. 305–315, 1917.
23. Warington, R. Investigations at Rothamsted Experimental Station. U. S. D. A. Office of Exp. Sta. Bul. 8, p. 64, 1892.
24. Whiting, A. L., and Richmond, T. E. Composition of biennial sweet clover as related to soil enrichment. Soil Sci., Vol. XXII, pp. 83–95, 1926.
25. Wilson, B. D. Nitrogen in the rainwater at Ithaca, N. Y. Soil Sci., Vol. II, pp. 101–111, 1921.
26. Wright, R. C. Nitrogen relations of certain crop plants when grown alone and in association. Jour. Amer. Soc. Agron., Vol. II, pp. 49–67, 1919.

CHAPTER VI

THE MINERAL THEORY



Milton Whitney.

For the third edition of his book on "Organic Chemistry in Its Application to Agriculture and Physiology," Liebig formulated a statement which, together with the supporting arguments, was destined to arouse a considerable amount of discussion and investigation. This statement was later termed "The Mineral Theory" and is as follows:

> "The crops on a field diminish or increase in exact proportion to the diminution or increase of the mineral substance conveyed to it in manure."

It was Liebig's intention to emphasize the importance of the mineral elements rather than humus in soil and plant economy. The reason for this lay in the fact that he believed that the nitrogen and carbon of plants are derived from the ammonia and carbon dioxide of the air, respectively. The exhaustion of soils from continued cropping had its explanation, in Liebig's opinion, in the removal of these mineral nutrients in the harvested crops.

VALUE OF THE ASH ANALYSES OF PLANTS

Liebig was confident that the analysis of the ash of the plant gives the clue to its mineral requirements. The continued productivity of fields in Holland, Hungary and Virginia, to which no nitrogenous fertilizers had been applied, was believed by Liebig to be adequate proof of the sufficiency of the ammonia of the atmosphere as the source of the nitrogen of plants. The fact that the acreages of turnips and mangold-wurzels were being rapidly increased in England indicated to him an exhaustion of the phosphates in the soil. These two root crops were known to contain relatively small amounts of phosphorus and, according

to Liebig, could be grown on soils which were too deficient in this element to satisfy the larger phosphorus requirements of the wheat crop.

Dissenting from Liebig's point of view, Lawes and Gilbert enlarged their investigations at Rothamsted and began a systematic test of his conclusions both in the field and laboratory. This resulted, as previously mentioned, in their proving that the ammonia of the atmosphere is by no means adequate to support agricultural crops. In their first season's test it was found that sulfate of ammonia was of greater importance than any of the salts of the mineral elements as a wheat fertilizer. By the use of manure, the wheat yield, in 1844, was increased from 16 to 27 bushels per acre but, when only the ashes of manure were applied, the yield of wheat was not improved. In contrast with this, it was found that turnips responded especially well to phosphates. It was also shown that leguminous plants, although high in their content of nitrogen, were not benefited by nitrogenous fertilizers but that they produced much larger yields following the use of an alkaline mineral fertilizer containing both phosphoric acid and potash. Commenting on Liebig's conclusions, Lawes and Gilbert write:

"Taking into consideration the tendency of all experiences in practical agriculture, as well as the collective results of a most laborious experimental investigation of the subject both in the field and in the laboratory, it is our deliberate opinion that the analysis of that portion of the crop which is sent off the farm, whether of its organic substance or of its ashes, is no direct guide whatever as to the nature of the manure required to be provided for its increased growth in the ordinary course of agriculture, from sources extraneous to the home manures of the farm; that is to say by artificial means."

As a result of some years of investigation of the means of increasing crop yields together with supplemental research relating to the requirements of plants, certain facts became established. Liebig did succeed in showing that the analysis of the ash of plants gives a clue as to their mineral requirements. His patent phosphate and potash manures were shown to be effective as a means of increasing the productivity of soils. Lawes and Gilbert proved, however, that the analysis of the ash of plants does not necessarily serve as a guide to fertilizer practice. They further proved that, in addition to the mineral elements, nitrogen must

be supplied for large yields of most crops. Later Hellriegel and Wilfarth demonstrated conclusively the ability of legumes, through the agency of the nodule bacteria, to secure their nitrogen from atmospheric sources.

SOIL ANALYSIS GIVEN CONSIDERATION

The controversy, in one or another of its aspects, continued for some years. The Rothamsted plots gave proof that mineral manures, supplemented by nitrogenous fertilizers, could take the place of the ordinary animal manures in common use. The investigations were continued in search of some fixed principles which could be used as a guide in the use of fertilizers. Plant analysis had been set aside as insufficient in itself, yet it was known that each plant group had special soil requirements which must be satisfied. Lawes and Gilbert had also considered very carefully the question of the importance of analyzing the soil. It was their opinion that differences in the composition of the soil resulting from fertilizer treatments are too small to be detected by chemical means. Nevertheless, samples of soil were chosen from the several plots and carefully preserved for future reference. For the most part, however, the method of attacking the problem was that of measuring the crop increases resulting from fertilizer applications and determining from these the special requirements of each crop under experiment.

THE PRINCIPLE OF THE "DOMINANT CONSTITUENT" IN FERTILIZERS

Over in France Georges Ville was a vigorous defender of the modified mineral theory. Judging from field investigations and from the results in practice, he had come to the conclusion that all crops require the use of fertilizers containing nitrogen, phosphorus, potassium and the alkaline compounds of calcium. He was also of the opinion that the composition of the soil is an important factor but that its analysis is not a reliable guide to fertilizer practice. Ville was so impressed with the beneficial results obtained from the use of fertilizers that he came to prefer them to animal manures. In the second edition of his book on "Artificial Manures" published in 1872, he writes:

"Till within the last twenty years it was thought that farmyard manure was the only fertilizing agent. We maintain that this is wrong, and that it is possible to compose artificial manures superior to and at the same time cheaper than farmyard manure."

Ville's preference for artificial fertilizers was in part due to the fact that they lent themselves more readily for use in connection with fulfilling the requirements of plants according to the principle of "dominant constituents" which he had proposed to account for differences in the effectiveness of the fertilizer elements when supplied to the several crops. Concerning this principle Ville writes:

"If it be true that a mixture of calcic phosphate, potash, lime and a certain amount of nitrogenous matter is sufficient for all the wants of plants, and may, therefore, take the place of farmyard manure in farming, it is no less true that each of these constituents, with regard to the three others, fulfills functions that are in turn subordinate or predominant according to the nature of the plants to be grown. Thus in the case of wheat, colza, beet root and tobacco, the nitrogenous matter is the predominant ingredient; while for lucerne, peas, haricots and horse beans, potash plays the most important part. For swedes, turnips, sugar cane, maize and Jerusalem artichokes, calcic phosphate takes the most prominent position. There is, therefore, for every description of plant one substance which predominates over the three others, which may for that reason be called its dominant constituent."

THE BEGINNING OF THE FERTILIZER INDUSTRY

As a result of the discussion which Liebig's mineral theory aroused and from the fact that his "mineral manures" were shown to be effective, a considerable amount of interest was aroused in inorganic fertilizers. In 1843 Lawes began the manufacture of superphosphate. Nitrate of soda was already being shipped to Europe from Chile. Some years later the enormous phosphate deposits of Florida and the Carolinas were discovered. As a result of Ville's statement to the effect that mineral fertilizers are preferable to animal manures, that they are more economical, and that in the long run they provide the only means of maintaining and increasing the productivity of the soil, the fertilizer industry, thus encouraged, began to develop quite rapidly.

THE MINERAL THEORY QUESTIONED

Meanwhile a new point of view was being developed in America as a result of some years of study of the soil problem by scientists in the Bureau of Soils of the United States Department of Agriculture. Milton Whitney, who had been in charge of this bureau since its inception, believed that the mineral theory of Liebig had been taken too literally in its application to the soil. That the mineral elements are required by plants was not questioned, but that the soil was in danger of being rapidly depleted of these elements seemed to him absurd. He argued that the soils of Europe and Asia are supporting much larger populations than those of America and yet they were much older agriculturally. Investigation appeared to show that there is little if any significant difference in the composition of European and American soils. It was also shown that, notwithstanding their having been under cultivation for a much longer period, the soils of Germany, France and England are producing considerably larger acre yields than are those of the virgin soils of America. In support of this statement Whitney presented among others the following statistics on wheat yields

TABLE XVIII

AVERAGE YIELDS OF WHEAT IN VARIOUS COUNTRIES IN BUSHELS PER ACRE

	1897–1906	1911–1913
United Kingdom	32.3	32.2
Germany	28.0	33.1
France	19.8	20.3
Austria	17.8	20.6
Hungary	17.6	19.9
United States	13.8	14.7
Russia (European)	9.2	10.0

For comparison, the average wheat yields for the three years preceding the World War are added to those originally given by Whitney. In Denmark the yield of wheat during the same period (1897–1906) averaged 40.8 bushels per acre. For the

three years preceding the World War the average yield was 35.8 bushels. In Rumania, commercial fertilizers have never been used and yet the wheat yields averaged 16.7 bushels for the period 1909–1913.

Whitney was of the opinion that the loss of mineral elements through leaching and erosion by wind and water was much greater than that occasioned by the growth and removal of crops. He further pointed out that many of the conclusions as to the depletion of the mineral elements were drawn from chemical analyses of soils without due consideration to the fact that there were unavoidable errors in such analyses which prevented their being too literally interpreted. The variation in analyses as reported by different chemists on the same sample were often greater than the differences used as proof of the decreases of mineral elements in soils.

THE SOIL AS AN INEXHAUSTIBLE RESOURCE

Whitney had also reached certain conclusions concerning fertilizer practice which were at variance with those commonly accepted. While he recognized that fertilizers when applied to soils had specific effects on crops, yet he did not believe the explanation of this lay in the quantities of the several elements that are supplied for plant food purposes. Whitney could not find himself in agreement with the "direful predictions" of the exhaustion of soils. He wrote:

"The soil is the one indestructible immutable asset that the nation possesses. It is the one resource that cannot be exhausted, that cannot be used up.

"We have in our soil moisture a solution which carries sufficient mineral elements for the support of plants. It is capable of maintaining its concentration by re-solution from the minerals to supply any portion of these plant food constituents that may be withdrawn.

"As we see it now, the main cause of infertile soils or the deterioration of soils is the improper sanitary condition originally present in the soil or arising from our injudicious culture and rotation of crops.

"It has been shown that from the modern conception of the nature and purpose of the soil it is evident that it cannot wear out, that so far as the mineral food is concerned it will continue automatically to supply adequate quantities of the mineral plant food for crops."

These and other statements by Whitney indicated his belief that the mineral elements in the soil solution are maintained at a practically constant concentration which is not materially influenced by the growing of crops or the application of fertilizers. The experiments of the Bureau of Soils indicated that there is no very definite relationship between the amounts of the several mineral elements in the soil solution and the yield of crops which



"Worn Out" "Rejuvenated"

FIG. 17.—Changing "worn out" New England soil into a productive soil, in two years' time, by the use of fertilizers. The land was cleared, treated with fertilizer and seeded to grass.

the soil is capable of producing. Another statement of interest in this connection is as follows:

"It appears further, that practically all soils contain sufficient plant food for good crop yields, that this supply will be indefinitely maintained and that the actual yield of plants adapted to the soil depends mainly, under favorable climatic conditions, upon the cultural methods and suitable crop rotation."

THE "TOXICITY THEORY"

From investigations extending over a considerable period of years, Whitney and Frank K. Cameron, who was associated with Whitney and was in active charge of the physical and chemical investigations of the Bureau of Soils, came to the conclusion that the good effects noted from the use of fertilizers were indirect

rather than direct. In examining a water extract of some unproductive soil from Maryland, they were able to isolate a water soluble, non-volatile substance which was toxic to wheat plants. This toxicity was overcome by the use of manure, green manures, limestone and various other chemical substances. From this date forward the explanation of the function of fertilizers was credited by them as being in part one of overcoming toxins present in the soil as excretions from the roots of plants or as products of the decay of plants that had previously been grown.

Quoting from a bulletin relating to this topic:

"The smallest yields are usually obtained when wheat follows wheat. In our present state of knowledge, it would seem that we must regard the excreta of growing roots as one of the main causes of the low yields obtained in improper crop rotation."

This was followed by experimental trial with plants in which thirty-eight different organic substances which might be assumed to be formed under certain conditions of decomposition were supplied to the plants in varying concentrations. Several of these were toxic in proportions of one part per million while others showed no toxic effect. Experiments were also conducted to determine how this toxicity might be overcome. It was shown that many of the materials ordinarily applied on soils were effective in reducing or entirely overcoming this toxicity. It was also found that growing crops overcame this injurious effect.

"The toxic solutions were markedly improved by treatments similar to those which benefit the extracts of unproductive soils. Treatment with absorbing agents for a brief period was beneficial. The toxic solutions were greatly improved after one set of wheat plants had been grown on them.

"While plants alone and fertilizer substances alone were able to accomplish a partial destruction of the toxic substances the combined action of plants and substances ordinarily employed as fertilizers caused a much greater destruction of toxic material and consequent improvement in growth."

The following statement from Whitney gives the characteristic viewpoint entertained by the Bureau at that time:

"There is another way by which the fertility of the soil can be maintained, viz., by arranging a system of rotation and growing each year a crop that is not injured by the excreta of the preceding crops; then when the time comes around for the first crop to be planted again, the soil has had ample time to dispose of the sewage resulting from the growth of the plant two or three years before."

FERTILIZERS AS ANTITOXINS

In a hearing before the Committee on Agriculture of the United States House of Representatives, in 1908, Cameron gave it as his opinion that the most important reason for applying fertilizers lay in their antitoxic and mechanical effect on the soil. The chief requisites of fertilizers were that they serve as antitoxins and that they were to be had in large quantities at relatively small cost. Cameron believed that common salt had been neglected as a fertilizer solely because it did not contain any of the ordinarily mentioned essential elements. This point of view had militated against the use of this material although salt was known to be quite effective in increasing crop yields.

A summarized statement of the point of view of the Bureau of Soils investigators was published by Cameron, in 1911, in book form under the title "The Soil Solution." The following paragraphs are taken from that book:

"1. Exponents of the mineral theory have generally assumed that the action of fertilizers is on the plant rather than on the soil.

"2. The plant-food theory has been temporarily useful as was once the phlogiston theory. But just as the phlogiston theory was set aside with the discovery of oxygen so the plant-food theory must pass with increasing knowledge of soils and plants.

"3. It seems probable that at least to some extent the basic mineral nutrients can replace each other in the economy of the plant. Thus sodium may partially replace potassium and other substitutions can probably be made in case of deficiency of any given nutrient.

"4. The rise of capillary water is capable of supplying a sufficient quantity of mineral nutrients from the sub-soil. The problem is dynamic rather than static as those who make analyses of soils for total constituents would have us believe.

"5. Soil exhaustion is not necessarily due to a deficiency of mineral constituents. It has been shown to result from the presence of toxic substances originating within the plant itself. In this may lie the explanation of the importance of crop rotation.

"6. Nitrates are efficient in reducing the toxicity of dihydroxystearic acid and vanillin; phosphates in the case of solutions containing cumarin; and potassium of solutions containing quinone. These and similar toxins are found in soils. The function of fertilizers lies, at least in part, in overcoming the toxic effects of such constituents."

NATIONAL INTEREST AROUSED IN THE SOIL PROBLEM

The teachings of Whitney and Cameron, because of their being associated with the United States Department of Agriculture, were extensively advertised. The controversy which arose between the more orthodox soil specialists and those of the Bureau of Soils served to keep the matter before the public. As an example of the widespread interest in the problem may be given a few quotations from a series of articles by Anderson which appeared in a well-known popular magazine and which were later published in book form under the title "The Farmer of Tomorrow." Anderson entered into a review of the problem and on final analysis summed the whole matter up as follows:

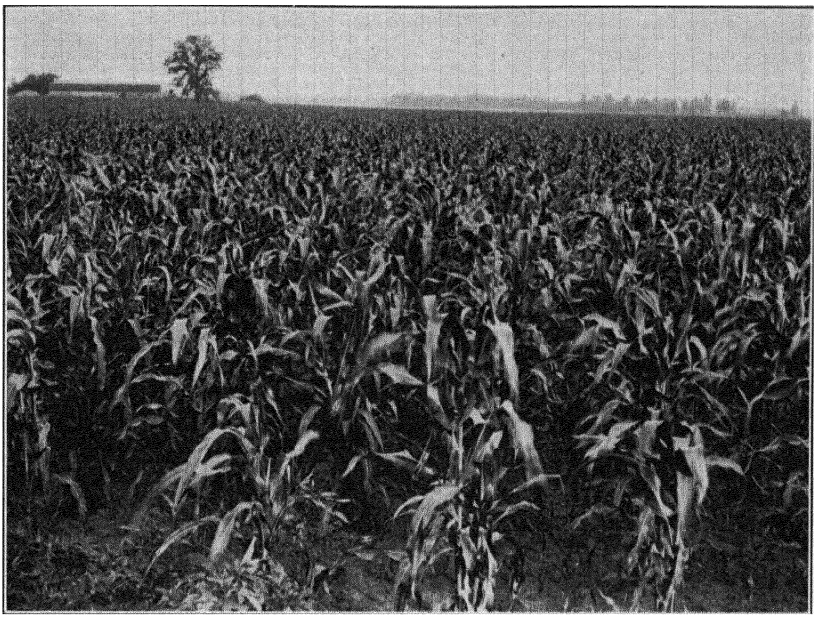
"The acreage, the floor space for food production is definite. The plant food, the innate fertility of the soil, is limited. The three elements, nitrogen, potassium and phosphorus, available as commercial fertilizers, have been blocked out by geological surveys. And lastly, the hungry world marches forward in numbers, its appetite increasing in geometrical ratio."

Finally he writes:

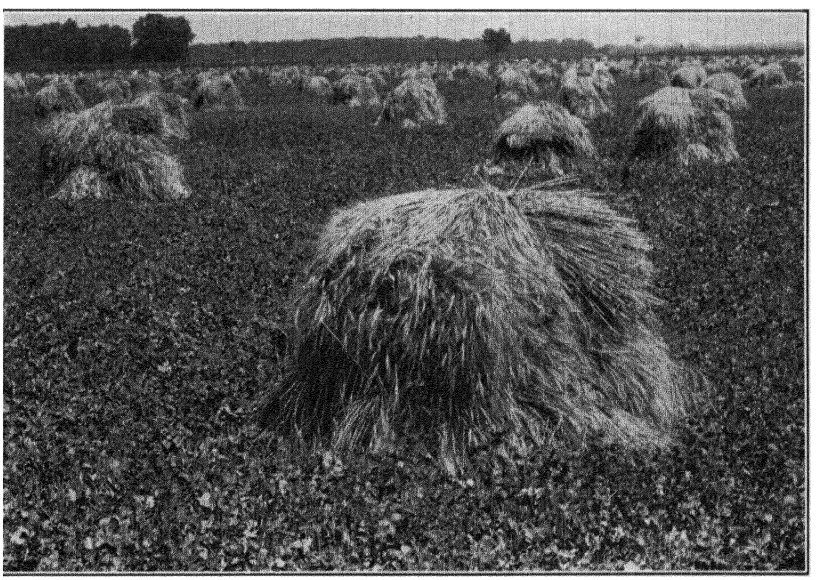
"This is not an illusory hypothesis. It is the accepted theory and practice of the civilized nations of the world, with the single exception of China, where agriculture has been going on for forty centuries; and her acres are still feeding a population fifteen or twenty times as dense as our own, without regard to potash and phosphorus in chemical form."

THE MINERAL THEORY DEFENDED

Probably no man in America played a more prominent part in the awakening of public sentiment with reference to soil conservation than did Cyril G. Hopkins, formerly Professor of Agronomy at the University of Illinois. A careful student and follower of Lawes and Gilbert and of Liebig and interested in the development of sound agricultural thought and practice in so far as it is related to the soil problem, Hopkins entered into the task of investigation and teaching with an enthusiasm which carried conviction to his students. To him the teachings of Whitney and Cameron were heresy of the most dangerous kind in that they tended to encourage the already too prevalent policy of rapidly exhausting the resources of the nation's soil.



(A) Corn removes nitrogen and mineral elements from the soil



(B) Clover adds only nitrogen to the soil

FIG. 18.—Corn, wheat and clover—a standard rotation in the Central States.

From a careful analysis of the investigational work on soils in Europe and America, Hopkins came to the conclusion that there was little danger of over-emphasizing the plant nutrient conception of fertilizers. It was evident to him that Liebig had been in error in certain particulars some of which have been previously noted, but that, in the main, the problem was one of taking an invoice of the soil as related to the requirements of crops. The problem was thereby reduced to one of bookkeeping with debit and credit columns which could be very definitely determined by analyses of the soil and crops and from records of the yields removed and of the fertility restored through the use of clover, limestone and the mineral fertilizers.

The most essential phases of Hopkins' teachings are contained in some of the soil reports for several counties in Illinois which were published just previous to his death in 1919. The following statements are selected as giving his point of view at the close of a very active career in behalf of the conservation of the soil resources of America:

"The productive capacity of land in humid sections depends almost wholly upon the power of the soil to feed the crop; and this, in turn, depends both upon the stock of plant food contained in the soil and upon the rate at which it is liberated, or rendered soluble and available for use in plant growth. Protection from weeds, insects, and fungous diseases, though exceedingly important, is not a positive but a negative factor in crop production.

"The chemical analysis of the soil gives the invoice of fertility actually present in the soil strata sampled and analyzed, but the rate of liberation is governed by many factors, some of which may be controlled by the farmers, while others are largely beyond his control. Chief among the important controllable factors which influence the liberation of plant food are limestone and decaying organic matter, which may be added to the soil by direct application of ground limestone and farm manure. Organic matter may be supplied also by green manure crops and crop residues, such as clover, cowpeas, straw and corn stalks.

"Probably no agricultural fact is more generally known by farmers and landowners than that soils differ in productive power. Even though plowed alike and at the same time, prepared the same way, planted the same day with the same kind of seed, and cultivated alike, watered by the same rains and warmed by the same sun, nevertheless the best acre may produce twice as large a crop as the poorest acre on the same farm, if not, indeed, in the same field; and the fact should be repeated and emphasized that with the normal rainfall of Illinois the productive power of the land depends primarily upon the stock of plant food contained in the soil and upon the rate at which it is liberated,

just as the success of the merchant depends primarily upon his stock of goods and the rapidity of sales. In both cases the stock of any commodity must be increased or renewed whenever the supply of such commodity becomes so depleted as to limit the success of the business whether on the farm or in the store.

"It should be kept in mind that crops are not made out of nothing. They are composed of ten different elements of plant food, every one of which is absolutely essential for the growth and formation of every agricultural plant. Of these ten elements of plant food, only two (carbon and oxygen) are secured from the air by all agricultural plants, only one (hydrogen) from water, and seven from the soil. Nitrogen, one of these seven elements secured from the soil by all plants, may also be secured from the air by one class of plants (legumes), in case the amount liberated from the soil is insufficient; but even these plants (which include only the clovers, alfalfa, peas, beans, and vetches, among our common agricultural plants) secure from the soil alone six elements (phosphorus, potassium, magnesium, calcium, iron and sulphur), and also utilize the soil nitrogen so far as it becomes soluble and available during their period of growth."

"Plants are made of plant-food elements in just the same sense that a building is made of wood and iron, brick, stone, and mortar. Without materials, nothing material can be made. The normal temperature, sunshine, rainfall, and length of season in central Illinois are sufficient to produce 50 bushels of wheat per acre; 100 bushels of corn, 100 bushels of oats, and 4 tons of clover hay; and, where the land is properly drained and properly tilled, such crops would frequently be secured if the plant foods were present in sufficient amounts and liberated at a sufficiently rapid rate to meet the absolute needs of the crops."

The chemical composition of the soil and of the crops grown on it were taken very definitely into consideration by Hopkins and his associates in formulating long-time programs of soil management. Thousands of samples of Illinois soil were analyzed. Compilations were made of soil analyses from various parts of America and Europe as well as Asia. The whole scheme for the maintenance of the productivity of soils was reduced to the mathematical problem of dividing the content of plant food elements of the soil by the requirements of the plants grown as a means of determining the length of time the supply would last.

An example of this type of calculation is shown in the following table chosen from one of Hopkins' publications on this subject.

Hopkins recognized that not all of the supply of the plant food elements, shown by analyses to be present in soils, was immediately available for use. Yet the total amount present repre-

sented the potential supply from which the available must be secured except as this was supplemented by the use of fertilizers. He emphasized the fact that efforts must be made to change these potential supplies into available forms and pointed to the value of limestone and fresh organic matter for this purpose.

TABLE XIX

RELATIVE "SUPPLY AND DEMAND" OF SEVEN ELEMENTS—HOPKINS

Plant Food Elements	In Soil,* Pounds	In 100 Bu. Corn,† Pounds	Years' Supply
Phosphorus	2,200	17	130
Potassium	49,200	19	2,600
Magnesium	48,000	7	7,600
Calcium	68,800	1.¼	55,000
Iron	88,600	½	200,000
Sulfur	2,200	¼	10,000
Nitrogen in air	70,000,000	100	700,000

* In two million pounds of the earth's crust.
† Grain only.

"Limestone and decaying organic matter are the principal materials which the farmer can utilize most profitably to bring about the liberation of plant food. The limestone corrects the acidity of the soil and thus encourages the development not only of the nitrogen-gathering bacteria which live in the nodules on the roots of clover, cowpeas, and other legumes, but also the nitrifying bacteria, which have power to transform the insoluble and unavailable organic nitrogen into soluble and available nitrate nitrogen. At the same time, the products of this decomposition have power to dissolve the minerals contained in the soil, such as potassium and magnesium, and also to dissolve the insoluble phosphate and limestone which may be applied in low-priced forms. Thus, in the conversion of sufficient organic nitrogen into nitrate nitrogen for a 100-bushel crop of corn, the nitrous acid formed is alone sufficient to convert seven times as much insoluble tricalcium phosphate into soluble monocalcium phosphate as would be required to supply the phosphorus for the same crop."

CONCENTRATION OF SOIL SOLUTION AS AFFECTED BY FERTILIZERS

Whitney and Cameron argued that mineral fertilizers cannot permanently increase the amount of soluble material in the soil solution. This argument was based on the law of Nernst which,

when applied to soil phenomena, would make it appear that, i a soluble salt such as potassium chloride were added to the soil the equilibrium would soon be re-established by the re-formatior of the insoluble alumino-silicate of potassium.

This point was discussed by Russell who doubted the accuracy of the application of the principles of this law to solutions in the soil. He believed that the minerals added in soluble form are only temporarily removed from solution and that the subsequen rate of re-solution is much more rapid. In other words, as the crop continues to remove from the soil water the required minera elements, those added in excess of their solubilities come again into solution rapidly enough to continue to satisfy the needs o the plant.

In 1904 F. H. King, at one time connected with the Bureau of Soils but later Professor of Soils at the University of Wisconsin published three papers on the relation of fertilizers and manuria applications to the soluble salt content of soils. The data in these publications were such as partly to contradict the poin of view held by Whitney and his associates. From these inves tigations the following conclusions were believed to be warranted

1. Applications of manure to a soil not only increase the cro yield but the larger crops grown as a result contain larger quan tities of the mineral plant food elements.

2. The addition of the mineral elements and nitrates in solubl form to the soil is followed by an increased concentration o these elements in the water solution of the soil. This is less witl phosphorus than with the other nutrient elements but there i usually an appreciable increase in water-soluble phosphorus alsc

3. Mineral elements and nitrates supplied at the base of a soil column tend to move toward the surface of the soil. This i particularly true with the nitrate and calcium ions but also occur with the potassium, magnesium and sulfate ions. The mos important exception is phosphorus which tends to be absorbed in the soil near the point of application. An appreciable chang in the concentration of water-soluble phosphorus is at time observed, however, in the upper layers of soil even though the phosphorus is supplied at the bottom of the soil column.

THE MINERAL THEORY AND ORIENTAL SOIL PRACTICES

In order to study the soil practices of older civilizations King visited the agricultural sections of China, Korea, and Japan. His book, entitled "Farmers of Forty Centuries," was published on his return and indicates the importance of knowing what these practices are in anticipation of what may be required in America as our population increases and the virgin soil has been exploited. King points out that the movement of feeding stuffs and mineral fertilizers to western Europe, and even to the lands of Eastern United States, has enabled us to maintain the productivity of our older soils at the expense of virgin soils. Such a system has long been impossible in China and Japan and must ultimately be abandoned in America. Even the supply of mineral fertilizers may not be inexhaustible.

King was very much impressed with the serious problem involved in the feeding of such large populations on the relatively small acreages at the disposal of these farmers. He writes:

"In 1907 the three main islands of Japan, with an area one-half of Ohio, had a population of forty million people or ten times Ohio's population at that time. This population was practically self supporting since the agricultural imports of Japan for 1907 exceeded the exports by less than one dollar per capita."

Citing a somewhat typical case of the intensity of the agriculture of the Orient, King writes:

"In the Shantung Province in China a farmer was interviewed who had a family of twelve and who kept a donkey, one cow and two pigs on 2.5 acres of cultivated land on which he grew wheat, millet, sweet potatoes and beans."

THE CONSERVATION OF HUMAN EXCREMENT IN CHINA AND JAPAN

As a result of having no available supplies of artificial mineral fertilizers, it has become necessary in China and Japan to save and return to the field every particle of organic refuse, the manure of animals and, in addition, all of the human excreta of these countries.

"In Japan it is estimated that 1.75 tons of human excrement is available yearly for every acre of land under cultivation. The International Concession of the city of Shanghai, in 1918, sold to a Chinese contractor the privilege of

entering residences and public places early in the morning of each day in the year and removing the night soil, receiving therefor more than $31,000 gold, for 78,000 tons of waste. All of this we do not only throw away but expend much larger sums for doing so."

The human excrement is sent out by canal boat and then carried on the shoulders of workmen to the field where it is applied. Stoneware or cement receptacles are built for storing the excrement when it is not to be used immediately. These receptacles have a capacity of from 500 to 1000 pounds. Where canals are not available the excrement is hauled away in carts drawn by laborers. King writes:

"As soon as we had entered upon the country road we found ourselves in a procession of cart men each drawing a load of six large receptacles of about 10 gallons capacity and filled with the city's waste. Before reaching the station (2 miles) we had passed 52 of these loads.

"From the analyses of mixed human excreta made by Wolff in Europe and by Kellner in Japan it appears that, as an average, these carry in every 2000 pounds 12.7 pounds of nitrogen, 4 pounds of potassium and 1.7 pounds of phosphorus. On the basis of that and of Carpenter, who estimates the average amount of excreta per day for the adult at 40 ounces, the average annual production per million of adult population is 5,794,300 pounds of nitrogen; 1,825,000 pounds of potassium and 775,600 pounds of phosphorus carried in 456,200 tons of excreta.

"The manure of the work animals, both urine and dung, is collected as voided and placed in receptacles. All the liquid manures are diluted with water 'before they are fed,' as the Chinese say, 'to their plants.' The application of all these materials to the soil has made it essential that all drinking water be boiled which probably accounts for the development of the tea industry, the tea being used as a means of making the water palatable."

ROTATION OF THE SOIL A PRACTICE IN CHINA

In addition to rotation of crops, the rotation of the soil and subsoil is also practiced. Mud is taken from the canal and scattered over nearby fields at the rate of 70 tons or more per acre. In the areas where canal mud is not available the soil and subsoil is carried into the villages and composted with organic refuse. After being dried and pulverized it is then carried back and used on the fields as fertilizer.

A common practice is to grow clover and compost this crop while still green with canal mud. After a fermentation period of twenty or thirty days the compost mixture is taken to the

field. This application of compost mud is made between the rows of a growing crop in preparation for the crop to follow. The applications of mud are made as often as every two years but at times not so frequently.

"Another equally or even more laborious practice followed by Chinese farmers in this province is the periodic exchange of soil between mulberry orchards and the rice fields, their experience being that soil long used in the mulberry orchards improves the rice, while soil from the rice fields is very helpful in the mulberry orchards."

The good effects of the mud can be explained in several ways. Near villages all kinds of refuse materials find their way into the canals. Soapy water is a source of certain fertilizer constituents. The mud also contains many snail shells which are rich in lime and undoubtedly contain nitrogen and phosphorus. In addition, the mud absorbs mineral plant food elements from the canal water.

LEGUMES PLAY AN IMPORTANT PART IN THE ORIENT

From many centuries of experience the farmers of the Orient have learned the value of legumes. The growing of soybeans in rotation is one of the well-established practices. Quite often the clover crop is harvested and composted with canal mud. At other times the clover is plowed under as a green manuring crop. As an example of the complexity of the processes involved in soil management the following statement by King is given:

"This manure had been collected, loaded and carried fifteen miles by water; it had been unloaded upon the bank and saturated with canal mud; the field had been fitted for clover the previous fall and seeded; the pits had been dug in the fields; the winter compost had been carried and placed in the pits; the clover was to be cut, carried by the men, on their shoulders, stacked layer by layer and saturated with mud dipped from the canal; the whole would later be distributed over the field and finally the earth removed from the pits would be returned to them, that the service of no ground upon which a crop might grow should be lost."

Such practices are possible only when human labor is cheap and plentiful. The ordinary laborer receives about twelve cents gold per day of ten hours, a part of which is credited to the meals received. Practically all of the most laborious work is done by hand labor, power machinery being almost unknown. The num-

ber of animals kept is limited to the amount of coarse food which has no value for human consumption.

Rotation of crops is followed in which legumes play a prominent part both for food and soil purposes. The scarcity of land available for agricultural use being limited this makes it necessary that the land be kept constantly busy growing crops. Usually more than one crop is grown on the land at the same time, each crop being at a different stage of maturity. As many as three crops may thus be in progress of growth, the oldest one being nearly ready to harvest and the youngest one being just planted.

THE MINERAL THEORY RECONCILED WITH ASIATIC PRACTICES

It is easily seen that such practices continue to draw heavily on the mineral elements in the soil and would appear to make it essential that every effort be made to return the elements removed in highly available forms. King comments on this phase of the problem as follows:

"From the amounts of nitrogen, phosphorus and potassium applied annually to the cultivated fields of Japan and from the data (as to that removed in crops) it may be readily seen that these people are now and probably long have been applying quite as much of these three-plant food elements to their fields with each planting as are removed with the crop, and if this be true in Japan it must also be true in China. Moreover, there is nothing in American agricultural practice which indicates that we shall not ultimately be compelled to do likewise."

It would seem from the preceding statements concerning the agriculture of China and Japan that the only reason they have not used commercial fertilizers was because they were not available. In lieu of commercial fertilizers they have found it necessary to save all of the waste materials, even to canal mud and material of every sort which contained any of the substances which have any fertilizer value, and to return them to the soil. The people of Japan and China are grappling with a food problem which is so difficult in comparison with ours that we in America, where millions of acres are still lying in waste, have no conception of the task involved. While it is to be hoped that our farmers may never be compelled to undergo such hardships as do those of these densely populated countries yet it seems worth while to keep in mind the problem which is before us and

to know that inevitably in time we must face a condition which will call for a very considerably greater effort in soil conservation on our part. There seems to be no choice save that of either restoring the elements to the soil in the form of mineral fertilizers or taking up the more laborious process of saving and returning the human excreta. The practices of China and Japan are thus explained and would seem no longer to prevent our acceptance of a modified mineral theory.

THE CONTRIBUTION OF THE BUREAU OF SOILS OF THE U. S. D. A.

On the other hand, it must be admitted that fertilizers perform many other functions in the soil and that the explanation of their good effects are not as simple as the more orthodox followers of Liebig believed. The investigational work carried on in the Bureau of Soils and later in the Bureau of Plant Industry and now being continued in the Bureau of Chemistry and Soils of the United States Department of Agriculture has been of a fundamental nature. The contributions from these laboratories have stimulated renewed interest in the problem and have made it necessary to reconsider certain supposedly well-substantiated facts in the light of modern chemical, physical and biological science. Many of the points raised as a result of these investigations are well taken and are given further consideration in the discussion which follows.

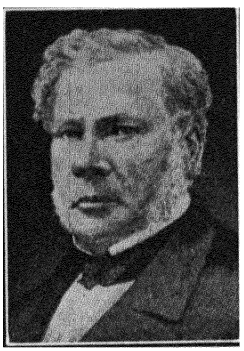
SELECTED REFERENCES

1. Anderson, F. I. The Farmer of Tomorrow. Macmillan Co., 1913.
2. Cameron, F. K. The Soil Solution, Chemical Publishing Co, pp. 31–58, 1911.
3. Hopkins, C. G. Soil Fertility and Permanent Agriculture, Ginn and Co., pp. 313–342, 1910.
4. Hopkins, C. G., Mosier, J. G., Van Alstine, E., and Garrett, F. W. Champaign County soils. Ill. Agr. Exp. Sta. Soils Report No. 18, 1918.
5. King, F. H. Investigations in Soil Management. Published by the author, Madison, Wisconsin, 1904.
6. —— Farmers of Forty Centuries. Published by the author, Madison, Wisconsin, 1911.
7. Lawes, J. B., and Gilbert, J. H. Agricultural chemistry, especially in relation to the mineral theory of Baron Liebig. Jour. Roy. Agr. Soc., Eng., Vol. XII, p. 1, 1850.

8. Lawes, J. B., and Silbert, J. H. On some points connected with agricultural chemistry; being a reply to Baron Liebig's Principles of Agricultural Chemistry. Jour. Roy. Agr. Soc., Eng., Vol. XVI, p. 411, 1855.
9. Liebig, Justus von. Natural Laws of Husbandry. Walton and Moberlay. London, 1863.
10. Livingston, B. E., and Associates. Further studies on the properties of an unproductive soil. U. S. D. A. Bur. Soils, Bul. 36, 1907.
11. Russell, E. J. The recent work of the American Soil Bureau. Jour. of Agric. Science, Vol. I, pp. 327-346, 1905.
12. Schreiner, O., and Shorey, E. C. The isolation of harmful organic substances from soils. U. S. D. A. Bur. Soils, Bul. 53, 1909.
13. Schreiner, O., and Skinner, J. J. Some effects of a harmful organic soil constituent. U. S. D. A. Bur. Soils, Bul. 70, 1910.
14. Ville, Georges. On Artificial Manures, Their Chemical Selection and Scientific Application to Agriculture. Trans. by W. Crookes, London, 1882.
15. Whitney, M. Soil fertility. U. S. D. A. Farmers Bul. 257, 1907.
16. —— Soils of the United States. U. S. D. A. Bur. Soils, Bul. 55, 1909.
17. —— Study of crop yields and soil composition in relation to soil productivity. U. S. D. A. Bur. Soils, Bul. 57, 1909.
18. Whitney, M., and Cameron, F. K. The chemistry of the soil as related to crop production. U. S. D. A. Bur. Soils, Bul. 22, 1903.
19. —— Investigations in soil fertility. U. S. D. A. Bur. Soils, Bul. 23, 1904.

CHAPTER VII

ASH ANALYSES OF PLANTS



J. B. Boussingault

THE earliest significant contribution on the ash constituents of plants was that of Theodore de Saussure, whose book entitled "Recherches Chimiques sur la Vegetation" was published in 1804. In this book, de Saussure, from data secured by the application of somewhat refined analytical chemical procedure to the analysis of plant ash, showed that plants are not agents for the production of inorganic matter, as had previously been supposed, but that they derive their ash constituents from the soil. The composition of the ash was found to vary with the nature and composition of the soil and the age and species of the plant. De Saussure also pointed out that the quality of the manure has a greater influence upon the ash than does the geological origin of the soil.

EARLY STUDY OF THE MINERAL ECONOMY OF PLANTS AND SOILS

Some years later, about 1835, Boussingault began his field and laboratory experiments at Bechelbronne in which he reintroduced the quantitative method of de Saussure in the study of the nitrogen and ash economy in plants. To him we owe the first careful analytical record of the ash content of the acre produce of crops. In these analyses Boussingault, aided by Letellier, "spent nearly a whole year" of "long and tedious labor." The purpose which he had in mind in this study is shown in the following comment taken from his book:

"Professor Liebig, in insisting with the greatest propriety on the useful part played by alkaline bases and saline matters in vegetation, has shown the necessity of taking inorganic substances into serious consideration in discussing

rotations. It is long since I came to the same conclusion myself; but it strikes me, that to be truly profitable such a discussion must necessarily rest on analyses of the ashes of plants which have grown in the same soil and have been manured with the same dung, the contents of which in mineral elements were already known. There is in fact a kind of account current to be established between the inorganic matter of the crop and that of the manure."

Accordingly, Boussingault kept a careful record of yield of the crops grown and from analyses of the crops and manures prepared a balance sheet of mineral income and outgo from the soil. Selecting one of his rotations which consisted of potatoes, wheat, clover, wheat, oats and turnips, the following records are given.

TABLE XX

MINERAL BALANCE SHEET FOR SOIL—BOUSSINGAULT

Pounds per Acre Removed in Crops and Added in Manures

Crop	Yield	Ash	P_2O_5	SO_3	Cl	CaO	MgO	K_2O–Na_2O	SiO_2
Potatoes	2828	113	13	8	3	2	6	58	6
Wheat, grain *	2104	50	24	...	...	1	8	15	
Wheat, straw *	5116	358	11	4	2	30	18	34	242
Clover	3693	284	18	7	7	70	18	77	15
Oats, grain	975	39	6	...	...	1	3	5	20
Oats, straw	1116	60	2	3	3	5	2	17	24
Turnips	656	50	3	5	1	5	2	19	3
Total in crops	....	927	77	27	16	114	57	225	310
Added in manure	....	7582	90	304	32	533	136	339	5049
Excess added	....	6555	13	277	15	417	79	114	4736

* Two crops.

"In the system followed at Bechelbronne, the farm dung laid upon an acre contains 26 cwts. 3 qrs. of ashes. On our clover leas we spread the first year seven cubic feet of turf ashes; and in the beginning of the spring of the second year we lay as much more, say, 14 cubic feet in all weighing about two tons."

ROTHAMSTED STUDIES ON ASH OF PLANTS

It will be recalled that Lawes and Gilbert were not convinced that Liebig was correct in assuming that the analysis of the ash of the plant gives a clue to its manurial requirements. Their investigations as to the composition of the ash of the turnip

and of its response to fertilizers indicated that, in this case at least, there was no correlation between the content of phosphoric acid and the effect on this crop of phosphatic fertilizers. Early in the investigations at Rothamsted plans were developed for the systematic study of the ash of the wheat plant a large amount of data for which was assembled and published in 1884. From these data the conclusion was drawn by Lawes and Gilbert that the composition of the wheat grain is strikingly constant. There were, however, wide differences in the content of the several mineral elements in the straw. Later investigations at Rothamsted indicated that the analysis of the crop could be used as a measure of the amount of available constituents in the soil. This was especially true for certain plants, the analysis of the ash of mangels being of particular value in connection with a deficiency of potassium and swedes in the case of phosphorus.

ASH ANALYSES COMPILED BY WOLFF

Meanwhile a large number of ash analyses of plants had been accumulating in European laboratories. In 1864, at the second convention of German agricultural chemists and physiologists at Göttingen, the suggestion was made that these analyses be compiled for reference use. Accordingly a committee was appointed of which Emil Wolff was the chairman. As a result of the work of this committee, a report was prepared and published in 1871 under the title "Aschen-Analyzen." Ten years later a second report was published which contained supplemental analyses of the ash of a great variety of agricultural products. This report has served as the basis for most of the subsequent computations which have been made on the mineral requirements of the several crops and the rate at which they tend to exhaust the soil of its necessary elements.

THE SIGNIFICANCE OF ASH ANALYSES

There has been considerable discussion as to the relation between the ash content of plants and their mineral requirements. In general it has come to be believed that of the eleven elements commonly found in plant ash phosphorus, potassium, calcium,

magnesium, sulfur, iron and manganese are essential, while sodium, silicon, chlorine, and aluminum are accidental. Usually the agriculturist has assumed, from the known composition of ordinary soils, that the first five of the above list of elements are the only ones which require consideration from the soil conservation and productivity point of view. He has also usually assumed that chemical analysis of the ash shows not only what is present in

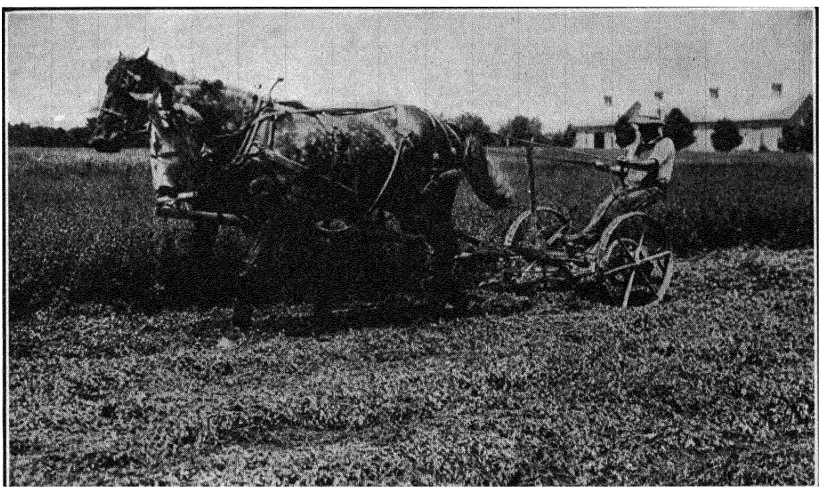


FIG. 20.—Alfalfa and all other legumes are very high in their content of mineral elements as shown by the analyses of the ash of these plants. This indicates the necessity of supplying them with liberal amounts of lime, phosphoric acid and potash.

the plant but, as to the essential elements, the amounts required. Thus Hopkins writes:

"On the whole it is as nearly correct to say that a 50-bushel crop of wheat requires 96 pounds of nitrogen and 16 pounds of phosphorus as it is to say that a measured bushel of wheat weighs 60 pounds."

Plant physiologists present a somewhat different view point as evidenced in the following statement of Duggar:

"Chemical analysis cannot tell with any degree of exactness what the plant actually requires from the soil; but it is important because it gives a general indication of the relation of the plant to soil solution, it sheds some light upon the general problem of nutrition and it makes possible an exact computation of the amounts of mineral nutrients which various crops remove from the soil."

Other plant physiologists are less positive as to the relation between composition and requirements of plants. Thus Coulter, Barnes and Cowles write:

"Analysis shows that the amount and content of the ash varies much in the same plant in different situations, thus indicating that in part (and doubtless in large part) these materials are determined not by the 'needs' of the plant but by the solutions which have opportunity to wander into it. Cultures under special conditions have shown that plants may be deprived of many of the chemical elements ordinarily found and no evil effects follow. But the absence of others has obvious ill effects. Thus silica is an abundant material in the cell walls of the epidermis of most cereals; yet corn has been cultivated through four generations with practically no silica."

Continuing further they write:

"When it is said that a definite amount of each 'indispensable' element is needed by a plant and that the minimum determines the crop (law of the minimum); that on potassium depends the formation of new organs at the growing point; that calcium is required for the transfer of starch, and so on, all such statements must be considered as extremely doubtful and liable to complete reversal when deeper insight is gained into the processes concerned."

Cameron is of the opinion that any attempt to calculate the permanence of productivity of a soil from its mineral content as related to the average analyses of plant ash is useless as is indicated in the following statement.

"The whole scheme becomes hopeless when it is realized that the same crop will yield widely varying ash analysis, depending upon the cultural methods employed, the judicious selection of seed, the amount and distribution of rainfall and sunlight, and possibly other agencies, all of which affect the growth and absorptive functions of the plant to as great an extent as does the particular soil upon which it may be growing."

ASH AS RELATED TO CONTENT OF MINERAL NUTRIENTS IN SOILS

As Duggar points out, the analysis of the ash of the plant does provide a means of determining how much of the mineral elements the plant has removed from the soil. It is also probably true that the quantities of the essential elements that are found in plants grown in the field approximate their total although not necessarily their specific salt requirements. On the other hand

it is desirable to have in mind that plants may take up considerably larger amounts of the mineral elements than they require, if these are available in sufficient quantities in the soil. Pember, for example, found that barley plants absorbed approximately three times the quantity of phosphorus required for optimum growth when this element was supplied in excess. Forbes reports the analysis of samples of wheat selected from thirteen different plots of the fertilizer test series of the Ohio Agricultural Experiment Station Farm at Wooster in which the variation in the ash content was as shown in the following table.

TABLE XXI

VARIATION IN MINERAL CONTENT OF WHEAT GRAIN—FORBES

Ash Element	Pounds per Tons of Dried Material		Per Cent Variation
	Minimum	Maximum	
Potassium	8.84	10.46	18
Phosphorus	6.74	8.12	21
Calcium	0.86	1.14	33
Sulfur	4.26	5.15	21
Magnesium	2.78	3.08	11
Sodium	2.26	3.36	49
Chlorine	1.46	2.24	53

RECENT ANALYSES OF PLANT MATERIALS

By reason of the fact that most of the analyses recorded in text books and used in computations in connection with studies of mineral economy in soils have been selected from Wolff's Aschen-Analyzen, it seems desirable to examine into the more recent analyses of plants which have been made by methods which have been much improved over those used by earlier investigators. The following tables of analyses by Forbes and his associates meet these requirements and, since they include a considerable variety of plant materials, will suffice for the purpose of this discussion.

TABLE XXII

MINERAL ANALYSES OF PLANTS AND PLANT PRODUCTS—FORBES

Material	Pounds per 1000 of Material							
	N *	K	Na	Ca	Mg	S	Cl	P
Grains and Grain Products:								
Corn	13.9	3.4	0.2	0.1	1.1	1.5	0.6	2.6
Kaffir corn	16.9	2.5	0.6	0.1	1.3	1.6	1.0	2.4
Oats	17.4	4.2	1.7	1.0	1.2	2.0	0.7	4.0
Rice	10.4	0.4	0.3	0.1	0.3	1.0	0.4	0.9
Wheat	16.5	5.2	0.3	0.5	1.3	2.0	0.8	3.7
Wheat bran	25.2	13.2	2.0	1.3	5.3	2.7	0.9	11.1
Fruits and Vegetables:								
Apple	0.4	1.2	0.1	0.0	0.1	0.1	0.1	0.1
Banana	1.8	3.5	0.7	0.1	0.4	0.1	1.2	0.3
Cabbage	1.9	1.7	0.0	0.4	0.2	0.6	0.2	0.2
Mangel	2.7	4.4	0.8	0.2	0.4	0.3	1.6	0.3
Onion	2.6	1.8	0.1	0.3	0.2	0.8	0.2	0.4
Potato	3.2	2.7	0.3	0.1	0.6	0.3	0.1	0.5
Hays and Roughages:								
Alfalfa hay	23.1	7.7	4.5	10.3	3.7	2.8	1.5	2.2
Bluegrass hay	14.6	12.9	1.3	3.1	2.2	3.1	2.2	2.2
Clover hay	20.8	17.0	0.6	11.4	2.7	1.8	2.4	1.7
Corn stover	8.8	17.2	0.6	4.7	0.9	1.7	2.9	1.0
Cowpea hay	35.6	7.8	6.5	18.1	9.8	3.2	1.5	2.5
Millet hay	9.6	12.7	0.9	3.1	2.5	1.5	1.2	1.7
Soybean hay	27.4	15.9	1.3	12.3	6.2	2.3	0.8	2.1
Timothy hay	8.5	5.6	3.2	1.8	1.0	1.5	1.8	1.1
Wheat straw	2.8	8.0	2.2	2.1	0.6	1.5	2.0	0.4
Legume Seeds and Concentrates:								
Cottonseed meal	57.4	16.6	2.6	2.7	5.5	4.9	0.4	13.5
Cowpeas	35.4	14.0	1.6	1.0	2.1	2.4	0.4	4.6
Linseed meal	56.8	11.0	2.5	3.6	4.9	4.1	0.9	7.1
Navy beans	35.6	11.8	0.7	2.0	1.8	1.9	0.4	3.7
Soybeans	63.1	19.1	3.4	2.1	2.2	4.1	0.2	5.9

$K \times 1.2 = K_2O$; $Ca \times 1.4 = CaO$; $Mg \times 1.7 = MgO$; $S \times 2.5 = SO_3$; $P \times 2.3 = P_2O_5$

* Nitrogen included by reason of its value in connection with the study of economy of this element in crops.

THE DISTRIBUTION OF ASH ELEMENTS IN PLANTS

A study of these analyses shows the following facts, viz.: phosphorus, sulfur and magnesium are concentrated in the seeds of plants, more particularly in the seed coatings. Potassium, sodium, calcium and chlorine are found in largest amounts in

the stalks of plants. Legume seeds and hays are especially high in their content of ash elements.

Of interest in this connection is the work of Latshaw and Miller, who made a complete analysis of 6 Pride-of-Salina corn plants grown at Manhattan, Kansas, and from this analysis calculated the total quantity of each element that was contained in each of the several parts of the 6200 plants that were grown on one acre of land.

TABLE XXIII

QUANTITIES AND DISTRIBUTION OF ELEMENTS IN AN ACRE OF CORN *—LATSHAW

Element	Roots †	Grain	Cobs	Leaves	Stems	Total
Carbon	520.63	1,592.06	487.90	1,320.62	1,217.91	5,139.12
Oxygen	528.63	1,612.65	489.40	1,403.41	1,201.13	5,235.22
Hydrogen	69.83	247.83	67.79	187.41	161.36	674.22
Nitrogen	13.72	76.52	14.73	41.60	22.91	169.48
Phosphorus	1.02	12.09	1.01	6.63	2.42	23.17
Potassium	8.69	14.86	4.89	47.53	33.69	109.66
Calcium	5.68	0.89	0.23	15.02	4.65	26.47
Magnesium	2.01	7.12	1.17	6.72	4.37	21.39
Sulphur	2.67	4.98	0.22	7.68	4.37	19.92
Iron	4.49	1.52	0.26	2.23	1.41	9.91
Silicon	38.31	0.42	1.42	82.93	11.45	134.53
Aluminum	8.14	0.81	0.56	2.37	0.35	12.23
Chlorine	1.74	1.17	1.28	7.11	6.12	17.42
Manganese	0.62	1.30	0.32	1.02	0.46	3.72
Total produce from 1 acre						11,596.47

* Calculated on dry weight basis.
† Roots and stubble one foot high.

THE SUBSTITUTION OF ONE ELEMENT FOR ANOTHER IN PLANTS

Elements may have more than one function in the plant. In certain of these functions it is probable that other elements, having similar chemical properties, may be substituted. Liebig, writing in 1840, said:

"Any one of the alkaline bases may be substituted for another, the action of all being the same. . . . This argument applies only to those alkaline bases which in the form of organic salts form constituents of plants."

A systematic study of one phase of this problem was begun by Wheeler and his associates, in 1894, in an attempt to determine the extent to which sodium could be substituted for potassium in the plant. A summary of this work is given by Hartwell and Damon. In this study forty-eight sixtieth-acre plots were used for a comparison of the crop yields produced by the use of varying amounts of each of the chlorides and carbonates of the two elements when used singly and in combination. The crops grown were turnips, rutabagas, radishes, beets, cucumbers, buckwheat, cabbage, sugar beets, mangels, oats, hay, onions, carrots, rape and potatoes.

It was found in these tests that sodium could not be substituted for potassium in toto. When the amount of potassium applied was reduced and the quantity of sodium correspondingly increased, the sodium was generally found to be of value. The larger crops produced actually contained more potassium in cases where the quantity of sodium was increased in connection with an insufficient amount of potassium although the percentage of potassium was frequently decreased. It appears, therefore, that the benefits derived from the use of sodium chloride are partly direct and partly indirect.

The extent to which other similar substitutions in plants may be made is not known. Thus silicon has been found to function in connection with phosphorus assimilation, according to Hall and Morison. When sodium silicate was added to the soil of phosphorus-starved plots there was an increase in the intake of this element. Brenchley believes that the silicon may serve as a partial substitute for phosphorus in the economy of the plant. In general, it is believed that under conditions of scarcity of any element the plant may still thrive providing there are sufficient amounts of other elements having similar chemical properties.

It is conceivable that an element may have several functions to perform. One of them may be nothing more than that of increasing the concentration of the nutrient solution or of the cell sap. Another may be that of the neutralization of acids or bases. A third may be a specific function in which a given ion cannot be replaced by any other. With reference to the first of these functions, it is known that a considerable proportion, perhaps as much

as 90 per cent, of the ash elements in plants is to be found in the vacuoles of the cells rather than in the cell tissues or organs. It is believed that not over 10 per cent of the ash elements are bound up in permanent molecular combinations in the plant.



(*A*) No fertilizer.



(*B*) A 2–12–2 analysis applied at the rate of 400 pounds per acre.

FIG. 21.—Effect of fertilizer on sugar beets when grown on a good soil at Mason City, Iowa.

OTHER ELEMENTS MAY BE ESSENTIAL

Strange as it may seem, there is still a dearth of information concerning the function of a number of elements which have stimulating effects on plant growth. Most analyses of soils

and of plants do not include such elements as manganese, titanium, boron, arsenic, zinc and many other elements that are known to be present in soils and to have stimulating effects on plants when added to the soil or to culture solutions. Robinson made detailed analyses of 26 samples of soil, representing as many distinct types and found that a considerable variety of elements which are usually given no consideration in studies of plant requirements were present in greater or less amounts in practically all of these soils.

No systematic examinations of plant ash have been made for most of these elements. It is possible that the exceptional productivity, or the lack of productivity, of some soils might be accounted for if the facts were determined concerning the usefulness of these elements to plants. Brenchley, McHargue, and others have studied the nutritional value of a number of the rarer elements including copper, arsenic, boron, fluorine, iodine, manganese, lithium, barium, strontium, chlorine and others. Positive results have been secured with the first six members of the list when they were used in dilute concentrations. Boron and manganese seem to have been shown to be essential for some plants. The latter of these elements has been considered to be of some importance as a constituent of fertilizers.

FURTHER STUDY OF MINERAL REQUIREMENTS OF PLANTS NECESSARY

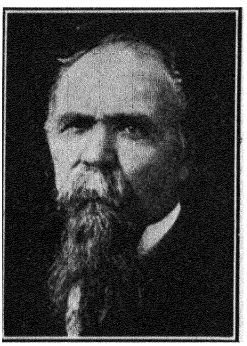
Unfortunately the soil chemist has been delayed in his progress by reason of the fact that plant physiology has not been developed to the point where it is possible to know what are the specific needs of each crop plant. Plants not only differ in their mineral requirements but they react differently to the various environments under which they are placed. The feeding capacity of the plant in the soil is determined in part by the chemical reactions which take place within the plant and by its spread of root system as well as the particular state or combination in which the elements that are needed exist in the soil. Once the requirements of the plant and its effect on the soil are known it will be possible for the chemist to determine with some degree of accuracy what must be done with the soil to enable it to satisfy these requirements.

SELECTED REFERENCES

1. Boussingault, J. B. Rural economy in its relation with chemistry, physics and meteorology, Trans. by Law, pp. 364–374, 1865.
2. Brenchley, Winifred E. Inorganic Plant Poisons and Stimulants. Cambridge University Press. Second Edition, 134 pp., 1927.
3. Coulter, J. M., Barnes, C. R., and Cowles, H. C. A text-book of Botany, pp. 415–416, 1910.
4. Duggar, B. M. Plant Physiology, Macmillian Co., p. 138, 1912.
5. Forbes, E. B., Beegle, F. M., and Menching, J. E. Mineral and organic analyses of foods. Ohio Agric. Exp. Sta. Bul. 255, pp. 228–231, 1913.
6. Hall, A. D., and Morrison, C. G. T. On the function of silica in the nutrition of cereals. Proc. Roy. Soc., Vol. 77, B. pp. 455–477, 1906.
7. Hartwell, B. L., and Damon, S. C. The value of sodium when potassium is insufficient. Rhode Island Agr. Exp. Sta. Bul. 177, p. 29.
8. Hopkins, C. G. Soil Fertility and Permanent Agriculture, Ginn and Co., p. 155, 1910.
9. Latshaw, W. L., and Miller, E. C. Elemental composition of the corn plant. Jour. Agr. Res., Vol. XVII, No. 11, March, 1924.
10. Lawes, J. W., and Gilbert, J. H. On the composition of the ash of wheat grain and wheat straw grown at Rothamsted in different seasons and by different manures. Jour. Chem. Soc., Vol. 45, p. 105, 1884.
11. McHargue, J. S. The rôle of manganese in plants. Jour. Amer. Chem. Soc., Vol. 64, pp. 1592–8, 1922.
12. Pember, F. R. Studies by means of both pot and solution culture of the phosphorus and potassium requirements of the barley plant during its different periods of growth. R. I. Agr. Exp. Sta. Bul. 169, p 23, 1917.
13. Robinson, W. O. The inorganic composition of some important American soils. U. S. D. A. Bul. 122, 1914.
14. Saussure, Theodore de. Recherches Chimiques sur la Vegetation, Paris, 1804.
15. Wolff, Emil. Aschen-Analyzen von Landwirtschaftlichen, Fabrik-Abfallen und Wachsenden Pflanzen, Berlin, 1871, 1880.

CHAPTER VIII

THE MINERAL CONSTITUENTS OF THE SOIL SOLUTION



F. H. King.

A CONSIDERABLE portion of the chemical investigations of soil during the last half of the nineteenth century had to do with methods designed to measure the "available" constituents in soils. Analyses for totals had been found to yield disappointing results since soils which "analyzed poor" were often highly productive under good management while those which "analyzed rich" were sometimes unproductive. The first availability studies were based on the assumption that plant sap is excreted by the root hairs and that this has a solvent effect on the adjacent soil particles.

USE OF WEAK ACIDS IN AVAILABILITY STUDIES

Studies of the acidity of plant sap led Dyer to select 1 per cent citric acid as a reagent to simulate the solvent effect of plant juice on the soil. Other investigators have made use of weak solutions of oxalic, tartaric, aspartic, acetic, nitric and other acids in estimating the immediate productive capacity of soils. Dyer's statement as to the justification for the use of dilute citric acid is interesting in this connection.

"It has long been accepted as a fact that plants help themselves to a part of their mineral food by means of the solvent action of their acid root sap on the particles of soil with which the rootlets come into contact."

Later it was shown that the only excretory product of plant roots which could be assumed to have any considerable solvent effect is carbon dioxide. Accordingly, weak-acid digestion of soils fell into more or less disrepute. However, the data obtained by the use of any one solvent were shown to be of value for com-

parative purposes and were often found to be correlated with the known productive capacities of soils.

ABSORPTIVE POWER OF SOILS FOR ACIDS

The chief difficulty was encountered when attempts were made to compare the data secured by the use of these various solvents. The reason for these discrepancies was not satisfactorily explained until Russell and Prescott, in a study of the solvent effect of acids on soil phosphorus, showed that if the phosphoric acid is removed as dissolved, the solvent action of equivalent concentrations of all acids is quite similar. If, however, the dissolved phosphoric acid is allowed to remain in contact with the soil, the final quantity in solution is determined by the extent to which the acid used as solvent can be substituted for the dissolved phosphoric acid in satisfying the absorption capacity of the soil. The order in which acids are absorbed by soils was found to be as follows, beginning with the one most absorbed: oxalic, citric, phosphoric, sulfuric, hydrochloric and nitric.

THE ZEOLITIC THEORY

The work of Dyer and other chemists was duplicated in many American laboratories with the result that there came to be an impression that the "available" mineral nutrients are present in the soil in two rather well-defined forms, viz.: the primary mineral forms which have not undergone decomposition; and the "zeolites," or secondary minerals, composed chiefly of hydrated aluminum silicates but containing varying amounts of calcium, sodium, potassium and magnesium. These zeolites, while not known to be present in soils, were assumed to be by reason of certain properties which are common both to soil and to zeolites. Among these may be mentioned their solubility in strong acids and their capacity for base exchange. While all of the soil is not soluble in strong acids, a considerable percentage of it is and this was assumed to be the zeolitic portion. The phenomenon of basic exchange is a well-known property of both zeolitic powders and soils.

STRONG ACID DIGESTION OF SOILS

On the assumption that zeolites are present in soils and that the available mineral nutrients are held in these combinations it seemed desirable to increase the strength of acid employed in soil digestions to such as was known to dissolve completely the zeolitic minerals. At Hilgard's suggestion, Loughridge studied the solubility of soils in three different concentrations of hydrochloric acid and found that, of the three, the maximum solubility occurred with the use of acid having a sp. gr. of 1.115. As a result of these investigations, Hilgard writes:

"This (HCl sp. gr. 1.115) being the most readily obtainable by simple steam distillation of acid of any other strength, the writer adopted it as best suited to the purpose of soil analysis."

Later the Association of Official Agricultural Chemists adopted this concentration and solvent with certain arbitrarily chosen time and temperature requirements as "Official." Thus American soil literature is filled with data secured by what are known as "strong acid digestions" of soils.

The assumption on which this method of extracting soils was based appears also to have little foundation. While zeolites are recognized by geologists as being secondary minerals, they are not thought to be formed under conditions such as obtain in the soil. In fact, the tendency would seem to be in the opposite direction. Thus Merrill writes on this subject as follows:

"They [zeolites] are plainly a result of deep-seated processes going on in the rock masses long before atmospheric action began to manifest itself. Indeed the conditions prevalent in soil are unfavorable rather than otherwise to the formation of zeolitic compounds and it is more than probable that such traces of these as exist, are residuals from the breaking down of rock masses in which they had been previously formed."

A NEW ERA IN SOIL INVESTIGATIONS

Both Hopkins and Whitney recognized that little could be expected from any further use of purely empirical methods in the study of soils. Accordingly, both of them determined to break away from the usual European and American methods of study and to attack the problem on some more fundamental basis. Hopkins decided upon the complete analysis of soils and crops

as giving an inventory of the supply and demand of soil elements on which he based the well-known "Illinois system" of soil management. Whitney and his associates attacked the problem from the widely different point of view that the key to the explanation of differences in the productive capacities of soils was to be found in the soil solution as it exists in the soil without the use of supplemental solvents.

THE SOIL AS A DYNAMIC SYSTEM

Whitney and Cameron introduced into the study of the soil solution certain physico-chemical concepts which had previously been largely ignored. Cameron called attention to the fact that soil investigations had been based on the tacit assumption that the soil is a static system whereas it is essentially dynamic. Commenting on this point in his book on "The Soil Solution," published in 1911, he writes:

"In studying the soil as a medium for crop production we must consider the plant itself or at least that part of the plant which enters the soil, namely, the root; the solid particles of the soil; the soil water or the aqueous solution from which the plant draws all of the materials for its sustenance, excepting the carbon dioxide absorbed by its aerial portions; the soil atmosphere; the biological processes taking place. The one common characteristic of all these things is that they are continually in a state of change; therefore the soil problem is essentially dynamic."

THE SOIL SOLUTION

It was Cameron's opinion that it is not so important to know what the total or available quantities of the several elements in the soil or in its solution might be at any given time as it is to know the rate at which the several equilibria, when disturbed by dynamic agencies, are re-established. In common with Whitney, Cameron believed that the mineral resources of the soil were "inexhaustible" and that the soil would continue to yield up adequate amounts of the essential mineral elements indefinitely. Mineralogical investigations had shown that "practically every soil contains all the rock-forming minerals." Cameron argued:

"It follows that if every soil contains all the rock-forming minerals, every soil should give the same saturated solution barring the presence of disturbing factors."

Among these factors were mentioned the presence of some uncommon mineral in unusual amounts, "differences in temperature, surface effects, or extraneous substances" and adsorption.

A difficult problem was presented in connection with securing adequate amounts of the soil solution containing the mineral constituents in the concentrations in which they exist in the soil and are presented to the plant. The centrifugal method, employed by Cameron, was not entirely satisfactory for the reason that only the excess of water over that of the critical moisture content could be extracted from the soil. However, from a study of the solutions thus obtained, Cameron concluded:

"The concentration of the soil solutions thus obtained, with respect to phosphoric acid and potash, varied but little for soils of various textures from sands to clays and the variations observed could not be correlated with the known crop-producing power of the soils."

From these studies and from other considerations Cameron argued that such variations as occur in the composition of soil solutions were not sufficient to set aside his original working hypothesis. He writes:

"Priori reasoning as well as the experimental evidence at hand indicates that the various processes taking place in the soil as a whole continually tend to form and maintain a normal concentration of mineral constituents in the soil solution."

"PLANT FOOD THEORY" OF FERTILIZERS QUESTIONED

In defense of this position it was necessary to make two assumptions: first, that the rate of solution of soil minerals having only a slight but a selective solubility is rapid; second, that the reaction between the silicate minerals and the soil solution is reversible. Under these conditions neither the removal of the mineral elements by plants or by running water nor the addition of soluble mineral salts in the amounts in which they are supplied as fertilizers should have any appreciable effect on the concentration of the soil solution. These assumptions, taken in connection with the fact of adsorption, made it seem probable that ordinary systems of soil management would have

little, if any, effect on the composition or concentration of the soil solution.

The publication of these investigations and of the conclusions reached as a result of them was destined to arouse a considerable amount of controversy. The effects of fertilizers were more deep-seated, according to Cameron, than had ordinarily been assumed. It was necessary, therefore, to reconsider the "plant food theory" as being entirely inadequate to explain the crop increases resulting from fertilizer applications. As was expected, those who interpreted the teachings of Liebig literally found it difficult to agree with Cameron's conclusions. But a younger school of soil and plant scientists were coming on to whom the field opened up by the pioneer work of Whitney and Cameron provided a wealth of material for investigation.

Preliminary studies by King, previously mentioned, had indicated that the addition of manure and fertilizer salts did alter appreciably the composition of the soil solution. A considerable number of soil investigators began the study of soil solutions, not only with reference to the total concentrations of the several essential mineral elements, but also, and later more particularly, as to the reaction of the solution, the effect of the reaction on the concentration of the elements in solution and the ratios of the quantities of the dissolved ions to each other. Meanwhile plant physiologists were giving consideration to the question of balance in solution cultures and the effect of the plant upon the culture solution as well as of the solution upon the plant. Setting aside, temporarily, these other highly important phases of investigation of the soil-plant system it seems desirable to consider in some greater detail what modern soil solution studies have shown in verification or otherwise of Cameron's assumptions.

METHODS OF OBTAINING TRUE SOIL SOLUTION

The problem of securing the soil solution in the concentration in which it exists under conditions which were favorable to the growth of plant presented itself. As early as 1866 it had been shown by Schloesing that it is possible to displace the soil solution simply by adding water to the top of a percolator containing the soil. Later it was found that ethyl alcohol can be substituted

(A) Consumption of Fertilizer in the United States from 1910 to 1935

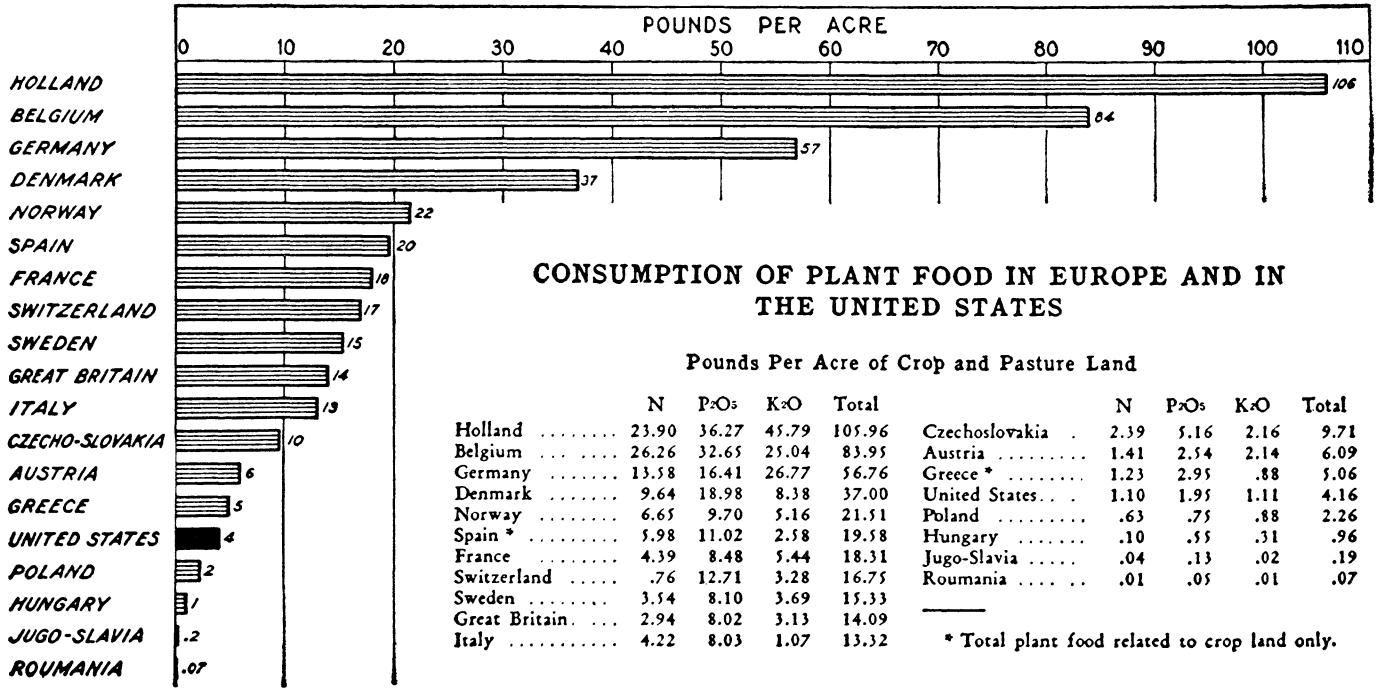
From "The Fertilizer Review," April–May–June, 1936.

State	1910–1914 average	1920–1924 average	1930–1934 average	1935
Maine	113,760[1]	168,275[1]	173,930[2]	125,000[2]
New Hampshire†[1]	15,050	15,800	11,800	16,000[2]
Vermont[4]	13,040	17,200	13,568	15,295
Massachusetts†[4]	48,140	62,819	62,121	63,208
Rhode Island[2]	7,300	8,800	8,201	12,000
Connecticut	54,200[2]	71,000[2]	57,200[1]	51,000[1]
New York[2]	257,580	246,000	238,600	234,000†
New Jersey‡[4]	142,415	163,011	139,482	149,408
Pennsylvania[4]	331,123	320,969	273,541	275,466
Delaware[4]	36,600	42,541	35,192	37,800
Maryland[4]	163,670	155,006	145,471	164,843
West Virginia	30,680[2]	36,468[2]	41,658[2]	55,000[4]
Virginia[3]	385,353	429,785	350,391	378,536
North Carolina[3]	750,252	1,012,353	941,559	1,000,071
South Carolina[3]	984,826	752,361	589,583	613,561
Georgia[3]	1,146,284	683,013	587,541	617,439
Florida[3]	199,709	334,066	412,904	418,239
Alabama[3]	476,829	346,444	383,100	422,400
Mississippi[3]	131,235	149,871	190,378	214,015
Tennessee[3]	75,739	94,731	103,061	96,444
Arkansas[3]	51,370	62,451	60,170	39,630
Louisiana[3]	88,880	90,278	91,427	92,532
Texas[3]	56,977	63,503	66,750	61,802
Oklahoma	1,500†[2]	3,220†[2]	4,720[3]	6,619[3]
Ohio[4]	165,652	298,058	243,673	306,509
Indiana[3]	177,654	204,004	143,462	194,946[3]
Illinois	6,200[2]	14,991[2]	25,097[4]	23,827[4]
Kentucky[3]	69,200	82,400	79,039	73,502
Missouri[3]	47,326	58,596	43,972	59,398
Michigan	48,786[2]	92,116[1]	100,603[1]	105,000[2]
Wisconsin[4]	3,300	13,800	31,865	28,414
Minnesota[4]	1,800	6,000	11,606	10.776
Iowa	.....	3,700[2]	13,319[2]	5,000[1]
Kansas[3]	4,910	6,111	3,823	7,298
Nebraska	.....	470[2]	400[2]	200[1]
South Dakota	.....	145[2]	120[2]	100[1]
North Dakota[2]	.....	160	696	300
Montana	.....	.....	450[2]	300[1]
Wyoming	.....	.....	460[2]	1,308[1]
Idaho	.....	340[2]	1,220[2]	1,500[1]
Colorado[2]	.....	230	1,715	1,200
Utah	.....	300[2]	1,760[2]	750[1]
Nevada	.....	28[2]	148[2]	500[1]
Arizona	.....	425[2]	1,980[2]	3,393[4]
New Mexico†	20[2]	780[2]	1,065[2]	1,636[4]
California[4]	43,234	70,384	134,796	178,156
Oregon[2]	3,960	6,900	10,400	10,500
Washington[2]	1,300	5,400	15,600	16,500
United States	6,135,854	6,195,363	5,849,618	6,191,321

[1] Estimated by state authorities. [2] Estimated. [3] Based on tag sales. [4] Compiled by state authorities. † Year ended June 30. ‡ Year ended October 31.

(B) **CONSUMPTION OF PLANT FOOD IN EUROPE AND IN THE UNITED STATES**

POUNDS PER ACRE OF CROP AND PASTURE LAND



CONSUMPTION OF PLANT FOOD IN EUROPE AND IN THE UNITED STATES

Pounds Per Acre of Crop and Pasture Land

	N	P_2O_5	K_2O	Total		N	P_2O_5	K_2O	Total
Holland	23.90	36.27	45.79	105.96	Czechoslovakia	2.39	5.16	2.16	9.71
Belgium	26.26	32.65	25.04	83.95	Austria	1.41	2.54	2.14	6.09
Germany	13.58	16.41	26.77	56.76	Greece *	1.23	2.95	.88	5.06
Denmark	9.64	18.98	8.38	37.00	United States	1.10	1.95	1.11	4.16
Norway	6.65	9.70	5.16	21.51	Poland	.63	.75	.88	2.26
Spain *	5.98	11.02	2.58	19.58	Hungary	.10	.55	.31	.96
France	4.39	8.48	5.44	18.31	Jugo-Slavia	.04	.13	.02	.19
Switzerland	.76	12.71	3.28	16.75	Roumania	.01	.05	.01	.07
Sweden	3.54	8.10	3.69	15.33					
Great Britain	2.94	8.02	3.13	14.09					
Italy	4.22	8.03	1.07	13.32					

* Total plant food related to crop land only.

FIG. 23.—Consumption of fertilizer in the United States and in Europe.

to advantage for the water. Further studies with paraffin oil subjected to pressure have shown that this method of separation of the soil solution is also effective. While not all of the soil solution can be obtained by these methods as much as 75 per cent of the total water known to be contained in the soil has been secured under favorable conditions. Studies of the total salt content of successive portions of the solution thus obtained show that it is practically constant in composition. This indicates that it is the true soil solution with which the plant roots would be in contact if present in the soil at the time that the extraction occurred.

THE COMPOSITION OF SOIL SOLUTIONS

Some idea of the composition of soil solutions may be obtained from the following data selected from Morgan's investigations by the paraffin-oil pressure method of extraction.

TABLE XXIV

COMPOSITION OF THE SOIL SOLUTION—MORGAN

Soil Type	Water Content, Per Cent	P. P. M. of Oven-dried Soils				
		K	PO_4	Ca	Mg	NO_3
Fine sand	46	21	2	92	51	4
Miami silt loam	38	27	5	26	..	1
Miami clay	25	11	1	11	33	2
Muck	155	86	4	90	..	20

These and other analyses indicate that the concentration of the several mineral elements in the soil solution may vary between rather wide limits. Other data, to be considered later, will also show that the presence of negative factors, as well as the absence of positive factors, in the soil solution may explain some of the discrepancies noted by Cameron between the composition of soil solutions as to the essential elements, and the crop-producing powers of soils.

EFFECT OF THE CROP ON THE SOIL SOLUTION

A means of study of the concentration of the soil solution in which use is made of freezing-point determinations has been extensively applied to this problem by McCool and Bouyoucos and their associates. By this method it has been possible to measure the concentration of the soil solution as it exists in contact with the soil and as influenced by the crop, by climatic conditions and by the application of fertilizer salts. An example of the first is given by McCool and Millar in which a comparison was made of the freezing-point lowerings of cropped and bare soils. The data follow.

TABLE XXV

EFFECT OF GROWING CROP ON SOLUBLE SALT CONTENT OF SOIL—McCOOL

Soil Class	Kind of Crop	Freezing Point Lowerings C.°	
		Cropped Soil	Bare Soil
Silt loam	June grass	.020	.090
Sandy loam	Wheat	.017	.043
Sand	Rye	.013	.016
Muck	Oats	.048	.842

EFFECT OF FERTILIZERS ON SOIL SOLUTION

The above data indicate that the rate of solution of the soil minerals is not sufficiently rapid to maintain a constant composition of the soil solution while plants are growing on the soil. Further evidence on the rate of solution of soil minerals and on the effect of the addition of fertilizer salts on the rate of renewal of the solution is given by Bouyoucos. In these tests the soils under study were treated with the various salts and then leached with water to a constant freezing point. The moist soils were then examined from time to time to determine the extent and rate of the freezing-point depression. An example of these studies is given in the following table.

TABLE XXVI

RATE AND EXTENT OF SOLUBILITY OF WISCONSIN SUPERIOR CLAY *—BOUYOUCOS

Treatment	Freezing-point Depressions C.°							
	Days 0	1	2	5	13	29	51	82
Sodium nitrate	.017	.020	.025	.042	.052	.071	.072	.072
Potassium chloride	.017	.025	.032	.035	.040	.044	.050	.050
Ammonium sulfate	.016	.040	.048	.053	.060	.085	.083	.074
Mono-calcium phosphate	.010	.018	.020	.024	.028	.030	.030	.035
Check	.002	.005	.010	.015	.017	.020	.022	.023

* Treated with fertilizer salts and then washed to constant freezing point.

Bouyoucos writes as follows concerning these data:

"The study on the rate and extent of solubility of soils treated with salt, and then washed until all their free soluble salts were eliminated seems to prove quite conclusively the two general facts: (1) the rate of solubility of the treated soils is comparatively very slow and gradual and the process continues for a long time, but usually about sixty days, and (2) the extent of solubility of these same soils is very considerable with few exceptions.

"It may be stated as a general principle that while the solubility factor is not an absolute and reliable criterion for the state of fertility of a soil, a very rich or heavily fertilized soil tends to give a high solubility product or a high soluble-salt content."

THE SOIL SOLUTION AS AN INDEX OF SOIL PRODUCTIVITY

It has been rather definitely shown, as a result of the large amount of investigation of the soil solution stimulated in large part by Cameron's discussion of this subject, that soils differ considerably in the concentration of the various ions in solution. In general it may be said that productive soils show a higher content of essential elements in solution than do unproductive ones. Exceptions to this general rule can probably be explained by consideration of the reaction of the soil solution, of the ratios in which the ions are present or of the presence of some negative factor, such, for example, as an excess of soluble aluminum, which may be toxic to plants.

The concentration of the essential elements in the soil solution is decreased by the growing crop. The rate of renewal of the solution from the natural soil is relatively slow. Under condi-

tions of good management, or where manure or fertilizers have been used, both the concentration and the rate of renewal of the essential elements is increased. In other words, the composition of the soil solution is not constant but fluctuates with the demands made by crops and with the addition of fertilizer salts or manures. While fertilizers may have other functions, there is in general a correlation between productive capacities of soils and the content of soluble salts in solution resulting from their use.

EFFECT OF THE SOIL ON SOLUBLE FERTILIZER SALTS

One of the difficulties in connection with the use of fertilizers is that the soil exerts certain chemical and physical effects on the added salts. The result is that the total amounts and the ratios of the several ions are very considerably changed from what they would have been if dissolved in the same amount of water as is contained in the soil. Liebig originally believed that soluble fertilizer salts would be leached from the soil. Accordingly, he attempted to render the alkalies insoluble by "fusing them with lime and calcium phosphate." It was later shown, by Way, that this is unnecessary since the soil has the property of "fixing" certain substances supplied in soluble form. He estimated that an acre of soil to a depth of 10 inches could take up 3 tons of ammonia, or over sixty times the amount which might normally be applied in fertilizers during any one year. He showed, however, that the removal from solution of the ammonia of ammonium sulfate was accompanied by a corresponding loss of calcium as sulfate in the leachings from the soil. Similarly, it was shown that the several bases were replaced in the soil in the order sodium, potassium, calcium, magnesium and ammonium, each dislodging the one preceding.

FIXATION OF POTASSIUM BY SOILS

Way was of the opinion that the fixation is complete although it is now known that this is never the case, the percentage fixed being determined in part by the quantity of the element already taken up by the soil. This is shown by the following example selected from experiments of Schreiner and Failyer on absorption of potassium by soils.

TABLE XXVII

POTASSIUM ABSORBING POWER OF A SOIL *—SCHREINER

Total Volume of Percolate	Potassium in Percolate of Successive Fractions	Total Potassium Retained by Soil
	P.p.m.	P.p.m.
50	62	70
320	78	440
410	104	520
610	133	690
750	155	760
1140	173	890

* From a solution of potassium chloride containing 200 p.p.m. of potassium.

It will be observed that the amount of potassium in the percolate was reduced from 200 p.p.m., that in the original solution, to 62 in the first 50 cubic centimeters of percolate. The amount of potassium in successive portions of the percolate increased, however, until it reached 173 p.p.m. in the last 170 cubic centimeters. The rate of percolation was approximately 50 cubic centimeters every twenty-four hours. The amount of soil was 100 grams. The total potassium extracted from the solution was at the rate of 1780 pounds of the element in two million pounds of soil. The rate of removal of the potassium from the solution was such as to guarantee that little of the element would be lost in the drainage water under field conditions following the ordinary fertilizer applications.

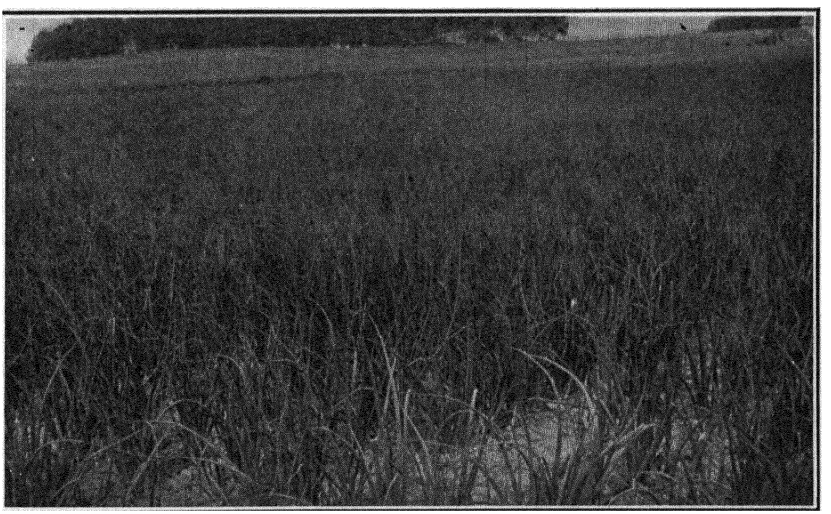
THE NATURE OF THE FIXATION PROCESS

There has been considerable controversy as to the nature of the fixation process in soils. Way came to the conclusion that it is due to precipitation with the liberation of a corresponding amount of some other base by double decomposition. Liebig believed, from a consideration of Way's researches, that the process is physical and comparable with the absorption of dyes or coloring matters by charcoal. Most of the early studies were with salts such as nitrates, sulfates, and chlorides in which the acid radical was found not to be retained by the soil. Later investigations showed that similar fixation occurs with phos-

phoric acid, a part of which could apparently be explained in the formation of insoluble phosphates of iron, aluminum and calcium.



(*A*) No fertilizer.



(*B*) 500 pounds 0–8–32 per acre.

FIG. 24.—Effect of fertilizer on onions when grown on muck soil at Hollandale, Minnesota.

It was found, however, that the fixation of bases and acids is greatest in those soils which are highest in their content of

colloidal matter. One of the well-known properties of colloids is that of absorption. What appears to be basic exchange can be accounted for on the assumption that one ion replaces another in the absorption complex.

THE NATURE OF SOIL COLLOIDAL MATTER

Critical examinations of these colloidal materials in soils have been conducted in a number of soil research laboratories. Among the many papers presented on this subject may be mentioned those of Bradfield, who prepared a synthetic colloidal mixture of the oxides of iron, aluminum and silicon, in the proportions in which these elements occur in the colloidal complex which he had isolated from Putnam subsoil, and compared the properties of the synthetic mixture with those of the natural soil colloidal material. In these tests it was shown that the natural colloidal material does not contain any appreciable amounts of free SiO_2 or of Al_2O_3 but that these exist in the form of alumino-silicates, probably with very complex molecules.

THE PHENOMENA OF BASE-EXCHANGE

The explanation of base-exchange is to be found in these complex alumino-silicate compounds which react with added salts to effect a replacement of the cations already present in the silicate complex. Gedroiz of Russia, Hissink of Holland, Kelley of California and workers in the Bureau of Soils of the U. S. D. A. have thrown considerable light on the subject of base-exchange.

If we take the case of orthoclase, which, according to Van Hise, passes on decomposition through the successive stages of $KAlSi_3O_8 \rightarrow HAlSi_3O_8 \rightarrow HAlSi_2O_6 \rightarrow H_4Al_2Si_2O_9 \rightarrow H_4Al_2O_5 \rightarrow H_6Al_2O_6$, with the loss of KOH and SiO_2 and the taking up of water, one can conceive of these secondary silicate complexes as having very definite capacities to absorb cations. Part of these base-absorbing capacities will have been satisfied by taking on those cations which have been liberated by the decomposition of orthoclase and other silicate and carbonate minerals and rocks. With the free movement of water through the soil a time must come when these base-absorbing capacities cannot be satisfied by the alkalies and alkali-earths. The iron and aluminum yielded up on rock decay

must, therefore, substitute in part for the other cations. Further, at any given time these decomposition products may have their base absorbing capacities only partly satisfied, the cation in this case being in part hydrogen.

No matter whether the soil solution is acid or alkaline it is to be expected that on treatment with a soluble salt the cation of that salt will replace equivalent amounts of cations present in the silicate complex up to a point of equilibrium that is determined by the nature and quantities of the cations present in the soil complex and the cation added in the salt. In the case of soils which are saturated with respect to bases, the use of a solution of ammonium chloride should and does yield equivalent amounts of magnesium, calcium, potassium and sodium sulfates. The amount of each of these cations yielded to the soil solution will depend upon the quantities of each present in the soil complex and the order in which they are replaceable as well as upon the concentration of the salt solution used.

It must be kept in mind that the basic elements present in soils evidently exist in two forms one of which is that of the primary minerals which have never been decomposed, and the other that of the decomposition products which have undergone alteration. If one treats a soil with successive portions of a solution of ammonium chloride until no more base is replaced, he can measure the total amount of base present in the form of these secondary mineral complexes. After heating the soil to a sufficiently high temperature to volatilize the ammonium chloride, he can then determine what per cent of the total amount of the basic elements is tied up in the form of primary minerals.

However, if one powders orthoclase to a degree of fineness that is comparable to that of the colloidal particles in soils he finds that, by treating it with successive portions of ammonium chloride the potassium is replaced in part by the ammonium, indicating that not all of the replaceable bases of soils need be from the secondary mineral complex. Organic substances are also involved in this phenomenon of base-exchange.

BASE-EXCHANGE IN ALKALI AND ACID SOILS

Kelley's studies have shown that neutral or slightly alkaline soils are characterized by having a relatively large amount of

replaceable calcium and a relatively small amount of replaceable sodium. From 50 to 60 per cent of the replaceable bases in such soils was found to be calcium, 20 to 30 per cent magnesium and the remainder potassium and sodium. Alkali soils contain relatively large amounts of replaceable sodium and smaller amounts of replaceable calcium. On the other hand, acid soils are characterized by having a low content of replaceable alkalies and alkali earths and relatively large amounts of replaceable iron, aluminum and manganese.

ABSORPTION OF PHOSPHORIC ACID BY SOILS

The soil is a very effective agent in the fixation of phosphoric acid. Bear and Salter have shown that almost the entire amount of phosphorus applied during a fifteen-year period to a Dekalb soil as acid phosphate could be accounted for in the surface layers of the soil and in the crops removed. This confirms the earlier investigations of Dyer, who reported the phosphorus content of the soils of the Broadbalk plots in 1893 as compared to the amounts of phosphorus contained in them fifty years previously. Taking into consideration the quantities of phosphorus supplied in fertilizers and that estimated to have been removed in crops, the balance sheet was as shown below.

TABLE XXVIII

FIXATION OF PHOSPHORUS BY BROADBALK SOIL *

Plot	Pounds per Acre in First Nine Inches of Soil	
	Calculated Excess	Recovered in Soil
7	2452	2100
13	2587	2359
14	2667	2323
12	2651	2255
11	2759	2151
5	3049	2722

Estimated from analyses in 1844 and 1893.

While the recovery is not complete, it is probable that the remainder, not accounted for in the analyses, was contained in the subsoil. The major portion, however, is shown to have been

retained in the plowed soil of the first 9 inches where it was evidently fixed in close proximity to the original point of contact.

ABSORPTION OF AMMONIA BY SOILS

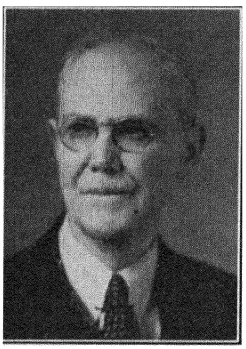
While Way had shown that ammonium as well as potassium is fixed by soils, it is apparent from previous considerations that this does not prevent the loss of nitrogen in the drainage water. The explanation of this lies in the fact that the ammonia of soils is rapidly changed to nitrates for which the soil has little absorbing power. The carry-over effect of potassium and phosphorus fertilizers is, therefore, not noted with nitrogen fertilizers except as the nitrogen may have been used by crops and left behind in their residues where it may remain for a time in an unavailable form. Apparently, in the case of potassium and phosphorus, the re-solution or re-availability processes are sufficiently rapid to satisfy the ordinary requirements of plants.

SELECTED REFERENCES

1. Bear, F. E., and Salter, R. M. Residual effects of fertilizers. West Virginia Agr. Exp. Sta. Bul. 160, p. 19, 1916.
2. Bouyoucos, Geo. J. Rate and extent of solubility of soils under different treatments and conditions. Mich. Agr. Exp. Sta. Tech. Bul. 44, 1919.
3. Bradfield, Richard. The chemical nature of colloidal clay. Missouri Agr. Exp. Sta. Res. Bul. 60, 1923.
4. Dyer, B. On the analytical determination of probable available mineral plant food in soils. Trans. Chem. Soc., Vol. 65, pp. 115–167, 1894.
5. Hilgard, E. W. Soils, The Macmillan Co., pp. 23, 342, 1906.
6. Kelley, W. P., and Brown, S. M. Replaceable bases in soils. Cal. Agr. Exp. Sta. Tech. Paper 15, 1924.
7. King, F. H. Investigations in Soil Management, by the Author, Madison, Wis., 1904.
8. McCool, M. M., and Millar, C. E. Soluble salt content of soils and some factors affecting it. Mich. Agr. Exp. Sta. Tech. Bul. 41, 1918.
9. Merrill, Geo. P. Rocks, Rock Weathering and Soils, The Macmillan Co., pp. 28 and 363, 1913.
10. Morgan, J. F. The soil solution obtained by the oil pressure method. Mich. Agr. Exp. Sta. Tech. Bul. 28, 1916.
11. Patten, H. E., and Waggaman, W. H. Absorption by Soils. U. S. D. A. Bur. of Soils Bul. 52, 1908.
12. Russell, E. J., and Prescott, J. A. The reaction between dilute acids and the phosphorus compounds of the soil. Jour. Agr. Sci., Vol. 8, pp. 65–111, 1916.
13. Schreiner, O., and Failyer, G. H. The absorption of phosphates and potassium by soils. U. S. D. A. Bur. Soils Bul. 32, 1906.
14. Way, T. J. On the power of soils to absorb manure. Jour. Roy. Agr. Soc., Vol. 13, pp. 123–143, 1852.

CHAPTER IX

MINERAL ECONOMY IN SOILS



T. L. Lyon

SOIL analysis had its origin in the work of Sir Humphry Davy, who was especially interested in the alkalies and alkali earths. Since the soil contains considerable percentages of these elements it was to be expected that Davy would investigate in some detail its chemical composition. Having an interest also in agriculture, he devoted a considerable amount of time to soil analysis in an attempt to explain the known productivity of certain soils. While the methods of analysis (1813) were not sufficiently refined to permit of the more detailed separations of the soil elements, his results are interesting as indicating the progress of chemical science of soils at that time.

"I found the soil taken from a field at Sheffieldplace in Sussex remarkable for producing flourishing oaks, to consist of six parts of sand and one part of clay and finely divided matter; and one hundred parts of the entire soil submitted to analysis produced:

	Per Cent
Silica	54
Alumina	28
Carbonate of lime	3
Oxide of iron	5
Vegetable matter	4
Moisture and loss	6

VALUE OF SOIL ANALYSES QUESTIONED

Up until 1840 Liebig's contribution to soil science had been largely one of piecing together the various bits of experimental data which had been accumulating in European laboratories into

a set of principles as a basis for further investigation of soil and crop relationships. Discussing at that time the importance of knowing something as to the composition of the soil Liebig states:

"It is evident that a knowledge of its [the soil] state and composition must enable us to discover the circumstances under which a sterile soil may be rendered fertile. It is the duty of the chemist to explain the composition of a fertile soil."

After more than twenty years devoted quite largely to the study of the means of increasing the productivity of soils, Liebig came to the conclusion that something more than mere knowledge of the quantities of the mineral elements in a soil is essential to an interpretation of its productivity. Thus in his "Natural Laws of Husbandry," published in 1863, Liebig comments as follows:

"As a matter of course a soil to be fertile for cultivated plants must, as a primary condition, contain a sufficient quantity of the nutritive substances required by plants. But chemical analysis which determines this relation gives but rarely a correct standard by which to measure the fertility of the different soils, because the nutritive substances therein contained, to be readily available and effective, must have a certain form and condition which analysis reveals but imperfectly."

Similarly Boussingault had contented himself with the analyses of the ash of plants as a means of determining their mineral requirements and as a basis for the use of manure and artificial fertilizers. In his opinion little was to be expected of soil analyses as is indicated in the following comment made in 1865:

"Chemists of great talent have made many complete analyses of soils noted for their fertility; still practical agriculture has hitherto derived very slender benefits from labors of this kind. The reason for this is very simple; the qualities which we esteem in a workable soil depend almost exclusively upon the mechanical mixture of its elements; we are much less interested in its chemical composition than in this; so that simple washing, which shows the relation between the sand and clay, tells, of itself, much more that is important to us than an elaborate chemical analysis."

Ville, with his characteristic positiveness, after a careful survey of the analyses of Davy and others and from analytical experiences of his own, wrote in his "Artificial Manures" in 1862 as follows:

"Chemistry is powerless to throw light upon the agricultural qualities of the soil, its resources and its needs, because it confounds in its indications the active assimilable agents with the assimilable agents in reserve, the active with the inert or neutral principles."

ESTIMATION OF AVAILABLE CONSTITUENTS IN SOILS

Recognizing the need for determining something as to the quantity of the mineral elements in the soil which might be available to plants under suitable conditions of management and within a reasonable length of time, chemists changed their plan from that of determining the total constituents of the soil to that of estimating the "available" amounts by the use of various solvents. The previous chapter contains a discussion of this phase of soil analysis. Suffice it to say at this point that, for the period from 1890 to 1910, large numbers of strong-acid-digestion analyses were reported.

Whitney, in 1908, made a compilation of these analyses, both for Europe and America, which amounted to a total of 4142. These included 1857 samples reported from various parts of the United States, 226 from Great Britain and Ireland, 1550 from France, and 449 from Germany. From a study of these analyses, Whitney came to the conclusion that there were no significant differences between the composition of the older agricultural soils of Europe and the virgin and therefore unexhausted soils of America. It was his opinion that the errors in the methods of analysis, as carried out in the various laboratories were greater than any apparently significant differences in mineral composition of the soils of the two continents and that little was to be expected of chemical analysis, in the ordinary sense in which the term is used, in the interpretation of soil exhaustion.

REVIVAL OF INTEREST IN SOIL ANALYSES

Later Hopkins (1910) headed a movement for the reconsideration of soil analysis as a means of determining the potential supplies of mineral nutrients from which available supplies could be secured by proper management of the soil. In contrast to the opinions of Liebig, Boussingault, Ville, Whitney and others, Hopkins' point of view is of special interest, particularly by reason of its similarity to that of Davy a century earlier. Hopkins writes:

"There are three methods of determining with some degree of satisfaction which elements, if any, are deficient in the soil:

"First, we may compile from the composition of the soil and the requirements of crops the probable durability of a soil with reference to any element of plant food. . . .

"Second, we can assume for a rough estimation that the equivalent of 2 per cent of the nitrogen, 1 per cent of the phosphorus and $\frac{1}{4}$ of 1 per cent of the total potassium contained in the surface soil can be made available during one season by practical methods of farming. . . .

"Third, we may apply different elements of plant food to the soil and note the effect, if any, in increasing the yield of crops. . . ."

The last method, according to Hopkins, frequently leads to erroneous conclusions due to the fact that the material thus applied may serve to liberate elements from the soil and thus have only an indirect effect which may ultimately lead to land ruin.

COMPOSITION OF THE LITHOSPHERE

Of interest in this connection is the estimated composition of the entire lithosphere as given by Clarke.

TABLE XXIX

AVERAGE PERCENTAGE COMPOSITION OF THE LITHOSPHERE—CLARKE

	Igneous Rocks	Shales	Sandstones	Limestones	Weighted Averages
SiO_2	59.14	58.10	78.33	5.19	59.08
Al_2O_3	15.34	15.40	4.77	0.81	15.23
CaO	5.08	3.11	5.50	42.57	5.10
FeO	3.80	2.45	0.30	.....	3.72
Na_2O	3.84	1.30	0.45	0.05	3.71
MgO	3.49	2.44	1.16	7.89	3.45
K_2O	3.13	3.24	1.31	0.33	3.11
Fe_2O_3	3.08	4.02	1.07	0.54	3.10
H_2O	1.15	5.00	1.63	0.77	1.30
TiO_2	1.05	0.65	0.25	0.06	1.03
CO_2	0.101	2.63	5.03	41.54	0.35
P_2O_5	0.299	0.17	0.08	0.04	0.285
MnO	0.124	.....	.....	0.05	0.118
Cr_2O_3	0.055	.....	.....	.....	0.052
BaO	0.055	0.05	0.05	.....	0.051
S and SO_3	0.052	0.64	0.07	0.14	0.075
C	.....	0.80	.....	.....	0.040
Others *	0.218	.....	.....	0.02	0.191

* Including zirconium, chlorine, fluorine, nickel, vanadium, strontium, copper, zinc, lead and lithium.

SOIL FORMATION

It was originally assumed that the most important factor in determining the nature of the soil is the rock from which it was formed. Geological surveys formed the basis of soil surveys on this assumption. The chemical and physical analyses of the soils thus classified were believed to be all that was necessary to bring the survey to completion and to provide the basis for the development of sound practice in soil management.

In proceeding with the survey on this basis, certain inconsistencies in the soil and geological maps were noted for which no logical explanation was at hand. It happened, however, that a school of Russian pedologists, headed originally by Sibirtzov and subsequently by Glinka, found an enormous area of "black earth" in southern Russia which overlay rocks of several different geological formations. The only rational explanation seemed to be that the predominating factor was the climate and that this became fully operative only under conditions in which the soil remained in position through a long enough period of time to have reached maturity. This point of view finally came to prevail. It was eventually adopted by Marbut and now forms the basis of the soil survey of this country.

SOIL DEVELOPMENT

Rock materials, in the course of development of soils, are subjected to agencies which effect progressive changes in them. The extent of these changes is determined by the age of the soil and the nature of the climatic factors which operate in the process. The successive stages in soil development have been termed infancy, youth, maturity and old age. In order that a soil may mature and age, it must remain undisturbed over a long period of time. Such a condition obtains only on areas that are practically level and which are not subjected to erosion. In the event that maturity is attained, the nature of the rock material from which the soil was formed is relatively unimportant. The predominating factors in its development are those of the climate, of which rainfall is the most important. If the topography is rolling, or the rainfall is limited, the soil may never develop beyond the stages of infancy and youth, in which case the nature of the rock material from which the soil is being formed is of considerably greater importance.

As previously stated, the significance of the climatic factors in soil development was first made apparent by a study of what are known as the "chernozem," or black soils, of south-central Russia and western Siberia. It was shown that these soils, which have been developed under an annual rainfall of only 15 to 20 inches, are underlain with a great variety of rocks in different areas, but that, throughout the region, the soils are quite uniform in their characteristics. In the lower part of most of these soils there has accumulated a layer of concretions of carbonate of lime, no matter what has been the nature of the underlying rock. A study of the climatic factors and the related vegetation shows, without question, that these are the primary agencies that were involved in the development of these soils. Some years later a group of tropical soils, known as "laterites," was found to be correlated in its distribution with regions of high temperatures and very heavy rainfall. These laterities are characterized by high percentages of the hydrated oxides of iron and aluminum, particularly the latter, and the almost complete absence of alumino-silicates, the silica other than quartz having been entirely leached away.

A CLASSIFICATION OF SOILS ON THE CLIMATIC BASIS

A preliminary classification of the soils of the world, in the scheme of which the climatic factors and their related vegetation are given a primary place, divides soils into eleven groups as follows.

TABLE XXX

SOIL GROUPS OF THE WORLD—MARBUT

No.	Group Name	Color of Soils		Climatic Factors		Natural Vegetation
		Surface	Subsoil	Temperature	Rainfall	
1	Tundras	Gray-black	Gray	Cold	Low	Shrubs and mosses
2	Podsols	Gray	Brownish	Cool	Moderate	Evergreen forests
3	Gray forest	Dark gray	Yellowish-br.	Moderate	Moderate	Oak, beech, maple
4	Chernozems	Black	Black	Moderate	Light	Grass
5	Chestnut-br.	Chocolate	Brown	Warm	Very light	Grass
6	Brown soils	Brown	Yellowish-br.	Hot	Scanty	Grass and shrubs
7	Gray desert	Gray	Yellowish	Very hot	Very scanty	Shrubs
8	Yellow soils	Yellowish	Yellowish-red	Warm	High	Hardwood forests
9	Prairie soils	Black	Brown	Moderate	Moderate	Grass
10	Red loams	Red	Reddish	Hot	High	Forests
11	Laterites	Red	Reddish	Very hot	Very high	Tropical forests

The soil groups listed above were first largely described by Russian workers, who were apparently the original discoverers of the significance of the climatic factor in determining the nature of the soil. Counterparts of most of them are found in the United States. Undoubtedly, other groups will be added with more detailed study of the soils of this and other continents.

THE SOIL PROFILE

The whole series of horizons taken together is known as the soil profile. In general, the profiles of mature soils consist of two layers, known as the A and B horizons. The former is a zone of extraction from which the water has removed, in part, the finely divided particles of soil, the alkalies and alkali-earths, the organic matter, and the oxides of iron and aluminum. No carbonates remain in this horizon of a mature soil. The B horizon is a zone of accumulation in which is deposited the materials that have been leached out of the soil above. A third horizon, C, consists of unweathered material. The depth to the horizon of accumulation is largely determined by the rainfall. As the amount of rainfall decreases, the zone of deposit of carbonates approaches the surface more and more closely until, in semi-arid and arid regions, it may be only a few inches deep.

FROM ROCKS TO SOIL

Since soils result from decomposing rock masses, every inorganic element which exists in the parent material will be found in soils. Practically all the elements known can be detected if sufficient care is exercised. In any one sample of soil many of the stable rock-forming minerals may be found. McCaughey and Fry in the examination of twenty-five important types of soil found the minerals which are given in Table XXXI in the order of the number of soils in which they occurred.

It must be remembered that the failure to find any mineral in one or another of the soils examined microscopically does not guarantee that it is not present in any soil. The presence of kaolin and limonite in every soil other than a practically pure sand cannot be questioned even though the identification of such minerals is difficult optically due to their fineness. The same may be said of the hydrated forms of alumina and silica.

TABLE XXXI

SOIL MINERALS AND THEIR COMPOSITION—MCCAUGHEY

Mineral	Composition
Quartz	SiO_2
Epidote	$Ca_2Al \cdot (OH)\ (Al, Fe)_2\ (SiO_4)_3$
Hornblende	$Ca\ Mg_3\ Si_3O_{10}$
Zircon	$Zr\ SiO_3$
Chlorite	$H_8\ Mg_5\ Al_2\ Si_3O_{18}$
Biotite	$(HK)_2\ (MgFe)_2\ Al_2\ (SiO_4)_3$
Tourmaline	B, Al, Fe, etc.
Muscovite	$KH_2\ Al_3\ Si_3O_{12}$
Orthoclase	$K\ Al\ Si_3O_8$
Microcline	$K\ Al\ Si_3O_8$
Rutile	TiO_2
Anorthite	$Ca\ Al_2\ Si_2O_8$
Albite	$Na\ Al\ Si_3O_8$
Apatite	$Ca_4\ (PO_4)_3\ CaF_2$ or $\cdot CaCl_2$

The processes of weathering are quite complex. Selecting two important minerals, quartz and orthoclase, it is of interest to trace the changes which may occur in them as they take on the nature of particles of soil. Crystalline quartz constitutes a considerable percentage of many igneous rocks. It is very resistant to weathering and continues to constitute an important part of all soils irrespective of their age. In fact about the only thing that happens to quartz in the weathering of rocks to soil is the constant diminution in size of its particles as they are broken to pieces and worn away by mechanical processes.

In the case of orthoclase the fate of the silica that is contained in this mineral is quite different in that in the process of weathering the silica moves into solution and is carried off in the drainage water. Appreciable amounts of silica having its origin in orthoclase and other silicate minerals are found dissolved in the water of all streams, their content of this constituent being from 1 to 60 parts per million. The ash of plants contain considerable amounts of silica which must have been in solution in the soil water before it could move into the plant.

According to Van Hise, a foremost authority on the processes

of weathering and metamorphism of rock masses, the decomposition of orthoclase proceeds as follows.

TABLE XXXII

DECOMPOSITION OF ORTHOCLASE—VAN HISE

1.	$2KAlSi_3O_8$	$+ H_2O$	$= 2KOH$	$+ 2HAlSi_3O_8$	("orthoclasite")
2.	$2HAlSi_3O_8$	$- 2SiO_2$	$= 2SiO_2$	$+ 2HAlSi_2O_6$	(pyrophyllite)
3.	$2HAlSi_2O_6$	$- 2SiO_2$	$= 2SiO_2$	$+ H_4Al_2Si_2O_9$	(kaolin)
4.	$H_4Al_2Si_2O_9$	$- 2SiO_2$	$= 2SiO_2$	$+ H_4Al_2O_5$	(bauxite)
5.	$H_4Al_2O_5$	$+ H_2O$	$= H_6Al_2O_6$		(gibbsite)
6.	$H_4Al_2O_5$	$- H_2O$	$= H_2Al_2O_4$		(diaspore)
7.	$2KOH$	$+ H_2CO_3$	$= 2H_2O$	$+ K_2CO_3$	(potassium carbonate)

For the other soil-forming silicate minerals similar reactions have been hypothecated. Thus as soils age the calcium, sodium, magnesium and potassium are dissolved and carried off in the drainage water to be subsequently deposited either in the ocean, in salt lakes, in alkali deposits or in lower horizons of the soil. Accompanying this there is also the somewhat more gradual solution of the silica of silicates. The net result is that the soil comes to be formed more and more largely of hydrated iron and aluminum oxides and finely divided particles of quartz. All of the stages of weathering, from the beginning decomposition of rocks and their mineral constituents to the final product that contains very high percentages of the oxides of aluminum and iron, are to be found, depending upon the age of the soil. It is significant in this connection to note that the most important kaolin deposits lie in the northern half of the temperate regions while the diaspores, bauxites, and laterites are found in the southern half of the temperate regions and in the tropics.

CHEMICAL COMPOSITION OF REPRESENTATIVE SOILS

With the above facts in mind it is interesting to note the chemical composition of representative American soils as given in Table XXXII.

It is evident from these analyses that the potential supplies of the mineral elements in soils vary between wide limits. An examination of the large amount of the more recent analytical data relating to total constituents in soils will show isolated cases of smaller and larger amounts of each element than any indicated

TABLE XXXIII

PERCENTAGE INORGANIC COMPOSITION OF REPRESENTATIVE AMERICAN SOILS—ROBINSON *

Series and Type	State	Depth, Inches	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5	SO_2
Ruston fine sandy loam [1]	La.	6	95.51	0.36	1.70	0.68	0.02	0.12	0.00	0.16	0.04	0.04	0.23
Norfolk sand [1]	S. C.	8	94.81	0.51	1.42	0.60	0.02	0.19	0.01	0.08	0.12	0.10	0.08
Cahaba fine sandy loam [6]	Ga.	12	91.39	0.52	3.72	0.97	0.07	0.21	0.09	0.90	0.12	0.06	0.06
Louisa loam [2]	Va.	12	84.58	1.51	5.54	3.30	0.05	0.21	0.25	0.74	0.14	0.12	0.15
Sassafras silt loam [2]	Md.	8	82.88	1.09	7.49	2.25	0.04	0.41	0.36	1.87	0.90	0.15	0.05
Clarkesville silt loam [4]	Ky.	10	81.85	1.37	7.35	2.79	0.15	0.29	0.23	1.36	0.95	0.08	0.08
Memphis silt loam [3]	N. Y.	6	81.13	0.78	8.52	2.92	0.03	0.31	0.39	1.78	0.52	0.08	0.03
Durham sandy loam [2]	N. C.	10	80.79	0.53	10.55	1.61	0.02	0.89	0.19	3.96	0.87	0.12	0.06
Richfield clay loam [7]	Texas	10	79.64	....	8.27	2.74	....	0.63	0.87	1.83	1.12	0.10	....
Decatur clay loam [5]	Ala.	4	79.35	1.15	8.89	4.44	0.07	0.63	0.39	0.67	0.24	0.18	0.13
Colorado sand [7]	Col.	14	78.85	0.32	9.68	2.72	0.03	0.94	0.72	2.31	2.02	0.11	0.07
Miami silty clay loam [3]	Ind.	10	77.79	0.91	9.74	2.68	0.08	0.61	0.62	2.18	1.09	0.29	0.03
Carrington loam [3]	Wis.	12	77.28	0.53	8.93	2.89	0.06	0.84	0.56	1.35	1.15	0.14	0.10
Marshall silt loam [3]	Mo.	15	75.61	0.71	9.67	3.54	0.12	1.08	0.77	2.28	1.03	0.22	0.17
Clermont silt loam [3]	Ohio	6	75.30	....	10.27	6.34	....	0.77	0.95	1.84	....	0.15	
Volusia silt loam [3]	N. Y.	8	75.12	0.68	10.49	4.13	0.02	0.49	0.48	1.40	0.90	0.18	0.09
Oswego silt loam [7]	Kan.	14	71.38	0.68	12.29	3.63	0.05	1.09	0.36	2.28	1.14	0.10	0.12
Hagerstown loam [5]	Pa.	8	70.99	1.01	11.39	4.23	0.18	0.93	1.08	2.71	0.82	0.19	0.34
Palouse silt loam [8]	Idaho	12	69.60	....	13.62	5.30	0.00	2.47	1.41	1.99	2.91	0.20	
Gloucester stony loam [3]	N. H.	8	65.68	0.79	14.15	5.67	0.07	1.36	0.83	2.16	1.39	0.11	0.03
Stockton clay adobe [9]	Cal.	38	63.52	1.21	14.34	7.98	0.16	2.34	1.81	0.78	1.68		
Dekalb silt loam [4]	W. Va.	7	.....	1.20	8.12	2.77	0.31	0.15	0.37	1.45	....	0.07	0.16
Highest percentages	.....	.....	95.51	1.51	14.34	7.98	0.31	2.47	1.81	3.96	2.91	0.29	0.34
Lowest percentages	.....	.....	63.52	0.32	1.42	0.60	0.00	0.12	0.00	0.08	0.04	0.04	0.03

* A few of these analyses were taken from other sources.

[1] Coastal Plain Province. [2] Piedmont Plateau Province. [3] Glacial and Loessial Province. [4] Appalachian Mountain and Plateau Province. [5] Limestone Valleys and Uplands Province. [6] River Flood Plain Province. [7] Great Plain Region. [8] Northwest Intermountain Region. [9] Pacific Coast Region.

in the table. Thus some unproductive black soils, analyzed by Conner and Abbott, were found to have a nitrogen content as high as 3.82 per cent and a potassium content as low as 0.16 per cent. Averitt reports the phosphorus content of the Trenton soils of Kentucky as having a range from 0.13 to 1.16 per cent with an average of 0.47 per cent.

PRESENCE OF RARER ELEMENTS IN THE SOIL

In addition to the elements mentioned which, together with the oxygen in combination with them, make up the major portion of the soil, analyses have shown the presence of smaller amounts of various other elements. Robinson, as previously stated, examined twenty-six samples of soil chosen from as many localities in the United States. In these soils, chromium, vanadium, rare earths, zirconium, barium, strontium, lithium and rubidium were found to be present in every case. Molybdenum was found in two samples and caesium in one. Titanium was usually present in largest amounts in the subsoil. Manganese, like phosphorus, was shown to be concentrated in the surface soil. Robinson was not able to detect the presence of copper, nickel or cobalt, although undoubtedly they, as well as many other rarer elements, must be present in soils in close proximity to those areas in which the minerals or ores containing them are found.

COMPOSITION OF SOILS OF WELL-KNOWN EXPERIMENTAL FARMS

It is of interest to note the differences in the chemical composition of the soils of the several experimental farms which are given prominent consideration in the study of fertilizer practice. The following analyses have been reported from the stations indicated and while the systems of management on the several farms are different and their histories have been in no way similar, yet the analytical results have a certain comparative value.

The Rothamsted analysis is in part that reported by Hall of a sample selected from plot 4 in Broadbalk Field which had been unmanured for fifty years. The amounts of calcium, magnesium and sulphur represent only that soluble in strong hydrochloric

acid. Dyer reports the total phosphorus in plot 4 as amounting to 0.05 per cent in 1893. Hall gives the total potassium content of the soil of the Broadbalk Field at 2.26 per cent.

TABLE XXXIV

MINERAL ANALYSES * OF SOILS OF PROMINENT EXPERIMENTAL FARMS

Station	Phosphorus	Potassium	Calcium	Magnesium	Sulphur	Nitrogen †
Rothamsted	980	45,200	35,360 ‡	4320 ‡	400 ‡	2000
Rhode Island	1100	2,542 ‡	8,130 ‡	.....	.....	4540
Pennsylvania	1440	55,460	5,470	4180	.....	2200
Ohio	660	33,110	4,720	7790	412	2000
Illinois	1060	35,430	10,680	9500	.....	4800

* Pounds of elements per 2,000,000 of surface soil.
† Included for later consideration.
‡ From acid digestion analysis.

The Rhode Island analyses are reported by Wheeler in 1910. They show the total phosphorus and the acid-soluble potassium and calcium. The depth of soil sampled was apparently less than the $6\frac{2}{3}$ inches required for two million pounds. Nevertheless the amounts were calculated to the two million basis for comparison. "The land had neither been manured nor plowed for many years."

The Pennsylvania analyses are those recorded by White from the unmanured plot 24 on the State College Farm from samples selected in 1911. The Ohio analyses are those given by Ames and Gaither from samples chosen in 1896 from unfertilized and unlimed sections of the fertilizer series of plots at Wooster. The Illinois analyses are those reported by Hopkins and his associates as being representatives of the brown silt loam soil of Champaign County which corresponds to that on the experimental farm at the University of Illinois.

These analyses indicate that the potential mineral supplies in the Wooster soil are low as compared to those of the farms of the other three stations mentioned. The potassium content of all of the soils is relatively high. The Illinois soil, as previously shown, is particularly high in nitrogen. The Pennsylvania soil is rich in phosphorus. The Rothamsted soil is very high in its content of calcium.

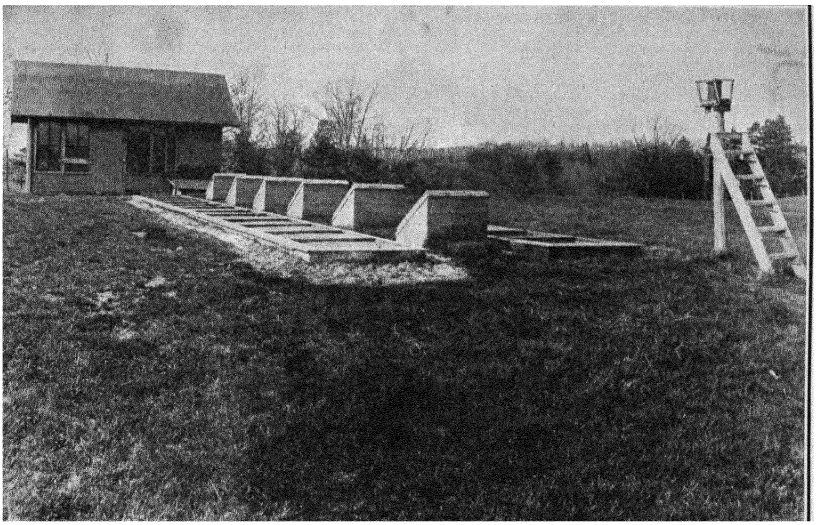
LEACHING EFFECT OF WATER ON THE SOIL

As the weathering and decomposition processes continue in the soil, the soluble products formed tend to be dissolved and carried away in the drainage water except as they are held back by absorption and precipitation or are temporarily retained in the tissues of plants growing on the soil. The accumulation of salts in the ocean or in inland lakes is evidence of the enormous losses of constituents from soils during their formation from the parent rocks. Alkali deposits may be formed in the absence of sufficient rainfall to carry the soluble materials away. Both, surface run-off and underdrainage carry their loads of dissolved mineral constituents from the soil. Under natural conditions, a point is finally reached at which the losses are relatively small after the more readily soluble materials have escaped. The growing vegetation thrives in proportion to the amounts of soluble mineral nutrients and nitrogen remaining that are available. With the advent of agricultural processes the losses are again hastened, particularly with cultivation and during periods in which the soil is bare of vegetation.

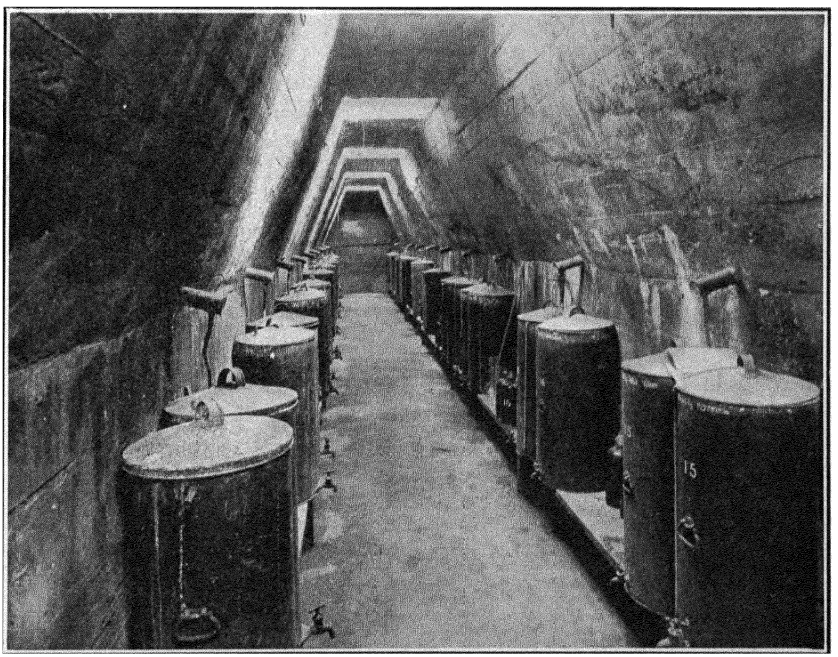
LOSSES FROM CULTIVATED FIELD SOILS

The composition of the drainage water from soils under cultivation has been reported by Voelcker from data secured at the Rothamsted Experiment Station. These analyses were made of water collected from tile which are buried beneath each plot to which access is afforded by a trench extending the entire width of the field and into which the tile empty. Considerable variation is shown in the mineral content of the drainage water depending on the fertilizer and manurial treatment the soil has received as shown in Table XXXV.

Practically no ammonia is present in the drainage water. The quantities of potassium and phosphorus are both relatively small. These three are held rather firmly in the soil by absorption processes. Hall estimates that the mean annual loss could not be more than "two pounds of phosphoric acid and ten pounds of potash per acre, both of which in normal cases would be arrested



(*A*) Exterior view.



(*B*) Interior view of cave beneath.

FIG. 26.—Lysimeter used at Cornell University in study of drainage losses of nitrogen and mineral nutrients from soils.

in the subsoil below the drains." The two constituents of which the loss is most serious are nitrogen as the nitrate and calcium as the bicarbonate. Hall estimates that "on the unmanured plots the normal loss of calcium carbonate in the drainage water amounts to about 1000 pounds per acre." More recent investigations would indicate that the loss of sulfur was one which might require attention since this constituent is normally present in the soil in about the same amounts as phosphorus and is required by certain plants in quantities equal to or greater than those of phosphorus.

TABLE XXXV

COMPOSITION OF DRAINAGE WATER * FROM BROADBALK FIELD—VOELCKER

Elements	Highest Amounts	Lowest Amounts
Iron	5.6	1.8
Calcium	161.0	69.7
Magnesium	6.9	2.9
Potassium	4.4	0.8
Sodium	41.5	3.8
Chlorine	39.4	10.7
Sulfur	59.6	8.8
Phosphorus	0.7	0.1
Silicon	16.8	5.0
Nitrogen	6.3	1.0

* Parts per million.

Analyses of river waters show that the common bases are present normally in the order, as to quantities, of calcium, sodium, magnesium and potassium. However, a number of factors influence the mineral content of drainage waters. Among these may be mentioned the nature of the rocks in the watershed, the rainfall, the nature of the soil and the density of the population. Of interest in connection with the nature of the rock and its resulting soil is a comparison of the mineral content of the water of the Miami and Muskingum rivers of Ohio, the former of which has its origin and course through a limestone area of productive soil and the latter through a sandstone-shale area.

TABLE XXXVI

COMPARISON OF MINERAL CONTENT * OF MIAMI AND MUSKINGUM RIVERS—CLARKE

Element	Miami River † Limestone Watershed	Muskingum River ‡ Sandstone-shale Watershed
S as sulfate	4.13	6.12
Cl	1.42	17.07
N as nitrate	0.69	0.16
Ca	20.46	18.36
Mg	8.33	4.06
Na	2.49	9.39
K	0.83	1.28
Si	2.76	2.81
Fe	0.06	0.07
Salinity, p.p.m.	244.0	289.0

* Percentages of total mineral content.
† Average of 34 composites chosen during year 1906–07 at Dayton.
‡ Average of 27 composites chosen during year 1906–07 at Zanesville.

MINERAL LOSSES IN DRAINAGE IN LYSIMETER TESTS

Lyon and Bizzell review the investigations relating to the losses of bases in drainage waters from field soils and from lysimeters. It is clearly shown in the review and in their supplemental investigations that the drainage tends to remove calcium, sodium, magnesium and potassium, in the order named, although there was little difference between the last two. The drainage losses of all of these elements, except potassium, were greater than the losses through removal by crops. The drainage losses of sulfur were three to six times as great as those occasioned by the growth of crops. In no case was there more than a trace of phosphorus in the drainage water.

All of these losses of soluble compounds can be very much reduced by the presence of growing vegetation. On the other hand, large amounts of vegetable material left behind in crop residues in the soil stimulate the solution processes through the formation of acids such as carbonic and nitric. Increased solubility means increased availability of nutrient materials and larger crop yields.

CAPACITY OF SOIL TO CONTINUE TO SUPPLY ESSENTIAL ELEMENTS

The fact that nitrogen can be secured from the air and stored in the soil in combined forms through the agency of certain soil organisms is now well established. There is, therefore, the opportunity through these agencies to maintain the supply of this element in the soil in quantities sufficient for crop needs under some system of soil management. With regard to the other elements required from the soil by plants the problem is not so simple. Certain facts need consideration in making any very



0–12–6 No fertilizer 0–12–6

FIG. 27.—Effect of fertilizers on corn on good soil in Bureau County, Illinois. The center three rows received no fertilizer. The remainder of the field received 200 pounds per acre of an 0–12–6 analysis. Note the man standing in the corn that received fertilizer.

accurate estimation of the effect of long-continued cropping on the mineral content of soils.

The experimental work conducted at the Pennsylvania Station Farm on a Hagerstown loam soil shows that when 48 pounds of nitrogen and 96 pounds of phosphoric acid were supplied every four years, the yields were maintained for a period of thirty-five years at 48 bushels of corn, 40 of oats, 20 bushels of wheat and 3400 pounds of clover hay. Nitrogen was supplied as nitrate of soda and the phosphorus as dissolved boneblack. The elements sulfur, calcium and sodium were, therefore, also added to the soil. The experiment is cited to show that considerable amounts of potassium can be extracted from the soil. It is

estimated that these crops removed an average of about 45 pounds of potassium per acre yearly for the thirty-five-year period. The question arises as to how long this could be continued without very material reduction in yield.

SUBSOIL AS A SOURCE OF MINERAL ELEMENTS

It is ordinarily argued that the elements phosphorus and potassium, as well as sulfur and calcium, must be returned to the soil in the quantities in which they are removed in crops and in drainage otherwise the soil will ultimately be exhausted of them. Certain compensating factors, however, need consideration. The subsoil constitutes a reserve of materials which become available through the action of deep-rooted plants, through the agency of organisms such as earthworms, by the process of erosion, by diffusion and by capillary movements of materials dissolved in the soil water at lower levels.

Hopkins gives the analyses of twenty samples of soil chosen at three depths, viz.: 0 to $6\frac{2}{3}$ inches; $6\frac{2}{3}$ to 20 inches and 20 to 40 inches. The average for each depth of these twenty samples is shown in the accompanying table.

TABLE XXXVII

AVERAGE ANALYSES * OF TWENTY ILLINOIS SOILS—HOPKINS

Depth	Soil Weight	Nitrogen	Phosphorus	Potassium	Carbonates †
Inches					
0–$6\frac{2}{3}$	2,000,000	4,054	1155	33,652	1,719
$6\frac{2}{3}$–20	4,000,000	2,218	994	34,474	1,340
20–40	6,000,000	504	508	17,360	8,900
Totals to 40 inches depth. .		10,002	4667	154,680	31,099

* Pounds per two million of soil.
† As $CaCO_3$.

DEPTHS AT WHICH PLANTS ABSORB MINERAL NUTRIENTS

It is apparent that large supplies of these elements are stored in the subsoil and the possibility of their being used is quite evident. One of the good effects of sweet clover is credited to the ability of its roots to penetrate considerable depths into the sub-

soil and to leave behind in its residues on the surface of the soil the substances that have been taken from these depths. This is especially desirable from the point of view of conserving calcium in the soil. If the roots are able to reach the carbonate of lime, which is quite often present in larger amounts in the subsoil, the calcium utilized by the plant may be ultimately returned to the soil after the plant materials have been oxidized to carbon dioxide and water. Some evidence in favor of such accumulation of elements in the surface soil at the expense of the subsoil is found in the fact that phosphorus, even though utilized by plants, is found in greater amounts as a rule in the surface soil than in the subsoil. The percentage of phosphorus in the average of the twenty soils cited in the table is greater in the surface than in the subsoil. Phosphorus is chemically fixed in the soil and cannot move readily from place to place in the soil water. Its presence in large amounts in the surface soil must be accounted for apparently in the work of deep-rooted plants. Hopkins commenting on this point writes:

"This is probably due to the fact that the prairie grasses that grew here for centuries extracted some phosphorus from the subsurface in which their roots fed to some extent and left it in the organic residues which accumulated in the surface soil."

Concerning the value of the mineral elements in the subsoil, Hopkins writes:

"The plant food in the subsurface and subsoil is unquestionably of some value but even the total supplies of nitrogen and phosphorus that are held within the feeding range of ordinary plant roots are not unlimited when measured by crop requirements in permanent agriculture. However, the thing of first importance is to maintain a rich surface soil, for no subsoil is of much practical value if it lies beneath a worn-out surface. On the other hand, if the subsoil will act as a reservoir for moisture, then a rich top soil will produce large crops."

Russell commenting on this point writes:

"It is well known that only the top 6 or 8 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 almost exclusively to the surface layer."

Weaver, Jean and Crist have shown from a study of the root systems of crop plants under favorable conditions the penetration

of roots to a depth of 6 or 7 feet in the soil in sections in which they were investigated, viz.: Peru, and Lincoln, Nebraska; Phillipsburg, Kansas, and Burlington, Colorado. The following table selected from their monograph on this subject is of value in this connection.

TABLE XXXVIII

DEVELOPMENT OF PLANT ROOTS AT PERU, NEBRASKA—WEAVER

Crop	Growth Record of Plants		Growth Record of Plants	
	Age, Days	Height, Feet	Depth, Feet	Spread, Feet
Oats, Swedish Select	19	0.2	0.8	0.4
	60	1.0	3.7	0.8
	63	3.0	6.8	1.3
Wheat, Marquis	20	0.2	0 9	0.6
	70	1.7	5.8	1.3
	93	2.7	6.7	1.3
Barley, Manchuria	20	0.4	1.2	0.7
	54	0.9	4.5	1.3
	84	2.3	6.3	1.3
Corn, Silver Mine	36	1.0	1.3	2.6
	57	4.0	4.7	4.0
	116	8.5	8.2	4.0
Potatoes, Early Ohio	56	0.9	1.5	2.2
	94	2.3	4.7	2.1

Following these investigations, a series of tests was conducted to determine the amount of water and nutrients absorbed by roots from the lower depths. Soil was placed in containers in the same relative position in which the several layers occurred in the field. Nitrate of soda was mixed with 6-inch layers distributed at various points in the soil columns in the several cylinders. The nitrate of soda was prevented from movement by separating the soil layers containing it from the remaining soil by wax seals through which the roots could penetrate. Their final conclusions were as follows:

"In every case where roots came in contact with a fertilizer layer they not only developed much more abundantly and branched more profusely but such a layer apparently retarded normal penetration into the soil below. Thus it seems that the depth at which fertilizer is placed in field practice would considerably affect root position and development. Fertilizing the surface layers of soil in regions where these have very little or no available water during

periods of drought would appear to be distinctly detrimental to normal crop production. . . . We must conclude that the deeper soils are not only suited to plant life but that they play an exceedingly important part in the life of the plant and deserve careful consideration in a study of crop production.

While their investigations do not throw any light on the extent to which the subsoil will yield up its mineral stores to the plant, they do indicate that in the event of mineral elements being dissolved in the subsoil water they may be available for the use of the plant.

EFFECT OF EARTHWORMS IN RENEWING THE SOIL

Darwin estimates that an inch of material is carried from lower levels to the surface by earthworms every five years. This calculation is based upon observations in which materials, such as marl and stones, supplied to the surface of the soil, have been known to be gradually buried to a considerable depth. The finer materials are taken internally and given off in the castings and the whole is mingled with organic matter to form the vegetable mold or rich surface soil. For the most part the earthworms live in the upper stratum of soil rich with vegetable mold, but they are known to penetrate to considerable depths in cold weather and during dry seasons. It was Darwin's conclusion that the burial of the ruins of ancient buildings could be accounted for by the action of earthworms. A total of more than ten tons of dry earth was estimated to pass through their bodies per acre annually in many parts of England. The number of earthworms per acre was estimated at approximately twenty-seven thousand. In a study of the number of earthworms in the soil on the Ohio State University Farm it was found that they were present in plots of soil covered with bluegrass in numbers averaging over one million per acre. These were concentrated at the time the numbers were estimated, in July, in the upper foot of soil.

In addition to the carrying upward of earth and the formation of vegetable mold or rich surface soil, the earthworms are also known to excrete calcium in the form of carbonate. Apparently, in consuming the leaves of plants, the calcium that is left behind after the organic acid radical with which it was combined has been utilized by the earthworms is excreted as the carbonate from three sets of calciferous glands about midway between the ends

of the body. In the event of an underlying layer of calcareous soil or marl this might also be carried to the surface and left behind in their castings.

If Darwin's conclusions are correct, the surface soil is being constantly renewed by material carried up from lower levels. The method of calculating the year's supply of plant food materials from the chemical analyses of the present surface soil and of the crops removed would have to be modified therefore, to take this fact into consideration.

REMOVAL OF SURFACE SOIL BY EROSION

According to McGee, the rate of erosion of lands is estimated by geologists at one inch for every 200 to 500 years. This rate will of course vary with the slope and the elevation above sea level. Dole and Stabler calculate that the United States is being denuded at an average rate of one inch in 760 years. Lands under cultivation, particularly the silt loams with only a moderate slope, may be expected to be eroded at a rate of an inch or more per century under climatic conditions such as exist in the humid regions of the United States.

An investigation of the losses by erosion under ordinary field conditions is under way at the Missouri Station. In these investigations it has been shown that with a slope of perhaps 3.6 degrees, Shelby loam soil erodes under the weather conditions at Columbia, Missouri, at the following rates.

TABLE XXXIX

ANNUAL RATE OF REMOVAL OF SOIL * BY WATER EROSION—DULEY

Soil Treatment, Annually	Soil Removed, Tons per Acre	Rain Absorbed, Per Cent	Years Required to Remove 7 Inches
Uncultivated, weeds pulled	207	49	29
Cultivated throughout summer	247	31	24
Same with deeper plowing	214	28	28
Continuous sod	2	12	3547
Wheat every year	40	25	150
Three-year rotation	14	14	437
Corn every year	107	27	56

* Shelby loam soil with slope of 3.6 degrees.

MOVEMENT OF DISSOLVED SALTS IN CAPILLARY WATER

The soluble salts in areas of scanty rainfall tend to accumulate as alkali at the surface of the soil as the water is lost by evaporation. In the humid regions the percolation of the water off and through the soil prevents the accumulation of alkali deposits. A matter of interest in humid regions is as to the extent to which these two operations tend to counterbalance each other. In his experiments on the movement of salts in soils, King showed that when water is supplied at the bottom of the soil column, with no opportunity for percolation, there is a very definite upward movement of certain salts as is evidenced by their accumulation at the surface of the soil. The following table, chosen from King's work, shows the distribution of the dissolved salts in a Hagerstown clay loam soil at the end of a fifty-day period of

TABLE XL

DISTRIBUTION OF WATER-SOLUBLE SALTS IN SOIL * DUE TO CAPILLARITY—KING

Depth, Inches	Ions in Parts per Million of Dry Soil								
	K	Ca	Mg	NO_3	HPO_4	SO_4	HCO_3	Cl	SiO_2
0–1	33	1500	503	3298	11	430	90	240	12
1–2	24	170	55	303	13	320	143	0	13
2–3	21	150	49	165	14	260	160	0	13
3–4	20	150	48	151	14	250	160	0	13
4–6	20	143	45	158	13	230	155	0	12
6–8	19	140	43	107	14	230	165	0	13
8–10	19	132	39	110	14	200	160	0	13
10–12	19	120	36	63	14	160	160	0	13
12–14	18	112	36	67	13	155	165	0	13
14–16	17	110	35	41	13	150	170	0	13
16–18	22	110	34	10	13	150	185	0	13
18–20	23	90	33	3	13	143	185	0	12
20–22	25	76	26	12	13	125	195	0	13
22–24	43	62	24	8	11	113	170	0	12
In soil at start	13	116	34	234	10	75	135	0	15
Solution added †	120	30	42	56	50	163	144	24	10

* Hagerstown clay loam—50-day period.

† This solution was added at the bottom of the soil column as rapidly as capillarity would permit until the soils became wet on the surface after which distilled water was supplied as required to replace that lost by evaporation.

capillary action of water undisturbed by rainfall and drainage losses.

The tendency toward accumulation at the surface of the soil of the calcium, magnesium, nitrate, sulfate and chlorine ions is very apparent. A similar but less marked tendency was shown by the potassium but none whatever by the phosphate ion. Further discussion of these variations will be reserved for later. It is apparent that certain of the mineral ions, if present in soluble form in the subsoil, would move toward the surface under conditions in which capillary movement is in progress.

The losses through drainage in humid regions are, however, likely to more than counterbalance the gain from the subsoil through the action of capillarity. This is one very good reason for applying fertilizers, manure and limestone to the surface of the soil, although the extent to which losses might occur in the presence of growing plants with deep root systems is problematical.

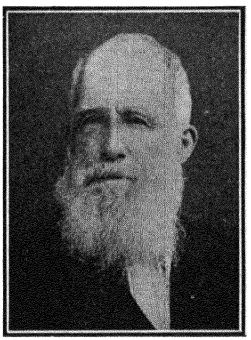
SELECTED REFERENCES

1. Averitt, S. D. The soils of Kentucky. Kentucky Agr. Exp. Sta. Bul. 193, 1915.
2. Boussingault, J. B. Rural Economy, Translation by Law, New York, p. 206, 1865.
3. Clarke, F. W. Data of geo-chemistry. U. S. G. S. Bul. 770, 1916.
4. Conner, S. D., and Abbott, J. B. Unproductive black soils. Indiana Agr. Exp. Sta. Bul. 157, 1912.
5. Darwin, Charles. The Formation of Vegetable Mould through the Action of Worms, Appleton and Co., 1915.
6. Davy, Humphry. Elements of Agricultural Chemistry, London, p. 142, 1813.
7. Dole, R. B., and Stabler, H. Denudation. Report National Conservation Commission, Vol. II, pp. 126–140, 1905.
8. Hopkins, C. G. Soil Fertility and Permanent Agriculture, pp. 82–86, 107–111, 1910.
9. King, F. H. Investigations in Soil Management, by Author, Madison, p. 80, 1904.
10. Liebig, J. von. Natural Laws of Husbandry. Translation by Blyth, London, p. 63, 1863.
11. Lyon, T. L., and Bizzell, J. A. Lysimeter experiments. Cornell Agr. Exp. Sta. Memoir 12, 1918.
12. McGee, W. J. Soil erosion. U. S. D. A. Bur. Soils Bul. 71, 1911.
13. Robinson, W. O. The inorganic composition of some important American soils. U. S. D. A. Bul. 122, 1914.
14. Van Hise, Richard. Treatise on metamorphism. U. S. G. S. Monograph 47, 1904.

15. Ville, Georges. On Artificial Manures. Translation by Crookes, London, p. 174, 1882.
16. Voelcker, A. On the productive powers of soils in relation to the loss of plant food by drainage. Jour. Chem. Soc., Vol. 24, p. 276, 1871.
17. Weaver, J. E., Jean, F. C., and Crist, J. W. Development and activities of roots of crop plants. Carnegie Institution at Washington, 117, p. 1, 1922.
18. Wheeler, H. J. Studies of the needs of Rhode Island soils. R. I. Agr. Exp. Sta. Bul. 139, p. 98, 1910.
19. Whitney, Milton. Study of crop yields and soil competition in relation to soil productivity. U. S. D. A. Bur. Soils Bul. 57, 1909.

CHAPTER X

DEVELOPMENT OF THE FERTILIZER INDUSTRY



John B. Lawes.

WRITING in his book on "Rural Economy," or "Chemistry Applied to Agriculture," Boussingault, in 1885, makes the following interesting comment concerning the early use of mineral substances on soils.

"Practice got the start of science in the application of mineral manures or stimulants. If their useful influence cannot be denied, as it cannot, if the circumstances in which it is advantageous to administer them, if the conditions and the doses in which they ought to be given to the ground have been the subject of long and careful observation with farmers, it must still be admitted that we are far from understanding exactly in what way they act; this is another motive for continuing to study them with perseverance."

A study of the history of the development of the fertilizer industry shows that it is simply an outgrowth of practices of farmers that were built up entirely independently of science. It happened that many of these practices were subsequently supported by the findings of science. Furthermore, science found ways and means of improving fertilizer practice and discovered and developed new sources of fertilizer materials. A short review of the history of the early use of a number of fertilizer materials, still commonly employed, may be of interest in this connection.

EARLY USE OF LIME

The Romans are known to have recognized the value of lime. They are believed to have introduced the practice of liming into the British Isles during their period of invasion. Likewise they were probably responsible for the introduction of this practice into France and the neighboring countries. The enormous

deposits of chalk in England and of marl in France have long been recognized as valuable assets by the farmers of those countries.

The need for lime in America was recognized as early as 1637, as recorded by Carrier in his "Beginnings of Agriculture in America." Oyster shells, accumulated in very large amounts on the camping sites of Indian tribes, were the first source of lime to be employed. There is evidence that these shells were burned for lime, both for building and agricultural purposes, as early as 1645.

The present enormous lime and limestone industry of this country plays a most important part in our program of national development. The tonnage of these materials that finds a use in agriculture is constantly growing. The problem of acid soils is common to all regions of heavy rainfall such as occurs over much of the vast agricultural regions of the United States. Refinements in the practice of using liming materials and improvements in methods of production of these materials are the contributions of the science of the last century.

DISCOVERY OF VALUE OF GYPSUM

The use of gypsum as a fertilizer is believed to have had its origin in the vicinity of a quarry at Montmartre, near Paris, where it was secured for building purposes. Its use in America dates from some years previous to 1770. The practice was introduced by German farmers who had learned of its value in the mother country from the experiences of a mortar-mixer who had been working with gypsum. In going back and forth to his cottage nearby, this workman made a path across the field along which the crops appeared to grow better than they did back farther in the field. Noticing this he surmised that the dust on his clothing and shoes must have been responsible for it. On experimenting with gypsum in his garden he became convinced of its value. As a result the practice spread, the name of gypsum being changed to "landplaster."

In this country the practice of using landplaster spread as far west as Ohio. In the spring of the year, after the wheat was well started, German farmers, in those localities where the

material was available, scattered landplaster over the wheat field at the rate of several hundred pounds per acre. It was known to be of especial value to the clover crop, the seed of which had been previously sown in the wheat.

The practice of using landplaster was in greater vogue in Pennsylvania where many German farmers were located. Benjamin Franklin is reputed to have been so impressed by the effects produced by landplaster that he planned a demonstration on a hillside near Philadelphia on which one could read "This land has been plastered" in the much better growth of grass produced.

Later the use of landplaster fell into disrepute, since it came finally to be believed that the same effects could be produced at less cost by the use of lime. It is of interest to note, however, that simultaneously with the growth in the popularity of lime there came into practice the use of increasingly large amounts of superphosphate which contained approximately 50 per cent by weight of this same landplaster.

ANCIENT USE OF WOOD ASHES

The value of ashes for fertilizer purposes is believed to have been known by farmers in very early times. Certainly the Romans had used them although they were undoubtedly not the originators of the practice. The burning of camp fires and rubbish heaps must always have left a record behind in the increased growth of surrounding vegetation. The good effects noted in such cases was at one time erroneously credited to the effect of this burning on the soil itself rather than to the ashes but this error was subsequently recognized. It will be recalled that de Saussure showed, in 1804, that the ashes of plants contain the mineral constituents which find their way into these plants from the soil.

In the early days of American agriculture many opportunities were provided for learning the value of ashes since the work of clearing the country of forest and burning not only the brush and stumps but the trees themselves had to precede the plowing of the land. For a time large quantities of wood ashes were used in soap making, the necessary potash for soft soap being secured

by leaching the ashes with water. Until recent years ash hoppers for this purpose were a common sight on the farms of this country. Later, when hard soaps were made by substituting soda for potash, fresh wood ashes became a popular source of potash for fertilizing purposes.

THE FIRST EXPERIMENT WITH SALTPETER

Johann Rudolph Glauber of Germany is believed to have been the discoverer of the value of saltpeter for fertilizing purposes when he reported, in 1650, his experiment with this material which he had obtained from the soil that had been removed from cattle sheds. He argued that its origin was manure and that its occurrence in the manure indicated that it had come originally from the plants which the cattle had consumed. His experiment confirmed his conclusions in this regard.

Subsequent tests of potassium nitrate having shown its value for nutritional purposes in plants this material was much sought after since this meant that it had a use in agriculture as well as in the manufacture of gunpowder. Later when the enormous deposits of Chilean nitrate were discovered, the value of this discovery to agriculture was recognized immediately by scientists although the Chilean salt was sodium rather than potassium nitrate.

The first shipments of Chilean nitrate were made from Iquique in 1830. Altogether about 800 tons of the crude salt were exported that year. The first boat load of this material that was sent to England for agricultural purposes is reported not to have found any purchasers with the result that it was dumped overboard into the sea. Subsequently when its value for crop-producing purposes became more fully realized by farmers, millions of tons of the refined salt were required annually to supply the demand for it.

BEGINNINGS OF THE SULFATE OF AMMONIA INDUSTRY

De Saussure had shown that nitrogen is a constituent of plants and believed that it is not secured from the supply of this element in the atmosphere but that it has its origin in decomposing organic matter in soils. Boussingault, agreeing with this

point of view, took the economy of nitrogen as well as the ash constituents of plants into consideration in his "bookkeeping" records of the income and outgo of soils.

Liebig, on the other hand, was of the opinion that plants derive their nitrogen largely from the ammonia of the atmosphere which is carried down to them by the rain. Lawes and Gilbert, testing Liebig's conclusions, not only measured the ammonia content of rain but tried nitrogen fertilizers. Both ammonia

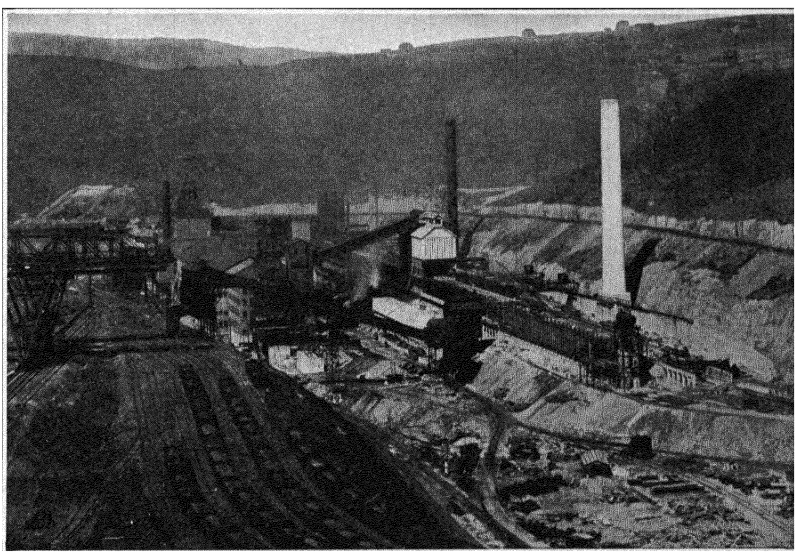


FIG. 29.—View of modern by-product coke plant at Hamilton, Ohio, one of the important by-products of which is sulfate of ammonia. (Courtesy Barrett Company).

salts and nitrates were employed in these tests. The results were very striking.

The origin of the ammonium chloride and sulfate used by Lawes is not recorded. However, their value for fertilizing purposes having been demonstrated, it is quite natural that industry should be on the alert for supplies of these materials. When it was discovered that coal contains ammonia which can be recovered as a by-product in the coking industry, steps were taken to effect this recovery. The first by-product coke oven was erected at St. Denis, in 1858. Subsequently, large amounts of by-product

sulfate of ammonia became available until in 1928 the quantity from this source reached nearly two million tons.

THE INTRODUCTION OF GUANO

One of the oldest and most popular fertilizers is guano, the excrement and remains of sea fowls and marine animals. Wheeler in his book on "Manures and Fertilizers" records that guano was known to have been used as a fertilizer as early as the twelfth century. However, the exploitation of the extensive guano deposits of Peru did not take place until the early years of the nineteenth century. About 1840, during the period of controversy between Liebig and Lawes, guano was being given experimental trials both in England and Germany. Soon afterward it became a very popular fertilizer. By 1885 the total export from Peru had reached the enormous figure of 400,000 tons annually.

In 1832 the first Peruvian guano was imported into the United States. These importations gradually increased until in 1856 they had reached a maximum of 50,000 tons. An additional 10,000 tons of Mexican guano was imported the same year. Baltimore was the principal market for this material, there being very little demand for it at any other place except as the package containing it bore the brand of the Baltimore inspector. The Peruvian Government agent who received and disposed of all guano importations was located there.

EARLY USE OF BONES AS FERTILIZER

Undoubtedly ancient peoples observed the effects of the bones of animals on grass. However, general recognition of the value of bones for fertilizer purposes seems to have first come from England, their value being mentioned in English agricultural literature of the middle of the seventeenth century. By early in the nineteenth century English land owners had not only used up all of the local supply of bones but their agents were collecting bones from all over the world and shipping them to England. The remarks of Liebig in this connection have previously been noted.

Machines for grinding bones were developed, according to Wheeler, as early as 1778. The product resulting from the grinding was undoubtedly very coarse. Subsequently when it was discovered that products of value could be removed from bone by treatment with steam and volatile solvents and that the value of the bone for fertilizer purposes was not impaired by this treatment, this was done and the pulverization of the bone then became an easier problem. Very finely divided bone products finally became available for purchase.

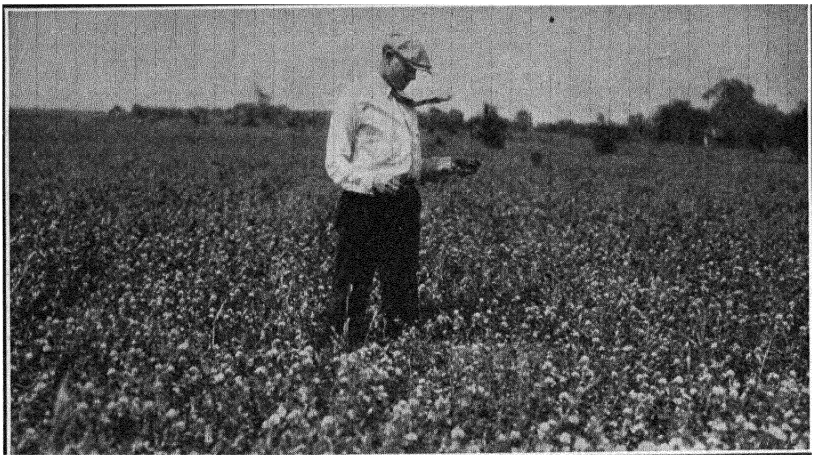
The production of boneblack for use in sugar refineries consumed an increasingly large amount of bones, but this material subsequently found use on the land after it had lost its purifying power. Spent boneblack, either as such or after being acidulated, was at one time a well-known fertilizer. It is of interest to note that in the old fertilizer experiments at Pennsylvania State College, begun in 1881, use was made of "dissolved boneblack" as the source of phosphoric acid.

BEGINNING OF THE SUPERPHOSPHATE INDUSTRY

The fertilizer industry, as it is known today, owes much to the stimulus provided for it by the genius of Liebig and of those who were inspired by him to investigate the possibilities of chemical manures. It was Liebig who first suggested, in 1840, that bones could be effectively treated with sulfuric acid in the production of soluble phosphate. Lawes was quick to follow up Liebig's suggestion and in 1842, after considerable litigation with another Englishman who seems to have preceded Lawes in the use of this process, secured a patent for this method of manufacturing superphosphate. The unique feature of Lawes' claim for the patent was that he was making use of sulfuric acid in the treatment of mineral phosphates.

In 1845 the attention of the British Association for the Advancement of Science was called to some phosphatic nodules that had been excavated in making roads in Cambridgeshire. This material, known as copolites, was found to have a chemical composition quite similar to that of bone. A few years previously similar phosphate deposits had been located in Spain. Lawes, anticipating the demand for acidulated phosphates, had

apparently been experimenting with the production of superphosphate from such materials before the importance of these discoveries had become generally recognized.



(*A*) No fertilizer.



(*B*) Superphosphate.

FIG. 30.—Effect of superphosphate on red clover at the Moran Experimental Farm, Kansas.

Lawes' first factory was erected in 1843. A second larger factory was built in 1857. The area of this factory site was about 100 acres. A plant for the production of sulfuric acid

was also installed. By 1862 the quantity of superphosphate being produced in Great Britain amounted to more than 150,000 tons annually. In 1872 Lawes sold his fertilizer business for a sum equivalent to approximately $1,500,000.

THOMAS PHOSPHATE OR BASIC SLAG

The use of the improved process for refining pig iron developed by Thomas and Gilchrist rapidly spread over Europe with the result that large amounts of alkaline slag were being piled up near the furnaces for which there was no demand. In 1883 German investigators called attention to the value of this material for fertilizer purposes. By 1887 some 300,000 tons of ground slag were being used in Germany alone. By reason of the fact that Germany has no important phosphate deposits this material has continued to be a very popular source of phosphoric acid.

In England, likewise, the discovery was of considerable importance and large quantities of slag began to be used. However, the superphosphate industry had already gained such headway that it was not seriously disturbed by the competition of basic slag. As a result of considerable study of the problem it has come to be the general practice to apply the slag largely to permanent pastures and to depend upon superphosphates for the crops that are grown in rotation.

Much of the iron ore of this country contains only very small amounts of phosphorus and the slag is therefore of little value as a source of phosphoric acid. Some consideration has been given to making a synthetic slag by roasting phosphate rock and limestone together but nothing much has been accomplished along this line because the process apparently cannot compete with the sulfuric method of treatment of phosphate rock.

DEVELOPMENT OF THE POTASH INDUSTRY

In 1843, in boring for common salt, near Stassfurt, Germany, a deposit of a variety of salts was discovered, including the chlorides and sulfates of sodium, potassium, calcium and magnesium. The discoverers were very much disappointed with their find. Further search was made for common salt that was not so contaminated.

When it was subsequently found that these salt deposits were spread over a wide area and that the quantities of salts contained in them were enormous, very serious consideration was given to finding uses for them. The only important outlet seemed to be agriculture. Liebig's experiments with potash salts on the growth of plants provided a clue. The good effects of wood ashes were well known.

It happened that much of the land in northern Germany is very sandy and that such land, as a rule, is deficient in available potassium. Some phenomenal effects were produced in experimental trials of potash fertilizers. In 1845 Liebig purchased, from the town of Giessen, ten acres of this barren sandy land. A number of mineral manures were prepared for him according to his prescriptions based on analyses of the various plants such as wheat, rye, barley, clover, potatoes and turnips. A small amount of animal manure was added at the beginning of the test. In writing of this experiment Shenstone says:

"Gradually, without any further supply of manure except mineral manure, the land so improved in productiveness that in the fourth year his [Liebig's] crops excited the wonder of all who had known the original state of it [barren sandy soil]."

It was not until 1860 that the potash deposits began to be worked extensively. More borings were made and new mines were located from time to time until the number had reached about 150. At first the crude salts were sold as such. Later, processes of refinement were put into operation with the result that salts which were almost pure sulfate or chloride of potassium became available for purchase. Very aggressive propaganda resulted in large amounts of potash salts being consumed not only in Germany but all over the world. The importations of potash salts into the United States alone amounted to nearly a million tons annually for the last few years preceding the World War.

THE DEVELOPMENT OF A NEW POINT OF VIEW

Liebig's clear and forceful presentation of the case for chemical manures bore fruit in a variety of ways. It stimulated Lawes and Gilbert to further efforts in field research in their use. It induced Lawes to proceed with the development of his factory

for the production of superphosphate. In France a worthy champion of the cause was found in Georges Ville, whose book on artificial manures, first published in 1876 and translated into English by Sir William Crookes, further clarified the problem and paved the way for a better understanding of the principle involved in a rational fertilizer program. A few comments selected from Ville's book are of considerable interest as indicating the changing point of view of that period. Thus Ville writes in the introduction to his book:

"The traditions of the past are not sufficient for the necessities of the present. We want more rapid, more economical and more powerful processes. These processes, however, are already discovered and described in a single maxim: 'Give back to the soil by the permanent importation of chemical manure an amount of fertilizing materials larger than that lost by the growth of crops. Thanks to these new fertilizing agents, instead of being still obliged to grow meat in order to have corn, we may grow corn for profits sake in the first place and afterwards for straw, cattle feeding and manure.

"When farmyard manure only is used, the improvement of the land requires length of time and an enormous outlay of capital. With chemical manures the result is more rapidly arrived at. We may almost immediately obtain large crops from the most barren land and realize a profit at the very outset.

"Till within the last twenty years it was thought that farmyard manure was the only fertilizing agent. We maintain that this is wrong and that it is possible to compose artificial manures superior to and at the same time cheaper than farmyard manure."

THE MIXED FERTILIZER INDUSTRY

The fertilizer industry of the United States was somewhat slow in its development by reason of the fact that enormous acreages of very fertile land have always been available for exploitation. Nevertheless, in certain regions of New England and in Maryland and Virginia, where land had been under cultivation since early in the seventeenth century, farmers were prepared to give very serious consideration to the doctrines of Liebig and his coworkers.

Our present fertilizer industry had its beginning in these regions. Baltimore early came into prominence in this connection, being favorably located for receiving importations of materials from Europe and South America as well as for shipping out both by rail and water, the compounded mixtures which were being produced.

In most European countries fertilizer materials have long been sold as such, the farmer either applying them separately or mixing them together in such proportions as experience may have taught him are best suited to the needs of his crops. In the United States the fertilizer industry early became a mixing industry, materials being collected from all over the earth and being compounded according to formulas suggested by experimental trials as being suited to the needs of the various crops.

The following letter written by Dr. R. W. L. Raisin of Baltimore, for the 12th Census, is of considerable interest in this connection, although it leaves much to be desired as to a knowledge of what must have been very interesting developments in the industry.

"The manufacture of chemical fertilizers in the United States began about 1850. In that year Dr. P. S. Chappell, and Mr. William Davison, of Baltimore, made some fertilizer in an experimental way. About the same time Professor Mapes was experimenting. Later De Burg utilized the spent bone black derived from the sugar refineries and made quite a quantity of 'dissolved bone black' (Superphosphate). In 1852 or 1854 Mr. P. S. Chappell commenced the manufacture of fertilizers as did B. M. Rhodes, both of Baltimore. In 1855 Mr. John Kettewell, recognizing the fact that Peruvian guano (then becoming quite popular and containing at that time 18 to 21 per cent of ammonia) was too stimulating and deficient in plant food (phosphates), conceived the idea of manipulating the Mexican guano, containing no ammonia but 50 to 60 per cent of (bone) phosphate of lime and called his preparation 'Kettewell's manipulated guano.'"

Seven fertilizer plants are known to have been in operation in the United States by 1860. By 1900 this number had grown to 475 of which 422 were listed in the census of that year as being in Class A. Five years later the number of fertilizer plants in this country had reached 553. The tonnage has continued to grow as is indicated in the following table.

TABLE XLI

FERTILIZER TONNAGE SOLD IN UNITED STATES

Year	Tons	Year	Tons
1880	1,150,000	1910	5,735,355
1890	1,950,000	1920	7,403,356
1900	2,200,000	1930	8,163,257

Following the outbreak of the World War the industry found itself without potash supplies and with a deficiency of nitrogen. Considerable progress was made during this period in the development of an American potash industry. High prices for farm products continued for some time after the war was over with the result that the tonnage grew rapidly as soon as supplies of nitrogen and potash in quantity again became available. Subsequently the tonnage dropped but recovered again in 1926 only to fall behind again in 1927 because of agricultural depression. Increasing again with the recovery movement, fertilizer sales are now higher than ever before and should continue to grow.

RECENT DEVELOPMENTS IN THE FERTILIZER INDUSTRY

The foregoing statistics do not tell the complete story of the development of the fertilizer industry. Originally it was more or less of the nature of a scavenger industry in that all manner of waste materials were employed in compounding the mixtures that were sold. Guanos, fish, slaughterhouse refuse, dead animals, tobacco waste, cottonseed meal, muck, peat and a great variety of similar materials went into these mixtures.

As time went on more of the phosphoric acid came from phosphate rock. German salts supplied most of the potash required. Chilean nitrate, supplemented more and more by by-product sulfate of ammonia and later by air-nitrogen products, came to be used as the sources of nitrogen. As a result an enormous chemical industry is being developed the product of which is largely a mixture of nearly pure salts containing very little organic matter and having no resemblance, either as to appearance or odor, to the highly organic formulas formerly sold.

Advances in chemical science are constantly being made. It is now possible to produce mixtures of much higher concentration than are most of those that are being used. Whereas the early superphosphate contained only from 12 to 16 per cent of available phosphoric acid, a large percentage of it now contains 20 per cent of this constituent. Large amounts of double superphosphates, produced both by re-acidulation and by distillation processes, are coming onto the market. What is known as "Treble-superphosphate" contains 46 per cent of available phosphoric

acid. Commercial ammonium phosphate contains 10 to 12 per cent of nitrogen and 45 to 50 per cent of available phosphoric acid.

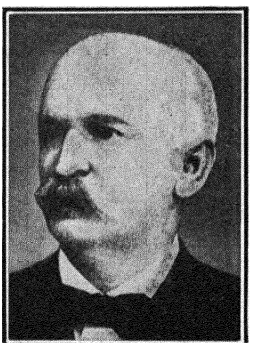
These concentrated materials, and others having their origin in improved processes of nitrogen fixation, are finding their way into mixed fertilizers with the result that fertilizer analyses are becoming higher each year. For comparative purposes, what is needed is not the tonnage of fertilizers sold but the tonnages of each of the three valuable constituents of these fertilizers, viz.: nitrogen, phosphoric acid and potash.

SELECTED REFERENCES

1. Aikman, C. M. Manures and Manuring, 592 pp., Blackwood & Sons, London, 1911.
2. Anonymous. Fertilizer tonnage by years. American Fertilizer Handbook, p. D–9, 1927.
3. Anonymous. Sales of fertilizer in the United States, 1920–1927. The American Fertilizer, Vol. 69, No. 1, p. 32, 1928.
4. Boussingault, J. B. Rural Economy in its Relation with Chemistry, Physics and Meteorology. Translation by Law, Orange Judd Co., New York City, p. 303, 1865.
5. Hall, A. D. The Book of the Rothamsted Experiments, 2nd edition, pp. XXI–XL, Dutton and Co., 1917.
6. Raisin, R. W. L. History of fertilizer industry. Twelfth Census of United States, p. 562, 1900.
7. Shenstone, W. A. Justus von Liebig. His Life and Work, 215 pp., London, 1901.
8. Ville, Georges. Artificial Manures, Their Chemical Selection and Scientific Application to Agriculture. Translation by Crookes. Revised edition, London, 1909.
9. Wheeler, H. J. Manures and Fertilizers, 389 pp., The Macmillan Company, New York City, 1913.

CHAPTER XI

NITROGEN FERTILIZERS



Edward B. Voorhees.

It has long been believed that our chief dependence for nitrogen for replacing that lost from the soil through crop removal and in the drainage water would have to be placed on bacterial fixation. This point of view originated when fertilizer nitrogen was very expensive; when practically the only important source of nitrogen for fertilizer purposes was Chilean nitrate of soda the supply of which was known to be limited; and before much was known as to the possibilities in the scientific use of nitrogen fertilizers. Hopkins, as late as 1910, wrote as follows concerning this matter.

"Of course a part of the nitrogen removed in crops may be returned in the manure produced on the farm; and nitrogen may also be bought in the markets in such forms as dried blood, sodium nitrate and ammonium sulfate. But when we bear in mind that such nitrogen costs from 15 to 20 cents a pound and that a bushel of corn contains about one pound of nitrogen it will be seen at once that the purchase of nitrogen cannot be considered practicable in general farming.

"Considering all of these facts and the additional facts that there are about seventy-five million pounds of atmospheric nitrogen resting on every acre of land and that it is possible (by bacterial fixation) to obtain unlimited quantities of nitrogen from the air for the use of farm crops and at small cost, the inevitable conclusion is that the inexhaustible supply of nitrogen in the air is the store from which we must draw to maintain a sufficient amount of this element in the soil for the most profitable crop yields."

Löhnis, commenting on the same problem somewhat later, has the following to say:

"If 25 per cent of the total farm area were planted to the right kind of legumes, it would mean that at a rate of 80 pounds per acre not less than 3.5

million tons of nitrogen could be gathered annually from the air, and if the non-symbiotic nitrogen bacteria could fix 20 pounds of nitrogen per acre year another 3.5 million pounds of nitrogen from the air would be made available for our crops. With proper management and by making full use of the possibilities offered by bacterial nitrogen fixation, restoration, maintenance, and increase of soil productivity, as far as nitrogen is concerned, could be assured."

ECONOMY OF THE LEGUME PROGRAM

There seems little doubt that if attention is paid to maintaining the supply of mineral nutrients and lime in the soil, the nodule bacteria of legumes and Azotobacter can be made to accumulate adequate amounts of nitrogen to meet the requirements for the production of large yields of the non-legume crops. This is on the assumption that a legume crop appears frequently in the rotation; that it is used either for green manuring or for feeding purposes; and that in the latter case, the manure that is produced from it is carefully saved and applied to the field where the legume had grown.

There are a variety of conditions under which the above program, either in part or as a whole, may not be feasible. In intensive farming, land is too valuable for use in the production of relatively low-priced crops, if this can be avoided. In the extensive types of grain farming there may be little use for large acreages of legume feeds particularly with the use of modern power machinery. Under climatic and soil conditions such as those which obtain in the New England states, grasses are much more easily grown for pasture and hay purposes than are the legumes. In the semi-arid West large amounts of plant refuse are objectionable in the soil by reason of the slowness of its decay. Finally, cheaper prices for fertilizer nitrogen, as a result of the improvement of chemical process for the synthesis of its compounds, make it necessary to reconsider the whole matter from the point of view of relative costs of the element in fertilizer and in legume forms.

In the intermediate systems of farming, such as are followed in the Corn Belt of the Central West and in the Cotton Belt of the South, there are some interesting possibilities in the utilization of certain legume crops for manure production and for green manuring purposes. Sweet clover and cowpeas are especially promising legumes for these two respective areas.

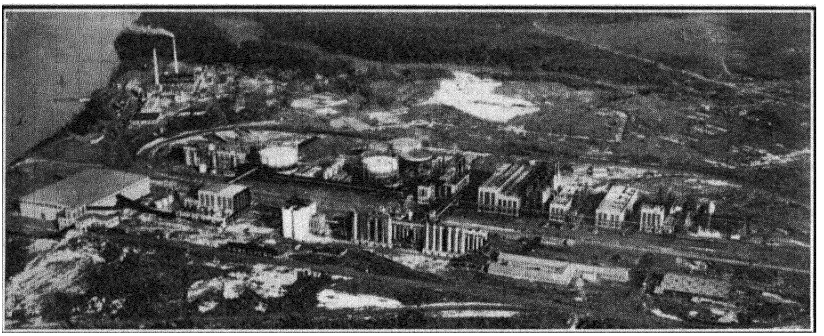
EMERGENCY NEEDS FOR FERTILIZER NITROGEN

No matter how effective these crops may be, when rightly used, in securing nitrogen from the air for fertilizer purposes, one is impressed with the fact that their systematic use for this purpose is likely to continue to be far less than one might hope. If one were to analyze the practices on one hundred typical Corn Belt or Cotton Belt farms, or had available for study an accurate record of what has taken place on any one of these farms during a century of farming, he would be convinced that a state of emergency exists as to the nitrogen supply in the soil and that it bids fair to continue to exist indefinitely. Fertilizer nitrogen has the advantage that no matter how much a well-planned legume program offers for the future, today's emergency need for the element can be met.

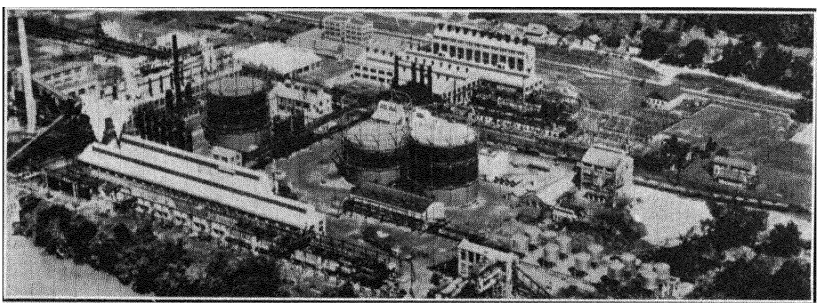
It is well to keep in mind that only a portion of the nitrogen that is accumulated by a legume comes from the air. In proportion as there is available nitrogen in the soil, the nitrogen-fixing organisms fail to function in this capacity. The level to which the nitrogen content of the soil can be raised by fixation processes is not necessarily as high as would be required to supply sufficient available nitrogen for maximum yields, particularly of those crops which do not immediately follow the plowing under of the legume crop. In proportion as the legume crops are harvested and removed from the field, the quantity of nitrogen added to the soil is lessened. It is of interest in this connection to note that alfalfa is often very much benefited, both in getting started and after several years of growth, by applications of available nitrogen.

There is the further important fact to consider that however high the content of nitrogen in the soil may be the rate at which this nitrogen is supplied to the plant at critical periods in its growth may be entirely inadequate. As previously mentioned, soil microörganisms may compete with the crop plant for available nitrogen under conditions in which the organic matter that is worked into the soil is high in its content of carbohydrate materials and low in nitrogen. Under conditions of drought the surface soil, to which the microörganisms are largely confined, may be so dry as to cause the cessation of nitrification with

resulting nitrogen starvation, if the plant has only organic forms of nitrogen at its disposal. Plant roots may be able to secure adequate amounts of water and mineral nutrients from the subsoil but in dry weather they must depend on the surface soil for



(*A*) Allied Chemical and Dye Company Plant at Hopewell, Virginia.



(*B*) E. I. du Pont de Nemours and Company Plant at Belle, West Virginia.

FIG. 32.—Air-nitrogen plants for taking this element from the air and combining it with other elements to form fertilizer compounds.

their nitrogen. The "firing" of crops may be caused by nitrogen starvation as well as by a lack of water.

CARRIERS OF FERTILIZER NITROGEN

Nitrogen fertilizers, in the order in which they have come into use, may be grouped into the various by-product organics; Chilean nitrate of soda; by-product ammonia from the coking industry; and synthetic nitrogen compounds of which cyanamid, nitrate of soda, nitrate of lime, ammonium sulfate, ammonium nitrate, and urea are the most important so far produced.

Possibilities in the synthesis of other nitrogen compounds are also being investigated.

Numerous factors are involved in determining the choice from among these various carriers of nitrogen. Consideration must be given to the form in which the nitrogen occurs in the compound; to the secondary effects of other elements, radicals or compounds that are present in the material; to the nature of the soil and the climate; to the requirements of the crop to be grown; and to the applied cost of a unit of nitrogen as compared to the algebraic sum of the values of the several effects produced by the quantity of each material that is required to supply that amount of nitrogen.

TABLE XLII (A)

COMPARATIVE VALUES OF NITROGEN CARRIERS AS TO VARIOUS QUALITIES

Material	Per Cent of Nitrogen *	Availability of Nitrogen †	Acidity or Alkalinity‡	Retention by Soil §	Quality for Condition‖
Ammonia (anhydrous)	82	90	Acid	Medium	Fair
Urea	46	90	Acid	Medium	Poor
Ammonium nitrate	35	95	Acid	Low	Fair
Leunasaltpeter	26	95	Acid	Medium	Fair
Ammonium chloride	26	90	Acid	Medium	Fair
Ammonium sulfate	21	90	Acid	Medium	Fair
Calcium cyanamid	22	90	Alkaline	Medium	Good
Calcium nitrate	17	100	Alkaline	Low	Poor
Sodium nitrate	16	100	Alkaline	Low	Fair
Ammonium phosphate	11	90	Acid	Medium	Good
Dried blood	10	80	Acid	High	Good
Animal tankage	6	70	Neutral	High	Good
Cottonseed meal	6	70	Acid	High	Good
Fish scrap	5	70	Acid	High	Good
Activated sludge	4	70	Acid	High	Good
Steamed bone	2	70	Alkaline	High	Good
Tobacco stems	2	70	Alkaline	High	Good
Garbage tankage	2	30	Alkaline	High	Good
Peat	2	20	Neutral	High	Good

* Minimum percentages.
† Rate of availability compared to nitrate at 100.
‡ Tendency in soil.
§ Capacity of soil to retain until used by plants.
‖ For mixing purposes.

AVAILABILITY OF NITROGEN OF FERTILIZERS

In so far as the form of nitrogen is concerned, carriers of the element may be conveniently grouped into nitrates, ammonium compounds, amides and by-product organics. In general, the order of the rate at which the nitrogen of these various groups of materials becomes available to crop plants is that in which they are named above. Thus the nitrogen of nitrates is usually immediately effective while that of the other materials requires varying periods of time before its full effects are secured. The time factor depends upon the soil and the weather conditions as well as upon the nature of the nitrogen carrier and the requirements of the crop. Differences in the effectiveness of the nitrogen of these various groups of materials that are often noted in comparative tests in which they have been applied at planting time can be overcome in large part by regulating the time of application with regard to the nature of the material and the period at which the full effect of its nitrogen is desired.

Usually the availability of the nitrogen of ammonium compounds is placed at 90 and of high-grade organics at from 70 to 80, if that of nitrates is given a rating of 100. The original field and pot tests from which these figures were obtained were conducted by Wagner and his associates in Germany. However, similar results have been secured by a number of other workers, including many in America, of whom the pioneer was Samuel W. Johnson of the Connecticut Agricultural Experiment Station.

So many variables are involved that it is impossible to give a product a rating that will apply under all conditions. For example, nitrates cannot be used in growing paddy rice by reason of the denitrification of the nitrate radical. Ammonium sulfate does not give satisfactory results on soils that are acid in reaction except for certain acid-tolerant crops like potatoes, which frequently give a higher yield of better quality tubers with ammonia salts than with nitrates. Organic materials decompose at very different rates depending upon the temperature, the water supply and the efficiency of the microörganisms with which the soil is populated. Thus in the Southern States cottonseed meal has long been a very popular source of nitrogen for cotton. The evidence indicates that under the climatic conditions that

there obtain this popularity is well placed, if all of the nitrogen is to be applied at the time of planting the crop. This is particularly true in sandy soils. Experimental data covering a wide range of soil and climatic conditions and long periods of time indicate that mixtures which carry part of this nitrogen in organic form will produce better yields, on the average, than will those carrying only the inorganic forms of nitrogen.

Recently developed evidence indicates that the superiority of such organic-containing mixtures tends to disappear when the comparisons are made with inorganic mixtures which have been made neutral in their reaction effects on the soil by the addition of limestone. This would indicate that one function of organic materials in fertilizer mixtures is to supply ammonia for its temporary alkaline effect on the soil. Conceivably organic materials of plant and animal origin may have other effects as well. The plant physiologist gives credit to hormones, or growth-promoting substances. The soil chemist thinks in terms of trace elements.

SECONDARY EFFECTS OF CARRIERS OF NITROGEN

There is still considerable doubt as to the validity of our conclusions concerning the respective merits of the several carriers of nitrogen. Most comparative field tests have measured not alone the positive effect of the nitrogen but also the sum of the positive and negative effects of the carriers of this nitrogen. All nitrogen materials supply other elements in addition to nitrogen. These elements may have acid or alkaline effects. A nitrogen material may produce an initial alkaline effect and later an acid effect. It may supply some other active element of which sodium, calcium and sulfur are the most common examples. The differences in the effectiveness of the several carriers of nitrogen under any given set of conditions appear to be largely due to these associated elements. These may affect both the nutrient supply of the plant and the reaction of the soil.

Ammonia and its compounds have economic advantages. They are not subject to serious losses by leaching. They can be applied under the crop rather than as side-dressers. If it is permissible to apply all the nitrogen that is required by the crop with the mixture which goes on before or at planting time, the cost of nitrogen to the consumer can be considerably reduced.

On the other hand, there are certain conditions under which split applications involving side-dressing or top-dressing with nitrates may be preferable as, for example, where quick effects are desired on vegetables. It is also a well-known fact that the root systems of some plants tend to be more extensive if the crop is started with a minimum quantity of readily available nitrogen. Under conditions of severe drought, or for crops that are planted in the fall and must survive bad winter weather, applying all the nitrogen at planting may not be advisable.

ACID EFFECTS OF NITROGEN FERTILIZERS

Other than the nitrates and calcium cyanamid, the one outstanding characteristic of all nitrogen materials is their acid effect when applied to the soil. As the nitrogen of ammonia, urea, or by-product organics, as well as that which is fixed by soil bacteria, is nitrified in soils, its acid effect becomes apparent. In proportion as the nitrate radical is built up into protein form by plants it is removed from the field of action. In general, however, the recovery in the immediate crop of the added nitrogen does not exceed 50 per cent of the amount applied. The remainder may, in part, be used by soil micro-organisms, in which case it also is stored in protein forms. The permanently acidulating effect is measured by the amount of nitrate that escapes in the drainage water. This varies from very small amounts in grass-covered soils to quite large amounts in soils under clean cultivation that carry few or no growing vegetables during considerable portions of the year.

An added complication as to the effect of nitrogen fertilizers on the soil reaction is involved in such a material as sulfate of ammonia. As the nitrogen of this compound is changed to nitrate and used by the crop or by soil micro-organisms, the sulfate radical is liberated and, except as it is absorbed by the plant and built up into organic combinations, has an additional acidulating effect on the soil.

The whole problem was carefully studied by Pierre who took into consideration not only the several carriers of nitrogen but also those of phosphoric acid and potash. As a result he drew the following conclusions with respect to the net effect of these plant-food materials on the soil:

1. One-half of the nitrogen is acid forming.
2. One-third of the phosphoric acid is acid forming.
3. In determining the net effect of any fertilizer material or mixture of materials on the soil the following balance of elements is involved:

Acid-Forming Elements		Base-Forming Elements
All sulfur		All calcium
All chlorine	Versus	All magnesium
$\frac{1}{3}$ of the phosphorus		All sodium
$\frac{1}{2}$ of the nitrogen		All potassium

A method was then proposed for determining the "equivalent acidity or basicity" of fertilizers. It consists in titrating the excess of acidic or basic elements in the fertilizer after igniting to destroy any organic matter present. This method has now been quite widely adopted. Some states require an examination of and report on the acidity or basicity of all fertilizer materials or mixtures sold within their boundaries.

The following table shows the acidity or basicity of the most commonly used nitrogen materials as determined by Pierre's method of analysis.

TABLE XLII (B)

Net Acidity or Net Basicity of Nitrogen Materials—Pierre

Material	Nitrogen	Net Basicity as $CaCO_3$ per 100 lb of Material	Net Acidity as $CaCO_3$ per 100 lb of Material
Basic	Percentage	Lb.	Lb.
Calcium cyanamid	22.0	62.3	.....
Tankage (low grade)	4.3	31.0	.....
Nitrate of soda	16.0	28.8	.....
Nitrate of potash	13.0	26.0	.....
Nitrate of lime	15.0	20.3	.....
Tobacco stems	2.8	12.0	.....
Tankage (packing house)	6.0	9.9	.....
Acidic			
Anhydrous ammonia	82.2	.....	148.0
Ammonium sulfate	20.5	.....	110.0
Urea	46.6	.....	84.0
Urea-ammonia liquor	45.5	.....	82.0
Ammonium phosphate	11.0	.....	55.0
Dried blood	13.0	.....	22.6
Guano (Peruvian)	13.8	.....	13.1
Cottonseed meal	6.7	.....	9.4
Fish scrap	9.2	.....	8.4

THE CHOICE IN RELATION TO SOIL FACTORS

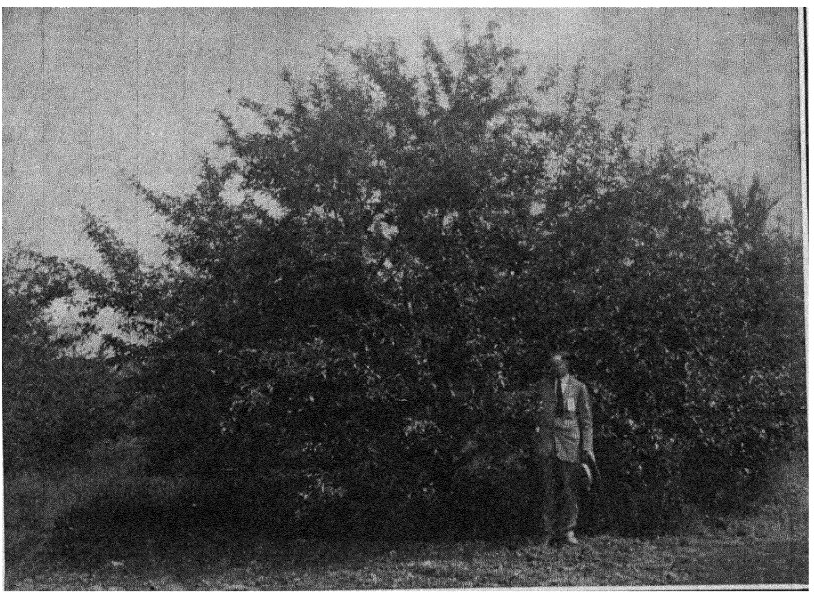
An important problem involved in nitrogen economy in soils is that of preventing loss of this constituent in the drainage water. The nitrate radical is not only readily soluble in water but it is not absorbed by the soil to any appreciable degree. Unless the nitrate is used by crops or soil microörganisms it may be carried away in the drainage. No especial difficulty is likely to be experienced when a crop is growing on the soil except as heavy applications of nitrogen have been made or the soil is very open in its texture such as is the case with sands and sandy loams.

It happens that the nitrogen of ammonium salts, while it is also readily soluble in water, is not leached from the soil as ammonia but only after it has been changed to the nitrate form by the nitrifying bacteria. The clay fraction of soils has a very definite capacity to take out of solution each of the basic ions such as ammonium, calcium, magnesium, potassium and sodium when they are applied as fertilizer salts. An exchange takes place between the cations of what is termed the " base-exchange complex " of the soil and the cation of the added salt. If the soil is neutral in reaction the added ammonium radical will normally displace calcium and magnesium and these will subsequently be found in the drainage water. If the soil is acid in reaction, iron, aluminum and manganese are more likely to be displaced. In alkaline soils, sodium and potassium are more largely displaced. It will thus be seen that the first effect of an application of an ammonium salt is that of liberating some other cation to be used by the plant or carried off in the drainage. Subsequently, after nitrification has taken place, hydrogen or some other cation is substituted for the ammonium ion. As is apparent, there is a delay between the time of application of an ammonium salt and the time at which its nitrogen is available as nitrate. Until such time as this change is effected, loss of nitrogen by leaching does not occur.

Under conditions in which the soil is sandy or where the rainfall is heavy it is common practice to use a mixture of several carriers of nitrogen, including organic materials and ammonium



(*A*) No nitrogen.



(*B*) Nitrogen fertilizer applied at rate of 3 to 5 pounds per tree annually.

FIG. 33.—Effect of nitrogen fertilizer on apple trees. (Courtesy Massachusetts Agricultural Experiment Station.)

compounds. This permits of supplying the crop with nitrogen throughout its period of growth without loss of much of the nitrate that is produced from the non-nitrate forms. The rate of nitrification of the nitrogen of organic compounds and ammonia salts is somewhat in proportion to the growing conditions since the same climatic factors influence the activities of microörganisms and of crop plants.

Mixtures containing several forms of nitrogen may be expected to be most useful on sandy soils for crops like wheat and cotton which have a long growing season. However, an equally satisfactory means of guaranteeing an adequate supply of nitrogen for the use of the crop throughout its period of growth is that of making divisional applications of nitrate as top dressings, from time to time during the growing season. Thus one can choose the carrier of nitrogen on the basis of the cost per unit of nitrogen and apply it all at planting time or in part as top dressing, depending upon whether it is an organic form of the element or an ammonium compound, or a nitrate.

THE CHOICE IN RELATION TO CLIMATIC FACTORS

Nitrates have a distinct advantage over other forms of nitrogenous fertilizers for use in regions of sparse rainfall. Under such conditions the rate of ammonification and of the oxidation of ammonia to nitrates is too slow. Soils of such regions are normally not acid in reaction and the plants that are there grown are those which utilize the nitrate nitrogen to best advantage. In times of drought in humid climates, nitrates may also be preferred. For rapidly growing vegetables, for short season crops such as barley, for regions of short summers and for cold, backward seasons, the nitrate is quite likely to be more effective than is any other form of nitrogen.

The problem of drought is in many ways the most serious one with which the crop grower has to deal. In the Corn Belt especial precautions must be taken to conserve the moisture supply. Phosphates have certain advantages in stimulating root growth and permitting greater resistance against drought. By bringing wheat and oats to earlier maturity they avoid the drier

weather of July and August. Under such conditions nitrogen must be used in such a manner as to prevent excessive vegetative growth or delay in maturity. Excessive use of phosphates on corn and tobacco tend to bring these crops to maturity too early in the summer before the drought is broken unless this effect is counteracted by the use of nitrogen and potash. If large amounts of available nitrogen are present in the soil at seeding time, rank vegetative growth may be produced at the expense of root development and early maturity. If the nitrogen is applied in available form somewhat later in the growth of the plant, its effect may be largely an improvement in quality and yield of grain.

In the Great Plains region, by reason of inadequate moisture supply, considerable difficulty is experienced in effecting the decay of organic matter. Manure, unless well rotted and rightly used, may have disastrous effects. The growing of legumes robs the soil of water and brings about conditions of drought for the crop that follows. Under such conditions it will be seen that readily available fertilizer nitrogen applied at the proper time has certain advantages over that which is present in the soil in the form of legume and other crop residues.

In the production of grass and of hay crops other than legumes, lack of nitrogen is usually so seriously a limiting factor that even the root systems of the plants fail to develop adequately. This is because these crops have the capacity to consume large amounts of nitrogen although the conditions in the soil during their growth are such as to bring nitrification almost to a standstill. The evidence indicates that, in spite of the enormous increase in vegetative growth produced as a result of the use of nitrogen top dressings, the grass is less subject to drought than when nitrogen is not used. This same drought resistance has been noted with nitrogen-treated fruit trees when grown in sod culture. This indicates that very large amounts of nitrogen must be applied to grass before the nitrogen-carbohydrate ratio in the upper portions of the plants becomes such that vegetative growth takes place at the expense of the development of adequate root systems.

In eastern United States phosphoric acid is not so dominant in fertilizer analyses as it is farther west. Nitrogen percentages are considerably higher. This has been explained on the assumption that the excessive use of phosphates has built up a reserve

of phosphoric acid in the soil with the result that it is no longer the plant food constituent that is in greatest deficiency. The explanation, however, probably lies in the better moisture relationships that there obtain as a result of which nitrogen comes into the leading rôle. It is further evident that in proportion as the effects of drought are overcome to the end that higher acre yields are produced, whether by plant breeding, improvement in soil management, or the development of more scientific methods of plant feeding, nitrogen is quite likely to occupy a more prominent place in fertilizer analyses.

THE CHOICE IN RELATION TO CROP REQUIREMENTS

Under conditions in which the soil is saturated with standing water for some time the nitrogen of nitrates is ineffective, probably by reason of its loss in elemental form as a result of denitrification. The frenching of tobacco and the yellow appearance of corn and other crops in wet areas in a field are evidence of nitrogen starvation resulting from nitrate reduction. Crops, such as paddy rice, which grow normally under flooded conditions, must have their nitrogen supplied in some form other than nitrates, normally as ammonium salts. This shows that some plants do not require their nitrogen as nitrate. There is evidence to support the belief that potatoes, buckwheat, and other crops which grow well on quite acid soils also use ammonia nitrogen as such. The grasses seem to be capable of taking up large amounts of ammonia and of converting it very rapidly into proteins. In fact the use of heavy dressings of nitrate nitrogen on pastures has been found to be objectionable since under certain weather conditions the nitrates are absorbed by the grass more readily than they are converted into amide or protein nitrogen and therefore tend to accumulate in concentrations that are toxic to livestock.

Experiments in the technique of feeding plants show certain advantages in being able to supply them with nitrogen at particular stages in their growth. Orchardists apply organic or ammonia nitrogen in the fall or early spring, or nitrates any time up to blossoming. Tomato growers desire a small amount of readily available nitrogen to start the plants, slowly available

nitrogen until the blooming period, and more highly available nitrogen after the fruit is set. Strawberries should have a light application of nitrogen in the spring of the first year after planting and a heavy dressing of nitrogen in the early fall for a heavy set of fruit the following year. Some of the best farmers in Europe apply phosphate and potash fertilizers at seeding time for winter cereals and use most of the nitrogen as a top dressing before growth starts in the spring. The protein content of wheat can be increased by applying nitrogen at the heading stage. Many other possibilities suggest themselves.

If the soil contains carbonates, as is the case in semi-humid regions and in areas in which irrigation is practiced, the use of acid-forming carriers of nitrogen is to be preferred. Most soils in humid regions are not improved for crop-producing purposes by further acidulation. This is particularly true for the growing of such high-lime-requirement crops as sugar beets, alfalfa, celery and onions. It is of much less significance in the case of potatoes, oats, rye, cotton and alsike clover.

The synthetic nitrogen industry of Germany makes the claim that in Central Europe one pound of nitrogen, intelligently used, can be depended on to produce 20 pounds of grain, 100 pounds of potatoes, 150 pounds of sugar beets, 45 pounds of hay or 20 pounds of milk. An examination of the experimental evidence indicates that these figures are not too high for the climatic conditions that there obtain, for the varieties of crops which are grown and for the relatively high acre rates at which nitrogen is being applied.

When one considers the differences in the nature of soils as, for example, between sands and clays or between those of irrigated deserts and those of tropical regions; the variations in the climatic conditions as between regions of frequent showers and relatively slow rates of evaporation and areas like the Corn Belt that are often subjected to considerable periods of drought between times of heavy rainfall; the differences in the requirements of plants as between the acid-tolerant grasses of putting greens and acid-sensitive cabbages, he is impressed with the need for a considerable variety of nitrogen fertilizers having a wide range in their chemical properties.

SPECIAL USES OF NITROGEN FERTILIZERS

Attention should be called to certain very interesting possibilities in the further use of nitrogen fertilizers. A few years ago some investigations were reported from Rothamsted, England, on the production of artificial manure made from straw and similar materials by reinforcing them with nitrogen, phosphoric acid and lime in sufficient amounts to meet the needs of the bacteria of decomposition. For a time the process was viewed with considerable skepticism but continued investigation reveals that it is entirely feasible. A material can be produced that has all of the desirable qualities and none of the undesirable ones of the product of animal origin. Furthermore, the cost of this artificial manure is probably no greater than is that of the animal manure that is produced on the average American farm, if consideration is given to all of the items which should enter into cost accounting in manure production.

It has also been shown that there are important possibilities in the factory production of high-protein foods and feeds by growing yeast plants in nutrient solutions containing the ordinary fertilizer salts and including some form of nitrogen. The economy of this process is dependent upon having a cheap source of soluble carbohydrate such as molasses or some product resulting from the hydrolysis of starch, cellulose or other inexpensive similar forms of plant materials.

THE SYNTHETIC NITROGEN INDUSTRY

In his presidential address, in 1898, before the British Association for the Advancement of Science, Sir William Crookes, a famous English chemist, reviewed the world's wheat problem and pointed out some of the difficulties ahead for the wheat-eating peoples unless something be done to augment the rapidly diminishing supplies of Chilean nitrate of soda, a highly important constituent in wheat fertilizers. He showed that the acreage of land that was being devoted to wheat could not be very materially increased except at the expense of some other crop that was also needed, or by the use of land illy suited to wheat. The requirements of a growing population would, therefore, have to be met

by the production of higher acre yields. This is easily possible by the use of nitrogen fertilizers but the exhaustion of the natural deposits of Chilean nitrate was in sight and the supplies of nitrogen from other sources were entirely inadequate to meet the requirements.

The newspapers of that time saw in the address an occasion for headlines which led their readers to believe that the old Malthusian law of population's tending to overtake the food supply was about to become effective. In fact so much discussion was aroused as a result of the newspaper comments that it became necessary for Crookes to publish his original address with supplemental comments and replies to his critics in self-defense.

SYNTHETIC NITRATES SUGGESTED

Reading this address to-day one is impressed with the fact that this great scientist was thinking so far in advance of the public mind that the people failed to grasp the real intent of his words. What he really saw and meant to point out was that some means must be found for synthesizing nitrogen fertilizers from the inexhaustible supply of nitrogen gas in the air. This was shown by Crookes to be essential in order to supplement the other supplies of nitrogen in meeting the need for increased consumption of this element for producing larger acre yields of wheat and other crops.

Further than that, Crookes knew this could be done. He, himself, had demonstrated experimentally that nitrogen could be made to combine with oxygen in the intense heat of the electric arc. It had long been known that the oxide thus formed, when dissolved in water, forms nitric acid. This acid, when brought into contact with sodium carbonate, or preferably with limestone, forms a nitrate. The problem was not one of determining whether the nitrogen of the atmosphere could be changed to a nitrate but that of discovering means by which it could be accomplished at a cost that was low enough to make it feasible. According to Crookes' calculations, by using the cheap electric energy that could be produced at Niagara Falls, nitrate of soda could be produced at less than $25 per ton. At that time Chilean nitrate was selling at about $35 per ton. He concludes:

"The future can take care of itself. The artificial production of nitrate is clearly within view and by its aid the land devoted to wheat can be brought up to the 30 bushels per acre standard. In days to come, when the demand may again overtake supply, we may safely leave our successors to grapple with the stupendous food problem.

"And, in the next generation, instead of trusting mainly to foodstuffs which flourish in temperate climates, we probably shall trust more and more to the exuberant foodstuffs of the tropics where, instead of one yearly sober harvest jeopardized by any shrinkage of the scanty days of summer weather, or of the few steady inches of rainfall, Nature annually supplies heat and water enough to ripen two or three successive crops of foodstuffs in extraordinary abundance.

". . . We must develop and guide Nature's latent energies, we must utilize her inmost workshops, we must call into commercial existence Central Africa and Brazil to redress the balance of Odessa and Chicago."

PROGRESS IN PRODUCTION OF AIR-NITROGEN COMPOUNDS

Forty years have passed since Crookes' memorable address was made. During a part of this period the World War was fought. In time of war explosives are of first importance. For the manufacture of explosives nitrates are indispensable. The Chilean nitrate industry flourished as never before. But Germany, in spite of the fact that she had no access to Chile, succeeded in defending herself against the combined armies of almost the entire world for more than three years. And when she was finally compelled to sign the peace treaty it was not because of a lack of nitrate.

So successfully had Germany developed the processes for taking nitrogen from the air that when the war was over she no longer needed to import nitrogen for agricultural or any other purposes. In fact, Germany entered into competition with Chile for the world market for nitrogen materials. Considerably more nitrogen is now taken from the air annually in Germany than is exported from the natural deposits of Chile.

Meanwhile rapid advances have been made in the technique of air-nitrogen fixation. Air-nitrogen plants are in operation in most of the more progressive countries of the world. The world's annual production capacity of fixed nitrogen in 1934 was nearly four million tons of the element, equivalent to nearly twenty-four million tons of nitrate of soda. In comparison, the present

production capacity for Chilean nitrate of soda is a little more than four million tons.

Two large air-nitrogen plants are now operating in the United States and two others across the line in Canada. The problem is no longer one of our ability to supplement the natural supplies of nitrate. Nitrogen is now abundant and relatively cheap the world over. In other words, before the supply of the natural product has been used up, the synthetic product is available in quantity to take its place.

THE ARC PROCESS

It was originally believed that a cheap source of electrical energy was a requisite for the production of synthetic nitrogen compounds, if they were to be available at a price that the farmer could afford to pay for them. Thus the first air-nitrogen plant that was put into operation, in 1905, employed what is known as the "arc process." In this process nitric acid is produced by first passing air at ordinary pressures through an electric arc heated to a temperature of from 2500° to 3000° C. The first product is nitric oxide (NO). This, on cooling, takes on more oxygen to form nitrogen peroxide (NO_2). On absorbing this in water, nitric acid (HNO_3) is formed which on being neutralized with lime forms nitrate of lime ($Ca(NO_3)_2$).

The power required in this process amounts to 10 to 12 horsepower years per 2000 pounds of nitrogen fixed. Its commercial success depends upon cheap water power with the result that the process is in successful operation on a large scale only in Norway whence comes the "Norwegian Saltpeter" which, in chemical terms, is nitrate of lime or calcium nitrate. No new installations of machinery for this method of production have been made since 1918 because much less expensive methods of fixing air-nitrogen are now known.

THE CYANAMID PROCESS

In 1906 the first commercial plant for the production of calcium cyanamid was put into operation. In this process limestone and coke are heated together in an electric furnace with the formation of calcium carbide (CaC_2). Pure nitrogen gas secured

by the liquefaction of air is passed over the pulverized carbide heated to such a point as to start the reaction which then maintains sufficient heat to form calcium cyanamid ($CaCN_2$). The commercial product contains, in addition to the calcium cyanamid, some free lime and other impurities. If desired, the nitrogen of the calcium cyanamid may be changed to ammonia by treatment with steam under pressure. This ammonia can be combined with phosphoric or sulfuric acid to produce ammonium phosphate or ammonium sulfate.

The power requirements for the production of calcium cyanamid are only about one-fourth of those required in the synthesis of Norwegian nitrate.

THE AMMONIA PROCESS

In 1913 the Haber process of synthesizing ammonia was put into operation on a commercial scale in Germany. This method requires the bringing together of free hydrogen and nitrogen in the presence of catalysts. The nature of these catalysts is a secret but oxide of iron, containing some alumina and potash, is known to be effective for this purpose. Temperatures of from 500° to 700° C. and pressures of from 300 to 2000 atmospheres are required. The power requirements are only about one-half horse-power year per ton of nitrogen fixed. In fact the power requirements are so reduced in this process, as modified by subsequent research, that cheap electrical energy is no longer a primary consideration.

The chief item of expense in the synthetic production of ammonia is pure hydrogen gas. In the Haber, Claude and Casale processes the hydrogen is obtained from water-gas, coke-oven gas and the electrolysis of water, respectively. Cheap electrical energy is important only in the last-named method. The Liljenroth process is of special importance in this connection. In this process, elemental phosphorus is produced by the reduction of phosphate rock with coke in an electric furnace heated to a temperature of 1200° to 1500° C. The phosphorus distilled from this, on being run into steam, produces phosphoric anhydride (P_2O_5) and hydrogen. This hydrogen may be used for the production of ammonia to combine with the phosphoric anhydride

and water to form ammonium phosphate ($NH_4H_2PO_4$). This product is of particular importance by reason of its high concentration of plant nutrients since it contains over 12 per cent of nitrogen (N) and 60 per cent of phosphoric acid (P_2O_5).

There are certain other nitrogen-fixation processes that are of interest chemically but which are not yet in operation in large scale production. Of these may be mentioned the Bucher process for producing sodium cyanide (NaCN) and the Serpek method for synthesizing aluminum nitride (Al_2N_2).

WORLD PRODUCTION-CAPACITY OF NITROGEN MATERIALS

The first air-nitrogen plant began operations in 1905. Twenty years later the world's annual production of fixed nitrogen amounted to approximately 600,000 tons of the element, equivalent to more than 3,500,000 tons of nitrate of soda. By 1934, the tonnage of air-nitrogen materials had been increased to six times these amounts. The data in the following table give some idea of the growing importance of the industry in comparison with the by-product-ammonia and the Chilean-nitrate industries.

TABLE XLIII

WORLD PRODUCTION-CAPACITY OF NITROGEN * (JANUARY 1, 1934)

	Tons	Percentage
Synthetic processes (from air)	3,770,800	74.19
By-product processes	621,500	12.23
Chilean nitrate processes	690,000	13.58
All processes	5,082,300	100.00

* In terms of nitrogen. The tonnages must be multiplied by 5 to find the sulfate-of-ammonia equivalent, and by 6 to find the nitrate-of-soda equivalent.

Nitrogen is now available in such large quantities for agricultural purposes and its cost per pound to the consumer is so low that increasing advantage is being taken of its use as an aid in increasing crop yields. Recommended acre applications of nitrogen for haylands and pastures, cane, cotton, corn and small grains in the United States are 50, 40, 30, 25 and 20 pounds per

acre respectively. Used at these rates, in conjunction with the necessary mineral elements, a pound of nitrogen will produce, under good farming conditions, about 40 pounds of hay, 25 pounds of sugar, 5 pounds of lint cotton, 25 pounds of shelled corn, 20 pounds of wheat, or 25 pounds of oats. There are very important possibilities for profit in the use of more nitrogen on crops.

WORLD PRODUCTION AND TRADE IN NITROGEN

Some very significant changes have taken place in the world production and trade in nitrogen. Formerly, but no longer, Chilean nitrate constituted the major portion of the nitrogen on the world market. The world price for nitrogen is now fixed by the producers of air-nitrogen materials and by-product materials rather than by the natural-nitrate producers. In response to such competition, the producers of Chilean nitrate have been forced to improve their processes and their product. It is now being delivered in excellent granular condition and at a price per unit of nitrogen that is about half that obtained before the World War.

Whatever may be the outcome of the competitive struggle, cheaper nitrogen and a much-increased use of this element for fertilizer purposes are inevitable. Rapid changes in the percentage distribution of nitrogen from the various sources have occurred. The following figures are of interest in this connection.

TABLE XLIV

DISTRIBUTION OF NITROGEN PRODUCTION OF WORLD—1934

Materials	Tonnage of Nitrogen*	Percentage
Ammonium sulfate (by-product)	342,625	16.2
Other by-product nitrogen	50,980	2.4
Ammonium sulfate (air-nitrogen)	580,015	27.5
Calcium nitrate (air-nitrogen)	143,165	6.8
Calcium cyanamid (air-nitrogen)	238,530	11.3
Other air-nitrogen	608,695	28.9
Chilean nitrate of soda	144,485	6.9
Total world production	2,108,495	100.0

* Tonnage of nitrogen as element.

ECONOMIC EFFECTS OF CHEAP FERTILIZER NITROGEN

Highly important economic adjustments among the various agricultural areas of the world are sure to result from an abundance of nitrogen. China and India, where fertilizers have never been used, are now being propagandized and are becoming interested. Russia, almost three times the size of the United States and with vast areas of excellent farming land, is an unexplored field. The great plains of Hungary and Rumania can probably be made to produce double their present yields when fertilizers are applied. The tropical regions of the world, where nitrogen is an especially important constituent in the fertilizer, have enormous possibilities, as yet untouched, in the production of crops for use in the manufacture of clothing and of carbohydrate foods. Vast areas of level land, capable of producing high acre yields, are to be found in Brazil and the neighboring countries of South America. In Canada conditions are especially favorable for the use of large amounts of nitrogen in the growing of cereal crops. English agriculture is taking on new life as a result of its having been found possible, with liberal dressings of nitrogen fertilizers, to grow enough pasture on one acre to support two steers or milk cows, instead of requiring two acres or more for one animal unit. Germany is now much more nearly capable of feeding herself.

The immediate effect of cheaper and more abundant supplies of nitrogen will probably be that of raising the yield on the better farming land and forcing a larger acreage of other land into pasture and forest. This will have the effect of reducing the percentage of the total population that can profitably be employed in agriculture and of releasing relatively more workers for industry.

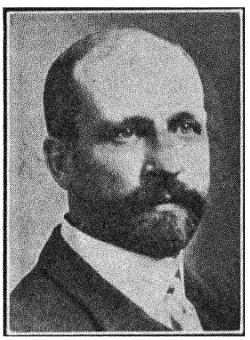
SELECTED REFERENCES

1. Bear, F. E. The scientific use of nitrogen fertilizers. Jour. Ind. and Eng. Chem., Vol. 20, p. 65, 1928.
2. —— The Second International Nitrogen Conference. Jour. Ind. and Eng. Chem., Vol. 20, p. 1112, 1928.
3. Crookes, William. The Wheat Problem, Putnam's Sons, London, 272 pp. 1900.
4. Hopkins, C. G. Soil Fertility and Permanent Agriculture, Ginn and Co., Boston, p. 207, 1906.

5. Lipman, J. G. The nitrogen problem in agriculture. Jour. Chem. Education, Vol. 4, pp. 845–860, 1927.
6. Pierre, W. H. Nitrogenous fertilizers and soil acidity. Jour. Amer. Soc. Agron., Vol. 20, pp. 254–269, 1928.
7. Pierre, W. H. Determination of equivalent acidity and basicity of fertilizers. Anal. Edit. Ind. Eng. Chem., Vol. 5, p. 229, 1933.
8. Skinner, J. J. Experiments with nitrogen fertilizers on cotton soils. U.S.D.A. Tech. Bul. 452, 1934.
9. U. S. Tariff Commission. Nitrogen statistics. Released May 1, 1936.

CHAPTER XII

PHOSPHORIC ACID FERTILIZERS



Cyril G. Hopkins

THE use of guano, fish and bones for fertilizer purposes is a practice of very long standing. The ancient Carthaginians, the Romans, and even the Indians, at the time of the discovery of America, were aware that one or more of these materials could be used as a means of increasing crop yields. The explanation of the value of these substances in terms of their content of phosphoric acid was naturally impossible until the preparation of the element phosphorus, in 1755, by the Swedish chemist, Scheele, and the subsequent discovery by Gahn in 1769 that this element is a necessary constituent of the bones of man and other animals.

The practice of using bones for fertilizer purposes was well under way in Europe by the beginning of the nineteenth century. Originally it was believed that the value of bones lay largely in their fat and gelatine, those of fat cattle being especially prized. Later, when chemists pointed out that bones are made up in large part of phosphate of lime, this compound was given credit for the effect produced as a result of their use.

Bones became so popular as fertilizers in England that the home supply was soon exhausted and importations were made from whatever sources of them could be found. Liebig became alarmed at the rate at which continental Europe was being robbed of bones by the English and called attention to their practices in this connection in no uncertain terms. Aikman's translation of Liebig's statement follows:

"England is robbing all other countries of the condition of their fertility. Already in her eagerness for bones she has turned up the battle-fields of Leipsic,

of Waterloo, and of the Crimea; already from the Catacombs of Sicily she has carried away the skeletons of many successive generations. Annually she removes from the shores of other countries to her own the manurial equivalent of three millions and a half of men whom she takes from us the means of supporting and squanders down her sewers to the sea. Like a vampire, she hangs upon the neck of Europe—nay of the entire world—and sucks the heart-blood from nations without a thought of justice towards them, without a shadow of lasting advantage to herself."

DISCOVERY OF MINERAL PHOSPHATES

As early as 1779 phosphorus had been found in mineral form, as pyromorphite, by Gahn. From 1845 to 1852 discoveries of other mineral phosphates found in nodular deposits of phosphate of lime and known as coprolites were made in England and France. In 1887 large deposits of phosphate rock were found in Florida. Subsequently other deposits were located in the Carolinas, in Tennessee, Arkansas, Montana and Utah in this country; in Belgium, France, Germany, Spain and Russia in Europe; in Algeria and Tunis in northern Africa; and in certain islands of the Pacific Ocean. By far the largest known deposits of phosphate rock of the world are found in the United States, particularly those in the western states indicated above.

THE SUPERPHOSPHATE INDUSTRY

In 1840 Liebig had suggested that bones might well be dissolved in sulfuric acid as a means of increasing the availability of their phosphate. Lawes, of Rothamsted, secured a patent for the process in 1842. Subsequently the use of sulfuric acid as a dissolving agent was applied to phosphate rock with the resulting beginning of our present enormous superphosphate industry. Later developments have been the production of double- and treble-superphosphates by acidulation of phosphate rock with an excess of sulfuric acid and the use of the liberated phosphoric acid to treat additional quantities of phosphate rock; the volatilization of phosphoric acid anhydride from phosphate rock and added silica by heat and the use of this when dissolved in water, for acidulating purposes; and the volatilization of the element phosphorus from a mixture of phosphate rock, silica and coke in an electric furnace, this phosphorus on subsequent

oxidation with steam, yielding phosphoric acid and hydrogen, the latter of which is used in the production of synthetic ammonia to be combined with the phosphoric acid to form mono- or di-ammonium phosphate.

Another important source of phosphoric acid for fertilizer purposes is basic slag, a product resulting from the refining of phosphatic iron ores. Thomas and Gilchrist of England in 1877 found it possible to separate the phosphorus from such ores by adding limestone to the flux, the resulting slag containing the phosphorus in a form which, while not soluble in water, seems to be fairly readily available to plants when applied to the soil.

PHOSPHORUS ECONOMY IN THE SOIL

Van Hise, in his book on "The Conservation of Natural Resources in the United States," writes as follows:

> "The problem of the conservation of our phosphates is the most crucial, the most important, the most far-reaching with reference to the future of this nation of any of the problems of conservation."

The explanation of his conclusion on this subject lies in the facts that phosphorus is an essential constituent in plants and animals; the quantity of it in the average soil is relatively small; it is being removed from the farm in considerable amounts in cereal grains and in the bones of animals, including man; the known deposits of mineral phosphates are very small as compared to those of all other mineral elements that are required in large amounts by plants or animals; and there is no atmospheric supply of phosphorus on which plants can draw.

While the livestock system of farming, in its best developed forms, permits of maintaining the nitrogen content of the soil at a fairly high level without the supplemental use of this element in the form of commercial fertilizers, this is not the case with phosphorus. The greater the acreage of legumes, the larger the sales of livestock or products of livestock from the farm, the more rapid is the rate of depletion of the phosphorus content of the soil. This fact is so generally recognized that it is the usual practice of many livestock farmers to reënforce their manure with phosphate or to apply phosphatic fertilizers separately when their crops are planted.

Similarly, in the grain system of farming, the phosphorus content of the soil is soon reduced to the point where the lack of this element becomes a limiting factor in crop growth. This is because phosphorus is more concentrated in the grain, which is sold, while the other mineral nutrients are contained in larger amounts in the roots and stalks of plants, which are returned to the soil. Grain farmers as well as livestock farmers, early in the agricultural history of most farming areas, find it necessary to employ some carrier of phosphorus for fertilizer purposes.

Phosphorus is not of such great importance in the economy of the soil in market gardening and truck farming as it is in grain or livestock farming. Nevertheless it is usually supplied in liberal amounts as a fertilizer in these more intensive systems of farming. This is not only for the reason that increased intensity of farming permits using all plant nutrients more nearly up to the limit of their capacity to increase yields, but also because phosphatic fertilizers have very marked effects in the development of root systems of plants, in causing greater rapidity of early growth and in bringing the crop to earlier maturity, all of which are of considerable importance in market gardening and trucking. The fundamental difference between the problems of the use of phosphates in general farming and in market gardening and other similarly intensive systems of farming lies in the fact that in the former case phosphorus is, as a rule, the predominating element in the fertilizer while in the latter case nitrogen and potash, particularly the former, are of equal or greater importance.

CARRIERS OF FERTILIZER PHOSPHORUS

Following the discoveries of large deposits of phosphate rock and of the superphosphate process, bones came to occupy a much less important place as a source of the element phosphorus for fertilizer purposes. In fact much of the bone having its origin in slaughtering houses is used for purposes other than fertilizers, while most of the human bones are buried at such depths as to be permanently lost to agriculture. In those countries in which the phosphate rock deposits are relatively small, considerable amounts of basic slag are produced and used. In the United States more than 90 per cent of the total phosphorus that is applied to the

soil has its origin in phosphate rock. This is sold under the names of ground phosphate rock, superphosphate, treble-superphosphate, and ammonium phosphate and in mixtures of these materials with carriers of other fertilizer nutrients in what are known as "mixed fertilizers."

Plant and animal materials carry their phosphorus in part as organic compounds. These, on oxidation in the soil, yield orthophosphates as their end product. It is conceivable that certain of the organic phosphorus compounds in the soil are available for plant use and that they may be absorbed as such by the plant. In fact, phytin and lecithin, when supplied to nutrient solutions, seem to have a favorable influence on plant growth, the plant apparently being able to absorb them without change in form. The inorganic phosphate in soil is present largely in the form of crystals of the mineral apatite.

All inorganic phosphate fertilizers, including bone, carry their phosphorus in the orthophosphate form. In bone the phosphorus is found as the tri-calcium phosphate. Bone is sold both in the raw state and after it has been put through the steaming process. Raw bone meal usually contains much coarser particles since very fine grinding is not so easily possible until steaming has taken place. Bone meal has long been a very popular fertilizer. It contains a small amount of nitrogen varying from 1 to $1\frac{1}{2}$ per cent in steamed bone meal to $2\frac{1}{2}$ to 3 in the unsteamed product. The steamed bone is to be preferred, not that any change has been effected in the tricalcium phosphate to render it more suitable but because steaming permits of much finer grinding and, therefore, makes possible better distribution in the soil and the exposure of more surface area to the solution processes.

PHOSPHATE ROCK AS A SOURCE OF PHOSPHORUS

Raw phosphate rock is sometimes used as such when very finely pulverized. Experimental tests of phosphate rock have shown that its phosphorus is slowly available to crop plants. By reason of the cheapness of the material one can supply much larger amounts of phosphorus for the same investment in phosphate rock than after the acidulation process has been effected.

The cause of phosphate rock was well championed by Hopkins, who advocated its use in large amounts until the phosphorus content of the soil had been raised to about 0.1 per cent or 2000 pounds (equivalent to 4600 pounds of P_2O_5) in the plow depth of an acre after which only such amounts need be applied annually as were required to replace the loss in crops and livestock.

TABLE XLV

COMPARATIVE VALUES OF PHOSPHORUS CARRIERS AS TO VARIOUS QUALITIES

	Per Cent of Phosphoric Acid	Availability of Phosphorus	Acidity or Alkalinity	Retention by Soil	Quality for Condition
Phosphate rock	30–35	30	Alkaline	High	Very good
Superphosphate	14–20	90	Neutral	High	Good
Treble-superphosphate	40–45	95	Acid	High	Good
Ammonium phosphate	45–50	100	Acid	High	Good
Bone crude	20–25	70	Alkaline	High	Very good
Bone dust and ash	25–38	80	Alkaline	High	Very good
Tankage	3–12	80	Neutral	High	Very good
Guano (bird and fish)	12–26	80	Acid	High	Very good
Basic slag	10–25	80	Alkaline	High	Very good
Apatite	38–42	30	Alkaline	High	Very good

The three most important arguments presented by Hopkins in favor of phosphate rock are (1) that the cost of phosphorus in the form of phosphate rock is very low as compared to its cost in any other form; (2) that lower grades of phosphate rock can be used for direct application to the soil than is possible when they are first made into superphosphate (a matter of great importance in the conservation of our supply of phosphates); and (3) that, in common with bone and basic slag, phosphate rock is free of acid and has none of the tendency to develop soil acidity that is experienced in the use of superphosphates, particularly the water-soluble forms.

Viewing these arguments in the light of more recent investigational work and considering the facts that agriculture is constantly increasing in its intensity and that marked improvements are being effected in the technique of manufacture of super-

phosphates and phosphoric acid, there is considerable doubt concerning the validity of any of them. Phosphorus in the form of ground phosphate rock is cheap but more must be applied to secure as high yields as are produced by the use of more highly available forms of phosphorus. Recent developments in manufacturing technique have shown the possibility of using low-grade rock for the production of phosphoric acid. Experimental evidence does not show any increased acidity in the soil as a result of the use of superphosphate.

Ground phosphate rock, frequently termed floats, is being used in certain portions of the world because of the cheapness of local supplies of phosphate rock or, as is the case in Illinois, because of very active propaganda in its favor. However, considered from the world point of view the amount of phosphate rock that is used for direct application to the soil is relatively very small as compared to the quantities of superphosphate, basic slag and bone meal that are employed. It must be admitted that the entire weight of influence of the superphosphate and mixed fertilizer industries is behind the use of the more available forms of phosphorus. It is conceivable that much more favorable evidence toward the use of raw phosphate rock might be secured if adequate study were made both of the means of increasing the fineness of its state of division and the conditions under which it can be most effectively used.

Two points concerning the effective use of phosphate rock seemed to be fairly well established. One of these is that the soil should not have been too heavily limed previous to the use of the phosphate rock. Thus it has been shown in Germany that phosphate rock is quite effective when used on acid peat soils. Similarly, in Indiana, it has been found that the use of approximately equal money's worth of phosphate rock and superphosphate (four times as much phosphorus was applied in the case of the phosphate rock) resulted in the production of practically the same yields, when the phosphate rock was applied to an unlimed acid soil and the superphosphate to adjacent plots of the same soil type after they had been limed. In this case the phosphate rock had the advantage that no lime was necessary to be applied. However, the crop yields in the Indiana test were not especially high even with the best supplemental fertilizer or

manurial treatments. In proportion as conditions in the soil are made favorable for higher yields the advantage lies with the more readily available phosphorus in the superphosphates.

It has been shown that certain plants, such as sweet clover, buckwheat, rye and alfalfa are able to make use of the phosphorus of phosphate rock to much better advantage than are others. The explanation of this is assumed to lie in the fact that these plants either have a need for large amounts of calcium which being removed from the field of action permits of the solution of more phosphoric acid, or their root systems are so fibrous that the root hairs are able to come into contact with much more of the surface of the particles of phosphate rock that are exposed to solution in the soil. Whatever the explanation, the fact remains that plants vary in their response to the use of phosphate rock. The evidence indicates that a particularly favorable use for phosphate rock would be found in growing sweet clover for green manuring purposes.

BONE MEAL AS A SOURCE OF PHOSPHORUS

As previously indicated, bone meal should be very finely pulverized for best results. This is only feasible if the bones have been subjected to steaming or the action of solvents to remove the fatty and gelatinous substances in them or have been heated to fairly high temperatures as in the production of animal charcoal and bone ash. Raw bone meal contains somewhat more nitrogen while steamed, naphtha-treated, charred or ashed bone contains much less or no nitrogen and more phosphorus.

Ground bone is held in much higher esteem as a fertilizer than is ground phosphate rock. The explanation of this is found in part in the fact that farmers are prejudiced in favor of manures of plant or animal origin. There is the further fact to consider that the phosphate of lime of bones is deposited on a framework of organic matter. By reason of the porosity of the bone, a greater surface area is exposed to solution than would be the case with an equal weight of phosphate rock.

More recently the conclusion has been reached that the two products are fundamentally different in their chemical composition. The phosphorus in bone is present largely in the form of tri-

calcium phosphate while that in phosphate rock is present in the form of calcium fluorphosphate—a much less readily soluble compound.

Much of the bone that was formerly used in England was treated with sulfuric acid before being applied to the field. Sir John Lawes' first superphosphate was made from bone. At the present time, most of the bone is sold as such without acidulation. The control chemist determines only the total amount of phosphoric acid in bone on the assumption that all of its phosphoric acid gradually becomes available in the soil.

Bone is not soluble in water but is quite soluble in neutral citrate solution as used for the determination of available phosphoric acid in superphosphate. Steaming increases its solubility in this solution and makes it more effective as a fertilizer.

In general it has come to be believed that the phosphorus of steamed bone meal is about as effective as that of superphosphate. Under conditions in which acidity of the soil is a limiting factor in plant growth the bone meal has the advantage in that it carries more calcium in proportion to its acid constituents. If the soil contains adequate amounts of lime, superphosphate is usually somewhat more effective than bone meal, either raw or steamed, notwithstanding the fact that bone carries appreciable amounts of nitrogen that should add to its value. Here again farmers of the past were prejudiced in favor of the bone, for several reasons. One was that often the soil needed liming. A second was that superphosphate (long known as acid phosphate) was believed to make the soil more acid in reaction, a belief that subsequent research has shown not to be valid. A third arose from the fact that in comparative trials by farmers equal weights of bone meal and superphosphate were often applied although the content of phosphorus in the latter, as then manufactured, was only about half that in bone.

BASIC SLAG AS A SOURCE OF PHOSPHORUS

A considerable portion of the phosphate that is used in Europe has its origin in phosphatic iron ores. A mixture of the iron ore and limestone is heated to a molten state of the former in a converter that is also lined with limestone. The supernatant

slag produced is a calcium silicate-phosphate, the exact formula for which is unknown, plus some free lime. This slag usually contains from 16 to 20 or more per cent of phosphoric acid. It should not be confused with the ordinary blast furnace slag which usually contains only a trace of phosphorus.

Early experimental tests showed that this phosphorus was at least partially available although marked differences in effectiveness were noted with different slags. Later it was shown that there was some relation between the content of silica and the effectiveness of the slag. This made it necessary to devise some scheme of testing in the laboratory the availability of the phosphorus of slag. Most of the investigational work on the subject has been done in Germany where slag is a particularly important source of phosphorus for fertilizer purposes. As a result of coöperative research an agreement was reached that the official test to be applied to slag should be the solubility of its phosphorus in 1 per cent citric acid solution. This test being applied, it was necessary to regulate the conditions of production to make as much of the phosphorus as possible soluble in this solvent.

CALCINED PHOSPHATE ROCK AS A SOURCE OF PHOSPHORUS

Phosphate rock carries its phosphorus not as tri-calcium phosphate, but as calcium fluorphosphate ($Ca_{10}F_2(PO_4)_6$). When this material is heated to a temperature of 1400° C. in the presence of water vapor, the fluorine is dissociated and a product carrying 30 to 35 per cent of available phosphoric acid is obtained. This product is in the form of semi-fused clinker which, on grinding, can be used for fertilizer purposes. Pot tests indicate that this material is as effective as superphosphate as a source of phosphoric acid for ordinary use.

Fine grinding is essential for high availability of the phosphoric acid. This grinding makes the material very dusty and disagreeable to handle. It would seem necessary therefore, that the powdered material be granulated by the use of some chemical that is readily soluble in water and which, on being applied to the soil, would dissolve, allowing the finely divided particles to re-separate.

SUPERPHOSPHATE AS A SOURCE OF PHOSPHORUS

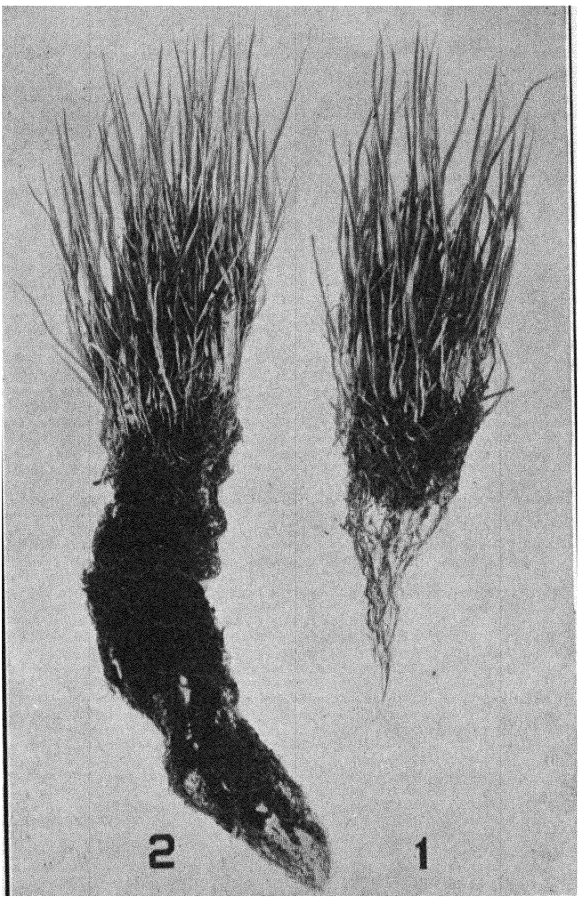
In the early history of the use of superphosphate, formerly known as acid phosphate in the United States, many objections were raised against it. As previously noted, it was thought to make the soil acid but experimental study of its action on the soil has shown that it has a neutral or slightly alkaline effect on the soil reaction. Similarly it was thought to have a cementing effect on the soil probably by reason of the fact that it carries, as a rule, approximately 50 per cent by weight of calcium sulfate, a close relative of plaster of Paris. It is difficult to determine whether these points of view originated among the farmers themselves or among the producers and salesmen of complete fertilizers who preferred that fertilizer materials be sold in mixtures rather than separately, for reasons that are quite apparent. The fact that the phosphorus in these complete fertilizers is largely in the form of acid phosphate is not stressed by the fertilizer salesman.

But no injury to the soil or crop resulted from the use of superphosphate and the tonnage applied grew very rapidly. Eventually, however, it came to pass that, by the use of only superphosphate, the lack of nitrogen and potash, as well as carbonate of lime, in the soil became the limiting factors in crop growth and a change to complete fertilizers became desirable. These complete fertilizers are usually more than 50 per cent superphosphate mixed with varying amounts of carriers of nitrogen and potash together with a small quantity of some inert material that may be used for conditioning purposes or for making the percentages of the nutrients conform to some chosen standard.

The method of procedure in the production of superphosphate is to treat the pulverized rock with sulfuric acid, have the mixture to undergo reaction in a pile where it is allowed to stand for some time as it goes through a "curing" process, after which it is ground and bagged as such or mixed with materials carrying nitrogen and potash. The curing process simply permits the several phosphates that are present in the treated product to come to equilibrium with each other.

It is evident that the action of the sulfuric acid will result in the production of phosphoric acid and mono- and di-calcium

phosphates and that some undecomposed phosphate rock may remain that has not been acted on by the acid. In the curing process, the phosphoric acid disappears as a result of secondary



(2) Superphosphate (1) No phosphorus

FIG. 35.—Effect of phosphoric acid on root development of wheat plants. (Courtesy Michigan Agricultural Experiment Station.)

reactions with the various phosphates that are present in the mixture.

Since the treatment with acid has for its purpose the making more available the phosphorus in the rock, it then becomes necessary to have some test of the effectiveness of the treatment.

The Association of Official Agricultural Chemists, after many years of study of this problem, have agreed upon and published what is known as an "official" method for determining the "available" phosphoric acid in superphosphate. The method consists in washing the sample with water and then digesting it in a neutral solution of ammonium citrate. The size of the sample, the temperature of the solution, and the length of time of digestion are all specified in the official method. That part of the phosphate rock which has not been acted upon by acid is insoluble in either of these solvents.

A 16 per cent superphosphate is one which contains such an amount of phosphorus in forms that are soluble in water and in a neutral solution of ammonium citrate as will, when calculated in terms of phosphoric acid (P_2O_5), be equal to 16 per cent of the weight of the product.

The ammoniation of superphosphate, or the addition of limestone or hydrated lime, tends to cause "reversion" of some of the mono- and di-calcium phosphate to tri-calcium phosphate. This "reverted" phosphoric acid is, however, much more available to plants than was the phosphoric acid in the original phosphate rock.

If the phosphate rock were pure tri-calcium phosphate it would contain 20 per cent of phosphorus, equivalent to approximately 46 per cent of phosphoric acid. This, on being treated with an equal weight of sulfuric acid, should yield a superphosphate of over 20 per cent of available phosphoric acid and an additional small amount of insoluble or unavailable phosphoric acid. Ordinarily commercial phosphate rock has a purity of from only 65 to 80 per cent. Superphosphates which contain more than 20 per cent of available phosphoric acid are, therefore, made by mixing ordinary superphosphate with some double or treble superphosphate which contain much higher percentages of available phosphoric acid.

CONCENTRATED SUPERPHOSPHATES AS A SOURCE OF PHOSPHORUS

Liquid phosphoric acid can be produced from phosphate rock by treating it with an excess of sulfuric acid and removing the calcium sulfate that is formed in the process. It may also be produced by heating the rock, when mixed with silica and lime-

stone, to high temperatures and dissolving the resulting volatilized phosphoric acid anhydride in water. A third method of production involves the addition of coke to the mixture as a result of which phosphorus is produced which, on being treated with steam, yields phosphoric acid and hydrogen.

It is not feasible to use liquid phosphoric acid for fertilizer purposes. By employing it as a substitute for sulfuric acid in the treatment of phosphate rock a concentrated superphosphate, containing from 40 to 45 per cent of available phosphoric acid, may be produced. This contains no calcium sulfate, the material which makes up about 50 per cent of the ordinary 16 to 20 per cent superphosphate. It can be used as a fertilizer with equally as good effect as the ordinary superphosphate except under conditions in which the soil is deficient in sulfur or is not adequately supplied with lime in which case the calcium sulfate, known as gypsum or landplaster, of the ordinary superphosphate is of value.

AMMONIUM PHOSPHATES AND AMMONIATED PHOSPHATES

Liquid phosphoric acid may be used for the production of ammonium phosphate. Such phosphates are available both in the mono- and di-ammonium phosphate forms. These products are completely soluble in water. The mono-ammonium phosphate contains 10 to 12 per cent of nitrogen and 45 to 50 per cent of phosphoric acid.

A more recent development is the production of ammoniated superphosphate. It is produced by treating ordinary superphosphate with anhydrous ammonia or with ammonia liquor. An ammoniated superphosphate contains ammonium sulfate, mono-ammonium phosphate, and one or more of the calcium phosphates. Such a product ordinarily carries 3 to 4 per cent of nitrogen and 16 to 18 per cent of available phosphoric acid. Ammoniated double superphosphates can also be produced.

The advantage of these concentrated phosphates lies in their increased solubility and availability for plant use and in the economy of freight and handling costs. The ammonium phosphate is the more concentrated but has the disadvantage that it carries little or no calcium sulfate or other readily available form of calcium.

AVAILABILITY OF PHOSPHORUS IN FERTILIZERS

As previously indicated, fineness of grinding is particularly important for such materials as phosphate rock, bone meal and basic slag since by this means a much increased surface area may be exposed to solution in the soil. This is particularly true if a distribution has been effected which permits of each individual particle of phosphate being in contact on all sides with soil and later with root hairs rather than with other particles of phosphate.

With phosphates that are soluble in water, a second factor is introduced. Coming into contact with water in the soil such phosphates are dissolved. They are then in the molecular or ionic state which is the finest state of division in which they can exist. Not being taken up by a root hair immediately on going into solution, these dissolved phosphates are precipitated in the soil in an insoluble state. Their degree of solubility is then reduced to one similar to that of di-calcium phosphate which does not dissolve in water but is soluble in neutral citrate solution. This solution is believed to correspond in its dissolving effect to soil water that is saturated with carbonic acid.

Experiments have shown, however, that soluble phosphates, when applied to the soil, lose their solubility to such an extent that only the merest traces of them can be found in the soil solution or in the drainage water coming from the soil. They are evidently precipitated or absorbed by the soil. Iron and aluminum are present in all acid soils and form relatively insoluble phosphates. Soil microorganisms are stimulated by applications of phosphates as a result of which they increase in activity and in numbers. A considerable part of the added phosphoric acid may be tied up in their bodies.

When soluble phosphates are precipitated in the soil, the surface area exposed to the action of root hairs is far greater than would have been the case had the insoluble phosphate rock been finely pulverized and applied without acidulation. The acidulation is, in effect, a means of greater pulverization. In this case, however, acidulation also has the effect of breaking up the highly insoluble calcium-fluorphosphate molecule which is not reformed in the soil. The simple calcium, iron and aluminum phosphates, precipitated in the soil, are more readily soluble than was the original phosphate rock.

The phosphoric acid that is utilized by microorganisms is later

released for crop use. The processes of absorption and release are no doubt similar to those that occur with nitrogen when it is added to straw or similar materials in the production of artificial manure. In either case, the fertilizing effects are temporarily lost but as the material decomposes the nitrogen and phosphoric acid again become available to the crop.

To some extent, root hairs come in direct contact with particles of superphosphate in the soil and absorb the phosphoric acid before it has had an opportunity to be fixed by the soil. This is especially true in the case of band applications of superphosphate, or of complete fertilizers containing it, and where the granular forms of superphosphate are employed.

It is also probable that even though the quantity of phosphoric acid in the soil solution at any one time is relatively small, the rate of renewal of this supply is quite rapid. In due time the root hairs spread over the surfaces of the precipitated phosphate and exercise a solvent effect through the excretion of carbonic acid.

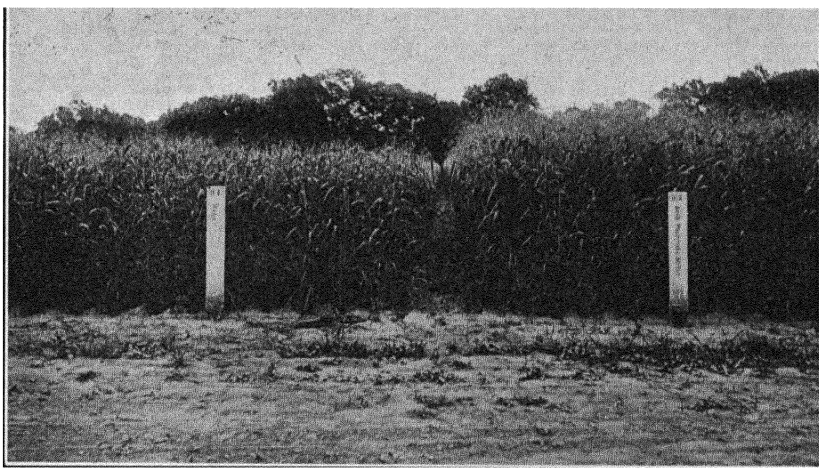
However, only a relatively small percentage of the phosphoric acid applied to the soil in fertilizers is recovered in the crop increase produced from its use. That not recovered in the immediate crop remains in the soil in a relatively unavailable condition.

SECONDARY EFFECTS OF CARRIERS OF PHOSPHORUS

As is the case with nitrogen and potassium fertilizers, phosphatic fertilizers have effects on the soil and crop other than those produced merely as a result of their supplying additional quantities of phosphorus. Bone meal, phosphate rock, and basic slag carry lime that is combined with the phosphate radical. This may be of value as a source of calcium to the plant and may affect the nature of the base-exchange-complex of the soil. All of them, but particularly basic slag, contain additional calcium in the form of the carbonate or oxide which has a value for neutralizing purposes in the soil.

Bone also carries a certain amount of nitrogen. Basic slag contains some silica in such form as to make it of some value to the plant, it having been shown that soluble silica may improve the yield of crops on soils that are deficient in phosphates. Superphosphate carries calcium sulfate, or landplaster, which has long

been known for its stimulating effect on the growth of clovers and grasses. Soluble phosphates, when applied to an acid soil, tend to reduce, at least temporarily, the amount of soluble aluminum and iron in the soil solution. Some of these secondary effects may at times be of primary importance in determining the usefulness of the product for soil improving purposes. However, where this is true, these other effects may usually be secured at



Left, no fertilizer. Right, superphosphate.

FIG. 36.—Effect of superphosphate on oats. (Courtesy Ohio Agricultural Experiment Station.)

less cost by the use of materials that are employed for that purpose since such materials are usually less expensive than are phosphates.

THE CHOICE IN RELATION TO SOIL FACTORS

Basic slag has long been a popular phosphate fertilizer for use on pastures under conditions in which the soil is somewhat acid in reaction. Because it has a neutralizing value that is approximately half that of pure calcium carbonate, and also carries phosphorus, it meets the requirements of white clover the better growth of which in pastures soon results in an increased yield of the grasses as well. Under conditions in which the soil is adequately supplied with calcium in the base-exchange or carbonate condition superphosphates, particularly the water

soluble forms, are likely to be much more effective than is basic slag.

Similarly, phosphate rock and bone meal are relatively more useful on soils that are deficient in lime. Both of these materials contain small amounts of calcium carbonate. In addition they contain three parts of calcium for each part of phosphoric acid. The plant absorbs its phosphoric acid from either the mono- or di-calcium phosphate form and builds this up in organic combinations. The calcium of the phosphate molecule is then free to be used for combining with other acids either in the crop or soil. Water-soluble superphosphates carry less calcium per unit of phosphoric acid and therefore are less effective as neutralizing agents in the soil.

If the soil already contains adequate supplies of calcium, nothing is gained by the addition of more of it than is necessary to serve as a carrier of the phosphate required. Under these conditions, liquid phosphoric acid and ammonium phosphate would be ideal sources of phosphorus, assuming in the latter case that nitrogen was also required for nutritional purposes. Superphosphates are used with best effects, relatively, when the soil is maintained by liming at such a point that no additional benefit is secured from the lime that is associated with the phosphate molecule. In the event that the soil had been overlimed, they would have an additional value in neutralizing the alkalinity.

Very marked effects are noted from the use of superphosphates on strongly acid soils. Under these conditions soluble phosphates serve to effect a precipitation of iron and aluminum, the latter of which is often present in toxic concentrations in acid soils. When the soluble phosphate has all been precipitated additional aluminum moves into solution. Perhaps the temporary absence of aluminum in toxic concentrations permits of such growth of the young plant that it is able to withstand the effects of higher concentrations of aluminum when they later occur. There is some question, however, whether the good effects resulting from the application of soluble phosphates are the result of reactions that take place in the soil or in the plant. Some evidence has been presented to the effect that plants contain as much aluminum when soluble phosphates have been added to the soil as they contain in the absence of fertilizer

phosphates. This would indicate that the added phosphate taken up by the plant had the function of offsetting any toxic effect of the aluminum within the plant rather than causing its precipitation in the soil and preventing its absorption by the plant.

By reason of the marked capacity of the soil to absorb phosphates, only a mere trace of phosphorus is found in drainage waters. Any excess of phosphate that may be supplied above the requirements of plants is, therefore, retained by the soil until it is subsequently utilized by plants that are grown later. It seems perfectly safe to apply phosphates in large amounts at whatever time in the rotation it may be desired. This is quite in contrast to what is good practice in the use of nitrogen fertilizers. No detrimental effect on the crop has been noted from very heavy applications of superphosphates to the soil, except as the hastening of maturity of the crop may not be desirable for climatic reasons.

On sandy soils, it is probable that there might be considerable loss of phosphoric acid in the drainage water as a result of heavy applications of soluble phosphates some time in advance of its being required by the crop. It happens, however, that the effects from phosphates are much less marked on sandy soils, since root growth on such soils is usually adequate without any additional stimulation with phosphates. There is, therefore, no good reason why one should apply phosphates in such large amounts to sandy soils.

THE CHOICE IN RELATION TO CLIMATIC FACTORS

It is to be expected that where the crop season is short or the climate is cool and moist more highly available forms of phosphorus are to be preferred, since their effect in speeding up the rate of growth of the crop is quite marked. This is particularly noticeable in the early growth stages. It is also apparent from the fact that heavily phosphated crops reach maturity earlier than do those that are not so liberally supplied with available phosphorus.

This tendency toward earlier maturity of crops that are liberally supplied with readily available forms of phosphorus is

objectionable under some climatic or seasonal conditions. For example, corn may be brought to the earing stage during a dry period, when perhaps a little slower development of the plant would have resulted in a delay that would have been sufficient for another rain to have occurred. In the growing of tobacco this early maturing effect often results in decreased yields, since delay in maturity permits the season to advance to the period when cooler weather retards evaporation.

However, this tendency towards early maturity that often occurs when superphosphates are used is often to be desired. Winter wheat can be brought to maturity before the drought of the summer season sets in. Barley may be made to mature in regions farther north. Potato tubers may be fully developed before frost occurs. Tomatoes may be ready for the early market before the lower prices resulting from abundant supplies have taken effect. Growth of all of the early vegetables is speeded up as a result of heavy applications of available phosphates.

In proportion as there is need of phosphorus for some of the special purposes noted above, the more readily available forms are to be preferred. Phosphate rock and bone meal find their greatest use in areas of extensive farming. In intensive farming, the superphosphates, and more recently such highly soluble forms as the ammonium phosphates, are more popular.

THE CHOICE IN RELATION TO CROP REQUIREMENTS

There are three classes of crops that respond especially well to phosphatic fertilizers. These are the legumes, the root crops and the cereals. The clovers grow to best advantage on soils that are well supplied with lime. For this reason basic slag and bone meal have long been especially popular with farmers who seed clover in their cereal crops. Equally good effects may be secured by the use of limestone and superphosphate but, if for any reason the liming has not been done and the soil is acid, there is reason to use the more alkaline carriers of phosphorus.

The fact that most of the legumes absorb large amounts of lime as well as phosphorus makes it possible for them to make better use of the phosphorus of phosphate rock than can many of the other crops. Thus in the growing of sweet clover, phos-

phate rock is quite an effective fertilizer. There would seem to be an additional reason for using phosphate rock in growing alfalfa since it is a perennial and rate of growth is not so important as it is in the case of the short-season annuals.

Phosphates are especially effective in the growing of roots and tubers. These are for the most part either annuals or used as annuals and a fairly rapid rate of growth is desired. Most of the root crops are favored by having the soil well supplied with lime. However, in the case of the potato crop, there is a greater tendency toward scab, if the soil reaction is too close to the neutral point. For this reason neither basic slag nor bone, but particularly the former, is normally used on this crop because of the alkaline effects produced.

In the growing of the cereal crops the superphosphates or other forms of readily available phosphorus are preferred for direct application. Where phosphate rock, bone meal or basic slag has been previously applied for the benefit of the legume crops, considerable amounts of available phosphorus may be contained in their residues that will be of use to the succeeding cereal crop. However, it is usually good practice to apply superphosphate broadcast for the small grains and in the row for corn even though considerable amounts of the less available forms have been applied previously.

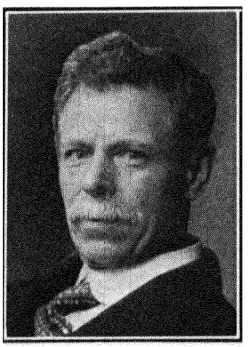
In general, the more rapid the rate of growth of the crop that is desired, the better the results from phosphatic fertilizers if the more highly available forms are used. The longer the growing period of the crop, particularly if it grows throughout the summer season or is a biennial or a perennial rather than an annual, the better the effects to be secured from slowly available phosphate such as phosphate rock. If the long-growing-season habit happens to be associated with a very high lime-requirement, then the conditions are even more favorable for using phosphate rock. These conditions would seem to be met with alfalfa, particularly in those regions in which it is grown on the same area for fifteen or twenty years or more in succession, such as is the case in Nebraska and Kansas. However, in these regions the soil usually contains such abundant supplies of calcium carbonate that the availability of the phosphorus of the phosphate rock might be too low for satisfactory results.

SELECTED REFERENCES

1. Aikman, C. M. Manures and Manuring, London, pp. 273–417, 1902.
2. Anonymous. The maintenance of soil fertility. Thirty years' work with manure and fertilizers. Ohio Agr. Exp. Sta. Bul. 381, 1924.
3. Bauer, F. C. The relation of organic matter and the feeding power of plants to the utilization of rock phosphates. Soil Science, Vol. 12, pp. 21–43, 1921.
4. Helper, J. R., and Kraybill, H. R. Effect of phosphorus upon the yield and time of maturity of the tomato. New Hampshire Agr. Exp. Sta. Tech. Bul. 28, 1925.
5. Hopkins, C. G. Soil Fertility and Permanent Agriculture, Ginn and Co., pp. 183–193 and 236–299, 1910.
6. Jacob, K. D., and Associates. Ammoniation of superphosphate. Jour. Ind. Eng. Chem., Vol. 22, p. 1385, 1930.
7. Mansfield, G. R. Phosphate rock in 1924. Mineral Resources of U. S., 1924. Part II, pp. 79–112, 1925.
8. Reynolds, D. S., and Associates. Phosphate fertilizers by the calcination process. Jour. Ind. Eng. Chem., Vol. 27, p. 87–91, 1935.
9. Van Hise, C. R. The Conservation of Natural Resources in the United States, Macmillan, pp. 320–339, 1910.
10. Waggaman, W. H., and Wagner, C. R. Analysis of experimental work with ground raw rock phosphate as a fertilizer. U.S.D.A. Bul. 699, 1918.
11. Waggaman, W. H., and Easterwood, H. W. Phosphoric Acid, Phosphates and Phosphatic Fertilizers. Monograph, A.C.S. 370 pp., 1927.
12. Wiancko, A. T. Report of Moses Fell Annex, Bedford, Indiana. Indiana Agr. Exp. Sta. Circ. 135, 1926.

CHAPTER XIII

POTASH FERTILIZERS



E. J. Russell.

IT would seem that the need of the element potassium as a fertilizer would be much less than that of either nitrogen or phosphorus and perhaps even less than that of calcium. Soils are relatively quite high in their content of potassium; most of the potassium that is absorbed by plants from the soil is contained in their vegetative parts which are normally not sold off the farm; this element is not required, except in mere traces, by animals or man and such amounts as are taken into their bodies as food are almost completely voided in their excrements; and the average soil has a very marked capacity to absorb potassium from solution and thus to prevent losses by leaching.

The point of view expressed by Hopkins is fairly typical of those of the earlier agronomists of the United States whose experiments with fertilizers were carried on under conditions in which potassium gave little return for its use. During that period when a country is relatively young agriculturally, and as long as high intensity of agriculture is not economic, the conditions are not favorable for the profitable use of potassium fertilizers. This is especially true since only the best land is farmed at first and this normally contains a fairly large amount of available potassium. Thus Hopkins commented as follows:

"The total supply of potassium in nearly all soils is exceedingly large compared with crop requirements; and while it has a money value in commercial fertilizers and is quite extensively used, there is much evidence to show that on many soils the influence which it produces is due in part at least, to indirect effects."

ECONOMY OF POTASSIUM IN SOILS

Hopkins' conclusions were reached as a result of the following logic:

> We can assume for a rough estimation that the equivalent of 2 per cent of the nitrogen, 1 per cent of the phosphorus and $\frac{1}{4}$ of 1 per cent of the total potassium contained in the surface soil can be made available during one season by practical methods of farming.

An acre of average soil to plow depth contains about 35,000 pounds of potassium, equivalent to a little over 42,500 pounds of potash (K_2O). A 100-bushel corn crop contains about 25 pounds of potash in the grain and 100 pounds in the associated $2\frac{1}{2}$ tons of stover. According to Hopkins' method of calculation, since the stalks are returned to the soil, the potash supply in the plowed acre of average soil is sufficient to last the corn crop for 1700 years. Subsoils usually contain higher percentages of potash than do surface soils. Since the roots of corn plants penetrate to depths of five feet or more, the supply of potash would seem to be inexhaustible.

Assuming, as Hopkins does, that $\frac{1}{4}$ of 1 per cent of the potash in the soil can be made available for crop use each year, by suitable methods of soil management, the average plowed acre of soil would yield 85 pounds of potash to the crop plus whatever additional amount might have been left over from the previous season or had been returned to the soil in the form of crop residues and manure. Since the soil has a marked capacity to absorb potassium from solution and thus to prevent its loss by leaching, without reducing the availability of this potassium to the crop, it would seem that the need for the purchase of this element would not be likely to become serious at least for many years. Hopkins' field tests in Illinois, confirmed his conclusions in this regard.

EMERGENCY NEEDS OF POTASH FERTILIZERS

It is now apparent that Hopkins and his followers were in error with reference to a number of points in their theory concerning the lack of need of potash fertilizers. Investigation has shown that, of the total potassium in the soil, only that which is present in loose combination in the base-exchange complex can be con-

sidered as being "available" for crop use. This is only a very small fraction of the potassium that is contained in the soil. While that which is present in the soil in the form of as yet undecomposed silicate minerals can be dissolved by the use of strong acids, its rate of solution, as it exists in the soil, is so slow as probably to be practically negligible.

At any rate, it has been the experience of farmers that the continued use of the land for agricultural purposes results in a deficiency of available potassium for crop use by the time a half-century has passed. This can be explained only on the basis that the base-exchange complex of the original virgin soil was more nearly saturated with respect to potassium, calcium, magnesium and sodium ions, to the exclusion of hydrogen ions; that as time went on this state of saturation was reduced either as a result of crop removal or by loss of basic ions in the drainage water; that this loss was not compensated for by the passing into solution of sufficient amounts of these ions from the silicate minerals in the soil; and that finally a condition came to exist in which the potassium that was available to the crop from the base-exchange complex was insufficient to meet the needs for satisfactory yields.

In contrast with the experiences of Hopkins on the relatively new land of Illinois, agronomists of the eastern and southern states, on land that is much older agriculturally, find that potassium is an essential constituent of fertilizers. As soon as the land becomes old agriculturally and as the intensity increases above what might be considered the average, potash fertilizers show very marked effects on the health and vigor of plants as well as on the final yields. By careful saving of the manure that is produced and by the use of legume crops as foraging agents for potash in the subsoil, the time of need of potash can be delayed for a considerable period, but eventually a point is reached at which the lack of potassium becomes a seriously limiting factor in crop growth except as supplemental applications of the element are made in the form of fertilizers or manure.

It happens also that there are two classes of soils, of which there are large acreages in certain parts of the United States, that are naturally very deficient in potash. These are the sands and the peats. Many sandy soils are almost pure silica and con-

tain only relatively small amounts of potassium. Most of the potassium that is contained in them is held in undecomposed silicate forms and not in the base-exchange condition. Similarly, in peat soils, the content of potassium is very low. Peat is made up of plant residues. The potassium that is contained in plants can readily be washed from them by water as soon as death has occurred. Peat deposits are found in locations that are submerged in water. During overflow periods the potassium of the plant residues constituting the peat is carried away in solution.

BASE-EXCHANGE POTASSIUM IN SOILS

Considering further the condition in which the available potassium of soils exists, it is apparent that with continued action of water on the soil, a removal of potassium takes place, notwithstanding the fact that when solutions of potassium salts are applied to soils the drainage water may contain the acid radical that was added in combination with cations other than potassium. These cations are largely calcium and magnesium if the soil is approximately neutral; iron, aluminium and manganese, if the soil is distinctly acid; and sodium, if the soil is alkaline.

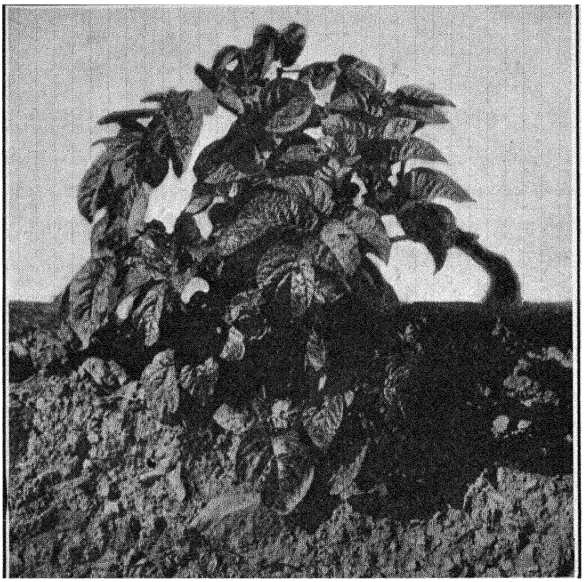
But the capacity of the soil to retain potassium is not unlimited. Thus in Schreiner's test of the potassium-absorbing power of a soil, previously referred to, it was shown that although the soil reduced the amount of potassium from 200 parts per million in the original solution to about 60 parts per million in the first 320 cubic centimeters of percolate, yet, even at this high rate of absorption, 30 per cent of the potassium was not being retained by the soil. Furthermore, by the time 1000 cubic centimeters of percolate had passed through the soil, the retention by the soil had been reduced to less than 15 per cent. If the experiment had been continued a point of equilibrium would finally have been reached at which no further potassium could have been absorbed by the soil.

If now the process is reversed and the soil is washed with water instead of a solution of a potassium salt, the hydrogen of the water displaces potassium until a final new point of equilibrium is reached at which little or no potassium is displaced. In

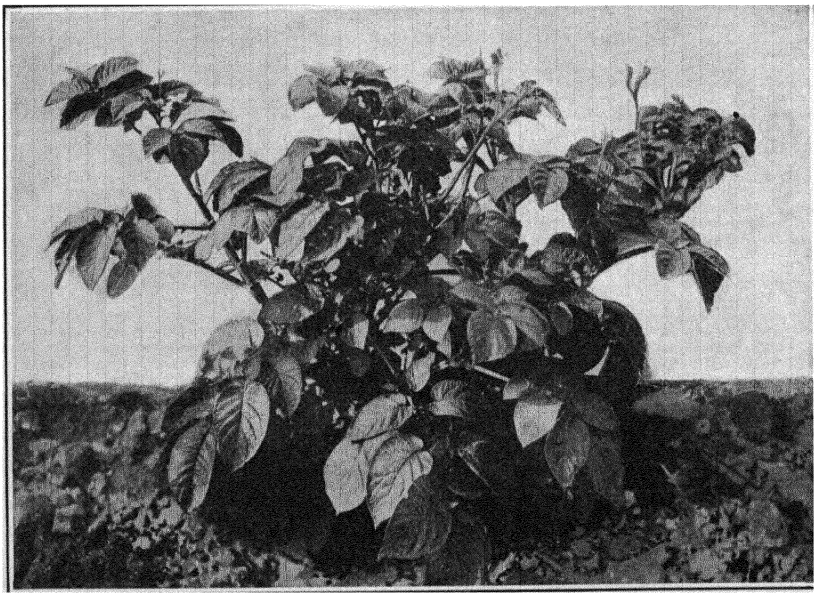
lysimeter experiments at Cornell it was shown that the average content of potash in the crops removed amounted to 95 pounds per acre. Nevertheless, in spite of the fact that this amount of potash was removed by the crops and that the soil had a marked capacity to retain potash against loss by leaching, the annual acre loss in the drainage was 56 pounds. Where the soil was kept bare, the drainage loss amounted to an average of 88 pounds per acre annually from the four-foot column of soil. The total potash content of the first foot of this soil was 1.83 per cent, of which probably less than 10 per cent was in the base-exchange condition.

The water with which soils are washed in the field carries dissolved cations of which ammonium, hydrogen and calcium are of particular importance. Thus all of the nitrogen that is gained from the atmosphere by fixation processes goes through a process of change in the soil as a result of which ammonia and later nitrous acid are produced. The calcium carbonate contained in the soil or supplied in the operation of liming also goes into solution as the bicarbonate. All of the resulting cations tend to effect a displacement of potassium until the point of equilibrium is reached with that cation which is most effective in displacing potassium. In addition to the above cations, such others as sodium and magnesium are also applied in the form of fertilizer salts and liming materials. Unless special precautions are taken to effect a solution of more of the silicate potassium in the soil; to moving the potassium in the exchange form in the subsoil to higher levels through the medium of deep-rooted plants; and to the careful saving and return to the soil of the potassium that has been removed in crops, this element gradually diminishes as to the quantity in available form until it becomes a seriously limiting factor in crop production.

It is of further interest in this connection to note that a soil which is high in colloidal matter, the seat of the base-exchange phenomena, may finally come to have such a shortage of potassium in this complex that when potash fertilizers are added the soil competes to such an extent with the crop for the added potassium that little or no effect from the use of the fertilizer can be noted. Thus a much heavier application of potash fertilizer may be required on a clay loam soil than on a sand, for satisfactory results,



(*A*) Fertilizer containing no potash.



(*B*) Potash added to fertilizer.

FIG. 38.—Effect of potash deficiency on potato plant. (Courtesy U.S.D.A.)

since in the latter case the soil offers much less competition against the plant for available potassium.

For a time, liming of the soil, or the use of such fertilizers as sodium nitrate, may serve to make it unnecessary to add potash fertilizers. Out of farmers' experiences in this connection has come the old adage that "lime makes the father rich but the son poor." While the capacity of calcium to displace potassium is not easy to show in laboratory tests, nevertheless that such displacement does occur is certain. Similarly nitrate of soda has both direct and indirect effects on the soil and plant. Of the latter, its capacity to liberate potassium from the soil-complex must be recognized. Ultimately, in the use of any of these materials, a point is finally reached at which a deficiency of potassium becomes so apparent that very marked effects from the use of potash fertilizers is noted.

In proportion as the agriculture of any region becomes more and more intensive, there is little to be gained by attempting to avoid the use of potash fertilizers even for short periods of time. The susceptibility of plants to disease in the absence of sufficient available potassium in the soil and the fact that, as a rule, crop yields are less on soils to which potash fertilizers have not been added, except as these soils are relatively new agriculturally or have been very carefully managed and liberally treated with manure, make it desirable to include potash salts in the fertilizer mixture.

CARRIERS OF FERTILIZER POTASH

One of the best known sources of potash is wood ashes. These contain from 3 to 8 per cent of potash in the carbonate form. In the old ash-hopper method of making soap, this potassium carbonate, known as lye, was leached from the ashes with water. The resulting dark-brown liquid was boiled with animal fats to produce a soft soap. More recently the use of soda ash has been substituted for the potash of wood ashes with the consequent production of hard soap.

If wood ashes are applied to the soil the potash contained in them is dissolved by rain and becomes fixed in the base-exchange complex of the soil in a form that is available for crop use. The good effect of wood ashes on crop yields, particularly of clovers,

has long been known. A part of their value lies in their content of lime which, when calculated as calcium carbonate, often constitutes as much as 50 per cent of the ash. It happens also that the potassium carbonate of wood ashes serves not only as a source of potash but as a neutralizing agent as well.

It is apparent that the ash of all plant residues will contain potash. Thus the ash of citrus skins contains from 25 to 30 per cent of potash (K_2O). Ashes of banana skins have been found to contain more than 40 per cent of potash. Corn cob ashes may contain as much as 20 per cent of potash. Corn stalks and straw, when burned, leave their potash behind in the resulting ashes. The only exceptions to the general statement that all plant remains contain considerable amounts of potash are found in the case of those that have been subjected to the leaching action of water as a result of which practically all of their potash can be removed. Thus peat and coal, because of the conditions under which they were deposited, have very little potash in their ashes. Coal ashes normally contain considerably less than $\frac{1}{2}$ of 1 per cent of potash.

Many seaweeds have been shown to contain considerable amounts of potash. Depending upon the species to which they belong the potash content of their dry matter may be from 1 to 5 per cent. Of these the kelps have received considerable attention because of their enormous growth as well as their high content of potash. The giant kelp (Macrocystes pyrifera) is a perennial from which several crops may be harvested annually. It contains about 1.5 per cent of potash in the dry state. The percentage of potash in the ash may be 30 or more.

During the World War the kelp industry received considerable attention. Investigation showed that four products of value could be produced from kelp, viz.: iodine, acetone, carbon and potash. Enough was learned concerning the handling of kelp and the production of these and other materials to make it apparent that under conditions of scarcity of one or another of these products, large plants for their drying and reduction could readily be put into operation.

A very large percentage of the potash used in fertilizers has its origin in natural salt deposits of Germany and France. These deposits are found at considerable distances below the surface

of the earth. They are made up largely of the chlorides and sulfates of potassium, sodium, calcium and magnesium. The natural crude salts are known to the fertilizer trade as carnallit, kainit, sylvinit, hardsalt and manure salt containing approximately 10, 12.5, 16, 16 and 25 per cent of potash, respectively.

For long shipment these products are often refined with the resulting production of the sulfate and muriate of potash containing 48 and 50 per cent, respectively, of K_2O. Of recent years further refinement has been introduced as a result of which potassium nitrate, potassium phosphate and potassium-ammonium phosphate have been produced. These latter have certain advantages in that they carry only ions that have value for nutritive purposes.

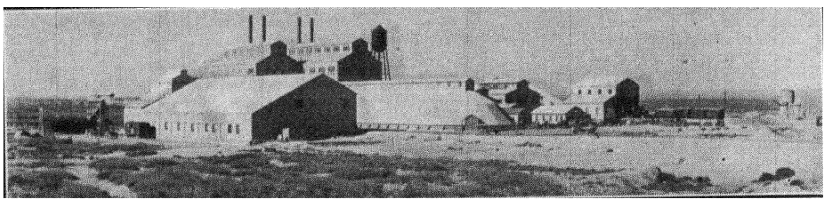
THE AMERICAN POTASH INDUSTRY

For several years previous to the outbreak of the World War, the United States had been importing annually from Germany approximately one million tons of potash salts containing more than a quarter-million tons of actual potash (K_2O). Most of this went into the fertilizer trade. With the beginning of war, importations ceased and potash salts became very high in price. An attempt was made to develop an American potash industry. By 1918, 55,000 tons of potash were being produced in this country. Some of this was derived from kelp; some of it came from salt brines of Searles Lake, California. The remainder had its origin as a by-product of the cement, iron, beet sugar, alcohol, tobacco, hardwood and wool industries. With the cessation of hostilities, Germany had lost part of her potash deposits to France. Competitive production and sale of potash salts soon resulted in prices so low as to hinder any further development of the American industry.

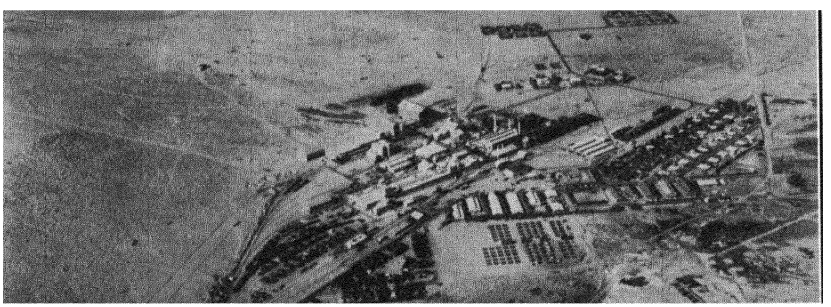
However, the potash development at Searles Lake, California, continued by reason of the fact that the potash salts are produced as a co-product with borax and other sodium salts. Later the potash deposits near Carlsbad, New Mexico, were developed with the result that large amounts of American potash came on the market. The output during 1935 amounted to 357,954 tons of potassium salts, equivalent to 192,793 short tons

of actual potash. The total potash consumption in the United States for that year was 420,000 tons.

Large deposits of potash salts are known to be located near Barcelona, Spain. Russia is believed to have considerable deposits of potash in the region of the Caspian Sea. Recently



(A) United States Potash Company Plant at Carlsbad, New Mexico.



(B) American Potash and Chemical Corporation Plant at Searles Lake, California.

FIG. 39.—These plants produce about half of the potash consumed in the U. S. A.

an English company has been formed with the purpose of taking potash from the Dead Sea. Undoubtedly other deposits of potash salts will subsequently be found and may ultimately be worked.

It may be well also to note that there are such enormous deposits of potash-bearing rocks from which this material could be extracted if required that all other sources become relatively insignificant. Of these rocks may be mentioned the feldspars, potash shales, alunite and leucite. There are also large quantities of easily accessible deposits of greensand in New Jersey, Delaware, Maryland and Virginia. The last is of especial significance

because of the ease with which its potash can be extracted. In fact plants for the production of potash from this source are now in operation in a small way, this being possible by reason of the value of the other products that are also secured in the process of extracting the potash.

AVAILABILITY OF POTASH FERTILIZERS

The test of availability of potash fertilizers is solubility in water. This being the case, it is evident that there is no problem of availability in the sense in which this term is used with nitrogen and phosphoric acid fertilizers. It has been shown that different effects are produced from the use of chlorides, sulfates, carbonates, phosphates and nitrates of potassium, but these differences may be credited to the anions rather than to the potassium itself.

On solution of the potash salt in the soil water an exchange is effected between the potassium and one or more ions of the soil complex. With normal applications of potash salts, no marked increase in the content of potassium in the soil water is to be expected. However, the rate of renewal of potassium in the soil solution, as the latter is robbed of this element by the root hairs, may have been considerably increased.

THE CHOICE IN RELATION TO SOIL FACTORS

It is evident that the choice in relation to any soil factor which might influence the effect of potash salts is dependent entirely upon the associated anion and upon foreign salts with which the potash carrier may be contaminated. The presence in excess or the deficiency of any of these ions in the soil would, therefore, be the determining factor in the choice in so far as the soil is concerned.

Normally the problem reduces itself to a choice between the chloride or sulfate of potash or between these and one of the salt mixtures, such as kainit and manure salts, which contain various percentages of the chlorides and sulfates of sodium, magnesium and calcium.

For use on soils that are deficient in magnesium, calcium or sulfur, three essential nutrient elements, one might well choose the salt which supplied one or another of these elements, assum-

ing that sufficient quantities of that element were not supplied by the carrier of nitrogen or phosphoric acid which had been used or that, in the case of calcium and magnesium, the deficiencies of the soil could not better be cared for by the use of limestone or one of its burned products.

It has also been shown that common salt, a constituent of crude potash salts, is in itself useful under some conditions. As to whether its effects are direct or indirect is difficult to say. An increased salt concentration in the soil may be of some importance itself, irrespective of the nature of this salt, assuming that it has no toxic effects. Sodium is also known to have certain indirect effects such as effecting a partial substitution for potassium in plants; displacing potassium in the soil complex; altering the reaction of the soil solution in the direction of alkalinity; and effecting changes in its physical characteristics, tending toward deflocculation. One might, therefore, choose kainit or some other crude potash salt, rather than the refined chloride or sulfate, to effect certain desired changes in the chemical or physical characteristics of the soil, since the commercial value of the contaminating salts is very low as compared to that of the chloride and sulfate of potash. On chalk soils kainit is usually preferred to the purified salts.

THE CHOICE IN RELATION TO CLIMATIC FACTORS

In regions of limited rainfall, the lasting qualities of soils, as to their potash, is very much improved since losses by leaching are very much reduced or may be practically nil. It is to be expected, under such conditions, that potash fertilizers will be of much less value than they are in regions of abundant rainfall and serious leaching. Certainly in the event of their need because of some peculiar type of potash-deficient rock from which the soil had orginated, one would choose the most concentrated forms and probably such as carry some necessary ion rather than chlorine or sulfate. Thus potassium phosphate or ammonium-potassium phosphate would be preferred under such circumstances.

In regions of heavy rainfall, considerable value might be secured from the contaminating salts contained in kainit and

other crude potash salts, since the leaching effects are such as to rob the soil of all of its soluble constituents. The use of cheap mixed salts in quantity as a means of keeping the soil complex more nearly saturated with cations other than hydrogen should have a sparing effect on soil potassium, preventing excessive loss by leaching and reducing the quantity necessary to be applied for optimum effects.

Potash salts are especially effective in unfavorable growing seasons. As to whether any particular salt is more beneficial than the others under such conditions is not known. Except as chlorine has an unfavorable effect on the quality of a crop, such as is sometimes noted in the case of tobacco, or as there may be a deficiency of sulfur, the use of the chloride rather than the sulfate is likely to produce better results in unfavorable seasons. Plants receiving chlorides tend to take on a more healthy color than do those receiving sulfates.

THE CHOICE IN RELATION TO CROP REQUIREMENTS

In general it may be said that better yields of most crops are secured by the use of the muriate than by the sulfate of potash. This statement applies best to regions of fairly heavy rainfall that are somewhat far removed from the seashore. It may be due in part to the fact that fertilizers normally carry considerable amounts of the sulfate ion, either as calcium or ammonium sulfate; that the sulfur content of rainfall is fairly high in regions where there is considerable industrial development; and that chlorides are, in general, deficient in soils in interior regions where the rainfall is such as to provide considerable runoff and underground drainage.

There are three crops concerning which there has been considerable discussion as to the use of chloride of potash. These are tobacco, potatoes and sugar beets. The evidence of injury to quality is best in the case of tobacco. These crops, because of their high acre value, are usually very liberally treated with fertilizer. It is to be expected that injury from excessive amounts of chlorine might develop under such conditions except as provision is made to supply part of the potash in some other form.

Under such conditions, it seems at least certain that the crude potash salts should not be used. In proportion as the quantity of potash that is added is increased, a substitution of the sulfate, nitrate or phosphate for the chloride of potash is likely to produce better quality of product and perhaps higher yields as well.

A committee of agronomists and tobacco specialists considering this matter in 1927 adopted a report from which the following statement is taken.

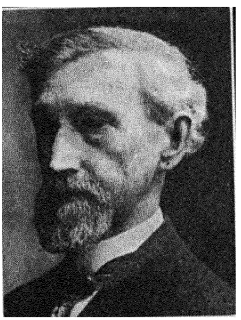
"High grade muriate of potash frequently produces tobacco of equal or better yield and market value than that produced by sulfate of potash. Experience has shown that an excessive amount of chlorine in fertilizers used on tobacco injures its growth, producing a thick, brittle leaf and also has an unfavorable effect upon its burning quality. It is recommended, therefore, that fertilizers be compounded from the above-named sources of potash (sulfate of potash-magnesia, high grade muriate of potash and high grade sulfate of potash) in such proportions that the fertilizer mixture shall contain not more than 2 per cent of chlorine."

SELECTED REFERENCES

1. Conner, S. D. and Abbott, J. B. Unproductive black soils. Indiana Agr. Exp. Sta. Bul. 157, 1912.
2. Coons, A. T. Domestic potash in 1926. American Fertilizer, Vol. 68, No. 3, p. 26, 1928.
3. Garner, W. W. and Associates. Fertilizers for tobacco. American Fertilizer, Vol. 67, No. 13, p. 36, 1927.
4. Hopkins, C. G. Soil Fertility and Permanent Agriculture, Ginn and Co., p. 107. 1910.
5. Lyon, T. L. and Bizzell, J. A. Lysimeter experiments. Cornell Agr. Exp. Sta. Memoir 41, 1921.
6. Russell, E. J. Soil Conditions and Plant Growth, 5th edition, Longmans, Green and Co., pp. 85–88, 415, 1927.
7. Turrentine, J. W. Potash, a Review, Estimate and Forecast, John Wiley & Sons, 188 pp., 1926.

CHAPTER XIV

MIXED FERTILIZERS



Chas. E. Thorne.

As previously indicated, the mixed-fertilizer industry has enjoyed its greatest development in America. Farmers of European countries have long purchased and applied fertilizer materials as such or have mixed them on the farm before application was made. In this country, early in the history of the use of fertilizers, a new industry was established which had for its function the gathering together of fertilizer materials from all over the earth, and of compounding these for the production of formulas and analyses suited to the needs of the several crops when grown under the wide variety of soil, climatic and economic conditions that obtain.

A serious objection to the use of mixed fertilizer was early found in the fact that it was possible for the producer to make use of low-grade materials carrying their constituents in very unavailable forms and to sell such mixtures in competition with those of high quality without fear of discovery on the part of the farmer. This possibility was soon recognized by farmers with the result that steps were taken to set up some type of official control of fertilizers.

FERTILIZER CONTROL

Almost every state in the Union now has a control law regulating the production and sale of fertilizers. Control officials collect samples of the fertilizers that are being offered for sale and subject them to analysis, both as to the quality and quantity of the nutrient materials that are contained in them.

As a result of some years of study of this problem, certain approved methods of fertilizer inspection and analysis have been developed and adopted by the Association of Official Agricultural Chemists, composed of representatives from each of the several states. In the case of nitrogen, determinations are made of the quantities each of nitrate, ammonia and organic nitrogen. The organic carrier is further subjected to tests of its quality by the use of the alkaline or neutral permanganate solutions which give a fairly satisfactory clue as to the availability of its nitrogen. With the phosphates the test, in the case of bone, is for total phosphoric acid; for basic slag, that soluble in one-per-cent-citric-acid solution; and for superphosphates, that soluble in water and in a neutral solution of ammonium citrate. For potash salts, the test of availability is solubility in water. A supplemental test for chlorine content is also usually made.

DIFFICULTIES IN FERTILIZER CONTROL

The chief difficulty in fertilizer control is experienced in determining the quality of the organic nitrogen which mixtures may contain. After many years of study of this problem, the standard tests, indicated above, have been adopted by control chemists. But no test so far designed makes it certain to the farmer that a product which passes the inspection does not carry a certain proportion of its nitrogen in worthless form. Ordinary garbage tankage, low-grade waste products of the packing and other industries, muck and peat still find their way in considerable amounts into mixed fertilizers and are "passed" on to the farmer at the same price per pound of nitrogen as is secured for high-grade materials.

This problem has become more complicated by reason of the production of very highly concentrated organic-nitrogen compounds, such as urea and cyanamid, from atmospheric nitrogen. By mixing small quantities of these very high-percentage and high-quality products with larger amounts of low-grade organics a fertilizer formula can be produced which will pass the inspection of the control chemist. In the change from low- to high-analysis fertilizers, abundant opportunity is provided for this type of fraud.

Another serious difficulty with fertilizer control lies in the fact that farmers are often very poorly prepared to understand the significance of various phases of the report that is published for their protection. Furthermore, many farmers never see these reports and do not appear to know they are available. This introduces the question of how far the state can go in protecting farmers, or any other class of people, against their own ignorance. The fertilizer bags are required by law to be properly labeled as to what they contain. The control bulletin gives a report on the analyses of samples of the fertilizer from several of these bags. The report is mailed to all those who request it. Nevertheless, some very low grade material finds its way from the factory to the farm at the same price per pound of nitrogen as is paid for that of highest quality.

WET-MIXED FERTILIZERS

Between the time that fertilizer mixtures are compounded in the factory and the date of their actual application to the field, these mixtures are subjected to a variety of conditions that tend to make them lose the drilling quality which they originally possessed. For example, they may have been subjected to considerable pressure when piled up in sacks in the factory or in the freight-car; to high temperatures under conditions of high humidity during portions of the summer months; and to moist conditions in rainy weather and when improperly stored on the farm. It is necessary to take these and other like contingencies into consideration at the time of mixing, if the farmer is to be able to effect an even distribution of the fertilizer over the field.

It is for this reason that organic materials are so highly valued by the fertilizer mixer. A few hundred pounds per ton, of tankage, tobacco stems, peat or similar materials, aid very materially in the production of a mixture that will pass through very bad conditions as to weather and handling without loss of drillability. In order to meet the requirements of control chemists and to overcome the sales arguments of competitors, who are quite likely to watch the reports in the control bulletins concerning the products of competing companies, fertilizer manufacturers

find it desirable to subject low-grade organics, when used both as conditioners and as sources of nitrogen, to acidulation as a means of making their nitrogen more available.

Such treatment, known as "wet-mixing," is much the same as that used in the production of superphosphate from phosphate rock. In fact, there are certain advantages in mixing the organic materials and the ground phosphate rock together before acidulation takes place. This and similar products are usually designated as "base-goods." Under this term may also be included the more recently developed product, resulting from spraying the fresh superphosphate with aqua ammonia as a means of neutralizing any excess of sulfuric acid and of producing an ammoniated phosphate, suitable for use as such or for mixing with potash and other salts in the production of a complete fertilizer.

USE OF FERTILIZER MATERIALS

In the newer portions of the United States, superphosphate or some other carrier of phosphorus is the only fertilizer that is used. Orchardists are accustomed to buying large amounts of some carrier of nitrogen, such as sulfate of ammonia, nitrate of soda or calcium cyanamid, for scattering about under their fruit trees. Similarly, top dressings of nitrogen fertilizer materials are made to vegetables, small fruits, meadows, pastures, wheat, cotton, sugar beets, tobacco and other crops.

It happens further that certain materials cannot be mixed with others without loss of nitrogen, a reduction in the availability of the phosphoric acid, or the production of an undrillable product. For example, basic slag should not be mixed with sulfate of ammonia; only limited amounts of pulverized calcium cyanamid should be used in mixtures containing superphosphate; and nitrate of lime is not suitable for use in mixed fertilizers. These materials are, therefore, largely used alone. If mixed with other materials, this is done immediately before application to the field. A certain amount of experience has thus been gained by farmers in the use of fertilizer materials as such. It would seem that it would be an easy matter to develop a home-mixing program if this was desired.

HOME-MIXING OF FERTILIZERS

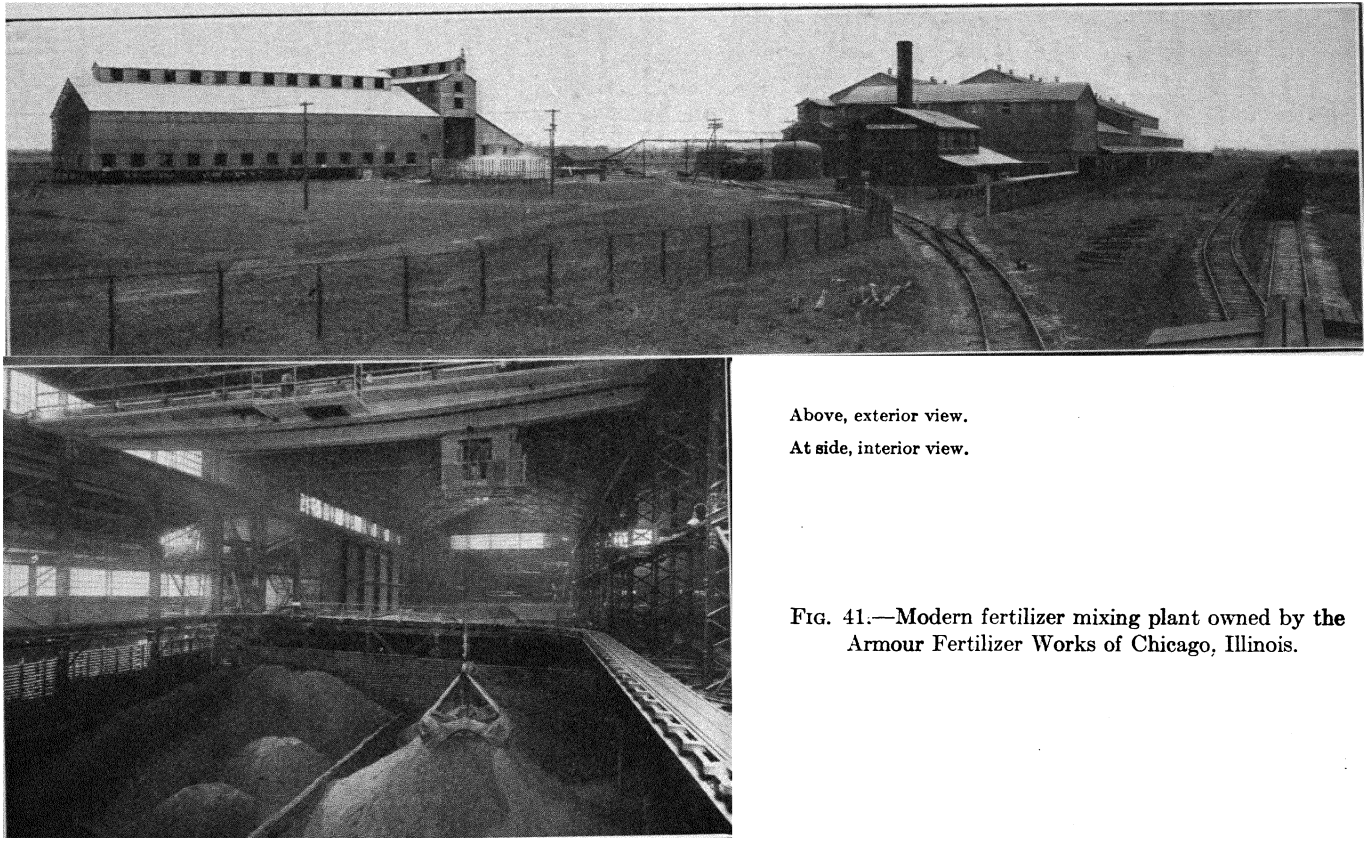
From time to time farmers have tried the home-mixing of fertilizer and have demonstrated that it can be done satisfactorily. This practice has its advantages, since it tends to educate the user as to the quality and value of each of the several materials that may be purchased for mixing purposes. If a large quantity of fertilizer is used, the saving effected may be considerable. This saving is, however, not that of the cost of mixing fertilizers, since this can be done more economically in the factory than on the farm. What the farmer saves by home-mixing is largely the cost of having fertilizers sold to him. This cost includes advertising, direct sales effort, service of various types and the cost of an overhead organization.

Nevertheless, home-mixing has never become popular in the United States. Farmers find, after a few experiences, that they have great difficulty in producing mixtures of uniform drilling quality. There is usually enough work to be done on the farm without taking on any additional tasks that can be done better elsewhere. To be relieved of the problem of buying materials and mixing them is often worth more than the difference in the costs of the materials and the same amounts of nutrients in mixed fertilizers. By taking advantage of discounts for cash and by ordering in carload lots, coöperatively if desired, the extra cost of the mixed fertilizers can be reduced to the point where home-mixing is no longer attractive.

It is evident that the fertilizer-mixing industry serves a very useful purpose in collecting materials from all over the world; treating these materials as required for increasing the availability of their essential constituents; putting them together in suitable mixtures that can be delivered to the field in good drilling condition; and encouraging the farmer to use sufficient amounts of well-balanced fertilizers such as are required for satisfactory yields of his crops.

NEUTRAL FERTILIZER MIXTURES

The continued use of certain fertilizer materials or mixtures of materials will result in the development of an injurious acidity in the soil. The remedy for this is lime. Generally it has been



Above, exterior view.

At side, interior view.

FIG. 41.—Modern fertilizer mixing plant owned by the Armour Fertilizer Works of Chicago, Illinois.

the practice to apply lime separately. However, there are many areas of acid soils in which little or no lime is being used. The standard crops that are being grown are those which are not particularly sensitive to acid-soil conditions. Considering the problem as a whole it seemed desirable that most fertilizer mixtures be made to carry enough alkaline material to produce a neutral rather than an acid effect on the soil. Exceptions to this occur in the soils already too alkaline in reaction for the crops to be grown. In any event, the buyer should be informed by the seller's guarantee as to the actual reaction of the fertilizer.

By the use of Pierre's method, previously described, it is entirely feasible for control chemists to determine the acidity or basicity of the fertilizer material or mixture. Many of them are so doing and reporting their results. This has forced the industry to include alkaline materials of which dolomitic limestone is the one in most common use. The dolomitic stone is usually chosen by reason of its low reactivity. Neutral fertilizer mixtures are now being made by the inclusion of the necessary amounts of this material.

GRANULAR FERTILIZER MATERIALS AND MIXTURES

There are a number of reasons why it is desirable to produce fertilizers in granular form. Of primary importance is the fact that granular fertilizers are much more uniformly drillable. They have much less tendency to stick together. In the superphosphate or other soluble carriers of phosphoric acid there is another advantage in that the granules expose less surface to the surrounding soil, thereby reducing the amount of fixation of phosphoric acid by the soil.

In the fertilizer mixtures, the producer may either make a mixture of granular materials or he may granulate the mixture as such. It remains to be determined as to which of these procedures will be followed by the mixed-fertilizer industry.

Other than for phosphoric acid, the importance of granulation lies largely in the greater ease of handling the product and the more even distribution which can be effected. Row applications tend to overcome the advantage of granulation of phosphates in so far as fixation is concerned.

FERTILIZER ANALYSES

Early experiments indicated that mixtures of carriers of nitrogen, phosphoric acid, and potash would meet all the ordinary fertilizer requirements of crops. Fertilizer producers, therefore, have confined their attention largely to compounding mixtures which are valued entirely on the basis of their percentage content of these three constituents.

Originally there was some confusion because nitrogen was sometimes calculated as such and at other times as ammonia. In some states the figure for the nitrogen percentage was placed first; in others the figure for phosphoric acid occupied this position.

In 1928, the National Fertilizer Association, after many years of discussion of this matter, finally adopted resolutions designed to standardize fertilizer terms for the entire United States. By these resolutions a 4–8–4 analysis is made to mean one which contains such amounts of total nitrogen, available phosphorus, and water-soluble potassium as would be equivalent to 4 per cent of nitrogen (N), 8 per cent of phosphoric acid (P_2O_5), and 4 per cent of potash (K_2O).

HIGHER ANALYSES

Originally fertilizer analyses were mostly of the 1–8–2 and 2–8–2 variety. Since most farmers were not inclined to use very many dollars' worth of fertilizer, it was necessary to have a fairly dilute mixture in order to have enough pounds of it to cover an acre. Accordingly, fertilizer mixtures were diluted with sand and other inert materials to increase bulk and reduce concentration.

As time went on, the fertilizer industry found it desirable to give consideration to means by which more pounds of actual nutrients could be delivered to the farm for a given amount of money. With such materials at hand as sulfate of ammonia, superphosphate and muriate of potash there was no reason why the concentration should not be increased. This meant considerable savings in freight and handling charges per unit of nutrients.

In some states the issue was forced by legislation requiring

14 or 16 units of "plant food" per ton of fertilizer. In other states recommendations by experiment-station workers were confined to analyses containing 20 per cent or more of nitrogen, phosphoric acid, and potash. Analyses such as 4–8–8, 5–8–7, 6–8–6, 4–12–4 and 0–10–10 came into prominence.

Meanwhile still more concentrated fertilizer materials, such as ammonium phosphate, ammoniated superphosphate, double- and treble-superphosphates and urea, became available for use. As a result considerable attention was given to the production of "double strength" analyses containing as much as 40 per cent of nitrogen, phosphoric acid and potash.

THE CALCIUM SULFATE PROBLEM

In a study of the comparative merits of single- and double-strength mixtures it soon became apparent that consideration had to be given not only to nitrogen, phosphoric acid and potash but to the other elements normally contained as impurities in ordinary fertilizer mixtures. Of these, two elements—calcium and sulfur—seemed of greatest importance. These two elements are normally contained in ordinary superphosphate in the form of calcium sulfate. The substitution of ammonium phosphate or treble-superphosphate for ordinary superphosphate results in the almost complete elimination of calcium sulfate in the mixture.

A crop like cotton requires only about 60 per cent as much sulfuric acid (SO_3) as phosphoric acid (P_2O_5). Except for the legumes and crucifers, this ratio holds fairly well for most crops. When one takes into consideration the sulfuric acid content of the rainfall and the relative solubilities of sulfates and phosphates in the soil solution, it seems logical to conclude that the total quantity of sulfuric acid required in a fertilizer mixture is not more than one-fourth of the phosphoric acid contained therein. A 4–8–4 fertilizer mixture made from sulfate of ammonia, superphosphate and muriate of potash contains more than 20 per cent sulfuric acid instead of the 2 per cent theoretically required.

Investigation revealed that the inclusion of calcium sulfate was especially necessary on acid sandy and gravelly soils having little or no buffer capacity. The amount required seems to be relatively small, as little as 25 pounds per acre being adequate.

If, in addition to including calcium sulfate, the mixture was made neutral in its effect on the soil by the addition of finely pulverized dolomitic limestone, the double-strength mixtures were found to be at least the equal of the single-strength mixtures.

FERTILIZER RATIOS

In a regional conference held in Chicago, January 5 and 6, 1928, attention was given to the problem of reducing the number of fertilizer analyses. In view of the possibility of producing fertilizers of very high concentration as compared to those being offered for sale, it seemed desirable to consider the whole matter in terms of fertilizer ratios. Having selected a series of ratios of the fertilizer nutrients, the concentration might then be whatever the fertilizer companies found it to their advantage to produce. Thus the 3–9–3, 4–12–4, 5–15–5, . . . 10–30–10 analyses all have their essential constituents present in the 1–3–1 ratio. A minimum analysis could then be adopted for each ratio. Setting this at 3–9–3 for the 1–3–1 ratio, the 2–6–2, although it has the 1–3–1 ratio of its nutrients, would then be eliminated. Fractional percentages could also be eliminated by agreement in order to prevent the offering of such an analysis as a $4\frac{1}{2}$–$13\frac{1}{2}$–$4\frac{1}{2}$.

Mathematicians have long been familiar with the fact that when three variables are involved, all possible ratios of these three are enclosed within the sides of an equilateral triangle the apex points of which each represent one of these variables when taken alone at 100 per cent. Use had been made of this principle by Oswald Schreiner in solution culture work, with the three fertilizer nutrients, reported in 1909. It had also been employed by him in laying out field experiments with fertilizers on potatoes and other crops. Arranging the ratios by the triangle plan, whether in solution studies, small pots or field plots, permits determining by inspection those which produce optimum effects. These observations can later be checked by actual weights.

THE FERTILIZER TRIANGLE

An equilateral triangle of any desired size is drawn. A line is then drawn from each apex to bisect the opposite side of the triangle. These three lines are each divided into the same

number of equal segments, these divisions being marked by points. This number may, for convenience, be set at 10. Nine lines are then drawn parallel to each side of the triangle through these points. The intersecting points of these three series of 10 lines are so located that each point occupies the same position with reference to its neighbors as does every other point.

The base of the triangle is taken as zero nitrogen, that of the right side zero potash and that of the left side zero phosphoric acid. Allowing the value on each succeeding line to increase by one over that of its predecessor, it will be found that each

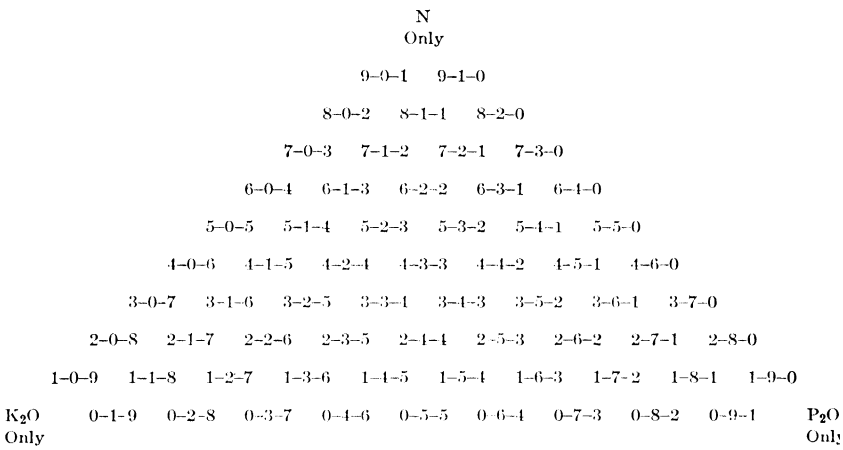


FIG. 42.—The fertilizer triangle by means of which fertilizer ratios can be selected in such a manner as to cover the field of need equally well at all points.

point of intersection of three lines has three values which total ten. The individual figures that combine to make the total of ten may be considered as the members of fertilizer ratios. Thus one point represents the ratio 3–2–5; a second, 2–5–3; a third 4–6–0; and a fourth, 0–6–4. Certain of these ratios can be factored but it seems best to leave them as they are, always totaling 10.

It is evident that only a very small percentage of the possible ratios fall on the intersecting points. The method is simply one of selecting ratios that are mathematically spaced with reference to each other in order to prevent having any two of them so closely related to each other as to have no reason for both of them being chosen.

ADVANTAGES OF THE TRIANGLE

One might choose to divide the perpendicular lines into more or less segments and have a greater or smaller number of intersecting points as desired. The advantages of the 10-segment plan lies in the fact that it is really developed on the percentage basis since a 3–2–5 ratio, signifies that 30, 20 and 50 per cent of the total content of nutrients are nitrogen, phosphoric acid and potash, respectively. At the same time the number of ratios permitted seems entirely adequate to meet the needs of agriculture and of the fertilizer-mixing industry.

Any existing analysis may be located on the triangle by interpolation to make the figures in the ratio total 10. Taking a 5–8–7 analysis, for example, this is reduced to total 10 by dividing each figure by 2, making a $2\frac{1}{2}$–4–$3\frac{1}{2}$. The location of this ratio on the triangle can easily be found.

If all of the more than 100 analyses now being offered for sale were placed in their positions on the triangle, it would be evident that many of them are very close to each other in their ratios—much closer than is warranted by our knowledge with respect to differences in the requirements of plants, when grown under the various edaphic, climatic and economic conditions.

In a program looking toward standardization and simplification, it is entirely logical to eliminate all those analyses which have no reason for existence. The triangle scheme permits of this. It serves further as a basis for the selection of new ratios in that part of the field of fertilizer need not adequately covered by the analyses now being sold.

It is evident that certain analyses that are now popular do not possess ratios that fall on intersecting points of the triangle. This need not interfere with the use of this scheme for selecting new ratios or for eliminating those which have no reason for existence. The 5–8–7 is a very popular fertilizer in the potato regions of the East, particularly in Aroostook County, Maine. There is no reason to attempt to set this ratio aside. If as time goes on, it is believed that some other ratio could be used to better advantage, the triangle makes it possible to locate this ratio with respect to others that are being used. It must be agreed, however, that a 5–8–7 could probably be replaced by a

6–8–6, a 6–6–8, a 4–8–8 or a 4–6–10, without producing any measurable difference in yield. All four of these analyses have ratios that are located on intersecting points. Considered from the economic point of view, it is logical to expect that variation in the relative costs of the three fertilizer constituents will take place in time which, if the 5–8–7 is the best selection under present price relationships, will eliminate it from this position when these relationships have changed.

POSSIBLE TRIANGLE RATIOS

A total of 63 ratios are possible, if the triangle is drawn as suggested above and the points of intersection of the lines are the only ratios permitted. These ratios are as shown in the following table:

TABLE XLVI

POSSIBLE FERTILIZER RATIOS BY USE OF TRIANGLE

$N-P_2O_5$	$N-K_2O$	$P_2O_5-K_2O$	$N-P_2O_5-K_2O$			
1–9–0	1–0–9	0–1–9	1–1–8	2–2–6	3–4–3	5–2–3
2–8–0	2–0–8	0–2–8	1–2–7	2–3–5	3–5–2	5–3–2
3–7–0	3–0–7	0–3–7	1–3–6	2–4–4	3–6–1	5–4–1
4–6–0	4–0–6	0–4–6	1–4–5	2–5–3	4–1–5	6–1–3
5–5–0	5–0–5	0–5–5	1–5–4	2–6–2	4–2–4	6–2–2
6–4–0	6–0–4	0–6–4	1–6–3	2–7–1	4–3–3	6–3–1
7–3–0	7–0–3	0–7–3	1–7–2	3–1–6	4–4–2	7–1–2
8–2–0	8–0–2	0–8–2	1–8–1	3–2–5	4–5–1	7–2–1
9–1–0	9–0–1	0–9–1	2–1–7	3–3–4	5–1–4	8–1–1

PROGRESS IN ADOPTION OF TRIANGLE RATIO

In two regional conferences that have been held, viz.: at Chicago, and at Boston, the triangle method of selecting fertilizer ratios has been adopted. Minimum analyses for these ratios have also been decided upon. None of these analyses so far selected have contained less than 20 per cent of nitrogen, phosphoric acid and potash, taken collectively. Thus the minimum analysis for the 2–6–2 ratio is the 4–12–4. If the fertilizer producer desires, there is nothing to prevent his raising this analysis to a 5–15–5 or higher as long as the ratio remains constant.

TABLE XLVII

FERTILIZER RATIOS CONFORMING TO TRIANGLE PRINCIPLE

Middle West *		New England	
2-6-2	5-3-2	2-6-2	4-3-3
1-7-2	1-3-6	1-7-2	2-3-5
1-5-4	1-6-3	1-5-4	4-2-4
2-5-3	0-7-3	2-5-3	
2-4-4	0-5-5	2-4-4	
3-4-3	0-2-8	3-4-3	

* Later four other ratios, 5-3-2, 1-9-0, 2-8-0 and 0-6-4, were added to this list.

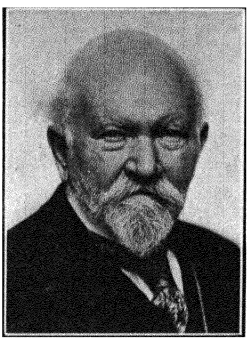
It remains to be seen whether or not this principle of selection of fertilizer ratios will be given general recognition in other parts of the United States. Many interests are involved, some of which will not easily be reconciled to the use of the principle. It is hoped, however, that it will be given unprejudiced consideration since it has much to offer in the way of a simplified program of standardization with consequent reduction in confusion and in the cost of fertilizers to the consumer.

SELECTED REFERENCES

1. Association of Official Agricultural Chemists, Official and Tentative Methods of Analysis. 417 pp., 1920.
2. Bear, F. E. The fertilizer triangle. Jour. Ind. and Eng. Chem. Vol. 21, 1929.
3. Brown, B. E., and Owen, F. V. Concentrated fertilizers for potatoes in Aroostock County. Maine Agr. Exp. Sta. Bul. 350, 1929.
4. Mehring, A. L., and Associates. Effect of particle size on the properties and efficiency of fertilizers. U. S. D. A. Tech. Bul. 485, 1935.
5. Pierre, W. H. A method of determining the acid- or base-forming property of fertilizers and the production of nonacid-forming fertilizers. Amer. Fert. Vol. 79, No. 9, p. 1, 1933.
6. Willis, L. G. The value of gypsum as a supplement to concentrated fertilizer. North Carolina Agr. Exp. Sta. Bul. 299, 1934.

CHAPTER XV

PRINCIPLES OF FERTILIZER PRACTICE



Paul Wagner.

It will be recalled that Liebig was of the opinion [1] that the ammonia of the atmosphere is sufficient to meet the nitrogen needs of plants and that this element is not a necessary constituent in fertilizers. The analysis of the ash of the plant was believed to be a sufficient guide to its mineral requirements. The fertilizers which Liebig used in his experimental tests were made up for each crop according to the analysis of the ash of that crop.

PLANT ANALYSES AS A GUIDE

Lawes and Gilbert not only disagreed with Liebig as to the sufficiency of the ammonia of the atmosphere for the nitrogen requirements of plants, but also as to the value of the analysis of their ashes in determining what type of mineral manure should be applied. Their experiments had demonstrated, however, that the various plant groups require different manurial treatments. Legumes were found not to respond to nitrogenous fertilizers as well as did the non-legumes. They had shown that the turnip crop, although low in phosphorus, was especially benefited by the use of superphosphate. Wheat yields were not increased by phosphate and potash fertilizers as much as by those supplying nitrogen. Their method of attack was simply that of trial. Various combinations of fertilizers were applied to the several crops and the yields of these crops were noted. The special requirements of each crop were thus determined.

[1] See page 9.

SOIL ANALYSIS AS A GUIDE

Lawes and Gilbert had given consideration to the analysis of the soil as a guide to fertilizer practice but had reached the conclusion that little of value in the selection of fertilizers was to be gained by that method of procedure.

Likewise Ville in writing on this subject in 1876, said:

"It might be believed that chemical analysis which has done so much in our time and which has attained such a high degree both of delicacy and of certainty, ought to enable us to test with certainty the richness of the soil and by so doing serve as a guide in the choice of manures best suited to its nature. It is not so, however, and I defy the cleverest chemist to tell beforehand what will be the yield of any land submitted to him and what manure ought to be used."

THE PRINCIPLE OF DOMINANTS

Ville showed that while plants contain ten different mineral elements, only nitrogen, phosphorus, potassium and the alkaline compounds of calcium are normally required in the fertilizers employed to increase their yields. Field trials had indicated to him that the various plants have different fertilizer requirements and that for each type of plant there is one constituent that is quite likely to be dominant. He, therefore, suggested the following principle.

"There is for every description of plant one substance which predominates over the three others which may for that reason be called its dominant constituent.

"Supposing we grow four crops in the following order—beets, wheat, clover and oats—we must concentrate the nitrogenous matter on the beets and wheat and the mineral matter on the clover which itself leaves sufficient nitrogenous matter in the soil for the wants of the oat crop."

According to Ville, the dominant constituent for cereals, grass, beets, and tobacco is nitrogen; that for legumes, vines, and potatoes is potassium; and that for swedes, turnips, sugarcane, sorghum, maize and Jerusalem artichokes is phosphorus. Flax is an exception in that it has no dominant. Accepting the principle of dominants, Ville pointed out the advantages of chemical manures

over those of animal origin. The latter cannot be changed as to composition to fit the specific needs of each crop.

FERTILIZER FORMULAS

Ville classified his fertilizer formulas into five groups, viz.: normal, homologous, stimulating, incomplete, and those with special functions. The normal manure contained nitrogen, phosphoric acid, potash, and lime as calcium sulfate. The homologous formulas differed from the normal by containing their phosphoric acid in the dibasic or reverted form and their potash as the chloride rather than as the nitrate or sulfate. The chief reason for this change was that of economy in cost for those plants the response of which to both formulas was practically the same.

The stimulating formula was one in which the dominant constituent was increased to the point at which maximum effects were produced. Such a formula might well be used if the weather conditions were especially favorable for growth. Incomplete formulas were those designed to meet the requirements of such crops as clover or for use on soils that were notably rich in one or another of the fertilizer elements. Special formulas were those in which quality as well as quantity of crop was considered whereby it sometimes became necessary to change the form of carrier employed. The substitution of the sulfate for the muriate of potash in the case of sugar beets would be a good example.

It is evident that Ville was influenced in his choice of formulas by the chemical composition of the plant; the quality as well as the quantity of produce; whether or not the plant was a legume; the condition of the soil; the nature of the weather; and by considerations of economy. But his method of procedure in determining what fertilizer formula to use was that of "falling back on the evidence of the plants themselves."

VILLE'S FERTILIZER RECOMMENDATIONS

Selecting a rotation of potatoes or beets, wheat, clover, wheat, Ville suggested the use of the following formulas.

TABLE XLVIII

VILLE'S SUGGESTED FERTILIZER FORMULAS

Material	Potatoes	Beets	Wheat	Clover	Wheat
Superphosphate	350	360	0	350	0
Potassium nitrate	265	175	0	0	0
Calcium sulfate	265	265	0	350	0
Ammonium sulfate	0	0	265	0	265
Muriate of potash	0	0	0	175	0
Sodium nitrate	0	265	0	0	0
Total pounds per acre	1080	1055	265	875	265
Approximate analysis	3–5–10	6–5–7	21–0–0	0–6–10	21–0–0

RUSSELL'S PRINCIPLES OF FERTILIZER PRACTICE

Lawes' field tests of fertilizers, begun in 1843 after Liebig had given his famous address before the British Association for the Advancement of Science, are still being continued. These tests consist in the use of chloride and sulfate of ammonia, nitrate of soda and various organic carriers of nitrogen, either alone or in combination with "minerals," on wheat and barley grown continuously and in rotation with root crops and legumes. No specific fertilizer formulas of Lawes and Gilbert are recorded, but some definite suggestions have been made by those subsequently in charge of the experimental work on this farm.

Thus Russell, the present director of Rothamsted, comments as follows on the question of the use of fertilizers:

"No definite scheme for manuring crops can be given for universal use because of the varying factors of soil, climate, market prices, and available capital, but certain guiding principles hold fairly generally and can be adapted to each locality.

"1. All of the fertilizing constituents, nitrogen, phosphoric acid, potash, lime and organic matter, must be applied to the land in the course of the rotation.

"2. The nitrogen being liable to loss should be distributed, a certain amount being added each year or each alternate year.

"3. The four other constituents are less liable to loss and may be applied to any crop that is convenient.

"4. Phosphates should predominate in the mixture for swedes, turnips, rape, etc., while potash should form a larger proportion of the dressing given to mangolds, sugar beets and potatoes.

"5. The cereal crop may need a little nitrogen in spring applied as nitrate of soda, nitrate of lime, sulfate of ammonia, etc.

"6. In late districts or in wet seasons, superphosphate may be desirable to hasten ripening of cereals.

"7. The grazing land should periodically receive basic slag alone or basic slag and kainit.

"8. Land laid in for hay should, in addition, receive an annual dressing of a nitrogeneous manure such as sulfate of ammonia, nitrate of soda, etc. Every four years or so, however, dung should be applied instead.

"At one time it was supposed that the ideal mixture was that represented by the composition of the ash as showing what the plant had actually taken from the soil. This is now known to be incorrect. The need for manures is determined not by the composition of the plant but by its habit of growth and the condition under which it lives."

ROTHAMSTED FERTILIZER RECOMMENDATIONS

The work of Lawes and Gilbert with fertilizers was summarized by Hall, in 1905, in "The Book of the Rothamsted Experiments." This was later revised by Russell. The following suggestions on fertilizer practice may be considered as a summary of the experiences at Rothamsted with these materials.

TABLE XLIX

HALL'S FERTILIZER RECOMMENDATIONS FROM ROTHAMSTED DATA *

	Wheat	Barley	Swedes	Potatoes	Sugar Beets	Hay
Fish guano †	0	0	224	560	0	0
Nitrate of soda	280‡	0	0	0	0	168
Sulfate of ammonia	0	168	112	112	112	0
Superphosphate	224	336	448	336	336	224
Sulfate of potash	0	0	0	168	112	0
Kainit	0§	0§	336	0	0	336
Total pounds per acre.	504	504	896	1176	560	728

* Recommendations in pounds per acre on crops grown in suitable rotations and when no manure is applied to the immediate crop.

† Or other suitable organic carriers of nitrogen.

‡ Three-fifths as top-dressing in February.

§ Kainit used on sandy and gravelly soils and in dry seasons.

FERTILIZER INVESTIGATIONS IN GERMANY

In Germany, more than in any other European country, experiment stations have been established for determining the best procedures in the growth of crops and livestock. Following the example of Lawes and Gilbert and stimulated by the influence of Liebig, many plot and pot tests, particularly the latter, have been carried out at a number of different places. Many of these were designed to determine the relative effectiveness of the various fertilizer salts and the ratios in which the several nutrients should be applied for best results. The discovery of the enormous deposits of potash salts at Stassfurt and, more recently, the rapid development in the production of air-nitrogen fertilizers have led to heavy expenditures in the exploitation of these materials and have furthered the research program.

Of the many students of this problem in Germany, Paul Wagner has long been one of the best known. His experiments for the most part have been of a practical nature designed to determine what the farmer should do as to his fertilizer program. In the eighth edition of his book on "The Use of Artificial Manures," published in 1926, Wagner suggests the following guiding principles in the use of fertilizers.

WAGNER'S PRINCIPLES OF FERTILIZER PRACTICE

1. The chemical composition of the estimated crop increase that should be produced is not a safe guide to the amounts of the several constituents necessary to be applied to secure that increase.

2. Chemical analysis of the soil for total constituents is of value in determining the fertilizer need only when the soil is very low or very high in its content of any given nutrient.

3. Tests for available constituents, of which those for measuring the easily soluble phosphorus by the use of weak solvents and the Neubauer method of testing the soil by growing rye seedlings on it and analyzing these seedlings for their content of nutrients, are useful guides to fertilizer practice.

4. The final answer comes only from the field tests on the particular soil, under the climatic conditions that obtain and with the crops in rotation that are to be grown. Consideration must be given to supplementary soil practices such as the growing of legumes and the use of manure. Economic factors are also involved.

5. On soils that are deficient in them, the crop recovers the first year only from 10 to 20 per cent of the added phosphoric acid and from 40 to 60 per cent of the added potash. The applications of phosphoric acid suggested by the analysis of the crop increases that it may be profitable to produce must, therefore,

be multiplied by from 5 to 10 and those of potash by from 2 to 3, if such increases in yield are to be produced.

6. Nitrogen fertilizers are applied more nearly in proportion to the need of the crop and the soil than are potash and phosphoric acid fertilizers. Any excess of nitrogen is likely to be lost by leaching since the soil has no capacity to fix this element once it has been changed to the nitrate form.

7. Rape, cabbages, potatoes, beets and clovers respond especially well to the use of phosphate fertilizers.

8. Beets, cabbages, potatoes and barley require large amounts of potash.

9. Cereals, beets, potatoes, rape, tobacco, maize, hemp, flax, hops, pastures and meadows are especially noted as requiring large amounts of nitrogen. Legumes generally are not benefited to a very marked degree by nitrogen fertilizers except at the beginning stages of growth and on nitrogen-poor soils.

WAGNER'S FERTILIZER RECOMMENDATIONS

As an example of Wagner's fertilizer recommendations the following program is outlined for a complete rotation of stock-beets, wheat, oats, clover, wheat, oats, when grown on a clay loam soil containing 0.16 per cent of total phosphoric acid and 2.25 per cent of potash.

TABLE L

WAGNER'S SUGGESTED FERTILIZER PROGRAM *

Material	Beets	Wheat	Oats	Clover	Wheat	Oats
Stall manure, tons.....	30	0	0	0	0	0
Liquid manure, † gallons.	3000	1500	0	0	0	0
Sodium nitrate, ‡ pounds.	800	250	250	0	500	500
Basic slag, § pounds.....	1000	300	1000	0	400	400
Potash salts, || pounds...	0	0	500	0	250	250
Total fertilizer per acre	1800	550	1500	0	1150	1150

* In recalculating the German figures to American equivalents, "kilograms per hectar" is assumed to be the same as "pounds per acre."

† Urine mixed with leachings from solid manure.

‡ Applied one-half at seeding time and one-half as top-dressing at thinning time, for beets; at the middle of March for the first wheat crop; at seeding time for the first crop of oats; one-half at the middle of March and one-half in April for the second crop of wheat; one-half at seeding time and one-half the last of April or the first of May for the second crop of oats.

§ Contains 16 per cent of phosphoric acid soluble in 1 per cent citric acid solution.

|| Raw potash salts containing 40 per cent of potash. The phosphate and potash are applied some time in advance of seeding.

THE STOCKBRIDGE PRINCIPLE OF FERTILIZER PRACTICE

One of the first men in America to outline a system for selecting fertilizers was Levi Stockbridge, Professor of Agriculture at

the Massachusetts Agricultural College from 1871 to 1882. The principle of his system is indicated in the following statement.

"To produce 100 bushels of potatoes per acre, without any manure, and their natural proportion of tops *more* than the natural yield of the land (and in like proportions for other quantities) apply 21 pounds of nitrogen, 34 pounds of potash and 11 pounds of phosphoric acid."

The principle involved is that of determining the composition of the fertilizer from the analysis of the plant. If the climatic and soil conditions are such as to make it feasible to produce 100 bushels more of potatoes per acre, then such amounts of fertilizer nutrients should be applied as are contained in that many bushels of potatoes and the tops associated with them.

It will be noted that this principle is somewhat the same as that suggested by Wagner except that the latter, having at hand the analysis of the crop, multiplies the phosphoric acid content of the estimated crop increase by from 5 to 10 and the potash content by from 2 to 3, since only the percentages of these nutrients indicated by these multiples are recovered in the crop increase of the first season after application of the fertilizer.

What were known as "Stockbridge's Formulas" were quite popular in Massachusetts and neighboring states for a time as a result of their having been advertised by one of the fertilizer companies located in that region. The following table gives the suggested composition of fertilizers for a number of different crops.

TABLE LI

STOCKBRIDGE'S FERTILIZER FORMULAS

Crop	Increase	Nitrogen *	Phosphoric Acid *	Potash *
Corn	50 bushels	64	31	77
Wheat	25 bushels	41	20	24
Oats	25 bushels	23	12	20
Hay	20 hundredweights	36	12	31
Tobacco	15 hundredweights	119	16	172
Rye	20 bushels	25	16	24
Cabbages	20 hundredweights	28	4	12
Beets	100 bushels	11	6	25

* Pounds of these in estimated crop increases and, therefore, believed necessary to be applied to secure these increases above the natural productivity of the soil.

and simply indicates the chemical composition of the crop increase, grain and stalk, etc., expected to be produced.

PENNSYLVANIA FIELD TESTS

The first elaborate scheme of plot tests of fertilizers in America was put into operation by W. H. Jordan at State College, Pennsylvania, in 1881. Four tiers, of 36 eight-acre plots each, were used for the growing of corn, oats, wheat and clover in rotation. The soil on this farm is classed as Hagerstown clay loam.

The reasoning by which Jordan arrived at the conclusion to apply nitrogen, phosphoric acid and potash at the rates of 24, 48 and 100 pounds, respectively, per acre as the standard treatment every second year is not given. Undoubtedly consideration was given both to the nitrogen-accumulating power of the clover and to the chemical composition of the crops to be grown. His uncertainty as to how much dependence could be placed on the clover to supply nitrogen for the crops in the rotation is shown in the fact that three different rates of applying nitrogen were included in the scheme, viz., at 24, 48, and 72 pounds per acre every second year on the corn and wheat crop.

GARDNER'S FERTILIZER RECOMMENDATIONS

After 40 years of study of the effects of fertilizers on these plots, Gardner and his associates offer the following suggestions as to fertilizer practice on the residual soils of Pennsylvania.

TABLE LII

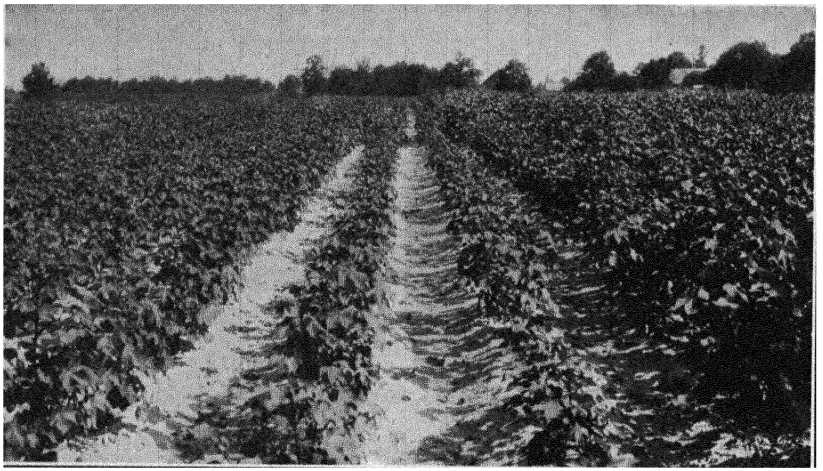
PENNSYLVANIA FERTILIZER RECOMMENDATIONS *

	Corn	Oats	Wheat	Clover	Timothy
Manure	6 tons	0	0	0	
Superphosphate	250 pounds	200 pounds†	325 pounds	0	150
Nitrate of soda	0	0	75 pounds	0	100
Muriate of potash	0	0	100 pounds	0	50
Total fertilizer per acre‡	250	200	500	0	300
Approximate analysis	0–16–0	0–16–0	3–10–10	0	5–8–8

* For the residual soils of Pennsylvania.

† Only on depleted soils.

‡ Enough lime should be used to insure good clover.



200 lbs. 3–10–3
No sulfate of ammonia

No fertilizer

200 lbs. 3–10–3
and sulfate of ammonia

(A) On cotton crop. Sulfate of ammonia applied at rate of 100 pounds per acre as side-dressing.



Phosphate and potash
No nitrogen

Phosphate and potash
and nitrate of soda.

(B) On corn crop. Phosphate and potash fertilizer at planting. Nitrate of soda applied when corn was 18 inches high.

FIG. 44.—Effect of top dressing with nitrogen fertilizers.

OHIO FIELD TESTS

When the investigational work on fertilizers at Wooster was begun in 1893, Chas. E. Thorne had available for study the experimental work at Rothamsted and at State College, Pennsylvania, together with a considerable amount of similar data which had been accumulated in tests that had been conducted on the University Farm at Columbus before the Ohio Station had been moved to Wooster. The nitrogen-fixing power of the nodule bacteria had been discovered and reported by Hellriegel and Wilfarth.

It is of considerable interest to note the reasoning by which Thorne arrived at his applications of fertilizer nutrients in the experimental tests. First it was necessary to decide upon the crops to be grown. It was found that the most important crops as to acreage were corn, oats, wheat, clover and timothy. Accordingly a rotation of these five crops was decided on to be arranged in the order named.

The average yields of these crops for Ohio for the 10-year period, 1880–89, as shown by assessors' statistics were 33.4 bushels of corn, 28.8 of oats, 13.7 of wheat, 19.6 hundredweight of clover and 23.8 of timothy. It was estimated from station statistics that there were 110 pounds of straw for every bushel of wheat, 70 pounds of straw for each bushel of oats and 60 pounds of fodder and 14 pounds of cobs for each bushel of corn.

To return the nutrients removed by these five average crops it was estimated that 18 tons of ordinary barnyard manure or 1157 pounds of nitrate of soda, 354 pounds of dissolved boneblack and 272 pounds of muriate of potash would be required. The ratio of the nutrient constituents in these amounts of fertilizer was 1 of phosphoric acid to 3.1 of nitrogen and 2.4 of potash.

On the assumption that the clover secured from the air all of the nitrogen which it carried off in its hay, the ratio would be 1 of phosphoric acid to 2.4 of nitrogen. If the clover secured the nitrogen of its roots from the air and left this behind in the soil, the ratio of phosphoric acid to nitrogen removed would be approximately 1 to 1.7. It was decided that this was the narrowest ratio at which these should be used in the scheme of fertilizer tests.

"For the sake of comparisons with other work it seems desirable to use nitrate of soda and superphosphates on wheat at the ratio of 160 pounds each per acre—one pound per square rod—as a standard. One hundred and sixty pounds of nitrate of soda would furnish enough nitrogen for thirteen bushels of wheat, if all were utilized, while 160 pounds of 16 per cent superphosphate would furnish as much more phosphoric acid as would be found in an increase of 4000 pounds of clover and timothy hay.

"This increase of wheat and hay would correspond to an increase of about 27 bushels of corn and 28 bushels of oats, at the ratio of crop yields in Wayne County, and to provide for this increase of oats and corn would require nearly 160 pounds more superphosphate and more than twice as much that quantity of nitrate of soda.

"In other words: a total application per acre of 320 pounds of superphosphate and 480 pounds of nitrate of soda in the course of such a rotation as that under consideration, would furnish as much phosphoric acid and nearly as much nitrogen as are contained in an increase of 13 bushels of wheat, 27 bushels of corn and 28 bushels of oats, with their straw and stalks, and phosphoric acid to spare sufficient for 4000 pounds of mixed clover and timothy hay, leaving the nitrogen in the hay crops unprovided for. The amount of potash required to balance the 320 pounds of superphosphate would be supplied in 260 pounds of the muriate."

Other series of tests at Wooster and at a number of other points in the state were subsequently inaugurated with the result that Ohio has one of the most extensive outlays of fertilizer plots of any state in the Union. A considerable variety of soils and crops are involved.

THORNE'S CONCLUSIONS ON FERTILIZER PRACTICE

Commenting on the the results of fertilizer tests at the end of 30 years of field investigation, Thorne presented the following conclusions in 1924.

"1. Crops grown in rotation give larger yields with a much lower expenditure for manure or fertilizers.

"2. The systematic addition of lime-bearing materials is indispensable to the attainment of the most profitable crop yields on soils overlying sandstone and non-calcareous shales and for old soils overlying limestone.

"3. Every soil and every crop under test has responded profitably to the use of phosphoric acid (except in the bed of ancient Lake Maumee) the most effective carrier of which is acid phosphate.

"4. The results from the use of potash salts have been irregular. A profitable increase of crop has resulted from their use on Miami soils.

"5. For Ohio conditions the nitrogen supply for cereal crops should be

secured through their systematic rotation with legumes and the careful saving of manure. Of the carriers of nitrogen employed, nitrate of soda has been the most effective.

"6. A lower estimate must be put on the composition of manure, if the effect of its nitrogen, phosphoric acid and potash is to equal that of the same elements in such carriers as nitrate of soda, acid phosphate and muriate of potash."

ILLINOIS FIELD TESTS

Antedating the fertilizer plots at State College, Pennsylvania, by two years, the Morrow plots at Urbana, Illinois, begun under the direction of Professor George E. Morrow in 1879, are the oldest soil experimental plots in America. The series originally contained seven plots on part of which use was made of fertilizers and manure. The development of the University of Illinois finally necessitated the use of some of the land for building purposes. Three of the original plots still remain on one of which corn is grown continuously, on the second corn and oats alternate and on the third a rotation of corn, oats, and clover is followed.

Subsequent field investigations, following in general the standard plan adopted by the University of Illinois, were begun in 1902, on another tract of land of similar characteristics on what is known as the North Farm and, in 1903, on the South Farm. Because of the large area of prairie land adapted to the growth of corn, oats, and clover which has physical and chemical characteristics somewhat similar to that of the soil at Urbana, Illinois, and further because of the active interest of Cyril G. Hopkins in the fertility problem, particularly as it applied to the use of limestone and phosphate rock on corn belt soils, it seems desirable to include a short discussion of the Illinois field tests with fertilizers.

The general scheme of these tests at Urbana and also at the several substation farms is shown in the following statement by Hopkins and his associates.

"Standard Rotation.—On a large number of the fields a standard four-year rotation is practiced. This is the famous Norfolk rotation of Europe in which a cultivated crop is followed by a spring grain, the spring grain by a legume, and the legume by a winter grain. Such a rotation permits the seeding of a cover crop of legumes in the winter grain, which may be plowed down the next spring before the cultivated crop is planted. The rotation as commonly practiced on the Illinois fields is corn, oats, clover, and wheat, a cover crop (usually

sweet clover) being seeded on the young wheat in the spring and plowed under in the fall or the next spring before the corn is planted. In the event of clover failure, soybeans are substituted. The seeding of a legume cover crop in the wheat is commonly made, however, only on the plots representing the grain system of farming, these and other crop residues serving as a substitute for farm manure.

"Standard Soil Treatment.—In connection with the standard four-year rotation mentioned above, a rather uniform system of soil treatment is practiced on most of the fields. Both the livestock and the grain systems of farming, as already described, are followed. In each system on each series an untreated plot is left, which serves as a check for the systems of soil treatment applied. There are plots receiving only the application of manure and residues, as described; some which receive in addition pulverized limestone; some which receive as a further application finely ground raw rock phosphate; and as a still further application, in the grain system, one plot receives potash salts; besides which there is a third, or extra, untreated plot. The manner of applying and the amounts of the materials applied are as follows:

"Manure.—The amount that can be made in farm practice from the produce of the land is usually applied for the corn crop.

"Residues.—The straw, stalks, chaff, and cover crops that are produced upon the land are returned at the most convenient time during the rotation.

"Limestone.—Four tons per acre is put on as an initial application, and thereafter two tons every four years, preferably after the land is plowed for wheat, the limestone being mixed with the surface soil in preparing the seed bed.

"Phosphate.—One ton is applied on the clover sod preceding the plowing of the land for wheat. Disking in order to mix the phosphate with the soil before plowing is desirable. (After four or five rotations, the amount applied will be reduced to 800 pounds per acre every four years.)

"Potash Salts.—The standard application is 800 pounds of kainit once during the rotation, usually with phosphate before the wheat."

HOPKINS' PRINCIPLES OF FERTILIZER PRACTICE

Outlining Hopkins' point of view as it is expressed in the 1910 edition of his book on "Soil Fertility and Permanent Agriculture," one has the following principles of fertilizer practice.

1. Of the plant food elements found in the soil, nitrogen and phosphorus are in one class; potassium, calcium and magnesium are far removed in a second class; iron is distinctly in a third class; and the position of sulfur is somewhat uncertain.

2. For practically all normal soils there are only three constituents that must be applied to permanently maintain the productive power of the soil. These are limestone, phosphorus and organic matter.

3. The chief reason for applying limestone is to neutralize soil acidity. Ground limestone is preferable to all other forms of lime.

4. Phosphorus is the key to permanent agriculture. Finely ground phosphate rock is normally to be preferred as the source of phosphorus.

5. Organic matter can be secured in sufficient amounts by adopting suitable rotations, including a legume, and plowing under the crop residues.

6. The nitrogen requirements of crops can be met by nitrogen from the air. The growing of legumes is essential. One of the best of these for improving poor soils is sweet clover.

RHODE ISLAND FIELD TESTS

Preliminary field tests at Kingston, Rhode Island, had convinced Homer J. Wheeler, the chemist in charge, that lime is a most important constituent that is required to be applied to the soils of that region. In investigating this problem, Wheeler had found that plants differ very materially in their need for lime some of them being benefited very much by its use and others being actually injured by applications of lime. Writing on this subject in 1893, Wheeler made the following very significant comment:

"It appears, therefore, that our agricultural plants are even more varied in their needs and adaptations than is generally supposed, and that instead of drawing general conclusions as to the value of fertilizers on soils from the result with one plant, we must employ in our experiments every plant to which we desire our results to apply."

The importance of the work of the Rhode Island Station under the early direction of Wheeler and later of Hartwell, in connection with the long continued use of lime in relation to the growth of a great variety of plants, is such that it merits very careful study.

HARTWELL'S PRINCIPLES OF FERTILIZER PRACTICE

What may be considered somewhat of a summary of the experiences with fertilizers at the Rhode Island Agricultural Experiment Station was given by Burt L. Hartwell in his presidential address before the Society for the Promotion of Agricultural Science in 1921. In this address the following principles governing the use of fertilizers were suggested.

1. The contributions which the soil makes are tremendously influenced by the weather. Until this can be predicted satisfactorily, the chemist cannot be expected to tell what will be needed to supplement its immediate effects.

2. The deficiency of soils and of animal manure in phosphoric acid and the fact that this material is relatively cheap has led to the use of 4 or 5 times as much of it as the crop removed has used. This has been profitable.

3. Fertilizers must be looked upon more and more as substitutes rather than supplements to manure. It seems probable that to replace the highly ammoniacal and potassic animal manure which has long been popular, the nitrogen and potash of fertilizers will have to be materially increased.

4. The current practice of applying phosphoric acid in excess of what the crop removes tends to modify the soil so that there is no longer any more of a deficiency of this nutrient than of the others.

5. The idea of the farmer that a given crop should receive a fertilizer especially adapted to it should be given more serious consideration. The farmers' powers of observation may well be respected.

6. Where the cost of fertilizers is low or is a minor consideration, as in the case of the market gardener, there need be no hesitation to use more fertilizer than is actually needed. Under such conditions there is less necessity for carefully adapting the fertilizer to the crop.

7. Growth response to fertilizer constituents differs widely. Farm crops must be grouped in accordance with their response to each of the fertilizer nutrients before they can be fed intelligently.

8. Fertilizer constituents may have effects other than those attributable to their nutritive values, and it is desirable to know these influences on the growth of crops.

9. It is to be expected that, aside from the influence of the soil, the results obtained in one locality may differ from those secured in another by reason of differences in the climate or weather.

10. Frequently there are economic reasons for growing a crop for which soil or climatic conditions are somewhat unfavorable and changes in the fertilizer recommendations must be made accordingly.

11. Crops may be divided into those which are "good foragers" and "poor foragers" and large and small "yielders" when fed.

12. Millet, parsnip, buckwheat, lettuce, barley, squash and onion respond especially well to nitrogen fertilizers.

13. Cabbage, beet, cucumber, onion, parsnip, squash and turnip respond especially well to phosphate fertilizers.

14. Squash, sunflower, beet, onion, parsnip, lettuce and cucumber respond especially well to potash fertilizers.

VOORHEES' PRINCIPLES OF FERTILIZER PRACTICE

In 1898 Edward B. Voorhees made a highly important contribution to fertilizer practice in the publication of a book entitled "Fertilizers." For many years he had been Professor of Agriculture at Rutgers College and had later become Director of the

New Jersey Agricultural Experiment Station. In the preface to this book is the following statement.

"There is no question as to the desirability of the use of commercial fertilizers on most farms, though the methods now generally practiced are such as to indicate the very great need of a better understanding of what the functions of a fertilizer are, of the terms used to express their composition and value, of the kinds that shall be used, and the time and method of application for the different crops under the varying conditions that exist."

Under the heading "Conditions which Modify the Usefulness of Fertilizers," Voorhees suggested the following principles of fertilizer practice which are of considerable interest.

1. The first consideration is the soil itself and its influence. As a rule potash is a very essential constituent for sandy soils. Clay soils, on the other hand, if well supplied with lime and phosphoric acid, may not require the addition of potash.

2. It is important that the physical as well as chemical imperfections of soils be considered. Premature ripening or burning of crops and losses of fertilizer by leaching are features to be considered in sandy soils. Clay soils are often cold soils. Later in the season crops often suffer from drought on such soils. The best effects from fertilizers are secured from soils that are in good "condition."

3. The previous treatment and cropping of soils must be considered. Wheat farming tends to exhaust the nitrogen and phosphoric acid of soils. Timothy hay tends to remove relatively more potash than phosphoric acid. Land devoted continuously to tobacco or cotton is likely to be deficient in the elements that are removed in largest amounts by these crops. Grain, hay and potatoes in rotation tend to keep the nutrient supply in the soil balanced or exhausted to about the same extent. Clover may be classed as a soil renovating crop in so far as nitrogen is concerned.

4. The character of the crop is an important matter. Some crops require large amounts of fertilizer nutrients and have a low commercial value. Others are low in nutrients and have a high commercial value. In the former group are corn, oats, wheat and hay. In the latter group are fruits and vegetables. A ton of asparagus, worth perhaps $200, contains only 6 pounds of nitrogen, 2 of phosphoric acid and 6 of potash. A good wheat crop has a much smaller acre-value but contains, in the grain alone, perhaps 6 times as many pounds of nutrients.

5. The fertilizer requirements of crops are very different, depending upon whether they are grown extensively or intensively. In the latter case fertilizers can be used much more nearly up to the limit of their efficiency.

6. Plants vary in their capacities to forage for the nutrients in the soil. The cereals, grasses, clovers, root crops, market garden crops and fruits must be considered in separate groups in this connection.

7. The cereal crops have roots which branch below the surface and distribute themselves in all directions. They have a very considerable foraging power for mineral nutrients. Other than for corn, applications of readily available nitrogen, early in the spring, are likely to be beneficial.

8. The grasses, like the cereals, have branching fibrous root systems that enable them to forage in the soil. They differ in being perennial, in requiring more nitrogen and less phosphoric acid, because they are used for hay or forage rather than seed production.

9. The clovers have tap roots, penetrate the soil to considerable depth and are good foragers. They secure their nitrogen largely from the air. Their fertilizer requirements are chiefly phosphoric acid and potash together with some form of lime.

10. The root crops do not possess fibrous root systems. They are not good foragers but must be liberally fed with nutrients in readily available forms. Phosphates are especially important for turnips. Beets and carrots require more nitrogen. Potatoes and sweet potatoes, on soils to which they are adapted, respond especially well to potash.

11. Market garden crops must be kept growing rapidly. This requires abundant supplies of very available nutrients, particularly nitrogen. Their market value is such that little consideration need be given to the cost of the nutrients.

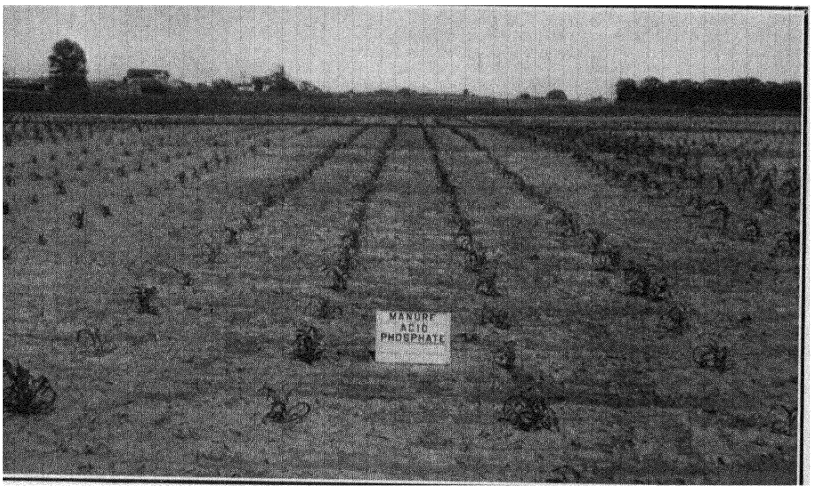
12. The fruit trees present a special problem since it is first required that conditions be favorable for the growth of a tree, after which consideration must then be given to the fruit. For the latter nitrogen is an especially important constituent.

In commenting on the various systems of using fertilizers, Voorhees mentions Ville's principle of dominants; Wagner's system of keeping the soil well supplied with mineral nutrients, which are not lost by leaching and are relatively cheap, and then applying nitrogen as required; Stockbridge's system of depending upon the analysis of the plant; a fourth system of applying most of the fertilizer for the rotation to the "money crop"; and the usual rather "hit or miss" system. He points out that there are certain good features in all of them excepting the last. In his own suggestions, however, he is guided by "the results of experimental inquiry" and the "results of the observation and experience of practical men."

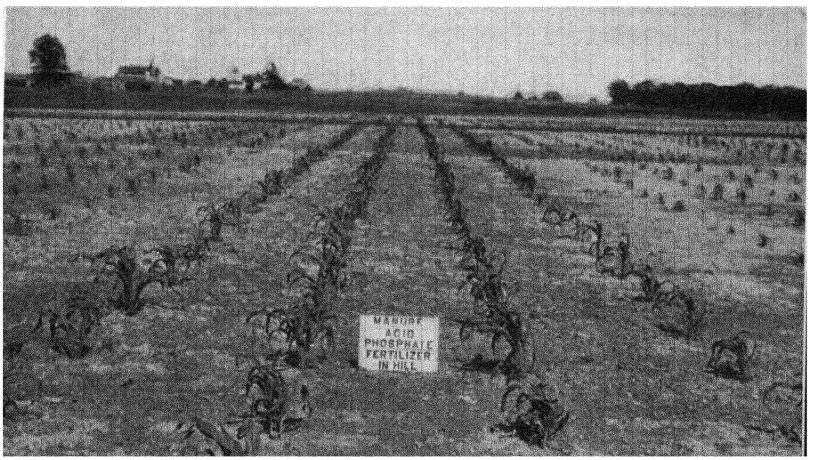
SOUTHERN EXPERIMENT STATION TESTS

It is not feasible to attempt a survey of the field work on fertilizers at all of the various agricultural experiment stations in

America. It is, however, of considerable interest to point out a few of the somewhat outstanding characteristics of the fertilizer practice in certain areas not mentioned in the preceding discussion.



(A) Superphosphate applied broadcast.



(B) Superphosphate applied in the hill.

FIG. 45.—Except as there is injury to the seed, the nearer the fertilizer is placed to the seed, the more rapid the early growth of the plants.

Tests of the value of fertilizers for tobacco and cotton were begun at an early date in certain of the Southern States. The

reason for their especial interest in this problem lay in the fact that no large amount of manure is available for use on the soil on farms on which a high percentage of the land is devoted to one or another of these crops. Furthermore, the acre-value of these crops is relatively high as compared to that of the staple farm crops that have been given so much consideration in most of the experimental tests in cooler climates.

Undoubtedly tests with fertilizers on tobacco were conducted by many planters in Virginia early in the history of their use. The fact that the fertilizer industry originated at Baltimore and spread rapidly toward the South at an early date indicates this. However, no systematic plot work on tobacco seems to have been undertaken by the experiment station until 1908. Twenty years previous to this, fertilizer tests on cotton were started at Darlington, South Carolina, and a few years later at Calhoun, Louisiana.

The use of complete fertilizers in relatively large amounts is now characteristic of the agriculture of the Southern States. Liberal quantities of nitrogen are also used for top-dressing purposes. This is to be expected, not only because of the high acre-value of the staple crops, but because the system of farming employed fails to take advantage of the renovating power of legume crops; animal manure produced from feeding legumes and grain is scarce; the rainfall is relatively heavy and the temperature is high, both of which tend to hasten the depletion of the soil when it is placed under cultivation.

FUNCHESS' RECOMMENDATIONS FOR CORN AND COTTON

A summary of the experiences with fertilizers on corn and cotton at the Alabama Agricultural Experiment Station is given by M. J. Funchess and his associates in a recent circular from that station. The conclusions drawn are applicable over a large part of the Cotton Belt other than that of the Mississippi Delta; the black lands of Texas; and the drier cotton-growing areas of Texas and Oklahoma. Funchess' suggestions are as follows:

" For corn, on average soils of Alabama which have been well fertilized with phosphate and potash for other crops, 36 pounds of nitrogen per acre (225 pounds of nitrate of soda or its equivalent) is the only fertilizer needed. It is possible

that additions of phosphate may be necessary for the most profitable production on bottom land if corn is grown every year.

" The best fertilizer for cotton on average Alabama soils is one that supplies at least 36 pounds of nitrogen, 48 pounds of phosphoric acid, and 24 pounds of potash per acre. To supply these amounts of plant food, it would require 225 pounds of nitrate of soda, or its equivalent; 300 pounds of superphosphate; and 48 pounds of muriate of potash; or a 6–8–4 fertilizer applied at the rate of 600 pounds per acre. This amount of plant food may also be supplied by an application of 600 pounds of a 4–8–4 fertilizer and a side application of 75 pounds of nitrate of soda, or its equivalent, per acre."

In the Delta, only nitrogen seems to be required. In the black lands of Texas and in the cotton-growing areas of Oklahoma and West Texas, a need for nitrogen and phosphoric acid is indicated.

TOBACCO RESEARCH COMMITTEE RECOMMENDATIONS

Tobacco specialists of Virginia, the Carolinas and Georgia, together with those of the U. S. Department of Agriculture, have agreed on the following recommendations with respect to this crop.

A. For bright flue-cured tobacco:
   1. For heavy soils, 800 pounds of 3–10–6; for light soils 1,000 pounds of 3–8–6.
   2. One-third of the nitrogen of plant or animal organics; one-third nitrate; and one-third other inorganic sources.
   3. Phosphoric acid from any source, provided enough available calcium is included to be equivalent to 6 per cent CaO.
   4. Potash from any source provided chlorine content does not exceed 2 per cent of mixture.
   5. Magnesia recommended to extent of 2 per cent MgO of which half is water-soluble.
   6. Sulfur should be reduced in quantity as compared to most ordinary fertilizer mixtures.

B. For dark tobacco (sun-cured and shipping):
   1. For all soils, 1,000 pounds of 3–10–6; or manure plus 600 pounds of 3–10–4.
   2. Other recommendations same as for bright flue-cured tobacco.

WESTERN EXPERIMENT STATION TESTS

In addition to the states mentioned, series of fertilizer tests of more or less extensiveness are being conducted in Kentucky, Tennessee, Indiana, Michigan and Wisconsin; in Arkansas, Missouri, Iowa, Kansas, Nebraska and the Dakotas; Texas, New Mexico, Colorado and Utah; and in Washington, Oregon and California. A considerable amount of investigation of the use of fertilizers on vegetables, apples, citrus fruits and grapes is under way in the last-named states.

In general, the newer the land the less the response to nitrogen and potash. Except as the soil is naturally deficient in some nutrient, such as is the case with potash in sands and mucks, phosphoric acid alone is often the only fertilizer nutrient applied on such soils. The only exception to this is in the phosphate-rich soils of Kentucky and Tennessee or in regions farther west where land is so extensively farmed that no fertilizers are applied. It is of interest at this point to note that it is unnecessary to apply potash in western regions of low rainfall and high rates of evaporation since in such cases there is little or no loss of this nutrient by leaching. It is also important to note that nitrogen fertilizers are especially valuable in cool, moist regions of the North and in regions of high temperature and heavy rainfall of the South, whereas the clovers and azotobacter make their largest contribution to the nitrogen supply in the great central corn and wheat area of the United States.

SELECTED REFERENCES

1. Gardner, F. D., and Associates. Forty years results with fertilizers. Pennsylvania Agr. Exp. Sta. Bul. 175, 1922.
2. Funchess, M. J., and Associates. Grades of fertilizers for corn and cotton. Alabama Agr. Exp. Sta. Cir. 70, 1935.
3. Hall, A. D. The Book of The Rothamsted Experiments. Second Edition revised by E. J. Russell, London, 332 pp., 1917.
4. Hartwell, Burt L. Relative growth response of crops to each fertilizer element and the use of this response in adapting a fertilizer analysis to a crop. Jour. Amer. Soc. Agron. Vol. 13, pp. 353–359, 1921.
5. Haskell, Sidney B. A thirty-year fertilizer test. Massachusetts Agr. Exp. Sta. Bul. 212, 1922.
6. Hopkins, C. G. Soil Fertility and Permanent Agriculture. Ginn and Co. 653 pp., 1910.

7. Russell, E. J. Soils and Manures. Cambridge University Press. 205 pp., 1915.
8. Thorne, C. E., and Associates. The maintenance of soil fertility. Thirty years work with manure and fertilizers. Ohio Agr. Exp. Sta. Bul. 381, 1924.
9. Ville, Georges. Artificial Manures. Translation by Sir William Crookes. New edition revised by Crookes and Percival. 347 pp., 1909.
10. Voorhees, E. B. Fertilizers. Macmillan Co. 335 pp., 1898.
11. Wagner, Paul. Anwendung Künstlicher Düngemittel. Achte Auflage. Berlin, 199 pp., 1926.
12. Williams, C. B., and Associates. Tobacco recommendations for 1937. Comm. Fert. Vol. LIII, No. 4, p. 26, 1936.

CHAPTER XVI

THE SELECTION OF FERTILIZERS



M. J. Funchess

SOME of the principles governing fertilizer practice have been given in the previous chapter. It remains to consider somewhat more specifically the various means of determining soil deficiencies and crop needs, the influence of the climate upon these needs and the extent to which the scheme of soil management in operation and the several economic factors may influence the selection of fertilizers.

DIAGNOSING SOIL DEFICIENCIES

Preliminary to any laboratory tests, it is often possible to foretell certain deficiencies by superficial examination of the soil. A few general principles which are useful in this connection are outlined below.

A. Nitrogen deficiency indicated:
   1. If the soil is sandy and light in color.
   2. If the soil is low in humus.
   3. If the soil is strongly acid.
   4. If the soil contains coarse organic material having a high carbon-nitrogen ratio.

B. Phosphoric acid deficiency indicated:
   1. If the soil is heavy in texture.
   2. If the soil is low in humus.
   3. If the soil is strongly acid.
   4. If the soil is poorly drained.

C. Potash deficiency indicated:
   1. If the soil is sandy.
   2. If the soil is peat or muck.

3. If the soil is low in humus.
4. If the soil is of chalk or limestone origin.

PLANTS AS INDICATORS OF SOIL DEFICIENCIES

The language of plants is not easy to understand but the observant grower learns to diagnose soil deficiencies by noting the color of the leaves and the rate and manner of growth of his plants. A few suggestions are offered in this connection.

A. Nitrogen deficiency indicated:
   1. If the plants grow slowly and their leaves are yellowish.
   2. If leaves of trees are shed prematurely.
   3. If leaves of corn tend to "fire."
   4. If plants produce seed prematurely.

B. Phosphoric acid deficiency indicated:
   1. If plants are stunted and leaves are pale green.
   2. If cereals are slow to mature and to produce grain.
   3. If yields of legumes are low.
   4. If tomato leaves have a purple color.

C. Potash deficiency indicated:
   1. If lower leaves of alfalfa are covered with small white spots.
   2. If cotton leaves become reddish brown and die prematurely.
   3. If potato leaves become puckered and curl under at edges.
   4. If corn leaves fire along margins and green color between the veins fades.

CLIMATIC FACTORS AND FERTILIZER NEEDS

There is abundant evidence to prove that rainfall, sunshine and temperature are important factors to be considered in the choosing of fertilizers. Thus it is apparent that, in regions of limited rainfall and where the soil contains alkali salts, potash fertilizers are not likely to be required. On the other hand, where the rainfall is heavy, losses by leaching make it necessary ultimately to supply all those nutrient elements which are readily removed by the drainage water. The following sug-

gestions are offered in connection with the choice of fertilizers in relation to climatic factors.

A. Nitrogen fertilizers are especially effective:
   1. If the climate or weather is cool and moist.
   2. If the climate is one of high temperatures and heavy rainfall.
   3. If the season is excessively wet.
   4. If there is an abundance of sunshine.

B. Phosphoric acid fertilizers are especially effective:
   1. If the climate or weather is cool and moist.
   2. If the seasonal conditions favor rank vegetative growth.
   3. If the climate is moist in early spring and dry later in season.

C. Potash fertilizers are especially effective:
   1. If the climate or weather is cool and cloudy.
   2. If the climate or weather is warm with plenty of rainfall and high humidity.
   3. If the rainfall-evaporation ratio of the region is high.

THE SYSTEM OF SOIL MANAGEMENT

By knowing something of the previous treatment of the soil and the system of soil management in operation one can often be reasonably sure whether or not a given element is in deficiency. Assuming that satisfactory yields are not being produced, the following suggestions in selecting a fertilizer are offered in this connection.

A. Nitrogen deficiency indicated:
   1. If little or no manure has been applied.
   2. If legumes have not been grown regularly in the rotation.
   3. If the previous crop and the immediate crop are non-legumes.
   4. If the surface soil has been removed by erosion or otherwise.
   5. If the land is kept constantly under cultivation.

B. Phosphoric acid deficiency indicated:
   1. If cereal crops are grown continuously or frequently.

2. If legume crops are grown continuously or frequently.
3. If a livestock system of farming is being followed.

C. Potash deficiency indicated:
1. If little or no manure has been applied.
2. If hay, straw and similar materials are sold off the farm.
3. If legumes are grown and removed from the land.

ECONOMIC FACTORS IN RELATION TO FERTILIZER NEEDS

The more intensive the agriculture the less consideration need be given to the relative costs of the several fertilizer nutrients or to the total cost of the fertilizer, since the outlay for fertilizers is often only a very small part of the total expense involved in growing the crop. Generally, in intensive farming, all three of the ordinary fertilizer elements are applied in considerably larger amounts than are required for optimum yields. In extensive farming more dependence is placed upon the air for nitrogen and upon the soil for potash with the result that the fertilizer employed is usually relatively high in its content of phosphoric acid. In much of the grain farming of the Central West the fertilizers used are either superphosphate alone or those in which the phosphoric-acid content is from two to three times that of either nitrogen or potash.

Various other economic factors and their influence on the selection of fertilizers are indicated in the following outline.

A. Nitrogen fertilizers required in larger amounts:
1. If the farmer changes from extensive to intensive farming.
2. If the value of the land becomes too high to permit of growing the clovers for green-manuring purposes.
3. If motor power is substituted for horse power and less manure is available.
4. If the prices of crops increase to the point where nitrogen can be used with profit more nearly up to the limit of its efficiency.

B. Phosphoric acid fertilizers required in large amounts:
1. If the farmer changes from extensive to intensive livestock farming.

2. If larger yields of legume crops are required for feeding purposes.
3. If higher prices of cereal crops make their more intensive production profitable.

C. Potash fertilizers required in larger amounts:
1. If the farmer changes from extensive to intensive crop farming.
2. If motor power is substituted for horse power and less manure is available.
3. If straw, cornstalks and other crude plant substances find a market for the production of clothing or other manufactured articles.
4. If the sand and muck soils now lying waste are needed for crop-producing purposes and higher prices for farm products make it feasible to farm them.

QUICK CHEMICAL TESTS FOR SOIL DEFICIENCIES

It is now generally recognized that it is possible by examining a sample of soil in the laboratory to determine any excesses or deficiencies of plant nutrients contained in it and from this examination to recommend a fertilizer analysis which can be depended upon to give good results. A great deal of work along this line has been done during the last decade. A number of agricultural experiment stations have established special soil-testing laboratories in order to answer the questions raised by farmers concerning their soils and the fertilizers to be used on them.

TESTS FOR SOIL ACIDITY

Among the earliest tests that were made use of in this connection was one to determine the lime needs of soils. A number of different methods were proposed, among which may be mentioned the lime-requirement method of Veitch, the Comber thiocyanate test, and the Truog hydrogen-sulfide test. All of these were of value but, for the most part, have been replaced by newer methods designed to determine the *p*H of the soil and its content of replaceable bases, of which calcium is in many ways

the most important. Practically all soil tests now include *p*H determinations either by electrometric or colorimetric procedures. Further consideration of this subject will be given in Chapter XVIII.

TESTS FOR AVAILABLE NITROGEN

Nitrogen is present in soils in the form of organic materials. Generally speaking, the darker the color of the soil the higher its content of nitrogen. This nitrogen becomes available for crop use as a result of the activities of soil microörganisms which effect a change from protein forms to ammonia and nitrate. If the soil contains an adequate amount of lime, nitrification proceeds quite rapidly as the temperature increases in the spring, assuming that the moisture supply is adequate.

In the absence of a growing crop, a test for nitrates in the soil is useful as a means of determining the quantity of nitrogen readily available for crop use, when it is subsequently planted. In the presence of a growing crop, both the ammonia and nitrate nitrogen tend to disappear.

The best procedure for determining whether the supply of nitrogen is adequate for the growing crop is to examine the crop itself. The directions given by Thornton and his associates for this test follow:

"Nitrate reagent: Dissolve one gram of diphenylamine in 100 cc. of concentrated sulfuric acid. This solution is very corrosive.

"Testing for nitrates: With large-stemmed plants, split open several stalks or leaf petioles and with smaller plants cut thin discs from stems or petioles and place on a strip of waxed paper or in a glass vial. Add a few drops of the nitrate reagent and note the color produced. A dark blue indicates an abundant or excessive supply of nitrogen; a pale blue or green color, an adequate supply; and no color accompanied by a pale green color of foliage, a deficient supply."

TESTS FOR AVAILABLE PHOSPHORIC ACID

Phosphoric acid is present in soils both in mineral and in organic forms. Most soils are able to supply only such small amounts of available phosphoric acid to the growing crops that the supplemental use of phosphate fertilizers is essential.

Both the soil and the growing plant can be tested to advantage

for phosphoric acid deficiency. The reagents employed for both tests are the same. The directions given by Thornton and his associates for these tests are outlined below:

" Phosphoric acid reagents:

" Reagent No. 1: Dissolve 4 grams of ammonium molybdate in 500 cc. of distilled water and add, slowly and with constant stirring, a mixture of 63 cc. of concentrated hydrochloric acid and 437 cc. of distilled water. As this solution may become unsuited for use after standing for a few months, it is desirable to prepare a solution of five times this concentration and to dilute as needed.

" Reagent No. 2: Dry powdered stannous chloride or stannous oxalate.

" Testing for phosphoric acid in soils: Place 10 cc. of Phosphate Reagent No. 1 in a glass vial, add ½ teaspoon level full of soil (¼ teaspoon for greenhouse and sandy soils), shake vigorously for one minute, filter into another vial, add 2 or 3 cc. of Phosphate Reagent No. 1 and an amount of Phosphate Reagent No. 2 approximately equal in size to a pinhead. Mix and at once observe the color produced. Again add Phosphate Reagent No. 2 to make certain that enough has been used. If the color darkens, use the higher reading.

" A dark blue color indicates an abundant phosphorus supply; a medium blue, an adequate supply; a light blue, a medium supply; a green or bluish-green color, a moderately deficient supply; and no color or a yellow color, a very deficient supply.

" On alkaline soils the test does not give reliable indications of phosphorus needs. Such soils usually give high tests.

" Testing for phosphoric acid in plants: Place 1 teaspoon level full of finely cut stems of leaf petioles in a glass vial, add 10 cc. of Phosphate Reagent No. 1, shake vigorously for 1 minute, add an amount of Phosphate Reagent No. 2 approximately equal in size to a pinhead. Mix and at once observe the color produced. Add another portion of Phosphate Reagent No. 2 to make certain that a sufficient amount has been used. If the color darkens, use the higher reading.

" A dark blue color indicates an abundant phosphorus supply; a medium blue, an adequate supply; a light blue, medium supply; a green or bluish-green, a moderately deficient supply; and a colorless or yellow, a very deficient supply."

TESTS FOR AVAILABLE POTASH

Of the total amount of potash present in the soil, only a relatively small amount is available for use during any one year. The readily available potash in soils is present in replaceable form in the colloidal complex.

Both the soil and the growing plant can be tested to advantage for potash deficiency. The reagents employed for both tests are

the same. The directions given by Thornton and his associates for these tests are outlined below:

" Potash reagents:

" Reagent No. 1: Dissolve 5 grams of sodium cobaltinitrite and 30 grams of sodium nitrite in distilled water, add 5 cc. of glacial acetic acid, make to 100 cc. volume and allow to stand for several days. Add 5 cc. of this solution to a solution of 15 grams of sodium nitrite in 100 cc. of distilled water and adjust to *p*H 5.0 with acetic acid. Sodium cobaltinitrite from different sources has been found to vary widely in cobalt content. The directions given here are based on the use of the " Baker's Analyzed " product. Cobaltinitrite concentration is an important factor in determining the sensitivity of the test.

" Reagent No. 2: Isopropyl alcohol (anhydrous).

" Reagent No. 3: Ethyl alcohol (95 per cent). When ethyl alcohol for use as a reagent is difficult to obtain, a mixture of 60 parts anhydrous methyl alcohol, 40 parts anhydrous isopropyl alcohol and 5 parts of distilled water may be substituted. If this mixture becomes turbid it should be filtered. Completely denatured alcohol is not satisfactory.

" Testing for potash in soils: Place 10 cc. of Potash Reagent No. 1 in a glass vial, add 1 teaspoon level full of air-dried soil ($\frac{1}{2}$ teaspoonful for mucks and greenhouse soils), shake vigorously for 1 minute, filter into another vial until the filtrate amounts to 5 cc., carefully add $2\frac{1}{2}$ cc. of Potash Reagent No. 2 and mix. After it has stood 3 minutes, note the amount of precipitate formed.

" No precipitate, or only a trace, indicates a very deficient potassium supply; a light precipitate, a moderately deficient supply; a medium precipitate, a medium supply; and a dense precipitate, an adequate or abundant supply.

" Testing for potash in plants: Place $\frac{1}{2}$ teaspoon level full of finely cut fresh plant material in a glass vial, add 10 cc. of Potash Reagent No. 1, shake vigorously for 1 minute, carefully add 5 cc. of Potash Reagent No. 3 (with tobacco and sugar beets, omit Potash Reagent No. 3 and use 15 cc. of Potash Reagent No. 1), and mix. After 3 minutes, note the amount of precipitate formed.

" No precipitate or only a trace indicates a very deficient potassium supply; a light precipitate, a moderately deficient supply; a medium precipitate, a medium supply; and a dense precipitate, an adequate or abundant supply.

" Temporary standards corresponding to the above interpretations for either soils or plants may be made by using varying amounts of potassium chloride and making the test as described for plants with the potassium chloride replacing the plant material. Tests corresponding to very deficient, moderately deficient, and adequate or abundant supplies are obtained with the use of 0.2 cc., 0.4 cc., 0.6 cc. and 1.0 cc., respectively, of a solution of 1.0 gram of potassium chloride dissolved in 100 cc. of a 15 per cent sodium nitrite solution."

The methods described and the reagents employed for testing soils and plants with respect to their content of available nitro-

gen, phosphoric acid and potash were chosen as being illustrative. A number of soil and plant chemists are prominently identified with the study of methods of analysis for this purpose and offer somewhat different suggestions with respect to methods of procedure. It is hoped that ultimately a committee of these chemists will be able to agree upon methods which can be adopted as official.

TESTS FOR OTHER CONSTITUENTS OF SOILS

It is recognized that consideration may also have to be given to the amount of available calcium, magnesium, manganese, iron and aluminum in soils that are unproductive. Some soils must be examined as to their content of chlorides, sulfates and carbonates.

The determination of the available quantities of any or all of the cations indicated is founded on the principle of base exchange. This calls for the use of an extracting reagent carrying some cation, other than those in which the soil chemist is interested, for the purpose of replacement.

Morgan suggests a "universal soil-extracting solution" for this purpose. Extracting the soil with this solution is assumed to replace a definite ratio of the total amount of exchangeable cations. The extract thus secured can also be used for the determination of available nitrogen, phosphoric acid and potash and for certain other constituents in the soil. The directions for making this solution follow:

"Add 100 gms. of sodium acetate to 500 cc. of distilled water. After this is dissolved, add 30 cc. of glacial acetic acid and make up to one liter. This solution is approximately 0.5 N. in total titrable acidity and is buffered at 4.8 *p*H."

By the use of the additional reagents specified by Morgan, colorimetric measurements may be made of the quantities of each replaceable cation, in relation to its content in soils of known productivity. The correct interpretations of these tests can be made only by men of considerable experience in soil-testing work. In the hands of such men, they provide a safe guide to fertilizer practice—not necessarily the best practice but one which can be depended upon to give good results.

THE NEUBAUER TEST WITH RYE SEEDLINGS

This method was devised for the purpose of finding a rapid means of determining soil deficiencies on a large scale. It was Neubauer's hope that examinations of soil could be made for every farmer who requested them and in a relatively short time as an aid to him in the choice of fertilizers. The difficulty, as with all of the methods suggested for this purpose, is to find some means of translating laboratory results into practice. The method is as follows:

" One hundred grams of the soil to be tested are placed in a circular glass dish about four inches in diameter and three inches high. With this soil is mixed 50 grams of quartz sand. Over this soil-and-sand mixture is placed 250 grams more of the sand. A small tube is placed in the center of the dish for aeration and watering purposes. One hundred rye seeds, carefully selected and treated with a disinfecting agent, are then placed on top of the soil and covered with a thin layer of sand.

" The small dishes, thus prepared and moistened with water, are weighed and placed in a warm room which receives no direct sunlight. Distilled water is added as required to maintain a constant weight. After 18 days, the seedling plants and their rootlets are removed, washed free of sand, and analyzed for their nutrient content."

The phosphoric acid content of these seedlings has been found to vary from 0 to 25 milligrams while that of potash varies from 5 to 100 milligrams. As a result of some years of study of this

TABLE LIII

NEUBAUER'S LIMITING NUMBERS *

Plant	Phosphoric Acid	Potash
Rye, wheat	5	15
Barley, oats	6	18
Red clover	5	25
Alfalfa	9	35
Potatoes	6	47
Sugar beets	6	42
Meadow grasses	7	38
Mangles	7	65

* Milligrams of P_2O_5 and K_2O in 100 seedlings, at end of 18 days, below which a need of these nutrients in fertilizer form is indicated.

problem Neubauer has placed the minimum content of phosphoric acid and potash of rye seedlings at 5 and 15 milligrams, respectively. If less than these amounts are found, fertilizers supplying these nutrients are required.

Recognizing that plants differ in their foraging power, a series of tests with other plants have been conducted as a result of which "limiting numbers" have been decided upon.

THE MITSCHERLICH POT TEST

The pot-test method of procedure is one which was first extensively employed by Wagner, who found it a very useful



FIG. 47.—The Mitscherlich pots for testing soil deficiencies as the tests are carried on at the Agricultural Experiment Station of the I. G. Farbenindustrie at Limburgerhof, Germany.

means of getting an indication of soil deficiencies under normal conditions as to sunshine and other weather influences. Various modifications of the Wagner method have been devised. The most recent of these is that of Mitscherlich which has found such wide use in Germany that thousands of the pots are now being manufactured and sold, not only to experiment station workers but also to commercial concerns, for testing soils for fertilizer needs.

The pots used are enameled sheet iron, light in weight and with no poisonous effects on plants. The vessels are standardized as to size, having heights and diameters of 20 centimeters each. The bottom has a slit opening for drainage. The drainage water is collected in a pan beneath and returned to the soil at the next period of watering. This pan is so fitted to the pot that no outside water can enter nor can any be lost by evaporation, a projecting rim of the pot meeting this requirement. All pots used in the test are brought to the same weight by the use of small quartz stones. The pots are run in quadruplicate.

The soil to be tested is run through a 1 centimeter sieve and thoroughly mixed. Six kilograms of soil are placed in each pot. Fertilizers are applied in quantities of 6 grams of basic slag, 3 grams of potassium sulfate and 3.5 grams of ammonium nitrate or corresponding amounts of other carriers of the nutrients required. Insoluble fertilizer materials are thoroughly mixed by hand with the soil. Soluble materials are dissolved in water and applied separately.

In the ordinary method of procedure, four pots are given a complete fertilizer and four others are given all but nitrogen. Twelve other pots are prepared by using $\frac{5}{6}$ quart sand and $\frac{1}{6}$ of the soil under test. Four of these receive a complete fertilizer; four lack phosphoric acid, and four lack potash.

Some plants, such as oats, are used for experimental purposes. The water is applied in optimum quantities and kept constant by weighing and adding more water as it may be lost by evaporation and transpiration. The water which drains through is returned to the soil each day. At maturity the crops are harvested and weighed. By this means the need of a soil for a given nutrient is determined.

Both Mitscherlich and Neubauer have suggested rates of application of fertilizers based upon the quantitative determinations secured by their methods of procedure.

SPECIAL REQUIREMENTS OF CROPS

As previously indicated, the several species of plants differ considerably in their soil requirements. Plants are found growing luxuriantly under a wide variety of conditions as to reaction of the soil. Some plants thrive only on acid soils; others grow satisfactorily on soils that are quite alkaline in reaction. Similarly there are differences in their nitrogen, phosphoric acid and potash requirements. Attempts have been made to classify crops on the basis of their relative response to each of the nutrient

elements. A great deal of investigational work remains to be done before such a classification will be dependable for practical purposes. Ville and Hartwell have paved the way for such study.

Perhaps the best method of procedure is to select a basic fertilizer treatment that would be generally suitable for all non-legume crops, if they were being grown under the climatic conditions that obtain over most of the area east of the Mississippi River. Such a fertilizer might well have ratios of nitro-

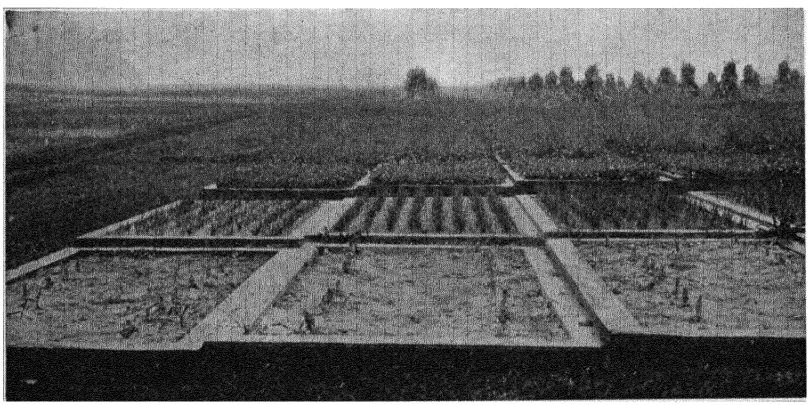


FIG. 48.—Small plot tests as they are conducted at the Cornell Agricultural Experimental Station, Ithaca, N. Y.

gen, phosphoric acid and potash of 3–4–3. One would not go far amiss to apply 400 pounds of a 6–8–6 fertilizer (3–4–3) ratio to any non-legume crop when grown under ordinary soil conditions in that area. A study of the fertilizer recommendations that are made by the agronomists of the various states indicates the general usefulness of such an analysis, in the quantity indicated, to be applied when the crop is planted.

With this as a starting point, one may then proceed to add or subtract constituents or increase or decrease the quantity applied as the soil, the climate, the previous management of the soil, the economic factors or the peculiar needs of the crop as related to all of these factors might demand. Thus the acre rate of application may well be 2000 pounds for potatoes in Maine, or the ratio may be changed to 2–12–6 for row-application to corn in Indiana.

The use of additional nitrogen would normally be desirable:

1. On lawns, pastures, non-legume meadows and summer, grass-hay crops.
2. On small grains; and on corn in the South.
3. On vegetable crops of which the leafy portions are sold.
4. On fruit trees and small fruits.
5. On cotton and sugar cane.
6. On sugar beets, the later their season of maturity the greater the quantity used for top-dressing purposes.
7. On tomatoes, melons, cucumbers, pumpkins and squashes.
8. On rhubarb, asparagus, pineapples and other perennials, including flowers.

The potash percentage might well be increased at the time of application:

1. For potatoes, sweet potatoes, sugar beets, mangels and other root crops.
2. For tobacco.
3. For onions, celery and similar muck and sandy soil crops.
4. For asparagus.
5. For strawberries and other small fruits.
6. For cabbage, cauliflower, Brussels sprouts and similar vegetables.
7. For annual legumes.

The rate of application per acre suggested could well be multiplied by three to five in the case of crops of high-acre value, such as vegetables, fruits and dark tobacco.

SELECTED REFERENCES

1. Hester, J. B. Truck crop investigations. Microchemical soil tests. Virginia Truck Exp. Sta. Bul. 82, 1934.
2. Morgan, M. F. Microchemical soil tests. Connecticut Agr. Exp. Sta. Bul. 333, 1932.
3. Morgan, M. F. The universal soil-testing system. Connecticut Agr. Exp. Sta. Bul. 392, 1937.
4. Spurway, C. H. Soil testing. Michigan Agr. Exp. Sta. Tech. Bul. 132, 1935.
5. Thornton, S. F. Soil and fertilizer studies by means of the Neubauer method. Indiana Agr. Exp. Sta. Bul. 399, 1935.
6. Thornton, S. F., and Associates. The use of rapid chemical tests on soils and plants as aids in determining fertilizer needs. Indiana Agr. Exp. Sta. Cir. 204, 1936.

CHAPTER XVII

THE APPLICATION OF FERTILIZERS



Emil Truog

THE analysis, the formula, the quantity of fertilizer to apply, and the time and method of its application are all problems about which there is still considerable uncertainty as to the best answers. In solving them, consideration must be given to the nature of the fertilizer materials, the type of soil, the kind of crop, the climatic conditions, the economic factors and the nature of any other materials that are to be added to the soil and their time of application. Thus the nitrogen of nitrate of soda is readily leached from the soil while that of sulfate of ammonia is not. High concentrations of soluble fertilizer salts are more likely to cause damage in sandy soils than in clay loams. The time to apply nitrogen fertilizers is determined in part by the nature of the crop and the product to be marketed. Liming materials and phosphate rock should not be applied to the soil at the same time. The quantity of fertilizer to apply and its analysis depend upon a number of economic factors of which the acre-value of the crop and the relative costs of the several fertilizer ingredients are most important. Any time or method of fertilizer application that is inconvenient or requires an additional operation with some implement especially designed for that purpose increases the cost of production of the crop.

BASIC ANALYSES

From among the fertilizer ratios shown in the triangle (Fig. 42), one could select five which would meet all ordinary requirements. These ratios and their suggested uses follow:

A. 5–3–2 for use on pastures, meadows, lawns, and fairways.
B. 2–6–2 for use on cereal crops.
C. 2–4–4 for use on potatoes and tobacco.
D. 3–4–3 for use on cotton and truck crops.
E. 2–3–5 for use on muck-soil crops such as onions and celery.

To any one of these could be added a supplemental top-dressing or side-dressing of some carrier of nitrogen, once the crop had gotten under way, the quantity of this nitrogen carrier to be determined by the intensiveness of the farming, the acre value of the crop, and the use to which it is to be put.

The above ratios could be sold in such analyses as the mixer found it most economic to produce. Thus the 2–6–2 ratio might be purchased as a 4–12–4, 5–15–5, 6–18–6,.....or 10–30–10 analysis, the farmer choosing the one which gave him the greatest value per dollar invested when applied to the field.

SPECIAL ANALYSES

If the conditions are such as to indicate that more potash can be used to advantage, then the above analyses might well be changed in that direction. This may be the case with muck soils or others that are notably low in their potash content; for crops such as tobacco that require especially large amounts of this nutrient; if a tendency toward disease indicated an especial need for potash; or if the price of potash salts was relatively low as compared to that of those carrying nitrogen and phosphoric acid. Under such conditions the 3–4–3 ratio might well be changed to 3–3–4 and the 2–6–2 ratio to 1–4–5.

Similarly if the conditions were such as to require less nitrogen, then the 3–4–3 ratio might well be changed to 1–5–4 or 0–5–5 and the 2–6–2 to 1–7–2, 0–7–3 or 0–6–4. This might be the case if the soil was black in color; if a crop of sweet clover had been plowed under; if large quantities of well-rotted manure had been applied; or if the price of nitrogen was relatively high.

For some crops and conditions the fertilizer used is largely some carrier of nitrogen. This is true for orchards, timothy meadows, pastures and lawns. But from time to time even for these crops phosphate and potash fertilizers must also be applied for best results. These may be added separately in the form of phosphate-potash mixtures, such as the 0–7–3 or 0–6–4 ratios

previously suggested, or in the form of such ratios as the 5–3–2, which are especially designed for late fall or early spring applications to these crops. In some cases, extra top-dressings may be desirable.

STANDARD FORMULAS

Except as there may be some special reason for doing otherwise, mixed fertilizer formulas generally consist largely of some ammonium salt, such as sulfate of ammonia, ordinary or ammoniated superphosphate, muriate of potash, and dolomitic limestone. In some cases organics of plant or animal origin or such a material as calcium cyanamid will be used for conditioning purposes. However, plant and animal organics are usually high priced or, if not high priced, they are too low in their content of nitrogen to permit of the use of large amounts of them in high-analysis mixtures. Urea combines the qualities of being organic and having a high concentration of nitrogen in highly available form. Possibly this material will in due time be used in considerably larger amounts in fertilizer mixtures.

The 4–12–4 and 4–8–8 analyses may readily be formulated from the following materials:

TABLE LIV

STANDARD FORMULAS FOR 4–12–4 AND 4–8–8 ANALYSES

Materials	Nutrient	Percentage	4–12–4	4–8–8
Sulfate of ammonia *	N	20	400	400
Superphosphate *	P_2O_5	20	1200	800
Muriate of potash	K_2O	50	160	320
Dolomitic limestone	....	....	240	480
			2000	2000

* Sulfate of ammonia and superphosphate will react and harden on standing. If such mixtures are not used immediately, they must be " based " and reground.

In looking about for a conditioner or filler, the manufacturer gives consideration to various organic materials, calcium cyanamid, dolomitic limestone, and gypsum, or to sand or other inert

materials. If organic materials or calcium cyanamid are employed, the quantity of sulfate of ammonia or other nitrogen carrier will be reduced. Various substitutions may be made for the several fertilizer materials, depending upon price relationships.

SPECIAL FORMULAS

Under some soil and crop conditions there may be reason for changing the formulas suggested. For tobacco and sugar beets and, to a less extent, for potatoes it is not desirable to have too much chlorine in the fertilizer because of its bad effects on the quality of the crops. Sulfate of potash may therefore be substituted for part of the muriate of potash.

Where the soil is sandy or the rainfall is very heavy there may be reason for including both organic and inorganic carriers of nitrogen. It may also be desirable to include some nitrate nitrogen and to make the mixture neutral in reaction. Formulas such as the following would be found satisfactory.

TABLE LV

SPECIAL FORMULAS FOR 4-8-8 AND 4-10-6 ANALYSES

Material	Nutrients	Percentage	4–8–8	4–10–6
Calcium cyanamid	N	22	50	50
Nitrogenous tankage	N	$4\frac{1}{2}$	360 *	200
Nitrate of soda	N	16	100	100
Sulfate of ammonia	N	$20\frac{1}{2}$	85	60
Ammon. superphosphate	$N-P_2O_5$	2–16	1000	1250
Muriate of potash	K_2O	50	100	100
Sulfate of potash	K_2O	48	230	150
Dolomite to neutrality	....	....	75	90
			2000	2000

* Eight per cent tankage.

HIGH-ANALYSIS FORMULAS

With increasing concentration of fertilizer materials it is possible to raise the analyses much higher than are many of those

that are being sold. In the 2–6–2 and the 2–4–4 ratios, highly effective mixtures can be produced as 6–18–6 and 7–14–14 analyses as well as a number of intermediate analyses.

TABLE LVI

HIGH-ANALYSIS FORMULAS FOR 2–6–2 AND 2–4–4 RATIOS

Materials	Nutrients	Percentage	6–18–6	7–14–14
Ammonium phosphate....	N–P_2O_5	11–48	648	504
Sulfate of ammonia.....	N	$20\frac{1}{2}$	205	172
Superphosphate.....	P_2O_5	16	324	252
Nitrate of potash.....	N–K_2O	$13\frac{1}{2}$–44	50	410
Muriate of potash.....	K_2O	50	200	200
Dolomitic limestone.....	....	....	573	335
Other supplement.....	....	....	0	127
			2000	2000

These mixtures are neutral in reaction; they contain adequate amounts of calcium sulfate; they include suitable amounts of chlorine; and they are high-analysis—about as high as it is safe to go for use on the soils of the humid regions.

THE QUANTITY OF FERTILIZER TO APPLY

The quantity of fertilizer to apply depends upon the concentration of the analysis; the relation between the cost of the fertilizer and the selling price per bushel or ton of the crop; and the intensity of the agriculture. An application of 1000 pounds of 6–8–6 analysis per acre might well be used for intensive farming with special crops and 300 pounds of 4–12–4 for extensive farming with cereal crops. These quantities may be either increased or reduced depending upon the above conditions. Naturally, if the concentration of these analyses was raised, the quantity to be used would be correspondingly reduced. Only a little more than half as much 7–14–14 as 4–8–8 is required to produce a given effect. Since increasing the concentration may reduce the applied cost of the fertilizer and reduce the danger of injury from too

high concentration of salts, the quantity applied may not necessarily be reduced the indicated amount.

The relation between the acre-value of the crop and the amount of fertilizer one can afford to buy to produce a given increase in yield is nicely shown in the accompanying table.

TABLE LVII

ACRE VALUE OF CROPS AS RELATED TO EXPENDITURES FOR FERTILIZERS

Crop Grown	Acre Yield *	Farm Price	Acre Value	50 Per Cent Increase	Fertilizer, Pounds †
Corn	28.2	$0.72	$20.30	$10.15	507
Wheat	14.9	1.12	16.69	8.34	417
Oats	28.3	0.45	12.74	6.37	318
Potatoes	114.7	0.96	110.11	55.05	2752
Tobacco	768.7	0.22	169.11	84.55	4227
Cotton	152.3	0.20	30.46	15.23	761

* Average yields, in bushels or pounds, and average December 1 selling prices in the United States for the year 1927.

† The number of pounds of fertilizer costing $40 per ton that could have been purchased from the proceeds of sales of a 50 per cent increase in crop yields.

Considering next the question of the fluctuations in crop prices it is evident that much larger amounts of fertilizer can be applied to advantage if the selling price of the crop is high than if it is low. This is well shown in the accompanying table which gives the increases in yields of potatoes that were produced by using various amounts of a 4–8–10 fertilizer and estimates the value of the increase at different rates per bushel.

TABLE LVIII

SELLING PRICE OF POTATOES AS RELATED TO AMOUNT OF FERTILIZER (JORDAN)

Fertilizer, Pounds	Cost per Acre *	Increase, Bushels	Value of Increase above Cost	
			At $0.50	At $1.50
500	6.25	23.3	$5.40	$28.70
1000	12.50	44.2	9.60	53.80
1500	18.75	55.4	8.95	64.35
2000	25.00	61.4	5.70	67.10

* The cost of the fertilizer at the time the experiment was conducted was, in a home mixture, $25.00 per ton.

At $0.50 per bushel the 1000-pound application is to be preferred. At $1.50 per bushel the 2000-pound application gave the largest gross return and the 1500-pound application the largest net return on the investment.

TIME OF APPLICATION OF FERTILIZERS

Wagner writes "one manures the soil with phosphate and potash and the plant with nitrogen." By this he means that the quantity of phosphoric acid and potash to apply is determined by the nature of the soil. The time of application can be at any convenient point in the rotation. The soil's capacity to fix these two constituents is such that little loss from leaching is normally to be expected. With nitrogen fertilizers, however, the soil has little power to hold them for any considerable length of time; it does not compete with the plant for them; and they must, therefore, be applied in such quantity as is required by the plant and at such time as will make them of most use to the plant.

THE EUROPEAN SYSTEM

Accordingly, Wagner suggests that the basic slag to be used for stock beets [1] should be distributed before the manure is applied; that for wheat should be plowed or harrowed in before seeding the wheat; the basic slag and potash salts for oats should be scattered over the wheat stubble or later in winter over the plowed ground; the phosphate and potash salts for the second crop of wheat should be scattered over the clover stubble; and that for the second crop of oats should again be applied over the wheat stubble or later on the plowed ground.

The nitrogen fertilizer, on the other hand, is applied separately and at a time when it is required by the crop. Thus the nitrogen for the beets is applied half at seeding time and half as top-dressing; that for wheat, about the middle of March; that for oats at seeding time; that for the second crop of wheat, half in the middle of March and half in April; and that for the second

[1] See page 245.

crop of oats, half at seeding time and half the last of April or the first of May.

The quantity of nitrogen to be applied as top-dressing depends somewhat upon the condition of the crop at the time when the application should be made. Thus if the season has been very favorable for the crop and there is less apparent need for nitrogen, the quantity applied may be reduced. If the season is backward more may be applied. With the phosphate and potash fertilizers no such change in program is contemplated.

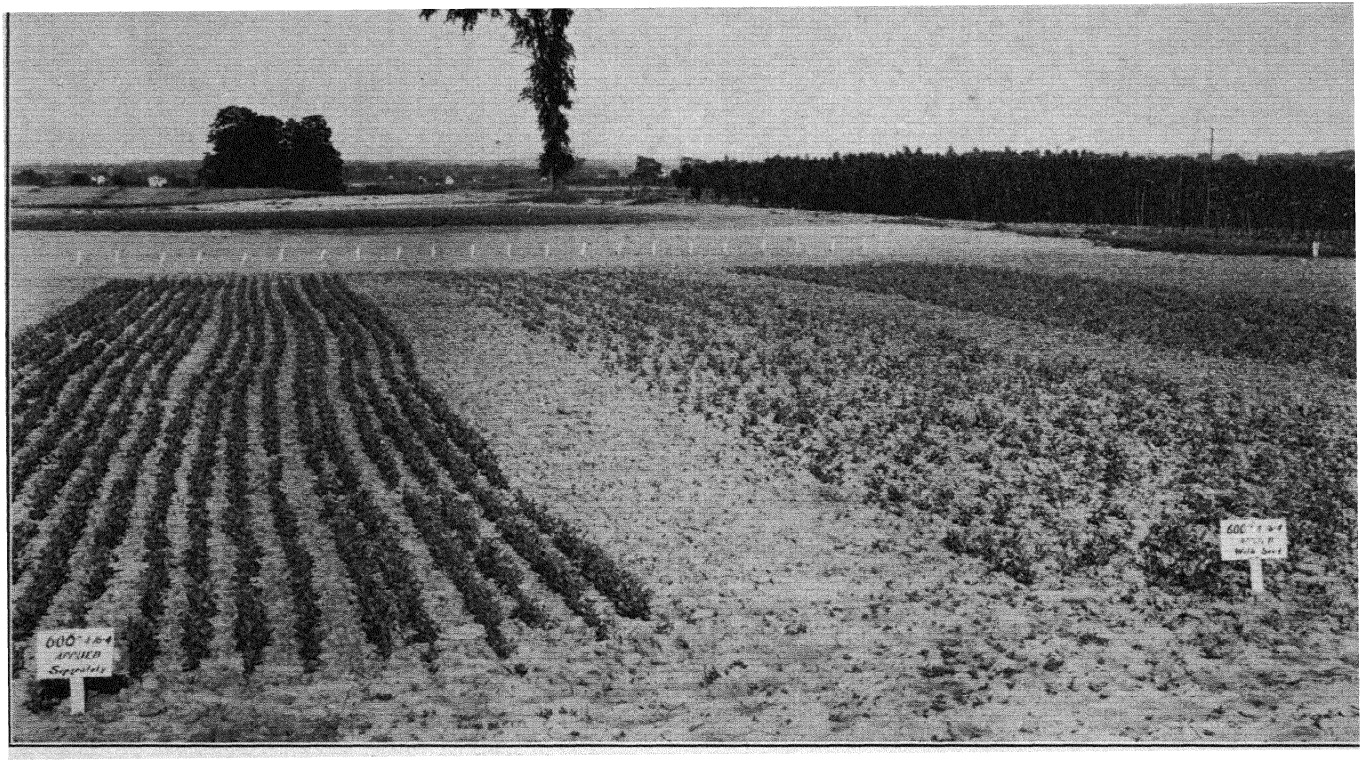
The above system of applying fertilizers is one that is in common use in Germany and in the neighboring countries of Continental Europe. Cheap labor, the relatively high state of productivity of the soil, and the liberal use of fertilizers all operate against sowing the fertilizer at the time of seeding and particularly against placing it in the row at seeding for intertilled crops. There is the additional important fact to consider that, until quite recently, fertilizer materials were bought separately rather than in the form of factory-mixed, complete fertilizers.

THE AMERICAN SYSTEM

In this country labor is expensive; machinery is relatively cheap and highly efficient; the state of productivity of the soil is relatively low in the fertilizer-using regions; and fertilizers are used in rather small amounts, except in intensive farming. The tendency is, therefore, to choose a complete fertilizer and to apply it at the time of seeding and with the same machine.

Until such time as our agriculture becomes much more intensive than it is at present and until much larger amounts of fertilizer are applied there would seem to be little reason to change the present plan of applying phosphates or mixed fertilizers at the time of seeding and, at least part, in the row. There is, however, need to consider the problem from the point of view of using much larger amounts of fertilizers and of applying extra applications of nitrogen at particular stages in the growth of the crop.

An interesting comparison of the times of application of small amounts of complete fertilizer to crops in rotation when grown



Applied separately 600 pounds 4–16–4 Applied with seed

FIG. 50.—With increasingly heavy applications of highly soluble salts, there is greater need to sow the seed and fertilizer separately, or to make use of a combined seed-and-fertilizer distributor which places the fertilizer at the side of the seed. (C. B. Sayre and G. A. Cummings).

on a soil in a relatively low state of productivity is shown in the accompanying table.

TABLE LIX

INCREASE * FROM 500 POUNDS 4-16-4 ON CROPS IN ROTATION

When Applied	Corn, Bushels	Oats, Bushels	Wheat, Bushels	Clover, Hundredweight
To all four crops equally	11.05	7.00	10.69	9.33
On corn,† oats and wheat	12.76	8.05	13.47	6.31
On corn,† and wheat	12.59	5.26	14.39	7.15
All on corn †	14.89	7.62	8.34	3.85
All on wheat	8.95	2.15	16.23	11.38
All on clover	12.58	2.43	6.87	14.49

* 13-year average at Ohio Agr. Exp. Sta. at Wooster.

† Applied broadcast with fertilizer drill previous to planting the corn.

Changes in the quantity of fertilizer applied, in the ratios of the nutrients, and in the method of application for corn would undoubtedly make fundamental differences in the results secured. As it stands, the application of the entire amount at the time of seeding the wheat is perhaps the best.

TIME OF APPLICATION OF NITROGEN FERTILIZERS

While a certain amount of nitrogen may well be applied at the time of seeding the crop, there is reason to believe that, if large amounts are to be used, better results will be secured by applying part of it later in the crop season except, perhaps, as the nitrogen carrier is some organic form, such as fish, tankage or cottonseed meal. As previously indicated, both quantity and quality of product are involved in the decision as to the time of application of nitrogen.

It is a matter of considerable interest that soft wheats can be changed in their protein content to make them resemble hard wheats by the application of nitrogen fertilizers at the heading stage. The protein content of hard wheats can also be increased by the same procedure. The present tendency is to pay a premium for increased protein in wheat. Thus on the Kansas City market wheat that can be classed as "choice dark red" is worth

10 cents more per bushel than is that which is designated as "best yellow hard."

TABLE LX

EFFECT OF TIME OF APPLYING NITRATE OR PROTEIN * CONTENT OF WHEAT (GERICKE)

Days after Planting	White Australian	Turkey Red
0	8.9	14.6
17–21	9.2	13.8
33–36	10.6	14.7
48–60	11.4	13.4
72–81	13.0	14.3
100–110	15.2	17.9

* Protein expressed as per cent.

TOP-DRESSING CROPS WITH NITRATE NITROGEN

It is not feasible to attempt to present the evidence in favor of the following suggestions as to the time of applying top-dressings of nitrate fertilizers but such evidence, while not always as conclusive as one might desire, is available.

1. For lawns and pastures, in early spring at the start of growth and at several times during the season of growth.
2. For non-legume meadows, early in the spring.
3. For cotton, a month after planting.
4. For wheat and rye, to increase yield, early in the spring at the start of growth.
5. For wheat, to increase protein content, at the heading stage.
6. For sugar beets, at thinning time.
7. For tobacco, when the plants are 10 to 15 inches high.
8. For corn, when the stalks are $2\frac{1}{2}$ to 4 feet high.
9. For cabbage, at heading time.
10. For fruit trees and small fruits, in early spring before blossoming.
11. For tomatoes, melons, cucumbers, pumpkins and squashes, after the fruit is set.
12. For rhubarb, asparagus, and other perennials, including flowers, in early spring.

It will be noted that the preceding top-dressing suggestions are for nitrate fertilizers. If ammonia salts are used it is desirable to apply them a week to ten days earlier than is suggested for nitrate. This is particularly true for such crops as tobacco and sugar beets which apparently require their nitrogen mostly as nitrate. It is essential that calcium cyanamid be applied at a different time and in a different manner. Thus for cotton, corn and vegetables, it is best to apply this material well in advance of planting. Calcium cyanamid is not, as a rule, used as a side-dresser. Where used as a top-dressing, as for haylands, pastures and orchards, fall application is suggested. If used in the spring for these crops or for top-dressing small grains, the application should be made as soon as possible after the frost is out of the ground. Weeds in small grains can be controlled by the use of pulverized calcium cyanamid if it is applied when they are wet with dew and bright sunshine follows. The small grain crop stops growing for a few days but soon responds to the effects of the nitrogen.

Organic carriers of nitrogen of plant and animal origin are ordinarily applied at planting or in advance of planting. The nitrogen in such materials becomes available in proportion as conditions are favorable for growth, thus supplying this element to the crop as it is required. Such materials are usually preferred for use on soils that are subject to excessive leaching. However, as previously indicated, it now appears probable that ammonia salts, if supplemented by limestone, will produce equally as good effects as are obtained by the use of organics.

In areas where irrigation is practiced, it is possible to distribute nitrogen fertilizers in solution in the water. Anhydrous ammonia and nitrates have been used thus in California. Soils have considerable fixing power for ammonia and thus interfere with its even distribution. Nitrates are preferable for this purpose.

TIME OF APPLICATION OF PHOSPHATES

It will be recalled that in the Hopkins system of supplying phosphoric acid to soils, one ton of phosphate rock is applied to the clover sod preceding the plowing of the land for wheat. This system is continued for four or five rotations until the phosphoric acid content of the soil has been raised to about 5,000

pounds per acre of soil to plow depth after which only as much phosphate is applied once every four years as is required to replace that lost by crop removal.

This method assumes that the loss of phosphoric acid by leaching is negligible; that heavy applications once during the rotation are as satisfactory as to apply part of the phosphate to each crop; and that an economic advantage is gained by one large application rather than several small ones.

There is ample evidence in support of the first assumption to the effect that phosphoric acid applied to the surface soil is not lost by leaching, to any appreciable extent. There is some doubt concerning whether occasional large applications of phosphoric acid fertilizers will give as good results as will the same amount of phosphate applied in smaller amounts to each crop. This applies particularly in the case of soils in a low state of productivity, where the applications of phosphates are relatively small, and for intertilled crops where there is opportunity for row applications.

However, under conditions of intensive farming and when the soil is in a relatively high state of productivity, there may be little reason for applying phosphate to each crop. This is especially true for those rotations which contain one crop that has a considerably higher acre-value than do the others. In this case all of the phosphates might well be applied to that crop, assuming that the crop responds well to the use of phosphates and that no bad effects are noted by reason of overfeeding with phosphoric acid.

TOP-DRESSING CROPS WITH PHOSPHORIC ACID

It is a matter of considerable interest that, notwithstanding the power of the soil to fix phosphoric acid at or near the point of contact, very marked effects are produced by applications of basic slag or superphosphate on pastures. Worn-out pastures containing very little grass can be brought back to a relatively high state of productivity in about three years' time by an application of 500 pounds per acre of one or the other of the above carriers of phosphoric acid. Normally, white clover, in the North, or Japan clover, in the South, appear first and produce a luxuriant growth, after which the grasses come in and cover the ground. Phenomenal effects are often noted by the treatment.

Whether anything is to be gained by using soluble phosphates for top-dressing purposes on annual or biennial crops to which they could have been applied at planting or seeding time remains to be demonstrated. The ammonium phosphates that are now available are readily soluble in water and might be able to penetrate the soil for a short distance before being precipitated. Certainly very marked effects might be anticipated from the use of water-soluble phosphates on sandy soils. The effects on other soils would be expected to be most marked in the early spring when the soil is moist and root-hairs are securing more of their nutrients from the soil on the immediate surface of the ground. It seems probable that ammonium phosphate would be very useful for top-dressing purposes on the cereal crops and especially if spring seedings of clover are to be made in these crops.

TIME OF APPLICATION OF POTASH FERTILIZERS

What has been said above concerning the time of application of phosphates applies to a certain degree to potash salts. There is the difference that potash salts are all soluble in water and they are fixed in the soil in the base-exchange complex rather than by precipitation, as the term is ordinarily used. If all of the potash to be added to the soil during the course of the rotation was applied to one crop, that crop would probably absorb much more potash than it required with resultant waste of this constituent. Furthermore, the loss by leaching of this element, while relatively small as compared to that of nitrates, is appreciable and would be considerably increased by unduly heavy applications of potash salts. This applies especially to the sandy soils that have little power to absorb potash salts from solution by reason of their low content of colloidal material, the seat of the base-exchange reactions.

There is another difficulty that is involved in the use of large amounts of potash salts, if the soil is acid in reaction. When the chloride or sulfate of potash is applied to such soils, the immediate effect is to cause an exchange of potassium and hydrogen ions in the soil complex with resulting increase in the acidity of the soil solution. With good drainage conditions, this effect may only be temporary. In fact by this means a large proportion

of the hydrogen ions can be removed from the soil with the consequent formation of what might be termed a "potassium soil." This can be effected only by very heavy applications of potash salts.

The immediate effect is of greatest importance. The acidity thus developed in an acid soil is at times such as to produce very marked effects on acid-sensitive crops. Altogether, it does not seem best to apply all of the potash salts at one time during the course of the rotation except as some crop appears in the rotation which combines the qualities of having a high acre-value and of giving a very marked response to potash fertilizers.

TOP-DRESSING CROPS WITH POTASH FERTILIZERS

Some very marked effects have been produced by top-dressing cotton with potash fertilizers. In the report of a series of field demonstrations of potash thus applied in the Coastal Plain Region it is shown that 200 pounds of kainit or 100 to 200 pounds of muriate of potash yielded, on the average, $8.21 worth of seed cotton for every dollar invested in potash. In several cases the increase amounted to more than 600 pounds of seed-cotton per acre, although the basic fertilizer applied at planting time normally contained from 3 to 5 per cent of potash. The average acre application at planting time amounted to 539 pounds of a complete fertilizer containing 3.8 per cent of potash.

There is some uncertainty as to whether equally good results might not have been secured by applying this extra potash at seeding time. On the other hand, this suggests possibilities in studying the crop and determining the quantity of potash to apply by the appearance of the crop as the season advances. In bad seasons, those of heavy rainfall and cool temperature and little sunshine, more potash as top-dressings could undoubtedly be applied to advantage.

Since there are salts combining nitrogen and potash, the use of such salts for top-dressing purposes affords interesting possibilities, not only on cotton, but on corn, potatoes, tobacco and truck crops. It is of especial interest in the case of sandy soils which may have little capacity to fix potash salts. There is the further possibility that it may later be shown that with potash,

and also with phosphoric acid as well as nitrogen, the time of application may be important in determining not only the yield but the quality of the crop produced.

Potash fertilizers may be used to good effect as top-dressings on pastures and on old stands of alfalfa. Here again the best results are secured by applying them early in the season when the soil is moist, the temperature cool, and the root hairs are able to absorb more of their nutrients from the surface soil. Phosphates are likewise very effective fertilizers for top-dressing purposes in the growing of alfalfa.

TOP-DRESSING CROPS WITH COMPLETE FERTILIZERS

Assuming that it may be more convenient or desirable to apply a complete fertilizer one may well consider the possibilities as to the time of its application. For the sake of economy of labor it is desirable that it be applied at planting time. Since a complete fertilizer contains nitrogen as well as phosphoric acid and potash it should normally be applied to each crop rather than to use all of it on any one crop, except as that crop has a much higher acre-value than the other crops in the rotation, or has an especially great need for nitrogen.

Considering the fact that top-dressings of phosphate and potash fertilizers do produce marked increases in yield of crops under certain circumstances, the question is raised as to whether one might not well apply a complete fertilizer whenever the time for top-dressing with nitrogen fertilizers had arrived. It happens that some carriers of nitrogen cannot be mixed with other materials with the production of a drillable product. Such is the case with nitrate of lime and urea. However, sulfate of ammonia, nitrate of soda, and other soluble carriers of nitrogen can be used in mixtures without difficulty.

It is possible that the use of a complete fertilizer at the time when one would normally use a nitrogen top-dressing might be advisable, in which case one might select those carriers of phosphoric acid that are highly soluble, such as ammonium phosphate, together with similarly soluble carriers of nitrogen and potash. Such mixtures could be used to good advantage as spring dressings on lawns, pastures and meadows. The 10–6–4 analysis is suggested for this purpose.

There may be very good reason also for using a complete fertilizer as a spring top-dressing on alfalfa and clovers or for the wheat, oats, barley or rye crop in which clover is to be seeded. It is, of course, quite likely to be shown that the phosphate and potash part of the top-dressing mixture are not particularly valuable under conditions where large amounts of fertilizer are applied at planting time. Nevertheless, there are many times when a bad season or a change in plan, or the possibility of high prices make it desirable to apply more fertilizer than was applied at planting time or to make a change in the nutrient ratios that are being supplied to the crop. There are, therefore, many interesting possibilities in top-dressing crops with complete fertilizers.

ROW APPLICATIONS OF FERTILIZERS

For intertilled crops, such as cotton, tobacco, corn, potatoes, and truck crops, there is reason to believe that there are some advantages in row application, either before or at the time of planting, as compared to broadcast applications before planting. This problem has come in for much consideration recently both by reason of the development of machinery for row application and the fact that there is considerable economy of labor in applying fertilizer in the row at planting rather than broadcast previous to planting.

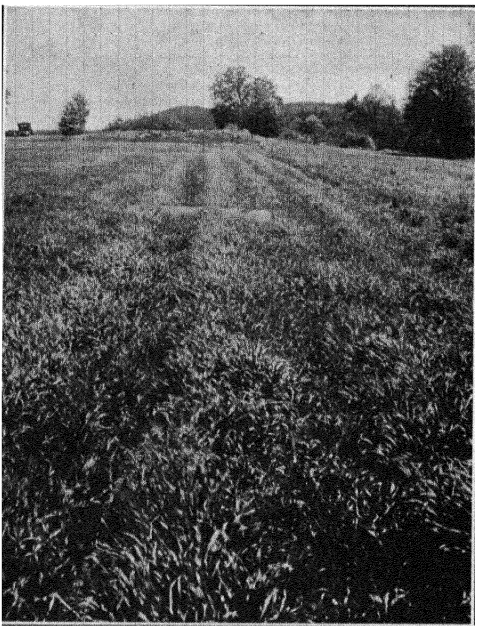


FIG. 51.—Showing residual effect of row application of fertilizer.

It was formerly believed that row applications tend to effect a bunching or restricted growth of the roots of plants. This opinion is expressed by Thorne. It has been shown to have an irregular effect on the

crop following. The first of these objections has not been supported by the experimental tests. The second is set aside by making the row applications small and the broadcast application on the same or succeeding crops somewhat larger.

CONDITIONS FAVORING ROW APPLICATIONS

From what is now known on this subject, one can be reasonably sure of the following statements as to when hill or row applications are likely to be most effective.

1. If the soil is in a low state of productivity.
2. If the amount of fertilizer applied is small.
3. If the rows of the crop are far apart from each other.
4. If the soil is a heavy silt loam, clay or clay loam rather than being sandy.
5. If the soil is a muck or peat.
6. If the soil is relatively high in its content of moisture.
7. If the soil is approximately neutral in reaction.
8. If the season or climate is not subject to droughts.[1]
9. If the fertilizer is relatively high in its content of phosphoric acid rather than nitrogen or potash.
10. If the fertilizer is not placed directly in contact with the seed but at one side and below the plane of the seed.
11. If rapid, early growth is desirable.
12. If injury from frost is likely to occur.

PRINCIPLES GOVERNING ROW APPLICATIONS

If large amounts of fertilizer are applied, row applications must be made with care otherwise injury to the young plantlets may result. A few general principles may be stated as a guide to the use of fertilizers in the row.

1. Except as it may reduce the stand, the nearer the fertilizer is to the seed the better it promotes early growth of the plant.
2. Carriers of nitrogen cause the greatest injury; those containing potash are intermediate; and those containing phosphoric acid are least injurious to the young seedlings.

[1] If superphosphate alone is used, row applications may be preferable to broadcast applications in dry seasons by reason of its marked effects on root development.

3. Fertilizer placed above or below the seed has much the same effect as that placed in direct contact.
4. Cottonseed meal should not be applied in contact with the seed.
5. Superphosphate applied close to the seed may be absorbed before fixation takes place.
6. Ammo-phos and treble-superphosphate are more readily soluble than is superphosphate.
7. A placement of fertilizer that is safe under all weather conditions is not one that gives the best results in all cases.
8. For best results with row applications, the placement should be at the side of the seed and somewhat below.
9. The injury is not ordinarily to the seed but to the young plant after germination has occurred.
10. At times the stand may be reduced by row applications and yet the yield may be increased.
11. In regions of drought, row applications may induce more early growth than the subsequent weather may make it possible to mature.
12. Fertilizer should not be deep if plants are to be forced early.
13. Corn is less subject to injury than are potatoes, cotton or peanuts.
14. Field peas, cowpeas, navy beans, soybeans, squash, cucumber, watermelon and muskmelon are very sensitive to row applications of fertilizers.
15. Small seeds like rape, kale, alfalfa, vetch and clover may be mixed with superphosphate before drilling if the soil in which they are to be placed is well supplied with moisture.

BROADCAST AND ROW APPLICATIONS

It seems apparent that as the quantity of fertilizer applied per acre increases, particularly when the more soluble forms of fertilizer come into larger use, difficulty will be experienced with row applications. The practice of the European farmer to apply his fertilizer broadcast a week or ten days in advance of planting the crop cannot be said to be entirely explained by the cheapness

of labor or the lack of suitable machinery. The general level of productivity of the soil in Europe is usually quite high. There is sufficient nutrient material in the soil to give the plant a good start even when only a small part of the total amount of fertilizer applied is available to the young seedling.

Nevertheless the good effects from fertilizer applications when properly placed in the row are such that they cannot be ignored. The following example with potatoes is one of considerable interest in this connection.

TABLE LXI

EFFECT OF METHOD OF APPLICATION OF FERTILIZER ON POTATO YIELDS (COE) *

At sides, lower plane, narrow spread	216
At sides, same plane, narrow spread	202
$\frac{1}{4}$ below seed, $\frac{3}{4}$ at side, narrow spread	200
$\frac{1}{2}$ in ridge ahead, $\frac{1}{2}$ at sides, narrow spread	200
At sides, same plane, wide spread	191
$\frac{3}{4}$ in ridge ahead, $\frac{1}{4}$ at sides, narrow spread	188
In made up ridge ahead	183
$\frac{1}{4}$ above seed, $\frac{3}{4}$ at sides, same plane, narrow spread	183
Above seed, soil interposed, wide spread	165
Above seed, soil interposed, narrow spread	162
Check yields, no fertilizer	149
Mixed with soil in row	131
Direct contact in row	117

* Acre yields in bushels.

The potato crop is one on which well-placed row applications would be expected to be particularly effective. With corn and many other crops which develop wide-spread root systems during the growing season, there may be advantages in a combination of row and broadcast applications, a heavy phosphate-potash application being made broadcast and plowed under before planting; a lighter row application of a complete fertilizer later; and a subsequent top-dressing of nitrogen fertilizer being given when the plants are well started.

There is some indirect evidence in favor of this scheme in the accompanying table although it must be admitted that there are a number of very inconclusive features about the test which make further study of the problem desirable.

TABLE LXII

COMBINING HILL AND BROADCAST APPLICATION OF FERTILIZERS (WOOSTER)

Treatment per Acre	Planted May 13			Planted June 3		
	Days *	Moisture †	Yield ‡	Days	Moisture	Yield
None	117	48.3	17.7	110	69.1	5.5
200 lb., 3-12-4 in hill	98	36.8	37.2	97	53.1	24.6
8 tons manure, 225 lb., 0-16-0 broadcast	104	46.7	45.2	97	53.4	31.9
200 lb., 3-12-4 in hill, 8 tons manure, 225 lb., 0-16-0 broadcast	93	33.5	70.3	88	50.0	47.9

* From planting to silking.
† At husking time.
‡ Yield in bushels on 15.5 per cent moisture basis.

Such interest has been developed among agronomists, fertilizer producers and machinery manufacturers that a large amount of experimental work on various phases of this problem has been done.

APPLYING FERTILIZERS TO TRANSPLANTED PLANTS

It has long been desired to find some method for hastening the growth of transplanted plants without producing any injurious effect before the roots had become established in the soil. Attempts to dissolve fertilizer in the water used at transplanting or to make use of manure water for this purpose have not been particularly successful. A high concentration of salts in the water used in transplanting serves to aid transpiration in reducing the amount of water in the plant. In an experiment on tobacco in Kentucky it was shown that about 4 ounces of nitrate of soda in a barrel of water is about as much as it is safe to apply, this quantity having an appreciable effect in stimulating growth.

More recently it has been shown that the best means of procedure is to apply the fertilizer in liberal amounts to the plants as they are growing in the plant beds. The young plants are able to take up the nutrient elements in much larger amounts than they are required for immediate use. On being transplanted this larger content of salts tends to reduce transpiration

and to increase the rate of flow of water from the soil into the plants. Some very interesting and suggestive results with tomatoes have been secured, an increase of as much as 5 tons of tomatoes per acre during the first four pickings being produced by this means.

SELECTED REFERENCES

1. Anonymous. Field work of the Ohio Agric. Exp. Sta. 34 pp., 1928.
2. Gericke, W. F. Differences effected in the protein content of grain by application of nitrogen made at different growing periods of the plants. Soil Science, vol. 14, pp. 103–111, 1922.
3. Jordan, W. H. Commercial fertilizers for potatoes. New York Agr. Exp. Sta. Bul. 187, 1900.
4. Noble, Sid. Potash top-dressings pay in cotton demonstrations. Better Crops, vol. X, No. 4, p. 14, 1928.
5. Thorne, C. E. Why not fertilize in the hill? Ohio Agr. Exp. Sta. Month. Bul. Vol. 3, No. 6, p. 182, 1918.
6. Truog, E. and Jensen, O. F. Report of Proceedings of the Joint Committee on Fertilizer Application, 1925–28. National Fertilizer Assoc., Washington, 1928.
7. Wagner, Paul. Fünfzig Jahre Düngerlehre. Die Ernährung der Pflanze. Vol. 24, No. 14, p. 244, 1928.

CHAPTER XVIII

CONTROLLING THE SOIL REACTION



Burt Hartwell.

PLANTS differ markedly in their requirements as to the reaction of the soil on which they are to be grown. Some of them, such as watermelons and blueberries, thrive on strongly acid soils and are injured by the use of lime. Corn and soybeans may be cited as crops which may be grown satisfactorily on soils that are quite acid in reaction but which are materially benefited by liming. Cabbages and onions are examples of a third group that do not grow well except on soils whose reactions approach the neutral point. Asparagus and alfalfa are two members of a fourth group that are not only benefited by liming but can be grown on soils that contain considerable amounts of alkali, including the carbonates of sodium and potassium.

CLIMATIC FACTORS AND SOIL REACTION

The reaction of the soil is determined by climatic factors of which the most important is the rainfall in relation to the rate of evaporation. In regions where the rainfall considerably exceeds the rate of evaporation soils soon become acid in reaction as a result of the leaching action of water. In semi-arid regions and in those areas where irrigation must be practiced in order to grow crops the carbonates, that are normally carried away in regions of heavy rainfall, accumulate in the soil with the result that it often becomes strongly alkaline in reaction. In between these regions of strongly alkaline and strongly acid soils is an intermediate region, the center of which maintains a soil reaction more nearly approaching the neutral point.

FITTING THE CROP TO THE SOIL

Since crops vary in their soil-reaction requirements and soils of all the necessary degrees of acidity and alkalinity are to be found, it would seem that the solution of the problem would lie in fitting the crop to the soil. A study of the location of the centers of production of the various crops shows that this adjustment between crops and soils has been made to a considerable extent. Thus in the Eastern States, where Wheeler, as early as 1890, had shown that liming is absolutely essential for the growth of acid-sensitive crops, potatoes, red top, bent grass, alsike clover, timothy and buckwheat, all capable of growing satisfactorily on distinctly acid soils, are important field crops. In the Southern States where acid soils are the rule and practically no lime is applied, acid-tolerant cotton, cowpeas, Japan clover, rye and oats are the common field crops.

In the Western States, where the rainfall is less, the rate of evaporation is high and the soils are neutral to distinctly alkaline in reaction and normally contain a zone of carbonate deposits a short distance below the surface, alfalfa is a highly important field crop. More than half of the over 11,000,000 acres of alfalfa that are grown in the United States is produced in North and South Dakota, Kansas, Nebraska, Montana, Wyoming, Idaho and Colorado. The vast Central Basin of the United States, comprising soils that lie between these extremes of soil reaction, is used largely for the production of corn, wheat and red clover, crops which can be grown over a considerable range of soil reaction but which do best at a reaction that is slightly acid.

ECONOMIC FACTORS AND CROP DISTRIBUTION

The farther removed an area is from the region where the soil reaction that is favorable to a given crop is developed naturally, the more difficult it is to grow that crop satisfactorily until a point is reached at which it may no longer be advisable to make the attempt. On the other hand, economic factors enter into this problem and often permit of large expenditures for the control of the soil reaction in localities that are far removed from the natural climatic center of production of a given crop.

Thus some New England farmers may find it profitable to

grow alfalfa irrespective of the fact that the soil must be heavily and frequently limed. In densely populated areas, market gardening is a very important business no matter what the reaction of the soil around these cities may be. Most market-garden crops are very sensitive to acid soils. Potatoes are grown extensively in Colorado and California even though it is necessary to use sulfur or acid-forming fertilizers in order to produce a suitable soil reaction to control the scab organism. Golf players insist on having on their putting greens, without regard to where they may happen to be located, bent grasses and fescues, plants which cannot compete successfully with bluegrass and white clover if the soil contains carbonate of lime.

RELATIVE SENSITIVENESS OF PLANTS TO ACID SOILS

Since crops vary in their requirements as to the reaction of the soil in which they are to be grown it seems desirable to know somewhat definitely what these requirements are. The Rhode Island Experiment Station has conducted experiments with 280 different varieties of plants to determine their relative reaction requirements. From these experiments and others of a similar nature Table LXIII has been arranged as indicating the requirements as to soil reaction which must be met if these plants are to be given optimum conditions for growth.

The last column contains a list of plants which are not only very sensitive to acid soil conditions but which can be grown on soils that are somewhat alkaline in reaction. Thus alfalfa and sugar beets are two very important alkali-soil crops.

METHODS OF TESTING SOIL REACTION

The quantity and nature of the neutralizing agent to be applied depends upon the crop to be grown and the reaction of the soil. It is therefore highly important that some means be devised by which the reaction of the soil can be fairly accurately determined. A simple test for acidity has already been suggested in the chapter on "The Selection of Fertilizers." It was further indicated that if apparatus was at hand for the electrometric determination of the *p*H of the soil, this method might well be substituted for the more simple thiocyanate test.

TABLE LXIII

RELATIVE SENSITIVENESS OF PLANTS TO ACID SOIL CONDITIONS

Very Tolerant	Tolerant	Sensitive	Very Sensitive
Beans	Alsike clover	Barley	Alfalfa
Bent grass	Buckwheat	Bluegrass	Asparagus
Blackberry	Carrot	Brussels sprouts	Beet (red)
Blueberry *	Corn	Cabbage	Beet (sugar)
Cowpea	Cotton	Cauliflower	Berseem clover
Cranberry *	Crimson clover	Chard	Bokhara clover
Fescue (sheep's)	Cucumber	Egg plant	Celery
Flax	Endive	Hemp	Currant
Japan clover	Gooseberry	Horseradish	Gumbo (okra)
Lupine	Grape	Muskmelon	Leek †
Millet	Lentil	Mustard	Lettuce †
Oats	Pea	Orchard grass	Mangel
Peanut *	Pumpkin	Rape	Onion †
Potato	Rhubarb	Red clover	Parsnip
Radish	Raspberry (red)	Sweet clover	Pepper
Raspberry (black)	Strawberry	Turnip	Quince
Red top	Tomato	Tobacco	Salsify
Rye	Timothy	Wheat	Spinach †
Watermelon *	Vetch	White clover	Yellow trefoil

* Especially tolerant of acid soil conditions.
† Especially sensitive to soluble aluminium.

The common logarithm of the reciprocal of the hydrogen-ion concentration expressed in terms of normality is known as the *p*H. Pure water, free from carbon dioxide, has a *p*H of approximately 7. This means that it is a 1/10,000,000 normal solution of hydrogen and also of hydroxyl ions. A solution having a *p*H of 5 contains 100 times as many hydrogen ions as does pure water. One with a *p*H of 8 contains 10 times as many hydroxyl ions and only 1/10 as many hydrogen ions as water. The *p*H of water suspensions of the soils of the United States range from 4 to 10, normally lying between 5 and 8.

COLORIMETRIC METHODS FOR DETERMINING *p*H

A number of indicators are available which change color at different hydrogen-ion concentrations. By putting several of these indicators together a solution can be produced that changes from red to yellow, green and blue as its *p*H changes from 4 to 8.

By adding a few drops of water to a soil, collecting the filtrate from this, and adding a drop of this mixed indicator, the color that is produced gives a fairly accurate reading of the *p*H of the soil. A number of these combined indicator solutions are being offered for sale. The chief difficulty in their use lies in the fact that the color changes pass through yellow, a somewhat natural color of many soil suspensions, and unless considerable care is exercised in getting the suspension free of soil there is difficulty in being sure of the shade of color produced. Furthermore one who is not accustomed to noting small differences in shades of color will find considerable difficulty in making the distinctions that are necessary for accurate readings of the indicator.

THE LIME-REQUIREMENT OF SOILS

Four types of acid are found in all acid soils, viz.: hydrated silicates, mineral acids, organic acids and carbonic acid. Of these by far the most abundant are the acid silicates, present largely in the condition known as the base-exchange complex of the soil. These hydrated silicates are not highly soluble. Their acidity is therefore largely potential rather than active. They have the power to absorb either acids or alkalies up to the point of nearly complete saturation without showing as marked change in *p*H as one might expect. Knowing the *p*H of a soil does not permit the assumption that a given amount of acid or alkali will change the *p*H to one that may be desired to grow a given crop. Nevertheless, for soils of the same class, and partic-

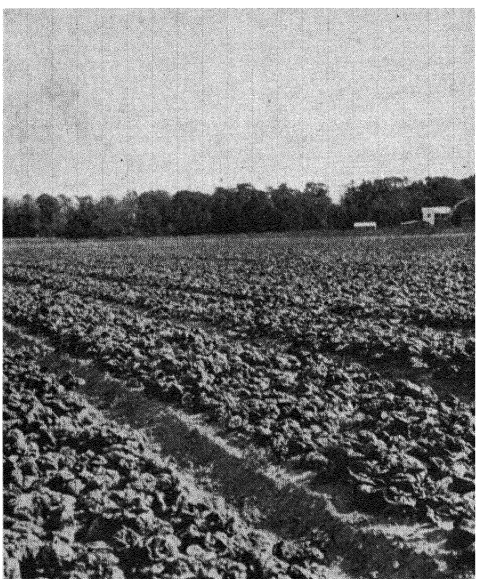


FIG. 53.—Spinach is very sensitive to acid-soil conditions. This soil was limed. (Courtesy Norfolk Truck Station.)

ularly for those of the same series and class, the ratios once experimentally determined between *p*H and lime-requirement, or acid-requirement, can be rather generally applied. However, much remains to be done before a dependable table of these relationships can be prepared.

A number of methods have been suggested for determining the quantity of liming materials to apply to effect a neutralization of the soil. The Hopkins method is one of shaking the soil with a solution of potassium nitrate and titrating the resulting filtrate. The Veitch method is that of treating the soil with varying amounts of standard lime-water until evaporation to dryness and taking up with water yields a solution that is alkaline to phenolphthalein.

THE JONES LIME-REQUIREMENT METHOD

The Jones lime-requirement method is similar to that of Hopkins except that the soil is triturated with calcium acetate. This method is the one that is in most common use, partly because of convenience but also because it gives data from which one can calculate with some degree of accuracy the amount of lime necessary to be applied to produce a given change in the soil reaction. The method is as follows:

Twenty-five grams of soil are mixed with one-half gram of calcium acetate by grinding one-half minute in a mortar. Fifteen cubic centimeters of water are then added and the mixture is ground with the pestle until well mixed (about $\frac{1}{2}$ minute) after which 20 cubic centimeters more of water are added and the grinding is continued one minute longer. This is transferred to a 250 cubic centimeter graduated flask. Water is added to a volume of about 200 cubic centimeters. This is then allowed to stand 15 minutes, shaking every 5 minutes. The flask is filled to the mark, mixed well and filtered. Two 100-cubic centimeter portions of the filtrate are titrated while hot with 0.05 N. sodium hydroxide using phenolphthalein as an indicator. The result secured, calculated in terms of $CaCO_3$ per 2,000,000 pounds of soil and multiplied by 2.4, gives the lime-requirement.

THE ALKALI CONTENT OF SOILS

Just as it is necessary to have a means of measuring the amount and intensity of the acidity in soils of humid regions and the amount of lime necessary to be applied to change the reaction

to that best suited to the needs of a given crop, so also it is necessary to have some means of determining the amount and intensity of the alkalinity of soils of arid regions and the extent to which it may be feasible to apply corrective measures.

In soils that are alkaline in reaction it is necessary to determine both the total content of soluble salts and the degree of alkalinity. The indicator method of determining *p*H can be employed as a measure of the intensity of the alkalinity. The quantity of alkali carbonates can be determined by titration of the soil extract with potassium acid sulfate and the use of phenolphthalein and methyl orange indicators. Phenolphthalein indicates the point of complete change of carbonates to bicarbonates from which the content of carbonates can be determined. Methyl orange indicates the neutralization point of the bicarbonates.

The total salt content of alkali soils can be estimated by the use of the Wheatstone bridge, by which the resistance to the passage of an electric current is measured. The resistance decreases in proportion to the increase in content of soluble salts in the soil solution. The usual procedures are followed for the determination of the quantities of each of the several cations and anions that may be present. Alkali soils contain varying amounts of sodium, potassium, calcium and magnesium as the sulfates, chlorides, carbonates and nitrates.

MATERIALS FOR REGULATING THE SOIL REACTION

The corrective agent employed to reduce the acidity of soils is usually calcium or magnesium in the oxide, hydrate or carbonate form. These products have their origin in limestones which vary in their composition from nearly pure calcium carbonate to nearly pure dolomite. The percentage of impurities varies within wide limits. Usually if these impurities constitute more than 15 per cent of the limestone it is not used for agricultural purposes both because of the wear on the machinery of pulverization and the weight of useless material that must be handled.

In some localities there are deposits of marl or chalk which are used on the soil after being pulverized. These often contain from 75 to 95 per cent of calcium carbonate. A number of manufacturing processes have hydrated lime or carbonate of lime as

by-products. These are also useful on acid soils. Blast furnace slag is another product which has been shown to be of value for this purpose. Most of the lime is present in the slag in silicate combination.

Of the products that are used for making soils acid and correcting alkali, four merit special mention. These are sulfur, sulfuric acid, ammonium sulfate and calcium sulfate. The first three, on being applied to the soil, produce acid effects. The last mentioned is useful in precipitating the carbonates of sodium and potassium as calcium carbonates as a result of which the alkalinity of the soil solution is reduced.

Sulfur and other acid-forming substances, on being applied to alkali soils, produce sulfates of the alkalies and alkali-earths. On acid soils the sulfates produced are those of iron and aluminum. If the soil is already somewhat acid in reaction and a greater degree of acidity is required, as may be desirable in controlling scab on potatoes, in growing bent grasses on golf greens, in making rhododendrons grow in locations outside of their natural habitat, commercial alum may be used, since it meets the requirements equally well and has the advantage that there is somewhat less danger of producing spots of excessive acidity such as may occur if sulfur is employed and even distribution is not effected.

For meeting the needs of acid-soil shrubs and flowers the beds are prepared by the use of leaf mold, sawdust, pine needles, apple pomace or even sour milk and are top-dressed from time to time with sulfate of ammonia.

EFFECT OF FERTILIZER SALTS ON SOIL REACTION

It will be recalled that sulfate of ammonia is particularly useful on golf greens or in other locations where the bent grasses and fescues are desired, because of its capacity, when used in considerable amounts, to make the soil acid. Similarly other fertilizer materials have secondary effects on the soil reaction. Of these cyanamid, basic slag, wood ashes, potassium carbonate and sodium, potassium and calcium nitrates may be mentioned for their alkaline effects and ammonia salts and some organic ammoniates for their acid effects.

A series of tests of the effects of fertilizers on the reaction of a

limed silt loam soil, normally very acid in reaction and having a *p*H of about 4.5, to which they had been applied each year for more than twenty years, is given in the following table.

TABLE LXIV

EFFECT OF FERTILIZER SALTS ON THE SOIL REACTION (BURGESS) *

Carriers of Nitrogen		Carriers of Phosphorus		Carriers of Potassium	
Material	*p*H	Material	*p*H	Material	*p*H
Nitrate of soda	6.3	Basic slag	5.87	Kainit	6.53
Hen manure	6.0	Bone meal	5.70	Extra sulfate	6.45
Dried blood	5.8	Phosphate rock	5.65	Sulphate of potash	6.40
Tankage	5.8	Acid phosphate	5.52	Manure salts	6.40
Sul. of ammonia	5.7*	Superphosphate	5.52	Muriate of potash	6.30
None	6.1	None	5.41	None	6.06

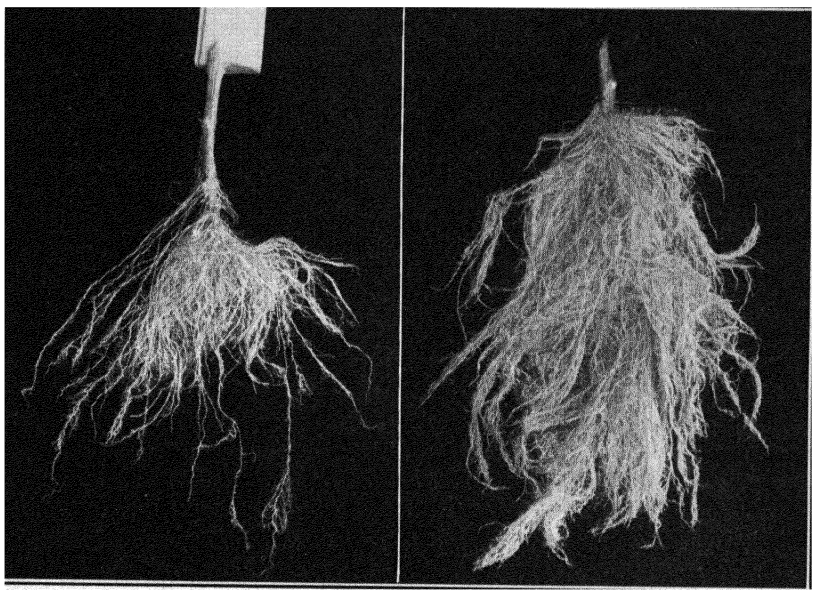
* In these tests, covering considerable periods of time, the soil received relatively small amounts of lime and other fertilizer materials. The data for each fertilizer element are comparable, with the exception of the case of sulfate of ammonia, where a calculation was necessary from other data that were available.

From the above data it is evident that the net effect of the use of fertilizers, other than most of the carriers of nitrogen, is to decrease the effective acidity of the soil.

RELATIVE MERITS OF VARIOUS LIMING MATERIALS

In general, the more intensive the agriculture the greater the tendency to use burned or hydrated lime or finely pulverized limestone. This is because the acreage is usually small; the crops have a high acre-value which makes the extra cost of less importance; and quick effects are desired. In the New England States, New York, Pennsylvania, New Jersey, Delaware and Maryland the burned and hydrated or carbonated products are employed in largest amounts. In Ohio, Indiana, and Michigan, more use is made of ground and pulverized limestone. Farther west, limestone screenings are largely used. These generalizations may be set aside in any given locality by reason of the local production of some other liming material or the convenience of obtaining some by-product that is useful on acid soils.

It is a well-known fact that the elements calcium and magnesium have other functions in the soil and plant than those of simply neutralizing acids. It is probable, therefore, that in some cases a high-calcium stone or its product will be more effective than will a dolomitic stone or its product. The reverse of this may also



Acid Soil Limed Soil

FIG. 54.—Effect of an application of lime to an acid soil on root system of plant. (Courtesy New Jersey Agricultural Experiment Station.)

be true. However, most investigators agree that the primary purpose of liming the soil is to regulate the soil reaction to correct certain acid-soil conditions which interfere with the growth of plants.

On this basis the relative merits of the several liming materials can ordinarily be ascertained from their neutralizing capacities and their rates of solubility. If, for any reason, it seems desirable to develop considerable alkalinity in the soil, which is ordinarily not the case, then there is reason for choosing from among the oxide or hydrate forms.

RELATIVE NEUTRALIZING POWERS OF LIMING MATERIALS

Assuming that the liming materials contain no impurities, their relative neutralizing powers may be calculated from their

formulas as indicated below, giving calcium carbonate a value of 100 as a standard for comparison.

TABLE LXV

NEUTRALIZING CAPACITIES OF EQUAL WEIGHTS OF LIMING MATERIALS

Assuming Chemically Pure Materials	Relative Capacity *
Calcium carbonate or limestone	100
Calcium oxide or burned lime	179
Calcium hydroxide or hydrated lime	135
Calcium-magnesium carbonate or dolomite	108
Calcium-magnesium oxide, magnesian lime	207
Calcium-magnesium hydroxide, magnesian hydrated lime	151

* Neutralizing capacity of 100 pounds of pure material in comparison with an equal weight of calcium carbonate.

As the table indicates, 100 pounds of hydrated lime are equivalent in neutralizing power to 135 pounds of limestone. Of particular interest is the fact that magnesian limestone, or dolomite, is more effective per unit of weight than is a high-calcium limestone. It happens, however, that the rate of solution of a dolomitic limestone, or of the dolomitic part of a limestone containing both calcium carbonate and dolomite, is only about 50 per cent as rapid as is that of a high-calcium stone. For coarsely ground products this is a matter of considerable importance. For finely ground materials, it is of much less importance since a point is finally reached at which the rate of diffusion is the limiting factor in the rate of solution and in the rate of effectiveness in the soil.

A more useful method of presenting the facts that are contained in the preceding table is to recalculate these values in terms of the amount of material that must be applied to secure results equivalent to that produced by the use of one ton of calcium carbonate. The results of these recalculations are shown in Table LXVI.

In proportion as the freight and handling charges increase, the delivered cost of a ton-equivalent of limestone is more likely to be less for the oxide or hydrated forms.

TABLE LXVI

POUNDS EQUIVALENT OF ONE TON OF CALCIUM CARBONATE

Assuming Chemically Pure Materials	Relative Amounts
Calcium carbonate, or limestone	2000
Calcium oxide, or burned lime	1120
Calcium hydroxide, or hydrated lime	1480
Calcium-magnesium carbonate, or dolomite	1850
Calcium-magnesium oxide, or magnesian lime	965
Calcium-magnesium hydroxide, or magnesian hydrated lime	1325

DETERMINING THE PURITY OF LIMESTONE

It is often desirable to have a simple test for determining the percentage purity of a sample of limestone that is being considered for use on the farm either after being burned in a home-made kiln or being pulverized by a small crusher. A very easy means of doing this is given below.

A 5-gram sample of the crushed material is placed in the bottom of a 500-cubic centimeter Erlenmeyer flask containing 25 cubic centimeters of water. The flask is closed with a 2-holed rubber stopper. In one hole of this is fitted a thistle tube with stop cock in which is placed 25 cubic centimeters of concentrated HCl. The second hole is fitted with a glass tube leading into a bottle also stoppered with a 2-holed cork and containing 100 cubic centimeters of concentrated sulfuric acid. One hole of this stopper is left open.

The whole apparatus, including the sample and liquid, is weighed on a torsion balance. The HCl is then allowed to run into the flask, care being taken to have the end of the thistle tube below the top of the liquid in the flask. After the reaction has come to completion, the entire apparatus is again weighed. The loss in weight is CO_2 from which can be calculated the $CaCO_3$ equivalent of the stone.

EVALUATING THE FINENESS OF LIMESTONE

In measuring the fineness of limestone, use is made of a set of screens varying in their fineness. Normally the screens employed are those containing 10, 50 and 100 meshes per square inch. Two products are compared on the basis of the percentage of each of them that passes these screens.

Since the rate of solution of limestone is proportional to the amount of surface exposed to the dissolving agent, ordinarily the

soil, it seems more logical to evaluate the fineness as determined by the sieve test, in terms of the relative surface exposed to solution. Assuming that the particles were spheres, cubes or any other regular or irregular design and assuming that this design does not change on continued pulverization, one can then calculate relative surfaces by the following method of procedure.

Taking two samples of ground limestone for examples, determinations are made of the quantities passing 100, 48, 28, 14, 8 and 4 standard mesh screens. By reducing a piece of limestone to smaller particles, as the diameters are cut in two the surface exposed is doubled. The factor to apply to each separate is thus indicated in the following table.

TABLE LXVII

SURFACE OF LIMESTONE IN TERMS OF 100 MESH PRODUCT

Sample I				Sample II			
Mesh	Per Cent	Factor	Product	Mesh	Per Cent	Factor	Product
100	46.0	1	46.0	100	83.0	1	83.0
48	19.0	$\frac{1}{2}$	9.5	48	12.4	$\frac{1}{2}$	6.2
28	19.2	$\frac{1}{4}$	4.8	24	4.6	$\frac{1}{4}$	1.1
14	13.6	$\frac{1}{8}$	1.7	14	0.0	$\frac{1}{8}$	0.0
8	2.2	$\frac{1}{16}$	0.1	8	0.0	$\frac{1}{16}$	0.0
4	0.0	$\frac{1}{32}$	0.0	4	0.0	$\frac{1}{32}$	0.0
	100.0		52.1 *		100.0		89.2 *

* Shows the practical contribution that has been made by the limestone producer. If one allows 5 cents for each per cent of " relative surface " the first product is worth $2.60 per ton at the plant as compared to $4.46 per ton for the second. An additional $1.50 per ton must be added to the second product if it is sacked. On this basis a limestone product all of which passes a 100-mesh screen would be valued at $5.00 per ton at the plant, plus $1.50 if sacked.

One knows from the " neutralizing power " and the " relative surface " the total and immediate values of the product for correcting soil acidity. The question naturally arises as to the extra value that the material that is finer than 100-mesh might be assumed to have. It is questionable whether this extra fineness is of any added value. Products that are 100-mesh, if properly distributed in the soil, will dissolve in a relatively short time. The gain in time by applying the 200-mesh material is not

important. Secondly, the machinery for spreading limestone does not have the efficiency that is required to bring each of the particles of the 200-mesh product, or even any large percentage of them, in touch with different particles of soil.

It seems quite logical to believe that, for any given limestone, the various products that may be made from it have relative values that are quite similar to those that may be secured by the above method of calculation, if immediate effects are desired for the crop to which the limestone is applied.

RELATIVE MERITS OF VARIOUS ACID-FORMING MATERIALS

In so far as is known there is little choice from among the several acid-forming materials that are applied to soils except

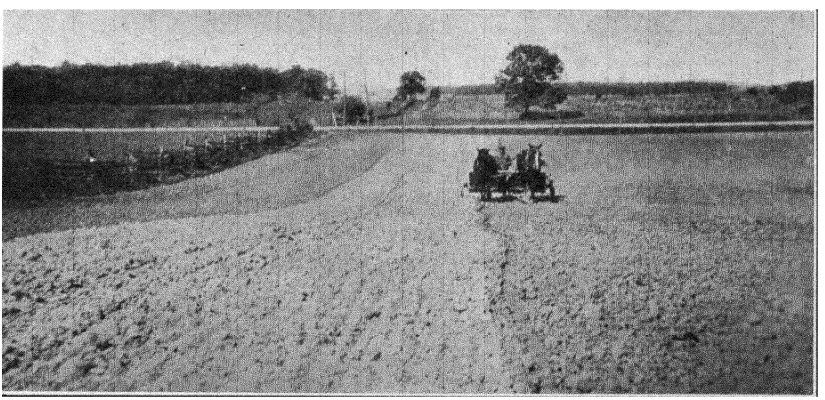


FIG. 55.—Unless some kind of liming material is applied from time to time, soils in humid regions usually become too acid for satisfactory yield of crops.

on the basis of their total neutralizing power. The equivalents of these materials can be calculated in terms of calcium carbonate, if desired. In the case of ammonium salts, two acids are produced as a result of their oxidation in the soil. One of these is nitrous acid and the other that of the acid radical combined with the ammonium.

The acidulating effect on the soil of any of these materials is determined by the balance between the amount of acid produced and that consumed by any vegetation that may be growing on the soil. Thus the ammonium radical, even though it is oxidized to

nitrous acid and neutralized by lime, may be absorbed by the plant. The lime, at least in part, may remain in the soil to neutralize other acidity that may be produced. In fact, the permanently acidulating effect of any material is determined by the amount of basic material that is required to combine with that portion of it that is not used by plants. In humid regions this can normally be determined from the quantity of the acid radical that escapes in the drainage water.

SOLUTION OF PROBLEM OF CONTROLLING SOIL REACTION

In general, the problem of regulating the soil reaction is one of adjusting it to some place between 6 and 7 *p*H by the use of either acid-forming or alkali-forming materials, as required. In humid regions it is the aim ordinarily to maintain the soil reaction at about 6 *p*H. For plants that are acid-loving, somewhat smaller amounts of lime than are required to maintain the soil at 6 *p*H may suffice. For crops that are especially sensitive to acidity, more lime may be required. Sugar beets, for example, grow best at a *p*H of 7 or better. Similarly it is best to have the *p*H for alfalfa and sweet clover near the neutral point.

Ordinarily, if the soil solution becomes very acid in reaction, aluminum will be present in toxic concentrations for plants that are sensitive to it. If the soil is too close to the neutral point there may be a deficiency of iron or manganese, and perhaps also of aluminum, if this is essential.

Fortunately soils seldom become more acid than is indicated by 5 *p*H. The quantity of limestone that is required to raise this to 6 *p*H and to maintain it at that point varies with the nature of the soil and the amount of rainfall. As a general rule, it is believed that if the original lime-requirement of the soil has been satisfied by the application of whatever amount of liming material may have been required to raise it to 6 *p*H, the soil can be maintained at this point by the use of one ton of finely ground limestone, or its equivalent in other materials, every five to eight years.

The problem is much more difficult in the case of alkali soils since both high salt content and alkalinity are involved and there is ordinarily little possibility of having the soil leached with

water except at considerable expense for tile and irrigation water. The complications involved are such that each case must be considered by itself and very little in the way of general suggestions can be made except as indicated in certain phases of the above discussion.

SELECTED REFERENCES

1. Bear, F. E. Soil Management. John Wiley & Sons, New York City. Second Edition, pp. 222–234 and 267–283, 1927.
2. Bear, F. E., and Allen, L. Relation between fineness of limestone particles and their rates of solution. Ind. Eng. Chem., Vol. 24, p. 998, 1932.
3. Burgess, P. S. The reaction of soils in the field as influenced by the long-continued use of fertilizer chemicals. Rhode Island Agr. Exp. Sta. Bul. 189, 1922.
4. Frear, W. Sour soils and liming. Pennsylvania Dept. Agr. Bul. 261, 221 pp., 1915.
5. Harris, F. S. Soil Alkali, Its Origin, Nature and Treatment. John Wiley & Sons, New York, 259 pp., 1920.
6. Hartwell, B. L. and Damon, S. C. The comparative effect on different kinds of plants of liming an acid soil. Rhode Island Agr. Exp. Sta. Bul. 160, 1914.
7. Hartwell, B. L. and Damon, S. C. A field comparison of hydrated lime with limestone of different degrees of fineness. Rhode Island Agr. Exp. Sta. Bul. 180, 1919.
8. Kelley, W. P. and Brown, S. M. Ion exchange in relation to soil acidity. Soil Science, Vol. 21, pp. 289–302, 1926.
9. Stephenson, R. E. Soil acidity methods. Soil Science, Vol. 6, pp. 33–53, 1918.
10. Tarr, L. W. and Noble, S. C. The effect of hydrogen-ion concentration upon the growth of seedlings. Delaware Agr. Exp. Sta. Bul. 131, 1922.
11. Truog, E. Soil acidity, its relation to the growth of plants. Soil Science, Vol. 5, pp. 169–197, 1918.
12. White, J. W. The value of limestone of different degrees of fineness. Pennsylvania Agr. Exp. Sta. Bul. 149, 1917.

CHAPTER XIX

SUPPLYING ORGANIC MATTER



Selman A. Waksman.

THE growing intensity of our agriculture; the necessity of having larger acreages under more nearly continuous cultivation; the substitution of motor power for horse power; and the sale of what were formerly crop residues for the production of materials to be used for purposes of food, clothing or shelter rather than to be plowed under, make the problem of maintaining an adequate supply of organic matter in the soil one that is increasingly difficult of solution.

There is no question but that fertilizers can be substituted for manure, clovers and crop residues in so far as they may be needed as sources of nitrogen, phosphoric acid, potash and other mineral nutrients. Their use also makes it possible to produce larger crop yields with heavier roots and stubble, if arrangements can be made for suitable rotations in which a satisfactory ratio between sod crops, legumes and similar uncultivated crops can be alternated with those which require clean cultivation.

In proportion as it becomes desirable to increase the acreage of cultivated crops and to reduce the area in sod, particularly under conditions in which little or no manure is available for use, resort to some scheme for providing extra organic matter would seem to be essential. The possibilities in this connection will be considered.

MANURE AS A SOURCE OF ORGANIC MATTER

The value of manure as a source of organic matter has been grossly exaggerated. This is apparent if one considers the composition of manure and the quantity which is available for applica-

tion on the ordinary farm. Thus the average manure is made up of about 75 per cent water and 25 per cent organic matter. In one ton of average manure there are 1500 pounds of water and 500 pounds of organic matter containing about 12 pounds each of nitrogen and potash and 5 pounds of phosphoric acid together with small amounts of calcium, magnesium, sulfur, iron and other nutrients that were contained in the feed.

A 12-ton application of manure supplies the soil with 6000 pounds of very readily decomposable organic matter. If the farmer succeeds in applying 12 tons of manure per acre to all of his land every third year, he is doing exceptionally well. This would give the soil an average yearly application of 2000 pounds of organic matter.

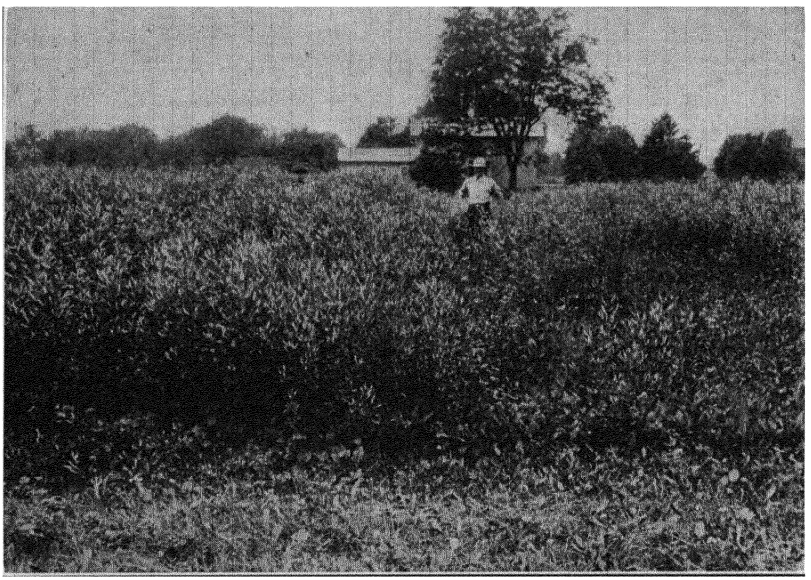
THE ORGANIC-MATTER CONTENT OF SOILS

The determination of the quantity of organic matter in soils is somewhat difficult. Estimates based on "loss on ignition" are not satisfactory since, by heating the soil to a low red heat, water and other volatile substances, as well as organic matter, are driven off and additional oxygen is taken on. However, it has been found by investigation that there is a fairly definite relationship between the nitrogen and organic matter content of soils. This ratio, in humid climates, averages approximately 1 : 20. In semi-arid climates it is somewhat higher, although the ratio seldom exceeds 1 : 30. The average soil contains about 3500 pounds of nitrogen per acre to plow depth. Assuming a ratio of 1 : 20, the organic matter content of the surface 2,000,000 pounds of such a soil amounts to about 70,000 pounds.

If a farmer applied 12 tons of manure every three years, as previously indicated, and thereby made an annual contribution of 2000 pounds of organic matter to his soil, it would require thirty-five years to double the organic matter content of the average soil, even if none of the manure ever decomposed. But manure is full of the bacteria of decomposition. If it is well cured before being applied, very little of it will remain at the end of the three-year period when the time for the next application arrives in the scheme suggested above. Certainly the organic matter content of the soil could not be materially increased by this procedure if the manure was the only source of organic matter.

CROP RESIDUES AS A SOURCE OF ORGANIC MATTER

The most important source of organic matter in soils on livestock farms is not the manure itself but the residues of the increased crops that are produced as a result of the use of manure. But crops yields, both as to roots and tops, can be increased by the use of fertilizers and lime as well as by the use of manure. In fact, manure alone is not entirely satisfactory as a crop pro-



Limed Not limed

FIG. 57.—Sweet clover is one of the best of the green-manuring crops. Note the two men in the picture.

ducer. Its effectiveness can be very much improved by reënforcing it with phosphate and by the supplemental use of some form of lime. The effect of the phosphate is nicely shown in the accompanying table giving the thirty-year average crop increases produced by manuring the soil at Wooster, Ohio. The soil in the case was limed as required. Other evidence indicates that if potash as well as phosphate had been added to the manure the crop yields might have been still further increased over those produced by the use of manure alone, although this need might have been met by applying more manure per acre.

TABLE LXVIII

AVERAGE * ACRE INCREASES WITH 8 TONS MANURE ON CORN (THORNE)

	Corn, Bushels	Wheat, Bushels	Clover, Hundredweight
Phosphated manure†	35.20	15.93	21.47
Stall manure	27.43	10.18	12.86
Open-yard manure	21.38	9.25	8.79

* Thirty-year averages.

† Sixteen per cent superphosphate, at a rate of 40 pounds per ton, was scattered over the manure before it was hauled to the field.

The organic matter of the manure, plus that of the increased yields produced as a result of the use of the manure reënforced by the superphosphate, may be sufficient to meet the need for this constituent in the soil, if a suitable rotation is followed. However, fertilizers can be substituted for manure and equally large yields can be produced as by the use of manure, if a suitable rotation is followed in this case as well. This is indicated in the accompanying table, which gives not only the total produce of crops resulting from the use of fertilizers and manure but the effect of the treatments on the soil organic matter as well.

TABLE LXIX

EFFECT OF FERTILIZERS ON ACCUMULATION OF ORGANIC MATTER (BEAR)

Treatment of Soils	Fertilizers Applied in 15 Years, Tons per Acre	Total Produce in 15 Years, Pounds per Acre	Organic Matter in Soil at End, Pounds per Acre
No fertilizer	None	40,960	42,800
Complete fertilizer	5	117,910	60,800
Manure	190	139,670	73,600
Complete fertilizer and lime	7½*	120,605	49,000
Manure and lime	212½	152,400	65,000

* 2½ tons of burned lime.

The use of 5 tons of complete fertilizer during the fifteen-year period resulted in an increase of over 40 per cent in the content of organic matter in the plowed acre of soil. Manure made an addi-

tional contribution to the supply of soil organic matter but the manure was applied in very large amounts. The total amount of nitrogen, phosphoric acid and potash in the manure applied is estimated at 1080, 450 and 1080 pounds, respectively, as compared to only 630, 675 and 815 pounds, respectively, in the 5 tons of fertilizer that were used. If as many pounds of nutrients had been applied in the form of fertilizer as in manure, the crop yields and the content of organic matter in the soil of the fertilizer-treated plots would probably have been as high as it was in that of the manured plots.

It is necessary to add that during the 15-year period of the test the soil was cropped to four clean culture crops, five small grains and six hay crops. No such increase in organic matter content could be expected if the soil had been kept under clean cultivation. On the plots on which lime was used, this was added in excess of the requirements with the result that the rate of decomposition of the soil organic matter was increased out of proportion to the ability of the lime to produce increased yields. As a result less organic matter was accumulated than where the lime was not used.

FERTILIZER AS A SOURCE OF ORGANIC MATTER

As a direct source of organic matter, modern fertilizers are of little or no value. Originally fertilizers that were dark in color as a result of the use of organic materials, either as filler or as sources of nitrogen, were much more popular than were those that were light in color. At present, no discrimination is made with respect to color. Most of the more concentrated fertilizer formulas carry little or no organic matter. It is becoming generally recognized that the function of fertilizer, as relates to soil organic matter, lies in the production of larger amounts of roots and stubble or in heavier growths of green manures or weeds for plowing-under purposes.

Thus the larger the amount of fertilizer used on wheat the larger the quantity of roots and stubble, the better growth of ragweeds after the wheat is harvested, and the more rapid growth of any clover that may have been seeded in the wheat. The following year the clover will be larger, it will yield a heavier

second growth containing a higher percentage content of mineral nutrients and nitrogen. This is available either for feed or for plowing under.



(A) Manure at rate of 32 tons per care. Yield 263 bbls.



(B) 16 tons of manure per acre, supplemented by complete fertiliser. Yield 302 bbls.

FIG. 58.—Fertilizer can be used to advantage to replace part of the manure. (Courtesy Rhose Island Agricultural Experiment Station.)

If the larger crops that may be grown by the use of fertilizers are consumed on the farm as feeds, there is more manure to take

back to the field. The net effect of the right use of liberal amounts of fertilizer in suitable rotation cropping is the production of large amounts of organic matter for plowing-under purposes. The quantity produced is determined by the amount and quality of the fertilizer that is applied.

FERTILIZER FOR THE PRODUCTION OF GREEN MANURES

In the absence of manure or as a supplement to only limited quantities of it, use may be made of green manures grown as catch crops between the regular money crops. Thus in the corn, oats, clover, wheat rotation, sweet clover may be seeded in the wheat as a catch crop to be plowed under for corn. If the wheat has been well supplied with phosphate and potash, the sweet clover often produces a heavy growth during the same season and a second rank growth before it may be necessary to plow the ground in preparation for corn the following spring.

On a well-organized livestock farm, there seems to be little reason for plowing under any crop or part of a crop that has a feeding value since the roots, stubble, weeds and manure meet the requirements for soil organic matter. A heavy crop of sweet clover such as that indicated above might better be used for hay or pasture.

In intensive market-gardening, where the supply of manure is limited and it is expensive to grow green manures because of the value of land, both in early spring and late fall as well as in the summer, for the production of money crops, the problem is somewhat more complicated. Some gardeners feed steers entirely for the sake of their manure, the steers being kept in the stables, fed purchased feeds and bedded with purchased straw. From time to time between crops the weeds are permitted to grow for plowing-under purposes. Many of these, as for example the ordinary pigweed (Amaranthus), are very valuable green manures. They grow very rapidly on well-fertilized soil.

In the absence of manure it seems probable that some system of cropping will have to be devised by which a portion of the land is set aside each year for rest and the production of its own organic matter. Probably if the land that was being used for intensive cropping could be divided into 5 or 6 tracts, each of

which was devoted in its turn to the purpose of self-rejuvenation by growing green manuring crops and turning them under, more could be produced on a given acreage of land than would be possible if all of the land was devoted to cropping from early spring to late autumn every year.

ARTIFICIAL MANURE

All the plant refuse about the farm that is not fed to livestock should be worked into the soil as such or after it has been decomposed in the compost pile. A good grade of manure can be made from such material by building it up into a heap in layers a foot in thickness, each of which is wet with water and sprinkled with nitrogen, phosphoric acid and lime. The heap should be built to a height of six feet or more and should be kept moist during the period of decomposition. After about three months the product will be ready for use.

For one ton of dry straw or similar material, use should be made of about 100 pounds of sulfate of ammonia, 100 pounds of limestone, and 50 pounds of superphosphate. If desired 100 pounds of calcium cyanamid can be substituted for the sulfate of ammonia and limestone. Other forms of ammonia or organic nitrogen may be used. Nitrates should be avoided by reason of possible loss of nitrogen by denitrification.

Any kind of organic materials may be employed for this purpose. However, if coarse products such as cornstalks and similar materials are to be used, more rapid decomposition is effected by having them shredded or cut into short lengths before placing them in the heap. The best season of the year in which to build the heap for the production of artificial manure is in the spring or autumn, when there is more rainfall and much slower evaporation. The essential point is to keep the pile moist throughout.

An equally effective method of procedure is that of growing a heavy sod or a mature cover crop, treating it with nitrogen, and plowing it under. Organic material having a dry weight of 5 tons per acre, treated with 100 pounds of nitrogen and the necessary lime and plowed under will produce about the same effect as an application of 10 tons of manure. It remains to be deter-

mined whether anything would be gained by applying a complete fertilizer, instead of nitrogen only, in advance of plowing. Possibly the phosphoric acid and potash can be used to better advantage, if saved for application along the row at planting time.

THE CARBON-NITROGEN RATIOS IN ORGANIC MATTER

It will be noted in the above method that the addition of nitrogen and phosphoric acid, as well as limestone, is essential to the rapid decomposition of organic matter. Reference has previously been made to this problem. It remains to consider this principle in connection with the use of fertilizers.

Gardeners have long known that manure should be well cured before being applied; that cornstalks and similar coarse materials are highly objectionable when mixed with the soil; and that mature rye plowed under is usually followed by poor crops. It is now known that a solution of the difficulty that is experienced in this connection is found in the application of liberal amounts of nitrogen and phosphoric acid fertilizers and limestone, the constituents which are in deficiency in these coarse organic products.

The rate of decomposition of soil organic matter depends upon the extent to which the requirements of the bacteria of decomposition have been met. All bacteria require large amounts of nitrogen and phosphoric acid for their nutrition. Limestone is required for neutralization purposes. Whether extra potash must also be supplied is problematical. In general, however, the greater the ratio of the ordinary fertilizer constituents to the organic matter the more rapid the rate of decomposition. In fact, it has been shown that if the supply of fertilizer nutrients is inadequate, the bacteria become such active competitors with the crop plants for such amounts of these as are available that the crop suffers. Therein is the explanation of the bad effects of strawy manure and similar materials except as they have been plowed under a long time in advance of planting the crop.

This points to the value of fertilizer for use in growing catch crops and other green-manures. By adding large amounts of a well-balanced fertilizer much larger quantities of green manure can be produced. This material, by reason of its high content

of fertilizer nutrients which it has absorbed from the soil, is a very suitable organic food for the soil organisms. It, therefore, decays very rapidly when plowed under.

THE DECOMPOSITION OF SOIL ORGANIC MATTER

It is evident that while the organic matter content of soils is an important factor in determining its productivity, certain types of organic matter have quite the contrary effect. It would seem that the value of organic matter is proportional to its rate of decomposition. What is desired, therefore, is not the accumula-

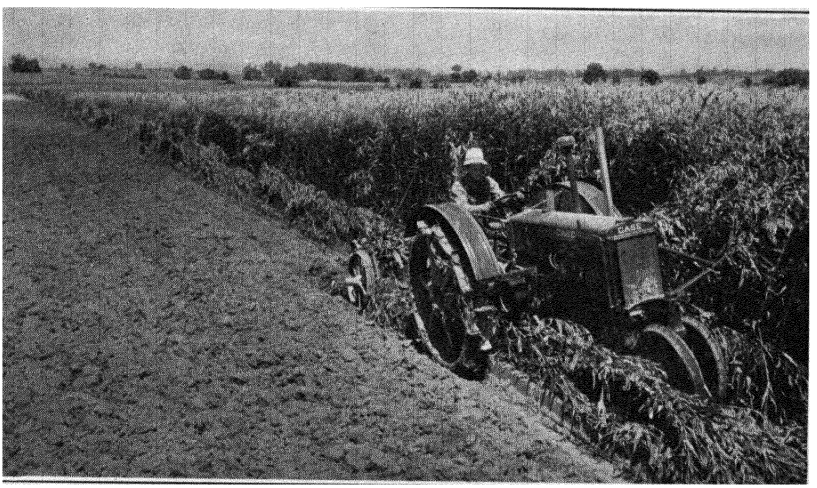


FIG. 59.—Treated with nitrogen and lime and plowed under, this type of material makes excellent manure in the soil.

tion of organic matter in soils but the constant passing through the soil of rapidly decomposing organic matter. However, in proportion as larger amounts of readily decomposable organic matter are added to the soil, the content of living organisms in the soil is increased to a higher level and these constitute a larger portion of the soil. In fact, a large proportion of the humus material in highly productive soils is nothing more or less than the living and dead bodies of soil bacteria, fungi, and protozoa.

The application of organic foods permits the rapid increase in numbers of certain groups of soil organisms. With the consumption of this organic matter, other groups come into the ascendency.

Crop plants profit by the constant struggle between competing groups of organisms to secure their necessary nutrients from the soil. With each application of lime, fertilizers, organic matter or manure and with each operation of plowing, cultivating, rolling, draining or other mechanical procedure, one or another group gains the ascendency only to lose it later to the advantage of the crop that is constantly standing by selecting what it requires and at times absorbing much more than it can use to advantage.

At present the farmer is the only producer of organic materials for improving the biological, physical and chemical properties of his soil. These materials are left behind in crop residues or applied in the form of green manures, animal manures and waste organic products. Often considerable expense is entailed in securing such materials for plowing-under purposes.

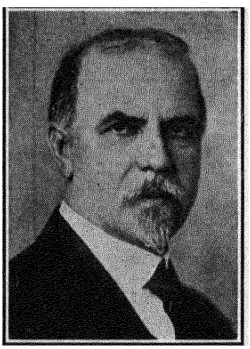
It is possible that as agriculture becomes more intensive and as land must be kept more continuously under cultivation the fertilizer industry may be called upon to produce organic manures in quantity for use as supplements to the inorganic types now being sold.

SELECTED REFERENCES

1. Albrecht, W. A. Artificial manure production on the farm. Missouri Agr. Exp. Sta. Bul. 369, 12 pp., 1936.
2. Bear, F. E. and Salter, R. M. The residual effects of fertilizers. West Virginia Agr. Exp. Sta. Bul. 160, 26 pp., 1916.
3. —— Soil Management, second edition, John Wiley & Sons, New York City, pp. 159–175 and 235–251, 1927.
4. Pieters, A. J. Green-Manures and Green Manuring. John Wiley & Sons, New York City, 1928.
5. Salter, F. J. and Others. Symposium on soil organic matter. Jour. Amer. Soc. Agron., Vol. 19, pp. 362–466, 1927.
6. Waksman, S. A. Principles of Soil Microbiology, Williams & Wilkins, Baltimore, pp. 504–520 and 669–708, 1927.

CHAPTER XX

TRACE ELEMENTS IN SOILS AND CROPS



Oswald Schreiner.

Terms such as "minor," "trace," or "rare" are used to designate those elements which, when present in small amounts, favorably influence plant growth. These elements were originally known as "plant poisons" because, when used in even moderate doses, they may be injurious to crops. Minute quantities, however, are often beneficial, acting as stimulants to plant growth. Some of the earliest work with such materials was carried on at the Rothamsted Experimental Station in England.

At the beginning of the twentieth century, most fertilizers were derived from plant and animal products. These products contain many of the so-called minor elements. The decreasing supplies of natural organics, including animal manures, and the increased use of synthetic fertilizers and pure salts, coupled with the loss of organic matter from the soil, have resulted in deficiencies which have been manifesting themselves more and more for a number of years. The economic importance which these deficiencies have assumed is evident when the widespread evidence of crop failure because of them is considered. However, most inorganic fertilizer materials carry appreciable amounts of one or more of these trace elements and may have added value by reason of this fact.

TRACE ELEMENTS IN FERTILIZER MATERIALS

The following table shows the results of spectrographic analyses of various commonly used fertilizers and soil amendments.

TABLE LXX

SOME MINERAL CONSTITUENTS IN FERTILIZER MATERIALS—GADDUM AND ROGERS

	Barium	Strontium	Nickel	Cobalt	Manganese	Vanadium	Titanium
Gypsum	.05–.1	.1–.5	N.D.	N.D.	.005–.01	TR	.03–.08
Limestone	.01–.05	.1–.5	N.D.	N.D.	.05–.1	.005–.01	TR
Dolomitic limestone	.01–.05	.01–.05	N.D.	N.D.	.05–.1	N.D.	.01–.05
Hardwood ashes *	1% †	1% †	.01–.05	.001–.005	1% †	TR	.1–.5
Superphosphate	.05–.1	.1–.5	TR	N.D.	.1–.5	.01–.05	.005–.01
Ammonium phosphate	.05–.1	.1–.5	.008–.03	TR	.08–.3	.1–.5	.005–.01
Bone meal (raw) *	.05–.1	.08–.3	N.D.	N.D.	.03–.08	N.D.	.008–.03
Sulfate of potash	.005–.01	.1–.5	N.D.	N.D.	.005–.01	N.D.	N.D.
Kainit	.005–.01	1% †	N.D.	N.D.	.005–.01	N.D.	.01–.05
Nitrate of soda No. 1	TR	.01–.05	N.D.	N.D.	.005–.01	N.D.	N.D.
Nitrate of soda No. 2	.01–.05	.01–.05	N.D.	N.D.	N.D.	N.D.	N.D.
Sulfate of ammonia No. 1	TR	N.D.	N.D.	N.D.	.005–.01	N.D.	N.D.
Sulfate of ammonia No. 2	TR	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Tobacco stems *	.03–.08	.03–.08	TR	N.D.	.08–.3	.008–.03	.01–.05
Cottonseed meal *	.001–.005	TR	TR	TR	.003–.008	N.D.	N.D.
Fish scrap (foreign) *	.008–.03	.01–.05	TR	N.D.	.01–.05	TR	.005–.01
High grade tankage *	.01–.05	.01–.05	N.D.	N.D.	.01–.05	N.D.	.005–.01
Bird guano *	.01–.05	.03–.08	N.D.	N.D.	.03–.08	N.D.	.008–.03
Calcium cyanamid	.05–.1	.1–.5	N.D.	N.D.	.05–.1	TR	.005–.01
Manganese sulfate	.005–.01	.01–.05	.01–.05	.001–.005	P	N.D.	N.D.
Zinc sulfate (crystal)	TR	N.D.	TR	N.D.	.005–.01	N.D.	N.D.
Copper sulfate	TR	TR	.01–.05	N.D.	TR	N.D.	N.D.

TABLE LXX—*Continued*

SOME MINERAL CONSTITUENTS IN FERTILIZER MATERIALS—GADDUM AND ROGERS

	Silver	Copper	Tin	Zinc	Lead	Chromium	Boron
Gypsum	N.D.	.005–.01	N.D.	N.D.	TR	.001–.005	TR
Limestone	N.D.	.003–.008	N.D.	N.D.	N.D.	.003–.008	.01–.05
Dolomitic limestone	N.D.	.005–.01	N.D.	.01–.05	N.D.	TR	.01–.05
Hardwood ashes *	N.D.	.1–.5	.01–.05	?	.05–.1	.005–.01	.1–.5
Superphosphate	TR	.05–.1	N.D.	.1–.5	N.D.	.008–.03	TR
Ammonium phosphate	N.D.	.01–.05	N.D.	.05–.1	.03–.08	.01–.05	.1–.5
Bone meal (raw) *	N.D.	.008–.03	N.D.	.03–.08	.005–.01	.001–.005	.03–.08
Sulfate of potash	N.D.	.01–.05	N.D.	N.D.	N.D.	N.D.	N.D.
Kainit	N.D.	.001–.005	N.D.	N.D.	N.D.	TR	TR
Nitrate of soda No. 1	N.D.	.001–.005	N.D.	N.D.	N.D.	N.D.	N.D.
Nitrate of soda No. 2	N.D.	.001–.005	N.D.	N.D.	N.D.	TR	.05–.1
Sulfate of ammonia No. 1	N.D.	.05–.1	TR	.01–.05	TR	N.D.	N.D.
Sulfate of ammonia No. 2	N.D.	.005–.01	N.D.	TR	N.D.	TR	N.D.
Tobacco stems *	N.D.	.01–.05	N.D.	?	.008–.03	.001–.005	.05–.1
Cottonseed meal *	N.D.	.008–.03	TR	.001–.005	TR	TR	TR
Fish scrap (foreign) *	N.D.	.008–.03	N.D.	TR	N.D.	TR	TR
High grade tankage *	N.D.	.01–.05	N.D.	.01–.05	TR	TR	N.D.
Bird guano *	N.D.	.01–.05	N.D.	.001–.005	TR	TR	.01–.05
Calcium cyanamid	N.D.	.01–.05	N.D.	TR	N.D.	.003–.008	.05–.1
Manganese sulfate	N.D.	.01–.05	TR	.08–.3	N.D.	TR	.1–.5
Zinc sulfate (crystal)	N.D.	.01–.05	N.D.	P	.08–.3	N.D.	N.D.
Copper sulfate	.01–.05	P	N.D.	1% †	.05–.1	N.D.	N.D.

The figures in the table denote "percentage" and are on the dry basis. "P" denotes "present but not estimated"; " N.D. " denotes "not detected"; "TR" denotes "trace"; "?" denotes "possible trace but not positive identification"; "†" following a percentage value signifies that "the value given is a minimum."

* The data for these samples are expressed on the dry basis, although the analyses were made on the dry ash.

TRACE ELEMENTS OF KNOWN VALUE

Chief among the trace elements which have definitely proved valuable under field conditions are boron, copper, iron, magnesium, manganese and zinc. Under certain conditions, one or more of these elements must be added to the soil, otherwise the crop fails to grow satisfactorily. However, many soils seem to contain adequate amounts of all of them.

BORON

It has been conclusively established that a trace of boron is absolutely essential for the growth of many plants. In its absence the meristematic tissues are adversely affected and death ultimately results. Boron is a widely distributed element in the earth's crust and appears in appreciable quantities in certain waters and springs and in deposits formed by the evaporation of these waters. It is not, therefore, a rare element. Some deposits of potash have a high content of boron which is removed in refining. Early experiments made by the U.S.D.A. involved the use of native supplies of potash with a high boron content. In most instances these salts caused injury when applied in close contact with seed. Boron has also been found in toxic amounts in some of the irrigation waters of Southern California. At the same time, it has been found to be an essential element for the growth of citrus trees in that state. Normal mature leaves of citrus or walnut trees may contain as much as 100 p.p.m. of boron, based on the dry weight of the leaf material. Leaves of the same species, injured by boron, frequently contain more than 1,000 p.p.m. The boron accumulates, gradually reaching its maximum as the leaves mature.

In other parts of the United States, crops of beans, corn, cotton, lettuce, potatoes, and tobacco have all shown some benefit from suitable amounts and methods of application of boron. A deficiency of boron adversely affects nodule production of legumes by inhibiting the development of the vascular strands which supply the carbohydrate materials needed as a source of energy for the bacteria. Abnormal nodules are formed which are capable of fixing only about one-tenth of the nitrogen fixed in normal plants.

Abnormalities of market garden and field crops have been traced more recently to a lack of boron. This has been manifested in Florida by " cracked stem " of celery; in the Middle West, by " heart and dry rot " of sugar beets; in New York, by " brown rot " or " red rot " of cauliflower; in Maine and other states, by " water core " or " heart rot " of rutabagas and turnips. Such deficiency symptoms are readily recognized by their popular names.

These maladies in diverse sections have been found to respond to approximately ten pounds of borax per acre annually, applied in conjunction with the regular fertilizer treatment. Larger applications have caused injury in many cases, and smaller applications have been ineffective. Applications in the row are more likely to be injurious than broadcast applications. The extent of injury from larger applications is dependent upon the amount of rainfall. As high as fifty pounds of borax per acre have caused no damage in rainy seasons. Apparently, the boron is not fixed in the soil and is easily leached out. This accounts for the necessity of annual applications.

In some apple-growing sections of the world, " corky core " and " drought spot " of the fruit have caused great concern. In Nova Scotia, New Zealand and British Columbia, particularly, the greatest advances have been made in diagnosing these diseases as boron deficiency. Injections of boric acid into the tree have proved effective in overcoming this nutritional lack, but have caused injury to the trunk. For general horticultural practice, soil applications have been found preferable. The current recommendation in British Columbia is eight ounces of boric-acid crystals applied as evenly as possible in a circle at least 20 feet in diameter around the tree. Such an application, if made in the fall of the year, will permit of adequate absorption by the tree during the winter months and will show results in the next year's crop.

COPPER

The natural supply of copper has been found to be inadequate in certain peat and muck soils of Florida, Indiana, Michigan and New York. Copper sulfate, or blue vitriol, is the principal source of copper for agricultural purposes. The original work

with this element as a soil amendment was done on the raw-peat soils of the Florida Everglades, where it was discovered that the copper in Bordeaux mixture used for the control of insects acted as a stimulant to truck crops. Copper sulfate applied directly to the soil in amounts of 30 to 50 pounds per acre resulted in superior crops and increased yields. The high-lime, low-lime, and very acid mucks of Michigan and Indiana all respond readily to 50 pounds of copper sulphate per acre. The greatest response to copper is shown by the onion and lettuce crops on these soils.

In New York, muck that produced onions with thin, poorly colored scales, the tops of which died prematurely (" blasted "), responded to applications of finely ground copper sulfate up to 300 pounds per acre. The application can be made either with the regular fertilizer treatment or separately, and should not be renewed until there is evidence that the effect of previous applications is wearing off.

Citrus trees in Florida and California suffering from " die-back " (exanthema) have benefited by applications of copper sulfate of $\frac{1}{4}$ to 1 pound per tree, depending upon the size of the trees. Under some conditions this disease has been reported to be due to manganese deficiency. The disease is characterized by the dying back of the shoots and the exudation of gum.

An interesting fact about copper has been brought out by Cornell University. Popular varieties of cut flowers put into copper-plated containers stayed fresh for considerably longer periods than those flowers in ordinary glass or tin containers. It was found that some of the copper from the plated containers was dissolved in the water. The metal served to prevent the growth of bacteria and other organisms that cause decay.

IRON

The absence of iron in plant growth is characterized by a pathological chlorosis in the green parts of the plant. The small amount of iron present in most soils is sufficient to care for the iron requirements of plants. Oftentimes, however, there is an actual deficiency of available iron in the soil. An excess of lime in the soil interferes with the absorption and utilization of

iron by the plant. A similar condition exists when there is an excess of manganese.

Iron chlorosis, caused by an insufficiency of chlorophyll, appears first on the younger portions of the plant and later spreads to the older parts. In leaves, the tissues between the veins become yellow. This gradually spreads, causing the edges of the leaves to curl and dry. While a similar yellowing exists when there is a nitrogen or magnesium deficiency, the chlorosis produced by iron deficiency is more rapid and consequently more striking. This condition can be overcome by the administration of iron in suitable form directly to the plant by spraying or injection, or by soil application.

In many instances, as, for example, in pineapple fields, spraying the plants has been more effective than application to the soil. Ferrous sulfate, or copperas, has been used to good advantage in the pineapple fields of Hawaii where a manganese-induced iron deficiency exists. The corrective method followed is that of spraying the plants with a solution made from 32 pounds of copperas in 50 gallons of water. This use of copperas is a regular procedure on over half of the fields where pineapples are grown. A lime-induced chlorosis of pineapples and sugar cane also exists in Puerto Rico, and of grapes in France.

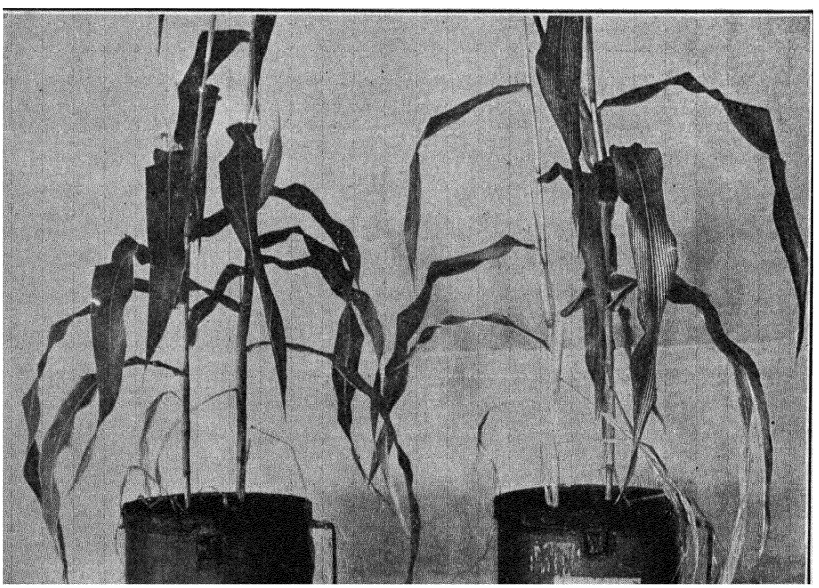
Applications of ferrous sulfate in combination with sulfur have been most effective in reducing the chlorosis of pin oaks. Fruit trees showing iron starvation have been known to respond to ordinary iron nails driven well into the trunk. This is not a generally recommended horticultural practice, however, and care must be taken not to injure the bark unnecessarily. Ferrous sulfate has been effectively used in California and New Mexico when placed in holes bored in chlorotic fruit trees such as pear, plum, prune, peach, and apricot. Bennett describes the procedure as follows:

" Wood contains about fifty per cent water and if a soluble iron salt is placed in a hole bored in live wood and the mouth of the hole is sealed, the salt absorbs water from the wood and dissolves and passes into the surrounding wood from which it passes to the branches with the sap stream. In applying this treatment $\frac{1}{4}$ to $\frac{7}{16}$-inch holes are bored in the larger roots, in the trunk above or below the ground level, or in branches. The holes should be bored three to four inches deep. In the bottom of each hole is placed from 1/100 to $\frac{1}{8}$ ounce of ground iron

salt. The hole and the amount of salt used should be so proportioned that the mass of salt does not come closer than half an inch from the mouth of the hole, in order to avoid burning of the bark around the hole by the salt. The mouth of the hole is then covered with a suitable wax."

MAGNESIUM

The greatest need to date for magnesium is in the sandy soils of those states along the Atlantic seacoast and those states bordering the Gulf of Mexico, as far west as the Mississippi River. Magnesium hunger is most frequently apparent on cotton, tobacco, potatoes, and truck crops. There is almost no crop



Magnesian Limestone No Magnesium

FIG. 61.—Effect on corn of a deficiency of magnesium. (Courtesy Massachusetts Agricultural Experiment Station.)

that escapes, however, since it affects citrus crops, and such field crops as corn, cowpeas, small grains and soybeans. Magnesium starvation is manifested by a yellow-brown mottling, together with a brittleness, raggedness and downward curling of the leaves —the older leaves being affected first. In cotton it is charac-

terized by green veins with purplish-red color between the veins. In tobacco and cotton this deficiency disease is known as " sand drown "; in potatoes as " potato sickness "; and in citrus as " bronzing."

The magnesium content of soils can be increased by applications of magnesium sulfate (epsom salts), kieserite, potassium-magnesium sulfate, magnesium-ammonium phosphate, and magnesium carbonate. Dolomitic limestones have a high magnesium content and serve the double purpose of correcting soil acidity as well as supplying magnesium.

To maintain the magnesium supply and prevent its being leached from the soil, green-manurial practices should be followed. As much as fifty pounds of this element is leached annually from uncropped soils, whereas if green-manure crops are turned under, as much as twenty to fifty pounds of magnesium will be retained in the soil. The use of animal manures, containing up to ten pounds of magnesium per ton, will considerably increase the amount of this element in the soil, especially when the manure is applied at the heavy rates recommended for truck growing. In most instances of potato sickness, the use of 20 to 30 pounds of MgO per acre have eliminated this disease, if the application was made before the growing season. If applied after growth starts, chlorotic leaves do not regain their green color but the new growth will have a healthy green appearance. For tobacco, it is recommended that fertilizers carry 2 per cent of MgO, at least half of which shall be water-soluble. Dolomitic limestones used as the source of magnesium can be used either alone to build up a reserve in the soil, or as a component of the fertilizer mixture to meet crop needs. Used in mixed fertilizers, dolomitic limestone prevents the cumulative, detrimental acidity caused by the continued use of ammonium salts.

The data in the following table, from the Sandhill Experiment Station in South Carolina, show the effect of various sources of nitrogen on the amount of magnesium deficiency in cotton. The fertilizer used was fifty pounds of nitrogen (N), 100 pounds of phosphoric acid (P_2O_5), and 50 pounds of potash (K_2O) per acre. The percentage of red leaves was determined on August 11—the red leaves being an indication of magnesium deficiency.

TABLE LXXI

MAGNESIUM DEFICIENCY IN COTTON WITH VARIOUS SOURCES OF NITROGEN

Source of Nitrogen	Per Cent Red Leaves
Sodium nitrate	28.3
Ammonium sulfate	24.2
Calcium cyanamid	24.2
Urea	20.3
Ammoniated superphosphate	18.4
Ammonium phosphate	2.7
Ammonium sulfate plus basic slag	1.0

The explanation of the differences is to be found in the amount of soluble magnesium supplied by the fertilizer material or made available as a result of its use on the soil.

MANGANESE

The calcareous glade soils of Florida have responded most markedly to applications of manganese. This fact was brought out when truck crops fertilized with manure shipped in from the Mississippi River Valley grew normally, and those which were not manured failed to grow. Analysis of the soil and manure showed manganese to be the responsible element. Growers who till these soils now use a few bags of manganese sulfate rather than truckloads of manure. Fifty to 100 pounds of this material stimulate growth and prevent chlorosis of beets, carrots, tomatoes, lettuce, corn, cabbage, beans, potatoes, forage crops and ornamentals in southern Florida.

Manganese sulfate, acting as an oxidizing agent in the soil, has appreciably increased both ammonification and nitrification when applied in amounts up to 100 pounds per acre.

McHargue has demonstrated that manganese is essential to the normal growth and functioning of all plants. In a series of tests in which all traces of this element were carefully eliminated, plants became stunted and developed chlorosis in their early growth after the supplies of manganese in the seed had been used up.

Manganese chlorosis is definitely linked with soil alkalinity. It may develop in naturally calcareous soils, or in soils which have been excessively limed. Pahala blight of sugar cane in Hawaii presents symptoms similar to those existing on truck crops in Florida, and has been correlated with manganese deficiency. The chlorosis developed by manganese starvation progresses from a pale green to a golden yellow or red color between green veins, depending upon the crop affected, gradually becoming white necrotic areas. The green persists longest along the principal veins.

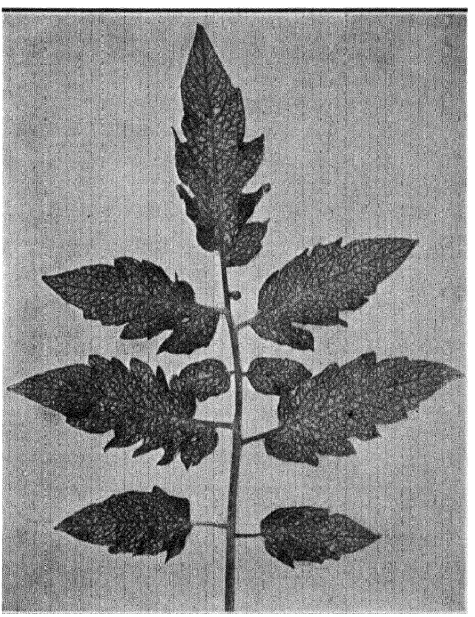


FIG. 62.—Effect on tomatoes of deficiency of manganese. Such a deficiency may occur on overlimed soils or on very sandy soils. (Courtesy Oswald Schreiner, U.S.D.A.)

These symptoms have also been noted on truck crops in Rhode Island where they have been controlled by the use of 30 pounds of manganese sulfate per acre. Eradication of chlorosis of spinach has been found possible by spraying with a solution of manganese sulfate. Citrus leaves exhibiting lack of manganese develop resinous spots on either or both sides, along with a chlorosis of the tissues. In acute stages the leaves drop off and the shoots die back.

Good crops of oats, wheat, cow peas, and soy beans have been grown following applications of manganese in North Carolina, in areas where nutritional deficiencies have been in evidence. The use of manganese with other minor elements for strawberries also gave a marked increase in yield. In these tests manganese sulfate was applied at the rate of 20 pounds per acre in conjunction with 10 pounds each of copper, zinc and nickel sulfates.

"Grey speck" disease, or "white wilt," of oats, which responds to manganese applications, is believed by some European investigators to involve factors other than a lack of manganese—a disturbance of ionic balance perhaps causing this condition.

Where heavy applications of basic slag have been made to soils, there is seldom likely to be an acute deficiency of manganese since the manganese content of slags runs from 2 to 6 per cent, and oftentimes much higher. Most, if not all, compounds of iron contain manganese as an impurity. This fact must be considered in any study involving the use of iron. Although a close relation exists between iron and manganese in plant growth, apparently neither one can take the place of the other. Characteristic chloroses are caused by a lack of manganese, and by an excess of manganese which depresses the assimilation of iron.

ZINC

Mottle leaf of citrus long attributed to a variety of deficiencies has now been definitely linked with zinc. This is true also of walnut yellows, pecan rosette, and little leaf of stone-fruit trees. Rosette is a characteristic symptom of zinc deficiency which starts with a yellow mottling of the leaves. In its less severe aspects, this mottling is often called "frenching." As the deficiency becomes more acute the leaves roughen and crinkle, and cluster together forming rosettes. The necessity for zinc in overcoming rosette was discovered accidentally by Alben and others of the U.S.D.A. while working with sprays of iron sulfate on pecan trees. Trees treated with sprays from an ordinary galvanized pail gave better response than the trees receiving the same spray from wooden buckets. It was conjectured from this that some of the zinc from the galvanized pail might have been dissolved into the spray solution. This proved to be the case, because subsequent use of zinc sprays were very satisfactory. The partial response obtained from ferrous sulfate sprays is due to their content of zinc impurities.

Generally speaking, zinc sulfate sprays have given better results than soil applications. Applications of the dry salt in a small concentrated area around the trees, as in a trench, have been effective in some tests and ineffective in others. Alben and his

associates recommend sprays of one pound of zinc sulfate to 50 gallons of water applied three or four times a season for the control of pecan rosette. For citrus in Florida, the most reliable spray is made up of 5 pounds of 89 per cent zinc sulfate, $2\frac{1}{2}$ pounds of finely ground hydrated lime and 50 gallons of water.

Walnut trees in California have responded to zinc wedges and zinc glazier points driven into the trees. The closer the zinc is placed to the foliage, the more rapid the response. Galvanized iron may also be a satisfactory source of zinc.

Rosette of pecans is found only on trees grown under cultivation, and never when growing in their wild state in the woods. This leads to the belief that the disease is caused by cultivation. The growth and incorporation of green manures and organic matter in the soil has a definitely corrective effect.

TOXIC ELEMENTS IN SOILS

Accumulations of arsenic in the soil as a result of the use of calcium arsenate dusts for the control of the cotton boll weevil have been found to be injurious to plant growth on some soils of South Carolina. The coarse-textured gray sandy soils are seriously injured by relatively light applications of calcium arsenate dust. The toxic effect of arsenic has been overcome by applications of iron sulfate and by the iron compounds naturally present in the red clay soils of South Carolina. Applications of lime and a high organic matter content may also be effective in rendering arsenic less toxic in soils.

The use of thallium for the control of rodents and of annual weeds might conceivably offer difficulties if the practice is widely followed. Thallium sulfate is very toxic to plants. Thirty pounds will sterilize an acre-inch of average soil. Thallium toxicity varies with soil type, being greater in soils of low fertility. It is characterized by retarded shoot growth, chlorosis of leaves, stunting of the older plants and early death where concentrations are high.

Continued use of ammonium sulfate, in the absence of lime, produces injurious effects due to the formation of excessive amounts of soluble salts of iron, aluminum and manganese. In some soils sulfates of these elements are formed in excess of the

need of plants for them. In such cases they have a toxic effect. Lime and phosphoric acid are the best correctives for such conditions.

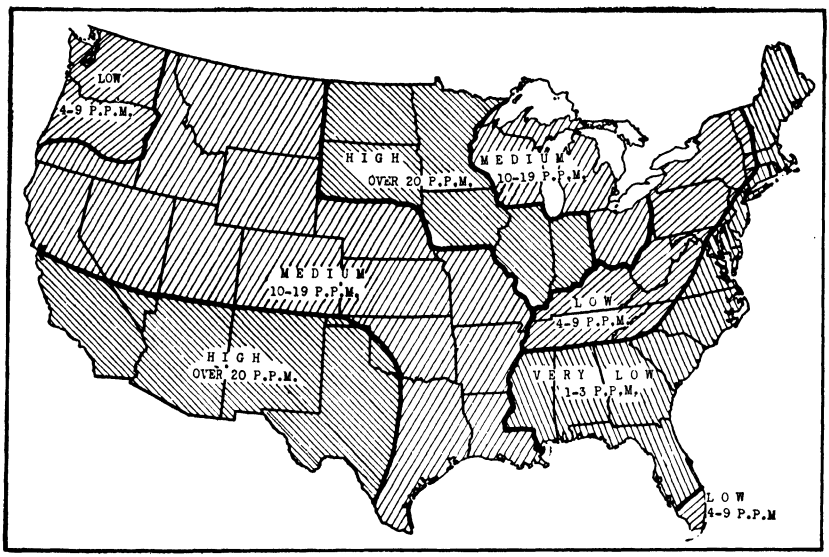


FIG. 63.—Regional distribution of MgO in river and lake waters. Based on compilation of analytical data from U. S. Geological Survey Professional Paper Number 135. Charted by S. B. Detwiler, U.S.D.A.

Considerable amounts of selenium have been found in wheat grown on certain irrigated soils of the West. The selenium content of some of these arid and semi-arid soils runs quite high. In many of these areas vegetation is sparse, and its selenium content is so great as to kill grazing animals.

SELECTED REFERENCES

1. Alben, A. O., and Associates. Chemical treatment of pecan rosette. Phytopath, Vol. 22, pp. 595–601, 1932.
2. Allison, R. V., and Associates. The stimulation of plant response on the raw peat soils of the Florida Everglades through the use of copper sulphate and special chemicals. Florida Agr. Exp. Sta. Bul. 190, 1927.
3. Bennett, J. P. The treatment of lime-induced chlorosis with iron salts. California Agr. Exp. Sta. Cir. 321, 1931.
4. Byers, H. G. Selenium occurrence in certain soils in the United States. U.S.D.A. Tech. Bul. 530, 1936.
5. Camp, A. F. The use of zinc sulphate on citrus. The Citrus Industry, Oct., 1934, pp. 16, 18.

6. Carolus, R. L., and Brown, B. E. Magnesium deficiency. I. The value of magnesium compounds in vegetable production in Virginia. Virginia Truck Exp. Sta. Bul. 89, 1935.
7. Haas, A. R. C. Injurious effects of manganese and iron deficiencies of citrus. Univ. of Calif., Hilgardia, Vol. 7, No. 4, 1932.
8. Lineberry, R. A. et al. Results of strawberry fertilizer and tillage experiments. North Carolina Agr. Exp. Sta. Agron. Inform. Cir. 75, 1933. W
9. McHargue, J. S. Manganese and plant growth. J. Ind. and Eng. Chem., Vol. 18, pp. 172–75, 1926.
10. McLarty, H. R., and Wilcox, J. C. From Death Valley to fertile fruit lands of British Columbia comes invigoration for trees. Country Life in B. C., Vol. 24, No. 11, pp. 7, 18, 1936.
11. McMurtrey, J. E. Distinctive effects of the deficiency of certain essential elements on the growth of tobacco. U.S.D.A. Tech. Bul. 340, 1933.
12. Schreiner, O., and Dawson, P. R. Manganese deficiency in soils and fertilizers. J. Ind. and Eng. Chem., Vol. 19, pp. 400–04, 1927.
13. South Carolina Agr. Exp. Sta. 45th Ann. Rept., pp. 23–28, 33, 44, 1932.
14. Willis, L. G. Bibliography of references to the literature on the minor elements. Chilean Nitrate Educational Bureau, 1935.

INDEX

A

Absorption, of acids by soil, 109
of ammonia by soil, 47
of potassium by soils, 214
Acid-digestion analyses of soils, 110, 128
Acid effects, of nitrogen fertilizers, 51
of sulfate of ammonia, 172
Acid soils, ammonia production in, 48
in relation to nitrogen economy, 70
nitrogen fixation in, 30
relative sensitiveness of plants to, 301
replaceable bases in, 124
use of phosphate rock on, 195
Acidity of fertilizer materials, 173
Acids, absorptive power of soil for, 110
Activated sludge, 169
"Agricultural Chemistry," by Davy, 6
Aikman, method of, for producing nitrate, 36
Alabama, fertilizer law in, 232
fertilizers for cotton in, 259
Alcohol industry, as source of potash, 219
Alfalfa and timothy, in association, 70
Alfalfa, complete fertilizer as top-dressing for, 291
composition of, 102
critical *p*H of nodule bacteria of, 70
effect of nitrate fertilizer on, 52
inoculation of, 63
nitrogen accumulated by, 68
nodule bacteria of, 26
*p*H requirements of, 312
soil reaction requirements of, 301
top-dressing of, with potash fertilizers, 290
use of phosphate rock for, 196
use of phosphates for, 209
Algæ, as sources of carbohydrate, 32
Alinit, use of, 33
Alkali content of soils, 312
Alkali soils, replaceable bases in, 124
Alkaline effect of nitrate of soda, 51
Alsike clover, growth of, on acid soil, 301
Aluminium, as constituent of plant ash, 99
in acid soils, 312
in soil solution, 214
precipitation of, by phosphates, 205
Alunite, as source of potash, 220
Amaranthus, nitrogen content of, 60
Ames, investigations of rainwater by, 61
Amino acids, as source of nitrogen, 50
production of, in soil, 46
Ammonia, absorption of, by soil, 125
application of in irrigation water, 287
from atmosphere, 12
in drainage water, 138
in rainwater, 9
produced in nitrification, 39
production of, in acid soils, 48
quantity in soil, 47
used by plants, 49
Ammonia nitrogen, availability of, 169
Ammonia process, of fixing nitrogen, 184
Ammonification, conditions favoring, 46
precedes nitrification, 45
Ammonium chloride, nitrification of, 38
Ammonium phosphate, composition of, 164
nature of, 202
qualities of, 194
Ammonium sulfate, acid effect of, 173
comparison of, with nitrate of soda, 51
effect of, on soil, 47
use of, in making artificial manure, 321
on alkali soils, 305

Anaerobic conditions, effect of, in soil, 44
Analyses, fertilizer, 232
of plants, as guide to fertilizer practice, 77
of soils, acid digestion method of, 128
as guide to fertilizer practice, 240
of prominent experiment farms, 137
value of, 86
the 4-12-4 and 4-8-8, formulas for, 281
Anderson, "Farmer of Tomorrow," by, 84
"Annals of Agriculture," by Arthur Young, 5
Annuals, top-dressing with phosphates, 288
Antiseptics, volatile, effect of, on soil, 38
Antitoxins, fertilizers as, 82
Apatite, composition of, 133
in soil, making phosphorus of available, 45
qualities of, 194
Apple, composition of, 102
corky core of, 329
Application of fertilizers, 276
American system, 283
European system, 282
row and broadcast, 292, 294
time of, 282
to transplanted plants, 296
Arny, experiments of, on inoculation, 63
Aroostook County, Maine, fertilizer used in, 236
Arsenic, effect of, on plants, 106, 337
Artichokes, Jerusalem, phosphate as dominant for, 240
Ash analyses, as guide to fertilizer practice, 76
by Wolff, 100
of plants, value of, 75
recent, 101
significance of, 99
Ash elements, distribution of, in plants, 103
Ash of plant, as related to composition of soil, 101
composition of, in relation to soil and plant, 96
discovery of source of, 6
Rothamsted studies of, 98
Ashes, as source of potash, 218
coal, as source of potash, 218
manure as fertilizer, 76
wood, use of, as fertilizer, 153
Asparagine, as source of nitrogen, 50
Asparagus, composition of, 255
soil reaction, requirements of, 301
top-dressing of, with nitrogen fertilizer, 286
Association of Official Agricultural Chemists, 226
Atwater, nitrogen-fixation experiments of, 20
Auburn method of using fertilizers, 259
Auximones, 34
Availability, relative, of nitrogen fertilizers, 170
tests of, in fertilizers, 226
Available constituents in soils, estimation of, 127
Averitt, studies of, on Trenton soils, 136
Azotobacter and acid soils, 30
as nitrate conservers, 68
critical *p*H for, 31, 70
discovery of, 30
in corn and wheat belts, 260
nitrogen fixed by, 66

B

Bacillus coli, 46
B. ellenbachensis, 33
B. fluorescens, 45
B. lactis viscosum, 31
B. mesentericus, 31
B. mycoides, 45
B. prodigiosus, 45
B. proteus, 45
B. radicicola, nitrogen-fixing power of without host, 26
Bacteria, as competitors with plants, 45
denitrifying, 43

nitrifying, 38
nodule, nitrogen fixation by, 61
non-symbiotic, nitrogen fixed by, 66
Bacterium aerogenes, 31
Bact. danicus, 31
Bact. malabarensis, 31
Bact. pneumonia, 31
Bact. pyocyaneum, 31
Bact. radiobacter, 31
Banana, composition of, 102
Banana skins, potash in, 218
Barium, nutritional value of, for plants, 105
in fertilizer materials, 326
Barley, capacity of, to absorb phosphorus, 101
complete fertilizers as top-dressing for, 294
effect of phosphates on, 208
fertilizers for, 243
nitrogen-fixation tests with, 22
root growth of, 145
soil requirements of, 13
Base-exchange in soils, 122, 124
Base-exchange potassium in soils, 214
Base-goods in fertilizers, 228
Basic slag, as source of phosphorus, 199
early use of, 158
effect of, on soil reaction, 306
in fertilizer mixtures, 228
production of, 190
Basicity of fertilizer materials, 173
Beans, form of nitrogen used by, 50
nitrogen-fixation tests with, 22
soil requirements of, 13
Bear, experiments of, on nitrification, 43
investigations of, on nitrogen-phosphorus ratio in soils, 72
Beets, sugar, effect of chlorine on, 223
*p*H requirements of, 312
time of application of nitrogen fertilizers for, 286
Beijerinck, discovery of Azotobacter by, 30
Bent grass, growth of, on acid soil, 300
Beri-beri, 34
Berseem clover, sensitiveness of, to acid soil conditions, 301
Berthelot, nitrogen-fixation experiments by, 19
Biennials, top-dressing of, with phosphates, 288
Bizzell, experiments of, with lysimeters, 58
Black clay loams, nitrogen content of, 56
Blueberry, sensitiveness of, to acid soil conditions, 301
Bluegrass, and white clover, in associations, 69
composition of, 103
Bonazzi, experiments of, with Azotobacter, 68
Boneblack, dissolved, use of, in fertilizer tests, 249
early use of, 156
Bone meal, as fertilizer, 193
as source of phosphorus, 196
raw, 196
Bones, early use of, 156, 189
value of, as fertilizer, 5
Boron, effect of, on plants, 105, 328
Bottomley, experiments of, with peat, 34
Boussingault, nitrogen-fixation experiments of, 16
"Rural Economy" by, 151
study of mineral economy of plants by, 96
Bouyoucos, studies of, on soil solution, 118
Bradfield, studies of, on soil colloidal matter, 122
Brazil, agricultural possibilities in, 187
Brenchley, investigations of, on rarer elements in plants, 105
Broadbalk, Field, soil of, 13
soil, phosphoric acid fixation by, 125
Broadcast and row applications of fertilizer, 294
Broomsedge, form of nitrogen used by, 48
nitrogen content of, 60
Brussels sprouts, sensitiveness of, to acid soil conditions, 301
Buckwheat, growth of, on acid soil, 299
use of ammonia by, 178

Buckwheat, use of phosphate rock for, 196
Bureau of Chemistry and Soils of U.S.D.A., scientific work of, 94
Burned lime, neutralizing value of, 308
Burned-over land, fertilizers for, 266

C

Cabbage, composition of, 102
fertilizers for, 245
soil-reaction requirements of, 301
top-dressing of with nitrogen fertilizers, 286
Calcium carbonate, effect of, on nitrification, 43
in drainage water, 139
Calcium in soil solution, 115
in subsoil, used by plants, 142
movement of, in soil, 148
Calcium nitrate, effect of on soil, 172
use of, on acid soils, 172
in superphosphate, 233
Cameron, comment of, on ash analyses, 100
on studies of effect of fertilizers in soil, 82
Capillary movement of mineral nutrients in soils, 89
Capillary water as source of mineral nutrients, 83
Carbohydrate, in relation to nitrogen-fixation, 66
plant food value of, 51
required by Azotobacter, 30
Carbonate of lime, neutralizing value of, 308
Carbon bisulfide, effect of, on nitrification, 37
Carbon dioxide, discovery of, 4
use of, by bacteria, 39
Carbon, in soils, 315
of plants, source of, 8
Carbon-nitrogen ratio in nitrification, 39
Carbon-nitrogen ratio in organic matter, 41
in relation to choice of fertilizer, 263
in soils, 315
Carbon-nitrogen ratios in organic matter, 322
Carnallit, as source of potash, 218
Carrier, "Beginnings of Agriculture in America" by, 151
Carrots, fertilizers for, 256
Catch crop, fertilizers for, 318
Cauliflower, red rot of, 329
sensitiveness of, to acid soil conditions, 301
Cavendish and discovery of hydrogen, 4
Celery, crack stem of, 329
sensitiveness of, to acid soil conditions, 301
use of nitrogen fertilizers on, 179
Cement industry, as source of potash, 219
Cereals, fertilizers for, 243
Chard, sensitiveness of, to acid soil conditions, 301
Chernozem soils, nature of, 131
China, farming in, 90
Chloride of ammonia, early tests of, as fertilizer, 11
Chlorine, as constituents of plant ash, 99
in fertilizers, effect of, 222
Chloroform, effect on nitrification, 37
Chromium, in fertilizer materials, 327
Citric acid, use of, in soil solution studies, 109
Citrus, dieback of, 330
mottle leaf of, 336
Clarke, investigations of drainage waters by, 58
Classification of soils on climatic basis, 130
Clay soils, fertilizers for, 255
Clermont silt loam, composition of, 135
Climate, as factor in soil development, 130
choice of phosphates in relation to, 207
in relation to choice of nitrogen fertilizers, 176
in relation to choice of potash fertilizers, 221

Climate, in relation to soil reaction, 299
Climatic factors and fertilizer needs, 265
Clostridium pastorianum, critical *p*H for, 71
discovery of, 30
Clover and timothy, grown in association, 69
Clover, effect of, on nitrification, 62
effects of fertilizer on, in grassland, 16
fertilizers for, 247
nitrogen content of, 57
nitrogen-fixation tests with, 18
power of, to accumulate nitrogen, 15
red, nitrogen-fixation tests with, 23
Clovers, fertilizers for, 245
Clubroot, as indicator of fertilizer need, 264
Cobalt, in fertilizer materials, 326
Cobs, corn, composition of, 103
nitrogen content of, 57
Collison, experiments of, on drainage losses, 58
Colloids, soil, nature of, 122
Colorado sand, composition of, 135
Color of soil, in relation to nitrogen deficiency, 262
Comber test for soil acidity, 266
Compost of clover and canal mud, 92
Conner, studies of, on unproductive black soils, 136
Control, fertilizer, 225
Copper, nutritional value of, for plants, 106, 329
Corn, and soybeans, in association, 69
effect of phosphates on, 208
fertilizers for, 277
methods of application of fertilizer on, 296
mineral requirements of, 87
nitrogen content of, 57
root growth of, 145
rotation of with oats, clover, wheat (sweet clover), 251
row applications of fertilizer for, 294
soil-reaction requirements of, 301
sugar as food for, 51
Corn, top-dressing of with nitrogen fertilizers, 286
Cornstalks, effects of, in soil, 225
potash in, 218
Cotton, fertilizers for, 258, 277
growth of, on acid soil, 301
row application of fertilizer for, 294
top-dressing, with nitrogen fertilizers, 286
with potash fertilizers, 289
use of nitrogen fertilizers on, 179
Cottonseed meal, as source of nitrogen, 171
row applications of, 294
when to apply, 285
Coudon, experiments of, on ammonification, 45
Coulter, comment of, on ash analyses, 100
Coville, comments of, on use of ammonia by plants, 49
Cowpeas, composition of, 102
growth of, on acid soil, 301
nitrogen fixed by, 28, 64
row applications of fertilizer for, 294
Cranberry, form of nitrogen used by, 49
sensitiveness of, to acid soil conditions, 301
Crookes, comments of, on world's wheat problem, 181
Crop, effect of, on soil solution, 117
fitting of, to soil, 299
Crop residues as source of organic matter, 56
Cucumber, fertilizers for, 255
sensitiveness of, to acid soil conditions, 301
Cumarin as soil toxin, 84
Cyanamid, for conditioning purposes, 278
for killing weeds, 287
in fertilizer mixtures, 228
process for making, 184
qualities of, 169

D

Daisy, as nitrogen conserver, 62
nitrogen content of, 60

Darwin, studies of, on earthworms in soils, 146
Davenport, experiments of, with Azotobacter, 31
on critical *p*H of bacteria, 70
on nitrification, 40
Davy, early studies of, on composition of soils, 125
on constitution of plants, 6
Dead Sea, potash deposits in, 219
Decomposition of organic matter, value of, in soil, 88
Deficiencies, soil, diagnosing, 262
Dekalb silt loam, composition of, 135
Dekalb soil, nitrogen-phosphorus ratio in, 72
phosphorus fixation by, 124
Denitrification, conditions favoring, 44
loss of nitrogen by, 59
Denmark, wheat yields in, 79
Depth, of fertilizers in relation to root development, 145
at which plants absorb nutrients, 141
DeSaussure, analyses of plant ash by, 97
experiments of, 6
Development of soils, 128
Digby, experiment of, with potassium nitrate, 2
Dihydroxystearic acid as soil toxin, 84
Disease, plant, effect of potassium on, 216
Distribution, crop, economic factors and, 299
Dole, investigations of drainage waters by, 58
studies of, on soil erosion, 147
Dolomite, neutralizing value of, 308
Dominant constituents in fertilizers, 77
Dominants, principle of, 240
Doryland, experiments of, on nitrification, 40
Drainage water, composition of, 138
loss of nitrogen in, 58
lysimeter tests of, 139
phosphoric acid in, 207
potassium in, 216
Drouth, choice of fertilizers in relation to, 176
Drouth, nitrogen fertilizers in relation to, 168
Duggar, comment of, on ash analyses, 100
Duley, studies of, on soil erosion, 147
Dupetit, investigations of, on denitrification, 44
Dyer, investigations of, with citric acid as soil solvent, 109

E

Earthworms, value of, in renewing soil, 146
Economic factors and fertilizer needs, 265
Elements required by plants, 86
Ellett, experiments of, on timothy and clover in association, 70
Emerson, experiments of, on nitrogen-fixation by, 31
Endive, sensitiveness of, to acid soil conditions, 301
Erosion, effect of, on soil, 147
in relation to fertilizer need, 264
Excrement, human, as fertilizer, 90
Exhaustion of soil, due to toxic substances, 83
reasons for, 80
"Experiments on Vegetables," by Ingen-Haus, 4

F

Factors, from elements to oxides, 102
Fallowing, effect on nitrogen supply, 17
"Farmer of Tomorrow," by Anderson, 84
"Farmers of Forty Centuries," by King, 90
Feldspar, as source of potash, 220
Fertilizer, and soil toxicity, 81
as substitute for manure, 77
Fertilizer control, 225
Fertilizer industry, beginning of, 78
development of, 151
mixed, beginning of, 160
recent developments in, 162
Fertilizer tests of Lawes and Gilbert, 76

Fertilizer tonnage, sold in United States, 114, 115, 162
Fertilizers, as substitute for manure, 256
availability tests for, 226
depth of, in relation to root development, 145
effect of, on clover in grassland, 16
on plant and soil, 83
on soil solution, 118
on solubility of soil, 120
farming without, in Orient, 90
granular, 231
mixed, 225
nitrate, loss by drainage, 58
phosphoric acid, 190
plant-food theory of, questioned, 113
Field peas, row applications of fertilizer for, 284
Filler in fertilizer, 278
Fineness of limestone, 310
Firing of crops, as indicator of fertilizer need, 264
cause of, 168
Fixation, nitrogen, biological, 25
by nodule bacteria, 61
by non-symbiotic bacteria, 66
Flax, dominant for, 240
fertilizers for, 245
sensitiveness of, to acid soil conditions, 301
Floats, use of, 196
Flowers, top-dressing of, with nitrogen fertilizer, 286
Fluorine, nutritional value of, for plants, 105
Food of plants, Tull's theory of, 3
Forbes, ash-analyses by, 102
Formation of soils, 128
Formulas, fertilizer, basic, 278
for 4-8-8 and 4-10-6 analyses, 279
high-analysis, 279
special, 279
for tobacco and sugar beets, 279
Ville's, 242
Frankland, experiments of, on nitrification, 39
Franklin, experiments of, with landplaster, 153
Fred, experiments of, on nitrogen fixation, 26
on critical *p*H of bacteria, 70
on inoculation, 63
on nitrification, 40
on nitrogen fixation, 65
with Azotobacter, 31
Frost, row applications of fertilizers to prevent injury from, 293
Fruits, small, nitrogen fertilizers for, 228
Funchess, fertilizer recommendations of, 258

G

Garbage tankage in fertilizers, 226
Gardner, fertilizer recommendations of, 247
Gayon, investigations of, on denitrification, 44
Gedroiz, studies of, on base-exchange, 123
Germination, injury of fertilizers to, 293
Gilbert, experiments of, at Rothamsted, 10
Glinka, soil development studies of, 130
Glucose, food value of, for plants, 51
Golding, experiments by, on nitrogen fixation, 27
Golf courses, grasses for, 300
Golf greens, use of alum on, 305
Gooseberry, sensitiveness of, to acid soil conditions, 301
Grain and stalk, ratio of, 57
Grain farming, use of phosphates in, 191
Grape, sensitiveness of, to acid soil conditions, 301
Grass, effect of nitrogen fertilizers on, 15
nitrogen as dominant for, 240
Grasses for golf courses, 300
Green-manure and soil toxicity, 81
fertilizer, for production of, 318
sweet clover for, 65
Green-manuring, effect of, on nitrogen supply, 17

Greensand, as source of potash, 220
Guano, introduction of, 155
Gumbo, sensitiveness of, to acid soil conditions, 304
Gypsum, discovery of value of, 152

H

Haber process for fixing nitrogen, 184
Hall, comments on use of ammonia by plants, 49
investigations of, on nitrogen economy, 67
Hartwell, experiments of, on nitrogen fixation, 64
principles of fertilizer practice of, 253
Hay, fertilizers for, 243
Headden, work of on "nitre-spots," 32
Hellriegel, nitrogen-fixation experiments of, 20
Helmont and discovery of carbon dioxide, 4
Hemp, fertilizers for, 245
Hippuric acid, as source of nitrogen, 49
Hissink, studies of, on base-exchange, 120
test of, for available potash in soil, 271
Home-mixing of fertilizers, 229
Homologous fertilizers, 240
Hopkins, as defender of mineral theory, 85
comment of, on ash analyses, 100
on potash fertilizers, 213
experiments of, on inoculation, 64
on nitrification, 45
method of, for lime-requirement of soils, 303
principles of fertilizer practice of, 252
Hops, fertilizers for, 245
Horizons, soil, 132
Hornblende, composition of, 133
"Horse Hoeing Husbandry," by Tull, 3
Humates, as source of nitrogen, 50
Humic acid, as source of nitrogen, 50
"Humogen," 34
Humus, as source of nitrogen, 56
Humus, theory, modified, 51
of Thaer, 7
Hutchinson, experiments on nitrogen fertilizers, 50
Hydrated lime, neutralizing value of, 308
Hydrochloric acid as soil solvent, 111
Hydrogen, discovery of, 4
Hydrogen sulfide, production of, in soil, 46

I

Illinois, Experiment Station soil, composition of, 137
field tests in, 251
soil of, composition of, 143
Incomplete fertilizers, 240
Ingen-Haus, experiments of, 4
Inoculation, experiments on, 63
in relation to liming, 63
of soils, 33
Iodine, from kelp, 218
nutritional value of, for plants, 105
Iron, as a fertilizer, 252, 330
in acid soils, 312
in corn, 103
need for, 263, 330
precipitation of, by phosphates, 206
Iron industry, as source of potash, 219
Iron sulfate, applied as a spray, 331
Irrigation, as means of distributing nitrogen fertilizers, 287

J

Japan, farming in, 90
Japan clover, growth of, on acid soil, 301
phosphates for, 288
Jones, method of, for lime-requirement of soils, 303
Jordan, field tests of fertilizers by, 247

K

Kaffir corn, composition of, 102
Kainit, as source of potash, 219
effect of, on soil reaction, 306
use of, as fertilizer, 221
on soil, 252

Kaolin, composition of, 133
Kelley, studies of, on base-exchange, 120
Kelp as source of potash, 218
King, investigations of, on soil solution, 89
Knudson, experiments of, on food value of carbohydrates, 51
Korea, farming in, 90

L

Landplaster, need for, 262
use of, 152
Laterite soils, nature of, 131
Latshaw, analyses of corn plants by, 103
Lawes and Liebig, controversy between, 12
Lawes, experiments of, on nitrogen-fixation, 15
patent of, for superphosphate, 157
Lawns, complete fertilizer as top-dressing for, 291
fertilizer for, 277
Leaching of soils, effects of, 138
Lead, in fertilizer materials, 327
Leaves, corn, composition of, 104
legume, capacity of, to fix nitrogen, 28
Lecithin, as fertilizer, 193
Legume, leaves, in relation to nitrogen-fixation, 27
nitrogen-fixation in absence of, 27
nitrogen in soil before and after growth of, 62
program, economy of, 166
Legumes, and nitrification, 62
and non-legumes, grown in association, 69
effect of nitrogen fertilizers on, 14, 76
fertilizers for, 245
forms of nitrogen used by, 51
inoculated, mineral content of, 63
nitrogen of, comparison with uninoculated, 61
in pasture, effect of nitrogen fertilizers on, 69
Legumes, nitrogen of, comparison with that of non-legumes, 61
proven to be nitrogen fixers, 20
relation of, to fertilizer program, 247
use of, in Orient, 92
Lentil, sensitiveness of, to acid soil conditions, 301
Lettuce, fertilizers for, 255
Leucine, as source of nitrogen, 50
Leucite, as source of potash, 220
Leunasalpeter, qualities of, 170
Liebig, comments of, on English use of bones, 189
lectures of, 7
mineral theory of, 75
"Natural Laws of Husbandry," by, 127
Liljenroth process of producing phosphorus, 184
Lime, amount to apply, 312
burned, neutralizing value of, 308
early use of, 151
in basic slag, 198
in relation to inoculation, 65
in relation to nitrogen fixation, 66
need of, for profitable crop yields, 241
replaces potassium in soil complex, 216
Rhode Island tests of, 253
Lime-requirement of soils, 302
Limestone, amount to apply, 312
and nitrification, 43
and soil toxicity, 81
determining purity of, 309
effect of, on ammonification, 47
effect of, on nitrification, 40
fineness of, evaluating, 309
ground, surface of, 310
importance of, in soil, 88
neutralizing value of, 308
to neutralize acid of sulfate of ammonia, 174
use of, in making artificial manure, 321
on soil, 253
Liming materials, neutralizing power of, 308
relative merits of, 307

Limiting numbers, Neubauer's, 271
Lipman, discovery by, of two species of Azotobacter, 31
estimate by, of nitrogen fixed by Azotobacter, 68
experiments of, on nitrogen-fixation, 29
on oats and peas in association, 69
Lithium, nutritional value of, for plants, 105
Livestock farming, use of phosphates in, 191
Livestock farms, organic matter for, 319
Lohnis, comment of, on nitrogen-fixation, 166
Losses by leaching, 138
Loughridge, studies of, on solvent effect of HCl on soils, 110
Lupins, nitrogen-fixation tests with, 22
Lyon, experiments of, with lysimeters, 58
Lysimeter experiments, nitrogen losses in, 58
Lysimeter tests, of drainage losses, 215
with soils, 140
on drainage losses, 140

M

Magnesium, as a fertilizer, 332
in soil solution, 115
salts, as cure for sand-drown, 333
Maine, fertilizers for potatoes in, 236
Maize, effect of, on nitrification, 62
form of nitrogen used by, 49
phosphate as dominant for, 241
Maltose, food value of, for plants, 51
Mameli, experiments of, on nitrogen-fixation, 29
Manganese, as constituent of plant ash, 99
in acid soils, 312
in corn, 103
in soil solution, 214
in soils, 135
in surface soil, 136
need for, 263, 334
Mangolds, fertilizers for, 243
Manure, artificial, 321
ashes of, as fertilizer, 76
as source of organic matter, 56, 314
effect of, on composition of crop, 89
on corn, 317
on soil reaction, 309
fertilizer as substitute for, 77, 254
human, as fertilizer, 90
phlogiston in, 5
production of, 179
raw, bad effects of, 43
denitrification effects of, 59
reenforced with phosphate, 317
stall and yard compared, 317
strawy, effect of, on fertilizer needs of soil, 263
tillage as substitute for, 3
value of fertilizer constituents in, 250
Manure salts, as source of potash, 219
Manures, green, fertilizer for production of, 318
Market garden crops, fertilizers for, 277
Market gardening, organic matter for, 322
Materials, fertilizer, 227
Maze, experiments of, on nitrogen fixation, 26
McCool, studies of, on effect of crop on soil solution, 118
McGee, studies of, on soil erosion, 147
McHargue, investigations of, on rarer elements in plants, 106
Meadows, complete fertilizer as top-dressing for, 291
fertilizers for, 277
Merrill, comment of, on zeolites in soils, 111
Methane, production of, in soils, 46
Method, for determining purity of limestone, 309
of testing soil reaction, 301
Miami, silty clay loam, composition of, 135
soils, need of potash by, 250
Miller, experiments of, on nitrogen fertilizers, 49
Millet, fertilizers for, 255
Milk, for making soil acid, 305

Milk, produced from use of 1 pound of nitrogen, 179
Milorganite, 171
Mineral constituents of soil solution, 109
Mineral content, of inoculated legumes, 63
of river waters, 140
Mineral economy in soils, 126
Mineral theory, 76
and Asiatic practice, 93
Hopkins as defender of, 86
Minerals, soil, composition of, 133
Mitscherlich, tests of, for soil deficiencies, 272
Mixed-fertilizer industry, beginning of, 160
Mixing, home-, of fertilizers, 229
Moisture, optimum for ammonification, 47
Molds, ammonia producing, 46
Montana, phosphate deposits in, 190
Morgan, studies of, on soil solution, 117
Morrison, records by, of plant analyses, 57
Muck, in fertilizers, 226
soils, fertilizer for, 277
Mud, canal, as fertilizer, 91
Mulberry and rice fields, soil exchange from, 92
Muntz, experiments of, on nitrification, 37
Muriate of potash, effect of, on soil reaction, 306
on tobacco, 223
Muskmelon, row applications of fertilizer for, 294
Mustard, nitrogen content of, 60
sensitiveness of, to acid soil conditions, 301

N

Nagaoka, experiments of, on nitrogen fertilizers, 49
Navy beans, composition of, 102
Neubauer test for soil deficiencies, 271
Neutralizing power of liming materials, 308
Nickel, in fertilizer materials, 326
Nitrate, as fertilizer for alfalfa, 52
Chilean, production of, 183
fertilizers, loss by drainage, 58
Nitrate nitrogen, in river waters, 59
in soil solution, 117
Nitrate of calcium, effect on soil, 172
Nitrate of soda, absorbed from subsoil by plants, 144
applied at planting time for tobacco, 296
comparison of, with sulfate of ammonia, 51
early tests of, as fertilizer, 11
effect of, on soil, 172
on soil reaction, 306
first shipments of, 154
in relation to potassium of soil, 216
Nitrate reduction, conditions favoring, 40, 43
Nitrates, accumulation of, in soils, 47
conserved by Azotobacter, 68
for reducing toxicity in soils, 84
in Colorado soils, 32
in drainage, 40
loss of, by denitrification, 59
movement of, in soil, 148
production of, in acid soils, 49
removal of, from soil by Amaranthus, 60
synthetic, suggested production of, 180
use of, by legumes, 22
by plants, 48
on paddy rice, 171
Nitre as food of plants, 3
"Nitre-spots" of Colorado, 32
Nitrification, and availability of soil constituents, 45
and carbon-nitrogen ratio, 41
and soil reaction, 42
conditions favoring, 39
critical *p*H for, 71
early study of, 37
effect of limestone on, 43
of crops on, 62
of organic matter on, 71
steps in process, 39
Nitrifying bacteria, isolation of, 38

Nitrites, production of, in soil, 43
Nitrobacter and nitrification, 39
growth of, in presence of organic matter, 41
Nitrogen, ammonia, availability of, 169
quantity of, in soil, 47
deficiency of, indicated by plant, 263
indicated by soil, 262
in relation to soil management, 264
test for, in soil, 267
testing plant for, 267
discovery of, 4
economy of, in relation to soil reaction, 70
in soils, factors, influencing, 57
phosphorus in relation to, 72
temperature in relation to, 71
effects of, on clover in grassland, 16
form of, used by non-legumes, 48
forms used by legumes, 52
from the air, 166
in air, 87
in cottonseed meal, 171
in crops, 57
in human excrement, 91
in plowed acre of soil, 56
in rainwater, 10, 60
in soil, before and after legume growth, 62
in soil in relation to nitrogen-fixation, 68
in subsoil at Rothamsted, 67
in tops and roots of legumes, 64
in weeds, 60
income and outgo, equilibrium between, 73
income and outgo, equilibrium point, 57
loss by denitrification, 59
losses of, in drainage, 58
nitrate, quantity in soil, 47
of humus, value of, 56
of plants, source of, 9
organic, in acid soils, 48
produce from use of 1 pound of, 179
synthetic, 180
volatilization of, by bacteria, 47
Nitrogen-carbon ratio in nitrification, 40
Nitrogen-carbon ratios in organic matter, 41
Nitrogen carriers, secondary effects of, 172
Nitrogen "conservers," crops as, 62
Nitrogen content, of soils, 55, 315
of subsoil, 56
Nitrogen fertilizers, 166
acid effects of, 172
cheap, economic effects of, 187
choice in relation to climatic factors, 176
choice in relation to crop requirement, 178
effect of, on grass, 15
on legume growth in pastures, 69
emergency needs for, 167
in regions of cool climates, 260
in relation to economic factors, 265
quality of, for mixing purposes, 170
recovery of, in crop, 173
relative acidifying effects, 173
relative availability of, 170
required by bacteria, 42
special uses of, 180
time of application of, 285
use of, in tropical agriculture, 187
when especially effective, 264
world production of, 186
Nitrogen fixation, are process of, 182
Atwater's experiments on, 19
Berthelot's experiments on, 19
biological, 25
Boussingault's experiments on, 16
by legume leaves, 27
by legumes, proven, 21
by nodule bacteria, 25, 61
by non-legume plants, 29
by non-symbiotic bacteria, 66
by soil organisms suggested, 19
critical *p*H for, 71
effect of temperature on, 71
experiments at Rothamsted on, 14
experiments on, 64
Hellriegel's experiments on, 21
in acid soils, 30
in relation to algæ, 32
in relation to nitrogen in soil, 68
Ville's experiments on, 18

Nitrogen fixation, Wilfarth's experiments on, 23
Nitrogen fixed, by bacteria, 166
Nitrogen-organic matter ratio in soils, 55
Nitrogen "wasters," crops as, 62
Nitrosococcus and nitrification, 38
Nitrosomonas and nitrification, 38
Nodule bacteria, nitrogen fixation by, 25, 61
Nodule organisms, differences in noted, 22
Nodules, soybean, nitrogen content of, 52
Non-legume plants, nitrogen-fixation by, 28
  form of nitrogen used by, 48
Norfolk sand, composition of, 135

O

Oats, and peas, grown in association, 69
  complete fertilizers as top-dressing for, 291
  fertilizers for, 249, 277
  gray speck of, 336
  growth of, on acid soils, 301
  nitrogen content of, 57
  nitrogen-fixation tests with, 17
  root growth of, 145
  time of application of nitrogen fertilizers for, 282
Official agricultural chemists, association of, 226
Ohio, Experiment Station soil, composition of, 137
  field tests in, 248
Oil in bones, value of, 5
Omelianski, experiments with Azotobacter, 30
Onion, composition of, 102
  fertilizers for, 255
  soil reaction requirements of, 301
Orchards, fertilizers for, 277
"Organic Chemistry in Its Application to Agriculture," by Liebig, 7
Organic matter, accumulation of, 314
  carbon-nitrogen ratios in, 322
Organic matter, coarse, denitrification effects of, 59
  content of soils, 315
  crop residues as sources of, 56
  decomposition of, 322
  effect of fertilizers on accumulation of, 318
    of plowing under, 42
    on nitrification, 40
  fertilizer as source of, 318
  food value of, 51
  in manure, 315
  supplying, 314
  unnecessary to plant growth, 52
  value of decomposition of, in soil, 88
Organic matter-nitrogen ratio in soils, 55
Orthoclase, decomposition of, 123, 133
Oxygen, discovery of, 4
Oyster shells as source of lime, 151

P

Parsnip, fertilizers for, 255
Pasteur, experiments of, on nitrification, 37
Pasture, complete fertilizer as top-dressing for, 291
  English, improvement of, 187
  fertilizers for, 243, 277
  legumes in, effect of nitrogen fertilizers on, 69
  nitrogen fertilizers on, 187
  top-dressing of, with phosphates, 288
    with potash fertilizers, 290
Pea, garden, nodule bacteria of, 26
Peanuts, row applications of fertilizer for, 294
  sensitiveness of, to acid soil conditions, 301
Peas and oats, in association, 69
  field, row applications of fertilizer for, 294
  form of nitrogen used by, 50
  tests on nitrogen fixation with, 21
Peat, as culture medium, 33
  in fertilizers, 226
  nitrogen content of, 56
  potash deficiency of, 214

Pecan, rosette of, 336
Pember, experiments of, on nitrogen fixation, 64
Pennsylvania, field tests in, 247
Perennials, top-dressing with nitrogen fertilizers, 286
Peterson, study of "nitre-spots" by, 33
*p*H, critical, for Azotobacter, 31
for nitrification, 71
for nodule bacteria, 70
meaning of term, 301
of soil, methods of determining, 301
Phenol, effect of, on nitrification, 38
Phlogiston in dung, 5
Stahl's theory of, 4
Phosphate, in relation to nitrogen fixation, 66
Phosphate rock, as a fertilizer, 193, 253
calcined, as source of phosphorus, 198
effect of, on soil reaction, 306
use of, on acid soils, 195
Phosphates, as top-dressing, 288
choice of, in relation to climate, 207
in relation to crop, 208
in relation to soil factors, 205
effects of, on root growth of plants, 192
for reducing toxicity in soils, 84
general need for, 250
mineral, discovery of, 190
soluble, effect of, on acid soils, 204
time of application of, 286
Phosphoric acid, absorption of, by soil, 122
as dominant constituent of crops, 78
availability tests for, in basic slag, 198
availability in superphosphates, 200
available, test for, in soil, 267
carriers of, 192
deficiencies, indicated by plant, 263
by soil, 262
deficiency, in relation to soil management, 264
testing plant for, 267
fixation of, in soil, 124, 203
in drainage water, 206
in soil solution, 115
Phosphoric acid, meaning of term, 230
movement of, in soil, 148
quantity to apply, 254
Phosphoric acid fertilizers, 189
availability of, 194
in relation to economic factors, 265
secondary effects of, 204
Phosphorus, accumulation of, in surface soil, 142
carriers of, 192
economy of, in soil, 191
in fertilizers, availability of, 202
in human excrement, 91
in relation to nitrogen economy, 72
made available during nitrification, 45
silicon as substitute for, in plants, 104
Phosphorus fertilizers, comparative values of, 194
Phytin, as fertilizer, 193
Pierre, study of acidity and basicity of fertilizers, 173
Pigweed, nitrogen content of, 60
value of, as green manure, 320
Pine needles, for making soil acid, 305
Plant analysis, as guide to fertilizer practice, 239, 244, 267
Plants, as indicators of fertilizer needs, 263
non-legume, capacity of, to fix nitrogen, 29
Podzols, development of, 131
Pollacci, experiments by, on nitrogen fixation, 29
Polyhalite, potash in, 219
Pomace for making soil acid, 305
Potash, as dominant constituent of crops, 78
available, test for, in soil, 268
carriers of, 217
deficiencies in, indicated by plant, 263
indicated by soil, 262
in relation to soil management, 264
meaning of term, 230
need for, on Miami soils, 250
testing plant for, 268
Potash fertilizers, availability of, 221

Potash fertilizers, choice in relation to climate, 222
choice of, in relation to crop, 223
in relation to soil, 221
in regions of low rainfall, 260
in relation to economic factors, 265
time of application of, 289
when especially effective, 264
Potash salts, discovery of, 158
for reducing toxicity in soils, 84
Liebig's experiments with, 159
Potassium, absorbed by soils, 214
available in soil, 213
base-exchange, in soils, 214
fixation of, by soil, 120
in human excrement, 91
in soil solution, 117
liberated by lime, 216
movement of, in soil, 148
sodium as substitute for, in plants, 104
Potassium nitrate, demand for, 37
early experiment with, 2
early use of, 154
Potatoes, effect of chlorine on, 223
effect of phosphates on, 208
fertilizer for, 243, 277
growth of, on acid soil, 302
methods of application of fertilizer for, 294
root growth of, 145
special fertilizer formula for, 279
use of ammonia by, 178
Pot test of soil deficiencies, 272
Priestly and discovery of oxygen, 4
Principle of dominant constituents, 77
Principles of fertilizer practice, 239
Productivity of soil, soil solution as index of, 119
Profile, soil, 131
Protein, wheat, high, value of, 285
time of applying nitrogen for, 285
Protein feeds, factory production of, 180
Proteins, ammonification of, 45
Pumpkins, top-dressing of, with nitrogen fertilizer, 286
Purslane, as nitrogen conserver, 62
Putnam soil, colloidal complex of, 122

Q

Quantity of fertilizer to apply, 280
Quince, sensitiveness of, to acid soil conditions, 301
Quinone as soil toxin, 84

R

Radish, sensitiveness of, to acid soil conditions, 301
Ragweed, nitrogen content of, 60
Rainfall-evaporation ratio, fertilizers in relation to, 265
Rainwater, ammonia in, 10
nitrogen in, 10, 60
Rape, as nitrogen conserver, 62
fertilizers for, 243, 245
sensitiveness of, to acid soil conditions, 301
Raspberry, sensitiveness of, to acid soil conditions, 301
Ratios, fertilizer, 234
possible triangle, 235
Reaction of soil, and ammonification, 46
and nitrification, 42
control of, 298, 312
controlling, 298
in relation to climatic factors, 298
methods of testing, 300
Red clover, critical *p*H of bacteria for, 70
Red top, growth of, on acid soil, 301
Reduction of nitrates, conditions favoring, 40, 43
Residues, crop, as source of organic matter, 316
use of, on soil, 252
Reverted phosphoric acid, tests for, 200
Rhode Island, Experiment Station soil, composition of, 137
field tests of fertilizers in, 253
Rhododendron, form of nitrogen used by, 48
on acid soils, 308
Rhubarb, sensitiveness of, to acid soil conditions, 301

Rhubarb, top-dressing with nitrogen fertilizer, 286
Rice and mulberry fields, soil exchange from, 92
denitrification losses in growing, 59
nitrates on, 171
use of ammonia by, 49
Richards, investigations of, on rainwater, 60
River water, mineral content of, 140
nitrogen content of, 59
Robinson, chemical studies of soils by, 135
Root crops, effect of phosphates on, 209
Root development in relation to depth of fertilizer placement, 146
Root hairs, absorption of phosphorus by, 205
Root nodules in relation to nitrogen fixation, 22
Root systems of various crops, 256
Roots, as source of organic matter, 314
corn, composition of, 103
excretions of, as cause of infertility, 81
nitrogen fertilizers in relation to development of, 177
Rotation, a reason for, 12
Illinois, 251
of corn, oats, clover, wheat (sweet clover), 251
of crops as means of collecting ammonia, 14
of soil, 91
Rothamsted, early work at, 13
Experiment Station soil, composition of, 137
nitrates in drainage at, 40
nitrogen economy studies at, 67
nitrogen-fixation experiments at, 14
nitrogen in rainfall at, 60
soil, nature of, 13
Row and broadcast applications of fertilizer, 294
applications of fertilizer, conditions favoring, 293
Rumania, wheat yields in, 79
Russell, comments of, on "Auximones," 34
comments of, on Nernst's Law in relation to soil solution, 88
investigations of, on rainwater, 60
principles of fertilizer practice of, 242
Russia, agricultural possibilities in, 187
potash deposits in, 219
Rutherford, and discovery of nitrogen, 4
Rye and vetch, in association, 69
complete fertilizers as top-dressing for, 291
effects of, in soil, 320
growth of, on acid soil, 299
nitrogen-fixation tests with, 18
use of nitrogen fertilizers on, 179
use of phosphate rock for, 196
Rye seedlings, Neubauer tests with, 271

S

Salt, as fertilizer, 82
effect on soil, 221
Saltpeter, Digby's experiment with, 2
early experiments with, 154
plantations, 37
Sand, as filler in fertilizers, 232
Sand-drown disease, as indicator of fertilizer need, 333
Sands, nitrogen content of, 56
potash deficiency of, 214
Sandy soils, drainage losses in, 58
fertilizers for, 255
top-dressing of, with potash fertilizers, 290
Sassafras silt loam, composition of, 135
Sawdust, for making soil acid, 305
Scab, potato, choice of phosphate in relation to, 209
control of, 305
Schloesing, experiments of, on nitrification, 37
Schreiner, fertilizer triangle studies of, 234
studies of, on fixation of potassium by soils, 120
Science, early soil, 1

Selection of fertilizers, 262
Selenium, in wheat, 338
Serradella, nitrogen-fixation tests with, 23
nodule bacteria of, 26
Sewage disposal plants, principle of, 45
Silica media for nitrifying bacteria, 40
Silicon, as constituent of plant ash, 99
in corn, 103
Silver, in fertilizer materials, 327
Slag, basic, as source of phosphorus, 198
early use of, 159
Sod, as source of organic matter, 314
Sodium, as substitute for potassium, 83, 104
in soil solution, 214
Sodium silicate, as a fertilizer, 105
Soil analysis, as guide to fertilizer practice, 240, 244, 266
comments as to value of, 126
Soil, as a dynamic system, 112
as an inexhaustible resource, 80
as food of plants, 3
as source of mineral elements, 141
effect of on soluble salts, 116
in relation to choice of nitrogen fertilizers, 174
management of, in relation to choice of fertilizers, 266
potash fertilizers in relation to, 220
Soil reaction, materials for regulating, 304
Soil solution, as index of soil productivity, 119
Cameron's book on, 82
concentration of, as affected by fertilizers, 88
effect of crop on, 117
effect of fertilizers on, 118
methods of obtaining, 114
mineral constituents of, 109
studies of, by Cameron, 112
studies of composition of, 117
Soils, chemical composition of typical, 134
choice of phosphates in relation to, 206
Solution, soil, methods of obtaining, 117
Sorghum, phosphate as dominant for, 240
Sorrel, form of nitrogen used by, 49
nitrogen content of, 60
South Carolina, field tests of fertilizers on cotton in, 258
Southern States, nitrogen economy in, 71
Soybean, critical *p*H of bacteria for, 70
Soybeans, and corn, in association, 69
inoculation of, 63
nitrogen fixed by, 64
nitrogen in nodules of, 52
row applications of fertilizer for, 294
soil reaction requirements of, 298
Spearmint, Woodward's experiment with, 2
Spinach, sensitiveness of, to acid soil conditions, 301
Squash, fertilizers for, 255
Stabler, investigations of, on drainage waters, 58
Stahl, phlogiston theory of, 4
Stalk and grain, ratio of, 57
Stewart, study of "nitre-spots" by, 32
Stimulating fertilizers, 240
Stockbridge, fertilizer formulas of, 246
Straw, bad effects of, 44
making artificial manure from, 321
Strawberry, use of nitrogen fertilizers on, 179
sensitiveness of, to acid soil conditions, 301
Strontium, in fertilizer materials, 326
Strowd, experiments of, with soybeans, 52
Stubble, as source of organic matter, 314
Subsoil, as source of mineral elements, 141
composition of, 142
nitrogen content of, 56
value of mineral elements in, 144
Sucrose, food value of, for plants, 51
Sugar beets, dry rot of, 329
effect of chlorine on, 223
fertilizers for, 243
special fertilizer formula for, 279

Sugar cane, phosphate dominant for, 240
use of extra nitrogen on, 275
Sulfate of ammonia, production of, 155
effect of, on soil reaction, 306
on wheat, 13
Lawes' experiments with, 76
tests of, as fertilizer, 10
use of, in making artificial manure, 321
Sulfate of potash, for sugar beets, 241
Sulfur, as a fertilizer, 252
in drainage water, 139
in soils, 135
need for, 263
use of, on alkali soils, 304
Sunflower, fertilizers for, 255
nitrogen-fixation tests with, 18
Sunshine, fertilizers in relation to, 265
Superphosphate, as source of phosphorus, 199
concentrated, 201
effects of, on clover in grassland, 16
on soil reaction, 306
first patent for manufacture of, 78
from bone, 197
row application of, 294
use of, in making artificial manure, 321
Superphosphate industry, beginning of, 157
early history of, 190
Surface, relative of limestone products, 310
Swanson, investigations of, on alfalfa soils, 68
Swedes, fertilizers for, 243
Sweet clover, analysis of, 66
as nitrogen gathering crop, 253
critical *p*H of bacteria for, 70
inoculation of, 63
*p*H requirements of, 312
use of phosphate rock for, 196
value of, as catch crop, 65
Sweet pea, nodule bacteria of, 26
Sweet potatoes, fertilizers for, 256
Sylvinit, as source of potash, 219
Synthetic nitrogen fertilizers, 180
Systems of using fertilizers, 257

T

Tankage, as conditioner in fertilizers, 227
effect of, on soil reaction, 306
garbage, in fertilizers, 226
qualities of, 194
Temperature, in relation to nitrogen economy, 71
optimum for ammonification, 47
optimum for nitrification, 40
Temple, experiments of, on ammonification, 47
Tests for soil deficiencies, 266
Texas, potash deposits in, 219
Thaer, humus theory of, 7
Thallium, toxic to plants, 337
Thatcher, experiments of, on inoculation, 63
Theory, mineral, 76
toxicity, 81
Thiocyanate test for acidity, 266
Thomas phosphate, early use of, 158
Thorne, field tests of fertilizers by, 249
Thornton, methods of soil analysis of, 268
Tillage as substitute for manure, 3
Timothy, and alfalfa, in association, 70
and clover, in association, 69
effect of, on soil, 255
on nitrification, 62
fertilizers for, 247
growth of, on acid soil, 301
Tin, in fertilizer materials, 326
Titanium, effect of, on plants, 106
in fertilizer materials, 326
in subsoil, 136
Tobacco, effect of chlorine on, 223
effect of, on soil, 255
phosphates on, 208
fertilizer for, 245, 259, 275
fertilizers applied in plant-beds for, 296
nitrogen-fixation tests with, 18
special fertilizer formula for, 279
top-dressing of, with nitrogen fertilizers, 286
Tobacco industry, as source of potash, 219

Tobacco stems, as conditioner in fertilizers, 225
nitrogen content of, 169
potash from, 219
Tomatoes, effect of phosphates on, 208
fertilizers applied in plant-beds for, 296
top-dressing with nitrogen fertilizer, 286
use of nitrogen fertilizers on, 179
Top-dressing, with complete fertilizers, 291
with nitrogen fertilizers, 286
with phosphates, 288
with potash fertilizers, 290
Toxicity theory, 81
Toxins, as cause of soil exhaustion, 83
Trace elements, in soils, and crops, 325
in fertilizer materials, 327, 328
Treble-superphosphate, composition of, 163
qualities of, 194
row application of, 293
Trees, fruit, nitrogen fertilizers for drouth resistance of, 177
Trefoil, sensitiveness of, to acid soil conditions, 301
Trenton soils, phosphorus content of, 136
Triangle, fertilizer, 234
Truck crops, fertilizer for, 277
Tull, theory of, on food of plants, 3
Tundras, development of, 131
Turnip, ash of, in relation to fertilizer needs, 98
as nitrogen collecting crop, 14
as soil improving crop, 12
fertilizers for, 243
heart rot of, 329
phosphorus in, 76
response of, to phosphates, 76, 240
soil requirements of, 13

U

Urea, as source of nitrogen, 49
in fertilizer mixtures, 278
qualities of, 169, 173
Uric acid, as source of nitrogen, 50
Utah, phosphate deposits in, 190

V

Vanadium in soils, 136
in fertilizer materials, 326
Van Hise, "Conservation of Natural Resources," by, 191
studies of, on rock weathering, 133
theory of, on decomposition of orthoclase, 120
Vanillin as soil toxic, 84
Vegetables, effects of phosphates on, 208
Veitch, method of, for lime-requirement of soils, 303
Vetch, and rye, in association, 69
nitrogen-fixation tests with, 23
nitrogen fixed by, 64
sensitiveness of, to acid soil conditions, 304
Ville, "Artificial Manures," by, 160
nitrogen-fixation experiments of, 18
principle of dominant constituents of, 77, 240
principles of fertilizer practice of, 242
Vines, potash as dominant for, 240
Virginia, field tests of fertilizers on tobacco in, 258
Voelcker, studies of, on drainage waters, 138
Volusia silt loam, composition of, 135
Von Helmont, classical experiment of, 1
Vorhees, principles of fertilizer practice of, 255

W

Wagner, experiments of, on denitrification, 44
principles of fertilizer practice of, 244
Waksman, review of evidence on nitrogen-fixation by, 31
Walker, experiments of, on drainage losses, 58
Warington, experiments of, on denitrification, 59
on nitrification, 38

Water, as a plant nutrient, 1
capillary, as source of mineral nutrients, 83
movement of dissolved salts in, 148
excess, effect of, on nitrate accumulation, 44
river, nitrogen content of, 59
Watermelon, row applications of fertilizer for, 293
sensitiveness of, to acid soil conditions, 301
Weathering of minerals, 132
Weaver, studies of, on root systems of plants, 145
Weeds, killing with cyanamid, 287
nitrogen content of, 60
value of, as green-manures, 320
Wet-mixed fertilizers, 227
Wet season, fertilizers for, 265
Wheat, as source of nitrogen, 50
ash of, in relation to fertilizer needs, 99
average yields of, in various countries, 79
complete fertilizers, as top-dressing for, 291
effect of phosphates on, 208
effect of sulfate of ammonia on, 13
fertilizers for, 247, 277
nitrogen content of, 57
nitrogen-fixation tests with, 17
response of, to nitrogen fertilizers, 240
root growth of, 145
time of application of nitrogen fertilizers for, 282
top-dressing of, with nitrogen fertilizers, 284
use of nitrogen fertilizers on, 179
variation of, in mineral content of, 102
Wheeler, comments of, on special needs of plants, 253
White clover, and bluegrass, in association, 69
sensitiveness of, to acid soil conditions, 301
White, experiments of, on nitrification, 43
Whiting, experiments by, on nitrogen fixation, 28
on nitrification, 44
with sweet clover, 66
Whitney, on soil exhaustion, 80
Wilfarth, nitrogen-fixation experiments of, 23
Willow, Helmont's experiment with, 1
Wilson, investigations of, on rainwater, 61
Winogradsky, discovery of Clostridium pastorianum by, 1
isolation of nitrifying bacteria by, 38
Wolff, compilation of ash analyses by, 99
Woodward, experiment of, with spearmint, 2
Wool industry, as source of potash, 219
Wright, experiments of, on association of legumes and non-legumes, 70

Y

Years' supply of nutrients in soil, 88
Yeast, for production of protein feeds, 180
Yellowing, of crop, cause of, 42
as indicator of fertilizer need, 264
Young, experiments of, 5

Z

Zeolites in soils, 110
Zeolitic theory, 110
Zinc, effect of, on plants, **105, 336**
Zircon, composition of, 133