Soils and Fertilizers



Frontispiece. The handwriting of erosion as seen from the air. The first essential of good land management is keeping the soil in place.

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Soils and Fertilizers

FOURTH EDITION

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Preface

The purpose of this book is to consider soils in relation to crop production. To that end, applications are made of those scientific facts and principles that are of use in planning constructive systems of managing soils and in increasing their productive capacities. It is assumed that the reader has had courses in geology, chemistry, physics, and botany, and that he is familiar with the ordinary vocabularies of these sciences.

Many of the more advanced phases of soil science are not touched upon, except in a very brief way. This is because the book is intended primarily for use in beginning courses in soils in agricultural colleges, many of the students of which are not interested in the more technical details of the subject and have little need for the course except as it may be useful to them in practice or in understanding work on the farm.

Since it was impossible to present all the experimental evidence on which the author's conclusions are based, illustrative material was chosen from whatever sources supplied the most conclusive evidence. Similarly, the references were limited to representative books, papers, and bulletins that give the student a fairly good idea of the nature of the research work that has been undertaken on the subject in question.

It is assumed that the classroom discussion will be supplemented with field and laboratory studies designed to fix some of the more important facts and principles more firmly in the students' minds.

The book has been completely rewritten for the fourth edition, and a large amount of new material has been added. The author is indebted to his colleagues in the soils department of the New Jersey Agricultural Experiment Station for many of the ideas presented. He also wishes to express his appreciation to Miss Louise P. Lab[illegible] and to Miss Florence H. Schork for aid in the typing of the revised manuscript and in the preparation of the index.

FIRMAN E. BEAR

New Brunswick, New Jersey
September, 1953

Foreword

Soil, like faith, is the substance of things hoped for, the evidence of things not seen. Some 2½ billion people depend on it for food and clothing. And, by and large, it never fails. Here and there, because of ignorance and inefficiency, mingled with war and pestilence, a few millions may starve, and other millions may go to bed hungry more or less regularly. The productive capacity of the land as a whole, however, is far greater than is required to feed all the people on earth.

Nevertheless, the Malthusian principle that population is kept under control by famine, pestilence, and war still applies over a large part of the earth. It remains to be determined whether this principle can be permanently set aside by man through the application of the sciences at his command.

In his book, *Human Fertility, the Modern Dilemma*, Robert C. Cook estimates that world population is increasing at the rate of 68,000 persons every 24 hours. This is equivalent to 25 million, or 1 per cent, a year. The rate of population growth in the United States is higher than the average for the rest of the earth.

When Captain John Smith first set foot on the shore of Virginia in 1607, the 1903 million acres of land that now constitute the United States of America were inhabited by some 800,000 Indians. Each of these Indians had 2400 acres of land at his disposal. Over this land the braves hunted, fished, and fought, while the squaws did the work. This was an Indian paradise. Today, only 346 years later, our population is 160 million, and the amount of land for each person has been reduced to 12 acres. Over half of this is desert, mountain, lake, or swamp.

How long is 346 years? As a small boy, I remember talking with my great-grandfather, who was then 94 years old. Through his eyes I can now look back nearly half that period of time. This is a very young country. We have come a long way in a very short time. But we have had time enough to lay waste great areas of forest and to ruin much of the land that we inherited from the Indians. This has been

a land of plenty, but we are catching up with the food supply. And over 2½ million more people are now joining us at the table every year.

Previous to their coming to America, our European ancestors had never seen corn, potatoes, tobacco, peanuts, or tomatoes. They tasted these Indian crops, liked them, and soon set about growing them. Cotton, another crop with which they had had no experience, grew well in the South. In a surprisingly short time the farmers of this country were growing 150 million acres of these crops every year. They plowed the land, planted the crops in long, straight rows, cultivated between the rows, and developed the most destructive type of agriculture the world has ever known.

Our people are mechanical minded. The 2000 tractors of 1910 grew to nearly 4½ million faster-moving types by 1953. The horse and mule population fell from 25 million to 7½ million. Fences, the Maginot line against erosion, were torn out to make more room for the tractors. This gave the wind and water a longer sweep. As a result, millions of tons of good topsoil were carried down the slopes and dumped into the rivers. Mud clogged the harbors. Silt poured into the reservoirs, reducing their storage capacity from 1 to 3 per cent a year. And, beginning in early 1934, dust storms tore the soil loose from its moorings in Kansas wheat fields, spread it over the country to the east, and carried some of it on out to sea.

The handwriting of erosion was plain for everyone to see. People in high places began to be cognizant of the damage that was being done. Public sentiment was aroused. The Soil Conservation Act was passed in 1935, and the Soil Conservation Service came into existence. Stripcropping, contour farming, the growing of more sod crops, the seeding of more cover crops, and the planting of forests got under way. Farmers began to realize that it was necessary to take greater advantage of roots as a means of sewing the soil to the earth. But millions of acres of good land had been ruined before this came to pass.

In 1607, virtually all the land east of the Mississippi River, except for the prairies of northern Indiana and Illinois, was covered with forest. A squirrel could have gone from Maine to Louisiana without touching the ground, merely by jumping from one giant tree to the next. These trees were in our way. Therefore, we cut them down, burned them up, laid bare the land, and put it to the plow.

Judging by the luxuriance of these forests, one would have thought that the soil beneath them was highly productive. For the moment, it was. Once the trees had been cleared off and the soil had been brought under cultivation, however, a large part of the accumulated

organic matter was soon used up. Then we discovered that the underlying soil had lost virtually all its soluble substance to the sea. Limestone, phosphate, and potash salts had to be supplied. Last year, American farmers applied nearly 50 million tons of these soil amendments. This is enough to fill a line of 40-ton freight cars extending more than 3½ times the distance from New York to San Francisco.

The farther west one goes in the United States the less the rainfall and the smaller the amount of soluble material that has been washed out of the soil. In the desert areas, soils are highly productive, once irrigation has been applied. Some 25 million acres of desert land are being irrigated, and there is water for some 25 million more. East of the 150 million acres that constitute the Great American Desert is a 600-million-acre area of semidesert with a rainfall of 10 to 20 inches. Some 300 million additional acres are contained in the subhumid portion of the Great Plains. All these regions need water more than lime or fertilizer.

Our cropland for 1950 totaled 360 million acres. Included in this is a vast area of rich, black soil that extends from the Dakotas south to Texas. This land needs phosphate and potash, but not lime. East of this black-earth area, where the rainfall is heavier, both lime and fertilizer have to be used in large amounts. By and large, it is easier to haul the necessary salts back from ancient seas and put them on the land from which they came than it is to provide the much larger tonnages of water that are required to bring more of the desert under production.

Nevertheless, the problem of maintaining adequate supplies of nutrient elements in the soils of humid regions becomes more and more troublesome as the years go by. Virgin fertility has largely been exhausted. We are no longer satisfied with the yields that unaided Nature can provide. The modern goal is 100 bushels of corn, 50 bushels of wheat, 500 bushels of potatoes, 20 tons of tomatoes, and 5 tons of alfalfa hay an acre.

As the soil becomes older agriculturally and the yields are stepped-up by growing improved hybrids and disease-resistant varieties, by using improved tillage implements, and by applying more lime and NPK fertilizer, other deficiencies develop. In certain areas magnesium must be supplied. In other areas sulfur is needed. Under some circumstances iron deficiencies develop. In still others the limiting factor in plant and animal production is a lack of boron, molybdenum, copper, manganese, zinc, cobalt, or iodine. These last seven trace elements present some of our most troublesome problems.

Take boron, for example. Over 12 per cent of the soil of New Jersey is known to be in need of this element for maximum productiveness. Field tests with alfalfa have shown that a 25-pound application of borax an acre may make all the difference between success and failure. It is not uncommon to be able to increase yields of hay as much as 1 ton an acre by applying 75 cents worth of borax.

More recently, we have been intrigued by the possibility of widespread need for molybdenum. In the beginning phases of our work on this element on alfalfa we had great difficulty developing a deficiency in plants grown in sand culture. Finally, by redistilling the water and recrystallizing all the nutrient salts, deficiency symptoms were developed in sand cultures. The plants stopped growing and turned yellow. However, all that was required to start them on again was 1 part molybdenum in 1 billion parts of the nutrient solution. Yet the year before last a New Jersey vegetable grower plowed under 45 acres of cauliflower that couldn't produce heads because the soil lacked available molybdenum.

The soil of this great land of ours is capable of producing food in abundance for possibly 1 billion people. It is to be hoped that there will never be that many people to feed. But if the time comes that this will be necessary, much more of the total expendable budget will have to be invested in food. Some outlying land will have to be reclaimed from the sea, as the Dutch have done. Additional water for irrigation will have to be distilled from the ocean. Tremendous tonnages of lime and fertilizer will have to be used. Floods will have to be brought under complete control. The soil on every acre of land will have to be conserved. The problems of growing enough food for all these people will be very serious. We will have to be satisfied with less meat and more bread, potatoes, and vegetables. Some of our less fortunate folk may go to bed hungry, as do millions of people every night in the more densely populated parts of the earth.

The soil scientists of America, of which I am proud to be one, are dedicated to the task of conserving the nation's soil, water, and life resources to the end that, whatever the final population may be, the issue can be met. We feel under obligation to leave no stone unturned to the end that our land is conserved and its productivity is not only maintained but raised to ever higher levels. Our aim is to see to it that our increasing numbers of fine young folk continue to enjoy the fruits of the earth in abundance.

F. E. B.

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Factors Affecting Plant Growth

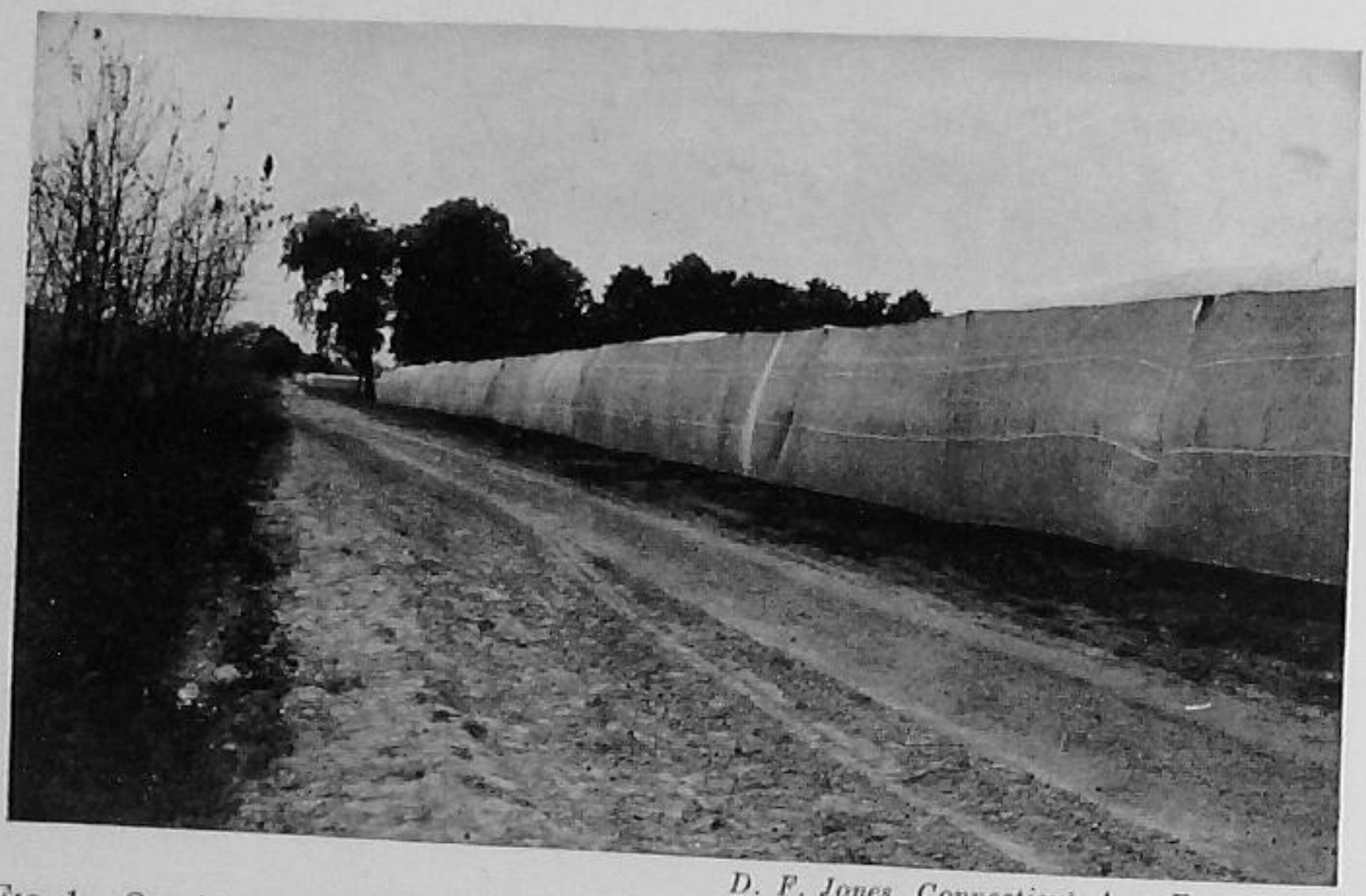
The factors affecting the growth of crop plants may be conveniently divided into climatic, biotic, and edaphic groups. The most important climatic factors are precipitation, sunshine, and temperature. The biotic group includes man, animals, other plants, and the crop itself in relation to its environment. The edaphic group comprises all those physical, chemical, and biological properties of the soil and processes in the soil that affect its capacity to supply the crop with the necessary water, nitrogen, and mineral nutrients.

Each of these factors may affect the crop positively or negatively, depending on the conditions that obtain. They are all interrelated in their effects. It is never possible to have all of them operating at their optimum at the same time. *The success of the farmer in growing crops is determined by the extent to which he is able to keep the several factors affecting them under control; to modify the effects of these factors to meet the needs of his crops; and to choose the crops that are best adapted to the conditions with which he has to deal.*

CLIMATIC FACTORS AND CROP GROWTH

Climatic factors are so closely related to each other in their effect on crops as to make it difficult to consider them separately. The water supply of plants is not so much dependent upon the amount of precipitation as it is upon the precipitation-evaporation ratio. Under some conditions the atmosphere is a serious competitor of the crop for water. Certain crops grow best in cool climates, but this may be due as much to the more abundant water supply under those conditions as to the direct effect of the temperature. The photosynthetic processes of plants are dependent upon light, but intensity of sunshine is ordinarily much in excess of their requirements. Length of day and of the crop season are important phases of the light factor.

A relationship exists between length of day and the flowering and fruiting of plants. This soon becomes apparent when one attempts to grow plants at latitudes far removed from those to which they are accustomed. Some plants do not bloom unless the days are relatively long; others bloom only when the days are short; and others bloom no matter what the length of day. Blooming is merely an index of other deep-seated phenomena that are governed by light.



D. F. Jones, Connecticut Agr. Exp. Sta.

FIG. 1. Outside view of field under cheesecloth used to control climatic factors. This method is effective in improving the quality of certain types of tobacco.

The farther north the locality the longer the long days and the shorter the short days of the year. At the Canadian border the longest days are 2 hours longer and the shortest days 2 hours shorter than the corresponding days on the Gulf coast. Furthermore, the twilight and the dawn are longer in northern latitudes.

In these light relationships are to be found, at least in part, the explanation of differences in crop yields, depending upon the latitude in which the crops are grown. Herein may lie the explanation of the relatively high percentage of sugar in Michigan beets, the relatively high acre yields of Maine potatoes, and the relatively high bushel weight of Scotland oats, in comparison with lower percentages, yields, and weights, respectively, of these same crops when grown in areas that are farther south.

It is not feasible to outline in detail the relationships that exist be-

tween climatic factors and crop growth and distribution, but some of the more important examples will be considered. *The farther removed an area is from the climatic center of production of any crop the more difficult it is for farmers to grow that crop successfully, until a point is reached at which it may no longer be advisable to attempt it.*

On the other hand, economic factors enter into this problem and often permit large expenditures for the control or the modification of



D. F. Jones

FIG. 2. Inside view of field shown in Fig. 1.

climatic factors in localities that are far removed from the natural center of production of a crop. Thus, in greenhouse culture it has been found profitable not only to control moisture and temperature but also to lengthen or shorten the day by artificial means and even to regulate the supply of carbon dioxide in the atmosphere.

CLIMATIC FACTORS AND CROP DISTRIBUTION

Although corn is grown under a wide range of climatic conditions the most favorable environment for the crop is in a relatively restricted area. The Corn Belt comprises that region in which the mean summer temperature is between 70° and 80° F. and the night temperature averages approximately 60°; in which the period between frosts is more than 140 days; and in which the annual precipitation is between 25 and 50 inches, 7 inches of which should occur during July and

August. The center of the Corn Belt comprises Iowa, Nebraska, Kansas, Missouri, Illinois, Indiana, and Ohio. These seven states produce more than half the corn grown in this country. It is of interest to note that most of the sweet corn is produced north of Mason and Dixon's line.

Winter wheat thrives best in those areas where the climate is cool and moist during the autumn, winter, and early spring months and then gradually develops into a warm, bright, and somewhat dry harvest period. The regions of highest acre yields of winter wheat include England, Scotland, Belgium, the Netherlands, Denmark, northern France, and Germany. In the United States, Kansas, Nebraska, and Oklahoma constitute the center of winter-wheat production. Other heavy winter-wheat-producing states are Washington, Missouri, Illinois, Indiana, Ohio, Pennsylvania, and Maryland. Low yields may usually be credited either to heaving, smothering, low temperatures, or drought. North of the mean winter-temperature line of 20° F. the climate is better suited to spring wheat, of which the center of production is the Dakotas and Minnesota.

It is apparent that a good winter-wheat climate is not the same as that described for corn. Nevertheless, these crops are grown successfully in rotation because winter wheat is essentially a winter and spring crop, whereas corn does its growing in the summer months. The two crop seasons overlap somewhat and, for that reason, the best winter-wheat-producing regions are often not entirely satisfactory for corn. Spring wheat cannot be grown to advantage in the Corn Belt because summer is too far advanced before the crop comes to maturity.

The same principle is involved with oats. This crop is adapted also to cool, moist climates and is much more seriously affected by high temperatures than is wheat. Not only are acre yields much lower in southern latitudes, but weight a bushel is considerably less. In Europe the center of oats production is virtually identical with that in which the highest acre yields of wheat are produced, although oats are grown as far north as the Arctic Circle. The most important oats-producing region of the United States extends from the Dakotas across the northern portion of the Corn Belt to western Pennsylvania and New York. Oats can be grown successfully in warm latitudes only when it can be sown in the autumn so that it can have its growing season largely during the winter and spring months. Selection for cold resistance has made it possible to grow winter oats considerably north of its former limit in southern Tennessee. Barley is another short-season crop that can be grown in high altitudes or more northern regions

where summers are short and days are long, and in semiarid regions where wet seasons last only a few weeks.

Potatoes grow best in moist, cool climates, somewhat north of the Corn Belt in the United States, and in the region of high acre yields of wheat and oats in Europe. Both quality and yield of tubers are better in regions of cool climate. Many smaller centers of production are not in areas where the climate is ideal but near large cities where saving in freight and shipping risks offset the disadvantages of lower acre yields. In the southern states, early potatoes are planted in November and December and harvesting begins about the middle of March. North of the latitude of New York City most of the potatoes are dug between the middle of September and the last of October. Production of sweet potatoes is largely limited to warmer regions where the growing season is over 175 days and the mean summer temperature is above 72° F.

The sugar beet is another crop that grows best and develops its highest sugar content in regions of cool, moist climates. Its southern limit in northern latitudes is at a summer temperature of about 72° F. Like oats and potatoes, sugar beets can be grown successfully in warmer latitudes if the seed are sown in the autumn and the crop is harvested before the warm summer weather begins. On the other hand, sugar cane grows best under conditions in which the temperature is uniformly high, sunlight is strong, and showers are frequent. Cool and cloudy weather during the growing season reduces cane yields and increases the percentage of fiber. Later in the season, cane requires either a lowered temperature or a lessened water supply to develop a high sugar content. Colorado, California, and Michigan are centers of sugar-beet production, and Louisiana of sugar cane.

Cotton is a highly important warm-climate crop in the United States. The northern limit of cotton growing is approximately a mean summer temperature of 77° F. and a frostless season of 200 days. Annual precipitation requirements are in excess of 23 inches. Within these boundaries the Cotton Belt is found, the best cotton being produced when the weather is warm and moderately moist from April to August and when it is dry and cool during the autumn picking period. On the other hand, cotton can successfully withstand periods of drought and still recover and produce satisfactory yields if the season later becomes favorable. Within recent years, centers of cotton production have developed farther west, notably in Texas, with the use of modern planting, cultivating, and harvesting machinery, and in California, under large-scale irrigation.

Rice has very high water requirements, being grown to best advantage under conditions in which irrigation can be practiced. It is, in fact, a tropical plant but it can be grown successfully in the warmer areas of the temperate zones. In Louisiana the water requirement of rice is approximately ½ inch a day as an average for the 90-day growing season. Since the rainfall during this period averages only about 20 inches, the remaining 25 inches must be supplied by irrigation. Temperature requirements of rice are at least 75° F. as a mean for the crop season.

Two examples of drought-resisting crops are found in olives and grain sorghums. The olive is sensitive to frost but grows well in arid regions. Its very shallow root system enables it to absorb moisture after a light rain and its leaves are of such a nature as to retard transpiration. Large acreages of grain sorghums are grown in Texas, Oklahoma, and Kansas in regions having average rainfall of 15 to 30 inches. During periods of drought these crops cease growing, but they again resume growth whenever rain falls.

Each of the several legume crops is confined to a fairly definite climatic area, although many of them can be grown over a considerable climatic range if soil conditions are favorable. Alfalfa, originally grown mostly in the West and Southwest in the United States, has spread through the northeastern Dairy Belt, following the adoption of improved methods of soil management and the introduction of hardier varieties. Cowpeas, velvet beans, lespedeza, crimson clover, kudzu, lupines, crotalaria, and peanuts are the important legumes of the southern states. Red clover, soybeans, and sweet clover have about the same climatic requirements as corn. Ladino clover, alsike clover, Canada field peas, and canning peas grow best in cool moist climates of the type in which the oat crop thrives.

Vegetables are being grown over a wide range of climatic conditions by reason of their wide range of adaptability and the large amount of care farmers can afford to give to crops of such high acre values. In general, market-gardening centers of production correspond to the areas of dense population. Truck farming is carried on either in warmer climates where crops can be produced for shipment to early market or on soils that, by reason of their physical characteristics, are especially suited to rapid growth of vegetables. Large acreages of vegetables are being grown under irrigation, either entirely or as a supplement to the natural rainfall. The more succulent types are being grown under glass and cloth. This permits bringing climatic factors virtually under control.

Of the fruits, the apple is the most important from the point of view of acreage. The climatic boundaries of this crop are a mean summer temperature of 79° F., a mean winter temperature not lower than 13° F., and an annual rainfall of not less than 18 inches. Cherries have about the same climatic requirements as apples. Peaches and plums will not survive under as severe winter temperatures as apples. Grapes, for wine or raisins, are grown largely in warm climates where rainfall is fairly abundant and the autumn harvest period is dry. A considerable acreage of grapes is found in the region of the Great Lakes, where they are naturally protected against extreme changes in temperature. Citrus fruits are grown only in regions where there are no severe frosts. In the United States, therefore, they are largely confined to the peninsula of Florida, southern California, and the Rio Grande Valley.

BIOTIC FACTORS AND CROP GROWTH

The wheat crop suffers in warm humid climates from parasitic fungi that find a favorable environment under such conditions. Hessian fly and blackstem rust are important biotic agents affecting this crop. Similarly, other crops are injured to varying degrees by insects, fungi, bacteria, and other parasites, the development of which is favored by certain climatic conditions. Although many of these biotic agents are injurious, some of them are beneficial to crop plants. Notable examples of these are found among the bacteria and fungi that have to do with making organic, mineral, and atmospheric elements available for crop use. It seems desirable in this discussion to include these beneficial organisms, as well as all the parasitic organisms that harbor in the soil, among the edaphic factors, since the only opportunity for their control lies in some operation that alters the physical, chemical, or biological properties of the soil.

Effects of crops upon other crops grown in association with them as well as upon the crops that follow merit consideration. Explanation of the injury done to a crop by weeds is probably not as simple as might be anticipated from the usual statement that they compete with the crop for water, soil nutrients, and light. Sorrel (*Rumex acetosella*), for example, leaves a toxic residue in the soil that has an injurious effect on crop plants. Variations in yields of [illegible]ollowing clover and timothy are not due entirely to known differences in the effects of these crops on the total nitrogen content of soils. That yields of wheat after potatoes, tobacco, and soybeans are higher than

those after corn is well known, but this has not as yet been satisfactorily explained. There are many interesting problems connected with plant associations and crop successions that merit more study.

Man is the most important biotic factor since, in addition to his ability to change, in part, the properties of the soil, to regulate the processes that take place in it, and to modify the effects of climatic factors, he is able to control other biotic agents that influence crop growth. *By breeding and selection, man is able to develop new varieties and strains of plants that thrive over a wider range of climatic conditions, have greater resistance to disease, and possess greater capacity to obtain from a given soil the elements that are required by crops.*

EDAPHIC FACTORS AND CROP GROWTH

Edaphic factors vary in their effects on crop growth, depending on the influence of climatic and biotic factors. *Productivity is not a property that is inherent in the soil but one that must be considered in relation to the environment of the soil and the requirements of the crops to be grown.*

The effects of factors other than the soil on the growth of crop plants is apparent in yield fluctuations on plots on long-continued fertilizer tests such as those at State College, Pennsylvania. Continuous yield records of four of these plots over a 44-year period are shown in Table 1. The rotation followed was corn, oats, wheat, and clover. By having four series of plots, it was possible to have each crop growing each year on one or the other of these sets. Each plot of which the records are shown in the table received the same amounts of the same complete fertilizer and should have produced virtually the same yield. The mechanical operations were the same on all plots, except as the weather may have made it necessary to change their nature or frequency of use. Climatic and biotic factors, however, could not be controlled except in a minor way. The fluctuations in yield of each crop from year to year that are to be noted in the table are very great. These make it apparent that productivity of a soil must be considered in relation to the environment in which that soil happens to be. Environmental factors are dynamic. Their effects are never quite the same for any two seasons. Often they are very different.

Nevertheless, it is possible to effect very marked improvement in the productive capacity of any soil, even though it is subject to influences of climatic and biotic factors. Thus, in the series of plots

TABLE 1

FLUCTUATIONS IN ACRE YIELDS DUE TO UNCONTROLLED FACTORS* (GARDNER)

Year	Corn, Bu.	Stover, Cwt.	Oats, Bu.	Straw, Cwt.	Wheat, Bu.	Straw, Cwt.	Hay, Cwt.
1882	44	40	42	23	27	31	..
1883	62	40	53	22	33	32	50
1884	79	29	48	15	33	24	36
1885	53	18	48	13	15	14	16
1886	48	27	64	28	11	16	41
1887	62	28	33	13	7	9	50
1888	78	58	41	15	23	13	32
1889	79	35	51	14	19	16	44
1890	57	30	23	10	27	36	31
1891	70	34	56	16	24	30	36
1892	56	34	39	16	22	25	31
1893	51	28	43	30	24	27	68
1894	46	32	26	14	21	30	67
1895	60	27	37	14	26	34	74
1896	43	18	62	21	23	14	22
1897	49	22	44	22	40	52	45
1898	70	37	30	18	33	38	58
1899	43	22	42	17	15	19	43
1900	35	22	40	19	8	7	20
1901	49	22	18	13	18	23	22
1902	42	25	44	9	27	18	69
1903	65	34	29	11	28	22	21
1904	45	24	33	24	9	11	61
1905	67	28	46	20	28	30	45
1906	73	28	24	11	29	26	42
1907	65	32	51	18	22	25	44
1908	51	23	40	21	28	28	59
1909	22	37	32	17	25	31	53
1910	58	30	53	19	23	30	43
1911	62	38	35	13	23	21	35
1912	67	28	51	16	25	28	39
1913	46	24	58	18	24	28	34
1914	57	28	41	11	22	21	27
1915	65	37	64	26	22	17	24
1916	53	24	48	22	24	25	51
1917	50	25	60	29	23	23	32
1918	55	15	52	15	23	20	32
1919	71	31	38	18	26	22	39
1920	66	36	59	21	25	22	49
1921	76	34	44	13	22	23	32
1922	62	24	49	19†	25	30	48
1923	49	33†	42	12	18	19†	19
1924	57	37	63	20†	21	25	40
1925	64	23†	50	13	32	24†	36

* Crop records of four plots on which corn, oats, wheat, and clover are being grown in rotation, the sequence being so arranged that all four crops appear each year.

† Yields probably influenced by supplemental treatments of lime.

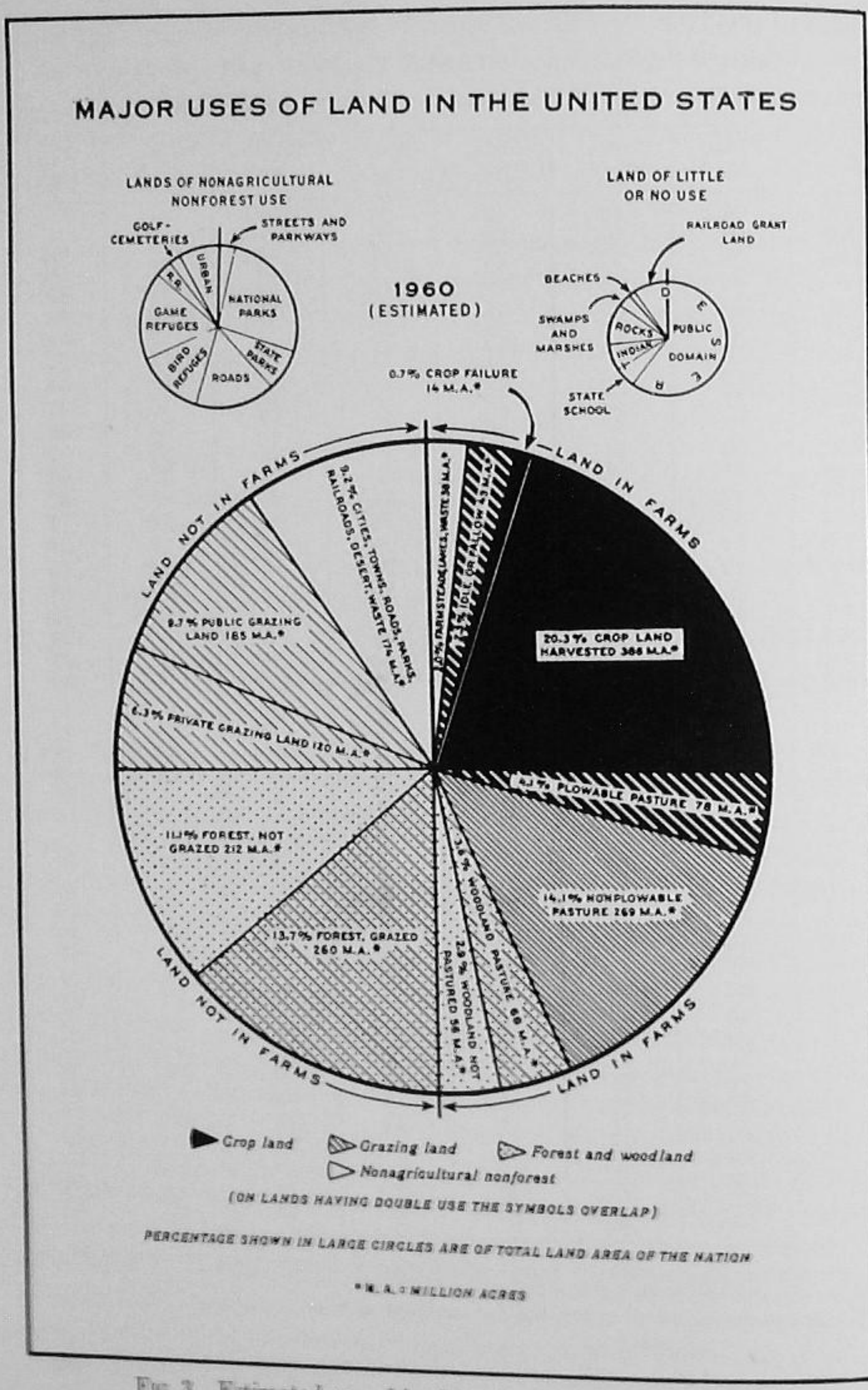


Fig. 3. Estimated use of land in the United States in 1960.

just mentioned the average annual yield has varied greatly (Table 2), depending on the fertilizer and manurial treatments the various plots have received.



Pennsylvania Agr. Exp. Sta.

FIG. 4. Field plots in a long-time fertilizer experiment at Pennsylvania State College. These tests were started in 1882 and have been continued ever since.

TABLE 2

IMPROVEMENT IN ACRE YIELDS DUE TO SOIL TREATMENTS* (GARDNER)

Soil Treatments	Corn, Bu.	Oats, Bu.	Wheat, Bu.	Hay, Cwt.
No fertilizer	33.7	30.5	12.4	21.9
Superphosphate	43.6	37.1	15.9	19.1
Phosphate and potash	52.1	42.3	19.1	39.9
Complete fertilizer	57.1	43.6	23.2	41.2
Manure (10 tons)	58.2	44.4	25.9	42.3
Manure (6 tons) and lime	62.5	43.7	23.8	42.2

* Average acre yields over a 44-year period of plots located at State College, Pennsylvania.

A 28.8-bushel increase in corn yield and corresponding improvement in yields of other crops, for which soil treatments alone are responsible, give an indication of the possibilities of improving the productive capacities of soils through control of edaphic factors alone. It is essential to remember, however, that the larger yields produced by applications of fertilizers, liming materials, and manure may be

accounted for in part by the capacity of these soil amendments to modify the influence of climatic and biotic factors. It is important also to keep in mind that climatic factors limit the distribution of a crop. Beyond a certain distance from the climatic crop center the crop may not thrive no matter how carefully the soil is managed. But *the farmer has the alternatives of modifying the soil to fit the needs of a given crop or of choosing another crop that may be better adapted to the soil under the environment in which it happens to be.*

SELECTED REFERENCES

1. Baker, O. E. A graphic summary of physical features and land utilization in the United States. *U. S. Dept. Agr., Misc. Publ.* 260, 1937.

2. Baker, O. E., and A. B. Genung. A graphic summary of farm crops. *U. S. Dept. Agr., Misc. Publ.* 267, 1938.

3. Gardner, F. D., C. F. Noll, and R. D. Lewis. Forty years' results with fertilizers. Pennsylvania Agr. Exp. Sta., Bull. 175, 1922.

4. Garner, W. W., and H. A. Allard. Flowering and fruiting of plants as controlled by the length of day. *U. S. Dept. Agr. Yearbook,* pp. 377–400, 1920.

5. Gray, L. C., and Associates. The utilization of our lands for crops, pasture and forests. *U. S. Dept. Agr. Yearbook,* pp. 417–505, 1923.

6. Hambidge, Gove, editor. Climate and Man. *U. S. Dept. Agr. Yearbook,* 1941.

7. Stefferud, Alfred, editor. Crops in Peace and War. *U. S. Dept. Agr. Yearbook,* 1950–51, 1951.

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Nitrogen and Mineral Requirements of Crops

Analysis of a plant does not necessarily show its quantitative need for the elements contained in it. So far as is known, there is nothing to prevent entrance into root hairs of any of the ions that may be present in the soil solution. Similarly, atmospheric gases all have access to the interior of the plant in proportion to their solubilities in its sap. Nevertheless, it is to be expected that the elements that are common to all plants and that are present in them in considerable amounts perform necessary functions. It is possible that certain of these functions can be performed by more than one element. For example, there is abundant evidence that sodium can partially replace potassium and that selenium may serve as a partial substitute for sulfur. Plant analysis provides a clue to plant requirements and permits fairly exact estimates of the amounts of nitrogen and mineral nutrients that are removed from the field in harvested crops.

COMPOSITION OF THE CORN PLANT

A large amount of analytical data is available on the chemical composition of plants. Much of this is of doubtful value from the quantitative point of view, at least for certain elements. Early chemists, of necessity, made use of methods of analysis that are now known to be faulty. For that reason, recent analyses are much to be preferred. Table 3 gives a dependable analysis, showing the elemental composition of corn harvested at the stage at which it would be put into a silo. The yield on which the calculation is based is about 16 tons of silage, or such an amount as would have contained 10,000 pounds of oven-dried material. The accuracy of the estimates is subject to the limitation that the data are calculated from analyses of only five stalks of corn representing one variety, one soil, and one climatic environment,

TABLE 3

POUNDS OF ELEMENTS IN 10,000 POUNDS DRY WEIGHT OF CORN (LATSHAW)

Element	Symbol	Roots	Stalks	Leaves	Grain	Cobs	Entire Plant
Oxygen	O	316.3	1056.7	1234.8	1418.9	430.3	4457
Carbon	C	307.1	1071.5	1161.6	1400.7	429.1	4370
Hydrogen	H	41.4	141.6	164.7	218.9	59.4	626
Nitrogen	N	9.2	20.1	36.6	67.3	13.0	146
Silicon	Si	32.2	10.0	73.0	0.5	1.2	117
Potassium	K	3.5	30.5	39.7	13.4	4.5	92
Calcium	Ca	4.4	4.1	13.2	0.8	0.2	23
Phosphorus	P	0.8	2.1	5.8	10.6	0.8	20
Magnesium	Mg	1.2	3.8	5.9	6.2	1.0	18
Sulfur	S	1.8	3.8	6.7	4.3	0.2	17
Chlorine	Cl	0.8	5.0	6.3	1.0	1.1	14
Aluminum	Al	7.1	0.3	2.0	0.7	0.5	11
Iron	Fe	3.7	1.2	2.0	1.3	0.2	8
Manganese	Mn	0.5	0.4	0.9	1.2	0.3	3
Sodium	Na	other elements and errors*					78*
Per cent of total crop		7.2	24.1	28.1	31.3	9.3	100

* In a quantitative analysis of any material, the sum of the constituents seldom equals the weight of the original material. The quantity 78 includes sodium and other elements that were not determined.

that of Manhattan, Kansas, under the conditions that happened to obtain during the summer of 1920.

Over 70 per cent of corn, at the siloing stage, is water. Nearly 95 per cent of the dry weight remaining after this water has been driven off by heat is made up of oxygen, carbon, and hydrogen. The nitrogen and mineral elements in the 10,000 pounds dry weight of crop totaled only 547 pounds, of which 117 pounds was silicon, an element of doubtful value to the plant or to the consuming animal.

SOIL IN RELATION TO PLANT COMPOSITION

Within limits, the total content of any one of the soil-derived elements in a plant is proportional to the quantity of that nutrient that was available to the plant in soluble form. Plants will absorb much larger amounts of nitrogen and individual mineral nutrients than may be required for optimum growth. This is especially true of potassium, which tends to accumulate in the plant at the expense of calcium and magnesium. By analyzing the plant one has an indirect method of analyzing the soil for available nutrients. The several species of

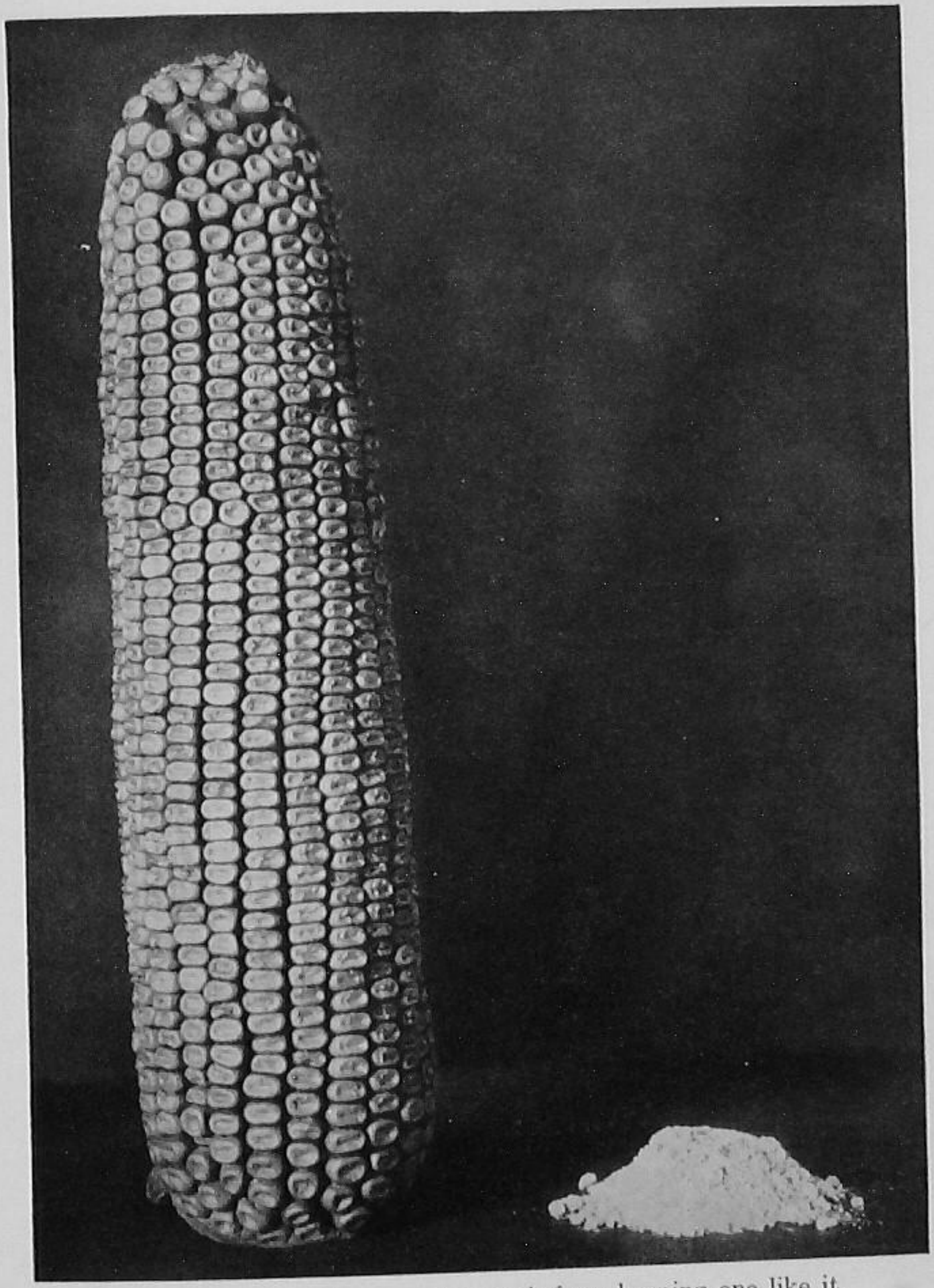


FIG. 5. An ear of corn and the ash from burning one like it.

plants differ in their capacity to extract specific mineral nutrients from the soil. This may be largely related to the nature of their root systems and the depth to which these grow. By growing the same plant species on a number of different soils under controlled conditions, one can get an idea of the relative capacities of these soils to yield up the several nutrients to plants and an indication of any deficiencies that may need to be overcome.

It has long been known that the quality of pasture grasses is related to the soil on which they were grown. English farmers choose certain pastures for young stock and others for fattening cattle. The same principle is being applied to finishing range cattle for market in this country. Evidence of variation in the nitrogen and mineral content of bluegrass is shown in Table 4. The soil in the Lexington,

TABLE 4

VARIATION IN THE PERCENTAGE COMPOSITION OF KENTUCKY BLUEGRASS* (FORBES)

Locality	N	Ca	K	P	Ash
Lexington, Kentucky	1.91	.295	2.15	.373	7.08
Wooster, Ohio	1.77	.229	2.09	.272	6.22

* Averages of four samples in each case.

Kentucky, area is exceptionally high in phosphorus and calcium, whereas that at Wooster, Ohio, is notably deficient in these elements. These soil differences are clearly reflected in the calcium and phosphorus content of the grass. Thus, there is good reason for believing that the grasslands of central Kentucky merit the reputation they enjoy of producing exceptionally fine horses and cattle. But it is believed that equally nutritious grass can be produced at Wooster, Ohio, by correct choice and use of soil amendments.

VARIATION IN PLANT COMPOSITION

Plants differ in composition, depending upon species, variety, strain, stage of maturity at harvesting, and the environment under which they have been grown. Table 5 is of interest in this connection in that it gives the nitrogen and mineral content of some of the more important crop plants, as revealed by very careful laboratory examination. For the most part, these plants were grown under virtually the same soil and climatic conditions.

TABLE 5

POUNDS OF ELEMENTS* IN 1000 POUNDS OF PLANT MATERIALS (FORBES)

Materials	N	K	Ca	Mg	S	P	Ash
Corn	13.9	3.40	0.12	1.08	1.47	2.60	12.1
Oats	17.4	4.19	1.02	1.18	1.95	3.95	33.8
Wheat	16.5	5.20	0.50	1.30	1.98	3.73	16.4
Soybeans	63.1	19.13	2.10	2.23	4.06	5.92	50.6
Corn stover	8.8	17.18	4.72	0.86	1.74	0.95	65.2
Wheat straw	2.8	7.96	2.05	0.60	1.50	0.36	34.5
Clover hay	20.8	17.01	11.42	2.70	1.76	1.69	67.6
Bluegrass hay	14.6	12.90	3.08	2.20	3.07	2.22	48.2
Apples	0.4	1.18	0.04	0.05	0.06	0.09	2.7
Potatoes	3.3	2.72	0.05	0.58	0.25	0.47	6.7
Onions	2.6	1.83	0.33	0.17	0.76	0.41	5.5
Cabbage	1.9	1.73	0.41	0.15	0.63	0.18	5.0
Wheat bran	25.2	13.20	1.25	5.31	2.67	11.10	60.6
Cottonseed meal	57.4	16.56	2.66	5.48	4.90	13.52	69.8

* K × 1.2 = K_2O; Ca × 1.4 = CaO; Mg × 1.7 = MgO; S × 2.5 = SO_3; P × 2.3 = P_2O_5.

It will be noted that soybean seed, in comparison with cereals, are high in nitrogen and ash. Clover hay contains higher percentages of nitrogen, calcium, magnesium, and phosphorus than does wheat straw. Corn stover and clover hay are relatively high in ash. Soybeans are highest in nitrogen and potassium, clover hay in calcium, and cotton-seed meal in magnesium, sulfur, phosphorus, and ash. The low nutrient content of apples, potatoes, onions, and cabbage is due to their high percentages of water. On a dry-matter basis, their nitrogen, mineral, and ash values would be much higher than indicated. The nitrogen content of soybeans ranges between 5 and 7 per cent, depending on the variety. Corresponding differences have been found in the nitrogen and mineral composition of seed and other portions of the several varieties of a large number of crop plants.

CHANGES IN PLANT COMPOSITION DURING GROWTH

Percentages of nitrogen and mineral nutrients in plants, on a dry-matter basis, are highest during the earlier stages of growth, whereas starch, cellulose, and fiber accumulate as the plants mature. Accompanying seed production, nitrogen, phosphorus, magnesium, and sulfur tend to concentrate in the seed of plants, notably in the seed coats. Most of the calcium and potassium remain in the leaves and stalks. As the plant matures, some of its nitrogen and a large part of its

mineral elements can be leached from it by use of water. A considerable part of this water-soluble material is likely to be washed out by rains and, therefore, may not be removed from the field in the harvested crops. This is indicated in Table 6, which shows the percentage

TABLE 6

PERCENTAGES OF ELEMENTS OF MATURE PLANTS SOLUBLE IN WATER (LE CLERC)

Plant	N	P	K	Na	Ca	Mg
Barley plant	2	36	65	52	..	45
Wheat plant	7	33	54	41	34	46
Oats plant	2	33	36	23	40	45
Apple leaves	8	32	36	20	9	12
Potato vines	3	25	18	22	6	12

solubility of the several elements when plants were soaked in water under laboratory conditions.

Much larger percentages of these elements may be dissolved if the leaching process is continued, as may well occur when the crop remains in the field for some weeks after it has matured. The extent of loss of nitrogen and mineral nutrients through crop removal is, therefore, highly variable. It depends not only on the nature of the crop and the soil on which it was grown, but also on the stage of maturity at which it was harvested, the length of time the crop remained on the field after it matured, and the climatic and weather conditions that obtained.

ESSENTIAL AND NONESSENTIAL ELEMENTS IN PLANTS

Some 15 elements are known to be essential to plants. Except for oxygen, carbon, and hydrogen, which are derived mainly from air and water, these elements are obtained by plant roots from the organic and mineral substances in the soil. These soil-derived elements include nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, iron, boron, molybdenum, zinc, copper, and manganese. The soil is restocked with available supplies of these elements, partly by decay of organic matter and by gradual release from soil minerals, partly by the use of legumes, manures, fertilizers, and liming materials, and partly by way of rain, which returns considerable amounts of nitrogen and sulfur to the soil.

All these elements, except boron and molybdenum, are known to be

required by animals. In addition, animals require cobalt, iodine, and fluorine, all of which are found in plants but none of which are known to be needed by them. These five elements, together with zinc, copper, and manganese, which are required by both plants and animals, are needed in such small amounts that they have come to be known as *minor* or *trace* elements. Ranges in total content of these elements in New Jersey plants are shown in Table 7. It will be noted that they are expressed in parts per million rather than as percentages.

TABLE 7

RANGE IN TRACE ELEMENT CONTENT OF NEW JERSEY PLANTS

(In Parts per Million Dry Matter)

Element	Alfalfa		Tomatoes, Average	Snapbeans, Average
	Highest	Lowest		
B	63	18	9	25
Mo	4.6	0.1	0.2	0.6
Zn	15	24	.....	.....
Cu	44	23	20	14
Mn	48	14	7	7
Co	0.24	0.07	0.08	0.03
I	1.90 *	0.66 *	.....	.....
F	.....	.....	35	40 †

* In Ladino clover. † In buckwheat.

A number of other elements are known to influence plant growth favorably, often effecting marked increases in yield when supplied to soils in soluble form. Sodium, silicon, and chlorine are included in this group. Of these, sodium and chlorine are also required by animals. A considerable number of other elements that are contained in most soils are known to affect both plants and animals, often negatively. In this group are aluminum, titanium, and selenium. Aluminum is often present in sufficient amounts to be toxic to plants and selenium is highly toxic to animals. Other elements that may cause injury to both plants and animals are lead, mercury, and arsenic, all of which are being used in the form of insecticides or fungicides.

It is possible that further study will show that additional elements

are required in mere traces by plants or animals, or by both. Virtually all the known elements may be required by one or another species of plant or animal, if not by all of them. Very small amounts may have highly stimulating effects, whereas larger amounts may have additional value or may be toxic. The matter of nutrient balance also enters into this problem. A great deal more work will have to be done before a complete picture is obtained of the mineral needs of plants and of the animals that consume them, including man.

THE MINERAL THEORY

Justus von Liebig, a famous German chemist who was prominent in scientific circles during the middle of the nineteenth century and who was known as the father of agricultural chemistry, formulated what has been called the *mineral theory* of plant nutrition. This was to the effect that "crops on a field diminish or increase in exact proportion to the diminution or increase of the *mineral* substances conveyed to it in manure." Liebig pointed out that it had long been known that the carbon of plants is derived from the carbon dioxide of the atmosphere. He believed that their nitrogen likewise was obtained from the ammonia in the atmosphere. His statement was designed to emphasize the special importance of mineral elements in soil and plant economy.

Liebig argued that soil exhaustion was simply the result of continued removal of these mineral nutrients in harvested crops. Accordingly, he suggested the use of mineral salts carrying these same elements as a means of renewing the supplies in the soil. His "patent manures" produced such remarkable effects as to arouse the curiosity of those who passed by his experimental farm. As a result, there was begun what has since developed into an enormous fertilizer industry, the function of which is that of supplying, in available forms, the nutrient elements that plant analyses show are being removed from the land in crops and livestock.

It has since been shown that nitrogen as well as mineral nutrients must be returned to the soil. It must also be kept in mind that water relationships, temperature, soil reaction, and a variety of other climatic, biotic, and edaphic factors influence plant growth. Also, it is important to remember that when any needed substance is available to the plant in excessive amounts it may have a negative effect. For example, excessive applications of lime interfere with the availability

to the plant of such elements as manganese, zinc, and iron. Further, even if all the necessary nitrogen and mineral requirements are present in optimum amounts and all influencing factors are under control, the plant is finally limited by the capacity of its protoplasm to do work.

If all the factors affecting plant growth were at the optimum except

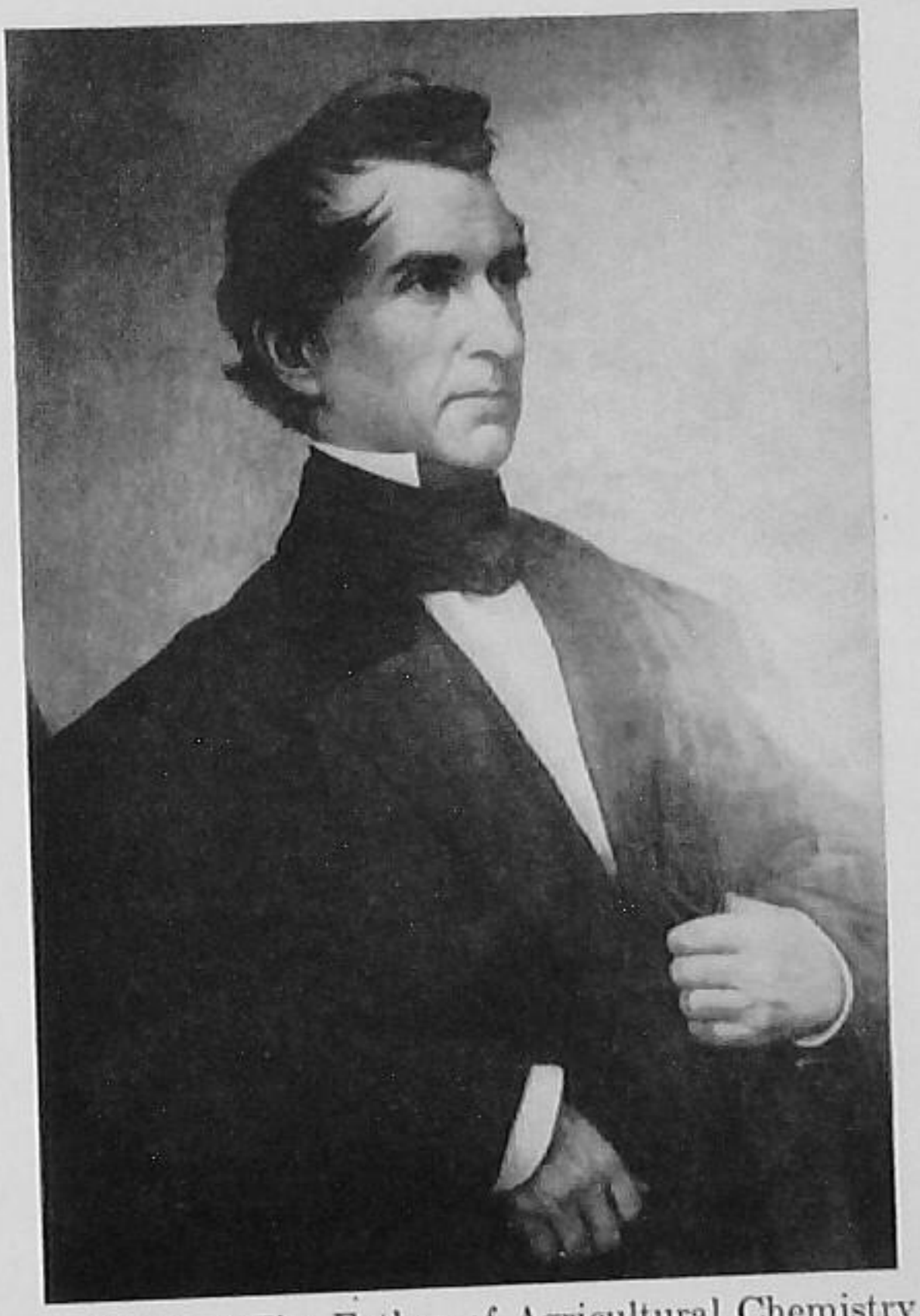


FIG. 6. Justus von Liebig, "The Father of Agricultural Chemistry," from a painting at the Ohio State University.

one, the yield of the crop would be expected to be proportional to the quantity of that factor at the plant's disposal. But since all growth factors are interrelated, the effect of a deficiency of any one is determined by its relation to the others as well as by the need of the plant for it alone.

EFFECT OF FERTILIZER SALTS ON CROP YIELDS

It has frequently been shown that various chemical compounds, when added to soils that have been under cultivation for some years,

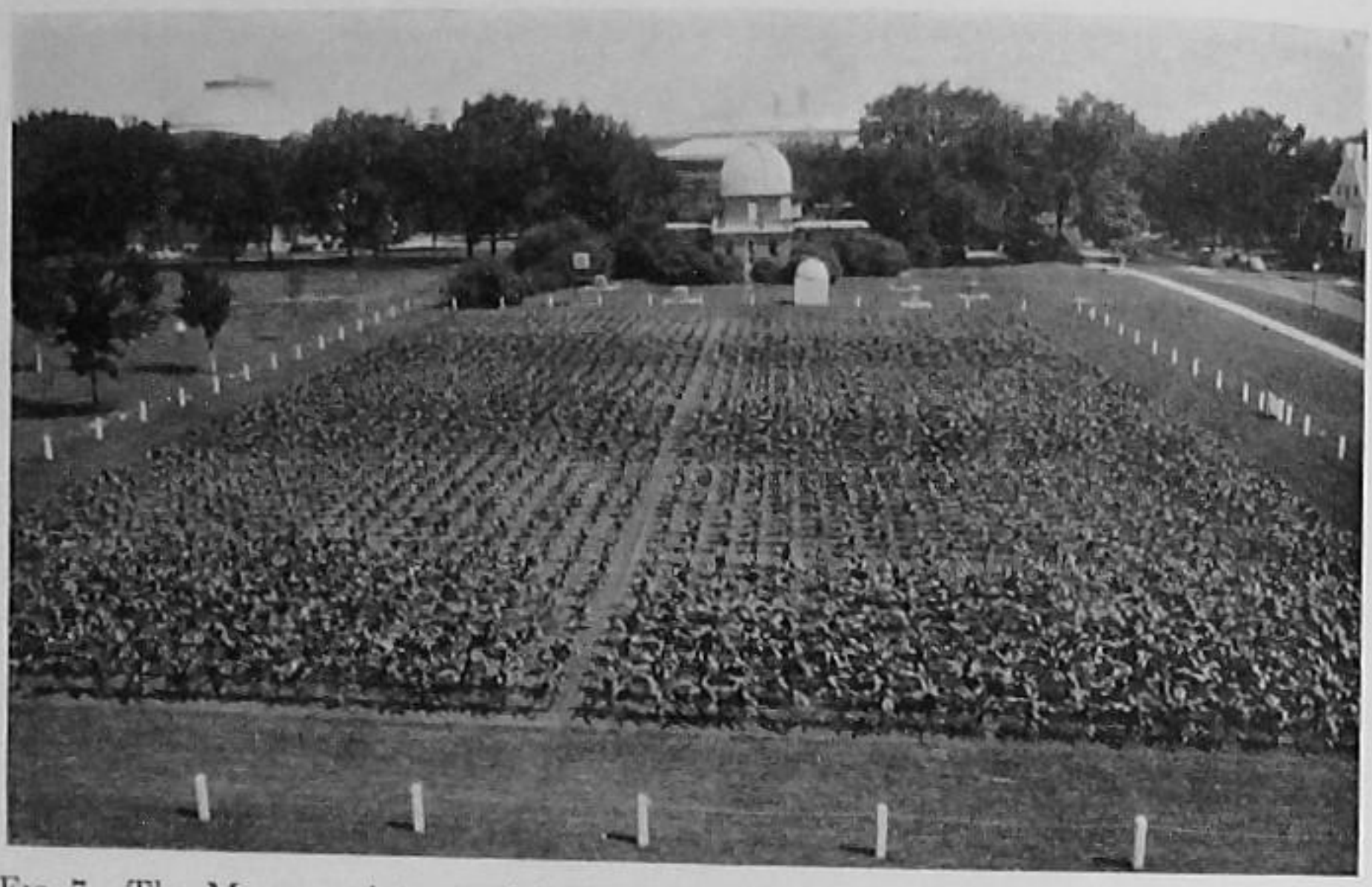


FIG. 7. The Morrow plots, established in 1876 on what is now the campus of the University of Illinois, are America's oldest soil-fertility plots.

materially increase rate of growth and total yield or improve the quality of crops growing on them. The example shown in Table 8 is one of many such tests that have been made the world over. It is

TABLE 8

EFFECT OF VARIOUS CHEMICAL COMPOUNDS ON CROP YIELDS* (BEAR)

Compounds	Amounts Added, Lb. per Acre	Produce in Lb. per Acre	
		Actual	Relative
None	0	40,034	100
Nitrate of soda	4,200	41,195	103
Muriate of potash	1,625	41,565	104
Nitrate and muriate	5,825	52,215	130
Superphosphate	4,200	63,415	159
Phosphate and muriate	5,825	76,995	192
Nitrate and phosphate	8,400	95,940	240
Nitrate, phosphate, muriate	10,025	117,910	295
Same and burned lime	14,525	120,605	301

* Total dry weight of crops produced on an acre during a fifteen-year period.

distinctive only in the sense that the applications of fertilizer salts were quite heavy and the soil, a Dekalb silt loam, was very unproductive, although not more so than large acreages of land in eastern and

southern United States. The data are calculated on an acre basis and give the total dry weight of crops produced during the 15-year period the experiment was in progress.

Each of the compounds employed, whether used alone or in combination with others, increased crop yields. If the conception of one limiting factor operating at a time were strictly applicable, one would not expect applications of nitrate of soda or muriate of potash to increase yields when an even larger increase was produced by the use of superphosphate alone. It is now known that each of these salts has indirect as well as direct effects on crops through their action in the soil. But it is apparent that the interrelationship existing among the various fertilizer compounds in their effects on plant growth are too complex to be explained by such a simple statement as Liebig's mineral theory.

SOIL-PLANT-ANIMAL-ATMOSPHERE-SOIL CYCLE

Modern field-irrigation systems have amply demonstrated that yield and quality of crops can be improved even in humid regions by using more water than rain supplies. Greenhouse studies have shown that plants are able to use carbon dioxide at a more rapid rate than it can be obtained from ordinary air. Yet dependence is usually placed on



FIG. 8. Aerial view of modern set of soil-fertility plots at Iowa State College.

the natural water and carbon dioxide cycles by way of soil, plant, animal, atmosphere, and soil. These cycles may be completed in relatively short periods that suffice to meet the ordinary requirements of plants. Similarly, there are cycles for return of nitrogen and sulfur to the soil.

Most mineral nutrients are not returnable through such cycles and, for that reason, they must be applied in the form of manures, liming materials, and fertilizers. For these elements the problem is one of determining the rate at which they are removed in crops and in drainage waters and then planning to replace them by the most economic or effective procedure. Certain compensatory processes operate in the soil to renew the available supplies of these mineral nutrients. But where land has been under cultivation for some years, addition of soluble forms of nitrogen, phosphorus, and potassium and of the alkaline forms of calcium and magnesium will usually result in marked increases in crop yields. This is especially true in humid regions, where losses by way of drainage waters are often very high. With increasing frequency, carriers of boron, molybdenum, zinc, manganese, and copper are being supplied to good effect. Extra cobalt and iodine may be required for the consuming animal, but no improvement in crop yields is to be expected from their use.

SELECTED REFERENCES

1. Ames, J. W. The composition of wheat. Ohio Agr. Exp. Sta., Bull. 221, 1910.

2. Bear, F. E. Experiments with fertilizers. West Virginia Agr. Exp. Sta., Bull. 155, 1915.

3. Beeson, Kenneth C. The mineral composition of crops with particular reference to the soils in which they were grown. *U. S. Dept. Agr., Misc. Publ.* 369, 1941.

4. Curtis, Otis F., and Daniel G. Clark. *An Introduction to Plant Physiology.* McGraw-Hill Book Co., New York, pp. 361–404, 1950.

5. Forbes, E. B., and Associates. The mineral nutrients in bluegrass. Ohio Agr. Exp. Sta., Bull. 222, 1910.

6. Forbes, E. B., and Associates. Mineral and organic analyses of foods. Ohio Agr. Exp. Sta., Bull. 255, 1913.

7. Latshaw, W. L., and E. C. Miller. Elemental composition of the corn plant. *J. Agr. Research,* Vol. 27, No. 11, 1914.

8. LeClerc, J. A., and J. F. Breazeale. Plant food removed from growing plants by rain or dew. *U. S. Dept. Agr. Yearbook,* pp. 389–403, 1908.

9. Russell, E. John, and E. Walter Russell. *Soil Conditions and Plant Growth,* eighth edition. Longmans, Green and Co., New York, pp. 30–67, 1950.

10. Truog, Emil, editor. *Mineral Nutrition of Plants.* University of Wisconsin Press, Madison, 1951.

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Water Requirements of Plants

Moisture relationships of plants are of primary importance in determining their natural distribution. These relationships may be considered in terms of the water requirements of plants and of the supply of water that is available for their use. *Water requirement* may be defined as the ratio between the amount of water transpired by plants and the amount of dry matter produced by them. It varies chiefly with the nature of the plant, the fertility of the soil, the humidity of the atmosphere, the temperature, and the amount and intensity of the sunlight. The water supply is normally determined by the rainfall and the extent to which this water escapes beyond the reach of plants by drainage, evaporation, and transpiration.

NATURAL VEGETATION REGIONS OF THE UNITED STATES

Distribution of native vegetation of the United States is an expression of the effects of the climatic factors that operate in the several regions. It seems probable that when ecologists have established the many subdivisions of these large regions they will be found to correspond to the centers of production of the several species of crop plants. Of particular interest is the very evident importance of the moisture factor in determining the natural distribution of forests and grasslands. It is no less important in determining the centers of production of the extensively cultivated field crops. Furthermore, within any region in which the climate is suitable for a given crop, it is this same moisture factor that, more than any other, is responsible for fluctuations in the yields produced.

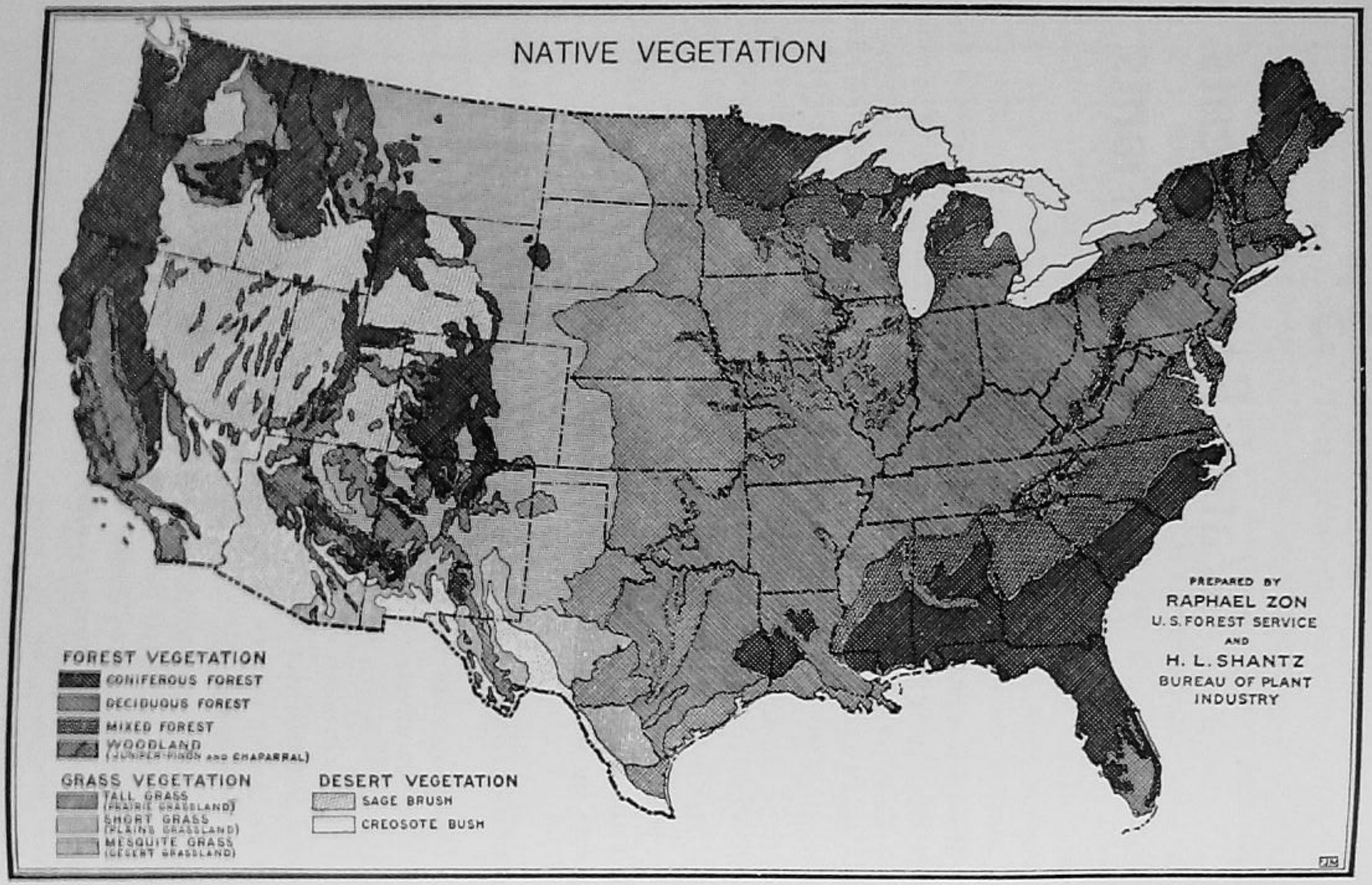
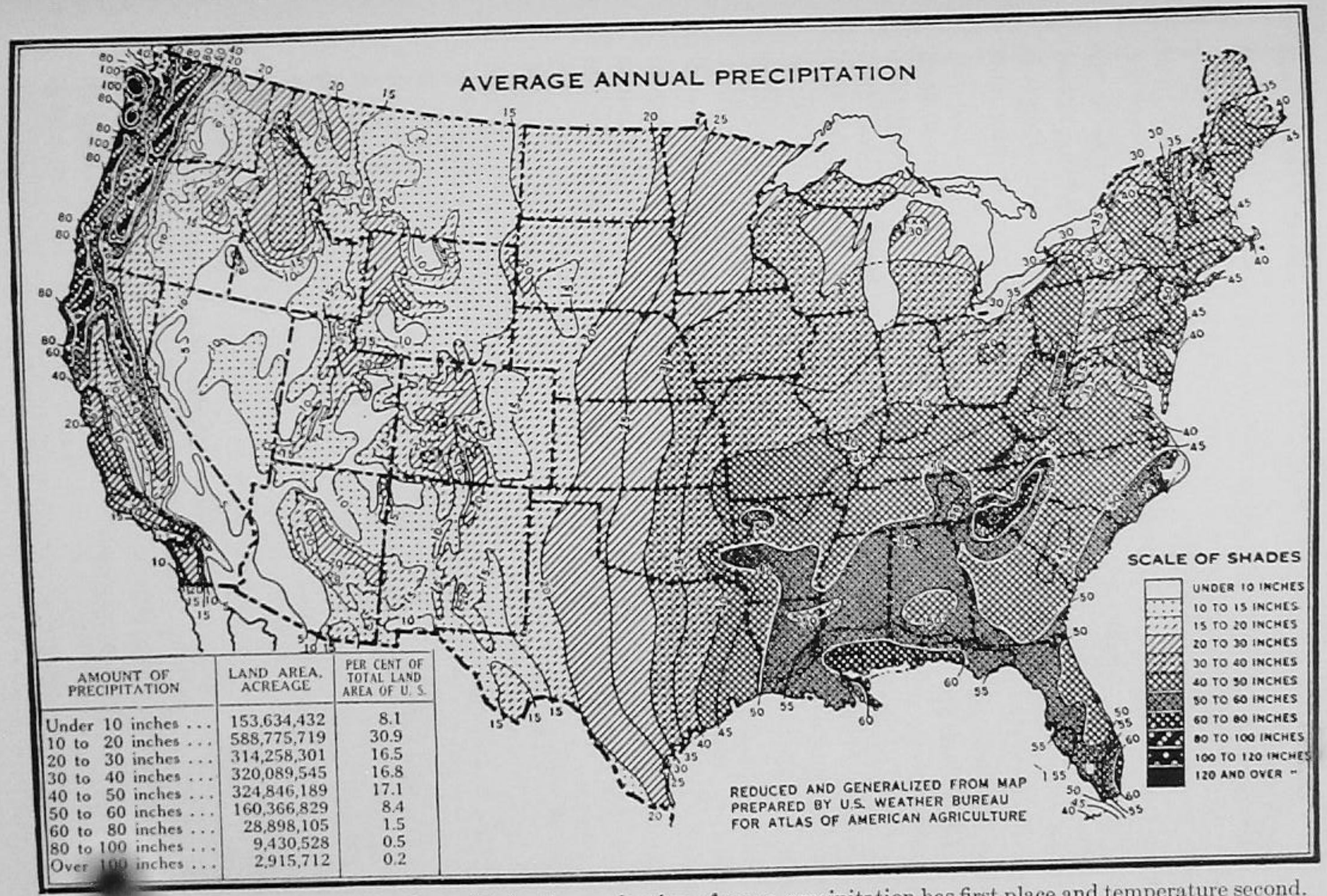


FIG. 9. Climate is the controlling factor in plant distribution.



AMOUNT OF PRECIPITATION	LAND AREA, ACREAGE	PER CENT OF TOTAL LAND AREA OF U. S.
Under 10 inches . . .	153,634,432	8.1
10 to 20 inches . . .	588,775,719	30.9
20 to 30 inches . . .	314,258,301	16.5
30 to 40 inches . . .	320,089,545	16.8
40 to 50 inches . . .	324,846,189	17.1
50 to 60 inches . . .	160,366,829	8.4
60 to 80 inches . . .	28,898,105	1.5
80 to 100 inches . . .	9,430,528	0.5
Over 100 inches . . .	2,915,712	0.2

FIG. 10.—In a latitude and elevation favorable for the production of crops, precipitation has first place and temperature second.

RELATION BETWEEN RAINFALL AND CROP YIELDS

After studying the relationship between rainfall and crop yields, J. Warren Smith showed that, in a latitude and at an elevation favorable for the production of any given crop, precipitation has first place and temperature second in determining yields. A high degree of correlation was found between rainfall for July and corn yields in the eight most important corn-producing states over a 25-year period. When July rainfall averaged less than 3.4 inches the yield of corn in those states averaged 10 bushels less an acre than when it was more than 4.4 inches.

Crops that are being grown at considerable distance from their climatic crop centers are replaced, in the direction of decreasing rainfall, by those that suffer less from drought. It is for this reason that grain sorghums are substituted for corn toward the southwest. The grain sorghums have water requirements quite similar to those of corn, but they have remarkable capacity to withstand dry weather without apparent injury. During periods of drought they remain dormant. When rain comes, the normal rate of growth is again continued. It is for this same reason that cotton tends to replace corn to the southwest. Cotton is able to withstand drought and still produce a fair crop even if rain is late in coming. The corn plant has only one ear, whereas the cotton plant has many bolls, the critical periods for which do not all come at the same time. Alfalfa, with its long taproot, survives drought much better than the shallow-rooted clovers, and this is one reason for its thriving in Kansas and Nebraska.

EFFECTS OF INCREASING IRRIGATION WATER

A somewhat better understanding of relationships between water supply and crop yields may be had by studying irrigation records in the western states. A point of greatest importance is that of determining when to discontinue application of water to any one acre and to begin enlarging the acreage under irrigation. The crop-yield data on sugar beets and potatoes in Table 9 are of interest in this connection. In this test, water was supplied at rates of 1, 2, 3, 4, and 5 inches a week by the flooding method. Total yearly rainfall amounted to 17.26 inches, as an average for the 5-year period. Of this, 1.20 inches fell during the 3 summer months. Since the soil, a well-drained clay loam, was manured each year, there was probably no lack of nitrogen and mineral elements to limit crop yields.

TABLE 9

ACRE YIELDS* OF CROPS WITH VARYING AMOUNTS OF IRRIGATION WATER (HARRIS)

Water Applied, Acre-inches	Sugar Beets			Potatoes	
	Roots, tons	Tops, cwt.	Sugar, per cent	Tubers, bu.	Tops, cwt.
0	10.3	102	15.2	96	44
10	18.2	215	16.0	248	84
20	19.8	235	16.5	254	90
30	19.7	217	15.6	249	90
40	19.3	237	15.4	279	100
50	19.2	243	15.8	286	102

* Five-year-average acre yields.

The optimum rate of application of water to sugar beets was 20 acre-inches, applied at the rate of 2 inches a week. For potatoes, 50 inches did not seem to be excessive. Experiments with other crops showed similar curves of yield increase from applications of irrigation water, the optimum quantity depending on the crop and the season.

PRECIPITATION-EVAPORATION RATIO

The climatic centers of crop production, insofar as water relationships are concerned, are determined not so much by the amount of precipitation, beyond a certain point, as they are by the rate of loss of water by evaporation. The ratio between the amount of precipitation and the rate at which water will evaporate from a free-water surface, called *precipitation-evaporation ratio*, is perhaps the best expression of the moisture factor that has so far been suggested. This ratio is more than 1 in the typical forest centers of the Atlantic seaboard, the Gulf coast, and the Great Lakes region and between 0.6 and 0.8 in the natural prairie regions of Illinois and Iowa. The desert may be said to begin when this ratio falls to less than 0.2.

Lines connecting points of equal rainfall in the United States tend to run north and south. Those connecting points that have the same precipitation-evaporation ratio bend far to the east in the central part of the United States. This is due to the action of dry westerly winds. In the absence of means for supplying extra water by irrigation, [illegible] tribution of crops as between semiarid-humid and humid climates will be determined quite largely by the water requirements of these crops and the precipitation-evaporation ratio.



FIG. 11. Lettuce grown under irrigation in arid area near Phoenix, Arizona.



FIG. 12. Caprock combine grain sorghum, a dry-land crop, being grown under irrigation in west Texas.

WATER IN PLANTS

Water is required in considerable amounts by plants as a food material. It is the solvent in which nitrogen and mineral nutrients enter plants. By its transpiration, plant temperatures are regulated. The importance of water as a food material is evident from the fact that it is the primary source of the hydrogen and oxygen that constitute such a large percentage of the dry matter in plants. If it were not for the fact that water provides a continuous medium for diffusion purposes, mineral nutrients would have no means of access to plant tissues. Between 200 and 500 pounds of water are transpired from the leaves of plants for every pound of dry matter produced. If the quantity of water falls far below this need, plants go through successive stages of wilting, firing, and dying.

With the corn crop, for example, it is found that, at the siloing stage of maturity, nearly 75 per cent of its weight is water. Only a little over one quarter of a given weight of silage remains after it has been dried at 105° C. This dry matter contains a considerable additional amount of hydrogen and oxygen, most of which had its origin in water that was taken up by the corn roots. As a result of photosynthetic processes in the leaves, simple organic compounds are produced in plants from water and carbon dioxide. These, together with nitrogen and mineral elements, are later synthesized into the more or less complex carbohydrates, oils, and proteins that comprise most of the dry matter of plants.

TABLE 10

PERCENTAGE WATER CONTENT OF PLANT PRODUCTS (FORBES)

Fruits and Vegetables		Mature Grains		Fresh Green Forage	
Apple	85	Buckwheat	12	Alfalfa	75
Beet	87	Corn	14	Bluegrass	68
Cabbage	93	Cottonseed	9	Corn silage	74
Carrot	88	Oats	9	Rape	83
Onion	87	Rice	10	Red clover	74
Potato	82	Soybeans	9	Sweet clover	76
Pumpkin	92	Wheat	12	(Clover hay)	8

Vegetables, root crops, and fruits are made up, in large part, of water. They are highly important in the diet as sources of carbohydrates, mineral elements, and vitamins, but they do not supply anything like the amounts of food and minerals as their weights would

indicate. In fact, for a crop like tomatoes, in which the vines are returned to the soil and the fruit contains as much as 95 per cent water, farmers, in effect, are selling mineralized and vitaminized water at a very high price. Fruits of tomatoes, like sugar from beets and butter from milk, are derived mostly from water and air, and little is lost from the soil by their sale.

WATER AS A MEDIUM FOR TRANSFER OF NUTRIENTS

If an animal or vegetable membrane, such as a cell wall, is interposed between two salt solutions of different concentrations, the substances in solution, as well as the water, tend to diffuse through the membrane until the concentration of each dissolved salt is the same on one side of the membrane as on the other. Similarly, nitrates and mineral nutrients in the soil solution tend to diffuse through the outer walls of the root hairs and find their way from cell to cell into the water-conducting tubes of the xylem, through which they are transported to the farthest portions of the plant. This xylem contains no interfering crosswalls to slow down the movement of the water and the dissolved salts contained in it. Access to the tissue cells along the way is only possible as the solvent and solute pass through the walls of these conducting tubes.

As ions of the dissolved salts are used in the construction of plant substances or in the formation of insoluble compounds, more of them diffuse into the root hairs from the soil solution. This continues until the concentration of each ion is again as high in the plant as it is in the soil solution. In the laboratory, movement of ions takes place with equal rapidity in either direction through an interposed membrane, depending entirely on the relative concentrations of the several ions on either side of the membrane. In the plant, protoplasmic colloids retard return movement of a nutrient ion once it has diffused through the cell wall. Peculiarly, salt concentration within the plant cells tends to become greater than it is in the soil solution. A large percentage of these entrapped ions do not seem to be tied fast in structural combinations within the plant, yet they function in its growth.

It is apparent that water serves as a carrying agent for nitrogen and mineral salts under conditions in which it is passing through tubes that contain no interposed membranes. This is true when water moves upward in the soil by capillarity or when it moves through the plant xylem tubes. The interposing of a membrane, such as a cell wall, alters the situation and makes the water merely a medium through which ions move in response to attractive forces within the plant.

FLOW OF WATER THROUGH PLANTS

Movement of the water itself through the root hairs and into the xylem is caused in large part by the concentration of dissolved materials, which is much higher in the cell sap than it is in the soil solution. The direction of flow of the water is determined by the total concentration of particles in solution, including both undissociated molecules, such as the sugars, and ions. The cell sap contains the entrapped ions obtained from the soil solution and the soluble compounds that have been synthesized by the plant from carbon dioxide and water. As water is lost from the leaves by transpiration, the concentration of soluble substances in the cells becomes greater and the rate of flow of water into the plant is increased.

The tendency of dissolved molecules and ions in the cell sap is to move in the direction of lower concentrations, such as obtain in the soil. Since the plant colloids prevent their escape from the cells, equilibrium can be reestablished only by movement of water into the plant. As a result, what is known as *osmotic pressure* develops within the cells. This pressure cannot be readily measured directly, but it can be measured by determining the height to which incoming water that is moving toward this higher concentration will pile up on that side of the membrane.

The osmotic pressure of cell sap is usually between 5 and 10 atmospheres, or from 75 to more than 100 pounds a square inch. *An atmosphere* is equivalent to the weight of 760 millimeters of mercury. It can be developed by dissolving the molecular weight, in grams, of an undissociated compound in 22.4 liters of water at 0° C. For compounds that dissociate in water, the quantity required is proportionally less, depending on the degree of ionization.

If, for any reason, the soil cannot supply water to the plant as rapidly as it is being lost by transpiration, wilting occurs. If this is only temporary, no harm will ordinarily result. If it continues for some time, firing of the lower leaves usually takes place, and gradually the entire plant dies. When plants are transplanted, the absorbing root hairs are broken off and wilting likewise occurs. In transplanting tobacco, tomatoes, and similar plants it is common practice to supply extra water around the roots as the plants are being set. Fertilizer salts are often added to this water in dilute concentrations as a means of giving the transplant a quick start. A good *starter-solution* can be made by dissolving 1 pound each of potassium chloride and monoammonium phosphate and ½ pound each of sodium nitrate

and urea in 50 gallons of water. Care must be taken not to use more than these amounts of fertilizer.

If large amounts of these or other soluble salts are applied around the roots of plants, movement of water from plant to soil is likely to occur, with disastrous results to the plant. Plasmolysis of the plant cells occurs, and death may result. Difficulty in this connection is sometimes experienced from use of heavy applications of fertilizer along the row or in the hill. Similarly, plants are often killed by alkali salts where rainfall is limited. This frequently occurs in irrigated arid areas where, as water evaporates from the soil surface, salts are deposited. When this occurs, these salts must be removed by supplying sufficient extra water to flush them off the soil or to carry them away in the underdrainage.

It sometimes happens after rains that atmospheric humidity is such that transpiration from the leaves of plants is very much reduced. Under such conditions, with bright sunshine, the phenomenon known as *scalding* occurs. This gives an indication of the usefulness of transpiration as a means of regulating plant temperatures.

WATER REQUIREMENTS OF TYPICAL CROP PLANTS

The water content of a plant is not an index of its water requirement. Transpiration studies have shown that 250 to 300 or more pounds of water pass through a corn plant and are lost into the atmosphere for every pound of dry matter produced. Calculated on an acre basis, this means that a 100-bushel corn crop will require about 11 acre-inches of water. This is very nearly the average rainfall of the Corn Belt for June, July, and August, the important months in the growing of this crop. Since a considerable percentage of water that falls as rain is lost by drainage and evaporation, extra water must be stored in the soil in anticipation of a deficiency. Unless this has been done, the crop will suffer from lack of this highly important constituent.

A mature apple tree probably transpires as much as a barrel of water a day during the growing season. Calculated on an acre basis and 40 trees, this would indicate a daily need for 5 tons of water. Similarly, vegetables require large amounts of water and usually suffer from a lack of it at some point during the growing season, unless irrigation is practiced. Hay crops thrive under conditions of abundant moisture and, for that reason, are grown to best advantage in northeastern United States or, as with alfalfa, under irrigation.

So many factors influence the rate of transpiration of water by plants that it is not possible to give an absolute value to their water requirements. It is not even safe to assume that the relative water requirements of plants, as calculated for any climatic region, will apply when these plants are grown under different soil and climatic conditions. These limitations must be kept in mind in studying Table 11,

TABLE 11

RELATIVE WATER REQUIREMENTS OF CROPS* (BRIGGS AND SHANTZ)

Crop	Per Cent	Crop	Per Cent	Crop	Per Cent
Millet	85	Sugar beet	110	Cowpea	155
Sorghum	90	Cabbage	145	Soybean	180
Corn	100	Watermelon	160	Hairy vetch	185
Wheat	140	Potato	170	Sweet clover	210
Oats	160	Turnip	175	Red clover	215
Cotton	175	Cucumber	195	Canada pea	215
Rye	185	Rape	200	Crimson clover	220
Rice	190	Pumpkin	225	Alfalfa	225

* On basis of water requirement of corn = 100.

which shows the relative water requirements of crops at Akron, Colorado, using corn at 100 as the standard. The actual water requirement of corn at that location, as an average for a 3-year period, was 368 pounds for each pound of dry matter produced.

SOIL AND CROP MANAGEMENT AND WATER REQUIREMENTS

There are three things a farmer might do that would affect the water requirements of his crops. The most important of these is to choose crops with high or low requirements, depending on the water supply. The quantity of water can be regulated within certain limits. When, however, the cost of its control is high, there may be a choice between making further expenditures for this purpose and growing another crop that is naturally better adapted to the soil and climatic conditions as they are. This is often the deciding factor in determining whether land shall be kept in pasture or put under cultivation. Classification of plants into zerophytes, mesophytes, and hydrophytes recognizes differences in their water relationships. Most of the common crop plants belong to the mesophytes, which means that they thrive best with reasonably good supplies of moisture in the soil. Some very important ones, however, are grown under semiarid-humid conditions and others under systems of flooding.

The number of stomatal openings that develop on the leaves of plants is much smaller if the soil does not contain excess water during the early stages of the growth of a plant. It is a matter of common observation that a corn crop that gets under way during a dry period can withstand drought much better later in the season than one that was subjected to wet weather during its early history. One explanation of this may be found in the smaller number of stomata on the leaves and the smaller subsequent loss of water by transpiration from them (Table 12).

TABLE 12

RELATION BETWEEN WATER SUPPLY AND NUMBER OF STOMATA (DUGGAR)

Water in Soil, Per Cent	Corn Plants		Wheat Plants	
	Weight*	Stomata	Weight*	Stomata
38	3.63	181	3.9	103
30	3.54	130	6.4	85
20	3.36	129	4.7	82
15	2.35	124	3.7	81
11	1.56	107	3.7	59

* Weight in grams.

Another fact that has been established is that the amount of water transpired for each pound of dry matter produced is much less on good soils than on poor ones. This is indicated in Table 13, data for

TABLE 13

THE SOIL IN RELATION TO WATER REQUIREMENTS OF CORN (KISSELBACH)

Class of Soils	Yield*	Requirement†	Yield*	Requirement†
Unmanured Soils:				
Poor soil	100	550	142	376
Intermediate	163	479	330	290
Good soil	239	392	417	262
Manured Soils:				
Poor soil	333	350	364	295
Intermediate	366	341	437	274
Good soil	419	346	447	250

* Relative yields on basis of crop produced on unmanured poor soil = 100.
† Requirement expressed as pounds of water transpired to produce one pound of dry matter.

which were obtained by comparing the water requirements of corn when grown, during a good and a poor crop year in Nebraska, on

manured and unmanured soils of several degrees of natural productivity. These data indicate that 1 pound of water will serve to produce twice as much corn on a good soil during a favorable season as it will under unfavorable conditions of soil and weather.

SELECTED REFERENCES

1. Briggs, L. J., and H. L. Shantz. The water requirement of plants. U. S. Dept. Agr., Bur. Plant Industry, Bull. 285, 1913.

2. Duggar, B. M. *Plant Physiology.* The Macmillan Co., New York, pp. 84–135, 1911.

3. Forbes, E. B., and Associates. Mineral and organic analyses of foods. Ohio Agr. Exp. Sta., Bull. 255, 1913.

4. Hambidge, Gove, editor. Climate and Man. *U. S. Dept. Agr. Yearbook,* pp. 157–236, 1941.

5. Harris, F. S., and D. W. Pittman. Irrigation experiment with sugar beets and potatoes. Utah Agr. Exp. Sta., Bull. 186, 187, 1923.

6. Kisselbach, T. A. Transpiration as a factor in crop production. Nebraska Agr. Exp. Sta., Res. Bull. 6, 1915.

7. Meyer, B. S., and D. B. Anderson. *Plant Physiology,* second edition. D. Van Nostrand Co., New York, pp. 81–205, 1952.

8. Sayre, C. B. Use of nutrient solutions and hormones in water for transplanting tomatoes, and their effect on earliness and total yields. *Proc. Am. Soc. Hort. Sci.,* Vol. 36, pp. 732–736, 1938.

9. Smith, J. Warren. Relation of precipitation to yield of corn. *U. S. Dept. Agr. Yearbook,* pp. 215–224, 1903.

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Origin and Classification of Soils

Soil is a product resulting from disintegration and decomposition of rocks and of plant and animal materials. If the processes in operation are largely physical, as may be true in arid regions, the soil will resemble the parent rock quite closely in its chemical and mineralogical composition, the difference being largely a matter of fineness of division. If, in addition, the rock particles are subjected to the solvent and leaching action of water containing carbonic and other acids and various salts in solution, such as occurs in humid regions, deep-seated changes will be effected. Under these conditions the inorganic part of the soil may become largely an accumulation of finely divided, relatively insoluble, mineral residues that bear little resemblance to the original rocks.

ROCKS, AND SOILS DERIVED FROM THEM

Rocks vary greatly in their chemical composition (Table 14). Igneous rocks, on the average, contain about 75 per cent silica and alumina. Limestones are made up mostly of calcium and magnesium carbonates. Yet the soils that are formed from these very different kinds of rocks are often surprisingly similar in composition. In fact, if rainfall and temperature conditions are identical and topography is level, there is a tendency toward production of a uniform soil product in humid climates, no matter what the nature of the original rocks may have been.

Even under such diverse conditions as have existed in the several parts of the humid regions of the United States, there is a striking similarity in the composition of the soils that have been formed in

TABLE 14

PERCENTAGE CHEMICAL COMPOSITION OF ROCKS (CLARKE)

Oxides	Igneous Rocks	Shales	Sandstones	Limestones
SiO_2	59.14	58.10	78.33	5.19
Al_2O_3	15.34	15.40	4.77	0.81
Fe_2O_3	3.08	4.02	1.07	0.54
FeO	3.80	2.45	0.30	....
MgO	3.49	2.44	1.16	7.89
CaO	5.08	3.11	5.50	42.57
Na_2O	3.84	1.30	0.45	0.05
K_2O	3.13	3.24	1.31	0.33
H_2O	1.15	5.00	1.63	0.77
TiO_2	1.05	0.65	0.25	0.06
CO_2	0.10	2.63	5.03	41.54
SO_3	0.13*	0.64	0.07	0.28*
P_2O_5	0.30	0.17	0.08	0.04
MnO	0.12	....	....	0.05
Others	0.28	0.05	0.05	....

* Includes elemental sulfur calculated as the oxide.

TABLE 15

PERCENTAGE COMPOSITION OF SOILS DERIVED FROM VARIOUS ROCKS* (BENNETT)

Oxides	From Granite	From Shale	From Sandstone	From Limestone
SiO_2	66.49	86.96	74.33	79.35
Al_2O_3	17.11	4.86	11.00	8.89
Fe_2O_3	7.43	2.86	4.64	4.44
TiO_2	1.02	0.69	1.04	1.15
MgO	0.31	0.43	0.69	0.39
CaO	0.36	0.71	1.13	0.63
Na_2O	0.16	1.07	1.53	0.24
K_2O	0.62	0.91	1.57	0.67
MnO	0.51	0.07	0.13	0.07
P_2O_5	0.20	0.07	0.16	0.18
Series	Cecil	Cherokee	Penn	Decatur
Texture	Clay	Silt loam	Silt loam	Clay loam
Sample depth (in.)	0–6	0–6	0–9	0–4

* The range in chemical composition of soils derived from any one class of rocks is often greater than that of soils derived from different classes of rocks.

the several land areas. This is well illustrated in Table 15, which gives analyses of four widely separated soils that had their origin in four very different kinds of rocks. The Cecil series consists of red-yellow lateritic soils that were formed under warm and humid climatic conditions. The Cherokee series is made up of brown-black prairie soils. Those of the Penn and Decatur series are gray-brown podzolic soils. Yet the content of silica, alumina, and iron oxide in the *A* horizons of these soils totals between 90 and 95 per cent.

To a certain extent, this tendency toward similarity in chemical composition of soils holds true with respect to their physical and biological composition as well. All agencies acting on rocks to produce soils tend to effect reduction in size of their constituent particles. These particles pass through successive sizes of gravel, sand, silt, and clay. While this physical disintegration is going on, deep-seated mineralogical changes also occur, so that the resulting clay bears little physical or chemical resemblance to the original rock from which it was formed.

As the soil particles are undergoing disintegration, living organisms begin to develop in them. At first these are of microscopic dimensions. Later the larger forms of plants and animals develop. But as these die and fall to the earth, they undergo decomposition, with the result that a very active microscopic soil flora develops. Except as conditions may later develop that are inimical to these microorganisms, they tend also to be quite similar over wide reaches of soils of very different origins.

Notwithstanding the tendency in the direction of uniformity of soils of humid regions, soil differences at any given time are many. Some of these differences are readily apparent even to the casual observer. Some that are not so evident are easily recognized by the experienced soil-survey worker. Others are brought to light only by careful laboratory study. These differences are physical, chemical, and biological. They are reflected in adaptabilities of soils to various crops and in their relative capacities to produce the same crop. It will be recalled, however, that crop growth and distribution are determined by interaction of several groups of factors, of which those of the soil itself comprise only one. These other factors affect crops not only directly but indirectly as well, through their influence on soil properties. There is the further complication that the ages of soils vary within very wide limits. All degrees of degradation of soil particles, therefore, will be found, depending on the time factor.

SOIL DEVELOPMENT

In the course of their development from rock materials, soils are subjected to processes that effect continuous changes in them. The successive stages in their development have been termed *infancy, youth, maturity,* and *old age.* In order that a soil may mature and age, it must remain positionally fixed and relatively undisturbed over a long period. Such a condition obtains only on areas that are virtually level and that are not subject to erosion. In the event that maturity is attained, the nature of the 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 steep or the location is a desert, the soil may never develop beyond the stages of infancy and youth. In this event, the nature of the rock material from which the soil is formed is of considerably greater importance.

The significance of climatic factors in soil development was first made apparent by a study of the *Chernozems,* or black soils, of south-central Russia and western Siberia. It was shown that these soils, which have developed under an annual rainfall of 15 to 20 inches, are underlain with a great variety of rocks in different areas. Notwithstanding this fact, they are quite uniform in their characteristics. No matter what the nature of the underlying rock, a deposit of carbonate of lime has accumulated in the *B* horizon. Study of climatic factors and related vegetation has shown, without question, that these were the primary agents that were involved in the development of these soils.

Some years later a group of tropical soils, known as *Laterites,** were found to be correlated in distribution with regions of high temperature and very heavy rainfall. Laterites are characterized by high percentages of the oxides of iron and aluminum, particularly the latter, and by almost complete absence of aluminosilicates, the silica other than quartz having been almost entirely leached out.

* The word *Latosols* has recently been substituted for Laterites as the name for this Great Soil Group. Laterite, as the term is now used, refers only to a cemented horizon that is found in some Latosols. This material, when d[illegible] is used as a substitute for stone in constructing houses.

GREAT SOIL GROUPS OF THE UNITED STATES

Soils are now classified into orders, suborders, great soil groups, catenas, series, and types. The three orders are zonal, intrazonal, and azonal. The *zonal order* includes all those soils having well-defined characteristics that reflect the influence of climate and vegetation. The *intrazonal order* contains those soils that reflect dominance of some local factor, such as topography, parent material, or age, over the influence of climate and vegetation. The *azonal order* embraces all the remaining soils that have no well-developed characteristics.

Some 36 soil groups are recognized. In arranging the many series of soils into these groups, consideration is given to the soil profile, native vegetation, climate, natural drainage, and soil-development processes. Thus, *Prairie Soils* are defined as being very dark brown or grayish brown, grading through dark brown to lighter-colored parent material at a depth between 2 and 5 feet. The native vegetation is tall grasses. These soils were formed under conditions of relatively dry, hot summers and moderate rainfall. They have good drainage and may possess a layer of calcareous material at considerable depth in the soil profile.

Soil orders, suborders, and groups of soils of the earth are shown in Table 16. Counterparts of most of these soil orders and groups are found in the United States. Undoubtedly, other groups will be added with more detailed soil surveys of this and other countries.

SOIL PROFILES

On examining a vertical column of soil one finds various *horizons*, or layers, having different characteristics. The whole series of horizons of any given soil taken together is known as a soil profile. Thus, examination of a typical, virgin Miami silt loam profile shows three major horizons, with minor subdivisions of the uppermost or *A* horizon. Table 17 is of interest in this connection.

In general, profiles of mature soils consist of two distinct layers known as *A* and *B* horizons. The former is a zone of extraction from which water, and the acids contained in it, have removed, in part, the finer particles of soil, such bases as sodium, potassium, calcium, and magnesium, soluble organic matter, and oxides of iron and aluminum. Little or no carbonate remains in the *A* horizon of any mature soil in humid regions. The *B* horizon is a zone of accumulation in which part

TABLE 16

THE GREAT SOIL GROUPS OF THE WORLD (BALDWIN)

Order	Suborder	Great Soil Groups
Zonal soils — Pedocals	Soils of the Cold Zone:	1. Tundra soils
	1. Light-colored soils of arid regions	2. Desert soils 3. Red desert soils 4. Sierozem 5. Brown soils 6. Reddish-brown soils 7. Chestnut soils
	2. Dark-colored soils of the semi-arid, subhumid, and humid grasslands	8. Reddish-chestnut soils 9. Chernozem soils 10. Prairie soils 11. Reddish prairie soils
	3. Soils of the forest-grassland transition	12. Degraded chernozem soils 13. Noncalcic brown soils
Zonal soils — Pedalfers		14. Podsol soils
	4. Light-colored podsolized soils of the timbered regions	15. Brown podsolic soils 16. Gray-brown podsolic soils 17. Yellow podsolic soils 18. Red podsolic soils
	5. Lateritic soils of forested warm-temperate and tropical regions	19. Yellowish-brown lateritic soils 20. Reddish-brown lateritic soils 21. Laterite soils
Intrazonal soils	1. Halomorphic (saline and alkali soils of imperfectly drained arid regions and littoral deposits)	1. Solonchak or saline soils 2. Solonetz soils 3. Soloth soils 4. Wiesenboden 5. Alpine meadow soils 6. Bog soils
	2. Hydromorphic soils of marshes, swamps, seep areas, and flats	7. Half-bog soils 8. Planosols 9. Ground-water podsol soils 10. Ground-water laterite soils 11. Brown forest soils 12. Rendzina soils
Azonal soils	3. Calomorphic	1. Lithosols 2. Alluvial soils 3. Sands (dry)

of the material leached out of the *A* horizon has been deposited. A third horizon, *C*, consists mostly of unweathered material. Depth to the *B* horizon is largely determined by rainfall. As the amount of rainfall increases, calcium carbonate deposits disappear entirely from the soil profile. As it decreases, calcium carbonate is found in the *B* horizon and, with still less rain, it may occur on top of the soil. Thus,

TABLE 17

PROFILES OF TWO SOIL TYPES (WHEETING)

Horizon	Thickness	Color	Other Characteristics
I* A0	2 in.	Humus	Forest mold
I* A1	4 in.	Dark gray	Silt loam, granular
I* A2	9 in.	Gray to drab	Silt loam
I* B	20 in.	Red-brown	Mottling, heavier texture
I* C	Variable	Gray	Compact, contains carbonates
II† A0	2 in.	Humus	Forest mold
II† A1	4 in.	Gray-brown	Sandy loam, granular
II† A2	10 in.	Yellow-brown	Sandy loam
II† B1	20 in.	Red-brown	Heavier, some gravel
II† B2	3 in.	Red-brown	Indurated, gravel, carbonates
II† C	9 in.	Gray	Unweathered, gravelly drift

* I — Miami silt loam. † II — Bellefontaine loam.

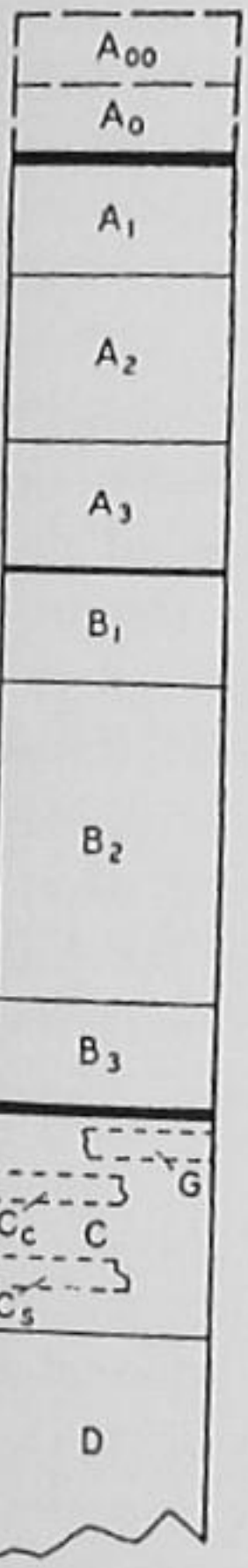
in desert regions the soil is high in carbonates, not only those of calcium and magnesium but of sodium and potassium as well. On addition of limited amounts of irrigation water these and other soluble salts form a crust on the surface of the soil.

In order to simplify the problem of classifying the soils of the earth, five diverse groups are chosen to represent them. These are the Desert Soils, Chernozems, Podsols, Laterites, and Alluvial Soils. The Chernozems and Laterites have already been specifically defined. The *Desert Soils* are implied in the previous paragraph.

Podsols are formed under conditions of cool, moist climate, such as that in the northeastern United States. The podsolization process is of such importance that it merits specific consideration. It consists of two distinct phases. One of these is an accumulation of leaf litter on the surface of the soil. The other involves the action of water, containing the acids that are developed in decomposition of organic matter, on the layer of soil immediately below the surface. The net effect is a whitening of the *A* horizon as a result of removal of iron and aluminum. These, and the finely divided clay, tend to accumulate in the *B* horizon. All soluble salts, including calcium and magnesium carbonates, have been leached out of the profile.

To recapitulate, Desert Soils are gray-red, alkaline, and, on addition of water, accumulate salts on their surfaces. Chernozems are black, essentially neutral in the *A* horizon, and have an accumulation of calcium and magnesium carbonates in their *B* horizons. Readily-soluble salts have been carried away in the drainage water. Podsols

are gray-brown, acid, have a grayish white zone in their *A* horizons, and a deposit of iron, aluminum, and clay in their *B* horizons. Not only the readily soluble salts but the calcium and magnesium carbonates have been lost by leaching. Laterites are red-brown, acid,



A_{00} — Loose leaves and organic debris, largely undecomposed.

A_0 — Organic debris partly decomposed or matted; frequently divided into subhorizons.

A_1 — A dark-colored horizon, containing a relatively high content of organic matter, but mixed with mineral matter. Thick in chernozem and very thin in podsol.

A_2 — A light-colored horizon, representing the region of maximum leaching (or reduction) where podsolized or solodized. The bleicherde of the podsol. Absent in chernozem, brown soils, sierozem, and some others.

A_3 — Transitional to *B*, but more like *A* than *B*. Sometimes absent.

B_1 — Transitional to *B*, but more like *B* than *A*. Sometimes absent.

B_2 — A deeper-colored (usually) horizon representing the region of maximum alluviation where podsolized or solodized. The ortstein of the podsol and the claypan of the solodized solonetz. In chernozem, brown soils, and sierozem this region has definite structural character, frequently prismatic, but may not have much if any alluviated materials and represents a transition between *A* and *C*. Frequently absent in the intrazonal soils of the humid regions.

B_3 — Transitional to *C*.

G, C_c, C, C_s — The weathered parent material. Occasionally absent; i.e., soil building may follow weathering so closely that no weathered material that is not included in the solum is found between *B* and *D*. Horizons lettered C_c and C_s represent possible layers of accumulated calcium carbonate or calcium sulfate found in chernozem and other soils.

D — Any stratum underneath the soil, such as hard rock or a layer of clay or sand, that is not parent material but which may have significance to the overlying soil.

FIG. 13. A hypothetical soil profile. *G* represents the glei layer of the intrazonal soils of the humid region. (*T. D. Rice, U. S. Dept. Agr.*)

have lost all their soluble salts, including the less soluble carbonates, and their silicate silica has largely disappeared, leaving largely oxides of iron and aluminum and particles of quartz. The intermediate soil groups can be thought of as being modifications of these four primary groups. Thus, we have a number of *Podsolic Soils*. These differ in minor ways, the "ic" suffix indicating that they resemble the Podsols but do not meet all the specifications for this group.

Alluvial Soils merit special mention because they constitute some of the earth's most productive land. The valley of the Nile and the

Mississippi River delta are two excellent examples of alluvial soils. These soils are made up of deposits left behind after overflowing rivers have dropped their load of sediment and have drained away, once the flood stage has passed. These deposits consist of whatever soil-erosion products the rivers have had dumped into them from their tributaries. Under conditions of extensive and continuous cultivation of land, rich *A* horizon soil material originally deposited may later be covered with much less productive *B* horizon material. Such conditions now obtain in the river valleys in many parts of the United States.

SOIL SURVEYS

It is highly important that every nation chart its natural resources, of which its soil is, in many ways, the most important. Most of the states, either alone or in cooperation with the United States Department of Agriculture, are engaged in careful surveys of their soil resources. The problem is complex. The land area of the United States is estimated at 1903 million acres. To make a detailed survey of this very large area will require many years of carefully planned effort. In large part, reconnaissance surveys will have to suffice in the less well-developed regions for many years to come. Coordinate with the soil survey are geological, ecological, and climatological surveys, which are highly important adjuncts to the soil survey.

It is now recognized that climate is the most important factor in determining soil development. Although the surveyor makes use of information available from geological surveys and notes the character of the native vegetation, he maps the soil as it is, a product of its environment. He recognizes that it is the result of climatic agencies, acting in conjunction with vegetation, on the rock materials from which soil is formed. Of the climatic factors, rainfall is ordinarily the most effective. But temperature, topography, and drainage conditions are also highly important factors in determining the nature of the soil.

In classifying soils by survey methods, an attempt is made to arrange them into units that have, in common, certain physical properties that can readily be recognized and differentiated in the field. Soils show considerable variation in size and arrangement of their constituent particles. They also vary in the color of the surface soil and of the several horizons in their profiles. Simple chemical tests for carbonates and for degree of acidity are usable in the field. The

natural vegetation reflects the physical and chemical properties of the soil and its water and air relationships.

The surveyor recognizes that variations in soil characteristics, as noted in the field or discovered in the laboratory, have their explanation in the nature of the rocks from which the soil was formed; in the physical, chemical, and biological agencies operating in their formation and location; in the climatic influences that have surrounded them; and in the length of time that has elapsed since the soils became located in their present position. Soils of widely different modes and sources of origin are not grouped together even though they may bear a very close superficial resemblance to each other. The surveyor anticipates that important differences in the properties of these soils will be revealed by further field and laboratory studies.

SOIL SERIES

Each of the Great Soil Groups is divided into *series*. All the members of a series have, in addition to a common mode of origin, similarity in topography and drainage, and in range of depth, color, structure, and reaction of their *A* and *B* horizons. The *series name* is usually that of the locality in which the soil was first recognized and mapped separately. Thus, the Miami series refers to a group of soils that was first recognized as a distinct entity when the first survey was made of the watershed of the Great Miami River of Ohio. The source of origin was largely the underlying limestone and the limestone and igneous-rock materials carried by glaciers from regions farther north. The soils of this series are defined as being grayish brown in the *A* horizon and mottled yellow and gray in the *B* horizon. The topography is rolling and drainage is fairly good.

Similarly, the Dekalb series refers to a group of soils the members of which are of residual origin; they were derived from sandstone and shale, and they have a yellow-brown *A* horizon and a yellowish *B* horizon, which contains fragments of the parent rocks. The topography of this series is hilly and the drainage is excellent. This series was first recognized and mapped in Dekalb County, Alabama.

As the survey progresses and as soils are mapped in greater detail, new series are named whenever large enough areas are found with sufficiently distinctive characteristics to justify separate classification. A few examples of variables in soils that have been used as bases for their classification into series are given in Table 18. Often several soil series that vary in only one property, such as drainage, are grouped

TABLE 18

VARIATIONS IN SOME CHARACTERISTICS OF FOUR IMPORTANT SOIL SERIES

Characteristics	Soil 1	Soil 2	Soil 3	Soil 4
Color of soil	Dark brown	Gray-brown	Brown	Brown
Color of subsoil	Yellow-brown	Yellow and gray	Brown-yellow	Red-brown
Reaction	Acid	Not acid	Acid	Not acid
Topography	Nearly level	Gently rolling	Very rolling	Gently rolling
Drainage	Fair to good	Fair	Good	Good
Mode of origin	Glacial	Glacial*	Residual	Residual
Source of origin	Prairie	Limestone	Sandstone†	Limestone
Series name	Carrington	Miami	Dekalb	Hagerstown

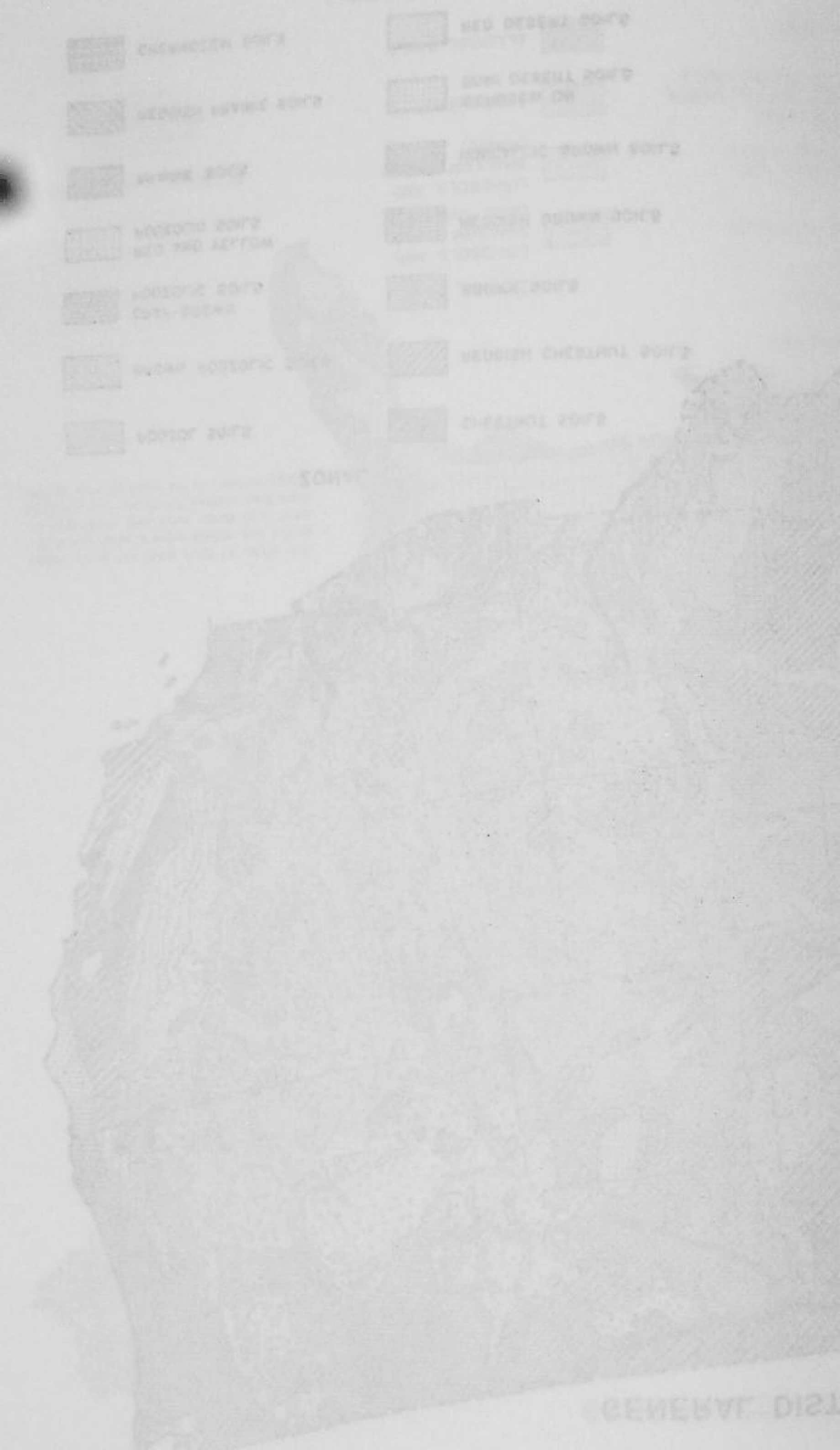
* Timbered soils. † Sandstone and shale.

into *catenas*. The total number of series will be quite large when the entire land area of the United States has been carefully surveyed.

The final unit of classification is the *soil type*. Series are divided into types on the basis of *texture*, which refers to the size-distribution of the particles of which the soil is constituted. Thus the Miami series includes Miami loam, Miami clay loam, Miami silt loam, Miami sand, and possibly other types, depending on their textures. A total of a dozen or more types is possible in any series, provided that the variation in texture of the soil is sufficient to justify that number. It is seldom, however, that all possible types are found in any one series.

The soil survey is fundamental to the planned use of land on a large scale. Once it has been completed, any experimental evidence or any well-established soil-management practice that has been found applicable to any given soil type will apply, in general, to all soil of that type. Similarly, crops that are adapted to production on one field of that soil type will be adapted to all the others of that type.

The Soil Conservation Service has surveyed a considerable part of the farmed land of the United States on the basis of its land-use capability. Seven classes are recognized in humid areas. These are mapped in green, yellow, red, blue, orange, brown, and purple colors. Green indicates very good land that can be cropped with little trouble from erosion. Yellow indicates good land that can be cropped with moderate precautions against erosion. Red indicates moderately good land that can be safely used for cropping only if well-planned conservation programs are put into effect. Blue, orange, brown, and purple colors indicate pasture land that can be cropped occasionally, permanent pasture land, forest land, and land suitable for wildlife, respectively.



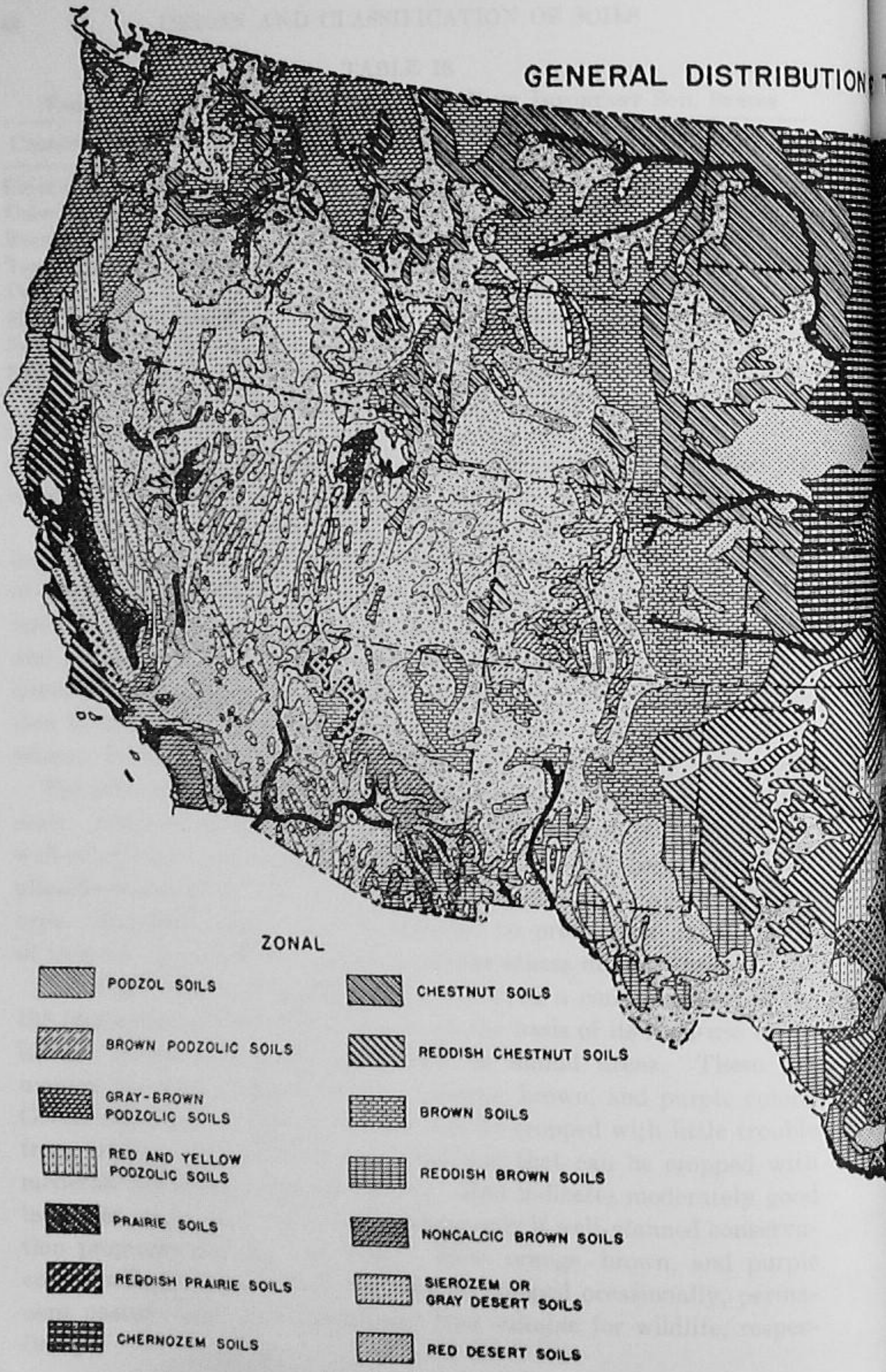
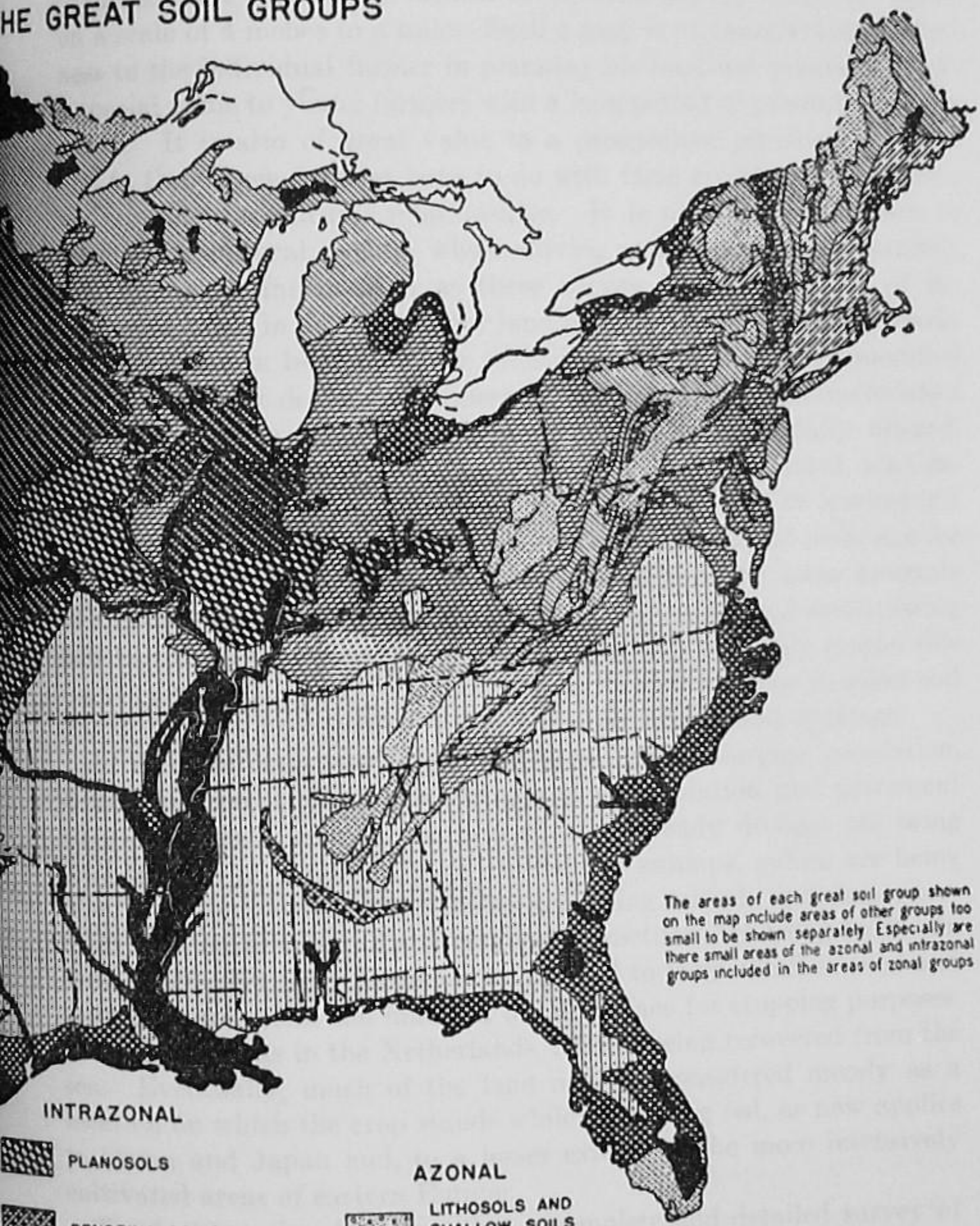


FIG. 14. General distribution of the Great Soil Groups in t

HE GREAT SOIL GROUPS



The areas of each great soil group shown on the map include areas of other groups too small to be shown separately Especially are there small areas of the azonal and intrazonal groups included in the areas of zonal groups

INTRAZONAL

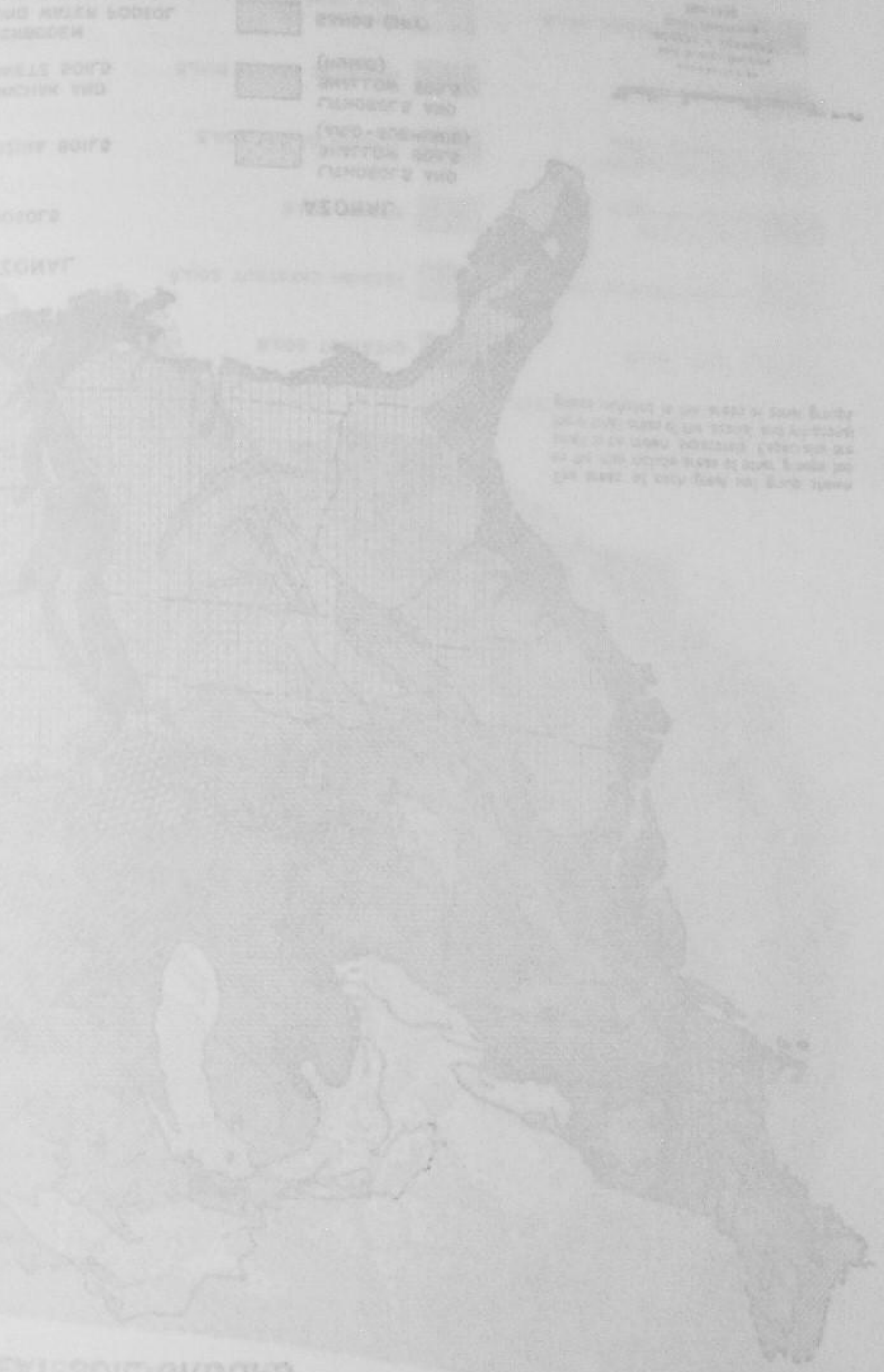
- PLANOSOLS
- RENDZINA SOILS
- SOLONCHAK AND SOLONETZ SOILS
- WIESENBODEN GROUND WATER PODZOL AND HALF-BOG SOILS
- BOG SOILS

AZONAL

- LITHOSOLS AND SHALLOW SOILS (ARID-SUBHUMID)
- LITHOSOLS AND SHALLOW SOILS (HUMID)
- SANDS (DRY)
- ALLUVIAL SOILS

MAP DRAFTED BY SOIL SURVEY DIVISION ROBERT F TURNURE CHIEF DRAFTSMAN NOV 1938

ed States. [*Courtesy of Division of Soil Survey, U.S.D.A.*]



In the more intensively farmed areas these survey maps are based on a scale of 4 inches to a mile. Such a map is of considerable usefulness to the individual farmer in planning his land-use program. It is a special value to young farmers with a long period of productive years ahead. It is also of great value to a prospective purchaser of land and to those agencies that have to do with farm credit, farm taxation, and similar agricultural relationships. It is of great importance to county agricultural agents, whose advice and assistance to farmers, based on such information as these survey maps supply, is of inestimable value in developing our land resources on a long-range basis.

As agriculture becomes more intensified, the soil may be modified to a considerable degree by farmers. Certain of the soil characteristics that are used as bases for classification can be materially altered. Thus, some wet land can be drained, acid soils can be limed, alkaline soils can be acidulated with sulfur, and excess salts can be leached out with irrigation water. Even the physical properties of soils can be changed by growing grass cover crops, incorporating large amounts of organic matter, or by making use of chemical soil-conditioning agents. Even climatic factors, which have been primarily responsible for the development of soil differences and which continue to affect soil properties, can be regulated by shading, irrigation, and drainage.

As need for increased production grows with enlarging population, more expensive methods, involving soil manipulation and movement on a large scale, will be put into effect. Already dredges are being used to open up large drainage channels in swamps, gullies are being filled with bulldozers, stone fences are being buried, and dams, terraces, and other types of soil-retaining structures are being built. In some cases, very large plows are being used to bury alkali or sand and to bring more useful soil material to the surface for cropping purposes. In some areas, as in the Netherlands, land is being recovered from the sea. Eventually, much of the land may be considered merely as a location on which the crop stands while it is being fed, as now applies to China and Japan and, to a lesser extent, to the more intensively cultivated areas of eastern Europe.

The fact remains, however, that a complete and detailed survey of soil and land resources is the starting point in formulating long-term plans designed to assure continued production of abundance of high-quality food for our rapidly growing population. We need to know how much good soil we have, where it is located, and what must be done to maintain and increase its productive capacity. Millions of acres are being carelessly farmed. Many thousands of acres of excel-

lent farming land are being taken over for industrial, military, and highway purposes. Much of this waste could be avoided by mapping the land in relation to the use to which it should be put, and then calling these surveys to the attention of those who formulate our local, county, state, and federal land policies.

SELECTED REFERENCES

1. Bennett, H. H. *The Soils and Agriculture of the Southern States.* The Macmillan Co., New York, pp. 1–16, 1921.

2. Clarke, F. W. The data of geochemistry. *U. S. Geol. Survey Bull.* 770, pp. 12–44, 1924.

3. Hambidge, Gove, editor. Soils and Men. *U. S. Dept. Agr. Yearbook,* 1938.

4. Hilgard, E. W. *Soils, Their Formation, Properties, Composition and Relations to Plant Growth in the Humid and Arid Regions.* The Macmillan Co., New York, pp. 1–62, 1906.

5. Joffe, Jacob S. *Pedology,* second edition. Pedology Publications, New Brunswick, New Jersey, 1949.

6. Kellogg, Charles E. *The Soils That Support Us.* The Macmillan Co., New York, 1941.

7. Marbut, C. F. Soil classification. *Ann. Rept. Am. Assoc. Soil Survey Workers,* 1922.

8. Wheeting, L. C. Some physical and chemical properties of several soil profiles. Michigan Agr. Exp. Sta., Tech. Bull. 62, 1924.

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Chemical Composition of Soils

The rocks from which soils are formed differ greatly in their mineralogical and chemical composition. Even those that belong to the same class show wide variations in chemical composition. Limestone may be almost pure calcium carbonate or it may be so high in magnesium carbonate as to be classed as dolomite. It may contain large amounts of impurities, such as chert, sand, or clay. Igneous rocks are commonly divided into acidic, intermediate, and basic groups, depending upon their percentage content of silica. This may vary between 40 per cent in basalts to nearly twice that percentage in granites. Sandstones and shales differ markedly in composition, depending upon conditions under which the materials of which they are made were deposited.

In the process of soil development, minerals are decomposed by the solvent action of water and of the various acids and salts that may be formed during decomposition. At any given time soil may contain products representing all stages of disintegration from the original rocks and their constituent minerals to the end products that are formed. Since soils have their origin largely in rocks, it is apparent that mineralogical analysis provides a clue to the nature of the rock or rocks from which they were formed.

MINERALOGICAL COMPOSITION OF SOILS

Most of the common rock-forming minerals are widely distributed in soils, notwithstanding great differences in rocks themselves. This is shown in Table 19, data for which were obtained from mineralogical



FIG. 15. Jean Baptiste Boussingault, French pioneer in soil-plant chemistry, on his eightieth birthday.

TABLE 19

PRIMARY MINERALS IN TWENTY-FIVE SOILS (MCCAUGHEY)

Minerals	Oxides Contained	Present*	Abundant*
Quartz	Si	25	25
Hornblende	Ca-Mg-Fe-Si	23	12
Orthoclase	K-Al-Si	20	14
Microcline	K-Al-Si	20	10
Epidote	Ca-Fe-Al-Si-H	24	8
Biotite	K-Mg-Fe-Al-Si-H	21	8
Muscovite	K-Al-Si-H	20	6
Zircon	Zr-Si	22	1
Chlorite	Mg-Fe-Al-Si-H	21	2
Tourmaline	Na-Al-B-Si-H	21	1
Rutile	Ti	17	0
Plagioclase	Na-Ca-Al-Si	13	5
Apatite	Ca-P-(F and Cl)	12	0

* Number of soils in which the minerals were present and abundant, respectively.

analyses of samples of 25 soils selected from an equal number of widely separated localities in the United States. Although distribution of the common minerals is general, some soils contain much larger amounts of certain of them than do others. Two facts brought out by these analyses are particularly significant. One is the general abundance of quartz and the other is the general scarcity of apatite, the most important phosphate mineral in soils.

During the weathering and leaching processes that take place in humid climates, any readily soluble products that are formed are carried away in drainage waters, whereas relatively insoluble products accumulate to form soil. Thus, a soil derived from limestone may contain no carbonates. Soil derived from sandstone and shale may differ very little in composition from that of the original rocks. Soil of igneous-rock origin tends to lose its base-forming elements as carbonates, chlorides, and sulfates. As a result, silica, alumina, and iron oxide, as such or in silicate combinations, tend to constitute the major portion of the soils of humid climates. Attached to the silicates are varying percentages of sodium, potassium, calcium, and magnesium in relatively stable combinations, from which they are very slowly released by further weathering and solution processes. Silicon in the silicate form tends gradually to dissolve also, notably in high-rainfall tropical climates, leaving Laterites. These consist largely of aluminum and iron oxides. Relative rates of solution of the elements constituting granite are shown in Table 20. The order of decreasing

TABLE 20

PERCENTAGE COMPOSITION OF GRANITE AND ITS SOLUTION PRODUCT (HEADDEN)

Oxides	Granite	Dissolved Material*	Order of Solution
SiO_2	65.76	40.72	5
Al_2O_3	19.29	2.70	6
Fe_2O_3	Trace	0.31	..
CaO	0.314	10.24	1
MgO	0.029	0.77	2
K_2O	11.60	10.97	4
Na_2O	2.73	5.25	3
Ignition	.....	16.37	..

* This product resulted from washing powdered granite with eighteen successive additions of water kept agitated by a stream of air to which some CO_2 had been added.

solubility of the elements listed is calcium, magnesium, sodium, potassium, silicon, and aluminum, the last mentioned having the greatest tendency to accumulate.

Marked differences are noted between the weathering and solution process of rocks in humid and arid regions. In arid regions there may be little difference between the total percentage composition of soils and of the rocks from which they were formed. In the absence of any large amount of rainfall, little may be leached from the soil during its developmental process. Although there is always some decomposition of the mineral constituents, the soil suffers little or no loss of its mineral elements unless leaching takes place.

Analyses of soils for total amounts of the several elements contained in them show wide variations. These depend not only on the nature of the rock from which they were formed but also on their age and the extent to which they have been subjected to the leaching action of water. Even in regions having the same rainfall, no two soils have the same chemical composition, since their rock and mineral origin and the combination of forces operating in their formation and continued alteration, including the element of time, are never identical.

INORGANIC COMPOSITION OF REPRESENTATIVE SOILS

The elements that make up the major part of inorganic soils in humid climates are of relatively little importance in plant economy. They are present in such large amounts in relation to any possible need plants may have for them that, even though they occur in relatively insoluble forms, it is seldom that a deficiency of any one of them becomes a limiting factor in crop production. The elements that are most readily leached out of the soil tend to be the ones that are required in largest amounts by plants. The rates at which the remaining quantities of these essential elements are released from soils bear relatively little relationship to the total quantities present in these soils. Nevertheless, exact knowledge of the chemical composition of soils for both those elements that tend to accumulate and those that are lost by leaching is a matter of considerable interest and importance. Such analyses of 23 important soils from widely separated regions of the United States are shown in Table 21.

Each of these soils represents a different series and comes from a different state. Their textures vary from sands to clays. It is important to remember that no one sample is representative of the soils of the state from which it came, but only of the soil type from which it was taken. Even different samples chosen from an area of the same soil type may vary considerably in their chemical composition, depending on the histories of the specific locations from which they came.

TABLE 21

PERCENTAGE INORGANIC COMPOSITION OF REPRESENTATIVE AMERICAN SOILS (ROBINSON*)

Series and Type	State	Depth	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5	SO_3
Norfolk sand[1]	S. C.	8 in.	94.81	0.51	1.42	0.60	0.02	0.19	0.01	0.08	0.12	0.10	0.08
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
Durham sandy loam[2]	N. C.	10 "	80.79	0.53	10.55	1.61	0.02	0.89	0.19	0.96	0.87	0.12	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
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
Clermont silt loam[3]	Ohio	6 "	75.30	....	10.27	6.34	....	0.77	0.95	1.84	....	0.15	....
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
Memphis silt loam[3]	Miss.	6 "	81.13	0.78	8.52	2.92	0.03	0.31	0.39	1.78	0.52	0.08	0.03
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
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
Wabash silt loam[3]	Neb.	15 "	72.37	0.58	12.23	3.35	0.10	1.07	0.93	2.35	1.20	0.14	0.16
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
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
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
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	0.23
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
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
Colorado sand[7]	Colo.	14 "	78.85	0.32	9.68	2.72	0.03	0.94	0.72	2.31	2.02	0.11	0.07
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
Richfield clay loam[7]	Tex.	10 "	79.64	....	8.27	2.74	....	0.63	0.87	1.83	1.12	0.10	....
Palouse silt loam[8]	Idaho	12 "	69.60	....	13.62	5.30	0.00	2.47	1.41	1.99	2.91	0.20	....
Stockton clay adobe[9]	Calif.	38 "	63.52	1.21	14.34	7.98	0.16	2.34	1.81	0.78	1.68	....	....
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 region. [2] Piedmont Plateau region. [3] Glacial and loessial region. [4] Appalachian Mountain and Plateau region. [5] Limestone valleys and uplands region. [6] River flood plain region. [7] Great Plains region. [8] Northwest intermountain region. [9] Pacific coast region.

Some soils are markedly different in chemical composition from those shown in Table 21. Certain beach sands contain over 98 per cent silica. This limits the amounts of other constituents to very low levels. The phosphorus pentoxide content of soils of the Trenton area around Lexington, Kentucky, is reported to average over 1 per cent. In no case is it less than 0.3 per cent and in some places it is as high as 2.65 per cent. The sulfur trioxide content of certain Oregon soils is less than 0.04 per cent. Young soils of limestone or calcareous shale origin frequently contain so much calcium carbonate that they effervesce copiously when tested with hydrochloric acid. Some unproductive peat soils of northern Indiana were found to contain nearly 80 per cent organic matter, whereas their content of potassium oxide was less than 0.2 per cent. Soils of arid regions are very high in soluble salts. Certain Hawaiian soils contain as much as 10 per cent manganese oxide, and so little available iron that pineapple plants grown on them become chlorotic unless sprayed with a solution of ferrous sulfate. Laterites may contain as much as 80 per cent aluminum and iron oxides. Soils in the vicinity of mines or smelters are often very high in such elements as copper, zinc, lead, or mercury. Long-continued use of arsenical sprays in orchards and cotton fields have resulted in arsenic accumulations that are toxic to crops.

Analyses of soils have long been reported in terms of soil and subsoil, plow depth being considered soil and that below plow depth subsoil. The tendency still remains to consider the top 6⅔ inches, which, for mineral soils, weighs about 2 million pounds an acre, as the soil. But the modern approach is to consider soils on a horizon basis. Analysis of a Collington loam, horizon by horizon, is shown in Table 22. This soil belongs to the gray-brown Podsolic group. The analysis

TABLE 22

CHEMICAL COMPOSITION* OF VIRGIN COLLINGTON LOAM SOIL (LIPMAN)

Horizon	Depth†	N	P	Ca	Mg	Mn	SiO_2	Fe	Al
A_0	3	0.91	0.09	0.33	0.29	0.23	60.0	2.23	1.74
A_1	9	0.11	0.07	0.18	0.27	0.05	84.1	2.56	2.69
A_2	23	0.03	0.04	0.20	0.31	0.10	85.4	2.96	3.07
B_1	18	0.02	0.06	0.18	0.42	0.13	79.6	4.18	3.75
B_2	26	0.01	0.06	0.15	0.46	0.16	79.5	4.60	3.37
C_1	13	0.01	0.06	0.16	0.50	0.12	80.5	5.15	2.65
C_2	..	0.01	0.03	0.15	0.41	0.14	84.8	4.73	1.59

* In terms of elements, except for silicon, which is reported as SiO_2. Figures are percentages of air-dry soil.

† Depth in centimeters (1 centimeter = 0.4 inch).

indicates a tendency toward accumulation of nitrogen, phosphorus, and silicon in the *A* horizon, and of magnesium, manganese, iron, and aluminum in the *B* horizon. Potassium percentages were not reported, but there was probably over 2 per cent of this element in the *A* horizon and somewhat more than that percentage in the *B* horizon. A distinctive feature of Collington soils is their high content of glauconite, an important potassium-containing mineral.

In examining the older literature on soils one finds hundreds of analyses that were made by digesting the soil with hydrochloric acid of specific gravity 1.115. By such digestion more than half the soil remains undissolved and is reported as acid-insoluble material. To obtain complete analyses, such as are shown in Table 21, it is necessary to fuse the soil with sodium carbonate, after which it can be completely dissolved in acid to form a clear liquid.

In testing soils for nutrient deficiencies, no attempt is made to determine the total quantities of all the elements contained in them but only the available amounts of such elements as are required by plants and animals. Sometimes it becomes important to analyze soils for certain other elements, such as aluminum, selenium, fluorine, arsenic, and lead. These elements, even at relatively low concentrations, may be toxic to plants or may accumulate in plants to the point where they are poisonous to animals that consume them.

TRACE ELEMENTS IN SOILS

In addition to the elements of which the percentages of their oxides in soils are shown in Table 21, soils contain small quantities of virtually every other known mineral element. Some of these, notably boron, molybdenum, zinc, copper, manganese, cobalt, iodine, and fluorine, are known to be essential to plants or animals, or to both. Others, such as titanium, vanadium, lithium, strontium, chromium, and zirconium, may or may not be of importance in plant or animal nutrition.

The first group of elements, which are known to be essential to plants and animals, are required in such small amounts that they are called *minor* or *trace elements*. Considerable knowledge has been gained about the amounts of these elements in soils and plants. But much remains to be learned about the actual quantities required and the functions these elements perform. It is possible that lack of productiveness of some soils for certain crops, and exceptional productivity of other soils for these same crops, may have their explanation,

in part, in the absence or presence of adequate amounts of these elements. Table 23 shows ranges in amounts of these elements found in

TABLE 23

RANGE IN TRACE ELEMENT CONTENT OF NEW JERSEY SOILS

(In Parts per Million Dry Soil)

Element	Highest, P.p.m.	Lowest, P.p.m.	Highest * Soil Type	Lowest * Soil Type
B	110	18	Rockaway	Norton
Mo	3	0.8	Evesboro	Dutchess
Zn	225	10	Sassafras	Norton
Cu	60	2	Sassafras	Annandale
Mn	5200	90	Evesboro	Norton
Co	31	0.2	Sassafras	Norton
I	12	0.0	Hazen	Norton
F	409	29	Hoosic	Lakewood
Ni	40	2	Sassafras	Norton

* Rockaway stony loam, Evesboro loamy sand, Sassafras gravelly loam, Hazen stony loam, Hoosic stony loam, Norton silt loam, Dutchess shale loam, Lakewood sand, and Annandale loam.

20 New Jersey soils. It is important to note that the quantities are expressed in parts per million rather than as percentages.

Likelihood of a deficiency of trace elements becomes greater as soils become older agriculturally and as the need for raising acre yields is increased. In their virgin state, soils normally contained considerable quantities of all these elements in readily available forms. As wild plants grew up and fell back on the land, all the elements contained in them were released for re-use by succeeding generations of plants. Thus, virgin soils normally contained adequate amounts of all the essential elements to produce high acre yields of crops for some years after they were first put under cultivation.

ORGANIC MATTER IN SOILS

In addition to inorganic materials, soils contain organic matter in amounts varying from as little as 1 per cent to more than 80 per cent. This organic matter is largely plant residues and microscopic life that feeds on them. It contains the mineral elements that are found in plants, subject to such losses as may have occurred through leaching. Organic matter also contains nitrogen, in protein and related forms, which is released as ammonia and nitrates during microbial

decomposition. The quantity of this element in the form of organic matter in inorganic soils normally ranges between 0.1 and 0.5 per cent. Peat soils may contain as much as 4 per cent nitrogen, on a dry-matter basis.

All soils contain organic matter. Without it, they would not be soils. This organic matter serves a variety of purposes, one of which is as a source of food for the many millions of microbes contained in each pound of good soil. But it has great value also as a source of inorganic elements for crop plants. About 4 per cent of the dry weight of fresh organic matter in the form of crop residues that are left behind on or in the soil will remain as ash when they are burned. This ash is the mineral matter that these residues contained. Its usefulness to the next crop is much greater than its quantity, as related to that of the total inorganic mass of the soil, would indicate. Organic matter also has highly important effects on the physical properties of soils. These, in turn, affect the rate of release of the soil's inorganic constituents to plant roots.

MODERN METHODS OF TESTING SOILS

It was early recognized that analyses of soils for their total content of each of the several nutrient elements was of little value in determining their productivity. As a result, an effort was made to devise means of simulating the nutrient-extracting capacity of plant roots. Use was made of weak solutions of carbonic, citric, oxalic, nitric, and sulfuric acids as solvents. After many years of study of this problem, fairly standard methods of extraction have been developed, of which the best known in the United States is that of Morgan. This method calls for the use of a solution containing 100 grams sodium acetate and 30 milliliters glacial acetic acid, made up to a volume of 1 liter with distilled water. A teaspoonful of soil is placed in a small beaker containing 10 milliliters of this solution. The mixture is stirred 1 minute and filtered. The resulting clear solution is tested, usually colorimetrically, for the elements in question. The effect of the solution is to replace the exchangeable calcium, magnesium, potassium, and other cations and to release the available phosphorus.

By applying the principle of electrodialysis, Purvis and Hanna have developed a new soil-testing method. Small dialysis cells, made of Lucite, are assembled in series. Each cell contains a perforated platinum sheet as the anode and a perforated nickel sheet as the cathode. A membrane, made of filter paper, is folded between the electrodes, and

the sample of soil is placed between the folds. The dialyzing solution consists of an 0.05 per cent solution of boric acid in water. The boric acid is of particular importance as an aid in releasing exchangeable magnesium. The cell is designed for electrodialysis of 5 grams of soil and holds 80 milliliters of solution. The cell is connected in series with a 40-watt light bulb, and a potential difference of 100 volts direct current is applied for 20 minutes.



FIG. 16. Testing farmers' samples of soil for *p*H values at the New Jersey Agr. Exp. Sta.

Another method of testing soils is by way of analyzing plants that grow on them. If plants grow luxuriantly, adequate amounts of the several mineral nutrients must have been delivered up by the soil. If they do poorly, one or more elements may be in deficiency. Examinations of plant tissues have revealed that, under optimum conditions, each species maintains fairly constant ratios of the essential mineral nutrients. Any departures from these normal ratios indicates excesses or deficiencies, as the case may be. This method of diagnosing soil deficiencies has been used to good effect by many workers. Its greatest weakness is that plants must be grown before their tissues can be



FIG. 17. Some 600 bottomless cylinders each 3 feet deep and 2 feet in diameter and filled with soil on horizon basis lying over *C* horizon Penn shale material at the New Jersey Agr. Exp. Sta. They are being used in studying nutrient-supplying capacities of soils.

tested, whereas soil can be examined before seed are sown or plants are set.

SOIL TESTING AS A GUIDE TO PRACTICE

If soil analysis is to be of any considerable value as a guide to practice, the sample must be carefully chosen so that it represents the area in question. Soils may vary greatly in chemical composition from point to point in the same field. Their composition changes with depth. In humid regions the soil to plow depth is normally acid, but that in the *B* horizon may contain free carbonates. Over the years, unequal distribution of wood ashes, liming materials, or fertilizers may have occurred.

For practical purposes it is best to choose one set of samples to plow

depth and a second set from a corresponding depth immediately beneath the first. Thin slices of soil, taken with a spade or auger at about a dozen different points from each soil type, make a satisfactory composite from which to obtain about one-half pint for laboratory examination. All the subsamples that go into each composite should have the same color and texture. It is to be desired that they have come from locations that have had the same agricultural history.



FIG. 18. Alfalfa thrives only on well-drained and highly fertile soils. This is an excellent crop for a farmer to grow in testing the fertility status of his soil.

By reason of the large amount of analytical work that has been done on soils and from their systematic classification by survey methods, the soil specialist is often able to judge the quality and anticipate the needs of a given field by a more or less superficial examination of it. An acidity test, the color, the feel of the soil between thumb and finger, and a knowledge of the crop to be grown permit a fairly reliable guess as to what is required for high acre yields. But the better farmers are far from satisfied by such a procedure. They want to know just how the soils of their farms rate in nutrient supplies in comparison with those of their neighbors. And they need to know to what levels these nutrient supplies must be raised to permit the production of the yields that they might reasonably hope to produce.

Considerable interest has been developed in *soil-test servicing*. This

calls for employing a capable chemist to aid in selecting representative samples, to run the necessary tests, and to make recommendations as to organic matter, liming, and fertilizing practices. In addition, however, it is important that he examine the crops from time to time during the growing season and make supplemental recommendations, particularly as to nitrogen needs, as required. Such a man must be able to distinguish between nutrient deficiencies and troubles arising from insects, diseases, poor physical conditions in the soil, and bad weather. Groups of farmers are cooperating in employing such men to service their soil-testing programs in a number of areas. Such practices will grow in proportion as it can be shown that the cost of such service is justified.

SELECTED REFERENCES

1. Averitt, S. D. The soils of Kentucky. Kentucky Agr. Exp. Sta., Bull. 193, 1915.

2. Bear, Firman E., and Associates. *Hunger Signs in Crops*, second edition. National Fertilizer Assoc., Washington, D. C., 1949.

3. Conner, S. D., and J. B. Abbott. Unproductive black soils. Indiana Agr. Exp. Sta., Bull. 157, 1912.

4. Headden, W. P. Silicic acid in mountain streams. *Am. J. Sci.*, Series 6, 166, pp. 181–189, 1903.

5. Kitchen, Herminie Broedel, editor. *Diagnostic Techniques for Soils and Crops*. American Potash Institute, Washington, D. C., 1948.

6. Lipman, J. G., and Associates. Analyses of United States Soils, North Atlantic States. Monograph, New Jersey Agr. Exp. Sta., pp. 18–19, 1940.

7. Lunt, H. A., and Associates. The Morgan soil-testing system. Conn. Agr. Exp. Sta., Bull. 541, 1950.

8. McCaughey, W. J., and W. H. Fry. The microscopic determination of soil-forming minerals. *U. S. Dept. Agr. Bull.* 91, 1913.

9. Purvis, E. R., and W. J. Hanna. Rapid electrodialysis of soils in dilute boric acid solution. *Soil Sci.*, Vol. 67, pp. 47–52, 1949.

10. Robinson, W. G. The inorganic composition of some important American soils. *U. S. Dept. Agr. Bull.* 122, 1914.

11. Robinson, W. O., and Associates. Variation in the chemical composition of soils. *U. S. Dept. Agr. Bull.* 551, 1917.

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Some Biological Processes in Soils

The productive capacity of a soil is often more or less directly related to the amount of organic matter it contains. This organic matter serves as a source of food for energy and growth of large numbers of microscopic organisms that inhabit the soil. Most of these are very simple forms of plant and animal life that function in the digestion of soil materials for the benefit of higher plants. A microbiological census shows that good soils contain many millions of microbes a



FIG. 19. The food of soil microorganisms is organic matter, and the larger the amount of crop residues one can compost in the soil the larger the microbial population and the better the working qualities of the soil.

gram. Of these, probably 90 per cent will be bacteria, 9 per cent actinomycetes, and 1 per cent algae, fungi, and protozoa. For any given class of soils, such as sands, silt loams, or clay loams, the total microbial population will be closely related to their content of organic matter, since this constitutes their primary food.

Any system of soil management that increases the soil's content of organic matter proportionately increases its microbial population, with all the advantages that may accrue from their activities. That is an important reason for developing a cropping program that maintains the soil organic matter at a reasonably high level. Some idea of the relationship between cropping systems and the amount of microbial food that will be present in the soil can be gained from a study of Table 24.

TABLE 24

CROPPING SYSTEM IN RELATION TO MICROBIAL FOOD SUPPLY (ALBRECHT)

Crops and Their Disposal	Organic Matter in Soil	
	Gain*	Loss*
Rye as green manure, followed by fallow	.....	14,400
Corn, wheat, clover — crops removed	.....	800
Corn, wheat, clover — manure returned	3,200	.....
Grass sod — clipped but nothing removed	10,000	.....
Alfalfa continuously — crops removed	10,400	.....

* Gain or loss of organic matter in pounds per acre of plowed soil, over a period of seventeen years.

SOME FACTS ABOUT SOIL MICROORGANISMS

Each of the five groups of soil microorganisms previously mentioned is composed of large numbers of distinct species having different morphological and physiological characteristics. The functions of some of these species are well known. The importance of others in soil and plant economy is unknown. In ordinary procedures for counting soil microbes, nodule bacteria of legumes, nonsymbiotic nitrogen-fixing bacteria, nitrite- and nitrate-producing bacteria, anaerobic bacteria, algae, fungi, and protozoa are not included, since they require quite specific types of media for isolation.

Ordinarily, bacteria are the dominant forms of microscopic life in soil, provided that the soil is reasonably close to the neutral point. If the soil is quite acid and contains considerable amounts of organic matter, fungi may predominate. Algae are not present in large numbers except under conditions of abundant moisture, and then they exist

mostly on or near the surface of the soil. Their greatest numerical development is in greenhouses, shady locations, and in soils that are kept continuously moist.

Of the bacteria, the non-spore-forming short rods are usually most abundant. After heavy applications of manure, filamentous actinomycetes may predominate. Micrococci are relatively unplentiful. When soils are given special laboratory treatments that favor one specific group of bacteria, members of that group increase rapidly in numbers. That is what is attempted when peat is sterilized and then used as a medium for the culture of nodule bacteria for inoculating legumes.

Soils also contain considerable numbers of protozoa, microscopic forms of animal life. It is believed that these protozoa play an important part in the cycle of changes that occur in the decomposition of soil organic matter, particularly in the rotting of manure. Following a period of rapid bacterial multiplication under suitable moisture conditions in the manure heap, protozoa probably consume large numbers of bacteria and rapidly increase in number. Later, the bodies of dead protozoa are decomposed and new groups of bacteria and actinomycetes gain the ascendancy.

A gram of rich soil may contain several billion bacterial cells, large numbers of algae and fungi, and 25 thousand or more of the much larger protozoa. An ordinary rod-shaped bacterial cell has a diameter of about 1 micron and a length that is approximately twice the diameter. Assuming that the soil contained 5 per cent organic matter, or 50 tons an acre to plow depth, Russell estimates its microbiological content at about 3 billion cells a gram and the total live weight at 3 tons an acre. The dry weight would be about 1300 pounds, with a nitrogen content of 130 pounds. It has been estimated that between 20 and 25 per cent of the dry weight of animal excrements consists of microbial cells. Since freshly voided manure contains about 20 per cent dry matter, the dry weight of microbial cells in a ton of fresh manure, on this basis, would be between 80 and 100 pounds.

The nitrogen and mineral content of microbial cells is of considerable interest. Analyses of two species of bacteria are shown in Table 25. The composition of these and other species no doubt varies to a considerable degree, depending on the medium on which they were grown. This is known to be true of crop plants grown on various soils and should apply equally well to the microscopic forms of life in the soil.

TABLE 25

PERCENTAGE COMPOSITION OF BACTERIA* (STOKLASA)

Material	*Azotobacter chroococcum*	*Bacterium mycoides*
N	11.30	10.84
P_2O_5	4.90	4.07
SO_3	0.29	0.49
K_2O	2.41	2.27
Na_2O	0.07	0.12
MgO	0.82	0.48
CaO	0.34	0.05
Fe_2O_3	0.08	....

* On dry-weight basis.

IMPORTANT FUNCTIONS OF SOIL MICROORGANISMS

Plant and animal refuse must undergo decay before most of the elements contained in it can be used again by plants. During the process of decay these organic substances undergo hydrolysis and oxidation, with intervening stages of reduction. The end-products of decomposition, under favorable relationships as to air and moisture supplies, are the oxides of the elements contained in plants, of which water, carbon dioxide, nitric acid, and sulfuric acid are examples. Such elements as calcium, magnesium, potassium, and the trace minerals are released in similar manner and combine with the acids formed to produce inorganic salts, such as carbonates, bicarbonates, nitrates, and sulfates.

Soils also contain important species of anaerobic bacteria that find favorable conditions for growth in those zones in which the oxygen supply has been reduced by action of aerobic bacteria or in those portions of the soil where the pore space is filled with water and carbon dioxide. Certain other species of bacteria have the capacity to assimilate nitrogen from the atmosphere and still others can assimilate the carbon of carbon dioxide. Thus, bacterial processes in the soil are in part those of decomposition and in part those of synthesis, depending on the conditions that obtain.

It is difficult to conceive of the mechanism by which insoluble organic materials may be attacked by bacteria, unless it be by some agency that operates on the outside of their cell walls. It is assumed that these cells excrete enzymes that serve as solubilizing agents, the soluble products diffusing through the cell walls to serve as food for

growth and energy of the bacteria. The process is similar to that occurring in the alimentary tracts of animals, where food materials are digested and then diffuse into the circulatory system. After these products have been utilized by the animal body, excretory products, such as water, carbon dioxide, urea, and other simple compounds, are given off by the lungs, skin, and kidneys. The undigested portion is excreted as feces. Similarly, soil microorganisms bring about the solubilization of organic materials, the final oxidation by-products of which are reutilized by plants. The undigested portion accumulates in the form of lignin and related products.

NITROGEN RELEASE FROM ORGANIC MATTER

The nitrogen that is used by most crop plants has its origin in soil organic matter. As this organic matter decomposes, its nitrogen is normally released as ammonia. This ammonia is later oxidized to nitrous and nitric acids through the action of distinct groups of soil microorganisms. Three groups are involved, the first of which releases ammonia, the second nitrous acid, and the third nitric acid. This process, in its entirety, is known as *nitrification,* although the first step is often referred to as *ammonification.*

Decomposition of protein substances, in which the organic nitrogen is contained, is accomplished by many different species of bacteria, actinomycetes, and fungi. The process may be either aerobic or anaerobic, depending on the conditions that obtain. The first products of protein hydrolysis are amino acids. These are broken down to form ammonia, carbon dioxide, and water. Under anaerobic conditions, free nitrogen, methane, and hydrogen sulfide may be formed. Hydrogen sulfide has an offensive odor. This makes it possible to know when anaerobic decomposition is taking place, as often happens when heavy applications of manure or other forms of organic matter are plowed under in heavy, poorly drained soils.

RATE OF NITRATE PRODUCTION IN SOILS

Methods for commercial production of nitrates were developed long before it was known that bacterial processes were involved. *Saltpeter plantations* were subsidized by several governments in Europe as a means of obtaining adequate amounts of nitrates for use in the manufacture of gunpowder. This consisted of heaps of nitrogen-rich organic matter, mixed with decomposing animal matter, ashes, lime, and

various other waste materials. The heaps were built on top of piles of brush, and they were watered from time to time with liquid manure, consisting mostly of urine. Care was taken to keep the mass porous to permit free movement of air. The heap was protected from rain by a covering. The nitrates gradually accumulated in the soil beneath the heap and were obtained by leaching this soil with water and evaporating the resulting solution to dryness.

In 1878, Schloesing and Muntz discovered that this was a biological process. Their discovery was followed by careful studies designed to determine just how it was accomplished. An attempt was being made to purify Paris sewage by passing it through soil. At first, the filtrate contained ammonia but no nitrate. Later, nitrate began to appear and, in time, ammonia entirely disappeared. When the soil was sterilized by use of chloroform the process ceased. When applications of chloroform were discontinued, ammonia again appeared in the filtrate, and later this ammonia was again replaced by nitrates. This indicated that the process was a microbial one, but pure cultures of the organisms could not be obtained. It was not until 1890 that Winogradsky succeeded in isolating nitrifying bacteria on media made of silica gel containing only inorganic constituents.

Two species of bacteria were found to be involved in changing ammonia to nitrate. One of these, *Nitrosomonas*, was shown to be responsible for changing ammonia to nitrite. A second species, *Nitrobacter*, changed this nitrite to nitrate. The end-product was normally nitrate of lime, which resulted from the action of the nitric acid on soil calcium. In due time it was found that the process could often be speeded up by applying an alkaline form of lime, such as the carbonate or oxide, to the soil. Otherwise the acid accumulated in the soil and the result was a slowing-down of the nitrification process.

It is now known that the rate of nitrification of the nitrogen in soil organic matter is determined largely by soil temperature, aeration, moisture, and reaction. The process virtually ceases when the temperature falls below 40° F., but it increases as the temperature rises to an optimum of nearly 90° F. Both ammonification and nitrification are at their optimum only when the moisture content of the soil is at about two-thirds saturation. Beyond that point the limiting factor is a lack of oxygen. But nitrate nitrogen will not be produced in quantity unless the soil contains organic matter of relatively recent origin, and this organic matter must contain at least 1.5 per cent nitrogen. Only that part of the total nitrogen in excess of the needs of the bacteria of decomposition for protein production within their

own cells will be released for nitrification. The nitrogen in this microbial protein itself will not be made available for crop use until after the excess of carbohydrate food has been used up and the extra microbial population dies from starvation.

The plow depth of an acre of good black Illinois corn land may contain as much as 6000 pounds of nitrogen. A 100-bushel corn crop requires about 150 pounds of nitrogen, largely in nitrate form. Yet it is seldom possible to obtain that high a yield of corn on such land unless the nitrogen supply in the soil has been supplemented by a heavy dressing of well-rotted manure, a plowed-under crop of clover or some other legume, or an application of a commercial form of nitrogen. Thus, it is now common practice to supplement the soil's supply of organic-matter nitrogen with 50 to 100 or more pounds of fertilizer nitrogen when attempting to produce corn yields of 100 bushels an acre or more.

Unless the first step in nitrification, the production of ammonia, has been effected, the others do not take place. But even if ammonification proceeds, nitrification may not follow unless the soil is well aerated and unless any acidity that may have developed in it has been neutralized. Thus, rapid nitrate production requires that the conditions in the soil be such as favor luxuriant growth of corn or similar crop plants. Under such conditions, and with a liberal supply of high-nitrogen organic matter, the nitrification process proceeds rapidly, as does the growth of the crop.

FIXATION OF NITROGEN BY LEGUME BACTERIA

If the nitrogen left behind by crop residues is supplemented only by that brought to the earth in rain, an amount estimated to be between 3 and 5 pounds an acre a year, nitrogen losses through crop removal and losses by way of drainage waters would soon deplete the soil's supply of this element. Fortunately, it has been shown that legumes have the capacity to accumulate nitrogen from soil air through the agency of the bacteria that live in the nodules on their roots.

The good effects of legumes on the crops that follow had been known for a long time before anyone was able to find out why this was so. It was not until 1886 that Hellriegel and Wilfarth (Table 26) were able to demonstrate that the nodule bacteria have the capacity to assimilate gaseous nitrogen and pass it on in combined form to legumes for protein production. If legumes are plowed under, their extra nitrogen is added to that already in the soil and, when released in

TABLE 26

NITROGEN CONTENT OF LUPINES* GROWN IN NITROGEN-FREE SAND (WILFARTH)

Number of Pot	Treatment of Sand	Dry Weight† of Lupines	Nitrogen† in Lupines
3	Soil solution	44.73	1.009
4	" "	45.63	1.156
5	" "	44.68	1.194
6	" "	42.45	1.337
9	Distilled water	0.93	0.014
10	" "	0.80	0.013
11	" "	0.92	0.013
12	" "	1.02	0.013

* A legume that is widely used for green-manuring purposes on acid sandy soils in northern Germany
† Grams.



FIG. 20. Legumes, such as these blue lupines growing in South Carolina, provide the preferred types of organic matter for plowing under, because of their high nitrogen content.

nitrate form, it produces marked effects on the nonlegume crops that follow.

Legumes are able to obtain all the nitrogen they require through the agency of the nodule bacteria. In the absence of these bacteria, however, legumes are as dependent on the nitrogen from soil organic matter as are nonlegumes. It is important, therefore, that precautions be taken to guarantee that the necessary nodule-producing bacteria are present in the soil when the seed is sown. To insure this it is now standard practice to *inoculate* the seed with a pure culture of nodule bacteria, such as are generally supplied by companies that specialize in their production.

The nodule bacteria of legumes develop and function in *symbiosis* with the legume. This means that both the legume and nodule bacteria profit by the association. The legume manufactures carbohydrate materials and collects mineral nutrients, which the nodule bacteria require. The bacteria add to the nitrogen supply by the fixation process.

These symbiotic bacteria belong to the genus *Rhizobium*. They are rod-shaped and do not produce spores. They often take on peculiar shapes, resembling clubs or the letters Y and T. Those taken from nodules on the roots of one legume species may not be able to develop nodules on the roots of another species of legumes. But *cross-inoculation* is possible among certain groups of legumes. Groupings of some of the common legumes in this respect are shown in Table 27.

TABLE 27

CROSS-INOCULATING GROUPS OF LEGUMES

1. Alfalfa, sweet clover, and bur clover.
2. Red, crimson, white, alsike, and mammoth clovers.
3. Garden, field, and sweet peas, and vetch.
4. Garden, navy, and kidney beans.
5. Lupines, both the annuals and perennials.
6. Soybeans.
7. Locusts.
8. Cowpeas, lima beans, peanuts, lespedeza, and crotalaria.

The several biological strains of any given species of *Rhizobium* vary greatly in their ability to fix nitrogen gas when in association with the legume to which they are adapted. One of the highly important tasks that continues to confront producers of inoculating materials for legume seeds is that of selecting highly efficient strains of nodule bacteria and multiplying them for commercial purposes. The most

effective strains normally produce large clumps of nodules on or near the main root of the plant. The final answer lies in isolating cultures from nodules that are so located on the roots of a considerable number of plants of a given legume species, developing the cultures, and trying them experimentally on plants under controlled conditions in the greenhouse.

NITROGEN FIXATION BY NONSYMBIOTIC BACTERIA

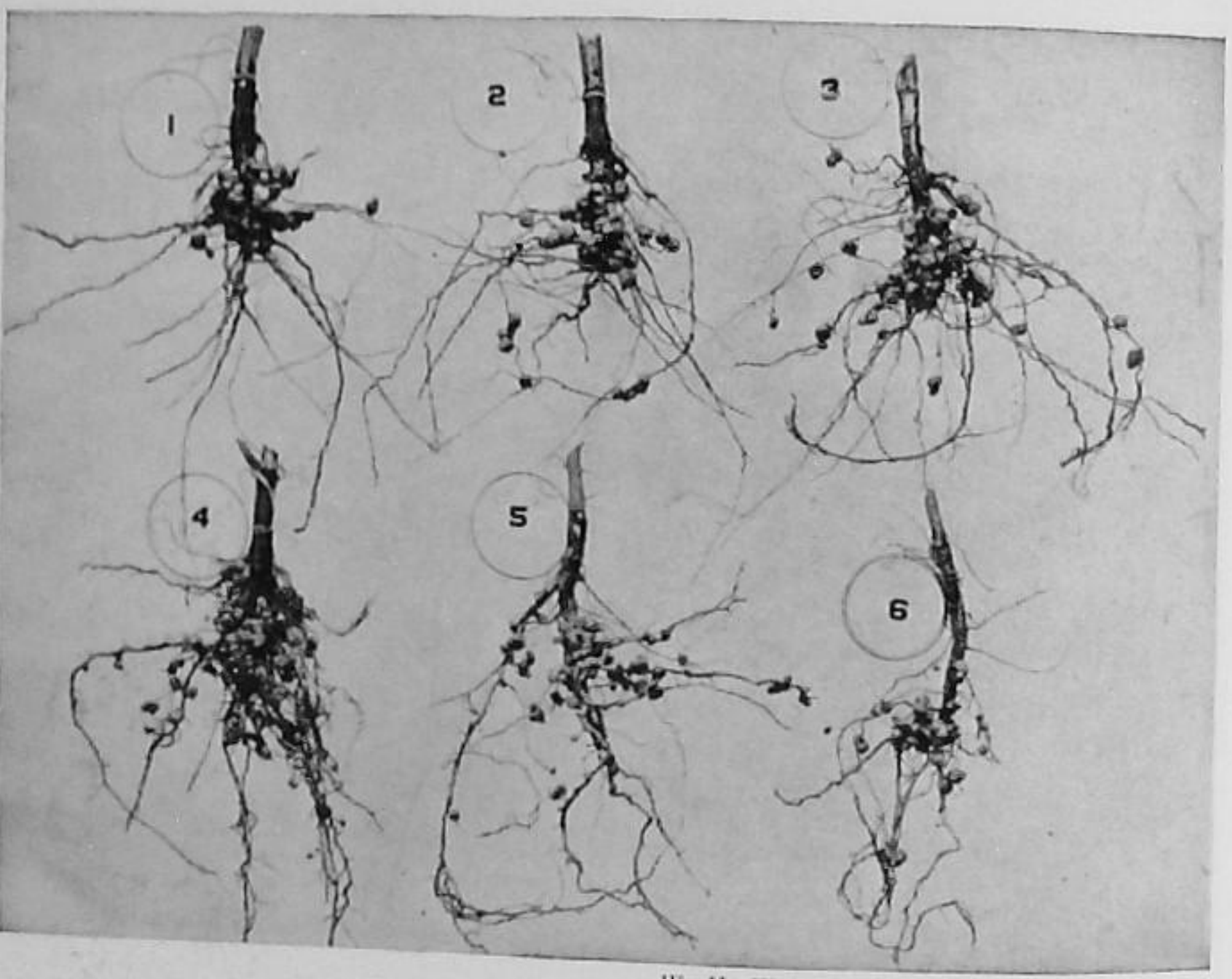
A considerable number of soil microorganisms are known to be able to fix free nitrogen independently of legumes. The most important



FIG. 21. Effect of inoculation of soybean seed at the New Jersey Agr. Exp. Sta. The whole area was seeded in the same manner at the same time, the only difference being that seed for the area on the right was inoculated, whereas that for the area on the left was not.

member of this group, discovered by Beyerinck in 1901, has been given the generic name, *Azotobacter*, of which the best known species is *Azotobacter chroococcum*. These bacteria have been found to be widely distributed in soils. Under optimum conditions in the laboratory, it has been shown that they are capable of fixing the equivalent

of 200 pounds of nitrogen in 2 million pounds of soil in 3 weeks. Optimum conditions include presence of a readily available source of carbohydrate, available phosphate, carbonate of lime, temperatures between 80 and 90° F., and soil moisture equivalent to about two-thirds saturation.



W. H. Wright, Wisconsin Agr. Exp. Sta.

FIG. 22. Difference in size, number, and location of nodules on roots of soybeans resulting from inoculation with 6 strains of bacteria. Strain 3, the most efficient, fixed nearly 3 times as much nitrogen as strain 5, the least efficient.

A second group of nonsymbiotic nitrogen-fixing bacteria, of the anaerobic type, was discovered by Winogradsky in 1893. These have been given the species name *Clostridium pastorianum*. They function most effectively in acid soils and under conditions that are unfavorable to most species of *Azotobacter*. It has been suggested that the two groups may effect symbiosis, the *Clostridium* producing available carbon in the form of butyric acid and the *Azotobacter* developing anaerobic conditions in the oxidation of this acid and of other organic substances.

A number of other species of soil microorganisms are known to be able to fix nitrogen. The necessary carbohydrate materials may be derived from plant residues or they may be developed by algea, which

are often found in abundance growing on or near the surface of the soil. Possibly the nodule bacteria fix some nitrogen while living in the soil during the years between the appearance of the legume in the crop rotation. However, there is considerable doubt whether the nitrogen-fixing capacities of all these nonsymbiotic groups of bacteria, put together, are sufficient to make any very important contribution to crop production. Yet it is important to remember that they have the advantage of being able to work more or less continuously during the warmer portion of the year, no matter what the nature of the crop that is growing on the land. This assumes, of course, that conditions not only as to temperature but also as to soil reaction, moisture, and food supplies are favorable.

MINERALIZATION OF SOIL ORGANIC MATTER

Plants are derived almost entirely from inorganic matter. All fifteen elements required by them originate in water, carbon dioxide, gaseous nitrogen, ammonia, or nitrates, and the necessary mineral salts that are obtained from the soil solution. Small quantities of simple organic substances, such as are produced during decomposition of plant wastes, may be used as such, but the portion of the plant that is derived directly from these organic materials is certainly much less than 1 per cent. Excellent plants can be produced in water cultures containing only dissolved mineral salts, with the condition that the leaves are exposed to the atmosphere and have light at their disposal.

The final result of microbial action on soil organic matter is its almost complete mineralization. Thus, the water and carbon dioxide that were used in its production are released, and this applies to all the nitrogen and mineral elements as well. The mineral food of plants consists mostly of nitrates, phosphates, sulfates, and carbonates of calcium, magnesium, potassium, and essential trace elements. The cycle from water, air, and soil through the plant and back again to water, air, and soil may be short or long, depending on circumstances. But the cycle is completed in due time, even for organic materials like coal, and the soil- and air-derived substances can be used over and over again during the course of the centuries. That lost to the sea in drainage waters or to the air in gaseous form must be made good by further release of mineral elements from the soil and their recapture from the air. Otherwise, it becomes necessary to replace these losses by applications of liming materials and fertilizers.

During the decay process the carbon, nitrogen, and sulfur are re-

leased in acid forms, which have solvent effects on the soil. The nitric and sulfuric acids are neutralized by soil bases, which, in humid regions, must be renewed from time to time in the form of liming materials. But the carbonic acid that remains in solution in the soil water continues to act as a solvent, notably that on the surfaces of root hairs, where it is excreted by plants. This acid serves as a continuous solvent for releasing mineral elements from the soil.

In addition to the microscopic forms of plant life, a considerable number of larger animal forms inhabit the soil. These include larvae of insects, many species of ants, and a variety of worms. Included among the worms is one group known generally as *earthworms*. These earthworms inhabit virtually all soils that contain suitable amounts of lime and organic materials. The number of earthworms in the plow depth of soil may be quite large, often more than 1 million an acre. These worms eat their way through the soil, consuming and digesting organic matter as they go. Their excretory products are soil, in aggregated form, and the by-products of organic-matter digestion.

The extent to which earthworms bring up subsoil and deposit it on the surface is unknown. But Darwin, in a highly interesting discussion of this subject, attributed to them a translocation of soil amounting to 1 inch in five years. This conclusion was based on the rate at which stones, applied to the surface of soils, became imbedded in them. Burial of ancient cities was credited by Darwin to the action of earthworms. According to his estimate, as much as 10 tons of soil annually passes through the bodies of earthworms in an acre of soil in certain parts of England. As the weather becomes dry during summer months, earthworms work their way down to greater depths. But they continue to return to the surface to deposit their casts, thus effecting a renewal of the surface soil at the expense of the subsoil.

Discovery and exploitation of *antibiotics* for prevention and cure of human diseases have resulted in considerable speculation as to the part such microbial products may play in the soil. There is reason to believe that such antibiotics are produced in soils and that they may play important parts in keeping disease organisms under control. They may also be absorbed by plants and result in protecting them against attacks of insects and diseases. It is, of course, apparent that desirable as well as undesirable forms of life might be controlled or destroyed by antibiotics. It is not at all clear as yet how their useful values can be exploited in crop production. Possibly extension of our present large-scale production of antibiotics in pure-culture techniques

for use in protecting animals and man can be enlarged in terms of plants as well. It is conceivable also that something could be done to favor the activities of certain antibiotic-producing microorganisms in soils by selecting specific types of cover crops for green-manuring purposes.

Not only earthworms but the various forms of microbial life have important effects on the physical properties of soils. The slimy intermediate products that are formed during the process of decomposition of organic matter tend to bind the finer clay particles together into groupings that, when dried, become soil *aggregates*. In proportion as larger amounts of organic matter are incorporated into soils and their decomposition takes place, the working qualities of these soils is greatly improved, largely as a result of better *aggregation*.

BIOLOGICAL ANALYSIS OF SOILS

In general, it may be said that the greater the number of microbes in soils the more productive these soils are likely to be. Thus, it is possible to obtain a fair index of the relative productivity of a series of soils by counting the number of microbial cells contained in unit weights of these soils. Similarly, soils can be evaluated in terms of nitrification, nitrogen fixation, and carbon dioxide evolution under controlled conditions. It is apparent that the rate at which these processes take place is largely dependent on the organic-matter content of the soils.

If, however, a soil is in a low state of productivity, the efficacy of a suggested remedy can often be fairly satisfactorily determined in the laboratory, in a few days or weeks, by measuring the effects of the treatment on microbiological processes. Thus, one can measure the rate of nitrate accumulation or of carbon dioxide evolution of the treated soil in comparison with an untreated sample. Applications of limestone and superphosphate may result in marked increase in development of *Azotobacter*. A biological analysis of a soil in the laboratory, therefore, provides a clue to its state of productivity and permits determining, in a relatively short time, the probable efficacy of any treatment one may contemplate using in the field.

SELECTED REFERENCES

1. Albrecht, W. A. Loss of organic matter and its restoration. *U. S. Dept. Agr. Yearbook,* pp. 347–376, 1938.

2. Burrill, T. J., and Roy Hansen. Is symbiosis possible between legume bacteria and non-legume plants? Illinois Agr. Exp. Sta., Bull. 202, 1917.

3. Conn, H. J. Soil flora studies. I. The general characteristics of the microscopic flora of the soil. II. Methods best adapted to the study of the soil flora. New York (Geneva) Agr. Exp. Sta., Tech. Bull. 57, 1917.

4. Fred, E. B., and Associates. Root Nodule Bacteria and Leguminous Plants. University of Wisconsin Studies in Science, No. 5, 1932.

5. Millar, C. E., and L. M. Turk. *Fundamentals of Soil Science*, second edition. John Wiley & Sons, New York, pp. 199–231, 1951.

6. Ruf, E. W., and W. B. Sarles. Nodulation of soybeans in pot culture by effective and ineffective strains of *Rhizobium japonicum*. *J. Am. Soc. Agron.*, Vol. 29, pp. 724–728, 1937.

7. Russell, E. J., and E. W. Russell. *Soil Conditions and Plant Growth*, eighth edition. Longmans, Green and Co., New York, p. 148, 1952.

8. Stoklasa, J. Méthodes pour les recherches biochimique dans le sol. *J. agri. prat.*, Vol. 49, pp. 453–455, 1924.

9. Waksman, Selman A. *Soil Microbiology*. John Wiley & Sons, New York, 1952.

10. Wilfarth, H. Über Stickstoffaufnahme der Pflanzen. *Landwirtsch. Vers. Sta.*, Vol. 34, pp. 460–461, 1887.

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Some Physical Properties of Soils

The physical properties of soils are determined largely by the size and arrangement of the primary particles of which they are constituted. For this reason it is desirable in studying the physical characteristics of any given soil to know its *particle size distribution* and the extent to which its finer particles are aggregated. A sandy soil contains a high percentage of relatively large particles, in comparison with the size of those that make up the larger part of a clay soil. The surface area exposed by the particles in a sandy soil is much less than that of the particles in a clay soil. As a result, a sandy soil has less capacity to retain water against loss by drainage, evaporation, and removal by plant roots. It is less able to adsorb any soluble salts that may be formed by decomposition of its organic matter or may be applied in the form of fertilizers. Sandy soils, therefore, are more subject to nutrient deficiencies than are clay soils. On the other hand, clay soils often develop bad physical states if, for any reason, the aggregates in which the very fine particles are normally grouped are broken down into their primary units.

MECHANICAL ANALYSIS OF SOILS

Mechanical analysis of a soil consists in determining the size distribution of the primary particles of which it is made. The aggregates in which the clay particles are grouped must be broken down before such an analysis can be effected. Various methods are employed for this purpose, of which shaking the soil in a dilute solution of ammonia was one of the earliest. Present methods call for treating the soil with 0.2 normal hydrochloric acid, washing it to remove displaced cations, and then shaking it for 10 hours in a 0.1 normal solution of sodium hydroxide. Preliminary boiling in a 6 per cent solution of

hydrogen peroxide, to oxidize the organic matter, is necessary in soils that are high in humus.

After dispersion of the primary particles has been effected, the particles are then divided into gravel, coarse sand, fine sand, silt, and clay fractions, the weight of each *separate* being determined and re-

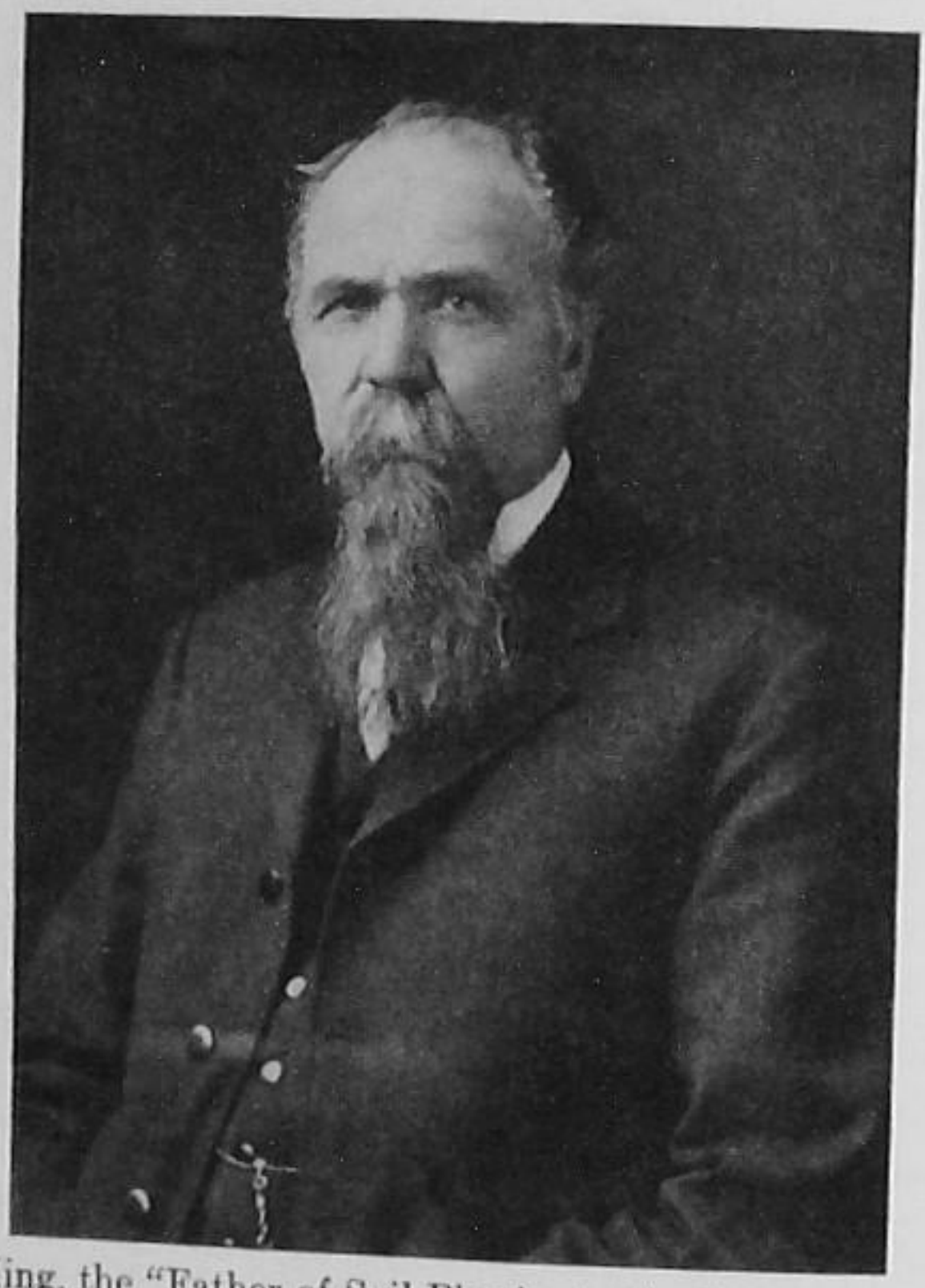


FIG. 23. F. H. King, the "Father of Soil Physics in the United States," and author of *Farmers of Forty Centuries*.

corded. The gravel and sands are removed by washing the sample over a standard screen. The silt and clay that pass through the screen are separated by sedimentation and decantation, use being made of a centrifuge. The water suspension containing the clay fraction is evaporated to dryness.

It is apparent that such an analysis is long and tedious. For that reason more convenient methods have been developed for estimating the proportions of the several separates in a soil. The most common procedure is that in which use is made of a specially constructed hydrometer. This is placed in a sedimentation cylinder containing the soil in suspension. By making hydrometer readings at definite time

intervals, one can estimate the percentages of the various-sized separates in the soil sample. The ease with which this can be done is such that most routine mechanical analyses of soils are now made by this method.

SOIL SEPARATES AND CLASSES

The dividing lines between the several soil separates, as now generally agreed upon, are shown in Table 28. These divisions are more

TABLE 28

SOIL SEPARATES ADOPTED BY THE INTERNATIONAL SOCIETY OF SOIL SCIENTISTS

Separate Names	Diameters* in Millimeters
Gravel	2.0 and larger
Coarse sand	2.0 to 0.2
Fine sand	0.2 to 0.02
Silt	0.02 to 0.002
Clay	0.002 and smaller

*The particles are not necessarily spheres. Diameters may be taken to mean their longest dimensions.

or less arbitrary. But it has been pointed out that fairly definite differences in particle properties occur at the dividing lines that are now being employed. Thus, water begins to be weakly held in the pore spaces at 2.0 millimeters; capillary attraction operates most efficiently at 0.2 millimeter; particles tend toward aggregate formation at 0.02 millimeter; and Brownian movement begins to be exhibited at 0.002 millimeter.

This classification was not generally adopted in the United States until 1937. Before that, silt separates were defined as particles with diameters between 0.05 and 0.005 millimeter, and clay separates as those with diameters less than 0.005 millimeter. In Illinois surveys the range in particle diameters was between 0.03 and 0.001 millimeter for silt, and less than 0.001 millimeter for clay. Similarly, in the English system of nomenclature, silt particles ranged between 0.1 and 0.002 millimeter in diameter and clay particles consisted of all those below the silt dimensions. In reading the older literature on soil physics it is necessary to keep these differences in mind.

The words sand, silt, and clay, when used as adjectives modifying soil, refer to soil *classes*, the predominating particle sizes of which are those indicated by the separate name employed. Thus, a clay soil is defined as one containing less than 45 per cent sand, less than 40 per cent silt, and 40 per cent or more clay. Soils of the United States are

now grouped into 12 major classes according to the predominance of one or another of the separates or to the size distribution of the various particles. This classification, it will be noted, is based entirely on particle size, or *texture*. The specifications for the most common classes of soil are shown in Table 29. Special attention is called to

TABLE 29

SAND, SILT, AND CLAY IN IMPORTANT SOIL CLASSES

Soil Class	Sand, Per Cent	Silt, Per Cent	Clay, Per Cent
Clay	Less than 45	Less than 40	More than 40
Clay loam	20–45	15–50	25–40
Silt loam	Less than 50	50–90	Less than 30
Loam	25–50	30–50	5–25
Sandy loam	45–85	Less than 50	Less than 20

the word *loam*. In common parlance this word means a soil that is high in organic matter and that has good working qualities. In soil physics, however, this word means a soil class containing between 25 and 50 per cent sand, between 30 and 50 per cent silt, and between 5 and 25 per cent clay. Organic matter is not considered in defining soil classes. But, *for any given set of conditions, the organic-matter content of a soil will be closely related to the class to which it belongs.* The sandier the soil the less organic matter it will contain under any given type of management. The more clay the soil contains, the higher its percentage content of organic matter will be.

COLLOIDAL MATTER IN SOILS

The quantity and nature of the *colloidal matter* in soils are of particular interest from the physical point of view. This colloidal matter consists of the very smallest particles in the clay fraction. Since clay is defined as a soil separate, the particles of which are 0.002 millimeter or less in diameter, the question naturally arises as to the lower limits of these particle sizes. This lower limit will be that of a molecule, at which point it goes into solution. A molecule of hydrogen is estimated to have a diameter of 0.16×16^{-6} millimeter, and a molecule of chloroform has a diameter about 8 times that of hydrogen. The longest diameter of a particle of *kaolinite*, the most highly weathered clay mineral, would be somewhat greater than that of chloroform. Between the longest diameter of an aggregate of clay particles and that of the largest particle of clay itself is a very wide range of dimen-

sions. As the state of division of a given mass of soil becomes finer, the total surface area of its constituent particles increases, although not in the same proportion. The relationship between particle size and surface area is shown in Table 30.

TABLE 30

NUMBERS AND SURFACE AREA OF PARTICLES* IN A GRAM OF SOIL

Diameter, Millimeters	Particles, Number	Surface Area, Square Millimeters
1.00000	72×10	226×10
0.10000	72×10^4	226×10^2
0.01000	72×10^7	226×10^3
0.00100	72×10^{10}	226×10^4
0.00010	72×10^{13}	226×10^5
0.00001	72×10^{16}	226×10^6

* Assuming spheres of given diameters with specific gravity 2.65.

It will be observed that for each reduction in particle diameter to one-tenth that of the one above it the number of particles in a given mass of soil is increased 1000 times. At the same time, the total surface area of the particles is increased 10 times. It is this surface-area enlargement that is of most significance. If all the particles contained in an acre of soil to plow depth had diameters of 1 millimeter each, the total internal surface area would be less than 500 acres. If the particle diameters were all 0.0001 millimeter, the internal surface area would be 5 million acres. In the latter case, cohesive and adhesive properties would become readily apparent. By *cohesion* is meant the tendency of particles to stick to each other. *Adhesion* refers to the tendency of water, and any substances dissolved in it, to adhere to the surfaces of the particles.

Soils containing high percentages of material in the colloidal state are likely to offer very serious competition against plant roots for water and for mineral nutrients in the soil solution. Similarly, rate of water movement through such soils may be very slow. The same applies to losses of nutrients through the leaching action of water. Difficulties may be encountered in plowing the soil, in preparing it for planting, and in developing effective drainage. But much depends upon the arrangement of these fine particles in the soil, since they may exist either as separate particles or in an aggregated state.

Most clay crumbs are aggregates of much smaller particles of colloidal dimensions. From a study of 32 soil samples, Gile and his asso-

ciates concluded that their colloidal content ranged from 6 to 61 per cent. A *colloidal particle* was defined as one having a diameter of 1 micron or less. A *micron* is 0.001 millimeter. In many of these soils the percentages of colloidal matter exceeded those of the clay separates, as determined by the usual method of mechanical analysis.

This colloidal material is not only present as a thin gelatinous film around the coarser particles but it also occupies a considerable portion of the space between the larger particles. Depending on its nature, it must play a highly important part in determining not only the physical characteristics of soils but their chemical characteristics as well. In fact, it is by taking advantage of the peculiar properties possessed by finely divided matter that it is possible to estimate the colloidal content of soil without going through the highly laborious process of separating the colloid from the soil mass. The method employed in this determination is that of measuring the soil's capacity to adsorb some suitable substance, such as ammonia, malachite green, or even water itself. This is, in effect, a rough measure of the surface area of the soil colloids. But it must be admitted that the chemical nature of colloidal matter in soils is an important factor also in determining its capacity to adsorb materials from solutions.

SOIL STRUCTURE

Up to this point it has been assumed that soil particles are spheres. This is not so. Microscopic examination reveals that the larger particles are covered with masses of more or less translucent material of a gelatinous nature. When this has been removed by use of hydrogen sulfide and dilute oxalic acid, the enclosed particles are found to be angular mineral fragments, the nature of the surfaces of which depends on the minerals comprising the fragments. The colloidal matter surrounding these particles may be either organic or inorganic in nature, but it is usually made up mostly of inorganic material.

Colloidal particles, such as are found in clay separates, may exist either in a highly *dispersed state*, as individual particles, or in a state of aggregation. Much depends on the relative amounts of the several cations in the *exchange complex*. This term refers to the capacity of the clay fraction of soils to adsorb cations from solution in exchange for other cations already adsorbed by the soil complex. If these cations are largely sodium or potassium, the soil will be in an extremely bad physical state, most of the particles being in a dispersed rather than an aggregated state. If the cations attached to the exchange complex

are hydrogen or calcium, the soil may be in a good state of aggregation, having what is known as a good *crumb structure.*

Good soil structure, however, or the extent to which the finer particles are present in a crumb or aggregated state, is determined also by the system of soil management that is employed. The conditions of a clay soil in aggregated and in dispersed states may, perhaps, be safely compared with those of bread in its fresh loaf and dough stages, respectively. If either the clay soil or the bread is rolled between the thumb and fingers when it contains a certain excess of moisture, a doughy mass results. In the case of clay, good structure can often be recovered merely by drying, which is accomplished either by sun, wind, freezing, or growing plants on the soil. Roots of grass crops are especially effective in this connection. The dispersion that has taken place in wet and acid soils can often be overcome by draining and liming the soil. Such alkaline compounds as sodium and potassium carbonates have highly dispersing effects, as is well known in regions of alkali soils. One of the best remedies for this situation consists in the use of gypsum, the calcium of which tends to replace the sodium in the exchange complex; the sodium being then carried away in extra irrigation water as it works its way down through the soil.

Soils tend to have very different types of aggregate structure, depending on the nature of the clay minerals that are contained in them and the conditions of soil formation. The adjective forms of *plate, column, prism, cube, nut,* and *sphere* are employed in describing the variations in structure that are noted in the field. Some soils do not possess any very definite structure, the several particles functioning individually. This is notably true of those that contain only very small amounts of colloidal material. The most difficult situation to deal with is that of soils that are made up largely of very fine silt, the particles of which fit together very compactly. If such material is cemented together by iron oxides or humates, it forms *hardpan* that is almost or completely impervious to water. Impervious layers are also formed in acid-soil areas, where highly dispersed colloidal matter gradually moves downward into the *B* horizon until it has accumulated to form almost watertight layers.

Soil structure will deteriorate or improve, depending on the system of management that is applied to it. If soil is plowed, worked, or tramped over when it is wet, or if it is exposed to the action of falling raindrops, it tends to lose its aggregate structure. This becomes apparent from the clods that are formed when it is prepared for planting, by the tendency of water to accumulate on the surface following rains,

and by the formation of a crust through which seedlings may have difficulty in emerging. Soils also develop a clod structure if plowed when they are very dry. It is apparent, therefore, that much depends on working the soil at optimum moisture content, which can be determined by kneading it between the hands and noting whether it will



FIG. 24. Soybeans, plus the weeds that grow up in them, provide excellent high-nitrogen organic matter for plowing under for improving the physical properties of soils.

readily fall apart afterward. The beating action of rain can be overcome only by developing a canopy of vegetative cover over the land as soon as possible after it has been worked, or by *trash-farming* systems, in which crop refuse is left on top the land.

Soil aggregates are also broken down by the shearing action of plows, discs, cultivators, and other farming implements. Consequently, it is necessary to reduce the number of tillage operations as far as possible, and to develop crop-rotation programs by which a good state of aggregation is regularly reestablished. This calls for growing crops that provide a complete cover over the land. Of these, the grass crops are most effective because of their very widely distributed root systems that tend to have a marked aggregating effect on

soils. This may result in part from desiccation, in part from pressures developed by the growing roots, and in part from the action of microbes on the organic matter left in the soil after the crop is harvested.

AGGREGATING AGENTS

The marked effects of plant residues and manures on the working qualities of soils are well known. The importance of plant roots, notably those of grass crops, has been mentioned. The net effects of root growth, crop residues, and manures is to improve greatly the state of aggregation of the soil, with the result that a clay soil may take on the qualities of a loam. Similarly, the physical properties of a sand can be greatly improved. Thus, any soil can be made into what the practical man calls "loam," even though mechanical analyses of the soil would not permit its classification in that category.

Organic matter, during the process of its decay, is an excellent aggregating agent. Filamentous growths of fungi and gelatinous by-products of microorganisms permeate the soil. When the soil dries, whether by heat and wind, the dehydrating action of plant roots, or freezing, the organic colloids, as well as those of an inorganic nature, dry and shrink, drawing masses of soil particles together into aggregates. Once these colloids have been dried out they take on water very slowly. Consequently, the aggregated condition thus developed tends to last for some time. But the process must be regularly repeated, since soil structure gradually deteriorates and must be redeveloped.

In sandy soils, the gelatinous residues of organic-matter decomposition tend to fill in between the large soil particles, thus tending to overcome the disadvantages of excessive oxidation, evaporation, and drainage. Here, again, regular additions of organic matter are required to maintain the soil in good physical state.

On the heavier types of soil, crop residues and manure are most effective if worked into the surface soil rather than being plowed under. Lack of air and resulting anaerobic conditions result in a very slow rate of decomposition of plowed-under manures and green manures under such conditions. The cruder types of organic matter, such as cornstalks, tobacco stalks, and brush can often be plowed under to advantage in such soils. It is important to keep in mind that undecomposed residues of organic matter of the lignin type, if well distributed through the soil, form lines of weakness in soil masses. When



FIG. 25. Nothing quite takes the place of a good sod as an aggregating and tilth-improving agent for soils.



FIG. 26. Repeated cultivation, as in this vineyard near Fresno, California, causes marked deterioration in soil structure by destroying soil aggregates.

such masses are subjected to the action of tillage implements they tend to fall apart along these lines.

Development of *chemical soil-conditioning agents* has provided a new means by which the working qualities of soils can be improved. These conditioning agents, the first of which was called "*Krilium*," are long-chain organic polymers that, when applied to a soil in a good physical state, tend to keep it in that condition for some time, possibly for several years. Such marked and long-lasting effects have been obtained from the use of some of the better products of this type as to make it appear that they have a permanent place of considerable importance in agricultural economy. The cost, as yet, is possibly prohibitive, except for the more intensive types of plant production, such as those in lawns, gardens, and greenhouses, and for golf courses, parks, and market-gardening enterprises. But since these organic conditioning agents resist the decomposing action of soil microbes and thus have long-lasting effects, the cost divided by the period of time they are effective is not as high as it first appears.

Good soil conditioners are capable of improving physical characteristics of soils to whatever depth they are mixed with them. To condition the plow depth of an acre of soil requires possibly 1000 pounds of the best of the soil conditioners now on the market. At present prices of around $2 a pound of active ingredient, the cost is prohibitive for large-scale field use. However, small amounts, mixed with a thin layer of soil over the seed to prevent crust formation until they have germinated, could possibly be used to economic advantage, notably on such crops as carrots. A further possibility in the use of soil conditioners is as a protective agent on slopes on lawns or along new highways to hold the soil in place until newly seeded grass has germinated and its roots have gotten a foothold. Rapid developments are to be expected in the discovery of new and possibly improved soil conditioners. It is possible that some of the *organic silicates* may be found useful in this connection.

VARIATIONS IN SOIL PROFILES

The nature of the subsoil is as important as that of the plow depth of soil in determining the crop-producing capacity of land. The characteristics of the *A* horizon more or less reflect those of the *B* horizon, but not necessarily so. It is important to know whether any of the lower horizons are only slowly permeable to water. If they are, it becomes necessary to find out where they are and the nature of the

material contained in them. It may then be possible to determine whether subsoiling or tiling can be employed to advantage.

Profiles of four important soil types and their physical characteristics are shown in Table 31. From a study of these profiles one can estimate the suitability of these soils for growing a given crop. He

TABLE 31

PROFILES OF FOUR IMPORTANT SOIL TYPES

I. Podsol: Becket fine sandy loam, Massachusetts.

Inches	
0–1	Dark-brown leaf mold.
2–4	Transition layer, sometimes absent.
4–7	Dark-brown to coffee-brown loam.
7–14	Deep yellowish-brown loam.
14–16	Pale yellowish-brown loam.
26	Compact greenish-gray gritty till.

Parent material: glacial till, largely of acid gneiss.
Vegetation: northern hardwoods, with hemlock, spruce, pine.

II. Latosol: Nipe clay, Cuba.

Inches	
0–26	Reddish-brown claylike material, iron concretions.
26–40	Reddish-brown friable clay.
40–156	Reddish and yellowish friable material.
156–192	Reddish and yellowish and some black material.

Parent material: serpentine, diorite, and peridotite.
Vegetation: Sierra palms, tree ferns, mahogany.

III. Chernozem: Barnes silt loam, South Dakota.

Inches	
0–12	Black silt loam.
12–23	Brown silt loam, little or no heavier than surface.
23–47	Gray-brown silt with calcium carbonate deposits.

Parent material: calcareous glacial till plain material.
Vegetation: tall grass.

IV. Red Desert Soil: Mohave loamy sand, Arizona.

Inches	
0–7	Pinkish-brown, noncalcareous, micaceous loamy sand.
7–9	Reddish-brown loamy sand.
9–20	Reddish-brown sandy loam, moderately calcareous.
20–44	Reddish-brown sandy loam, hard when dry, workable, moist.
44–74	Reddish-brown material with coarse sand and gravel.

Parent material: alluvial fans, from granites, schists, gneiss.
Vegetation: creosote bush, sagebrush, galleta grass, cactus.

can also estimate the probable usefulness of any contemplated scheme for improving their structural characteristics.

Soils of humid areas tend to become somewhat stratified as to particle sizes, the coarser particles remaining in the *A* horizon and the finer ones moving down into the *B* horizon. As a result there is a tendency toward stratification of the nutrient constituents as well. Sand particles tend to be high in silica, many of them being pure quartz. Clay particles are largely silicates, the colloidal members having a very marked capacity to adsorb and hold plant nutrients. If the soil is composed of transported materials, a much different type of stratification will be found. In arid regions, where weathering is more physical disintegration than chemical decomposition, the various-sized particles may differ very little in chemical composition.

In general, the coarser soil separates in humid climates are relatively high in silica. The finer separates tend to be much higher in iron, aluminum, phosphorus, sulfur, calcium, magnesium, and trace elements. Table 32 is of interest in this connection, in that it shows the

TABLE 32

PERCENTAGE COMPOSITION OF SOILS AND THEIR COLLOIDS (ROBINSON)

Oxides	Cecil Clay Loam		Marshall Silt Loam		Norfolk Fine Sandy Loam	
	Soil	Colloid	Soil	Colloid	Soil	Colloid
SiO_2	83.81	33.95	72.06	45.93	90.34	38.25
TiO_2	0.80	0.62	0.67	0.48	0.94	0.79
Al_2O_3	7.70	36.06	11.18	21.72	2.89	31.21
Fe_2O_3	2.97	11.02	3.66	8.94	1.88	11.25
MnO	0.20	0.15	0.05	0.07	0.00	0.03
CaO	0.28	0.31	0.90	1.19	0.01	0.54
MgO	0.15	0.40	0.66	2.01	0.08	0.53
K_2O	0.79	0.56	2.66	2.28	0.22	0.26
Na_2O	0.43	0.44	1.02	0.21	0.04	0.09
P_2O_5	0.06	0.25	0.21	0.46	0.02	0.23
SO_3	0.02	0.06	0.12	0.21	0.03	0.08
Cl	0.02	0.04	0.05	0.06	0.04	0.05
H_2O*	....	14.42	....	7.92	....	11.92
N	0.03	0.22	0.23	0.51	0.06	0.22
Colloid†	10.20	....	27.30	....	10.70	....

* Combined water.

† Per cent of colloid in soil as estimated by adsorption method.

percentage composition of entire soils in comparison with that of their colloidal fractions.

PHYSICAL ANALYSIS OF SOILS

Size distribution and arrangement of soil particles largely determine air-and-water relationships. They also affect the microbiological properties of soils. As the colloidal content increases, movement of air and water is more restricted. Capacity to retain nutrient elements is, however, increased. But it is a well-known fact that chemical analysis of a soil may reveal large amounts of nutrient elements and yet the soil may be unproductive because of poor physical properties. Effective structure is best determined by measuring those properties that are expressions of the arrangement of the soil's constituent particles. Physical analysis has to do with measurement of such properties, which include water-holding capacity, pore space, permeability to water and air, plasticity, cohesion, and aggregation. Unfortunately, many of these properties can only be measured in the field with the soil in place. In moving the soil to the laboratory little or no change is effected in its chemical composition, but marked changes occur in its physical properties, and in related biological properties.

SELECTED REFERENCES

1. Baver, L. D. *Soil Physics.* John Wiley & Sons, New York, pp. 125–192, 1940.

2. Gile, P. L., and Associates. Estimation of colloidal matter in soils by adsorption. *U. S. Dept. Agr. Bull.* 1193, 1924.

3. Gustafson, A. F. Using and Managing Soils. McGraw-Hill Book Co., New York, pp. 1–29, 1948.

4. Lyon, T. L., H. O. Buckman, and N. C. Brady. *The Nature and Properties of Soils.* The Macmillan Co., New York, pp. 45–78, 1952.

5. Rice, T. D., and L. T. Alexander. The physical nature of soil. *U. S. Dept. Agr. Yearbook,* pp. 887–896, 1938.

6. Robinson, W. O., and R. S. Holmes. The chemical composition of soil colloids. *U. S. Dept. Agr. Bull.* 1311, 1924.

7. Shaw, Byron T., editor. *Soil Physical Conditions and Plant Growth.* Academic Press, New York, pp. 1–38, 1952.

8. Thompson, Louis M. *Soils and Soil Fertility.* McGraw-Hill Book Co., pp. 8–25, 1952.

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Soil Water

The *water-holding capacity* of a soil is determined largely by the size distribution of its particles and their structural arrangement. Ordinarily, it amounts to between 30 and 50 per cent of the total volume occupied by the saturated soil in place. An acre of soil to a depth of 5 feet, a depth to which the roots of many crops extend, may have capacity to hold enough water to meet the needs of two 50-bushel wheat crops or an equal number of 100-bushel corn crops if none of the water was lost by evaporation or drainage and if all of it could be extracted by plant roots. Table 33 gives the percentage, by volume,

TABLE 33

WATER REQUIRED TO SATURATE A 6-INCH COLUMN* OF SOIL (KING)

Depth, Feet	Character of Soil	Weight, Pounds	Water Required for Saturation		
			Pounds	Inches	Per cent†
0–1	Marly loam	15.09	6.24	5.88	49
1–2	Reddish clay	18.94	5.33	5.03	42
2–3	Reddish clay	18.89	5.38	5.07	42
3–4	Clay with sand	19.94	4.95	4.67	39
4–5	Very fine sand	22.92	3.99	3.76	31
Totals to depth of 5 feet		95.78	25.89	24.41	41

* A column 6 inches in diameter. † Per cent of total volume of soil.

of water required to saturate columns of soil with diameters of 6 inches to a depth of 5 feet.

However, the water content of a saturated soil is greatly reduced by the action of gravity if the conditions in the subsoil are such as to permit the escape of *gravitational water*. It happens also that soils are not suitable for satisfactory growth of most crop plants until this gravitational water has been removed. Of greater interest, therefore, is the water-retaining capacity of a soil against the pull of gravity.

This is called *field capacity*. This, again, is largely determined by texture and structure of the soil, temperature, and height above some temporary or permanent water table. The element of time is also of considerable importance since, in humid climates or where irrigation water is applied, all the gravitational water may not have reached the level of the water table before more water falls on or is applied to the soil.

In an experiment, data for which are shown in Table 34, columns

TABLE 34

WATER RETAINED BY SOILS AFTER 60 DAYS OF PERCOLATION (KING)

Height of Column, Inches	Per Cent of Water Retained*	
	Sandy loam	Clay loam
84	16.16	21.26
72	16.55	31.05
60	17.59	31.21
48	18.70	31.99
36	20.90	32.45
24	21.46	34.40
12	22.68	35.97
6	27.69	37.19

* Percentage of total volume of soil.

of soil were saturated with water, after which free percolation was permitted to take place for 60 days. There was no water table at the base of these columns, except that the water from higher levels tended to maintain the lower part of the column at saturation throughout the period of the test. Evaporation was reduced to a minimum. The percentages shown in the table are those of the water present in 3-inch layers of soil chosen at 1-foot intervals to a height of 7 feet. The field capacity of the top 3 feet of the sandy loam was over 7 acre-inches and that of the same depth of the clay loam was more than 12 acre-inches. From this it would appear that the field capacity of these soils was sufficient to meet crop requirements for an entire summer, even if no additional rain fell or no irrigation water was applied.

Both air and soil, however, compete with plants for stored water. Losses by evaporation are heavy during dry periods, and the soil's capacity to retain water against the pull of plant roots is often very large. Plants wilt long before the soil is as dry as it would be if it had been subjected to drying in an oven or even if it had been merely air-

dried. The percentage of water in the soil at the time plants growing in it wilt is known as the *wilting coefficient*. Similarly, the percentage of water in the soil when in equilibrium with a saturated atmosphere is known as its *hygroscopic coefficient*. Such coefficients for six soil classes are shown in Table 35.

TABLE 35

WILTING AND HYGROSCOPIC COEFFICIENTS* OF SOILS (BRIGGS)

Soil Class	Wilting	Hygroscopic
Coarse sand	0.9	0.5
Fine sand	3.0	1.9
Sandy loam	5.6	4.0
Fine sandy loam	9.7	6.5
Loam	12.1	8.8
Clay loam	16.3	11.4

* Percentages of water calculated on dry weights of soil.

To recalculate the percentages shown in Table 35 to a volume basis requires use of factors lying between 1.25 and 1.75, depending on soil texture, the factor for clay loam being the smallest. Using the first factor, it is found that 20.4 per cent, by volume, of King's clay loam would have been occupied by water at the wilting point of plants. Thus the *available water* in the upper 3 feet of the clay loam soil mentioned in Table 34 may be only about one-third of its field capacity, or 4 acre-inches. Furthermore, a considerable portion of this available water may be lost by evaporation from the soil surface during the period of growth of crop plants. Experience has shown that even though the soil and subsoil may have contained their full field capacities early in the season, dry periods at some later date are quite likely to result in injury from drought.

ENERGY RELATIONS OF SOIL MOISTURE

It is now common practice to express soil moisture in terms of *pF* values. These are logarithmic values for tensions expressed in terms of the height, in centimeters, of a water column. The *pF* numerical values are the same as those used to express hydrogen-ion concentrations, or *p*H values. A *pF* value of 0 indicates tension equivalent to a column of water 1 centimeter high. Successive *pF* values of 1, 2, 3, and 4 represent tensions equivalent to 10, 100, 1000, and 10,000 centi-

meters of water, respectively. A *pF* value of 7 represents 10 million centimeters of water tension, which is equivalent to about 10,000 atmospheres negative pressure. The *pF* value of a soil at the oven-dry point is about 7, at the hygroscopic point about 4.5, at the wilting point about 4.2, and at the point of field capacity about 2.5.

Among the later techniques that have been employed for determining when extra water is needed by soil for which irrigation water is available is that involving the use of a *tensiometer*. This instrument consists of a porous cup that is sealed onto a manometer tube. The cup and part of the manometer are filled with water through a side opening, which is then corked and sealed. The water is in direct contact with the mercury column, the height of which fluctuates with the tension between the water in the porous cup and that in the soil. This instrument is useful only as long as the tension does not exceed 1 atmosphere, or a value of *pF*3. But this permits knowing when the available water has fallen to the point where its lack is beginning to be a limiting factor in plant growth.

WATER-MAINTAINING CAPACITIES OF SOILS

An important physical property of soils in relation to crop production is their *water-maintaining capacity*. Under any given climatic condition, some soils tend to maintain a relatively high content of water as compared to other soils. This tendency is related largely to texture, structure, content of organic matter, nature of the subsoil, and the depth to a temporary or permanent water table. That this water-maintaining capacity is often the determining factor in crop distribution is indicated by the fact that bluegrass grows most luxuriantly under conditions of a relatively high content of soil moisture, and tends to be replaced by weeds and poverty grass (*Danthonia spicata*) when the virgin humus supply has been exhausted. This also explains the better growth of bluegrass on the northern rather than the southern exposure of a high hill. It is commonly believed that chestnut trees grow only on noncalcareous sandy soils, but it has been shown that they grow equally well on the calcareous soils that overlie the Mammoth Cave in Kentucky. The moisture relationship rather than soil reaction is the important factor.

Explanation of the fact that some soils are better adapted to cereal crops and others to potatoes, truck crops, or grass may be found in this same moisture relationship. A suggestive classification of crops

according to their requirements as to the moisture-maintaining capacities of soils in which they grow best is given in Table 36. In this

TABLE 36

CROP ADAPTATIONS AND WATER-MAINTAINING CAPACITIES OF SOILS (WHITNEY)

Crop Adapted to Soil	Location, State	Water Maintained*
Truck crops	Maryland	6
Wheat	Maryland	13
Grass	Maryland	18
Light tobacco	Connecticut	7
Dark tobacco	Pennsylvania	18

* Percentage of dry weight of soil.

study, soil samples were selected to a depth of 1 foot each day during the growing season from fields in which crops known to be well adapted to the soil and climatic conditions were being grown.

RATE OF CAPILLARY-WATER MOVEMENT IN SOILS

The amount of water available to plants is determined not only by the field capacity of a soil and the extent to which evaporation is under control, but also by the rate at which this soil water moves toward the points at which it is being removed by plant roots. It is important also to note that the rate at which the roots grow out of the zone from which the available supply of water has been exhausted is also a factor. *Capillary* movement of water takes place in much the same manner as kerosene moves upward in a lampwick. The most rapid capillary movement of water is found in medium-textured soils of the loam and silt-loam classes. The total height to which water will rise above a water table is also greatest for these classes of soils. The most rapid rise for short distances is in sand, but the total height to which it will rise in such soils is very much limited. Both clay and sandy soils may be classed as dry soils, except under conditions of abundant rainfall or in situations in which the water table is not too far below the surface. Table 37 is of special interest in this connection in that it shows both the rate of flow and the total rise of capillary water in three classes of soil. The soils were placed in cylinders and uniformly compacted. The bottoms of the cylinders, in which the soil was retained by a fine screen, were then placed in water that was maintained at a constant level. In this test the soil was in an air-dry state and, as a result, the rate of flow was very much retarded.

TABLE 37

EFFECT OF TEXTURE ON RATE AND HEIGHT OF CAPILLARY RISE OF WATER*

Time	Height of Water in Inches at Periods Indicated		
	Sand	Silt loam	Clay
½ hour	13.5	7.3	5.4
1 hour	14.3	11.2	8.0
6 hours	16.6	26.6	15.5
12 hours	17.2	35.3	18.5
1 day	18.4	46.4	21.0
3 days	20.3	65.4	24.7
6 days	21.8	78.5	27.3
9 days	23.0	86.3	28.8
18 days	25.3	99.2	33.2

* Air-dried soils were used in these tests.

SOIL MULCHES

The rate of loss of water by evaporation from soils may be materially reduced if their surfaces are very thoroughly dried. This occurs naturally if sufficient time elapses between rains. But the time factor is important. In semihumid climates, the rate of drying of the surface soil is so rapid that cultivation to develop a *surface mulch* is of little value. In humid climates this may not hold true. In that event, it may be desirable to cultivate the soil as soon as possible after each rain.

The efficiency of the surface mulch in preventing loss of water from soils is indicated in Table 38. In this test, columns of soil, having depths of about 12 inches, were contained in evaporimeters, at the bottom of which water was added as fast as it was lost by evaporation.

TABLE 38

TONS OF WATER EVAPORATED FROM ACRE OF SOIL WITH AND WITHOUT MULCH* (KING)

Depth of Mulch	Clay Loam	Black Marsh	Sandy Loam
None	2414	588	741
1 inch	1260	355	373
2 inches	979	270	339
3 inches	889	256	287
4 inches	883	252	315

* Data for a period of 100 days.

Mulches were maintained by stirring the soil from time to time to depths of 1, 2, 3, and 4 inches, in much the same way as it might have been done in field practice.

Under the conditions of this test, water losses through surface evaporation were virtually cut in half by use of mulches. There has been considerable discussion of these and similar data in recent years because of discrepancies that seem to exist between the results obtained by such laboratory means and those obtained under certain field conditions. Failure to take into consideration the nature of the crop, the climate, the weather, and the soil, as factors that will determine whether or not moisture will be conserved by a soil mulch, is responsible for much of the confusion that exists on this subject.



FIG. 27. A surface mulch of soil formed by the first cultivation after the crop has been planted often greatly reduces loss of water by surface evaporation.

That a surface mulch may be important in conserving water in the field under some conditions is indicated by data from comparative tests at Cornell University (Table 39). In these tests cultivation was compared with scraping the soil only as much as was required to control weeds. Moisture determinations were made at 2-week intervals during the growing season. Definite loss of water was noted from cultivation of fallow soil in 1924, but conservation of water was effected in 1925. On the introduction of celery, a crop with a very restricted root system, cultivation resulted in positive conservation of water and in crop benefit every season. Apparently, the growing crop retards the drying-out of the soil by wind. In the event that the root system does not extend across the intervening space between the rows, considerable amounts of water can be conserved by cultivation.

TABLE 39

EFFECT OF CULTIVATION ON MOISTURE CONTENT* OF CROPPED SOILS (THOMPSON)

Crop Grown	1921		1922		1923		1924		1925	
	C†	S†	C	S	C	S	C	S	C	S
Beets	9.0	8.3	9.8	11.1	8.2	8.0	12.0	11.2	12.1	10.5
Carrots	8.7	8.2	11.1	11.5	9.0	8.0	13.1	12.3	12.7	11.7
Onions	8.7	8.2	11.2	11.2	9.5	9.4	12.0	11.2	11.9	11.4
Cabbage	10.0	9.6	15.2	14.6	10.5	10.6	11.1	10.3	11.4	10.5
Celery	10.1	8.8	13.5	11.7	10.8	8.6	10.8	8.6	10.4	10.0
Tomatoes	7.9	7.4	14.0	12.9	8.7	9.8	11.7	11.6	15.1	12.9
Fallow	...	...	15.3	14.9	10.3	10.4	11.6	13.2	13.8	12.2
Averages	9.1	8.4	12.9	12.6	9.6	9.3	11.8	11.2	12.5	11.3

* Average moisture content of soils (dry-soil basis) during crop seasons of years indicated.
† C = cultivated once each week during growing season. S = scraped with hoe when weeds appeared.

Whether cultivation will conserve water in a field where crops are growing depends on the nature of the top-growth of the crop, its root system, the humidity of the atmosphere, and the amount of water in the soil. If rain is followed by clear, hot weather with drying winds and the crop is not well developed, cultivation may be of little value. This is especially true following rains of ½ inch or less, when cultivation hastens loss of water. Of 280 moisture determinations in this test, the cultivated soil contained more water than the scraped soil in 188 cases. In this connection, it is important to note that the advantage in such tests is always with the scraped soil since, no matter how carefully the scraping is done to kill weeds, a light surface mulch is produced.

DEPTH OF PLANT-ROOT PENETRATION

Need for large amounts of available water in the soil a few inches below the surface becomes less as crop roots penetrate farther and farther into the subsoil. Light rains become less and less effective and surface mulches of less importance, since the available water is now largely that at lower levels, which has little chance to escape by capillarity past the widely spread root systems, with their masses of root hairs. It is probably because of this that cultivation tests with corn in humid climates have not yielded as good results as would have been expected from surface mulches.

Roots of many crop plants extend downward to depths of 3 feet or more if conditions in the subsoil are favorable for their development. In soils containing adequate supplies of nutrients, the most important factor in determining root depth is the moisture content of the soil.



H. C. Thompson, Cornell Agr. Exp. Sta.

FIG. 28. The root system of a half-grown carrot, in Dunkirk gravelly sandy loam soil.

In general, a relatively low moisture content in the plow-depth of soil favors a well-developed root system. This is especially true during the early period of crop growth. A moderately dry soil is much better than a relatively wet one for getting the crop under way and the roots deep into the soil.

Some idea of the relationship between top-growth and root-growth of crop plants may be obtained from Table 40, which shows the depths

TABLE 40

ROOT DEVELOPMENT OF CROP PLANTS (WEAVER)

Variety of Crop	Growth of Tops		Growth of Roots	
	Age, days	Height, feet	Depth, feet	Spread, feet
Oats — Swedish Select	63	3.0	6.8	1.3
Wheat — Marquis	93	2.7	6.7	1.3
Barley — Manchuria	84	2.3	6.3	1.3
Corn — Silver Mine	116	8.5	8.2	4.0
Potatoes — Early Ohio	94	2.3	4.7	2.1

of root penetration in the soil in Nebraska, Kansas, and Colorado, where no interfering subsoil conditions prevented their downward growth.

Some plants have relatively shallow root systems. If such plants are not xerophytic, they flourish only under conditions of frequent and abundant rainfall or irrigation, where the climate is cool and moist, or where a watertable is maintained relatively close to the surface by continued movement inward from surrounding higher levels. Advantage is taken of such differences in root systems in irrigated regions to kill weeds in old alfalfa stands, the alfalfa being the last to suffer from drought. Land that is difficult to drain and is continuously wet is quite commonly given over to shallow-rooted pasture grasses or to such crops as rice or cranberries.

The forces of gravity, transpiration, and evaporation operate to move water vertically in the soil. Differences in water content of soil areas in the same horizontal plane in any given cropped field of uniform soil are not likely to be very marked. This is indicated in the permanent grass plots at Rothamsted Experiment Station in England, where differences in the growth of grass and weeds are very sharply defined at the otherwise unmarked lines separating the several plots on which different fertilizers have been applied for the past century. This points to the desirability of thorough lateral distribution of liming materials, which need to be brought into contact with a large proportion of the soil. Lateral diffusion of dissolved material is too slow to be depended on.

OPTIMUM WATER CONTENT OF SOILS

Considered in relation to crop growth and microbiological activities, the optimum water content of soils is at about two-thirds saturation. Plants and microbes are not working at their highest efficiency during a large part of the time under ordinary soil conditions in humid temperate climates, since soil-moisture conditions vary between wide extremes. Droughts tend to hasten maturity of most crops, whereas abundant but not excessive moisture has much the same effect as nitrogen fertilizers in stimulating crop growth. It is a well-known fact that a good rain often stimulates nitrification to the point that as much extra nitrogen is made available as would have been supplied by a liberal application of such a fertilizer. Conversely, if plenty of fertilizer nitrogen has been supplied, an ordinary drought may cause little damage, the roots of the crops continuing to move rapidly downward to renewed supplies of water as the drought continues.

Working qualities of soils are at their best at about two-thirds saturation. A notable exception to this is found in sands, which, for best results, are worked in an overwet condition. The practical problem is that of meeting the requirements for working the various classes of soil that are often found in the same field. Furthermore, cultural operations cannot always be completed in a short enough period to take advantage of the most suitable moisture state. If soil in spots is overwet when worked, these spots will grow in size over the years until they become a very troublesome problem. Under conditions in which the subsoil is porous, a 2-ton-an-acre application of gypsum will often effect marked improvement in drainage of such wet spots.

WATER INFILTRATION

One of the most troublesome problems is that of avoiding water runoff as a result of crusting or the formation of some other type of relatively impervious layer on the surface of the soil. This water runoff is very troublesome because of its erosive effects, especially on long, steep slopes. It tends to carry away the soil itself, and oftentimes an abnormally large percentage of soil organic matter. Any soluble manure or fertilizer that may have been applied on the surface may be lost in the runoff. Such materials as finely pulverized limestone or rock phosphate may be carried away in suspension.

Several remedies can be applied to such situations. The most im-



FIG. 29. Organic mulches have the combined effect of reducing loss of water by surface evaporation and of increasing water infiltration following rains.



FIG. 30. By using a weedicide to kill old grass in a permanent pasture and then making use of a field cultivator that leaves the dead sod on top the ground, one can increase water infiltration and avoid serious erosion while a new seeding is getting established.

portant one is that of having the soil covered with some closely sown crop, the leaves of which break the fall of raindrops. For wide-rowed crops it is important that they be made to grow rapidly so as to develop a canopy at an early date. Another very effective system is that of having some kind of organic mulch on top the soil. This may be an applied mulch, such as is frequently used in orchards, or it may consists of crop residues that are left on top the soil, as in the trash-mulch system of farming. The rate of *infiltration* of water is greatly increased by such procedures, and much less trouble is experienced with drought. Earthworm holes are of considerable value in this connection. The number of earthworms in a farmed soil is largely determined by the amount of organic food at their disposal and the extent to which the soil has been adequately limed.

Much study is now being made of the possibility of growing row crops on land that has not been plowed. Only the soil along the row is sometimes prepared for planting, that lying in between being protected by whatever vegetative cover there may have been on the land. This growth between the rows can be controlled either by subsurface blades that cut off the roots or by the use of a small mower. Much interest in this subject has been developed in the more intensive corn-growing areas.

SOIL MANAGEMENT AND WATER CONTROL

As previously indicated, the available water supply in soils is of primary importance in determining crop yields. Successful soil management requires that much effort be expended in preventing lack of water from being a limiting factor in crop production. Tillage operations, crop canopies, trash covers, various types of mechanical-conservation measures, drainage, and irrigation are employed to keep the water supply at as near the optimum as possible. Soils in a low state of productivity often produce fairly satisfactory yields during seasons of favorable moisture conditions. But the practical problem is that of maintaining favorable moisture conditions during seasons of low rainfall. On a well-managed farm it is seldom necessary for crops to suffer serious injury either from drought or from standing water.

SELECTED REFERENCES

1. Bouyoucos, G. J. Classification and measurement of the different forms of water in the soil by means of the dilatometer method. Michigan Agr. Exp. Sta., Tech. Bull. 36, 1917.

2. Bouyoucos, G. J. A practical moisture meter as a scientific guide to irrigation practice. *Agron. J.*, Vol. 42, pp. 105–107, 1950.

3. Briggs, L. J., and H. L. Shantz. The wilting coefficient for different plants and its indirect determination. *U. S. Dept. Agr. Bur. Plant Ind. Bull.* 230, 1916.

4. Buckingham, E. Studies in the movement of soil moisture. *U. S. Dept. Agr. Bur. Soils Bull.* 38, 1907.

5. King, F. H. *Physics of Agriculture.* Published by the author. Madison, Wisconsin, pp. 129–203, 1907.

6. Olmstead, L. B., and W. O. Smith. Water relations of soils. *U. S. Dept. Agr. Yearbook*, pp. 897–910, 1938.

7. Richards, L. A., and C. H. Wadleigh. Soil water and plant growth. *Soil Physical Conditions and Plant Growth.* Academic Press, New York, pp. 73–251, 1952.

8. Thompson, H. C. Experimental studies of cultivation of certain vegetable crops. Cornell University Memoir 107, 1927.

9. Weaver, J. E., and Associates. Development and activities of the roots of crop plants. A study in crop ecology. Carnegie Institution of Washington, Publ. 316, 1922.

10. Weaver, J. E. *Root Development of Field Crops.* McGraw-Hill Book Co., New York, 1926.

11. Whitney, Milton. Some physical properties of soils in their relation to moisture and crop distribution. *U. S. Dept. Agr. Weather Bur. Bull.* 4, 1902.

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Soil Air

Carbon dioxide is absorbed by plant leaves and combined with water to form carbohydrates and related substances. During this process oxygen is released to the atmosphere. However, plants consume some of these synthesized products with the result that carbon dioxide is also excreted, notably by way of their roots. From this it is apparent that ventilation processes must be continuously in operation to effect repeated renewal of air at all points of its contact with plants. Otherwise, respiratory products will accumulate, growth will be retarded, and, finally, the plant may die. In the atmosphere this ventilation process is readily effected by winds and other types of air movement. In the soil it is not so readily accomplished.

As previously indicated, between 30 and 50 per cent of the soil volume is pore space. Part of this space is taken up by water and the remainder by air. As the quantity of water increases, rate of diffusion of air between atmosphere and soil is reduced. A point is finally reached at which addition of any more water to the soil may result in injury to the crop. If the soil on which the crop is growing is saturated for any considerable period, most of the plants will die. The cause of their death may be due to accumulation of carbon dioxide, deficiency of oxygen, or formation of reduced compounds of iron or manganese. It may be due to reduction of nitrates to nitrites or to loss of nitrogen in elemental form. It may be due to stoppage of bacterial processes that are essential to the growth of higher plants. It may also be that the crop is unable to obtain the essential mineral nutrients in adequate amounts from the soil.

OPTIMUM AIR SUPPLY

Ordinarily, optimum conditions for growth of crop plants obtain when about one-third of the pore space in the soil is occupied by air and two-thirds by water. The rate of diffusion of gases through soils is independent of their texture and structure, but is proportional to

the square of that part of their pore space that is occupied by air. Thus, if the air space is cut in half, the rate of diffusion of carbon dioxide from the soil to the atmosphere above it is reduced to one-fourth. As the diffusion process is slowed down, carbon dioxide may accumulate in the soil to the point where plant roots can no longer excrete this respiratory product from their roots. Meanwhile, anaerobic processes may have gained ascendency in the soil, with the results previously noted.

An interesting study of the effect of increasing the moisture and reducing the air supply in soils was reported by Greaves (Table 41).

TABLE 41

AIR AND WATER SUPPLY OF SOILS IN RELATION TO BACTERIAL ACTIVITIES* (GREAVES)

Percentage Saturation	Ammonia Production	Nitrate Accumulation	Nitrogen† Fixation
10	2	11	30
20	8	17	25
30	32	31	25
40	68	62	38
50	85	85	45
60	100	100	75
70	78	40	100
80	57	9	90
90	49	0	45
100	45	0	25

* Calculated in relative terms, the point of highest efficiency being given a value of 100.
† Nitrogen fixation by non-symbiotic bacteria.

Determinations were made of the rates of accumulation of ammonia and nitrates and of the rate of nitrogen fixation by nonsymbiotic nitrogen-fixing bacteria. Optimum conditions for ammonification and nitrification were found at 60 per cent saturation and for nitrogen fixation at 70 per cent saturation.

Much work has been done to determine the optimum moisture supply for crops grown under irrigation. The data recorded in Table 42 are of interest in this connection. Water was applied in these tests at weekly intervals during the growing season. The rainfall during the crop season amounted to 17.42 inches. Highest corn yields were obtained with 20 additional inches of irrigation water. It will be noted that the *law of diminishing returns* operates throughout the test, the number of bushels of grain for each inch of water falling from 4.35,

TABLE 42

THE CRITICAL POINT IN THE WATER SUPPLY FOR CORN (HARRIS)

Water Added, Acre-inches	Grain, Bu.*	Stover, Cwt.*	Bushels of Grain per Inch of Water
17.42†	75.9	78.4	4.35
22.42	91.4	89.7	4.08
27.42	92.5	85.0	3.37
37.42	99.1	97.1	2.65
47.42	95.7	95.4	2.02
57.42	90.0	90.0	1.57

* Six-year average acre yields with irrigation.

† This figure is the average yearly rainfall which occurred during the period of the experiment.

when no irrigation was practiced, to 1.57, following supplemental use of 40 inches of water.

AERATION OF CULTURE SOLUTIONS

If all the pore space in soils is filled with water, most crop plants are unable to survive. Yet it is common practice to grow a considerable variety of crop and ornamental plants in culture solutions. But need for aeration soon becomes apparent with these as well (Table 43).

TABLE 43

EFFECT OF AERATION OF CULTURE SOLUTIONS ON PLANT GROWTH (HALL)

Treatment	Weight in Grams per Plant	
	Barley	Lupines
Non-aerated	1.31	0.83
Continuously aerated	2.12	1.53

The standard procedure calls for continuous flow of air through the nutrient solution during the period while plants are growing in it. In lieu of this, experimental plants are often grown in sand culture to which the nutrient solution is applied drop by drop.

It must be admitted that conditions in culture solutions are far different from those to which crop plants are accustomed in their natural habitat. Nevertheless, it seems probable that even better effects from forced aeration would occur under field conditions if the soil became waterlogged. Such aeration would have the additional advantage that it would tend to overcome the tendency toward anaero-

bic bacterial decomposition and the production of reduced forms of iron and manganese.

Plants differ greatly in their requirements with respect to soil air and its renewal. Buckwheat, a crop plant that grows quite satis-



Fig. 31. Plowing and cultivating aerate the soil and stimulate bacterial action, with resulting loss of organic matter.

factorily on soils that are somewhat wet and acid, is not nearly as sensitive to such conditions as is barley. Redtop will grow on much wetter soil than timothy, and alsike and Ladino clovers grow much better on wet soil than red clover and alfalfa. Yet, if carbon dioxide is used to replace the air that is passed through culture solutions, all plants, including buckwheat, soon wilt.

COMPOSITION OF SOIL AIR

Soil air differs in composition from that in the atmosphere in that it contains somewhat less oxygen and much more carbon dioxide. The normal carbon dioxide content of the atmosphere is 0.03 per cent by

volume. Its concentration in soil air often exceeds 1 per cent. In exceptional cases it has been found to be as high as 15 per cent. The carbon dioxide content of soil air fluctuates considerably during the crop season, depending on soil and weather conditions, as they affect the activities of soil microorganisms and the growth of plants (Table 44).

TABLE 44

PERCENTAGE COMPOSITION OF THE SOIL AIR* DURING A YEAR (RUSSELL)

Date	Manured Plot		Unmanured Plot		Inches† Rain-fall	Degrees C.	
	CO_2	O_2	CO_2	O_2		Air	Soil
Feb. 11	0.55	18.97	0.13	19.86	0.60	8.3	....
Mar. 13	0.46	20.18	0.21	20.53	0.22	3.9	....
Apr. 14	0.65	19.70	0.22	20.64	0.68	1.7	....
May 13	1.45	19.42	0.35	20.53	0.56	10.5	11.1
June 3	0.42	20.56	0.50	20.77	0.35	13.9	17.4
July 11	0.35	20.66	0.29	20.79	0.42	15.0	15.5
Aug. 29	0.24	20.70	0.22	20.73	0.24	19.4	18.1
Sept. 22	0.17	20.79	0.11	20.83	0.52	14.4	13.3
Oct. 6	0.18	20.81	0.16	20.82	0.41	11.1	12.9
Nov. 10	0.54	20.72	0.35	20.56	0.21	5.0	6.5
Dec. 22	0.34	20.45	0.25	20.35	0.13	2.8	4.5

* Soil from Broadbalk Field, continuous wheat, at Rothamsted.
† During previous seven days.

Some investigators believe that the increased concentration of carbon dioxide that is found in soil air during the growing season is fairly closely correlated with the rate of growth of the crop. They believe it is definitely related to respiration of plant roots. The data in Table 44 seem to favor this conclusion. Thus, the wheat crop began to grow well in November, it was retarded during the colder weather of December and January, and it again came on rapidly during the spring, with maximum respiratory activity in May. Yet, soil microorganisms have a similar cycle of activity, with maximum and minimum points at about the same periods as those indicated by the percentages of carbon dioxide in the soil air.

SOIL AERATION AND PLANT GROWTH

Roothairs develop in abundance under conditions of adequate aeration, but they may be almost entirely absent in water-logged or poorly aerated soils. Absorption of water and soil nutrients takes place in large part through roothairs, the total surface of which is very large

in comparison with that of the roots alone. It is apparent, therefore, that a close relationship must exist between aeration conditions in soil and the rate of development of plants growing on it.

Subsoil air normally contains a higher percentage of carbon dioxide than does that of the topsoil. Subsoils are usually more compact, they contain larger percentages of water, and the rate of diffusion of gases



FIG. 32. One or two cultivations during the early period of growth of soybeans may have important effects as a result of soil aeration and moisture conservation.

through them is slower. It is because of this that root distribution is often largely confined to the plow depth of soil. Those roots that penetrate very compact layers of subsoil are probably not very efficient absorbers, except at occasional points of *macro pores*, which are much larger than those of capillary dimensions. These macro pores may be a result of earthworms burrowing or they may be openings left behind following decay of roots of a tree or some other large-rooted plant. At these points roothairs may develop in some abundance, but, for the most part, there are relatively few roothairs in compact subsoils. If deep-rooted crops can be made to grow on such soils, the channels left behind on decay of their roots pave the way for better functioning of roots of subsequent crops. The good effects of alfalfa and sweet clover may have their explanation in part in this fact. Earthworms, no doubt, are of considerable importance also in this connection.

One of the many explanations that have been offered for loss of productivity of soils under certain conditions is that plants excrete toxic substances from their roots. Both organic and inorganic toxins have been isolated from soils, but the question is as to their source of origin. They may have been excreted by plants, but it is probable that they are mostly by-products of *anaerobic decomposition* in the soil. Under conditions of inadequate aeration, the type of microorganisms that develop in the presence of organic matter are those that are able to obtain the necessary oxygen from the organic matter itself or from the oxidized forms of inorganic compounds. Thus, nitrates, sulfates, and oxides of iron and manganese tend to be reduced under such conditions, with the formation of nitrites, sulfides, ferrous iron, and manganous manganese. All these substances tend to be toxic to plants at relatively low concentrations. Such products are troublesome, particularly if large amounts of manure are plowed under deeply in a heavy soil that is a little too wet. A better procedure on such soils is to plow first, apply the manure, and then disc it into the topsoil. This permits more largely of aerobic decomposition, with better results in crop production. Insofar as is known, carbon dioxide is the only excretory product of plant roots that might accumulate in toxic concentrations in soil.

SIGNIFICANCE OF SOIL COLORS

The color of soils is closely related to aeration. In well-drained soils iron compounds are oxidized to the ferric state, which is indicated by reds, yellows, and browns. In the absence of good drainage, subsoil is greenish gray, or mottled, which indicates the presence of reduced forms of iron. Soil under a manure heap is usually bluish green. Reduction is brought about by anaerobic microorganisms acting in the absence of sufficient free oxygen to meet their needs. Peats, located in low-lying areas, are black or brown, depending on the nature of the decomposition that has taken place. On being drained, limed, and cultivated, brown acid peats turn black, at least throughout the plow depth.

Presence of reduction compounds in subsoils interferes with root growth. In fact, the tips of roots often turn brown and die under such conditions. Plants make use of small quantities of ferrous iron but, as the quantity available to them increases, toxicity effects are soon noted. Ferrous sulfate was formerly used as a spray to kill dandelions and other weeds.

Brown soils are of special interest in humid areas since they indicate high percentages of organic matter. Thus, a red or yellow soil can be changed to brown by additions of large amounts of organic matter. Under such conditions the plow depth of soil will be brown but the subsoil will usually be the natural red or yellow. A black soil in humid regions indicates a wet area. Such areas are found along streams or in low spots, where the soil maintains a relatively high content of moisture. This retards decomposition of any organic matter left on or in the soil in the form of plant residues. The underlying subsoils are often mottled.

The black *Chernozems* are of special interest, in that these soils were formed under conditions of limited rainfall. The native vegetation was grass rather than trees. Conditions were normally quite favorable for grass growth during the fall and early spring, with the result that large amounts of plant material was produced. But summers were relatively dry and hot, and this prevented such rapid decomposition of organic matter as would have occurred in humid regions. Thus the soils became black in the natural process of development and they so remain, even when put to agricultural use. In some areas erosion has removed the black soil down to the calcium carbonate zone in the *B* horizon and, in such areas, the soil material is grayish white. These marks of erosion can readily be seen when passing over the *Chernozem* soil region in an airplane, notably in Texas.

As one travels in the direction of the equator or the desert, the soil tends to take on brighter colors because of the higher degree of oxidation of the iron. Thus, *Laterites* and *Desert Soils* tend toward reds, yellows, and browns, except for the sandy deserts, which may have the natural gray of the rocks from which the surface material was derived. Naturally, many soils have inherited their colors from the rocks from which they originated. A red shale will produce a red soil, even though conditions during soil development were not particularly favorable for maintaining such a color. Red shales were formed from red clays deposited on the ocean floor. No reduction in their iron compounds could take place in the absence of organic-matter food for anaerobic microorganisms. Subsequently, when the resulting red shales were raised above sea level to again undergo disintegration, they gave rise to red soils, unless extensive reduction processes interfered.

MISCELLANEOUS SOIL-AIR RELATIONSHIPS

Seeds differ considerably in the oxygen required for their germination. Corn, oats, wheat, cabbage, melons, peas, and bean seeds are among those that germinate best under conditions of good soil aeration. Timothy, bluegrass, lettuce, carrots, white clover, red clover, sweet clover, and alfalfa will germinate under water, a condition in which the oxygen supply is confined to that dissolved in the water. White-clover seed have been germinated under water covered with paraffin oil, but they would not germinate in a vacuum. In general, the larger the seeds the greater the amount of oxygen required for their germination.

Bacteria are classified into three general groups, *aerobes*, *facultatives*, and *anaerobes*. In a manure heap the oxygen supply is abundant near the surface and very limited in the interior. Representatives of all three groups of microorganisms are found in such a heap. If the conditions are too strongly aerobic, *fire fanging* may occur. During this process most of the nitrogen will be volatilized. Anaerobic processes are primarily to be desired in a manure heap or compost pile since, under such conditions, cellulose materials are gradually decomposed without abnormal rise in temperature, and the processes of hydrolysis and mineralization are effected without loss of nitrogen through volatilization.

These same three groups of microorganisms operate in the decomposition of soil organic matter. Here, however, the end products are consumed by higher plants, which, for the most part, require their food materials in a highly oxidized state. If conditions were too anaerobic, as would be true if the soil contained excessive amounts of water or readily decomposable organic matter, then nitrates might be reduced to nitrites or to free nitrogen gas, sulfates might be reduced to sulfides, and ferric and manganic compounds might be changed to the ferrous and manganous states, with resulting injury to crop plants.

SOIL NITRATES

Ordinarily, nitrates are not produced in manure or compost piles. The nitrogen of proteins is released by hydrolysis as ammonium carbonate or closely related forms, and it may again be reconstructed into proteins in bacterial bodies. Meanwhile, the carbohydrate substances have largely been transformed into water and carbon dioxide. In

other words, the composting process is one of protein concentration. When manure or compost is added to the soil, the oxidation process is carried on more nearly to completion, with resulting production not only of more water and carbon dioxide, but of more nitrates, sulfates, and phosphates as well. Most crops utilize nitrates to better advantage than other forms of nitrogen, although considerable amounts of ammonia are absorbed as such.

It has frequently been observed, however, that any nitrate that may have been produced in or added to the soil will disappear from the soil under conditions of saturation with water, or of incorporation of large amounts of highly carbonaceous organic matter. Naturally, if the excess water referred to percolated through the soil and was carried away as drainage, the nitrate would disappear by that route, since all nitrates are readily soluble in water. But disappearance of nitrates can result also as a result of the *denitrification* process or through being consumed by the soil microorganisms affecting the decomposition of crude organic matter.

A number of species of bacteria have the capacity of liberating nitrogen gas from nitrates. The best-known member of this group is *B. denitrificans*. Laboratory tests show that nitrates disappear quite rapidly from soil that is saturated with water. This is one reason why ammonium sulfate rather than sodium nitrate is used as a source of nitrogen for rice. Denitrification may also occur as a result of the use of very large amounts of manure, even though it may have been well rotted before it was applied to the soil. Excessive evolution of carbon dioxide may develop anaerobic conditions in the soil. But loss of nitrogen because of this process is not believed to be very serious.

A considerably more troublesome problem is the loss of available soil nitrogen as a result of rapid decomposition of highly carbonaceous organic matter of low nitrogen content. Straw, cornstalks, grass sods, and sawdust are good examples of such materials. Most such materials contain less than 1 per cent nitrogen. They provide readily available carbohydrate food for microorganisms and, as a result, the microorganisms reproduce and multiply very rapidly. Soon they require more nitrogen than can be obtained from the organic materials themselves, and so they use any other form of available nitrogen at hand. This means very active competition with the roots of any crop plants that may be growing in the soil. Almost invariably the crop turns yellow, an indication of nitrogen deficiency.

There are several ways of dealing with this problem. One is to add enough fertilizer nitrogen to the organic material to raise the total to

2 per cent or more. This will provide enough nitrogen for the microorganisms and for the partial needs of the associated crop plant. A second method is to incorporate the organic matter into the soil some weeks in advance of planting the crop so that the decomposition process will have been largely effected and the extra microbial population will have begun to die off, thus releasing their own protein nitrogen for nitrification. A third procedure is to grow legumes for plowing under in association with these low-nitrogen types of organic matter. Thus, clover is often seeded in wheat or oats for plowing under with the straw left behind on the land by the combine.

EFFECTS OF CARBON DIOXIDE

Although excessive amounts of carbon dioxide in the soil may cause difficulty, yet organic-matter decomposition provides important supplies of carbon dioxide for use by plant leaves in carbohydrate production. Carbon dioxide is also an important agent for solubilizing soil minerals. One of the classic experiments revealed the etching effect of the carbon dioxide excreted from roothairs on a marble slab. Carbon dioxide serves also as a highly important buffering agent in soils for preventing bad effects from overacidity or overalkalinity. A very large part of the salts in the sea were carried there by rivers as carbonates of potassium, sodium, calcium, or magnesium. These carbonates were formed as a result of the action of carbonated water on the silicate minerals in the original igneous rocks.

The rate of evolution of carbon dioxide from soils under controlled conditions in the laboratory can be used as a means of determining the relative productive capacities of a group of soils. Effectiveness of liming materials and fertilizers can be estimated by measuring the increased evolution of carbon dioxide from the soil following their application to it. Similarly, rate of ammonia and nitrate production can be measured as a means of assaying soil productivity.

It is well to keep in mind that, unless the soil contains a liberal supply of organic matter, such tests are of little value. But the nitrogen and mineral needs of soil microorganisms are quite similar to those of plants. Bad effects from rapid decomposition of crude organic matter may result as much from lack of available phosphorus as from lack of available nitrogen. They may also result from unduly rapid reduction of iron and manganese compounds in the soil. This latter difficulty can usually be overcome by liming, which greatly reduces the solubility of these compounds.

It is possible to have a too rapid rate of aeration of soil, whereupon organic matter disappears so quickly that little can be retained in the soil. Such conditions obtain in sandy soils, which are also seriously



FIG. 33. A clover crop like this can be grown only on a well-aerated soil.

subject to losses of nitrates and other solubilized nutrients by way of drainage waters. But sandy soils can be made highly productive through repeated applications of green manures and well-rotted organic matter, together with extra water and frequent additions of supplemental soluble fertilizer elements.

SOIL MANAGEMENT AND AERATION

The oxygen supply of soils is renewed not only by diffusion but by ventilation processes resulting from changes in temperature and by movement of water in the soil. Thus, rain forces out old air, drainage pulls in new air, and water lost by evaporation and transpiration is



FIG. 34. A field cultivator breaking the crust and aerating the soil in a hop field at St. Paul, Oregon.

also replaced by atmospheric air. It is in the slowness of movement of water, particularly in fine-textured soils, that difficulty is experienced. Remedies are found in the use of tile drainage, growing of deep-rooted crops like sweet clover, and incorporation of very crude types of organic matter, such as tobacco stalks, corn stalks, brush, or clippings from trees. Deep plowing and *subsoiling* sometimes effect marked improvement. Use of dynamite has been suggested for breaking up pan formations. Something can be done by choice of crops for growing under such conditions.

Tests have shown that higher crop yields can be obtained in sand cultures than in solution cultures. The usual procedure in commercial sand culture is to flood the sand with the nutrient solution and then let it drain back into the storage tank. By repeating this process at suitable intervals, almost ideal conditions of aeration and nutrition can be developed. Tests of the nutrient solution will reveal such losses of nutrients as occur, and these can be replaced. Furthermore, the nutrient solution can be changed during the period of growth of the crop as fruit or flower production may require.

This points to the possibility that some improved means of aerating field soils might be developed. Specialists in grass production on golf greens are using an implement that removes small cylindrical plugs of soil as a means of introducing more air and permitting freer entrance of water in which fertilizer salts have been dissolved. Tree specialists often force air down into the soil around valuable shade trees in congested city areas. Considerably more work needs to be done toward exploring the many possibilities that exist in opening up field soils, to the end that better movement of air and water and better growth of roots are effected. The various means by which soil aggregation can be improved merit more detailed study in this connection.

SELECTED REFERENCES

1. Arnon, A. I., and D. R. Hoagland. Crop production in artificial culture solutions and in soils with special reference to factors influencing yields. *Soil Sci.*, Vol. 50, pp. 463–483, 1940.

2. Clements, F. C. Aeration and air content. The role of oxygen in root activity. Carnegie Institution of Washington, p. 183, 1921.

3. Greaves, J. E. The influence of irrigation water on the composition of the soil. *J. Am. Soc. Agron.*, Vol. 14, pp. 207–212, 1922.

4. Hall, A. D., and Associates. The soil solution and the mineral constituents of the soil. *Phil. Trans.*, Vol. 204, pp. 179–200, 1913.

5. Harris, F. S., and D. W. Pittman. Irrigation and manuring studies II. Utah Agr. Exp. Sta., Bull. 154, 1917.

6. Morinaga, T. Germination of seeds under water, etc. *Boyce Thompson Inst. Plant Res.*, Vol. 1, pp. 67–100, 1926.

7. Russell, E. J., and A. Appleyard. The atmosphere of the soil, its composition and the causes of variation. *J. Agr. Sci.*, Vol. 7, pp. 1–48, 1915.

8. Russell, M. B. Soil aeration and plant growth. *Soil Physical Conditions and Plant Growth*. Academic Press, New York, pp. 253–301, 1952.

9. Turpin, H. W. The carbon dioxide of the soil air. Cornell Agr. Exp. Sta., Mem. 32, pp. 319–362, 1920.

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Soil Solutions

For satisfactory growth of plants in culture solutions, it is necessary to control, within relatively narrow limits, total salt concentration, reaction, and ratios in which nitrogen and mineral nutrients are present. These requirements must also be met in a soil if it is to be productive. Unfortunately, it is difficult to determine the exact nature of the solutions with which roots of plants are bathed in soil. Various methods of displacement have been employed and, as a result, some idea of concentrations, reactions, and nutrient ratios has been gained. But there is a fundamental difference between soil solutions and culture solutions. The soil solution is in direct contact with the undissolved but slowly dissolving mineral complex. This tends to renew the solution as nutrient elements are removed from it by plants. Furthermore, roothairs adhere very closely to soil particles. The concentration of the solution that immediately surrounds these particles may be quite different from that of the main body of soil solution.

SALINE SOILS

In regions in which rainfall is so limited that loss of water through drainage is virtually negligible, substances dissolved from the soil may accumulate in the form of soluble salts. These dissolved salts may not result in the development of *saline soils* until irrigation is practiced, or except as water from surrounding higher levels may come to the surface and be lost to the air by evaporation. In whatever manner these salts may accumulate, they tend to form a grayish-white crust over the soil surface. This crust consists largely of carbonates, chlorides, sulfates, and nitrates of sodium, potassium, calcium, and magnesium (Table 45). Relative amounts of these salts vary considerably from place to place.

Accumulations of these salts interfere with plant growth because of abnormally high concentration, high alkalinity, or unfavorable ratios in which the several elements are present. If the salts are

TABLE 45

THE MOST COMMON SALTS IN SALINE AND ALKALINE SOILS

Neutral		Alkaline	
KCl	NaCl	K_2CO_3	$CaCO_3$
K_2SO_4	$MgSO_4$	Na_2CO_3	$Ca(HCO_3)_2$
Na_2SO_4	$MgCl_2$	Na_2HPO_4	$Mg(HCO_3)_2$
$NaNO_3$	$CaCl_2$	$NaHCO_3$	$(NH_4)_2CO_3$

largely sulfates and chlorides, the surface incrustations are white, or nearly so. If sodium and potassium carbonates are present in con-



FIG. 35. A large salt deposit at Searles Lake, California, that is now being worked for potash by the American Potash and Chemical Corporation.

siderable amounts, the soil becomes brown or black as a result of the presence of soluble humates. This *black alkali* is toxic to plants at much lower concentrations than *white alkali*, since it has the additional troublesome property of high alkalinity.

Plants differ greatly in their capacities to endure salinity. Alfalfa, sweet clover, millet, sorghum, rape, barley, rye, sugar beets, and cotton are among the most tolerant crops. Date palms and grapes also belong to this group. The capacity of a plant to withstand these soluble salts

depends not only on their concentration, ratios, and reactions, but also on their distribution in the soil profile. Deep-rooted plants may grow satisfactorily if the salts are concentrated on the soil surface, whereas shallow-rooted crops grow best when the salt deposits are located a considerable distance below the surface.

CONTROL OF SALINITY

Methods of control of excess salts depend upon their nature and the location of the land, with reference to supplies of irrigation water. With black alkali, applications of sulfur and calcium sulfate, plus extra water, may suffice. Sulfur, when oxidized by soil microorganisms to sulfuric acid, neutralizes the alkalinity. Calcium sulfate reacts with sodium carbonate, the most common alkaline salt, to produce the much less soluble calcium carbonate and sodium sulfate. The latter can be leached out of the soil by heavy irrigation and drainage. If salt deposits have accumulated on the soil surface, they may be removed by scraping or they may be plowed under very deeply with large plows specially designed for this purpose.

It was only after irrigation has been practiced for some years that saline deposits appear in many areas. Soluble salts, which may previously have been deposited at lower depths or which may have been fairly well distributed throughout soil and subsoil, are carried upward in capillary water and left as deposits on the surface, as this water is lost by evaporation. Such quantities of these salts as can be tolerated by crop plants when the soil is at optimum water content become injurious as the moisture percentage is reduced by evaporation and transpiration between irrigations. For these reasons, it is necessary to consider the time and rate of application of irrigation water. It is important also to take such measures as will reduce loss of water by surface evaporation. *The problem of saline soils is much more difficult of solution than that of acid soils.* But the area over which salt deposits are limiting factors in crop production is much less than that included in humid regions, where acid soils are the general rule.

ACID SOILS

In humid regions the soluble salts that are formed during decomposition of soil minerals are gradually carried away by drainage waters. Their accumulation is thus prevented. Evidence of their long-continued removal from the land is found in enormous deposits of lime-

stone, common salt, and potash salts that are widely distributed over the earth. The nature of the salt in ocean water, from which these deposits originated, is of interest in this connection. The total salt content of the ocean has been estimated as being sufficient to cover the entire surface of the United States, including Alaska, to a depth of 1.6 miles. The average salinity of ocean water is about 3.5 per cent. These salts contain the several cations shown in Table 46. Sodium

TABLE 46

CATIONS AND ANIONS IN SEAWATER *

(In Order of Abundance)

Cations	Anions
Na	Cl
Mg	SO_4
Ca	CO_3
K	Br

* Large deposits of $CaCO_3$ and other relatively insoluble salts have been precipitated and deposited on the ocean floor.

is the dominant cation, constituting 30.26 per cent of the total salt content. Chlorine is the dominant anion, constituting 55.18 per cent. A large part of the calcium and magnesium in the original runoff and drainage waters has been and is being precipitated.

Ocean sediments are very rich in calcium and magnesium carbonates, of which it is estimated that over 2 billion tons are being deposited annually. Nodular deposits of manganese oxide, phosphate, and potassium-bearing glauconite are widely distributed over the ocean floor. It is important to remember that *all the available limestone and phosphate deposits, which are of such tremendous importance for replacement purposes in farmed soils, have long since been elevated from the level of the ocean floor to that of dry land, where they are now accessible for use.*

Continuation of the leaching process that takes place during soil formation in humid climates results in accumulation of a relatively insoluble soil residue. This consists mostly of silicon, aluminum, and iron, in the form of their oxides or silicate combinations of these oxides. The silicates still contain sufficient percentages of slowly soluble sodium, potassium, calcium, magnesium, and other elements to meet the requirements of natural vegetative cover. Decay of plant residues, with resultant production of carbonic, nitric, and sulfuric acids, hastens the solution process.

NATURE OF SOIL ACIDS

Gradual removal from humid-region soils of their basic elements has resulted in accumulation of a potentially acid residue. *The average soil of humid temperate regions is made up of about 80 per cent silica, 8 per cent alumina, 3 per cent iron oxide, 4 per cent sodium, potassium, calcium, and magnesium oxides, 1 per cent titanium oxide, 1 per cent all other oxides, including about 0.1 per cent each of phosphorus pentoxide and sulfur trioxide, and 3 per cent organic matter.* Some idea of the nature of the silicate residues in such a soil can be obtained from studying the outline of processes involved in and end-products resulting from weathering of orthoclase, one of the primary soil minerals (Table 47).

TABLE 47

STAGES OF WEATHERING OF ORTHOCLASE (VAN HISE)

$2KAlSi_3O_8 + H_2O + CO_2$	$= K_2CO_3 + 2HAlSi_3O_8$	(" orthoclasite ")
$2HAlSi_3O_8 - SiO_2$	$= H_2Al_2Si_4O_{12}$	(pyrophyllite)
$H_2Al_2Si_4O_{12} + H_2O - SiO_2$	$= H_4Al_2Si_2O_9$	(kaolinite)
$H_4Al_2Si_3O_9 - 2SiO_2$	$= H_4Al_2O_5$	(bauxite)
$H_4Al_2O_5 + H_2O$	$= H_6Al_2O_6$	(gibbsite)
$H_4Al_2O_5 - H_2O$	$= H_2Al_2O_4$	(diaspore)

By application of petrographic and X-ray techniques, it has been shown that residues of primary minerals, of which orthoclase is an example, consist of definitely crystalline secondary clay minerals. Of these, the best known are *kaolinite, montmorillonite,* and *illite.* Crystal lattices of the kaolinite group, with a general formula $Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$, are made up of one sheet of silica to one of alumina. Those of the montmorillonite and illite groups, with a general formula $Al_2O_3 \cdot 4SiO_2 \cdot 5H_2O$, contain two sheets of silica to one of alumina. Kaolinite and illite lattices are fixed. Those of montmorillonite are of an expanding type, subject to a high degree of hydration and reactivity, both on the surface and within the crystal. The primary silicate minerals, still remaining in the silt and coarser soil separates, exist largely as central cores in the particles. These particles are surrounded by colloidal films of secondary clay minerals and by hydrous oxides and humates of iron and aluminum.

Climate is the dominant factor in determining the nature of the decomposition products of primary minerals. Thus, kaolinite is most prominent in Laterites and illite and montmorillonite in Podsols,

Chernozems, and Desert Soils. These secondary clay minerals, and the associated humates, have such low solubilities that they cannot develop any very high degree of active acidity.

INTENSITY FACTOR IN SOIL ACIDITY

The acids of acid soils are largely secondary silicates, of which kaolinite is a typical example. These silicates are virtually insoluble in water. Their acidity, therefore, is largely *potential* rather than *active*. In fact, soils in humid regions have base-adsorbing capacities long before their solutions become acid. The soil, meanwhile, is being bathed with water containing carbonic, nitric, and sulfuric acids, originating in the decomposition of organic matter. Additional nitric acid is contributed by nitrification of the extra nitrogen accumulated by nitrogen-fixing bacteria. As these acids develop increasingly acid soil solutions, more iron and aluminum dissolve, often to the point of toxicity to crop plants. Similarly, soluble manganese may accumulate in toxic concentrations in these acid soils.

In peat soils, larger amounts of humic acids are found. Some of the simpler organic acids, such as butyric, lactic, and acetic acids, may also be formed during decomposition of the peat, once it is put under cultivation. In addition, the usual carbonic, nitric, and sulfuric acids will be formed in somewhat larger amounts than in inorganic soils. Humic acids, like acid silicates, are virtually insoluble in water. Acid peat soils often have very high base-adsorbing capacities, much higher than those of equal weights of inorganic soils.

In acid soils, therefore, both *acid intensity* and *base-adsorbing capacity* are involved. The acid intensity determines the type of plants that can be grown in the soil as it is. This intensity is a product of the solubility of the acid and its degree of ionization. The important factor is the hydrogen ion, or what is known as the hydrogen-ion concentration of the soil solution. This is usually expressed in terms of *p*H values, which are negative logarithmic values of hydrogen-ion concentrations expressed in terms of grams in 1 liter of solution. These *p*H values normally lie between 1 and 14 and, for soil solutions, mostly between 4 and 8. A *p*H value of 7 indicates a neutral solution, containing 0.0000001 gram of hydrogen ions, and equivalent amounts of hydroxyl ions, in 1 liter. Acidity increases with lowering of *p*H values below 7 and decreases as *p*H values rise above 7. *Since pH values are logarithmic, a soil with a pH value of 5 is 10 times as acid as one*

having a pH value of 6. This means that it has 10 times as many hydrogen ions and only one-tenth as many hydroxyl ions.

The base-adsorbing capacity of a soil has no necessary connection with its *p*H value. It is mostly determined by the amount of clay and organic matter in the soil. The usual corrective for acid soils is limestone, either in pulverized, burned, or hydrated form. The amount of limestone, expressed in terms of pure calcium carbonate, required to raise the *p*H values of plow depths of 1 acre of 20 important New Jersey soils from 4.5 to 6.5 was found to vary between 550 and 7400 pounds. The lower value was for Sassafras sand and the higher value for Penn silt loam. Several times this higher amount might be required to raise the *p*H value of the same weight of peat from 4.5 to 6.5. But the weight of the plow depth of an acre of peat is much less than that of the same volume of mineral soil.

CONTROL OF SOIL ACIDS

With increase in soil acidity, such plants as alfalfa, sweet clover, lettuce, spinach, onions, beets, and cabbage may not grow well until



FIG. 36. Modern distributor for applying limestone as a corrective for acid soils.

lime has been applied as a corrective. With further increase in acidity, it becomes necessary to substitute less and less desirable crops, until a point is reached at which few of those commonly grown will thrive. The cause of this loss of soil productivity may lie in the development of toxic concentrations of hydrogen, aluminum, iron, and manganese ions. It may be due to the slow rate of nitrification of the nitrogen

in soil organic matter or of that added in the form of ammonium salts. Similarly, the nodule bacteria of many important legumes are very sensitive to soil acidity, and this applies to *Azotobacter* as well.

The most common method of controlling acidity of soils is by use of pulverized limestone. Draining a wet, acid soil may result in reducing its acidity. Certain fertilizer materials, notably basic slag and calcium cyanamide, leave alkaline residues in the soil. Incorporation of large amounts of well-decomposed organic matter serves to *buffer* soil acidity, thereby preventing development of extremely low *p*H values. It is also possible to choose crops that are not especially sensitive to acid-soil conditions. Among such crops are potatoes, soybeans, sweet potatoes, oats, rye, alsike clover, redtop, bentgrass, peanuts, watermelons, cotton, lespedeza, and blueberries. Fortunately, *soluble acids do not accumulate to any large extent in acid soils, since the water that carries away basic carbonates also removes any soluble acids.*

CULTURE SOLUTIONS

In saline soils the problem is one of excessive salt concentration and often of too high alkalinity as well. In acid soils the acid reaction of the soil solution is the primary limiting factor in crop growth. But even if both concentration and reaction of the soil solution were satisfactory, there still remains the problem of the ratios in which the several nutrient ions are yielded up to crop plants. It has been shown that ammonium, magnesium, sodium, and potassium ions, in the order named, are injurious to plants when supplied singly, as salts, to nutrient solutions in which plants are being grown. These injurious effects can be overcome by addition of other salts, of which those of calcium are the most effective. One of the difficulties appears to be that, in the absence of calcium, permeability of cell walls of plants is greatly altered, sometimes to the point where the protoplasmic contents may be lost to the nutrient solution. The other elements are of little use to the plant unless enough calcium is present to permit the construction of the necessary cell walls.

Widespread use of culture solutions for studying plant requirements finally led to consideration of their possibilities in practical agriculture. Most of the common plants can readily be grown to maturity and made to produce flowers and fruits in marketable quantities without use of soil. Large-scale production of carnations, roses, chrysanthemums, tomatoes, cucumbers, and a number of other plants is being carried on. Such water-culture systems, called *hydroponics*, have even been ap-

plied to production of potatoes, wheat, and corn. In the more modern form, use is usually made of beds of sand, gravel, cinders, or soil for anchoring the plant roots. An example of the type of solution used for such purposes is shown in Table 48.

TABLE 48

NUTRIENT SOLUTION FOR PLANTS GROWN IN WATER CULTURE (WITHROW)

Salts (Fertilizer-grade Chemicals)	Pounds	Ounces
Magnesium sulfate (anhydrous)	0	9
Treble superphosphate (0–48–0)	1	6
Potassium nitrate (13–0–44)	9	12
Calcium sulfate (gypsum)	6	10
Ammonium sulfate (10–0–0)	1	4
Total in 1000 gallons of water	19	9

In addition to ordinary fertilizer salts, it is necessary to make supplemental use of the essential trace elements, of which iron, manganese, copper, zinc, boron, and molybdenum are known to be the most important (Table 49). The quantities of these that must be added de-

TABLE 49

TRACE ELEMENTS REQUIRED FOR CULTURE SOLUTIONS

Element	Quantity, P.p.m.*	Element	Quantity, P.p.m.*
Fe	1.00	Zn	0.10
B	0.25	Mo	0.01
Cu	0.01	Mn	0.25

* These quantities can often be changed to advantage for individual crops and sets of conditions.

pend on the impurities in the salts employed in making up the nutrient solution containing the major nutrient elements. Sometimes, sufficient amounts of most or all the trace elements except iron may be present in the major-element solution.

In sand or gravel culture, the plant-anchoring materials are placed in watertight beds having a depth of 10 to 12 inches. The nutrient solution is pumped into these beds and allowed to drain through them into a receiving pit. This drainage is required for aeration purposes. The nutrient solution can thus be used over and over again by automatic controls, supplemental additions of the several nutrient elements

being made as chemical tests indicate need for them. The *p*H value of the solution is kept under control by use of acids or alkalies, as required. Both the quantities and ratios of the several salts in the nutrient solution can be varied, depending on the crop being grown, kind of weather, time of year, and age of plants.

Production of plants without use of soil has grown to considerable proportions, notably of roses and carnations and expensive winter vegetables. There are a number of advantages in such a method of intensive production of crop plants. The nutrient concentrations and ratios can be altered at will. Flowering and fruiting can be advanced or delayed, depending on market demands. Diseases can be more readily controlled. In proportion as more exact knowledge of the needs of the more valuable crop plants is developed, use of sand or gravel culture can be expected to increase, in greenhouse production in the colder climates and in the open in warmer regions.

SOIL SOLUTIONS IN HUMID CLIMATES

Composition of nutrient solutions is of special interest in connection with studies of solutions extracted from soils. To obtain such solutions from soils, use has been made of alcohol, oil, and even water itself as displacing agents. As previously indicated, there is considerable doubt whether the solutions thus displaced from the soil are actually the same as those with which plant roots and roothairs are in contact. The part of the solution in most intimate contact with soil particles may not be displaced. There is no way of knowing the rate at which any element that is absorbed by plant roots from the soil solution is replaced from the soil itself. Nevertheless, knowledge of such solutions is of value for comparative purposes in relation to variation in known productivities of various soils. Data given in Table 50 are of interest in this connection. The water extractions there shown were obtained from soils of the same series and type but of different degrees of productivity.

In addition to the elements listed in Table 50, soil solutions contain varying amounts of chlorine, sulfate, and carbonate ions and of the several trace elements. In acid soils, iron, aluminum, and manganese may be found in considerable quantities. In general, one is impressed with the low concentrations of the nutrient ions in these soil extracts. To calculate the values shown in terms of pounds an acre to plow depth, one has only to multiply the figures by two. It is important

TABLE 50

WATER EXTRACTS OF SOILS* IN RELATION TO THEIR PRODUCTIVITIES (BURD)

Productivity		Seasonal Averages of Water Extracts — Parts per Million				
General	Barley†	K_2O	CaO	MgO	P_2O_5	NO_3
Good	88.4	57	127	40	12	146
Good	86.5	48	48	38	5	131
Good	84.0	66	52	25	3	120
Medium	70.4	54	118	43	7	141
Poor	56.2	52	45	23	5	88

* Silty clay loam soils of the same series.
† Yield in bushels per acre.

to keep in mind that *the soil solution is in contact with the soil's mineral complex, which tends to renew the supplies of nutrient elements as they are removed by plant roots or lost in drainage water. The rate at which such renewal takes place is an important factor in determining the productivity of a soil.*

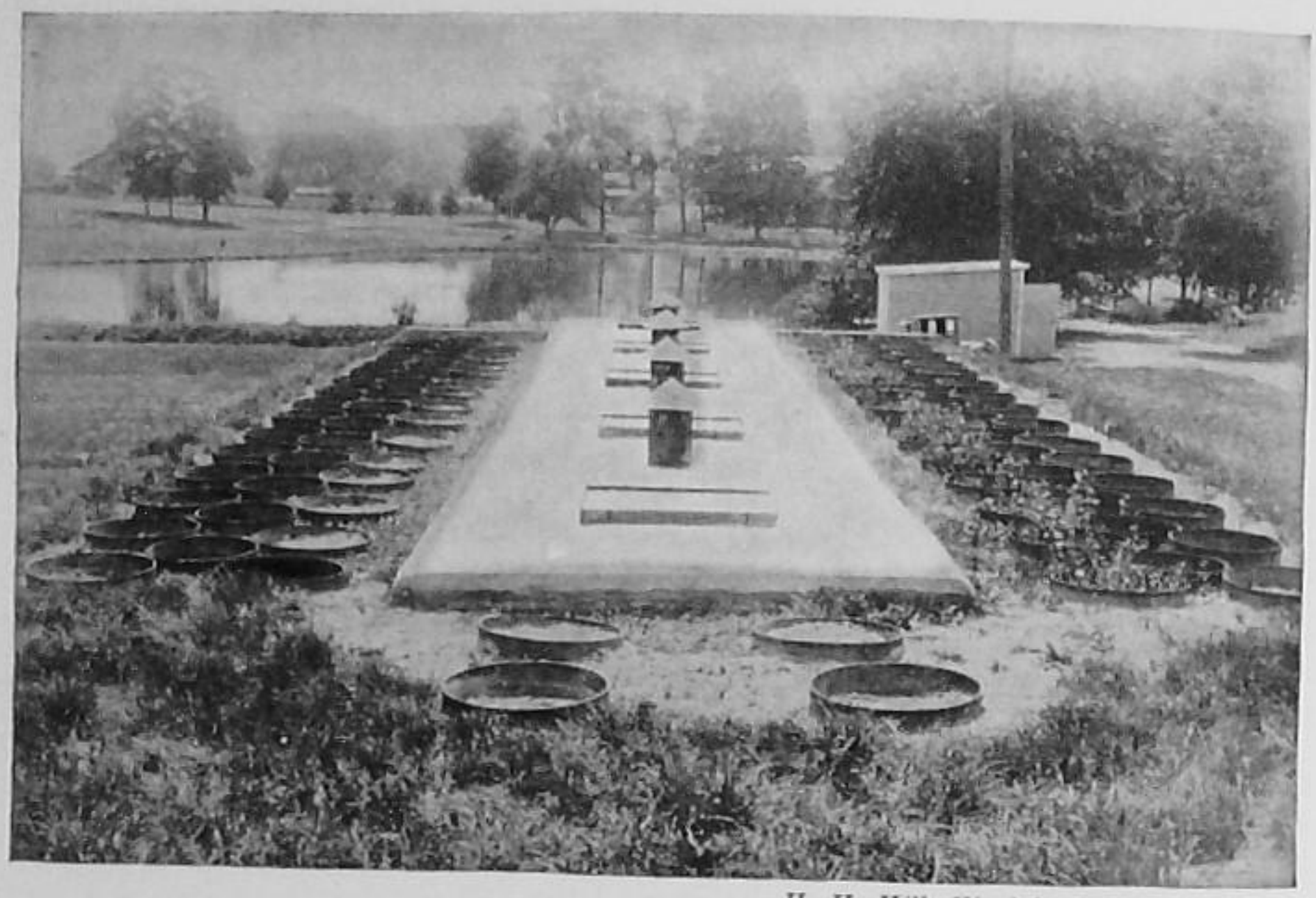
One might think that analyses of soils for their total content of the essential nutrient elements would be highly important in this connection. But it is doubtful whether such analyses are particularly useful in determining either present or potential productivity of most soils. Once the Great Soil Group, series, and type of a soil are known, together with the general facts as to its mineralogical, chemical, and textural properties, further complete analyses of samples from various fields of such soil are of little value. This is apparent from a study of the data shown in Table 51, in which complete fusion analyses are

TABLE 51

COMPARISON OF VARIOUS METHODS OF ANALYSIS OF SOILS (BURD)

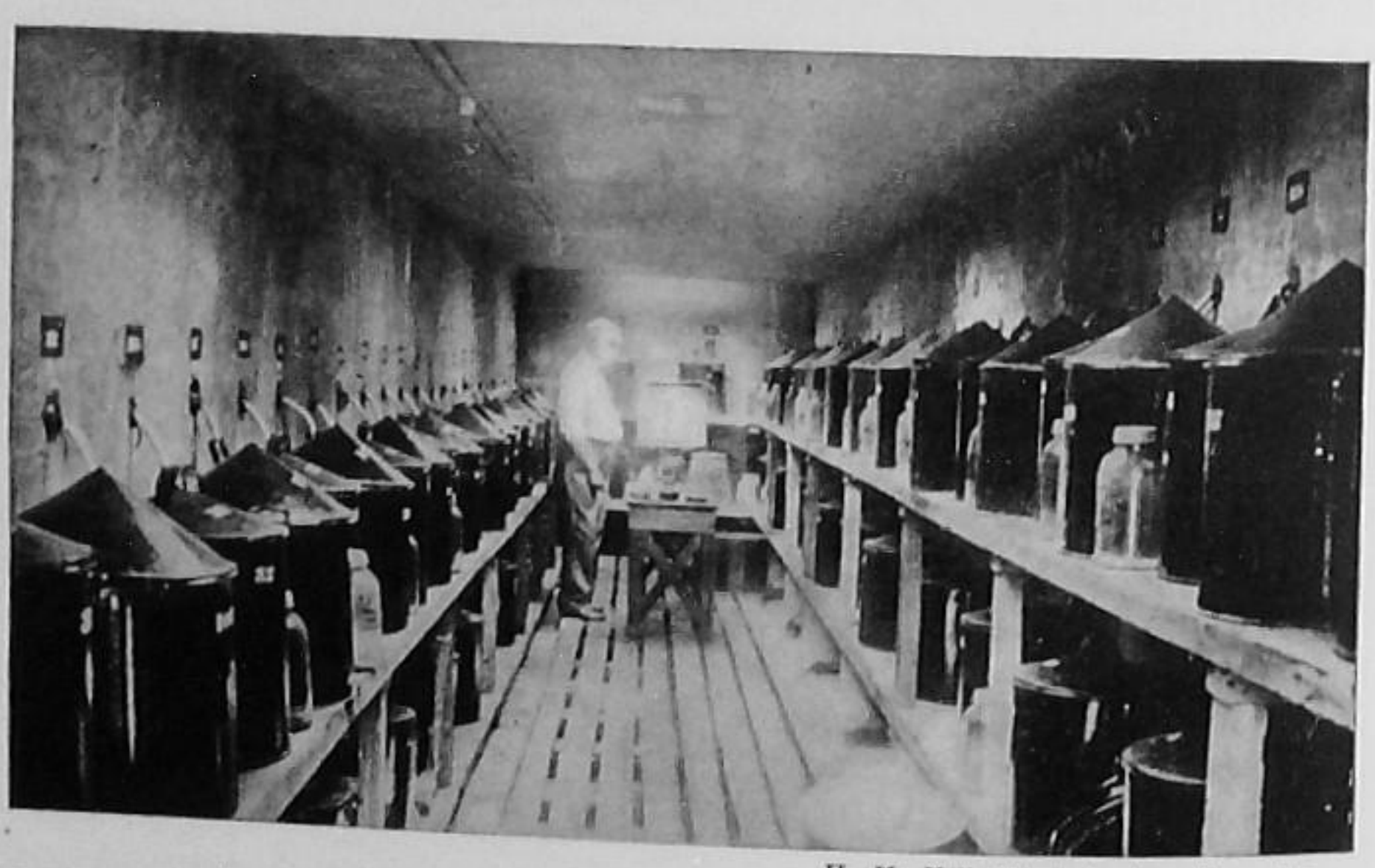
Percentages of	K_2O	CaO	MgO	P_2O_5	NO_3
Good Soil:					
Complete analysis -- fusion	1.98	1.48	2.66	0.23	....
Acid digestion — HCl 1.115	1.05	1.43	2.46	0.22	....
Acid extraction — 1% citric	0.04	0.45	0.22	0.10	....
Water extractions — p.p.m.*	57	127	40	12	146
Poor Soil:					
Complete analysis — fusion	1.85	1.50	3.57	0.21	.....
Acid digestion — HCl 1.115	0.89	1.48	3.32	0.20	....
Acid extraction — 1% citric	0.04	0.42	0.14	0.07	....
Water extractions — p.p.m.*	52	45	23	5	88

* Seasonal averages.



H. H. Hill, Virginia Agr. Exp. Sta.

FIG. 37*a*. The lysimeter method of study (view above ground).



H. H. Hill, Virginia Agr. Exp. Sta.

FIG. 37*b*. View of interior cave, lysimeter method of study shown in Fig. 37*a*.

compared with results from acid digestions and water extractions of good and poor soil. The data from water extractions appear to be most significant.

SOIL MANAGEMENT IN RELATION TO SOIL SOLUTIONS

Although it is possible to determine what constitutes an optimum culture solution for crop plants when they are grown in water or sand cultures, such information is of little value for field application. Soil tends to exercise precipitation and adsorption effects that immediately alter the concentrations and ratios of the ions in any nutrient solution that may be applied to it. But a large part of a farmer's efforts have to do with the problem of controlling the soil solution within such limits as are required for production of optimum yields. Manures, cover crops, liming materials, fertilizers, and cultivation operations all influence the composition of the soil solution.

Correct interpretation of any effects noted as a result of these or any other practices, whether good or bad, must take into consideration the effects they may have had on the concentration, reaction, and ion ratios of the soil solution. Sulfate of ammonia is used as a source of nitrogen on soils, but it also affects the soil reaction. Superphosphate supplies phosphorus, calcium, and sulfur to soils, but it also precipitates soluble aluminum and iron, and possibly some of the trace elements, notably zinc. Limestone is used to neutralize soil acids, but it may carry both magnesium and calcium, one or the other of which, notably magnesium, may be deficient in the soil. The sodium of nitrate of soda may be as important as the nitrate under some conditions as to soil and crop. A large part of soil research has for its purpose the determination of the concentration and reaction of the soil solution, its rate of renewal by the soil, and the influence of soil amendments on it.

Consideration must also be given to the soil below plow depth. Conditions in soil and subsoil may differ greatly. They may be such as to favor as good growth of roots in the subsoil as in the plow depth of soil, or they may be quite the contrary. In general, subsoils of humid regions are more acid and more compact than the plow depths. More attention is being paid to aerating such subsoils and introducing liming materials. As rates of application of both liming materials and fertilizers increase, there is marked tendency to plow larger amounts of them under in well-drained soils. *In proportion as conditions in the subsoil can be made more favorable, plant roots tend to penetrate*

to greater depths, thus tapping additional supplies of nutrients and water.

SELECTED REFERENCES

1. Burd, J. S. Chemical criteria, crop production, and physical classification in two soil classes. *Soil Sci.*, Vol. 5, pp. 405–419, 1918.

2. Byers, H. G., and Associates. General chemistry of the soil. *U. S. Dept. Agr. Yearbook*, pp. 911–928, 1938.

3. Clarke, F. W. The data of geochemistry. *U. S. Geol. Survey, Bull.* 770, pp. 122–155, 1924.

4. Harris, F. S. *Soil Alkali.* John Wiley & Sons, New York, 1920.

5. Hartwell, B. L., and F. R. Pember. The presence of aluminum as a reason for the difference in the effect of so-called acid soil on barley and rye. *Soil Sci.*, Vol. 6, pp. 259–279, 1918.

6. Kelley, W. P. The reclamation of alkali soils. California Agr. Exp. Sta., Bull. 617, 1937.

7. Parker, F. W. Methods of studying the concentration and composition of the soil solution. *Soil Sci.*, Vol. 12, pp. 209–232, 1921.

8. Shive, J. W., and W. R. Robbins. Methods of growing plants in solution and sand cultures. New Jersey Agr. Exp. Sta., Bull. 636, 1939.

9. Thorne, D. W., and H. B. Peterson. *Irrigated Soils, Their Fertility and Management.* The Blakiston Co., Philadelphia, pp. 46–82, 1949.

10. Van Hise, C. R. Treatise on metamorphism. *U. S. Geol. Survey, Monograph* 47, 1904.

11. Withrow, R. B., and J. P. Biebel. Nutrient solution methods in greenhouse crop production. Indiana Agr. Exp. Sta., Circ. 232, 1938.

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Control of Soil Water

One of the most important problems in soil management is that of regulating the water supply for plants within limits that result in the production of as high acre yields as other conditions permit. In humid regions, special consideration must be given to increasing water intake of soils and then to draining off any excess that may tend to accumulate in them. In arid regions, lack of water is the most seriously limiting factor in crop production. Under such conditions, irrigation is of primary importance. But whether water has been supplied by rain or irrigation, its conservation is essential. Such practices as cultivating, accumulating organic matter, and choosing the type of crop best adapted to the moisture supply merit special attention. It is important to note that irrigation is now in operation on a large scale in humid regions of eastern United States, and that artificial drainage is being employed extensively in removing excess salts from irrigated soils in arid regions of the West.

ARTIFICIAL DRAINAGE IN HUMID REGIONS

Over 100 million acres of land in the United States are unfit for farming until they have been drained. Possibly 40 million acres of this land could be drained at a cost of 20 to 30 dollars an acre. Two very different types of operation are involved in draining water off wet land. One is the development of open drainage channels that permit excess water to flow into rivers that carry it out to sea. The other involves drainage with underground tile that remove water from the lower part of the soil profile and thus permit development of deeper root systems.

Open drainage channels may consist of large ditches that are dredged out of the mud, and smaller side channels that lead into these ditches.

They may also consist of superficial furrows that carry away surface water from cultivated fields. Thus, in some areas of flat, poorly drained land, it is common practice to plow fields in long, narrow strips, with *finishing furrows* between them through which excess water is carried off to the nearest stream. Such land is often best adapted to grass crops rather than to cultivated types. In low-lying



FIG. 38. Ditching machines that dig trenches to exact grade for tile are being used on a large scale for draining wet land.

areas from which water cannot readily be removed by surface channels or ditches, pumps may be used to elevate the water into storage ponds or lakes from which it can be fed back into the soil during periods of drought later in the year. Such practices are in operation in some of the more intensively farmed peat lands in Florida and around Lake Michigan.

Much of the land now under cultivation has occasional lines of *drainage tile* that run through relatively wet areas to remove excess water. These tile are made either of clay or cement. They are usually cylindrical and about 15 inches long. Their inside diameters vary from as little as 3 inches to 18 inches or more, depending upon the drainage problem involved. These tile are placed in channels formed

by use of a ditching machine that can be set to grade, with a fall of not less than 1 inch for each 100-feet length of channel.

The extent to which tile drainage is necessary in humid regions is determined chiefly by topography of the land, nature of its subsoil, amount and distribution of rainfall, and crops to be grown. With land that is virtually level, and under conditions in which the water table tends to remain close to the surface of the soil for considerable periods in the spring or after heavy rains, it is common practice to install complete systems of tile drainage. Main lines are run along natural drainage channels, and regularly spaced laterals are extended out from the main lines. These laterals are placed at wide angles from the main lines and run parallel to each other. The distance from one lateral to the next is usually between 4 and 8 rods, but it may be less or greater than these values. Drainage tile are normally placed at a depth between 2½ and 3 feet, but greater or less depths may be required from place to place along the lines to maintain adequate fall. Sometimes, tile are placed just on top hardpan layers, which may not be very far below plow depth. In such circumstances, tile drainage is usually supplemented by some system of surface drainage.

When the nature of the subsoil is such that lines of tile cannot be placed to advantage at normal depths, it may be more desirable to change the cropping system to one in which only those crops are grown that thrive on wet soils. Wet land is better suited to grass hay and pasture crops than to cultivated crops. Such crops as buckwheat, soybeans, oats, alsike and Ladino clovers, timothy, and redtop grow quite satisfactorily on soils that are too wet for corn, sugar beets, tobacco, alfalfa, asparagus, and most truck and market-garden crops. Rice and cranberries are two highly important crops that are grown under continuously wet soil conditions.

SOME EFFECTS OF ARTIFICIAL DRAINAGE

If maintained for any considerable period, water in excess of that required to bring the soil to a point approximating two-thirds saturation will have an injurious effect on most crop plants. This is because of inadequate soil aeration, as a result of which plant roots find difficulty in excreting carbon dioxide, aerobic bacteria cannot function, and anaerobic bacteria bring about reduction of nitrates and formation of ferrous iron and manganous compounds in toxic concentrations. Another serious problem in wet soils is that of low temperatures because of the high specific heat of water and the amount of heat ab-

sorbed during evaporation. Some interesting data on this are shown in Table 52.

TABLE 52

TEMPERATURES* OF DRAINED AND UNDRAINED SOILS (KING)

Day of Month	Time of Day	Air Temperature	Drained Soil	Undrained Soil
April 24	4 P.M.	60.5	66.5	54.0
April 25	3 P.M.	64.0	70.0	58.0
April 26	2 P.M.	45.0	50.0	44.0
April 27	2 P.M.	53.0	55.0	50.7
April 28	8 P.M.	45.0	47.0	44.5

* In degrees Fahrenheit.

It is especially desirable that soil temperatures be raised as rapidly as possible in land devoted to early market-garden crops, and even for such crops as corn that require a long growing season. Since the water table normally falls as spring advances and summer comes on, crops like soybeans, which can be sown somewhat later and which have less extensive root systems, can be grown on land that is too wet for corn and for similar long-season crops. That crops differ in drainage requirements is well indicated in the data shown in Table 53

TABLE 53

EFFECT OF TILE DRAINAGE ON ACRE YIELDS* ON CLERMONT SILT LOAM (THORNE)

Crops Grown in Rotation	Undrained Land		Drained Land	
	Grain	Stalks	Grain	Stalks
Corn	41.8	19.5	44.5	28.4
Soybeans	16.7	22.2	14.9	17.8
Wheat	20.5	23.0	23.3	24.3
Clover†	....	29.1	....	33.5

* Yields in bushels of grain and hundredweight of stalks and straw.
† Red clover and timothy mixed.

obtained on Clermont silt loam during a period of 12 years. Corn and clover were materially benefited by tile drainage, whereas soybeans and wheat were not.

The land on each of the plots in this experiment was ridged in the center so that the water tended to be removed by way of finishing furrows. Benefits from tile drainage were not as great as they might have been if the land surface had been left in its naturally flat state.

However, yields were too low to permit profitable farming. In other words, such land should not be devoted to cultivated crops but to grass hay and pasture crops, in which either Ladino or alsike clover has been seeded.

TABLE 54

LIME REQUIREMENTS* OF DRAINED AND UNDRAINED ACID SOILS (CONNER)

Location	Tile-drained	Undrained
Westport	860	1280
North Vernon	1880	2840
Worthington	740	1600

* Expressed as pounds of calcium carbonate required for 2 million pounds of soil.

Interesting data on tile-drainage effects were developed by the Indiana Agricultural Experiment Station in some tests of the lime requirement of drained and undrained soils (Table 54). Samples of soil were chosen from the several plots, extracted with potassium nitrate, and titrated to neutrality. The values were then calculated to pounds of calcium carbonate required to neutralize the acidity in 2 million pounds of soil, the estimated weight of the plow depth of 1 acre. In each case the undrained soil had a considerably higher lime requirement than the drained soil.

This indicates that accumulations of soluble acids in soils can be carried away with the water through the tile lines. Of course, this drainage water will contain some useful nutrient elements as well. But soil productivity, and the means by which it can be maintained at high levels, depend upon having reasonably free movement of water and air through the soil. In proportion as this occurs, root systems are deepened and plants are able to obtain both water and mineral nutrients from a much larger volume of soil. Thus, the loss of soluble nutrients and water by drainage is more than compensated for.

AVAILABLE WATER IN DRAINED SOILS

For high acre yields of most crops, and particularly in intensive farming, it is essential that any temporary watertable that may be formed during a heavy rain be brought down below the root zone within 24 hours after rain has ceased. Otherwise, the crop will suffer because of carbon dioxide accumulation in the soil, formation of toxic reduction compounds, and loss of nitrate nitrogen as free nitrogen gas.

Within a relatively short time the crop turns yellow and, unless the water is removed, it dies.

If the water table is under control to a depth of 3 feet, so that roots can penetrate that depth of soil without danger of injury from excess water, damage from drought is very much reduced. Some idea of the amount of water that may be available for crop use in drained soils is obtained from a study of data shown in Table 55. In this test,

TABLE 55

PERCENTAGES* OF AVAILABLE WATER IN DRAINED SOILS TO 3-FOOT DEPTH†

	Dunkirk Fine Sand	Wooster Silt Loam	Brookston Clay
Water-retaining capacities	6.5	30.2	30.5
Wilting coefficients	3.5	7.7	17.5
Available water by difference	3.0	22.5	12.8
Available water in acre-inches	1.6	10.5	5.2

* Percentages of dry weights of soils.
† Water table at depth of 6 feet.

6-foot columns of soil were saturated with water and the excess was permitted to drain away from beneath the columns for 2 months. The bottoms of the soil columns were in contact with a water table.

It has long been known that silt loam soils are often highly productive, or can readily be made so. One important reason for this is that they have relatively high field capacities for water and relatively low wilting coefficients. Furthermore, moisture moves rapidly upward by capillarity in such soils.

One of the most important developments in the concepts of soil and water relationships is the growing realization that large amounts of water are unnecessarily lost by runoff in humid regions. Some surface drainage is desirable, but this must be kept to the minimum, especially during the late spring, summer, and fall. A great deal of attention is now being paid to means by which *water infiltration* can be increased in soils. If soil is exposed directly to the beating action of raindrops, aggregates are broken down and a hard *crust* is formed. This crust may be virtually impervious to water, in which case the only escape is by way of runoff. The problem is to get more of this water to infiltrate into the soil.

The ideal condition is to have the surface of the land covered with an organic mulch that prevents direct contact of falling raindrops with

the soil itself. This is possible only in relatively restricted areas. The nearest approach to this in extensive farming is to produce the type of crop that forms a canopy over the entire field surface, and does it very quickly after the crop has been planted. Grass and clover crops are especially effective in this capacity. If row crops can be grown in strips, with intervening strips of small grains, grasses, and clovers, a good bit of the runoff water can be saved. Such a system applies especially well to farming in areas of rolling topography, the strips being set up on the *contour*, each crop row being virtually on a horizontal line.

In some areas a great deal of attention is being paid to *trash farming*, in which crop refuse is left on top the land rather than being plowed under. Much of the rain that falls on such land strikes crop refuse rather than the soil itself, and fewer soil aggregates are destroyed. This same principle is now being applied in reseeding old grasslands in areas of rapid runoff. The old sod and all the weeds are killed by one of the standard weedicides, with the result that the land can be prepared for reseeding by the relatively simple procedure of discing or by use of a tool-bar cultivator rather than a plow. Mixed grass and clover seedings made among the old sod and weed refuse, as well as the soil itself, are protected against hazards of dashing rains until the plants get under way. Under such conditions, very little of the water that falls, even during heavy rains, runs off the land, most of it infiltrating into the soil where it serves the purpose for which it is needed.

In well-drained land, crop roots penetrate the soil to considerable depths during dry weather, often below the plane at which tile drains are placed. But such roots are protected only to the depth of the tile. Crops like alfalfa, which have very deep roots that often extend considerably below the tile lines during the summer, may suffer seriously during the wetter periods of the late fall, winter, and early spring. The lower portions of the roots die, with the result that, during a period of spring thawing and freezing, the plants are subject to *heaving*, the taproots being pulled out of the soil to lie exposed on the surface of the ground.

DRAINAGE AND IRRIGATION

The ideal situation in humid regions is one in which excess water can be withdrawn by way of tile drains and extra water can be supplied by irrigation as required. Sufficient water is available for irriga-

tion in humid regions, in contrast to the limited amounts, in relation to the wide expanse of desert land, in arid regions. Often, irrigation in humid regions could be made largely unnecessary and unprofitable if adequate attention were paid to designing soil-management systems that were conducive to water infiltration, and if excess water were drained away by tiling the land.

However, a wide expanse of sandy soils is found along the Atlantic Ocean and the Gulf of Mexico. The water-collecting powers of such



California Corrugated Culvert Co.

FIG. 39. Portable-pipe irrigating systems provide economical insurance against drought in humid areas.

soils are high, but their water-retaining powers are very low. It is for this reason that such land can best be used for cropping purposes in the late fall, winter, and early spring, when temperatures are relatively low and losses of water by evaporation and transpiration are also low. It is in such areas that irrigation is being employed on an ever-enlarging scale, with highly profitable results. Usually, water is available in quantity in nearby impounded streams or at relatively short distances below the surface. *Portable irrigation pipes* are used, the lines being moved from place to place as required. On some farms, supplemental soluble fertilizer is introduced into the irrigation stream.

Permanent installations of overhead watering systems are frequently employed on the more intensive types of market gardening. Where the soil contains a fair amount of silt and clay, considerable difficulty is experienced in maintaining soil in a good physical state, because of its being kept more or less continuously wet, and because of irrigation

water, as well as rain, falling on the soil. It is important that soil be thoroughly dried from time to time, so that the principle of aggregation becomes operative. The shrinkage resulting from the drying of the colloidal matter results in the formation of aggregates. Even under the best of conditions, such aggregates are not permanent, being



FIG. 40. Overhead irrigation pipes on market-gardening farm in New Jersey.

broken down by tillage implements, by falling rain, and by being kept more or less continually wet.

One solution of this problem has been found in the use of some type of rapid-growing cover crop, such as Sudan grass, in the middle of the summer, between spring and fall market-garden crops. Such a crop grows luxuriantly with the aid of unused nutrient supplies remaining in the soil after heavy applications of fertilizer and manure, such as are commonly employed in intensive systems of farming. As a result of its rapid growth during midsummer, the soil is thoroughly dried, and good aggregation is effected. When this cover crop is plowed under in a green state, it provides the necessary food for soil microorganisms, which have further important aggregating effects on the soil. It seems

probable that synthetic organic soil-conditioning agents will fill a highly important need in this kind of farming.

IRRIGATION IN ARID REGIONS

In regions in which annual rainfall is less than 25 inches, it is standard practice to apply irrigation water if it is available. Some 25 million acres of arid and semiarid land is now under irrigation, and additional water is available for possibly 20 million more acres. The quantities of water to apply and the time and manner of their application are problems with which experiment-station workers in California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Texas, Utah, and Wyoming are largely concerned. If the amount was unlimited, the aim would be to maintain the supply of water in the soil at the optimum, within economic limits. Usually, much more land is available for irrigation than is required for the utilization of the available water. The problem resolves itself into that of deciding between growing crops under optimum conditions on a restricted acreage or utilizing smaller amounts of water an acre over larger areas. The highest return an acre-inch of water is usually obtained when somewhat less than the optimum amount of water is applied.

Widtsoe developed some interesting data on what was known as the *evapo-transpiration ratio*. This was defined as the number of pounds of water lost from soil by evaporation and transpiration for every pound of dry matter produced. In this ratio, consideration is given to the total amount of water added to the soil during the crop season, both by rainfall and irrigation, as well as to the difference in the water content of the soil at planting time and at harvest. Table 56 shows

TABLE 56

THE EVAPO-TRANSPIRATION RATIOS OF IRRIGATED CROPS (WIDTSOE)

Water Added*	Corn	Beets	Wheat	Alfalfa	Potatoes
10	275	571	948	621	1255
15	356	663	1038	977	1411
20	416	682	1317†	946	1466
30	527	889	1530†	1253	2242
50	1087†	1186	1809	1480	3060‡
Inches Soil Water§	5.54	10.25	13.74	14.91	6.17

* Acre-inches of water added by irrigation.
† Five inches more water added than table indicates.
‡ Five inches less water added than table indicates.
§ Water in soil at beginning of season plus the rainfall.

such ratios for corn, sugar beets, wheat, alfalfa, and potatoes in Utah.

With wheat, oats, and corn, it is highly important that the water supply be adequate when the grain is at the filling-out stage. With sugar beets, potatoes, and carrots, best results are obtained when water is added throughout the summer. Onions and cabbage require continuously moist soil. It is best to water alfalfa immediately before or after each cutting.

Water may be applied by *subirrigation*, *flooding*, or *furrowing*. The first method is the most economical of water, but it is usually too expensive. Furthermore, it tends to effect concentration of soluble salts on the soil surface. Flooding is commonly employed for grain crops. Furrowing is the common method of irrigating potatoes and market-garden crops. Furrowing is somewhat more economical of water, because of reduction in loss by evaporation.

Two of the most difficult problems in irrigating land are knowing when to apply additional water and how much to apply. Bouyoucos has developed a plaster-of-Paris electrical-resistance technique that seems to meet an important need in this connection. A specially designed moisture meter, with *plaster-of-Paris block* attached, has been designed for sale. Two electrodes, with leads, are imbedded in the block, which is buried in the soil. The electrical resistance, as recorded on the meter, varies with the moisture content of the block. This, in turn, varies with the moisture content of the soil. When the block is wet, resistance is low. As the soil dries out, resistance increases. The meter is calibrated to read directly in percentage available moisture in the soil.

The plaster-of-Paris blocks are buried in the soil in representative parts of the field and at depths where most of the roots of the crop plants are located. Usually, they are placed at several depths, such as 6, 12, and 24 inches. Wire leads from each block are left exposed at the top of the ground. The meter covers the range between field capacity and wilting coefficient. The recommendation is that water should not be applied until the meter shows that available water has fallen below 50 per cent. On sandy soils, irrigation should follow immediately after this point has been reached. For sandy loams and loams, the meter reading should show between 25 and 40 per cent available moisture. For clay soils it is not necessary to irrigate until the meter reading falls to 20 per cent.

The most effective method of removing alkali salts from irrigated land is by use of excess water and its removal through tile drains. The problem is quite similar to that involved in land drainage in

humid regions, except that irrigation water takes the place of rain. Because of the high solubility of alkali salts, they can be readily leached out of the soil if it is underlain by tile. If the alkaline types of salts are present in considerable amounts, the *dispersed* condition of the soil may make drainage difficult. This makes it necessary to apply gypsum, the calcium of which tends to replace the sodium in the soil's exchange complex, with resulting flocculation of the soil and increase in rate of drainage.

In an experimental project in Utah, a 40-acre tract of land was tile-drained to a depth of 4 feet, the laterals being placed 150 feet apart. The soil, a silt loam, was underlain with somewhat heavier clay loam. Table 57 shows that, by combining drainage with irrigation, over 5300

TABLE 57

REMOVAL OF ALKALI BY IRRIGATION WITH DRAINAGE (DORSEY)

Date of Sampling	Water Added,* Inches	Alkali Salts in Soil in Parts per Million			
		1st Foot	2nd Foot	3rd Foot	4th Foot
Sept., 1902	0	17,038	19,250	22,075	24,775
May, 1903	14	6,238	8,125	13,325	15,813
Oct., 1903	50	1,263	2,288	4,125	7,608
Oct., 1904	47	475	1,600	2,650	6,250

* The water was added in varying amounts from month to month. An additional 13 inches was contributed by rain and snow.

tons of salts were carried away in drainage water. In addition, considerable amounts of salts were carried below the depth to which crop roots ordinarily penetrate the soil.

CONSERVATION OF SOIL WATER

Whether land is watered by irrigation or by rain, it is desirable to conserve the moisture supply in the soil. In humid regions, farmers must always be prepared for periods of dry weather. The starting point in such preparation is to have the soil well drained to permit deep penetration of roots. The soil should be well stocked with humus to increase its shortage capacity for available water. Weeds should be eliminated as competitors for water. The land surface should be protected by a mulch of fine earth or by some type of crude organic matter. Everything possible must be done to keep the soil in a well-aggregated state, to permit infiltration of as much as possible of the

water that is applied to the soil or falls as rain. Protection against evaporation from the soil surface is especially important in saline-soil areas to prevent salt accumulation at or near the land surface. Data previously mentioned (Table 38) present conclusive evidence of effectiveness of surface mulches in reducing loss of water by surface evaporation, when tests are made under controlled laboratory conditions. Further consideration must now be given to cultivation effects under field conditions.

Cultivation previous to seeding a crop, or between the rows of a clean-culture crop, such as corn, has long been thought to be essential for reducing loss of water by surface evaporation in the field. The success of dry-farming operations, in which the soil was kept fallow and frequently cultivated between crops, was believed to lie largely in prevention of loss of water by surface evaporation, as well as through transpiration by weeds. However, considerable doubt was cast on the validity of the concept that a surface mulch would save water, when data from the Kansas Agricultural Experiment Station were published in 1917 (Table 58).

TABLE 58

GAIN OR LOSS* IN SOIL WATER AS RESULT OF SURFACE MULCH (CALL)

Year	Rainfall†	3-inch Mulch	6-inch Mulch	Bare Surface
1914	17.93	−3.31	−1.86	−0.89
1915	44.97	0.70	−0.05	−0.70
1916	29.89	−2.39	−1.19	−2.50
1916 (diked)	29.89	0.20	2.37	2.88

* Gain or loss, expressed as per cent of water in the soil to a depth of 6 feet, in the autumn as compared with that in the spring.

† Rainfall from January to September. The rainfalls for 1915 and 1916 were considerably above the average for that region.

These findings had been anticipated by a statement made by Cameron, of the United States Department of Agriculture, some 10 years earlier, in which he said, in effect, that mulching inhibits capillary flow, and diffusion through the mulch is virtually negligible. This practice is very effective in conserving soil moisture and is founded on sound scientific principles. An especially interesting illustration is brought out in comparisons of water losses from soils under arid and humid conditions, respectively. As might be expected, loss at first is much more rapid under arid conditions, so rapid as to tax the soil's ability to move water from within to the surface by capil-

larity. In consequence, a dry layer is formed that keeps subsequent losses far below those that take place from soil under humid conditions, where capillary flow to the surface persists until the moisture content of the whole soil is very low indeed. King's laboratory experiments (Table 38), therefore, clear up in a very satisfactory manner the apparently contradictory effects, observed in the field, that soils of arid regions, at depths a little below the surface, are generally wetter and hold their moisture for much longer periods than do soils of humid areas in dry seasons.

Cameron's concepts still apply. But it is necessary to consider certain other facts that now modify our thinking. Introduction of *weedicides* into the production operations for row crops has again raised the issue of the necessity for any cultivation whatever for such crops. But the evidence indicates that weedicides can be used to replace only a part of the cultivation. For example, in tests with corn carried out by the Ohio Agricultural Experiment Station on ten outlying farms, yields where weeds were controlled by cultivation averaged 94 bushels an acre. Where weed control was effected entirely by weedicides, with no cultivation, yields averaged 78 bushels. But, where weeds were controlled by one early cultivation plus weedicides, yields averaged

TABLE 59

CORN CULTIVATION FOR VALUES OTHER THAN WEED CONTROL

A. Comparison of Cultivation and Scraping on Corn Yields
(Ohio Agricultural Experiment Stations)

Number of Cultivations	Miami * Soil, Bu.	Brookston † Soil, Bu.
No cultivation, weeds controlled by scraping with a hoe.	56.3	72.3
Ordinary cultivation, enough to control weeds, usually 3 times.	59.3	69.8
Once more than was necessary to control weeds, usually 4 times.	62.5	71.6

B. Comparison of Cultivation and Spraying on Corn Yields
(Average for 10 Ohio Experimental Farms, 1949)

Weeds controlled by cultivation.	94
Weeds controlled by chemical sprays.	78
Weeds controlled by one cultivation and sprays.	93

* Light-colored upland soil.
† Dark-colored old lakebed soil.

93 bushels. Thus, one deep early cultivation netted 16 bushels of corn an acre (Table 59).

When the row crop is small, its roots are confined to a relatively small volume of soil and its tops have little effect on air movement in the field. Furthermore, the crop has little shading effect on the soil. Under such conditions, the principle of the soil mulch can be applied to advantage. Cultivation aids in water infiltration and aeration, as well as in prevention of loss of water by surface evaporation. Once the crop is well under way, the roots will have spread out through the soil, thus effectively cutting off any flow of capillary water to the surface. More damage than good may result from further cultivation. By this time, the crop will have grown to sufficient size to reduce wind velocity in the field, and considerable shading is being effected.

DEPTH OF PENETRATION OF PLANT ROOTS

Need for large amounts of available water a few inches below the soil surface becomes less as roots of crops penetrate the subsoil. Light rains become less and less effective and surface mulches of less importance. Available water is now more largely that which lies at lower depths and which has little chance to escape beyond the reach of widely spread root systems bearing very large numbers of roothairs. Under these conditions, *roots often move more rapidly toward the unused water supply at lower depths than water moves toward the roots.*

Roots of many crop plants extend downward to depths of 3 feet or more if subsoil conditions are favorable for their development. In subsoils that are adequately aerated and contain considerable supplies of available mineral nutrients, the most important factor determining the depth to which roots will penetrate is the moisture supply. In general, a relatively low water content in the plow depth of soil favors deep root development. This is especially important during the early stages of growth of a crop. A moderately dry season at the start of the growing period is much to be preferred over a wet one, notably for corn.

Some idea of the relation between top and root growth of plants can be obtained from a study of Table 40. This shows data from Nebraska, Kansas, and Colorado, where no interfering subsoil factors prevented root development. Corn roots extended downward over 8 feet, small-grain roots nearly 7 feet, and potato roots nearly 5 feet.

Some plants have relatively shallow root systems. In humid regions, such plants thrive under conditions of frequent and abundant

rainfall, where the climate is cool and moist, or where the water table is maintained relatively near the surface of the soil. In irrigated areas, advantage is taken of such differences in root systems to kill weeds in alfalfa, which has a very deep root system. Land that is difficult to drain and that is continuously wet is quite commonly used for shallow-rooted grasses and legumes, such as bluegrass and white clover or bromegrass and Ladino clover.

SOIL MANAGEMENT AND WATER CONTROL

Lack of available water is more often likely to be a limiting factor in crop production than that of any other essential for plant growth.

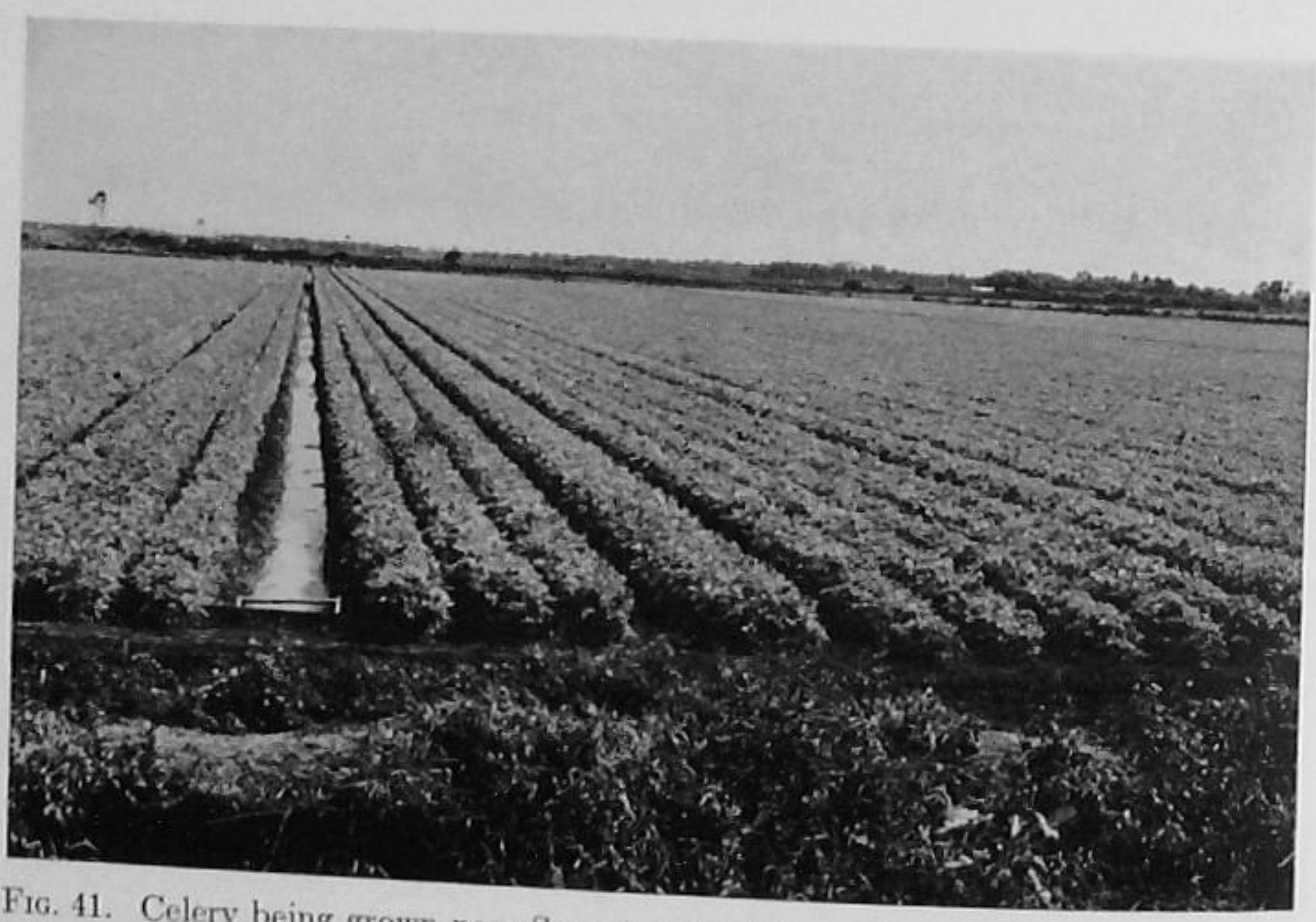


FIG. 41. Celery being grown near Sarasota, Florida, under conditions where water table is maintained at constant level by pumping water out and returning it later, as required.

As acre yields are raised to higher levels, more and more attention has to be paid to making increasing amounts of water available to the plant. In the drier humid regions, this requires that special attention be paid to preventing water runoff either by the use of contour furrows, which prevent escape of surface water, or by developing methods of soil management that aid in water infiltration. The trash-mulch system, such as is being employed over large land areas in Nebraska, is

of greatest importance. Drainage to lower the water table and permit of downward extension of root systems is of increasing importance. Irrigation is being employed not only in arid regions but to an ever-increasing extent in humid regions as well. Soils in a low state of fertility often produce quite satisfactory yields during seasons of favorable moisture conditions. But it is important to keep in mind that soils in a high state of fertility produce a unit of crop yield with less water than do those that are low in fertility. Soils that are well supplied with all the nutrient elements and that permit of development of deep root systems have very high yielding potentialities, when water is available in abundance. This indicates that much more attention might profitably be paid to those farming operations that aid in water storage and control. On a well-managed farm in humid regions, it is seldom necessary for the crop to suffer serious injury either from drought or from excess water.

SELECTED REFERENCES

1. Ayres, Q. C., and D. Scoates. *Land Drainage and Reclamation.* McGraw-Hill Book Co., New York, 1939.

2. Call, L. E., and M. E. Sewell. The soil mulch. *J. Am. Soc. Agron.,* Vol. 9, pp. 49–61, 1917.

3. Cates, J. S., and H. R. Cox. The weed factor in the cultivation of corn. Bur. Plant Ind., Bull. 257, 1912.

4. Conner, S. D. The effect of drainage on soil acidity. *Science,* Vol. 46, p. 346, 1917.

5. Dorsey, C. W. Alkali soils of the United States. *U. S. Dept. Agr., Bur. Plant Ind., Bull.* 35, 1906.

6. Duley, F. L., and J. C. Russel. The use of crop residues for soil and moisture conservation. *J. Am. Soc. Agron.,* Vol 31, pp. 703–710, 1939.

7. Gustafson, A. F. *Using and Managing Soils.* McGraw-Hill Book Co., New York, pp. 78–117, 1948.

8. King, F. H. *Physics of Agriculture.* Published by the author, Madison, Wisconsin, 1907.

9. Rummell, L. L., Director. Handbook of Ohio Experiments in Agronomy. Ohio Agr. Exp. Sta., Series B-1, pp. 77, 1951.

10. Thorne, C. L., and Associates. County experiment farms in Ohio. Ohio Agr. Exp. Sta., Bull. 344, pp. 306–309, 1920.

11. Weaver, J. E. *Root Development of Field Crops.* McGraw-Hill Book Co., New York, 1926.

12. Widtsoe, J. A. The production of dry matter with different quantities of irrigation water. Utah Agr. Exp. Sta., Bull. 116, 1912.

13. Widtsoe, J. A. *The Principles of Irrigation Farming.* The Macmillan Co., New York, 1914.

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Plowing and Cultivating

The manner in which a soil is mechanically managed has a great deal to do with its productivity. Some soils have good structure and a loamy texture, they are well drained, and they respond readily to good management. If not naturally productive, they can easily be made so by use of organic and mineral amendments. Other soils may have poor structure and texture, they may be too wet or too dry, and they may be difficult not only to prepare for planting but to manage afterward. Even when liberally manured, limed, and fertilized, they may not produce satisfactory yields unless special means are employed to improve their physical properties.

As a starting point, one has to decide how to break up the soil for seeding or planting. A great variety of farm tools is available for this purpose. These include *moldboard, breaker-rod, and disc plows; blade, shovel, disc, rotary, and sweep field cultivators; disc and spring-tooth harrows; listers, middlebreakers, and bedders.* Once the soil has been broken up, there is considerable choice in implements that may be used in preparation of a seedbed, if that is desired. These include *disc and spiketooth harrows, pulverizers, packers,* and *weeder mulchers.* If row crops are being grown under the clean-culture system, many different types of *row cultivators and weeders* are available for use.

PLOWS AND PLOWING

The most widely used implement for breaking up the soil is the ordinary moldboard plow. The popularity of this implement is due to its usefulness in burying crop refuse and sod, thus getting them out of the way of planting operations. The sod plow has a long moldboard that slopes gently upward with considerable twist. This prevents the furrow slice from falling back into the furrow and tends to break the



(*a*)



(*b*)

FIG. 42. (*a*) A moldboard plow in operation near Rockford, Illinois. (*b*) One-way disc plow being used in same field as that shown in (*a*).

sod apart. A jointer is usually attached to such a plow. This is merely a plow in miniature, which is designed to turn the exposed sod at the edge of the furrow slice. Otherwise, this strip of sod might quickly start growing and cause considerable trouble. The stubble plow has a short steep moldboard that pulverizes the furrow slice as it turns it over. A disc colter is often used with such a plow to prevent trash from collecting around the shank. If much trash has to be dealt with, a chain is often attached to the plow beam to drag this under so it will be completely buried. Breaker-rod and disc plows are used in soils that will not scour a moldboard. The disc plow is also used to advantage in soils that must be plowed when too dry.

Use of the wrong type of plow may make it almost impossible to prepare a good seedbed. Since most fields contain more than one soil type and many farmers have only one type of plow, it is especially important to know how to adjust this plow and its operation to best meet the average requirements of the field. Where climatic and weather conditions permit, plowing should be done when the soil is at its optimum moisture content. This can be determined by working a handful of soil in the hands and noting whether it can readily be broken into crumbs afterward. If the soil forms into a wet ball, plowing will tend to destroy its aggregates and have highly objectionable effects on its working qualities. If it is too dry, the plow may merely break it up into large clods that are difficult to deal with in preparing a good seedbed.

DEPTH OF PLOWING

Depth of plowing should be varied according to the nature of the soil, the climate, and the crop to be grown. Soils that have a high clay content are not usually plowed as deeply as those that are high in sand. Deeper plowing is usually employed in the more humid regions than in the drier ones. Especially deep plowing is recommended for root and tuber crops, notably for sugar beets, potatoes, carrots, and parsnips. Often, depth of plowing is largely determined by the level of productivity of the soil. The larger the amounts of organic matter, lime, and fertilizer that are incorporated in the soil the greater the opportunity to profit from deep plowing in a well-drained soil. Little is gained by deep plowing if by this means highly fertile topsoil is merely diluted with unproductive subsoil. *Rawness* of subsoils in semiarid regions is due largely to their lack of organic matter, with resulting low content of available nitrogen and phosphorus. In humid cli-

mates, there is the additional factor of toxicity from reduced forms of iron and manganese. Traces of such toxins may persist long enough after subsoil has been brought to the surface to injure young seedlings, especially in soils that have tight *B* horizons and are difficult to drain.

Roothair development does not take place to any considerable extent in subsoils, except in airspaces where such soluble substances as are present are in an oxidized state. If extra-deep plowing is to be practiced, it is desirable to do this as long in advance of planting as possible. In proportion as large amounts of subsoil are brought to the surface, extra nitrogen and phosphorus, especially the latter, are required for satisfactory crop growth.

A number of special devices have been developed for aerating compact subsoils. Some of these are designed merely to break up *plowpan* that may have developed as a result of repeated action of the plowshare on the bottom of the furrow or from compaction by the tractor wheel. For some years an interesting implement, consisting of two discs, one above the other, was tried experimentally. The top disc merely turned the plow depth of soil, whereas the bottom disc turned an equal depth of subsoil without bringing it to the surface. Comparisons of yields following use of the moldboard plow, use of such a plow with a subsoiler, and use of this *two-level disc plow* are shown in Table 60. No advantage over the moldboard plow was found from use of either of the other two types on Wooster silt loam.

TABLE 60

ACRE YIELDS* OF CROPS AS RELATED TO DEPTH OF PLOWING (WILLIAMS)

Crop	Ordinary, 7½ Inches	Double-disc, 15 Inches	Ordinary, with Subsoiling
Corn, bu.	61.1	59.4	61.3
Oats, bu.	49.0	49.2	49.0
Wheat, bu.	31.5	31.4	31.6
Clover, cwt.	53.0	50.6	52.0

* Twelve-year averages on Wooster silt-loam soil.

Use of *dynamite* is sometimes suggested for breaking up tight clay subsoil, such as that involved in the study for which data are shown in Table 61. Here, again, little advantage resulted from use of any other method of breaking up the soil over that of the ordinary moldboard plow. Yet it is of interest to note that *back furrows*, which consist of two plow depths of soil piled on top each other, are usually

TABLE 61

ACRE YIELDS* FROM DEEP TILLING, SUBSOILING, AND DYNAMITING COMPARED TO ORDINARY PLOWING (SMITH)

Tillage	Corn, 9 Crops	Soybeans, 7 Crops	Wheat, 6 Crops	Sweet Clover, 6 Crops
Plowed 7 inches deep	40.2	16.3	13.5	3.68
Subsoiled 14 inches deep	41.9	16.2	12.9	3.65
Deep-tilled 14 inches deep	37.4	15.2	10.8	3.18
Dynamited	40.3	16.4	11.7	4.25

* Bushels of grain and tons of sweet clover per acre on gray silt loam on tight clay.

much more productive than the remainder of the field. It seems probable that if especially deep plowing or any other method of working the soil to considerable depth is to be employed, it must be accompanied by heavier applications of organic matter, lime, and fertilizer to be fully effective. But the only known advantages of such deep plowing are in connection with very sandy soils lying over heavier subsoils, and with those that are covered with salt deposits. The deeper the salt deposits can be buried the better.

FIELD CULTIVATORS

The primary reason for the popularity of moldboard plows lies in their usefulness in turning trash under so that it does not interfere with planting the crop. It is now widely realized, however, that this type of plow has the disadvantage of exposing soil to direct action by wind and rain. This results not only in loss of soil by erosion but in destruction of soil aggregates through the beating action of rain. Accordingly, a great deal of effort is being directed toward finding suitable substitutes for moldboard plows. Among the most useful implements of this type are the vertical and horizontal field cultivators. Many different designs of such implements are being offered for sale. The net effect of all these is to loosen the surface soil and leave most of the crop refuse on top of the land.

The disc type of field cultivator is widely used in the wheat belt of Texas, Oklahoma, Kansas, and Nebraska. Such an implement may cover a width of 20 feet, which permits working over large areas of land in a relatively short time. The blade and shovel types of field cultivators are more commonly used in humid regions. The vertical soil openers are placed from 7 to 8 inches apart and open up the soil to a depth of 8 to 10 inches. The trash remains on top the soil to pro-

tect it against beating and eroding action of rain. The sweep type of field cultivator consists of V-shaped blades that are pulled through the soil horizontally at a depth of 3 or 4 inches below the surface.

No specially difficult problem is involved in sowing small grains, grasses, and clovers in soils that have been prepared for seeding by use of one or the other of these types of field cultivators. But, for row crops, the surface trash is troublesome to deal with. Special shoes



FIG. 43. A great deal of time is being devoted to study of methods of soil preparation that leave the crop residues on the surface, as aids against wind and water erosion.

are developed for planters that are to be used under these conditions. These shoes shove the trash aside and plant the seed in a cleaned row. Subsequently, the crop is cultivated by the use of *sweeps* that run under the trash in the spaces between the rows. Such a system is being employed on a large scale in corn-growing areas in Nebraska.

Wide use is being made of middlebreakers and bedders in the southern states, especially where row crops are grown in succession, with intervening cover crops. Often, the bed for one year's crop becomes the furrow between the beds for the next year's crop. In the drier regions of the Great Plains, it is common practice to use a lister to open up furrows in the bottom of which corn or sorghum is planted. This permits the accumulation of more moisture in the zone where it is needed in germinating the seed and for getting the young plants under

way. In areas of still more limited rainfall, use is frequently made of listers, with attachments that place small dams across the furrows at frequent intervals to prevent water runoff during rains.

Once row crops are under way, it becomes necessary to have some means of protecting them against serious competition from weeds. Many types of weeders, rotary hoes, and row cultivators are being employed. Some of these operations are now being replaced by weedicides. The growing practice appears to be that of cultivating the row crop once and then making use of a weedicide. This one cultivation may aid in a variety of ways, such as aerating the soil to speed up nitrification, developing a surface mulch to reduce evaporation, increasing water infiltration, and destroying weeds. Once the crop gets well under way, any further cultivation may not be justified under modern farming conditions.

SOIL-AGGREGATE DESTRUCTION

It is now widely recognized that every operation of machinery on and in soil tends to result in a reduction of its degree of aggregation. Some implements cause a great deal more damage to soil aggregates than do others. The rapidly revolving *rotary tiller* is an example of an implement that does its job of preparing soil for planting so effectively that many of the soil aggregates are sheared to pieces. Discs, rotary weeders, rod weeders, packers, and pulverizers have similar, although less pronounced, effects. The same applies to the several types of row cultivators. Knowledge of the destructive effects of such implements has led to studies of means by which the number of soil manipulations can be reduced. This is one of the reasons why weedicides for cultivated crops are of so much interest, since by their use the number of cultivations can be materially reduced.

One of the most interesting experimental developments along this line is that of the *once-over machine*, which prepares the soil, applies the fertilizer, and plants the seed, all in one operation. Such machines are being employed in preparing land for corn production, no matter what the nature of the previous crop or the kind of refuse or cover crop. Thus, if the field is covered with cornstalks, these are merely shoved aside and left lying between the rows. If the previous crop was clover or alfalfa, the new spring growth is left undisturbed between the 8-inch spaces that are prepared for the corn rows.

Once corn has been planted in these specially prepared rows, the problem is then one of deciding what to do with the sod crop or trash

that remains between them. If the corn is adequately fertilized and the season is favorable, it is sometimes possible to produce a good yield of corn without doing anything more to the field. But two other possibilities exist. One is to use a row cultivator with sweeps that cut off the roots of the sod crop or the weeds and leave the refuse lying on the surface. The other is to place the rows far enough apart so that use can be made of a mower to keep the weeds and clovers under control. Considerable attention is being paid to the development of such systems of soil and crop management in corn production in Indiana and Illinois. They have the highly important advantages of protecting the soil against the action of heavy rains and of greatly increasing water infiltration.

TRACTORS AND TRUCKS

Substitution of heavy tractors and trucks for horses has introduced another problem in the deterioration of soil structure. The tractor wheels tend to destroy soil aggregates, especially when the soil is a little too wet to work. This is especially noticeable in the bottom of the furrows during the use of the moldboard plow. The plow depth of soil may be just at the right moisture content for working, whereas that on the forrow bottom may be a little wetter than it should be. As a result, a more or less impervious layer is formed just below plow depth. It is for this reason that so much interest has been developed in various types of pan breakers, which are often attached to plows. Field cultivators of the blade or shovel type can be used to advantage from time to time under such conditions.

Special interest has been developed in tap-rooted sweet clover and alfalfa for overcoming pan development and for opening up compact subsoils to freer movement of air and water. These crops serve the double purpose of accumulating nitrogen, through the aid of the nodule bacteria on their roots, and of leaving holes in the soil when the plants die and their taproots decay. Furthermore, the microorganisms that effect this decay and their decomposition products have marked aggregating effects on the subsoil.

Insofar as the plow depth of soil is concerned, grass crops are more effective than legumes in aggregating soils. The mass of these roots spread through the soil and distribute their organic matter in a manner that cannot be duplicated by any other means. They also effect very severe drying of the soil during periods of drought, and this aids greatly in its aggregation.

One of the most troublesome problems that have arisen in connection with the use of tractors, and of spraying and harvesting trucks and other machinery as well, is that of the development of *wet spots* in otherwise well-drained fields. Fields usually contain a number of such spots, where the soil dries much more slowly after rains than it does over most of the field. Since it is not feasible to work around these spots, tractors, trucks, and other machinery are operated through them. As a result, the soil aggregates are destroyed. Thus, the spots grow worse, and they get larger year by year.

FLOCCULATING AGENTS

Under such conditions, use of a *flocculating agent* is sometimes highly effective. Gypsum is being used for this purpose on many New Jersey farms. Applied at the rate of about 2 tons an acre on top of the soil, it gradually works downward into the soil, where it has marked flocculating effects. If the underlying subsoil is naturally well drained, often the excess water in the wet spots can then escape and the soil can be dried out. In proportion as the drying process can be completed before the soil is again disturbed by machinery, this flocculation is often followed by improved aggregation, with more or less permanent effects, and the wet spot disappears.

Salts vary greatly in their flocculating capacity. Divalent cations, such as calcium and magnesium, have flocculating effects even when applied as carbonates and hydrates. But carbonates and hydroxides of ammonium, sodium, and potassium are very active *deflocculating agents*. Sulfate of ammonia, most neutral salts, and all acids are active flocculating agents. The cations of these salts and acids effect neutralization of the negative charge associated with colloidal soil particles and cause their precipitation. Saline soils, notwithstanding their alkalinity, possess definite structure because of their high content of soluble salts. If these salts are leached out of the soil, a state of deflocculation may develop, because of the large amounts of sodium that remain behind in the exchange complex. Under such circumstances, gypsum can again be used to advantage. In this case, its calcium replaces the sodium in the exchange complex, and the sodium is carried away in excess irrigation water as the sulfate. The special value of gypsum lies in its relatively high solubility, in comparison with calcium carbonate.

SOD CULTURE IN ORCHARDS

The usual procedure in orchards is to plow the land before planting the trees and then to continue to practice clean cultivation, with or without a row crop, between the rows until the trees have spread over nearly the entire land area. From that time on, sod is usually allowed to take over in apple orchards. But clean cultivation is often continued in peach and cherry orchards, vineyards, and citrus groves. If the soil is in a high state of productivity at planting time and if clean cultivation is followed each summer or fall by the growing of cover crops, which are subsequently disced into the soil, a clean-cultivation system, accompanied by the use of liming materials and fertilizers, may prove quite satisfactory. But there is considerable evidence to the effect that too much clean cultivation is being practiced in orchards, with resulting destruction of organic matter and of soil aggregates and serious loss of soil by erosion.

There is reason to believe that more attention should be given to permanent sod and clover covers, not only in apple orchards but in other orchards, and in vineyards and groves as well. The best procedure with these sod covers is to work them up occasionally with some type of field cultivator. This is known as the *sod-culture* system. Cultivation aids in the liberation of nitrogen from soil organic matter and reduces competitive action of the grass against the trees for applied nitrogen and other fertilizer elements. It is necessary to keep in mind that enough fertilizer must be supplied for both the ground cover and the trees. But long-time effects from this procedure are often exceptionally good, especially on rolling land that is subject to severe erosion.

SOIL CONSERVATION

Any field operation that exposes soil to the erosive action of wind and rain must be viewed with concern. It is for this reason that so much attention is being paid to *soil conservation*, the most important part of which is that of holding the soil where it is and retaining as much of the rainfall against runoff as possible. Grass and forest trees constitute our most effective means of keeping the soil sewed to the earth. In proportion as other types of crops must be grown, special means must be employed to prevent soil erosion. To do this, such practices as *planting on the contour, strip cropping,* use of *tractor-*

built terraces, maintenance of *sodded waterways*, and elimination of all cultivation of soils that cannot be conserved by any other practical means are being widely employed.

However, large areas of land have already been so badly eroded that they present a very difficult problem in reestablishing a cover.



FIG. 44. Contour plowing in Oklahoma increases water infiltration.

Sometimes, gullies can be filled up by use of a *bulldozer*, which shoves the soil and subsoil into the depressions and makes it possible to combine patches of land into much larger units. When this is accompanied by terracing and reseeding to permanent grasses and legumes, often excellent grazing land can be developed, with highly important possibilities for profitable agriculture.

Large areas of land lie waste also because they are covered with small trees, bushes, vines, and shrubs, which must be removed. This may be a very costly undertaking, unless it can be done mechanically on a large scale by the use of heavy machinery that will pull these large plants up by the roots and shake off the soil. Such implements

are now being developed. They not only accomplished these purposes but shred the organic material and spread it back over the land.

Where land must be put to the plow or some other type of tillage implement, no system of terracing or other mechanical method of dealing with the soil will suffice. It is essential that clean-culture crops be grown in rotation with sod or cover crops so that advantage can be taken of their very marked effects as aids in soil aggregation and water infiltration. Lloyd and Ely estimate that if the loss of soil by erosion under conditions in which a clean-culture row crop was being grown continuously was set at 100, this could be reduced to as little as 30 after several years of meadow. For the meadow itself, loss of soil by erosion would be less than 1.

MECHANICAL MANAGEMENT OF SOIL

Low crop yields are often the result of failure on the part of the man who farms the land to give adequate consideration to the mechanical phases of the problem of soil management. Time and manner of breaking up the soil, preparation of the seedbed, subsequent intertillage of row crops, prevention of erosion, and overcoming of errors of previous management of the land all merit serious study. Gardeners have long believed the old axiom that "tillage is manure." That adage originated in the days of Jethro Tull, whose *Horse Hoeing Husbandry*, written in 1733, is an agricultural classic. But it has long been known that Tull's concept that plants "insume" the very fine soil particles is erroneous. We now know that only as soil substances are dissolved in water can they be absorbed by plants.

It is important that more consideration be given to choice of implements with which to work the soil. The moldboard plow can often be replaced to advantage. The number of cultivations can often be greatly reduced. More use should be made of crop refuse as a soil protectant. Advantage can be taken of some of the heavier and more modern types of machines to fill up gullies, eliminate small trees, vines, and bushes, drain the land, and bring it under controlled cultivation. Farming on the contour, strip cropping, growing cultivated crops in rotation with sod crops, and developing permanent grass cover in waterways are highly important parts of good soil management.

Chemical agents can be brought into play directly in flocculating and aggregating soils. Or they can be employed in increasing acre yields to the end that more organic matter is left behind in and on the land in the form of roots and crop residues or is returned to the

land as manure. There is reason to believe that marked improvement will be effected in the mechanical management of soil during the next quarter century.

SELECTED REFERENCES

1. Baver, L. D. *Soil Physics.* John Wiley & Sons, New York, pp. 290–324, 1940.

2. Duley, F. L., and O. R. Mathews. Ways to till the soil. The Science of Farming, *U. S. Dept. Agr. Yearbook,* 1943–47, pp. 518–526, 1947.

3. Russell, E. John, and E. Walter Russell. *Soil Conditions and Plant Growth.* Longmans, Green and Co., New York, pp. 578–588, 1950.

4. Sewell, M. C. Tillage—A review of the literature. *J. Am. Soc. Agron.,* Vol. 11, pp. 269–291, 1919.

5. Smith, R. S. Experiments with subsoiling, deep tilling, and subsoil dynamiting. Illinois Agr. Exp. Sta., Bull. 258, 1925.

6. Williams, C. G., and Associates. Forty-first annual report of Ohio Agr. Exp. Sta., p. 11, 1922.

7. Winters, E. *Advances in Agronomy.* Academic Press, New York, pp. 2–92, 1951.

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Organic Matter

Plant residues are a very important part of a productive soil. They serve as sources of food for energy and growth of soil microorganisms. The substances liberated during their decomposition are used in the production of succeeding generations of plants. The carbon, nitrogen, sulfur, and phosphorus that are released in acid form during decay have a solvent action on soil minerals, thus liberating new supplies of nutrient elements from the soil. The microorganisms effecting decay, and the intermediate organic substances formed during this process, have very marked effects on soil aggregation. The *friability*, or working quality, of soils is greatly improved by additions of organic matter. In general, it can be said that the larger the amount of organic matter added to a soil and decomposed within it, the higher its productivity level will be raised. However, crude plant residues must be acted on by soil microorganisms before these values can be realized.

ORGANIC MATTER IN SOILS

The amount of organic matter in a soil can be estimated, but it cannot be determined exactly. If one dries a sample of soil in an oven, weighs it, heats it until its organic matter has been destroyed, and weighs the soil again, he gets a value known as *loss on ignition*. But this loss consists partly of bound water, the quantity of which is closely related to the amount of colloidal matter in the soil. If one washes the soil with a dilute solution of hydrochloric acid to remove the calcium and other basic elements that unite with soil organic matter to form *humates*, he can then extract the *humic acid* by use of a dilute solution of ammonia. The resulting solution is brown or black. If the soil is naturally acid, the humic acid can be extracted by use of an ammonia solution, without previous treatment with hydrochloric acid. The depth of color of the solution can be used as a crude index of the acidity of the soil.

The most exact method of determining the organic matter in soils involves use of a combustion furnace. By this procedure the carbon, which is the central element in organic matter, is released as carbon dioxide. This gas is caught in an absorption tube and weighed. From this weight one can calculate the amount of carbon released. Since organic matter is about 50 per cent carbon, its quantity will be roughly twice that of the amount of carbon. Another method of estimating the organic matter is by determining the nitrogen content of the soil by the standard Kjeldahl procedure. This consists of digesting the soil in strong sulfuric acid and releasing its nitrogen as ammonia. The amount of ammonia thus released can be determined by absorbing it in a standard acid solution and making use of the usual titration procedure. By multiplying the amount of nitrogen in the soil by 20, one has a rough estimate of the amount of organic matter the soil contained.

Summarizing, the ratios between nitrogen, carbon, and organic matter are fairly constant. In humid regions the *carbon-nitrogen ratio* is about 10 to 1, that of organic matter to carbon is about 2 to 1, and that of organic matter to nitrogen is about 20 to 1. Thus, if a soil contains 0.15 per cent nitrogen, it contains about 1.50 per cent carbon and 3 per cent organic matter. Calculated in terms of 2 million pounds of soil, the approximate weight of a plow-depth of $6\frac{2}{3}$ inches, the nitrogen value will be 3000 pounds, that of carbon, 30,000 pounds, and that of organic matter, 60,000 pounds an acre.

Soil organic matter varies in composition between that of the crude crop residues and the *humus* resulting from its decay. Both the original crop residues and the humus formed from them vary greatly in composition. The final product is so resistant to further decomposition that it is of considerably less value in the soil than are the intermediate products of decay. Accordingly, a great deal of work has been done to develop a method of estimating the *active organic matter* in soils. The procedure now commonly employed consists of digesting the soil with potassium dichromate and sulfuric acid and calculating the amount of carbon oxidized during the process. This is known as the *wet-combustion method.* Most organic matter data now being reported are estimated by this procedure. The carbon data thus obtained are multiplied by 1.724 to obtain values for the active organic matter.

Considered from the point of view of its usefulness as a source of nitrogen for plants, the quality of organic matter is closely related to the recentness of its origin and its percentage of nitrogen. Fresh or-

ganic matter is of much more value than that remaining as a more or less final decomposition product. But well-rotted manure, clover sods, and young green manures are much more useful as sources of nitrogen than are straw, cornstalks, or timothy sods. The smaller the percentage of nitrogen in organic materials the less the amount remaining for crop use after the microorganisms of decomposition have had their nitrogen requirements satisfied. *Unless organic materials contain over 1.5 per cent nitrogen, on a dry-weight basis, little or none of this element will be released for crop use during the season immediately following their incorporation into the soil.*

To be specific, suppose a crop of sweet clover that had been top-dressed with 10 tons of cattle manure an acre was incorporated into the soil in early May in preparation for planting corn. Judging by the values shown in Table 66, the dry weight of the roots and tops of the sweet clover might have been 5700 pounds and their nitrogen content might have been 219.4 pounds. Subtracting 1.5 per cent of 5700, or 85.5 pounds, of nitrogen required to feed the microorganisms that decompose the clover, leaves nearly 134 pounds of nitrogen that should be available for corn. The dry weight of the 10 tons of manure would be about 5000 pounds and its nitrogen content 100 pounds. Subtracting 1.5 per cent of 5000, or 75 pounds, of nitrogen required for the microorganisms, leaves 25 pounds for the corn. This makes a total of about 159 pounds of nitrogen, or enough to permit the production of a 100-bushel corn crop. Additional nitrogen would be released by the soil organic matter of less recent origin. When wheat straw, or some similar low-nitrogen kind of organic matter, is added to the soil, it is necessary either that considerable time be allowed to elapse before a crop is planted or that extra nitrogen be added to meet the further needs of the soil microorganisms and to feed the crop.

Quality of organic matter may be considered also from the point of view of its content of essential mineral elements. If one plows under cornstalks, after selling the grain in which the phosphorus is concentrated, it is safe to assume that lack of this element may become a limiting factor in crop growth. The bacteria of decomposition undoubtedly compete with the crop for this element just as they do for nitrogen, when the quantity is limited. The importance of phosphorus to microorganisms is revealed in their high content of this element, as shown in Table 25.

As a source of energy for nonsymbiotic nitrogen-fixing bacteria, the low-nitrogen types of organic matter are to be preferred. Thus, sugar, which contains no nitrogen, is an excellent food for nitrogen-fixing

bacteria, and they function very effectively when it is supplied to them. Other soil microorganisms also consume the sugar and, while so doing, help use up all the available nitrogen in the soil. The nitrogen-fixing bacteria, being then unable to obtain their needed nitrogen from the soil organic matter, function more effectively in fixing nitrogen from the soil air. Addition of phosphorus, as well as sugar, further stimulates the fixation process by preventing a lack of this element from being a limiting factor in the growth and functioning of *Azotobacter* and other nitrogen-fixing microorganisms. Starch, cellulose, and organic substances have nitrogen-fixation values similar to those of sugar. Accordingly, when low-nitrogen crop residues, such as straw and cornstalks, are added to the soil, nonsymbiotic fixation of nitrogen is encouraged. Such products, however, should be worked into the soil well in advance of planting, so that the decomposition and fixation processes will have been completed before the new crop gets under way.

PHYSICAL EFFECTS OF ORGANIC MATTER

The working qualities of soils are very much improved by additions of organic matter. This organic matter has value as a means of aggregating soil particles. Microbial growths and decomposition products aid in binding the finer soil particles together into aggregates that may remain stable for some months after they are formed. Such effects are much more important in the heavier types of soil than in sands. But organic matter has value in sands, as a partial substitute for clay. Gelatinous products of decomposition of manures and green manures tend to bind the coarse sand particles together, thus overcoming the undesirable effects of excessive drainage and aeration. With continued applications of organic matter, a point may finally be reached at which both sands and clays lose many of their distinguishing characteristics. Comparison of soil from a garden that has been heavily manured over the years with soil from a nearby field on which the quantity of manure applied has been so small as to have little physical effect makes this quite evident.

The reason for the effectiveness of organic matter in improving physical properties of soils is quite apparent when one considers the characteristics of peat and muck. These materials are capable of absorbing water to the extent of several times their dry weight. In absorbing this water their volume is considerably increased. Such soils have high porosity and are easily drained. They lack *cohesiveness* and they have low specific gravity, which makes them easy to

work. They have high specific heats and, therefore, are not subject to extremes in temperature. They have very high capacity to adsorb nutrient elements from solution and to hold them in exchange form for plant use. Thus, they possess qualities that are complementary to those of both sands and clays. Although the organic matter of mineral soils is not necessarily identical with that in mucks and peats, the physical effects obtained by mixing peat and muck with such soils are quite similar to those obtained by the use of corresponding amounts of manure.

The adsorptive effects of soil organic matter are quite similar to those of clay. Cations are adsorbed in relatively large amounts. This applies also to certain of the anions, notably to phosphorus. As a result, organic matter has a highly important *buffer* effect, in that it reduces the likelihood of damage from acids or alkalies or from the use of large amounts of highly soluble fertilizers. In common parlance, the word *loam* means a soil that is high in organic matter and that, as a result, is friable, easily worked, and remains in good physical state, even after being exposed to the beating action of heavy rains. This indicates that organic matter has the capacity to overcome the bad effects of excessive amounts of either sand or clay.

ACCUMULATION OF ORGANIC MATTER

The organic-matter content of soils usually grows less the farther removed they are from the virgin state. This makes it necessary to develop soil-management practices that tend to restore organic matter as rapidly as it is lost and raise it to higher levels. For this purpose, farmers find it necessary to adopt rotation procedures by which organic-matter losses during periods of cultivation can be made up during periods in which uncultivated crops are grown. They also find it desirable to make use of animal or green manures. It is also important that measures be taken to maintain crop yields at high levels so that large amounts of roots and other crop residues are left in and on the soil.

Continuous growth of a clean-culture crop, such as corn, is more destructive of soil organic matter than growing it in rotation with wheat and clover. If crop rotation is practiced and the proportion of clean-cultivated crops is not too large, the organic-matter content of a soil can be maintained at a relatively high level by use of purely inorganic fertilizers. These make their contribution entirely through the additional organic residues that remain after the resulting larger

crops have been harvested. This fact is well demonstrated in the data shown in Table 62, which gives the crop yields and soil organic matter

TABLE 62

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

* Two and one-half tons of burned lime.

results for a 15-year period of experimentation with manures, fertilizers, and lime on a Dekalb silt loam. Of the crops produced during this period, four were clean-culture crops, five were small grains, and the remaining six were hay crops. All the crops were harvested and removed, only the normal residues remaining on the land to contribute to the organic-matter supply.

Use of 5 tons of complete fertilizer during the 15-year period resulted in a 40-per cent increase in the soil organic matter in comparison with the no-fertilizer plots. Manure made an additional contribution, but not as much as would have been anticipated from the quantity applied. Lime apparently caused an increase in the rate of decomposition of organic matter and reduced its rate of accumulation. The evidence indicates that soil organic matter is largely a by-product of the crops that are grown. Thus, the amount of organic matter in the soil will be closely related to crop yields. The larger the crop the more residues that remain to plow under. *Assuming that the rotation includes sod crops, the organic-matter content of the soil can be maintained at a high level by the use of inorganic fertilizers alone.* In proportion as the soil is kept under clean cultivation, special attention must be paid to the supplemental use of animal and green manures. But *fertilizers are of great value in increasing the yields of green-manure crops. They also add to the nutrient content of these green manures. This means extra organic matter and highly important possibilities for extra yield of the crop that follows.*

ANIMAL AND GREEN MANURES

Well-rotted animal manure is probably the most valuable type of organic matter that can be added to a soil. It combines a number of highly desirable qualities. The preliminary stages of decomposition have been effected before the material has been added to the soil. Concentration of nitrogen and mineral nutrients has thus resulted. Furthermore, manure carries a very active bacterial flora. If it can be supplied at the rate of 20 to 30 tons an acre annually, as is desirable in market gardening, no supplemental green manuring may be necessary. But in extensive systems of farming the supply of manure is too limited, as a rule, to permit its meeting the organic-matter requirements of the soil. A 12-ton application of manure every 3 years to each acre of land in rotated crops is considerably more than the average farmer will have at his disposal. At such a rate of application, the annual contribution to the soil organic matter, on a dry-matter basis, would be only 1 ton an acre, since manure is about three-fourths water. Evidently, if any important increase in the supply of soil organic matter is to be effected in general farming, it must be provided by crop roots and residues. This requires that larger yields be produced. Either fertilizer or manure can be used for this purpose. Ordinarily, a combination of both manure and fertilizer, coupled with the use of a rotation that takes advantage of the nitrogen-accumulating powers of legumes, is necessary to meet the requirements on the general farm.

If green manures are employed, as is usually a necessity in truck farming, it is desirable that they be plowed under in an immature stage of growth rather than later. This is because, as maturity approaches, the percentage of carbonaceous substances increases and that of nitrogen decreases. When mature rye is plowed under, the bacteria that bring about its decomposition compete with the crop for any nitrogen and mineral nutrients that are released from it. This is well illustrated in the data shown in Table 63. In this test various green-manure crops were incorporated into a Dunkirk silty clay loam at different stages of their growth, and studies were made of the rate of accumulation of humus and nitrates and of the yield of the wheat crop that followed.

The efficiency of a green-manure crop, when measured by the yield of the crop that follows, is inversely proportional to its stage of maturity when plowed under. Its contribution to the supply of soil or-

TABLE 63

EFFECTIVENESS OF GREEN MANURES AS RELATED TO THEIR MATURITY (MARTIN)

Green Manure Used	Height of Plants, Inches	Dry Matter Added, Grams	Humus* Produced, Grams	Nitrates* Accumulated, p.p.m.	Wheat Yield, Grams
Rye	24	36	556	137	23.4
Rye	48	78	648	114	13.2
Rye	48	150	1215	3	9.4
Oats	11	34	689	225	19.0
Oats	30	63	1008	132	8.5
Oats	36	122	1706	102	4.8
Buckwheat	10	27	879	352	20.2
Buckwheat	20	69	1359	498	13.1
Buckwheat	26	100	1578	416	12.9

* At end of 5-month period.

ganic matter increases with its age. The choice, therefore, depends largely on the length of time that is to be permitted to elapse between the plowing-under of the green-manure crop and the planting of the crop that follows. It will be recalled that the carbon-nitrogen ratio of soil organic matter is approximately 10 to 1. Any extra carbon above this ratio will rapidly be lost from the soil as carbon dioxide. But the decomposition of this extra carbonaceous substance within the soil has important effects on soil aggregation.

LEGUMES FOR GREEN MANURE

Legumes are commonly preferred for green-manuring purposes because their associated nodule bacteria have the capacity to fix gaseous nitrogen. Furthermore, legumes contain relatively large amounts of mineral nutrients. Under conditions in which there is a deficiency of either nitrogen or mineral nutrients, the legume type of green manure is likely to be the most effective. Some of the possibilities of legumes as agents for improving the yields of crops that follow are indicated in Table 64. In this test, clover was sown in small-grain crops and the resulting growth was plowed under the following spring in preparation for oats, which was followed by corn and potatoes.

Among the more important legume cover crops are crimson clover, Austrian peas, cowpeas, lupines, and crotalaria for the southern states, and soybeans, vetch, and sweet clover for the northern states. Sweet clover plays an especially important part in the Corn Belt by reason

TABLE 64

EFFECT OF CLOVER AS A GREEN-MANURE CROP ON YIELD OF SUBSEQUENT CROPS (SAUNDERS)

Previous Crop	Oats, Bushels	Fodder Corn, Tons	Potatoes, Bushels
Wheat — no clover	63.5	16.4	353
Wheat — clover	72.9	22.8	396
Barley — no clover	61.1	17.3	346
Barley — clover	70.5	23.6	386
Oats — no clover	58.8	15.0	358
Oats — clover	70.5	20.4	392

of its very rapid rate of growth and accumulation of nitrogen. It can be sown in the spring with small grains to provide green material for plowing-under the following spring. It may also be sown in July in a clean-culture crop to provide winter cover and fresh new growth for plowing-under in the spring. Data on the height, dry weight, and nitrogen content of sweet clover, when it was being plowed under in preparation for planting corn in various localities in Illinois, are shown in Table 65.

TABLE 65

ACRE YIELDS AND NITROGEN CONTENT OF SWEET CLOVER (WHITING)

Field Location	Date of Sampling	Height, Inches	Green Weight, Tons	Nitrogen, Pounds
Urbana	May 2	13	5.8	98
Minonk	April 26	12	9.1	164
Joliet	April 29	9	7.9	133
Toledo	May 9	26	12.8	196
Newton	May 10	22	12.6	188
Rawleigh	May 1	19	12.7	129
Enfield	May 1	18	8.7	124

An abundance of nitrate nitrogen was found in the soil during the growth of the following corn crop. Considerable amounts of phosphorus, potassium, and other nutrient elements were supplied to the corn. This is shown in Table 66, which gives the weights of roots and tops of 1 acre of sweet clover at plowing time on May 10, and the quantities of the several nutrient elements that were contained in them. For comparison, the requirements of a 100-bushel corn crop and a 50-bushel wheat crop are also included in the table.

TABLE 66

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.

Ordinarily, only the residues of crops rather than the whole plants are incorporated in the soil. It is of interest, therefore, to compare the amounts of the more important plant nutrients in the roots and stubble of the several legumes, as shown in Table 67. The data indicate that the residues of red clover are much more valuable as sources of plant nutrients than are those of soybeans and cowpeas. The especially good effects of red-clover, sweet-clover, and alfalfa residues must be credited not only to their high content of nitrogen but to their content of phosphorus, potassium, and other mineral nutrients, including trace elements.

TABLE 67

POUNDS OF FERTILIZER NUTRIENTS IN ONE ACRE OF LEGUMES (WOODS)

Crop as Hay	Yield, Cwt.	Nitrogen		Phosphoric Acid		Potash	
		Tops	Roots*	Tops	Roots*	Tops	Roots*
Cowpea	36	95	22	20	6	68	13
Soybean	42	75	13	21	5	73	14
Soybean†	50	165	9	42	2	109	6
Horsebean†	58	171	32	30	6	153	20
Vetch	48	153	27	37	7	163	22
Clover (red)	50	138	44	32	13	152	32
Lupine	46	116	12	26	4	136	17

* Roots and stubble. † Seed partially developed.

OTHER ORGANIC-MATTER RELATIONSHIPS

Sod crops have special organic-matter values. During the period they are being grown, the soil is not only protected against organic-matter losses by cultivation and erosion, but large amounts of new organic matter are provided by the roots and sod. Furthermore, grass sods have very widely distributed root systems that permeate the soil



FIG. 45. Kentucky 31 fescue has been found to be a highly effective soil-aggregating and structure-improving type of grass crop for use on very heavy lakebed soils of northwestern Ohio.

to form virtually a mat. The habit of growth of these roots is highly important in that it leads to a very high degree of soil aggregation, which persists for a considerable period after the sod has been plowed under. A good example of this is found in the use of Kentucky fescue in regenerating good soil structure in the heavy lacustrine soils of northwestern Ohio. There the problem is one of overcoming the especially bad effects of growing such cultivated crops as corn and sugar beets.



(*a*)



(*b*)

FIG. 46. (*a*) Stalk shredders are being used to good effect in preparing crude types of organic matter for working into the soil. (*b*) A "Bushwacker" at work shredding bushes in reclaiming land for agricultural use.

Weeds have highly important values as sources of soil organic matter. They spring up at every opportunity, thus protecting the soil against erosion and aiding in developing improved structure. They also accumulate mineral nutrients from the soil, including trace elements, and leave these behind in more available form when the weeds are worked into the soil. Although weeds are usually abundant even when kept under reasonably good control, some of the more luxuriant but controllable types can be grown to advantage for their good effects on the soil.

It is generally stated that organic matter is of no direct value as a plant nutrient. But it has been shown that many plants are able to make use of a considerable variety of organic decomposition products, such as sugars, amides, and amino acids. In fact, there is reason to believe that any organic substance that is soluble in water can, if useful to the plant, be directly absorbed and used by it. Ordinarily, the plant is in direct competition with soil microorganisms for such products and may have little opportunity to absorb them.

Considerable interest has been developed in the concept that intermediate products of bacterial decomposition of soil organic matter, or organic products synthesized by soil microorganisms in the soil or in a factory, may have highly important growth-promoting and protective values in plants. *Indolebutyric* acid and *naphthaleneacetamide* are two such products that are being manufactured and used for stimulating root initiation on plant cuttings. Other growth-regulating organic substances are being used to improve the set of greenhouse tomatoes and to prevent fruit drop. For this purpose, *2,4-dichlorophenoxyacetic acid* is employed. Used in larger amounts, this substance, usually referred to as *2,4-D*, serves as a highly effective killer of weeds, since it overstimulates their growth. Subsequent tests indicated that such antibiotics as *terramycin* and *streptomycin* may have plant-stimulating or plant-protecting properties when applied to seed or soil, or to the plant itself.

When soils become strongly acid, humus substances contained in them frequently become dispersed, with the result that they are carried downward into the *B* horizon of the soil profile. Here they may be precipitated and contribute to formation of a hardpan layer. If the soil is limed, insoluble calcium humate is formed. The James River of Virginia is derived from the union of two rivers. One of these flows through a limestone region and is clear and sparkling. The other has its origin in a sandstone region and is colored with organic matter.

From the point of union onward, all the water is clear, showing the effect of the precipitating action of the lime. Stream pollution is overcome by passing waste water through beds of limestone or marl.

SOLUTION OF ORGANIC-MATTER PROBLEM

Soil organic matter is a by-product of plant growth. Its decomposition can be speeded up by cultivation. Its accumulation is aided by growing sod crops. By crop-rotation procedures, losses can be bal-



FIG. 47. A once-over combination cultivator-seeder that leaves a large part of the straw and stubble on or near the surface is widely used in the Wheat Belt.

anced by gains. In proportion as crop yields are raised, more organic matter remains behind in the soil in the form of plant roots, stubble, and late-fall and early-spring growth of sod crops and winter cover crops. In livestock systems of farming, these larger yields permit feeding more animals and having more manure to return to the land. In grain systems, straw, cornstalks, and similar refuse of the top portion of crops is left on the land. Under the more intensive systems of market-gardening and truck farming, more emphasis is placed on green manures. Sometimes they are grown between spring and fall crops, their rate of growth being rapid because of the large amounts of fertilizer residues that remain in the soil. Often, additional growth is stimulated by use of more fertilizer, especially nitrogen. These liberally fertilized green-manure crops dry the soil, have a marked aggregating effect on it, supply large amounts of organic matter that

has still greater effects, and, on decomposition, yield up large amounts of nitrogen and mineral nutrients for crop use.

The organic-matter content of any given soil fluctuates around a point that is characteristic for that soil for the particular location in which it happens to be. The organic-matter content of farmed soils decreases from north to south in the United States. It increases from east to west, coming to a maximum in the Chernozemic soils that extend from North Dakota southward through Texas, then decreasing westward because of increasing aridity. It is lower in sands than in clays. It is much higher in moist than in dry soils, reaching the point of constituting virtually the entire soil in peat bogs, and being very low in desert areas.

But *for any given soil in any given location, the organic-matter content fluctuates within relatively narrow limits.* Thus, if a farmed soil contains 3 per cent organic matter, it can be reduced to possibly 2½ per cent by poor management and it can be increased to possibly 3½ per cent by good management. Thus, it tends to fluctuate over a range of about 1 per cent. Only by exceptional measures, as by annual applications of large amounts of manure, can it be raised above the 3½-per cent level, and only by very drastic means, as by continued cultivation without supplemental use of animal or green manures, can it be reduced below the 2½-per cent level. However, crop yields at the higher organic-matter levels are often much greater than one might expect from this small percentage change. The essential point is that the organic-matter content of a soil should be maintained as nearly as possible at the top value for that soil and location.

SELECTED REFERENCES

1. Alway, F. J., and Associates. The determination of humus. Nebraska Agr. Exp. Sta., Bull. 115, 1910.

2. Bear, F. E., and A. L. Prince. Organic matter in New Jersey soils. New Jersey Agr. Exp. Sta., Bull. 757, 1951.

3. Bear, F. E., and R. M. Salter. The residual effects of fertilizers. West Virginia Agr. Exp. Sta., Bull. 160, 1916.

4. Doryland, C. J. T. The influence of energy material upon the relation of soil microorganisms to soluble plant food. North Dakota Agr. Exp. Sta., Bull. 116, 1916.

5. Hopkins, Donald P. *Chemicals, Humus, and the Soil.* Chemical Publishing Co., Brooklyn, 1948.

6. Jensen, B. P. *Growth Hormones in Plants.* McGraw-Hill Book Co., New York, 1936.

7. King, F. H. *Farmers of Forty Centuries.* Harcourt, Brace and Co., New York, 1929.

8. Martin, T. L. Decomposition of green manures at different stages of growth. Cornell Agr. Exp. Sta., Bull. 406, 1921.

9. Pieters, A. J. *Green Manuring.* John Wiley & Sons, New York, 1927.

10. Schollenberger, C. J. Determination of soil organic matter. *Soil Sci.,* Vol. 59, pp. 53–57, 1945.

11. Stewart, R. Quantitative relationships of carbon, nitrogen, and phosphorus in soils. Illinois Agr. Exp. Sta., Bull. 145, 1910.

12. Thorne, C. E. The function of organic matter in the soil. *J. Am. Soc. Agron.,* Vol. 18, pp. 767–794, 1926.

13. Waksman, S. A. *Humus, Origin, Chemical Composition, and Importance in Nature.* Williams and Wilkins Co., Baltimore, 1936.

14. Whiting, A. L., and T. E. Richmond. Sweet clover for nitrate production. Illinois Agr. Exp. Sta., Bull. 233, 1921.

15. Whiting, A. L., and T. E. Richmond. The composition of biennial sweet clover as related to soil enrichment. *Soil Sci.,* Vol. 22, pp. 83–95, 1926.

16. Woods, C. D. Fertilizing ingredients in crop and in roots of legumes. Connecticut Agr. Exp. Sta., Third Ann. Rept., pp. 29–36, 1891.

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Soil Conservation

With passage of the Soil Conservation Act in 1935, the Soil Conservation Service came into existence on a national scale. The primary task of this agency is to take advantage of old techniques for conserving the soil, to develop new ones, and to carry on demonstrational and educational programs that will result in general adoption of conservation measures. These involve not only keeping the soil in its present location, but in using it according to its capabilities, and maintaining it at a high level of productivity for such use.

CLASSIFICATION OF LAND

The starting point in land classification consists in surveying our land resources in relation to the use to which they are best adapted. This involves field studies to determine soil depth, permeability, moisture capacity, drainage, and organic-matter content in relation to climatic environment. It is essential also to know the slope of the land, its erosion hazards, the extent to which it may be subject to overflow, its wetness or dryness, and such other features as determine its suitability for cropping.

When all these facts are assembled, the land can then be classified in accordance with its plant-producing capabilities, on the assumption that adequate systems of soil and crop management are employed. The net result is a map that shows land classes in colors, which indicate what part is adapted to intensive cultivation, what part can be cultivated under suitable protective measures, what part had best be kept in grass, what part is better suited to trees, and the part that may find its best use as a wildlife preserve or for recreational purposes, or must remain virtually waste, as, for example, the unirrigated desert.

Eight land-capability classes have been developed, including the seven mentioned in Chapter 4 as applying to humid regions and another that applies to the drier range lands. The important point is to

use the land for the particular purpose for which it is adapted and in which it can be protected against the action of wind and rain, and against such other hazards as drought and flood.

Of the 1903 million acres of land in the United States, less than 400 million are being devoted to crops other than permanent pastures and forests. This cropped portion constitutes the most productive land and that which is least subject to loss of soil by wind and water ero-



FIG. 48. An area of 1,903,000,000 acres of land that must be conserved.

sion. Possibly another 100 million acres can be reclaimed for crop purposes by drainage, irrigation, bulldozing, clearing, and adoption of more intensive conservation practices. But all such cropped land is subject to some erosion or other hazards, and, in proportion as the angle of slope increases, these hazards become greater.

CROP ROTATIONS

Even the most level land must be protected against soil losses when put under cultivation. The starting point in its conservation is the adoption of a well-planned crop-rotation procedure. Under the more extensive systems of farming, this normally includes cultivated crops, small grains, hay legumes, and grasses. In intensive systems of market-gardening and truck-crop farming, small grains, hay legumes, and grasses may be of little economic value, in which case cover crops

and green manures must be grown in their place. Even so, the principle of crop rotation applies, and soil-conserving organic-matter crops constitute a highly important part of the rotation program.

TABLE 68

STANDARD CROP ROTATIONS

Norfolk, England	New England	Corn Belt	Cotton Belt	Special Crop	Truck Crop
Wheat	Corn	Corn	Cotton	Tobacco	Tomatoes
Barley	Oats	Oats	Corn*	Wheat	Peas*
Roots	Clover	Wheat	Oats*	Clover	Cabbage*
Clover	Timothy	Clover	——††	——†	Beets*
——†	Timothy	——†	Cotton	Tobacco	——†
Wheat	——†	Corn	Corn*	Wheat	Tomatoes
Barley	Corn	Oats	Oats*	Clover	Peas*

* Catch crops, for green-manuring purposes, may be grown at the periods indicated. In the Cotton Belt rotation, Austrian peas are employed. In the rotation of truck crops, supplemental truck crops are commonly grown instead of the catch crops.

† This signifies the end of the rotation, after which the crops are repeated.

Some typical crop rotations are shown in Table 68. These are only a few of the many that are being followed. They serve to point up some of the problems that are involved in the choice of a rotation, in which consideration must be given to market requirements and labor economy, as well as to the well-being of the crops themselves. Thus, in the Norfolk rotation, it is necessary to plow or otherwise break up the soil 3 out of every 4 years. The New England rotation takes advantage of a legume crop only once in 5 or more years. Three of the four crops in the Corn Belt rotation are grains that have much the same soil requirements. The Cotton Belt rotation fails to take advantage of a sod crop as a means of accumulating organic matter and improving soil structure. Not enough time elapses between the recurrence of any given species in the special-crop rotation to permit adequate control of parasitic microorganisms that may harbor in the soil. Large amounts of animal or green manures are required in the truck-crop rotation.

In some areas, continuous cropping to a given crop plant may be the rule, more or less of necessity. Thus, in the typical wheat-growing regions, wheat may be the only feasible crop to grow. Similarly, permanent pastures constitute a one-crop or crop-mixture system that is essential under the circumstances. But, in general, acre yields can be stepped up by adoption of cropping programs that permit the pro-

duction of a series of crops that are not closely related to each other.

One of the long-standing experiments in continuous cropping is that with wheat on the world-famous Rothamsted Experimental Farm at Harpenden, England. On the Broadbalk field on that farm, wheat has been grown continuously since 1844. The soil is a cherty loam that is fairly well endowed with mineral elements and contains an abundance of calcium carbonate. Climatic conditions in England are very favorable for wheat, the average acre yield for the period im-



FIG. 49. Broadbalk Field at the Rothamsted Experiment Station at Harpenden, England, where wheat has been grown continuously since 1844.

mediately preceding the First World War being approximately 32 bushels. Nevertheless, it is surprising to note the relatively high wheat yields under continuous cropping on those portions of the field that were liberally treated with manure or fertilizer (Table 69).

Notwithstanding the favorable opportunities for wheat parasites, yields have been maintained at high levels by the use of liberal amounts of manure or fertilizer. No mention is made in the literature of any special trouble with insects and diseases, the chief difficulty being with *Alopecurus agrestis*, known as black bent grass. This was first observed in 1869, and became a serious pest during the wet seasons of 1878 and 1879. Finally, in 1904 and 1905, and again in 1914 and 1915, halves of the plots were alternately fallowed, and this system was employed more or less regularly in later years.

In this experiment, quite satisfactory acre yields are produced by liberal use of manure and fertilizer. But the yields with such treatments would have been much higher under a suitable rotation pro-

TABLE 69

ACRE YIELDS OF WHEAT GROWN CONTINUOUSLY * AT ROTHAMSTED

(Data Supplied by H. V. Garner, May 22, 1947)

Periods *	Unmanured, Bu.†	Manured,‡ Bu.	Fertilized,§ Bu.
1852–61	15.9	34.2	36.0
1862–71	14.4	37.5	40.5
1872–81	10.2	28.7	31.2
1882–91	12.5	38.1	38.1
1892–01	12.5	39.1	38.5
1902–11	10.8	35.1	37.2
1912–21	7.9	26.4	25.4
1922–31	7.6	21.6	21.7
1932–41	12.7	26.1	31.0
1942–46	15.7	34.2	38.6

* Portion of each plot fallowed each year since 1925 to control weeds.

† An English bushel equals 1.032 American bushels.

‡ At rate of 14 tons annually.

§ At rate of 1392 pounds annually, containing 106 pounds N, 66 pounds P_2O_5, and 96 pounds K_2O, together with 200 pounds sodium and magnesium sulfates.

gram. Thus, on the nearby Agdell field, on which the Norfolk rotation is being practiced, wheat yields on the unmanured plot have been twice as high as those on the Broadbalk field. Similarly, with one-third as much fertilizer of virtually the same analysis, wheat yields have been 50 per cent higher on the Agdell field than on the Broadbalk field.

A variety of explanations of the better yields with rotation can be given. These include the capacity of the legume crop to supply extra nitrogen, better equalization of mineral losses from the soil, better control of insects and diseases, and greater accumulation of organic matter. Thus, crop rotation is important as a means of maintaining yields at a high level, with considerable saving in expenditures for fertilizers and with marked economy of production. The essential point is to see to it that cultivated crops do not constitute too large a percentage of the rotation, and that the necessary precautions are taken to avoid soil losses when such crops are grown.

SOIL LOSSES BY EROSION

When land is brought under cultivation, rate of movement of soil down the slopes is greatly hastened. The amount of soil lost by such

erosion increases with the degree and length of slope and the amount and intensity of rainfall. It also depends on the rate of infiltration of the water into the soil. This rate is much less on a soil that has been under cultivation for several years than on a newly plowed soil that has previously been covered with grass. Geologists estimate that the earth is being eroded by water at a rate of 1 inch every 200 to 500 years. The average rate at which the United States is being denuded is believed to be about 1 inch in 760 years. However, land that is being cropped may be denuded at a rate of 1 inch or more a century under climatic conditions such as prevail in the humid regions of this country. Often it is more rapid than this, as is shown in Table 70,

TABLE 70

ANNUAL RATE OF REMOVAL OF SOIL BY WATER EROSION (DULEY)

Soil Treatment	Tons of Soil Removed per Acre	Years Required to Remove 7 Inches	Percentage Rainfall Run-off
Uncultivated, weeds pulled	207	29	49
Cultivated throughout summer	247	24	31
Same with deeper plowing	214	28	28
Continuous sod	2	3547	12
Wheat every year	40	150	25
Corn, wheat, and clover	14	437	14
Corn every year	107	56	27

which gives data on soil erosion under field conditions in Missouri. The soil, a Shelby loam, had a fall of 3.68 feet in 100 feet. The average annual rainfall was 36 inches. The greatest damage was done by an occasional torrential rain, especially if it fell when the soil had recently been cultivated and was bare of vegetation.

It is apparent that soil losses such as those shown in this experiment cannot be permitted to continue. They constitute not only a serious hazard to the particular land area but they are also a menace downstream. Silt deposits present a troublesome problem in river channels, with removal costs running into millions of dollars annually. Storage reservoirs are being filled up with soil at a rate of 1 to 3 per cent a year. The cost of the great Hoover Dam is being amortized over a period of 75 years, it being assumed that by the end of that period virtually all of its storage capacity will have been filled with soil.

It is for these reasons that classification of land according to its capability becomes so important. Once a well-trained soil conserva-

tionist classifies the land on the basis of the use to which it is best adapted, the farmer's attention can be called to the degrees of risk that are involved in cropping the various classes of land on his farm. It is to be hoped that he can be made to apply a conservation program adapted to his land. Level land can be devoted to cultivated crops, with little danger of soil loss by erosion. Gently rolling land requires more attention to rotation programs, having the land in sod crops a



Soil Conservation Service

FIG. 50. Holding the hillside, with corn on the contours and hay in between.

larger part of the time, and farming on the contour. Steeper slopes require that crops be grown in rotation in strips on the contour, that some of the water be carried off by diversion terraces, that contour terracing be practiced in some locations, and that sodded drainage channels be developed for carrying off excess surface water.

Such practices alone, however, do not solve all the problems. The soil must be so managed that a large percentage of the water that falls on it infiltrates into the soil rather than runs off. This makes it necessary to maintain the soil in good physical state by growing crops that are big enough to provide large amounts of roots and stubble for organic-matter purposes. Cultivated crops must be preceded by sod crops. More research is needed to determine to what extent it may be possible to grow row crops without the use of the moldboard plow and the cultivator, so as to leave the refuse on top the land to break the fall of the rain.

A formula for the solution of probable soil loss by erosion has been developed by Lloyd and Eley for the northeastern region of the United States. In this region the *rainfall intensity frequency*, which is the heaviest 30-minute rainfall to be expected once in 2 years, varies between 1.25 and 0.75 from south to north. The formula is: $E = F \times S^{1.35} \times L^{0.35} \times P \times C$. E is the probable loss in tons an acre a year, and F is the relative erodibility of a given soil under continuous cultivation up and down the slope. For the northeast region it varied between 0.1 and 0.5. S is the percentage slope. L is the length of slope. P is the rainfall intensity frequency. C is the cropping factor, which may be a product of rotation $\times$ contour farming $\times$ strip cropping or terracing.

In solving this equation for a Chester soil with a 15 per cent slope extending 300 feet, on which a 3-year rotation of corn, wheat, and hay was being followed, the calculated soil loss by rotation alone was 23 tons an acre annually. The Chester soil factor, F, was set at 0.3. The factors for corn, wheat, and hay, C, were 0.45, 0.10, and 0.009, respectively, or an average of 0.186 for rotation alone. When contour farming was added, the loss was reduced to 13 tons. When strip cropping was employed in addition, the loss was reduced to 4.7 tons.

CONSERVATION FARMING

The 80-acre farm was once considered a satisfactory-sized unit in the more level regions and the 160-acre farm was standard in the more rolling parts of the humid regions of the United States. With the introduction of tractors and other improved types of farm machinery, such units were too small for economic farming. On level land it was found much more economic to operate 200 or more acres of land. In Illinois, owners of 160-acre farms of level land now operate neighboring farms of equal size to the advantage of both themselves and the landlord. On the more rolling land, still larger areas are often required, and considerably more attention must be paid to diversification of the farming enterprise. In one such enterprise in northern Pennsylvania, a farmer, who began with one uneconomic 160-acre unit of rough land, now owns 16 such units that are operated in a threefold farming enterprise. All land that is suitable for the production of forage crops is used for that purpose and heifers are grown for dairy-herd replacement purposes. Land that is somewhat too rough for hay-harvesting machinery is used in the production of Christmas trees. The remainder of the land is planted to forest trees. None of the land

on this large farm unit is now subject to erosion, since it is kept in grass or trees, except for an occasional crop of corn that follows a sod crop and is succeeded by a mixture of clovers and grasses.

However, conservation involves more than keeping the land covered with grass. Continuously grazed grasslands gradually lose their fertility, with the result that weeds begin to come in and bare spots develop. Thus, erosion gets under way, often with development of bad gullies. Considerable sheet erosion occurs, in which soil may be lost so gradually that little note is taken of it. To avoid such losses, it is necessary to adopt regular liming, manuring, and fertilizing programs that will maintain a dense cover of grasses and legumes. From time to time the old sod needs to be destroyed by the use of some type of disc or field cultivator, so that the soil can be prepared for reseeding. The important point in this operation is to keep the sod refuse on top so as to avoid sheet and gully erosion until the new grass-legume mixture has gotten a good start. It has been found possible to make use of chemicals to kill the grass, and thus to reduce the amount of tillage required to get the new seeding established. The chemically killed sod makes an excellent mulch that serves very effectively to increase the rate of infiltration of rain into the soil.

For the more intensive types of farming, an 80-acre farm may be entirely too large for one family to operate. Such farming requires relatively level land. Each acre may be used to grow two or more crops each year. Under such circumstances, more attention must be paid to the production of organic-matter crops. Such crops as sweet corn can often be grown to advantage to provide large amounts of stover for working into the soil. Occasionally, it may be necessary to sacrifice either a fall or a spring crop so that the winter cover crop will have a longer growing period. Where orchards are involved, tree rows can be contoured. It is sometimes feasible also to grow a hay type of crop on nearby waste land and haul this in for mulching purposes. Some vegetable growers find it worth while to keep about one-fifth of their land in a legume-grass sod crop in what is known as a *land-resting* program. This program is moved across the farm until the whole land area has been covered, after which it is repeated.

Many new conservation-cropping practices are being developed in the South. One of the standard procedures on badly eroded land is to plant kudzu vines, which grow rapidly and spread over wide areas of land. They provide good grazing, stop further erosion, and filter out soil from the water received from higher levels. In Louisiana, these vines grow so luxuriantly that they cover the trees in nearby wood-

lands. Extensive use is being made of sericea, a very hardy perennial legume that can be used for grazing, hay, silage, or mulching purposes. Lupines and crotalaria are being used on an ever-enlarging scale for green-manuring purposes, the latter notably in Florida citrus groves. These crops serve the double purpose of conserving and renovating the soil. In addition, much interest has been developed in a reseeding type of crimson clover. Once this crop is established, it comes on from seed each fall to provide grazing, winter cover, or green manure, as may be preferred. One standard rotation involves peanuts, crimson clover, and Bahia grass for 2 years, and corn the fourth year, after crimson clover has been used as a green manure.

In the West, from the Dakotas southward, more attention has to be paid to the control of wind erosion. This is accomplished largely by keeping a trash mulch on the soil surface, the land being prepared for planting by the use of disc, shovel, or sweep types of field cultivators, rather than the moldboard plow. In some areas, the only feasible method of dealing with this problem is to keep the land in grass. A great deal of attention is also being paid to *shelterbelt* plantings. These usually consist of from 1 to 3 rows of mulberry or cottonwood trees, arranged in an east-west direction, which is at right angles to the prevailing winds. A considerable variety of other trees and shrubs is being used for this purpose. The land is broken up into long, narrow fields, each containing 10 to 40 acres, somewhat like a design for strip-cropping. In some areas, all 4 sides of each field are enclosed by such plantings.

Another highly important need in areas of limited rainfall is that of storing as much as possible of the rain that falls. Where the land is kept in grass, contour furrows aid greatly in preventing runoff. In cultivated fields, use is made of basin listers that build small dams across the furrows. Thousands of farm ponds are being built to store water for livestock and for irrigation purposes. Much can be done to hold back the water of streams at its source; therefore it is kept where it is needed rather than being permitted to add to the flood damage in areas where the rainfall is heavier.

In irrigated arid regions, conservation involves practices that prevent salt accumulation on or near the surface of the land. Usually this calls for water in excess of that required for crops alone, to carry surplus salts away. Regular use of gypsum is of great value on alkaline soils as a means of replacing the sodium in the exchange complex that has such a marked effect in reducing the rate of percolation of water through the soil. Once excess salts have formed a surface incrustation,

it then becomes necessary to adopt more drastic measures, such as the use of very large moldboard plows that turn the salts under to a depth of as much as 3 or 4 feet. Other measures involve scraping the salts off the top of the soil, growing salt-accumulating crops and hauling them away, and further use of excess water for leaching purposes.

The growth of water requirements of cities and increased use of water for irrigation purposes has resulted in lowering the top levels of



FIG. 51. Laying out terraces on the contour for water control and as a guide to farming operations that are to follow.

underground water supplies over considerable areas of the West. In locations along the ocean, this has resulted in inland seepage of seawater. Since, during the course of any one year, large amounts of rainwater are carried out to the Pacific Ocean by rivers, it becomes important to find some means by which this water can be diverted from the river to areas that are specially prepared to absorb it into the earth to add to the underground storage supply. A great deal of study is being directed toward the solution of this problem.

CONSERVATION DISTRICTS

One of the unique features of the Soil Conservation Service program has been the development of soil conservation districts, with from

three to five farmers serving in the capacity of district supervisors without pay, except for recovery of expenses. State laws govern the operation of these conservation districts, which, for the most part, consist of one county each but may include an entire watershed. Any group of twenty-five landowners can petition the state conservation committee to approve organization of a district. This committee then holds a hearing and the matter is submitted to a referendum, at which each landowner or operator in the district is permitted to vote. If a majority approve, the district is organized. The state committee then holds an election for district supervisors.

Once a district is organized, every citizen in the district is invited and encouraged to aid in setting up a conservation program for the entire district as well as for his individual land unit. The supervisors consider the nature of the land and endeavor to get owners to use it in accordance with its capabilities. Bankers, equipment dealers, teachers, ministers, and other individuals and groups cooperate with the supervisors and the Soil Conservation Service in the enterprise. The purpose is to make the best possible use of all the land in the district to the end that soil and water are conserved. Special consideration is given to grasslands, where needed to protect the soil against erosion. Forest areas are protected, added to, and developed. Wildlife and game-protection areas are established in some of the more rugged and swampy areas. Once the district is well organized and directed, remarkable improvement in land use is often effected. Not the least important among the possibilities is the development of a more beautiful as well as a more productive district. Possibly 75 per cent of the land area of the United States is now covered by such districts, and there is a very active national association of district supervisors, who meet annually in convention to consider the problems they have in common and the most promising solutions for them.

INDEXES OF PRODUCTIVITY

Attempts have been made to assign an index value to each crop and to each soil treatment to represent their effects on soil productivity. These indexes may be either positive or negative, depending upon whether the crop or the soil treatment has soil-improving or soil-deteriorating effects. They are stated as percentage changes in the productive capacity of the soil. In Table 71 are shown values that were assigned by Salter and his associates to the several crops grown

TABLE 71

SOIL-PRODUCTIVITY INDEXES (SALTER)

A. Crop:	Index
Corn, as grain or silage	−2.0
Potatoes, tobacco, and sugar beets	−2.0
Oats, wheat, barley, rye, and buckwheat	−1.0
Soybeans, as hay or seed (straw not returned)	−0.5
Soybean and wheat straws, and cornstalks	+0.25
Alfalfa, for change effected by end of first hay year	+2.5
Alfalfa, for change effected during second hay year	+0.5
Alfalfa, for change effected during third hay year	0.0
Timothy and other grass sod	0.0
Clover-timothy mixed, as hay or pasture	+1.0
Common clovers, as hay or pasture	+2.0
Sweet clover, crop plowed green in April or May	+2.5
B. Soil Treatment:	
For each ton of protected manure applied	+0.15
For each 200 pounds of commercial fertilizer	+0.15

*C. Erosion Factors:**

Erosion class	Degree of erosion	No special control methods	Farmed on contour	Strip-cropped or terraced
1	Little or none	0.00	0.000	0.000
2	Slight	0.25	0.125	0.050
3	Moderate	0.50	0.330	0.125
4	Severe	1.00	0.800	0.300

* All negative values in the crop indexes are increased by an amount obtained from multiplying them by the correct erosion factor for the field or area.

in the Corn Belt states, and to the several soil-management practices being employed in those states.

Using these values, one can calculate the net effects of any system of soil management, such as the two that are shown in Table 72. For the first situation, involving a rotation of corn, wheat, and timothy, use of 5 tons of manure and 200 pounds of fertilizer an acre each rotation, slight (Class 2) erosion, and no special control measures, an annual negative value of −0.95 per cent is assigned. For the second situation, with a rotation of corn, wheat, alfalfa, alfalfa, use of 10 tons of manure and 400 pounds of fertilizer, and use of strip cropping on the same erosion class of land, a positive value of +0.45-per cent improvement annually is indicated. It is easily possible to step up these values materially by use of larger amounts of manure and fertilizer, particularly the latter, since it is readily available for purchase.

TABLE 72

DATA SHOWING METHOD OF CALCULATING ANNUAL SOIL-PRODUCTIVITY BALANCE AS APPLIED TO TWO DIFFERENT CROP ROTATIONS (SALTER)

Situation I

Rotation: corn, wheat, timothy.
Manure applied during the rotation equals 5 tons per rotated acre.
Fertilizer applied in rotation equals 200 pounds per rotated acre.
Class 2 erosion, no special control measures.

Crop	Productivity value	
	Positive	Negative
Corn		−2.0
Wheat		−1.0
Timothy	0.0	0.0
Total	0.0	−3.0
Balance due to crop factor		−3.0
Reduction in balance for erosion (0.25 × −3.0)		−0.75
Gain in balance for manure (5 × 0.15)	+0.75	
Gain in balance for fertilizer (200 ÷ 200 × 0.15)	+0.15	
Total	+0.90	−3.75
Soil-productivity Balance:		
(a) For rotation		−2.85
(b) Annual (−2.85 ÷ 3)		−0.95

Situation II

Rotation: corn, wheat, alfalfa, alfalfa.
Manure applied during the rotation equals 10 tons per rotated acre.
Fertilizer applied in rotation equals 400 pounds per rotated acre.
Class 2 erosion, strip cropping practiced.

Crop	Productivity value	
	Positive	Negative
Corn		−2.0
Wheat		−1.0
Alfalfa (2 yr.)	+3.0	
Total	+3.0	−3.0
Balance due to crop factor	0.0	0.0
Reduction in balance for erosion (0 × −3.0)		0.0
Gain in balance for manure (10 × 0.15)	+1.50	
Gain in balance for fertilizer (400 ÷ 200 × 0.15)	+0.30	
Total	+1.80	
Soil-productivity Balance:		
(a) For rotation	+1.80	
(b) Annual (+1.80 ÷ 4)	+0.45	

SELECTED REFERENCES

1. Ayres, Q. C. *Soil Erosion and Its Control.* McGraw-Hill Book Co., New York, 1937.

2. Bennett, H. H. *Soil Conservation.* McGraw-Hill Book Co., New York, 1939.

3. Darwin, C. *Earthworms and Vegetable Mold.* London, 1881.

4. Dole, R. B., and H. Stabler. Denudation. Report National Conservation Commission, Vol. 2, pp. 126–140, 1905.

5. Duley, F. L., and M. F. Miller. Erosion and surface run-off under different soil conditions. Missouri Agr. Exp. Sta., Res. Bull. 63, 1923.

6. Hockensmith, Roy D. Classification of land according to its capability as a basis for a soil conservation program. Proc. Inter-American Conference on Conservation of Renewable Natural Resources, U. S. Dept. Agr., Washington, D. C., 1949.

7. Lloyd, Charles H., and Gail W. Eley. Graphical solution of probable soil loss, formula for northeastern region. *J. Soil and Water Conservation,* Vol. 7, pp. 189–190, 1952.

8. Rummell, L. L. Handbook of Ohio Experiments in Agronomy. Ohio Agr. Exp. Sta., Series B-1, pp. 181–204, 1951.

9. Salter, R. M., and Associates. Our heritage—the soil. Ohio State University Extension Service Bull. 175, 1938.

10. Thompson, Louis M. *Soils and Soil Fertility.* McGraw-Hill Book Co., New York, pp. 270–326, 1952.

· 15 ·

Animal Agriculture

In a livestock system of farming, a large part of the nitrogen and mineral nutrients that are removed from the field in crops can be returned as manure. If a considerable percentage of the land is devoted to legumes, or if large amounts of supplemental feeds are purchased and used, the quantity of nitrogen applied to the soil in the form of manure may be greater than that removed in harvested crops and lost in drainage waters. Thus, it is possible to maintain the organic-nitrogen content of the soil at a higher level in *animal agriculture* than is possible with other types of extensive farming.

No such compensatory process operates to make good the losses of mineral elements from the soil. Although legumes accumulate nitrogen from the air, their mineral constituents come from the soil. Purchased feeds, for the most part, are relatively high in protein and carbohydrates, and relatively low in ash. Such elements as calcium, phosphorus, and potassium tend to be removed in crops and in drainage waters at a more rapid rate than they are returned to the soil in the form of manures. Calcium losses in the drainage water are greater than those occasioned by crop removal. The phosphorus content of drainage water is so low as to be virtually negligible, but this element is removed from the farm in considerable amounts in the bones of animals, including man, and in any milk or grains that may be sold. Loss of potassium from livestock farms is also considerable, partly in such products as milk and wool, but also by way of drainage. Virtually all the potassium in manure is soluble in water and, unless special care is taken to avoid exposing the manure to the action of rain or to loss by seepage, large amounts of this element will be lost.

Nevertheless, the possibilities of maintaining the productivity of soil at a high level in a livestock system of farming, with minimum expenditures for fertilizer, are such as to merit serious study from the point of view of realizing its maximum advantages. Unfortunately, manure is subject to serious depreciation through loss of urine, exposure to the leaching action of rain, and hot fermentation. The the-

oretical and actual amounts of nitrogen and mineral nutrients that are returned to the soil may differ considerably. *It is important also to remember that use of purchased feeds results merely in transfer of essential elements from one farm to another. To improve the pro-*



FIG. 52. Liberally fertilized grassland offers opportunity for profit in livestock and milk production which is far from being fully realized. In grassland farming, erosion is stopped, expensive cultivation is eliminated, and organic-matter maintenance in the soil is no longer a problem.

ductivity of one farm at the expense of another makes no real contribution to the solution of the problem of soil fertility.

SALE OF LIVESTOCK AND THEIR PRODUCTS

Very careful analyses of animal bodies were made many years ago at the Rothamsted Experimental Station. These involved complete carcasses of a considerable number of creatures. Data from these analyses are shown in Table 73. These animals were in good condition for market at the time of slaughtering.

The major portion of the ash of animals consists of calcium phosphate, most of which is contained in the bones. A 1000-pound steer contains the equivalent of about 16 pounds of phosphoric acid (P_2O_5).

TABLE 73

POUNDS OF NITROGEN AND MINERAL OXIDES IN ANIMALS* (LAWES)

Material	Calf	Steer	Lamb	Sheep	Pig
N	24.6	23.3	19.7	19.8	17.7
CaO	16.5	17.9	12.8	11.8	6.4
P_2O_5	15.4	15.5	11.3	10.4	6.5
K_2O	2.1	1.8	1.7	1.5	1.4
MgO	0.8	0.6	0.5	0.5	0 3

* Calculated on the basis of 1000 pounds live weight of animal.

Such a steer also contains about 18 pounds of calcium oxide and 23 pounds of nitrogen. The amounts of potassium and magnesium oxides in animal bodies are relatively small.

The composition of milk varies considerably, depending on the feed, kind of animal, and period of lactation. This is shown in Table 74.

TABLE 74

POUNDS NITROGEN AND MINERAL OXIDES IN 10,000 POUNDS MILK (FORBES)

Material	Highest	Lowest	Average*
N	114.6	41.1	61.0
P_2O_5	26.8	16.2	23.0
CaO	24.2	9.0	15.2
K_2O	19.6	4.2	14.3
Cl	28.7	8.6	14.3
SO_3	18.8	5.8	10.5
Na_2O	19.3	3.3	8.5
MgO	3.3	2.0	2.4
Total ash	90.4	68.3	77.9

* From eleven analyses of milk from Holstein cows.

data for which were obtained by analyses of eleven samples of milk from Holstein cows. The calculations are based on 10,000 pounds of milk, or what would be considered a satisfactory annual production for one cow.

The nitrogen content of milk is relatively high, and phosphoric acid is present in greater amount than any other mineral constituent. Loss of nitrogen can be compensated for by bacterial fixation by the nodule organisms on the roots of legumes. But those of phosphorus and other mineral constituents must be made good by purchase of feeds and fertilizers. Economy of phosphorus is of special importance in live-

stock farming. Assuming that each cow gave birth to a 90-pound calf and produced 10,000 pounds of milk during the year, the phosphorus sold in these products from thirty-two cows, a minimum number required for an economic dairy herd, would be equivalent to that contained in 2 tons of superphosphate of the 20-per cent P_2O_5 grade.

Wool is the only other animal product that is of any special significance in the economy of nutrient elements from the soil. Chemical composition of this product varies considerably, depending largely on the amount of suint adhering to it. The quantity of this material is especially high on the wool of Merino sheep, of which it may constitute as much as 50 per cent. The analysis shown in Table 75 is that

TABLE 75

POUNDS OF NITROGEN AND MINERAL OXIDES IN 1000 POUNDS OF WOOL (LAWES)

Material	Unwashed	Washed
N	54.0	92.0
K_2O	56.2	0.0
CaO	1.8	3.1
P_2O_5	0.7	1.2
MgO	0.4	0.7

of unwashed wool, from which the composition of that which has been freed of suint is calculated.

Losses from sale of wool are primarily those of nitrogen and potassium. The latter element is dissolved during the washing process. It can thus be recovered for use in the compounding of mixed fertilizers. The annual loss of potassium from the sale of wool from a flock of 100 sheep would be equivalent to 50 pounds potash (K_2O).

RECOVERY OF SOIL ELEMENTS IN MANURE

Since part of the nitrogen and mineral elements that are contained in feed are used by livestock and may later be sold in the form of the animals themselves or their products, it is of interest to calculate the percentage recovery of these elements in manure. If the animal is a mature male and is used only for work purposes, every pound of these elements contained in the feed may be returned to the soil in the form of urine, feces, perspiratory products, and wastes of skin, hoofs, and hair. This means 100 per cent recovery if the animal is never removed from the farm. In proportion as an animal is immature, or is used for

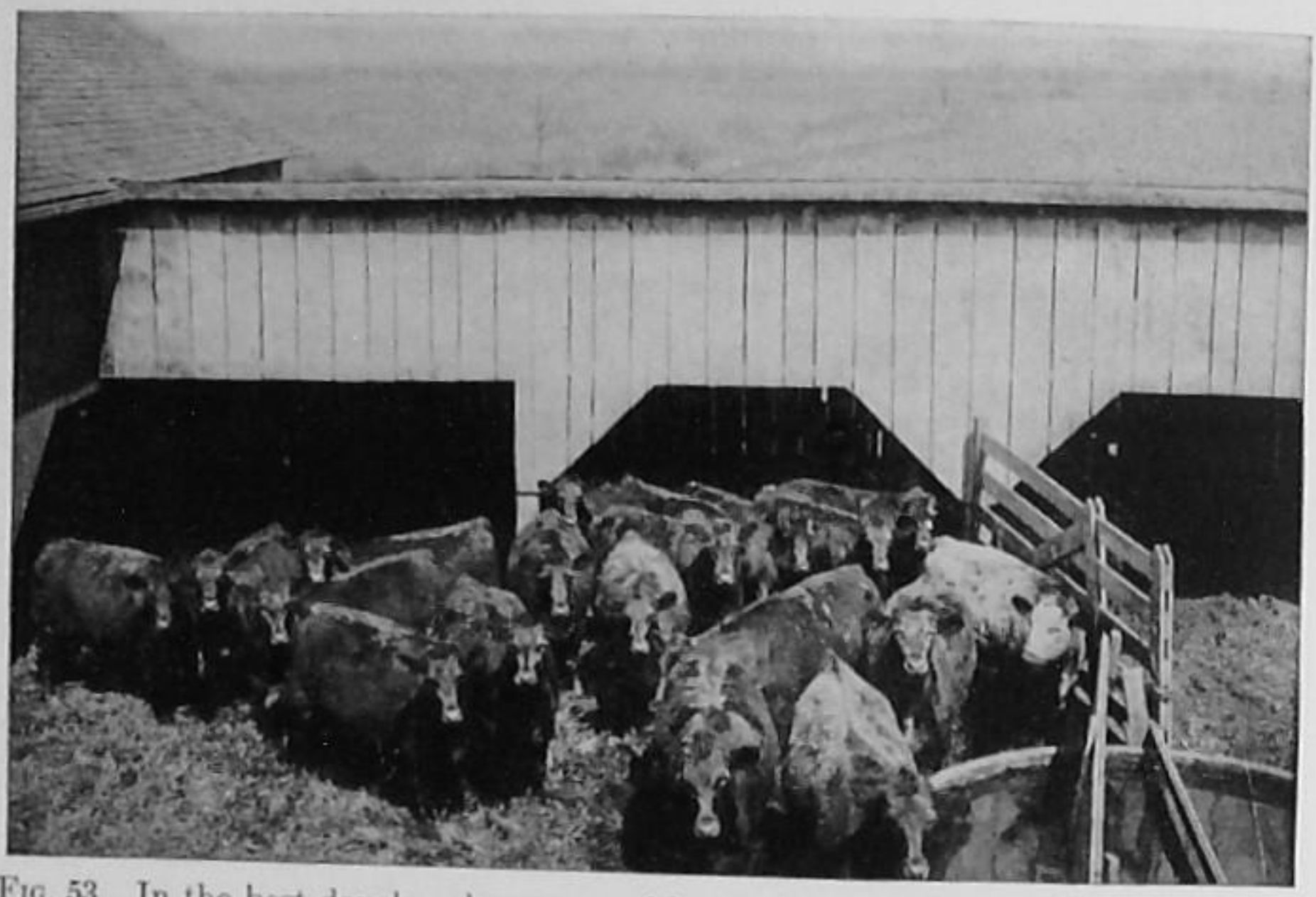


FIG. 53. In the best-developed systems of livestock farming, there is little loss of nutrient elements from the land.

production of milk, meat, wool, or young, the percentage recovery in excretory products is decreased.

A balance sheet for a Holstein cow is shown in Table 76. The ex-

TABLE 76

BALANCE SHEET FOR PRODUCTION OF 10,000 POUNDS OF MILK (FORBES)

Material	Food, Pounds	Milk, Pounds	Urine, Pounds	Feces, Pounds	Recovery* Per Cent
N	171.0	44.3	65.6	61.1	74
K_2O	98.0	14.9	76.7	6.4	85
CaO	82.7	14.6	1.3	66.8	82
P_2O_5	51.1	19.3	0.5	31.3	62
SO_3	42.3	6.8	16.0	19.5	84
MgO	34.7	2.2	3.6	28.9	94
Cl	20.3	10.9	4.6	4.8	46
Na_2O	17.5	4.7	9.2	3.6	73

* Percentage of the nitrogen and minerals of the feed that were contained in the combined liquid and solid excrements.

periment from which these data were calculated was carried out for 9 days, during the fifth month of lactation. The cow was not bred. Her daily average milk production was 37.9 pounds. The total quan-

tities of most of the several soil-derived nutrients in the milk, urine, and feces were slightly larger than those in the feed. The only explanation for this is found in feed consumed in advance of the beginning of the experiment. These differences have been accounted for in the table by adding them to the values given for the feed.

These and other tests indicate that recovery of phosphorus is less than that of any other essential element. Additional loss of this and other elements would have occurred if the cow had been pregnant. If the cow had been dry, larger percentages of all the soil-derived nutrients would have been recovered in the urine and feces. On the average, about 80 per cent of the nitrogen and essential mineral nutrients in the feed is recovered in the manure.

Distribution of soil-derived elements between urine and feces is shown in Table 77. The comparison is between two cows, one of which

TABLE 77

PERCENTAGE DISTRIBUTION OF MATERIALS BETWEEN URINE AND FECES (FORBES)

Material	Dry Cow		Milking Cow	
	Urine	Feces	Urine	Feces
K_2O	95	5	92	8
Cl	75	25	48	52
Na_2O	74	26	73	27
N	63	37	51	49
SO_3	51	49	44	56
MgO	11	89	12	88
P_2O_5	1	99	2	98
CaO	0	100	1	99

was dry and in the ninth month of gestation, whereas the other had not been bred but was in the fifth month of lactation. Over 90 per cent of the potassium and more than half the nitrogen were contained in the urine of both cows, whereas most of the phosphorus and calcium were excreted in the feces. Studies with pigs indicate similar distribution between urine and feces, but slightly more phosphorus and sulfur and slightly less potassium are found in the urine.

LOSSES OF SOIL ELEMENTS FROM MANURE

Animal manure is normally made up of urine and feces, mixed with bedding and residues from feed. One might assume that if such manure

were subjected to the leaching action of rain, only the urine would be lost. But there is abundant evidence that leachings from manure piles contain much more than the urine. The evidence in Table 78 supports

TABLE 78

COMPOSITION OF MANURE FRESH FFOM FEEDING STALLS (AMES)

Kind of Animal	Per Cent of Water	N		P_2O_5		K_2O	
		Per Ton, Pounds	Water-soluble, Per Cent	Per Ton, Pounds	Water-soluble, Per Cent	Per Ton, Pounds	Water soluble, Per Cent
Poultry*	68	28.8	..	19.8	..	7.8	..
Sheep	64	28.7	42	10.1	58	25.0	97
Steer	78	14.3	55	9.4	36	10.9	92
Horse	59	13.9	52	4.8	53	15.2	75
Cow	79	11.4	50	4.4	50	12.5	97
Hog†	87	10.0	..	7.0	..	8.0	..

* Brooks, Circ. 54, Mass. Agr. Exp. Sta.
† Van Slyke, Soils and Fertilizers.

this statement. The manure in this test was sampled as it came from the feeding stalls, where it had been protected against loss of urine, and, presumably, against *hot fermentation.* About half the nitrogen and virtually all the potassium in the manure were soluble in water. Most of the phosphorus in manure is contained in the solid portion, yet about 15 per cent of this phosphorus was water-soluble.

Losses of nitrogen and mineral elements from a livestock farm in sale of animals and their products are often less than those resulting from careless handling of manure. Those from manure may result from failure to haul it to the field, loss of urine by seepage, loss of soluble materials by leaching, and loss of ammonia by fermentation. If urine is not absorbed by bedding, it must be stored in a closed cistern to avoid loss of nitrogen as ammonia. As manure undergoes decomposition, additional amounts of nitrogen may be lost as ammonia. Considerable quantities of all the soil-derived elements become soluble during this process, and these may readily be leached out if manure is exposed to rains. Although it is desirable for manure to go through a fermenting process before it is applied to the field, this must be effected under cover and on a watertight floor if losses of nutrient elements are to be avoided.

A fermenting manure pile is always warm, as a result of microbial decomposition. Sometimes temperatures rise so high as to volatilize

most of the nitrogen and produce *fire fanging*. Horse, sheep, and poultry manures are especially subject to this. Prevention of overheating and of losses resulting therefrom can be accomplished by keeping the pile relatively wet and compact. Under such conditions, decomposition processes are largely anaerobic and high temperatures do not develop. Previously insoluble nitrogen compounds gradually be-



Portland Cement Association

FIG. 54. In order that manure may sustain as little loss of the essential elements as possible, it is important that it be covered with a roof and be stored on a tight floor.

come soluble, and carbonaceous materials are broken down into carbon dioxide and water. Under such conditions, little loss of ammonia occurs, because of the high concentration of carbon dioxide in which ammonium carbonate is stable.

Some loss of nitrogen as ammonia is certain to occur even under the best conditions of handling of manure. Much of this can be avoided by mixing manures from different classes of animals, by keeping the pile well packed, and by adding water if the temperature rises too high. When manure is applied over a field, loss of nitrogen as ammonia is likely to occur, unless the manure can be worked into the soil. If the ground is frozen when manure is applied, losses by surface runoff, especially on rolling land, may be very heavy. Once the manure

is incorporated into the soil, the products of protein hydrolysis rapidly yield up their nitrogen as ammonia, which is either adsorbed by the soil as such or is rapidly converted to nitrate. As long as this nitrogen is in the ammonia form, little loss is likely to occur, either by volatilization or drainage. If the soil is warm, nitrification proceeds rapidly and the resulting nitrates, if not consumed by soil microorganisms or crop plants, are readily leached out of the soil and carried away in drainage water.

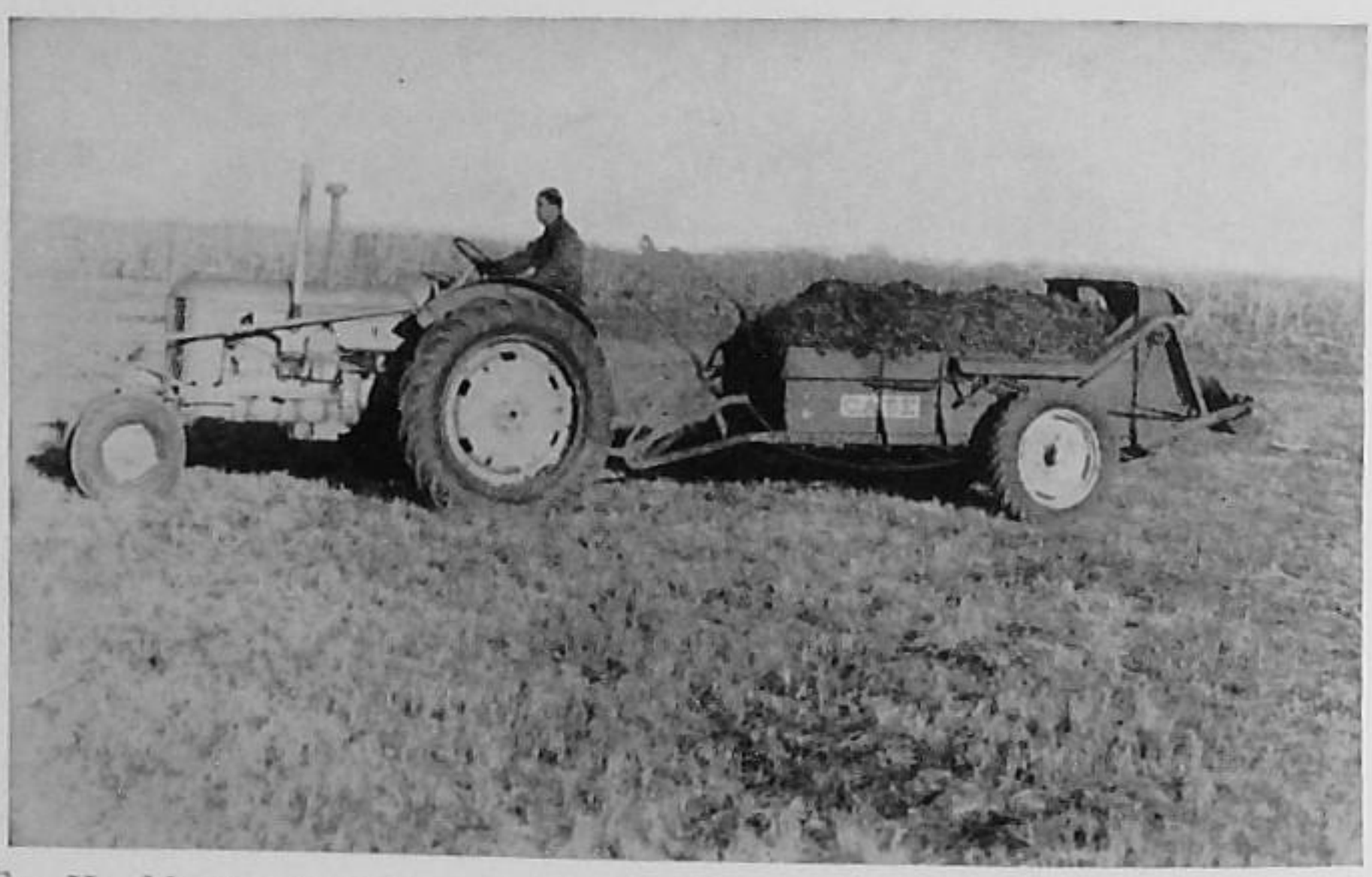


FIG. 55. Manure should be reenforced with phosphate. Many farmers apply 50 pounds of superphosphate over each load before it is hauled to the field.

Considerable attention has been given to use of preservatives on manure. The most promising materials in preventing escape of ammonia are calcium sulfate, or gypsum, and superphosphate, which is a mixture of monocalcium phosphate and gypsum. Gypsum is especially effective as a combined ammonia-absorbing agent and deodorant. Superphosphate has special value in that it supplies phosphorus, which is very useful in balancing the nutrient supplies in manure and improving its crop-producing capacity. Where flies are a problem, boric acid or sodium borate can be used to advantage. Hydrated lime is often used as a preservative for poultry manure. Its first effect is to volatilize any ammonia that may be present on the surface of the manure. But it then has the effect of virtually stopping further decomposition until the manure is applied to the field.

MANURE AS A CROP-PRODUCING AGENT

About 75 per cent of the nitrogen fixed by the nodule bacteria of legumes can be recovered in the manure of the animals to which these legumes are fed. The same applies to all other nitrogen contained in the feed. None of the nitrogen in the bedding need be lost. Similarly, over 60 per cent of the phosphorus and over 80 per cent of the potassium in the feed and all of these elements in the bedding are contained in the manure. Recoveries equal to those of potassium can be effected on all the other mineral nutrients, including the trace elements. If the manure is reinforced with superphosphate and if soil acidity is kept under control by use of liming materials, crop yields on a well-managed livestock farm can be maintained at relatively high levels without the use of other fertilizers. However, much depends on how the manure is managed. This is well shown in Table 79, in which

TABLE 79

AVERAGE* ACRE YIELDS WITH 8 TONS OF MANURE ON CORN (THORNE)

	Corn, Bu.	Wheat, Bu.	Clover, Cwt.
Phosphated manure†	67.7	28.6	49.0
Stall manure	61.9	23.8	41.5
Open-yard manure	55.9	22.8	36.6
No manure	36.8	14.2	29.4

* Twenty-six 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.

results of comparisons of crop-producing effects of yard and stall manure, with and without superphosphate, are shown. In this test, 8 tons of manure were applied to the clover sod before plowing the land in preparation for corn, which was grown in a 3-year rotation of corn, wheat, and clover. Limestone was applied as required to insure good stands of clover.

A ton of stall manure is considerably more valuable than one from an open yard. Exposure in the open yard reduces the number of tons of manure available for hauling to the field. Addition of superphosphate to the manure materially increases its crop-producing capacity. Part of this may be due to the ammonia-absorbing effect of the superphosphate, but the larger part is due to its supplying extra phosphorus.

A somewhat better idea of the possibilities of maintaining yields at relatively high levels in a livestock system of farming is obtained

TABLE 80

AVERAGE* ACRE YIELDS IN LIVESTOCK AND GRAIN FARMING (WILLIAMS)

Crops	Livestock System†	Grain System	Difference
Corn, bu.	73.5	66.7	6.8
Soybeans, bu.	22.6	19.6	3.0
Wheat, bu.	33.9	30.2	3.7
Clover, cwt.	44.0	....	...

* Sixteen-year averages.

† The average annual manure production has been 3.9 tons per acre, or 15.5 tons per acre for applying to the clover sod to be plowed under for corn.

from Table 80. In this test, the crops were grown and fed to livestock, after which the manure was returned to the field from which the crops came. A rotation of corn, soybeans, wheat, and clover was followed. All the crops were fed or used for bedding, except the wheat grain. In addition to the manure, 2 tons of limestone and 400 pounds of superphosphate were applied for corn and 300 pounds of additional superphosphate were used for wheat. The yields thus obtained are compared with those resulting from a grain system of farming in which the corn, soybeans, and wheat grains were sold and the clover, cornstalks, and straws were plowed under. The same amounts of limestone and superphosphate were used in both cases. The livestock system was superior to the grain system of farming, insofar as crop yields are concerned. It also had the possible advantage of extra profits from the sale of animals instead of grain. But crop yields under the grain system are quite satisfactory and no doubt they could have been raised considerably by use of extra nitrogen.

In this test, the grain, hay, and stover were fed to cattle that were allowed to run loose in a covered yard. The straw was used for bedding. The annual production of manure averaged nearly 4 tons an acre. The amount of manure was 1½ times the dry weight of the feed and bedding. Although the total excrement, plus the bedding, was considerably more than this, losses in weight by decomposition and evaporation were quite rapid. The daily excrement of animals varies between about 25 pounds a 1000 pounds live weight for poultry to as much as 75 pounds for the same weight of hogs, with intermediate amounts for other classes of livestock. *In calculating the amount of manure that is available for hauling to the field on a well-managed livestock farm, the factor of 1½ times the dry weight of the feed and*

bedding is probably as high as can safely be applied, even assuming that the manure is kept under cover until it is hauled to the field. *Manure production for 1300-pound Holstein cows at the New Jersey Agricultural Experiment Station was at the rate of 21 tons a year, of which 25 per cent was urine and 75 per cent feces. Manure production of 1000 hens was 72 tons a year, from feed consumption of 37½ tons.*

The quality of manure can be improved by use of *concentrated feeds*. One can choose between buying concentrates for both feed and fertilizer purposes and buying fertilizer for use as such. Some idea of the plant-nutrient values of concentrated protein feeds can be obtained by studying the data shown in Table 81. About 80 per cent of these

TABLE 81

COMPOSITION* OF STANDARD CONCENTRATED FEEDS (FORBES)

Feed	N	P_2O_5	K_2O	CaO	MgO	SO_3	Na_2O
Animal tankage	93.7	37.4	6.6	41.3	2.4	15.2	22.5
Soybeans	63.0	13.6	23.0	2.9	3.7	10.2	4.6
Cottonseed meal	57.4	31.1	19.9	3.7	9.0	12.3	3.5
Linseed meal	56.8	16.2	13.2	5.1	8.1	10.2	3.4
Gluten feed	44.0	12.5	3.0	3.5	3.6	3.5	5.7
Wheat bran	25.2	25.5	15.8	1.8	8.8	1.8	2.7
Alfalfa hay	23.0	5.1	9.2	14.6	6.1	6.9	6.1

* Pounds in 1000 pounds of feed.

values can be recovered in the manure. One ton of cottonseed meal contains as much nitrogen as 350 pounds of nitrate of soda and as much phosphorus as 150 pounds of 20-per cent superphosphate. Considerable amounts of potassium, magnesium, and sulfur are also contained in cottonseed meal. By the time the feed has passed through the alimentary tract of an animal, the plant nutrients contained in it are in a fairly high state of availability for crop use.

Manure from animals that are fed corn stover, timothy hay, and oats straw is of much less value than that from those that have been fed legume hays, grains, and supplemental concentrates. In proportion as more nitrogen and mineral elements are contained in the feed and in the resulting manure, possibilities for loss of nutrient value by careless handling are increased. Use of concentrated feeds, therefore, justifies larger investments in improved storage facilities, by which losses of nitrogen and mineral constituents in the manure can be avoided.

COMPOSTED MANURES

In grain-farming systems, large amounts of low-nitrogen organic matter are worked into the soil. This may result in troublesome competition between soil microbes and crop plants for available nitrogen and phosphorus, and possibly for other nutrient elements as well. Under such systems, use of extra fertilizer nitrogen would be desirable. The amount to apply can be calculated if one knows the dry weight of crop refuse and its nitrogen content. The problem is one of supplying enough extra nitrogen so that the total is equal to 2 per cent of the dry weight of the added organic matter. This will be sufficient to meet microbial needs, with some left over for crop use.

Need for extra nitrogen can be avoided either by feeding the crop refuse to livestock or by using it for bedding. By such procedures, the carbonaceous products are largely changed to carbon dioxide and water and the percentage nitrogen in the product is increased. *One ton of good cow manure, as it is hauled from the stalls, contains about 10 pounds of nitrogen, 5 pounds of phosphoric acid, and 10 pounds of potash.* Since such manure is about 75 per cent water, the dry matter in 1 ton is about 500 pounds. On this dry-weight basis, the manure contains 2 per cent nitrogen.

The effectiveness of manure can be increased either by permitting it to go through a rotting process or by a *composting* procedure. When manure is stored, as in a covered yard, gradual decomposition takes place, largely through activities of anaerobic bacteria. This results in reducing the percentage of carbon and increasing that of nitrogen. In proportion as the percentage of nitrogen increases, more of it will be released for crop use during the first season after the manure has been applied to the soil. Given a choice, one would always prefer well-rotted manure.

Gardeners often go to considerable trouble to compost manure, which aids further in getting rid of excess cellulosic materials and in solubilizing nitrogen. The compost pile is made up of alternate layers of manure, soil, and sod, with which any refuse organic material, ashes, or other suitable wastes may be incorporated. The heap is kept moist until the decomposition process is under way, and then it is turned so that the outside material becomes mixed with that from the inside. Such a compost is ideal for potted plants and for use in plant beds.

In making compost, use can also be made of *leaf mold*, which is produced by piling the leaves in some out-of-the-way corner where

they are allowed to undergo a natural process of humification over a period of 2 or 3 years. When compost containing leaf mold is placed in a flower pot, conditions as to aeration and moisture can readily be maintained at the optimum. The decomposed organic materials serve very effectively as buffers against overfeeding or overwatering.

In China and Japan, clover and *canal mud* are used in making compost, these materials being arranged in alternate layers in a pit and well compacted. When the fermentation process has been completed, the compost is spread over the land and subsequently worked into the soil. When such composts are used, nitrification is rapid, and the resulting nitric acid may react with soil minerals to liberate additional supplies of nutrients for crop use.

In Asiatic countries, extensive use is made of *human excrement* for soil-improving purposes. Elaborate precautions are taken to conserve all excretory products for application to the land. Modern sanitary systems do not permit using such materials. By suitable methods of sewage disposal, pathogenic species of bacteria can be destroyed and the resulting *activated sludge* can be used with safety. In this process, sewage is collected in tanks through which air is blown. The sludge that settles out after this operation possesses the remarkable quality of aiding rapid oxidation of the organic matter in fresh sewage. The residue that remains is virtually free of intestinal bacteria and its nature is such as to make it a very useful soil amendment. On the oven-dried basis, this material contains between 3 and 6 per cent nitrogen and between 3 and 4 per cent phosphoric acid, both in forms that become readily available to plants when applied to the soil. Per-capita production of activated sewage sludge, where produced, is estimated at 135 pounds a year. Raw sewage sludge is sometimes used on the soil but, unless this is plowed under, the user runs the risk of contracting disease. Furthermore, such material often has a very bad odor. This can be overcome by applying hydrated lime over the surface of the material.

SYNTHETIC MANURES

In many types of farming, little or no livestock is available for converting refuse plant materials into manure. Even on farms on which a considerable number of animals are kept, there are often appreciable amounts of waste materials that cannot be fed or used for bedding. In Europe, such materials are placed in heaps or in pits and watered with urine from time to time. In the event that sufficient

urine is not available, supplemental use is sometimes made of a dilute solution of sulfate of ammonia. Experience has shown that the concentration of this solution should not exceed 5 per cent.

Some years ago research workers at the Rothamsted Experiment Station investigated the problem of producing *synthetic manure*, and developed a process that is now being widely applied the world over. Straw, or similar organic material, is built into a heap in layers, each of which is about 1 foot in depth. As each layer is built, it is moistened with water, and a mixture of fertilizer salts is sprinkled over it. The heap is built to a height of at least 6 feet and is then kept moist while decomposition is taking place. A rise in temperature is soon noted. If the temperature tends to rise above 150° F., extra water is added. At the end of a month or so the heap is turned, and after about 3 months the product is ready for use. One ton of straw, treated with 75 pounds each of ammonium sulfate and lime and half that amount of superphosphate, will make about 2 tons of synthetic manure. Analysis of one such sample of manure showed 2.2 per cent nitrogen (N), 1.2 per cent phosphoric acid (P_2O_5), and 0.6 per cent potash (K_2O), on a dry-weight basis.

Much interest has been aroused in the production of synthetic manures, notably by suburban homeowners. Grass clippings, kitchen wastes, plant trimmings, leaves, and small amounts of soil are fed into a large box that is built in some secluded place in the back yard. From time to time, small amounts of any standard complete fertilizer and of lime are scattered over the pile, and extra water is added as required. Oak leaves are troublesome in such piles since they lie too flat and pack together. Leaves that curl around the edges are to be preferred. Shredded cornstalks are among the most satisfactory wastes for this purpose. Many home gardeners take special precautions that all plant waste materials about the yard, particularly leaves, are saved and used for mulching or compost purposes, and that they are eventually worked into the soil.

SELECTED REFERENCES

1. Ames, J. W., and E. W. Gaither. Barnyard manure; production, composition, conservation, reenforcement, and value. Ohio Agr. Exp. Sta., Bull. 246, 1912.

2. Bear, F. E., and Associates. The dairy cow as a conserver of soil fertility. New Jersey Agr. Exp. Sta., Bull. 730, 1950.

3. Bear, F. E., and J. R. Royston. Nitrogen losses in urine. *J. Am. Soc. Agron.*, Vol. 11, pp. 319–326, 1919.

4. Collison, R. C., and H. J. Conn. Fermentation and preservation of manure. New York Agr. Exp. Sta., Bull. 494, 1922.

5. Forbes, E. B., and Associates. The mineral metabolism of the milch cow. Ohio Agr. Exp. Sta., Bull. 363, 1922.

6. Lawes, J. B., and J. H. Gilbert. Experimental inquiry into the composition of some of the animals fed and slaughtered as human food. *Proc. Roy. Soc. London,* Vol. 9, p. 348, 1858.

7. Martin, J. P., and Selman A. Waksman. New Jersey Agr. Exp. Sta., Cir., 470, 1952.

8. Noer, O. J. Activated sludge: its production, composition, and value as a fertilizer. *J. Am. Soc. Agron.,* Vol. 18, pp. 953–962, 1926.

9. Thorne, C. E. *Farm Manures.* Orange Judd Publishing Co., 1914.

10. Vivian, A. *The First Principles of Soil Fertility.* Orange Judd Publishing Co., pp. 113–184, 1909.

11. Williams, C. G. Livestock versus grain farming. Ohio Agr. Exp. Sta., Bull. 328, 1918.

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Nitrogen Resources

The weight of the atmosphere above a square inch of the earth's surface is 14.7 pounds. Of this, 75.5 per cent is nitrogen. The total weight of nitrogen in the air over an acre of land is about 35,000 tons. This nitrogen gas cannot be used by crop plants or by animals until it has been combined with hydrogen or oxygen. This is accomplished through the activities of nitrogen-fixing microorganisms, by electrical discharges in the atmosphere, and by commercial fixation processes.

Maintenance of an adequate supply of available nitrogen in the soil to meet the needs of crops is one of the most troublesome practical problems in agriculture. Most plants obtain their nitrogen from that contained in the organic matter in the soil on which they grow, supplemented by such additional supplies as may be added in the form of farm manures and fertilizers. To yield its nitrogen up for plant use, organic matter must undergo microbial decomposition, as a result of which its nitrogen is liberated as ammonia. In well-managed soils this ammonia is quickly changed to nitrate by certain groups of soil microorganisms that have this as their primary function. Thus, crop plants may obtain a large part of their nitrogen as nitrate. Since roothairs are in intimate contact with decomposing organic matter, however, it is possible that considerable amounts of ammonia nitrogen are utilized as such, before the nitrifying bacteria can transform it to nitrate. Under acid-soil conditions, nitrate may not be formed or its rate of formation may be very slow and then plants must make use of ammonia as such. Possibly they are able to use small amounts of organic forms of nitrogen as well.

SOIL ORGANIC MATTER

The quantity of organic matter contained in any farmed soil depends on the physical nature of that soil, the climatic environment under which it exists, the conditions with respect to drainage, and the system of soil management that is being employed. The *A*-horizon

of the sandy coastal-plain soils along the Atlantic seaboard and the Gulf coast contains around 1 per cent of organic matter, whereas that of the black corn-belt soils of the central west may have an organic-matter content of 8 per cent or more. Dune sands and peats represent the extremes, the former containing only a fraction of a per cent organic matter and the latter as much as 80 per cent, on an oven-dry basis. About one-half the total organic matter in the profile of a mineral soil is found in the plow depth.

Soil organic matter, decomposed to the state that it has lost its identity, usually contains about 5 per cent nitrogen. Thus, a soil containing 2 per cent organic matter will have a nitrogen content of around 0.10 per cent. Assuming that the plow depth of an acre of soil weighs 2 million pounds, the organic-matter content of this plowed acre would be about 40,000 pounds, of which about 2000 pounds would be nitrogen. During the growing season the soil microorganisms are actively engaged in the decomposition of the organic matter and in changing its nitrogen to nitrate. The amount of nitrogen so liberated from the soil organic matter during any one crop season is not likely to exceed 5 per cent of the total, which, in this case, would be 100 pounds an acre. Once the crop gets well under way it may absorb the nitrate as fast as it is produced, with the result that a laboratory test of the soil will show very little nitrate.

NITROGEN-FIXING BACTERIA IN SOILS

Soils contain several distinct groups of nonsymbiotic nitrogen-fixing bacteria. The most important of these is the *Azotobacter* group that feeds on soil organic matter, absorbing the extra nitrogen it requires, over and above that liberated from the organic matter, from the soil air. This group of bacteria functions most effectively under conditions in which the soil is supplied with considerable amounts of fresh organic matter that is low in nitrogen. Thus, the conditions for nitrogen fixation by *Azotobacter* are improved by plowing under such materials as cornstalks, timothy sods, and wheat straw. If it were not for its high cost, molasses would be an excellent material to apply to the soil for stimulating nitrogen fixation by this group of soil microorganisms. When such low-nitrogen organic materials are applied to the soil they should be worked into it a month or more in advance of planting a crop in order that the nitrogen-fixation process will have been brought to completion.

The amount of nitrogen fixed by *Azotobacter* and other free-living, nitrogen-fixing microorganisms in the soil varies, depending largely upon the quantity and nature of the fresh organic matter in the soil, the extent to which other possible limiting factors, such as a lack of lime or phosphate, have been eliminated, the temperature and moisture conditions in the soil, and the amount of ammonia and nitrate nitrogen



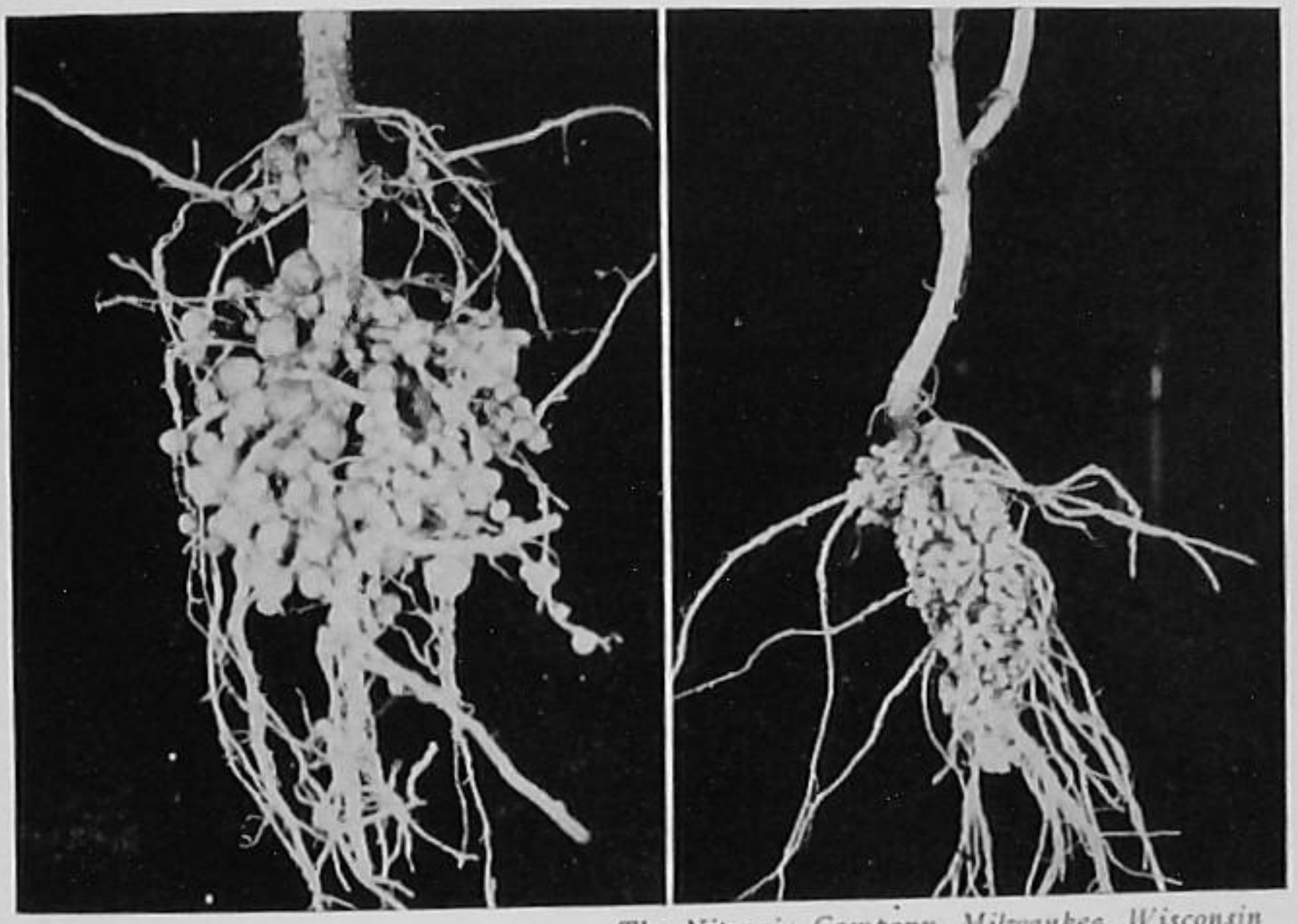
FIG. 56. White clover, such as this Ala-Lu type growing in Bullock County, Alabama, is a very important collector of nitrogen in pastures.

at their disposal. Under optimum conditions in the laboratory, fixation is relatively rapid. In the field, however, it is doubtful whether the amount of nitrogen fixed ever exceeds 25 pounds an acre during any one year. Under average field conditions, the rate of fixation by these nonsymbiotic types of nitrogen-fixing bacteria is believed to be considerably less than that amount.

The nodule bacteria inhabiting the roots of legumes are probably the most important group of nitrogen-fixing bacteria. These microorganisms, and the clovers, alfalfa, soybeans, peas, beans, vetch, peanuts, crotalaria, lupines, lespedeza, kudzu, locust trees, and other legumes on the roots of which they grow, operate under a cooperative system, each being dependent on the other. The net result of this cooperation

is the production of a high-nitrogen plant of special value both for feed and soil-improvement purposes.

Legumes normally contain about 2.5 per cent nitrogen (N), or 50 pounds a ton, on a dry-matter basis. Since the yield of a crop like alfalfa may be 4 tons or more dry matter an acre during a single crop season, the amount of nitrogen accumulated in the top portion of the



The Nitragin Company, Milwaukee, Wisconsin

FIG. 57. The seat of the nitrogen-fixation process in legumes is in the nodules, such as those of soybeans (left), and canning peas (right).

plant may reach 200 pounds or more, with possibly an additional 40 pounds in the roots and stubble. Not all this nitrogen would have been fixed by the nodule bacteria, however, part of it having been derived from the organic-matter nitrogen in the soil. A soil that is capable of producing such a yield of alfalfa hay might well have yielded half that weight of timothy hay containing around 50 pounds nitrogen, with an additional 10 pounds of nitrogen in its roots. Since timothy is a nonlegume and its roots carry no nodule bacteria, most, if not all, of the nitrogen it may contain had its origin in the soil organic matter or in the manure and fertilizer that may have been applied to the soil. The nitrogen in the timothy represents the soil's capacity to supply this element under sod conditions. To get a true picture of what normally happens with respect to nitrogen fixation by the nodule bacteria

of legumes, therefore, one must discount the nitrogen content of the legume crop by at least 25 per cent. On this basis, if a 4-ton yield of alfalfa hay is harvested, the crop can be credited with having captured possibly 150 pounds of nitrogen from the soil air.

NITROGEN IN LIVESTOCK FARMING

The only way in which the full value of such fixed nitrogen can be fully realized for soil-improvement purposes is by plowing the legume crop under. If, instead, the crop is harvested and sold, the soil may be poorer in nitrogen than it was before the legume was grown. This is especially likely to be true for the soybean, a crop having a relatively small root system. On the other hand, if the legume crop is fed to livestock and the resulting manure is saved and returned to the land, about 80 per cent of the nitrogen harvested with the crop can be recovered. On this basis, a 4-ton crop of alfalfa could be credited with contributing 120 pounds of fixed nitrogen to the soil by way of the manure produced by feeding it. This is equivalent to a gain of 30 pounds of nitrogen a ton of alfalfa hay grown and fed on the farm.

During the process of bacterial decomposition of organic matter, other than that contained within the soil, some of its nitrogen escapes as ammonia into the atmosphere. Losses of ammonia from free urine are likely to be very large. Ammonia is also rapidly lost from the surfaces of manure piles. Even after manure has been applied to the field, these losses continue as long as the manure remains in a moist state on the surface of the soil. As soon as it is plowed under or otherwise incorporated into the soil, however, such losses are stopped. A large part of any ammonia that escapes into the air is probably brought back to the soil in the rainfall. In addition, small amounts of atmospheric nitrogen are combined with oxygen during electrical storms. As a result, rain has a nitrogen-fertilizer value. Its contribution of ammonia and nitrate nitrogen normally is not believed to exceed 5 to 10 pounds an acre annually.

In theory, it should be possible to dispense with the buying of commercial nitrogen on livestock farms where legumes are grown as a regular part of the cropping system, where only livestock and its products are sold from the land, and where the manure resulting from feeding the crops is saved and applied to the land. Certainly, this should be true under conditions in which extra feed is bought. Such purchased feed, however, had to come from some other farm, the

nitrogen content of the soil of which was usually reduced by the sale of the crops that were grown on it.

Notwithstanding the possibilities, it is seldom that one finds even a livestock farm on which extra nitrogen cannot be used to advantage. The marked increase in the yield of hay and pasture grasses in the spots where urine is dropped by animals and the dark-green color of the resulting growth are ample evidence of the need for nitrogen on many such farms. The theory as to the adequacy of the nitrogen



FIG. 58. Urine spots in a grass-hay field, showing serious need for nitrogen.

supply in the soils of livestock farms is not borne out in practice because some loss of this element from the manure by way of both the air and the drainage water cannot be avoided. Furthermore, as the nitrogen content of the soil is raised, the efficiency of the nitrogen-fixing bacteria is correspondingly reduced. In proportion as the soil becomes richer in nitrogen, these bacteria use more of that nitrogen, collecting less of the element from the air.

On nonlivestock farms, or on those in which part of the crop is sold as such and not in the form of livestock products, the use of considerable amounts of commercial nitrogen is essential to high acre yields, once the virgin fertility of the soil has been exhausted. The need for nitrogen has been further increased as a result of the substitution of the tractor and automobile for the horse and the consequent reduction in the acreage of hay crops and in the amount of manure available for the land. The continuously upward trend in sales of nitrogen fertilizer materials and the increase in the content of nitrogen in com-

plete fertilizers is proof of the ever larger dependence of farmers on commercial forms of this element (Table 82).

TABLE 82

TONS OF FERTILIZER CONSTITUENTS CONSUMED IN CONTINENTAL UNITED STATES, HAWAII, AND PUERTO RICO (U S.D.A.)

Year	N	P_2O_5	K_2O	Total
1900	62,000	246,000	87,000	395,000
1910	146,000	499,000	211,000	856,000
1920	228,000	660,000	257,000	1,145,000
1930	377,000	793,000	354,000	1,524,000
1935	312,000	597,000	307,000	1,216,000
1940	419,000	912,000	435,000	1,766,000
1945	679,000	1,438,000	746,000	2,863,000
1950	1,126,000	2,071,000	1,215,000	4,412,000

NITROGEN-DEFICIENCY SYMPTOMS IN CROP PLANTS

Legume crops, with well-nodulated roots, show every evidence of an abundant supply of nitrogen. They grow luxuriantly, have a dark-green color, and retain their leaves well toward maturity. On non-legume plants, however, it is quite common to see very stunted top-growth, pale-green to yellow foliage, and "firing" of the lower leaves, especially in times of drought. These are indications of a lack of nitrogen. But such symptoms do not necessarily prove that the lack of this element is the only limiting factor in plant growth. Furthermore, plant leaves may turn yellow by reason of a deficiency of iron, magnesium, or some other element.

Temporary nitrogen deficiencies frequently result from the plowing-under or discing-in of fresh organic matter having a low nitrogen content, of which timothy sods and small-grain straws are good examples. Unless organic materials contain at least 1.5 per cent nitrogen they do not supply a sufficient amount of the element to meet the needs of the bacteria effecting their decomposition. Any deficiency is made up from the available nitrogen in the soil itself, as long as that supply lasts, after which the *Azotobacter* may then collect some from the soil air. The answer to the bad effects from plowing under low-nitrogen organic matter lies either in allowing a lapse of sufficient time after incorporating the material with the soil to permit of its decay, or in adding commercial nitrogen to the soil before a crop is planted. The rotting process can be speeded up by spreading the nitrogen fer-

tilizer over the organic material before it is plowed under or worked into the soil.

There are two standard methods for determining whether extra nitrogen is needed. One is to apply some quickly available source of the element and note its effect. In the soil contains sufficient moisture or if a rain follows shortly after the fertilizer has been applied, plant response to the applied nitrogen will be rapid and will be revealed both by the rate of growth of the crop and by the improvement in its color. The other method is to test the growing tissues of the plant for nitrates. If nitrates are present in appreciable amounts, a lack of nitrogen is not the limiting factor. If they are not present, an application of a nitrogen fertilizer will normally benefit the crop, unless some other element is also in equal or greater deficiency, in which event it also must be supplied if the best results are to be obtained.

COMMERCIAL NITROGEN

In supplementing the nitrogen derived from the soil organic matter, that collected from the soil air by nitrogen-fixing bacteria, and that brought back from the atmosphere by rainwater, use is made of one or more of a considerable variety of commercial forms of nitrogen.

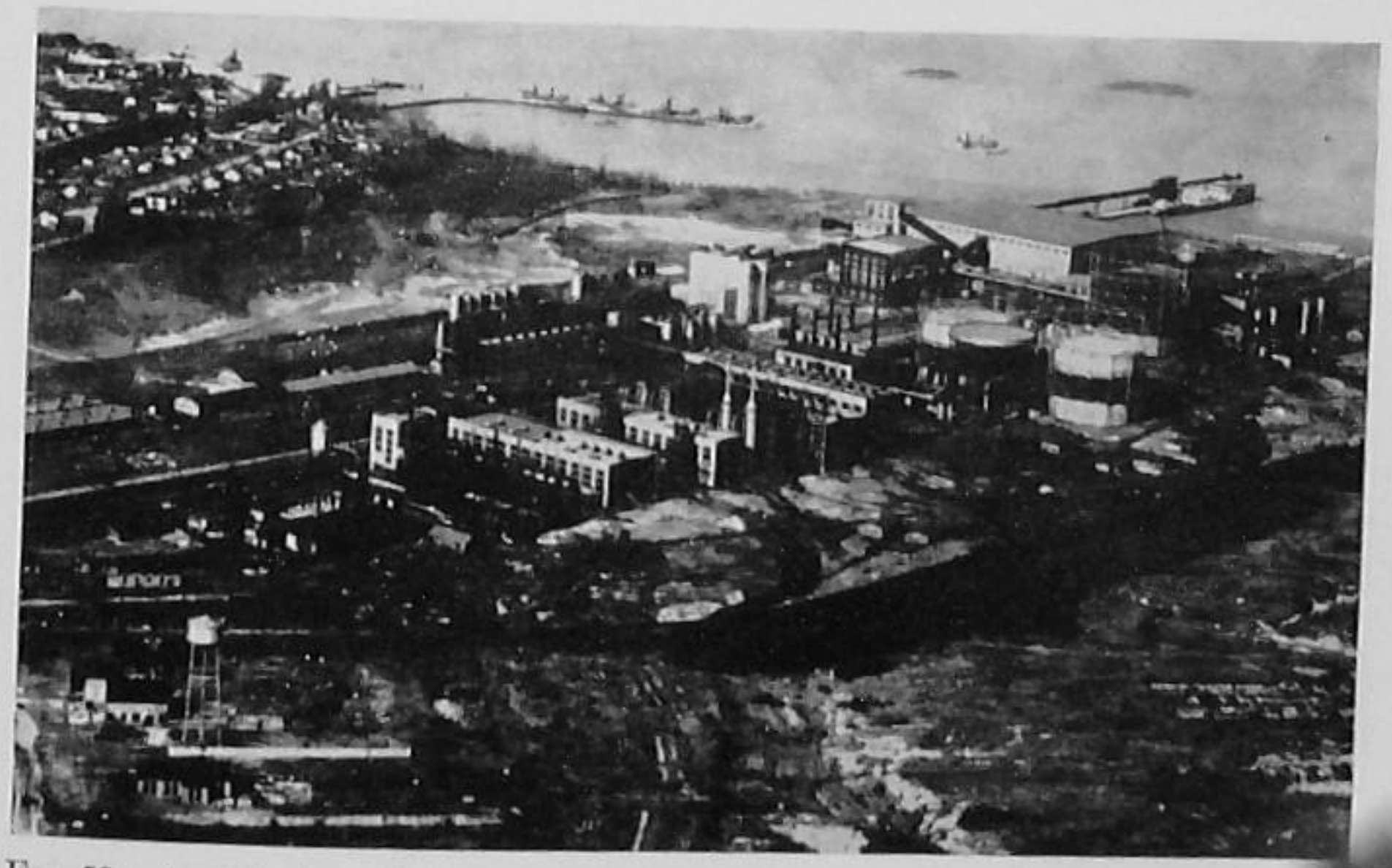


FIG. 59. Aerial view of nitrogen-fixation factory of the Allied Chemical and D[illegible] Corp., Hopewell, Virginia.

These may be conveniently divided into 4 groups: nitrates, ammonia and ammonium salts, calcium cyanamide and urea, and plant and animal by-products (Table 83).

TABLE 83

U. S. Agricultural Consumption of Nitrogen (N) (Mehring)

Material	1910, Tons	1925, Tons	1937, Tons	1941, Tons	1941, Per Cent of Total
Sulfate of ammonia	27,880	81,144	140,760	138,248	30.6
Ammonia liquor	.....	.....	6,250	8,900	2.0
Anhydrous ammonia	.....	.....	4,920	3,500	0.8
Ammoniating solutions	.....	.....	28,000	52,800	11.7
Nitrate of soda	35,030	104,562	128,150	140,400	31.1
Nitrate of soda-potash	.....	1,050	8,838	5,900	1.3
Calcium nitrate	.....	1,219	6,368	150	0.0
Calcium cyanamide	540	14,630	24,725	25,700	5.7
Ammonium phosphates	.....	1,300	7,800	6,200	1.4
Urea and calurea	.....	33	1,952	14,400	3.2
Other chemical nitrogenous	70	92	7,233	3,700	0.8
Cottonseed meal	29,502	21,018	8,250	9,500	2.1
Other seed meals	228	55	925	500	0.1
Castor pomace	850	1,700	2,630	4,350	1.0
Cocoa by-products	60	480	780	900	0.2
Tankage, process	240	9,600	9,440	9,000	2.0
Tankage, animal	15,960	6,020	2,800	4,000	0.9
Tankage, garbage	3,000	3,325	1,575	1,500	0.3
Fish scrap	7,000	6,450	5,781	4,000	0.9
Activated sewage sludge	.....	.....	4,320	6,960	1.5
Other sewage sludge	40	.....	500	1,000	0.2
Guano	1,634	1,242	619	2,000	0.5
Tobacco stems	1,127	1,526	1,800	2,000	0.5
Bone meal	4,347	2,812	2,590	1,200	0.3
Peat and humus	555	1,200	1,875	2,000	0.4
Dried animal manures	350	1,260	1,245	500	0.1
Dried blood	6,125	2,858	625	1,000	0.2
Miscellaneous natural organics	7,124	5,150	825	1,000	0.2
All materials	141,662	268,726	411,576	451,308	100.0
Recapitulation					
Ammonia nitrogen	27,880	82,508	175,547	179,665	39.8
Nitrate nitrogen	35,100	106,859	157,807	173,171	38.4
Synthetic organic nitrogen	540	14,663	31,642	47,062	10.4
Natural organic nitrogen	78,142	64,696	46,580	51,410	11.4
	141,662	268,726	411,576	451,308	100.0

For specific purposes, one or another of these forms of nitrogen is often used in preference to any of the others. Thus nitrates are often preferred for topdressing or sidedressing purposes, ammonium salts constitute the major part of the nitrogen in complete fertilizers, cyanamide is the popular form for plowing under with nonleguminous waste products, sods, and cover crops, and the organic by-product materials are in special favor for sandy soils in a relatively low state of fertility. Where nitrogen materials are used alone, there is a tendency to select them on the basis of the specific effect desired. For complete fertilizers, however, the competitive factor makes it necessary, as a rule, for the manufacturer to choose the materials that supply nitrogen at the lowest cost a pound of the element.

NITRATE NITROGEN

Sodium, calcium, and ammonium nitrates are the ones in most common use. Small amounts of potassium nitrate are available and some magnesium nitrate may be found in the commercial nitrate of lime. Of these the most popular form is sodium nitrate, commonly called nitrate of soda, or just "soda." The explanation of the popularity of this product is partly historical, because Chilean nitrate of soda has long been an article of commerce, partly because of aggressive propaganda in favor of its use, and partly because of its special merit as a source of nitrogen for topdressing and sidedressing purposes.

A great many comparisons have been made between nitrate of soda and competing products under a variety of field conditions and with many types of soil and many different crops. The results of such comparisons are predominantly in favor of nitrate of soda. Mixtures of nitrate of soda with ammonium salts and high-grade organics, however, are sometimes superior to nitrate of soda alone.

The soil has very little capacity to prevent nitrate, in any form, from being carried away by drainage waters. Nitrate of soda sometimes has an additional disadvantage in that its sodium tends to cause a breakdown of the soil granules with the result that, if large amounts of it are used over a long period of years on alkaline soil, that soil may develop a bad physical condition. These disadvantages, however, are more theoretical than real. When nitrate of soda is applied to a soil on which a crop is growing, its nitrogen is quickly absorbed by the roothairs. That not so absorbed may be temporarily utilized by soil microorganisms, with the result that it becomes a part of the living organic matter in the soil from which it is released only

by the usual process of decomposition. The sodium of nitrate of soda has value *per se* for some plants. In other plants it may be substituted in part for potassium, calcium, or magnesium. Sodium tends to have an alkaline effect on acid soils and, as a result of its use, the availability of soil phosphate is increased.

The nitrate portion of nitrate of lime has the same effect and value as that of nitrate of soda. The calcium may be more or less valuable than sodium, depending upon the soil and crop in question. One disadvantage of nitrate of lime is its very marked tendency to absorb water from the air, making it difficult to apply. This tendency has been overcome to a large degree by coating the granules with non-absorptive material and by shipping the material to the farm in moisture-proof bags. Once these bags are opened, however, the material must be applied soon thereafter.

Ammonium nitrate has both advantages and disadvantages over other nitrates. Its advantages lie in its relatively high content of nitrogen and its relatively low delivered-to-the-farm cost a unit of the element. There is the further theoretical advantage that half of its nitrogen is present in the ammonium form and, as such, cannot readily be leached out of the average soil. The disadvantages of ammonium nitrate are that it contains no sodium or calcium, which have value in themselves, and that it has an acidulating effect on the soil. On acid soils, therefore, extra lime is required to counteract the acidity resulting from the use of ammonium nitrate. To neutralize all the acid produced by 100 pounds of ammonium nitrate's being introduced into the soil would require the application of 59 pounds of calcium carbonate or pulverized limestone (Table 84).

AMMONIUM NITROGEN

The most important non-nitrate carriers of ammonium nitrogen are ammonium sulfate and ammonium phosphate. These are produced by absorbing ammonia gas in sulfuric and phosphoric acids, respectively, with the resulting production of white, crystalline salts. Liquefied gaseous ammonia is now being used as such, on a large scale, in Mississippi, Louisiana, and California. It can readily be supplied in tank cars for application in an irrigation stream, or directly into the soil by the use of an opener, on release from a container attached to the tractor. Application to the top of the soil results in partial loss of ammonia and, if the soil is covered with grass or similar over-all vegetation, may result in severe burning of the leaves.

TABLE 84

COMPARATIVE VALUES OF NITROGEN CARRIERS AS TO VARIOUS QUALITIES (BEAR)

Material	Percentage N *	Acidity or Alkalinity †	Retention by Soil ‡	Condition Quality §
Ammonia (anhydrous)	82	−148	Medium	Fair
Urea	46	− 84	Medium	Fair
Ammonium nitrate	35	− 59	Low	Fair
Ammonium chloride	26	−140	Medium	Fair
Ammonium sulfate	21	−110	Medium	Fair
Calcium cyanamide	22	+ 62	Medium	Good
Calcium nitrate	17	+ 20	Low	Poor
Sodium nitrate	16	+ 29	Low	Fair
Ammonium phosphate	12	− 65	Medium	Good
Dried blood	10	− 22	High	Good
Animal tankage	6	+ 10	High	Good
Cottonseed meal	6	− 9	High	Good
Fish scrap	5	− 8	High	Good
Tobacco stems	2	+ 12	High	Good

* Commercial products may contain somewhat less than these percentages.
† In terms $CaCO_3$ for 100 pounds of material: − = acid, + = alkaline.
‡ Capacity of soil to retain until used by plants.
§ For fertilizer-mixing purposes.

Ammonia or ammonium forms of nitrogen have the advantage that, notwithstanding their high solubility in water, their nitrogen is not readily leached from the soil, once it has been applied to it. The ammonium ion tends to replace calcium in the exchange complex, thereby becoming "attached" to the soil until such time as it has been acted upon by soil microorganisms that change it to the nitrate form. In other words, loss of nitrogen by leaching is delayed. The length of this period of delay depends upon the depth at which the ammonia or ammonium salt is placed in the soil and the conditions with respect to moisture, aeration, and the supply of lime, as they affect the activities of the soil microorganisms responsible for the production of nitrate. The practice of plowing down non-nitrate fertilizers or of dropping them on the bottom of the furrow at plowing time has arisen from the desire to slow down the rate of production of nitrate in the soil, thus supplying the nitrogen to the crop at a somewhat less rapid rate, comparable to that at which it is delivered by decaying organic matter.

The disadvantage of the ammonium forms of nitrogen lies in the acid effect on the soil (Table 84). With sulfate of ammonia, for example, experimental work indicates that, for every 100 pounds of

TABLE 85

U. S. Estimated Consumption Fertilizer Nitrogen by Sources (Gribbins)

[Thousands Tons (N)]

	1930	1935	1940	1945	1949
Ammonia and solutions	31	26	63	134	257
Ammonium sulfate	127	121	134	198	240
Ammonium phosphate	7	7	10	14	22
Ammonium nitrate	...	...	...	89	128
Sodium nitrate	95	93	122	173	147
Other nitrates	9	10	9	...	6
Calcium cyanamide	21	14	18	25	24
Other chemical N	5	8	25	26	45
Organics	60	51	48	30	34
Totals	355	330	429	689	903

it that may be applied to the soil, the acid produced in the soil will require the use of 110 pounds of calcium carbonate, or its equivalent in some other form of commercial lime, for its neutralization. Long-continued use of sulfate of ammonia on experimental plots without applications of the necessary lime as a corrective has resulted in greatly increasing soil acidity and in lowering yields. For acid-soil areas this can be a serious matter. Usually the problem is not trouble-some because lime must be applied as a corrective in such areas and the extra amount required to neutralize the acidity of any sulfate of ammonia that may be applied is normally not very great. As rates of application of nitrogen fertilizers are increased, as in the use of 100 pounds of nitrogen (N) for sidedressing corn, the matter needs watch-ing. To supply 100 pounds of nitrogen as sulfate of ammonia would require the use of nearly 500 pounds of the material. More than that amount of pulverized limestone would be required to neutralize the acidity resulting from its use.

In alkaline-soil areas, this acidity becomes an advantage, just as the alkalinity of nitrate of soda becomes a disadvantage. These ad-vantages and disadvantages of the several forms of nitrogen are weighed in practice, with the result that the several materials grad-ually are fitted into their proper uses. The low cost of ammonia or ammonium materials, calculated in terms of a given quantity of nitro-gen, often makes it possible to use them in spite of their disadvantages, and then to apply the necessary corrective.

AMMONIATED SUPERPHOSPHATE

The lowest-cost form of nitrogen on the market is ammonia. This is partly because ammonia is a by-product in the coking of coal but also because the combining of atmospheric nitrogen with hydrogen to form ammonia is the most economic fixation procedure known. Ammonia is not readily usable as such and, therefore, it is normally made to combine with some carrier, of which the most common is sulfuric acid. Large amounts of ammonia go to market in the form of nitrate of soda and urea, however, the necessary additional manufacturing processes required to produce these materials being justified supposedly by the extra advantages they possess.

Another important means of marketing ammonia is by running the gas into freshly produced superphosphate with which it will readily combine with the resulting formation of ammonium sulfate and a mixture of ammonium and calcium phosphates. The final product is known as ammoniated superphosphate. The nature of this product varies with the amount of ammonia that has been added to the superphosphate. Normally only from one-third to one-half of the ammonia-absorbing capacity of superphosphate is taken advantage of because of the tendency, with further ammoniation, to reduce the availability of the phosphorus in the superphosphate, as determined in the chemist's control laboratory.

Since most soils are in need of phosphorus as well as of nitrogen, the superphosphate serves as a very economic carrier of the nitrogen, with the result that considerable saving is effected by this procedure. Ammoniated superphosphate normally reaches the farm not as such but as a component of complete fertilizers.

CYANAMIDE AND UREA

The nitrogen of calcium cyanamide and urea is obtained from the atmosphere. In the cyanamide process, limestone and coke are employed, with the resulting production of a black material that supplies both lime and nitrogen to the soil. This product is almost ideal for preplowing application on top of grass sods or nonlegume cover crops because of its high content of calcium, which is yielded up to the soil in the form of hydrated lime. Its nitrogen is released in the form of [illegible] urea. From the point of view of the nitrogen itself, it makes little difference whether one uses calcium cyanamide or urea. The disadvantage of cyanamide is that, until such time as it has been changed

to urea and hydrated lime, the product is injurious to plant life. It is most useful, therefore, when thoroughly mixed with moist soil well before planting. Calcium cyanamide is one of the best forms of nitrogen for adding to organic wastes in the production of "synthetic manure." The pulverized product is widely used for selective killing of broad-leafed weeds in small grains and for defoliating cotton and other crops just preceding harvesting, its nitrogen value not being lessened by this procedure. For this purpose, the application is made in the early morning when the plants are covered with dew, or after the application of water by the use of spraying machinery.

Commercial urea is a condensation product of ammonia and carbon dioxide. It is a white, crystalline product, the most concentrated form of solid nitrogen on the market. On being applied to the soil, the nitrogen of urea is rapidly changed to ammonia. The effect of its use, therefore, is quite similar to that produced by sulfate of ammonia, except that the acid effect of the sulfuric acid that serves as the carrier of the ammonia in ammonium sulfate does not have to be dealt with. On the other hand, urea, like ammonia itself and like ammonium nitrate, supplies nothing of value except nitrogen, whereas the other carriers of nitrogen supply one or more additional elements that may have value in the soil. One of the most interesting uses for pure urea is as a protein supplement for cattle and other ruminants, the nitrogen of the urea being synthesized into proteins by the bacteria that are normally present in the rumen.

ORGANIC BY-PRODUCT NITROGEN

A great variety of plant and animal by-products of relatively high nitrogen content are available for use as fertilizer materials. These consist of bird guanos, fish scraps, slaughterhouse wastes, meals remaining after the oil has been extracted from cottonseed, flaxseed, soybeans, tobacco by-products, and wool wastes. In addition, there are a great variety of low-grade organics, such as garbage tankage, end-products of sewage-disposal systems, peat, and many factory refuse materials, of which leather wastes and peanut shells are good examples. Most of these materials are not used as such but as components of complete fertilizers, in which they have special value as conditioning agents. Frequently, the decay-resistant types are mixed with phosphate rock and acidulated with it as a means of increasing the availability of their nitrogen.

Nitrogen fertilizers are normally sold on the basis of their total content of the element. However, most control laboratories apply certain tests to mixed fertilizers in an effort to determine the quality of any low-grade organics that may be contained in them. These tests consist in digesting the insoluble portion of the fertilizer in a neutral or alkaline solution of potassium permanganate and determining what percentage of the nitrogen remains in an insoluble state after this treatment.

There is widespread belief that organic materials of plant and animal origin have extra values that cannot be accounted for by the nitrogen and ordinary ash elements that are associated with them. It seems probable that this belief is not without scientific foundation in that such products may supply small amounts of stimulatory substances, including some of the minor elements required by plants. The realization of these extra values is normally possible only on soils of very low organic-matter content, especially sands. Good effects from the use of organic fertilizers are most likely to be observed under conditions in which they are placed in bands along the row. Any organic type of plant stimulant that such materials may contain may soon be decomposed by microorganisms, once it has been applied to the soil.

The general trends in the manufacture of nitrogen fertilizers are in the direction of the product that can be made and used at lowest cost per pound of nitrogen. On this basis, ammonia, as such, and in the form of the sulfate and nitrate, leads (Table 85). Concentrated nitrogen solutions, made up of ammonium nitrate, anhydrous ammonia, and water, and containing 25 to 40 per cent nitrogen (N), are being used in the manufacture of complete fertilizers. They can be applied for sidedressing purposes with relative ease and a high degree of effectiveness. There is abundant evidence of tremendous possibilities for increasing row-crop yields through the use of sidedressings of as much as 100 pounds N an acre. For this purpose, anhydrous ammonia would appear to have definite advantages in terms of economy in its use.

NITROGEN FERTILIZER PRODUCTION CAPACITY OF UNITED STATES

Within the confines of the continental United States there are 16 producers of synthetic ammonia whose 21 plants have a total capacity of 1,395,000 tons of nitrogen (N). As of 1949, by-product sulfate of ammonia production was equivalent to 190,000 tons of nitrogen and processed organic-waste nitrogen fertilizers yielded 33,000 tons. Thus,

our total production capacity is about 1,618,000 tons of nitrogen. This is equivalent to over 8 million tons of sulfate of ammonia or 10 million tons of nitrate of soda.

Nitrogen compounds are articles of world commerce. They are used for a variety of purposes other than as fertilizers. Both imports and exports have to be considered. Thus, there are three producers of air-nitrogen materials close by in Canada with a total capacity of 160,000 tons of nitrogen. As of 1949, imports of Chilean nitrate were equivalent to 108,000 tons of nitrogen and those of sulfate of ammonia equivalent to 21,000 tons. Exports were equivalent to 132,000 tons of nitrogen.

Nitrogen-fertilizer consumption in the United States (Table 85) was (1949) over 900,000 tons of nitrogen. Since this is only slightly over 55 per cent of our production capacity, there need be no serious shortage of nitrogen fertilizers in this country for some years to come, except in the event of another world war. During each such war the capacity to produce air-nitrogen compounds is increased. When the war is over, there is a surplus of nitrogen fertilizers. Under such circumstances, consumption may increase or some of the plants may be converted to other uses.

SELECTED REFERENCES

1. Albrecht, W. A. Loss of soil organic matter and its restoration. *U. S. Dept. Agr. Yearbook*, pp. 347–376, 1938.

2. American Society of Agronomy and National Fertilizer Association. *Hunger Signs in Crops*. Judd and Detweiler, Washington, 1949.

3. Andrews, W. B., F. E. Edwards, and J. G. Hammons. Ammonia as a source of nitrogen. Mississippi Agr. Exp. Sta., Preliminary Bull., 1947.

4. Bear, Firman E. Making the most of our nitrogen resources. *Soil Sci. Soc. Amer., Proc.*, Vol. 7, pp. 294–298, 1942.

5. Bear, Firman E. Real values of soil organic matter. *J. Soil and Water Cons.*, Vol. 1, pp. 81–85, 1946.

6. Gribbins, M. F. Conversion of ammonia to fertilizer materials. Short Course in Fertilizer Technology, University of Maryland, 1950.

7. Keenan, F. G. Reactions occurring during ammoniation of superphosphate. *Ind. Eng. Chem.*, Vol. 22, p. 1378, 1930.

8. Krantz, B. A. Fertilize corn for higher yields. North Carolina Agr. Exp. Sta., Bull. 366, 1949.

9. Mehring, A. L. Consumption of commercial nitrogen as fertilizer. *Fertilizer Review*, Vol. 17, 1942.

10. Mehring, A. L. Fertilizer nitrogen consumption. *Ind. Eng. Chem.*, Vol. 37, pp. 289–295, 1945.

11. Pierre, W. H. Determination of equivalent acidity and basicity of fertilizers. *Anal. Ed. Ind. Eng. Chem.*, Vol. 5, p. 229, 1933.

12. *Proceedings.* Third Annual Meeting of the National Joint Committee on Nitrogen Utilization, 1944.

13. Rubins, E. J., and F. E. Bear. Carbon-nitrogen ratios in organic fertilizer materials in relation to nitrogen availability. *Soil. Sci.*, Vol. 42, pp. 411–423, 1942.

14. Schreiner, O., and B. E. Brown. Soil nitrogen. *U. S. Dept. Agr. Yearbook*, 1938.

15. Taylor, George V. Nitrogen production facilities in relation to future demand. Short Course in Fertilizer Technology, University of Maryland, 1950.

16. Waksman, S. A. *Humus, Origin, Chemical Composition and Importance in Nature.* Williams and Wilkins Company, Baltimore, 1936.

17. Waynick, D. D. Anhydrous ammonia as a fertilizer. *California Citrograph* 19, 1934.

18. Wilson, B. D. Nitrogen in the rainwater at Ithaca, New York. *Soil Sci.*, Vol. 11, pp. 101–111, 1921.

19. Wilson, P. W. *The Biochemistry of Symbiotic Nitrogen Fixation.* University of Wisconsin Press, 1940.

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Phosphorus Resources

The most common phosphorus-containing compound is calcium phosphate. This is the primary constituent of bones and of apatite, a widely distributed mineral in rocks and soils, having the formula $[Ca_3(PO_4)_2]_3 \cdot CaF_2$. Discovery of large deposits of phosphate rock in Florida in 1881 was a very important event, since the supply of bones was limited and only relatively small quantities of mineral phosphates had previously been located. Fortunately for the United States, other large phosphate deposits were later found in Tennessee and Arkansas. Finally, deposits still larger than any previously known were discovered in Idaho and neighboring states. Small deposits of phosphatic materials are known to exist in 19 other states. *Estimates of the more important deposits (Table 86) total over 13 billion long tons of phosphate rock. This is more than one-fourth of the world's known deposits.*

TABLE 86

TONS OF PHOSPHATE ROCK AVAILABLE IN THE UNITED STATES (MANSFIELD)

Eastern	Long Tons	Western	Long Tons
Florida	5,082,000,000	Idaho	5,736,000,000
Tennessee	194,000,000	Utah	1,741,000,000
Arkansas	20,000,000	Montana	391,000,000
S. Carolina	9,000,000	Wyoming	116,000,000
Kentucky	1,000,000		
		Total	13,290,000,000

Search for other deposits of phosphate rock continued the world over. As a result, very large tonnages were located in Morocco, Algeria, Tunisia, and Egypt, in North Africa, in European Russia and Poland, and in Nauru and certain other islands in the Pacific Ocean. An estimate of the foreign reserves of phosphate rock and apatite is shown in Table 87.

TABLE 87

ESTIMATED WORLD RESERVES OF PHOSPHATE ROCK (JACOBS)

Country	Metric Tons
French Morocco	21,000,000,000
United States	13,535,000,000
Soviet Socialist Republics	7,568,000,000
Tunisia	2,000,000,000
Algeria	1,000,000,000
Brazil	572,000,000
Islands, Pacific and Indian Oceans	182,000,000
Egypt	179,000,000
Other countries (23)	670,000,000
Total	46,706,000,000

SOIL PHOSPHORUS

The phosphorus (P) content of igneous rocks is about 0.15 per cent, whereas that of limestone is around 0.02 per cent, with intermediate percentages of the element in sandstones and shales. The phosphorus content of the lithosphere has been estimated at 0.12 per cent. Soil derived from limestone tends to contain more phosphorus than the rock from which it was formed. As the limestone dissolves and disappears and the residue accumulates to form the soil, there is a concentration of the relatively insoluble phosphate. Soils derived from igneous rocks tend to have a somewhat lower phosphorus content than that of the rocks themselves. The phosphorus contained in the plow depth of soil ranges normally between 0.025 and 0.125 per cent, the average being about 0.06 per cent. This is equivalent to about 1200 pounds of the element in the plowed acre. The soil of the Bluegrass region of Kentucky, which is noted for its natural fertility and fine livestock, is very high in phosphorus, averaging around 0.50 per cent. In some parts of that area the soil contains over 1.0 per cent phosphorus, or more than 15 times as much as the average soil.

The rate at which the apatite in the soil dissolves is very slow. The only practical means of speeding this up is by the addition of organic matter. On decomposition, this yields carbonic and nitric acids that serve as supplemental solvents. Much of the added effect of these acids is spent on other soil minerals, however, only a small part of it being available for the liberation of phosphorus.

Soil organic matter is a supplemental source of phosphorus for plant use. This phosphorus is in a much more readily available form than

that in the mineral portion of the soil. Much of the value of cover crops and clover sods lies in their accumulated reserves of mineral elements that are liberated during the process of decomposition for reuse by the next crop. Phosphorus is one of the elements that are thus made available for plant use. Evidence exists to the effect that organic forms of phosphorus maintain a higher state of availability in the soil than the inorganic forms, and consideration has been given to the possibility of large-scale production of synthetic organic phosphates.

SOIL FIXATION OF PHOSPHATES

One of the problems in the use of phosphate fertilizers is that of the fixation of applied phosphate by the soil. The mechanism of this fixation process has been the subject of a great deal of study by soil chemists. If a soluble phosphate is applied to the soil it loses its solubility almost immediately on coming in contact with the soil, with the result that its availability to any crop that may be planted is greatly reduced. This loss of solubility, termed "fixation," may be due to precipitation as calcium, iron, or aluminum phosphate, depending upon whether the soil is alkaline or acid. It may also be the result of a more complex adsorption process, as a consequence of which the phosphate radical becomes more or less firmly attached to the soil complex.

To avoid fixation losses, the usual procedure is to apply the phosphate in bands along the row. By this means part of the phosphate may be kept from direct contact with the soil or some of the soil may be so nearly saturated with phosphate that the release of available phosphorus to plant roots is readily accomplished.

Fixation of phosphates is a much more troublesome problem in acid soils than in those that have been limed to a *p*H value approaching neutrality. One effect of the lime is to reduce the solubility of iron and aluminum in the soil with the result that the phosphate will be precipitated as the more soluble di- or tricalcium phosphates, or compounds closely related thereto. Another effect of the lime is to increase the number of hydroxyl ions, which tend to compete with the phosphoric acid ions for a position on the adsorption complex.

The problem of phosphate fixation is especially troublesome under conditions in which low rates of fertilizer application are used on strongly acid soils. In proportion as more lime and phosphate are added to the soil and the general level of fertility is raised over a period of years, row applications become less important. Thus, in areas

where lime is applied over the land in advance of plowing, phosphate fertilizers may also be plowed under to good effect. This is on the assumption that the rate of application is liberal and that a small amount is retained for use along the row. This latter may be applied either in bands, as in planting corn and wheat, or as a starter solution at the time of transplanting such crops as cabbage and tomatoes.

PHOSPHORUS IN LIVESTOCK FARMING

Calcium phosphate is the primary constituent of bones. The production and sale of livestock is a means of hastening the loss of phosphorus from the land. The bones of a 1000-pound steer weigh approximately 35 pounds and contain about 7 pounds of phosphorus. Similarly, 10,000 pounds of milk, the yearly produce of a good cow, contains some 11 pounds of the element. The loss of phosphorus from the land through the sale of livestock and its products would not appear to be very serious for any one year, but it ultimately becomes apparent, both in the reduction of crop yields and in the lowering of the quality of the livestock. Bones of animals are, in part, returned to the soil in the form of fertilizers. Once phosphorus is tied up in the bones of man, however, it is more or less permanently lost from the soil.

The legumes, which serve so effectively in collecting nitrogen for their own use and in producing protein for food and feed purposes, have very high phosphorus requirements. Unlike the nitrogen, the phosphorus of legumes can be obtained only from the soil. A 4-ton crop of alfalfa hay contains some 18 pounds of the element, all of which is lost from the soil when the crop is harvested for hay or silage. If the manure produced from feeding the alfalfa is brought back to the land without loss, as much as 75 per cent of the phosphorus that was contained in the hay may be recovered. A similar recovery of the phosphorus from other crops and from purchased feeds occurs if they are fed to livestock and the resulting manure is applied to the land. A ton of cottonseed meal contains about 25 pounds of phosphorus, of which over three-fourths is recoverable in the manure of the animal to which it is fed.

PHOSPHORUS-DEFICIENCY SYMPTOMS IN CROP PLANTS

Plants require only between one-fifth and one-tenth as much phosphorus as nitrogen. The phosphorus content of a 100-bushel corn crop,

including both grain and stover, is only about 20 pounds, compared with 150 pounds of nitrogen. Nevertheless, phosphorus is just as essential to plants as nitrogen. In the absence of adequate amounts of the element, plants fail to get off to a quick start, their root systems do not develop satisfactorily, the plants become dwarfed, and they tend to show a purplish discoloration of the stems and of the petioles and lower sides of the leaves. The tomato is one of the best indicator plants for phosphorus deficiency of soils, as revealed by the development of this color. Such discoloration is an indication of a piling up of unassimilated sugars, which are essential constituents of plant pigments. Similar accumulations of sugars may occur as a result of a deficiency of one or another of the other nutrient elements. Thus discoloration is not always a dependable sign of an inadequate supply of phosphorus.

Phosphorus deficiency sometimes occurs in livestock that have eaten only the products of the area where they are located. If the soil of an area is very low in phosphorus, so is the vegetation that makes up most of the land cover in that area. Under such conditions the animals become dwarfed, their joints tend to stiffen, their skins lose their velvety feeling, and they fail to shed their hair properly. Such animals also have abnormal appetites for bones, and even for the soil itself.

COMMERCIAL PHOSPHORUS

In supplementing the soil's supply of phosphorus, use is made of one or more of a considerable variety of commercial forms of this element. The most important source of phosphorus is phosphate rock from which superphosphates, ammonium phosphates, calcined phosphates, and metaphosphates are being made (Table 88). Also, large quantities of bonemeal and basic slag, by-products of the livestock and steel industries, respectively, are available for use.

The choice from among these various materials depends largely on the conditions of use and the prices at which they can be made available for purchase. A large quantity of finely pulverized phosphate rock is used as such on the Corn Belt soils of Illinois and neighboring states. Basic slag has long been a very popular phosphate fertilizer in central Europe, largely because the iron ores of that region are high in phosphorus and because the local supplies of phosphate rock are very limited. Bonemeal is a time-honored product that is preferred by gardeners and florists. The ammonium phosphates, by reason of their high content of both nitrogen and phosphorus, are in greatest

TABLE 88

PHOSPHORUS CARRIERS AND THEIR QUALITIES (BEAR)

	Per Cent P_2O_5	Phosphorus Availability	Acidity or Alkalinity
Phosphate rock	30–40	30	Alkaline
Superphosphate	14–20	90	Neutral
Double superphosphate	40–45	95	Acid
Ammonium phosphate	45–50	100	Acid
Bone crude	20–25	70	Alkaline
Bone dust and ash	25–38	80	Alkaline
Tankage	3–12	80	Neutral
Guano (bird and fish)	12–26	80	Acid
Basic slag	10–25	80	Alkaline
Apatite	38–42	30	Alkaline

demand in areas of heavy use of fertilizers that are far removed from the sources of supply. The metaphosphates also have the advantage of high concentration of phosphorus, but their use is largely in the experimental stage. The most widely used phosphate fertilizer is superphosphate, a product derived from treating phosphate rock with sulfuric acid for the purpose of increasing the solubility of its phosphorus.

PHOSPHORUS AND PHOSPHORIC ACID

It has long been the established custom of chemists to report the percentages of phosphorus in soils, plants, and other products in terms of the pentoxide of phosphorus (P_2O_5) rather than of the element itself. A later school of scientists preferred to report its data in terms of the element, and this has resulted in considerable confusion. The manufacturers of superphosphate and complete fertilizers and the chemists who serve in the control of these products still prefer to report on the P_2O_5 basis, and speak of this as "phosphoric acid." The phosphoric acid of the fertilizer trade, therefore, is the product that would be formed by dehydrating orthophosphoric acid.

The factor from phosphorus to phosphoric acid is 2.29 and that from phosphoric acid to phosphorus is 0.437. The 1200 pounds of phosphorus (P) in the plow depth of 1 acre of soil is equivalent to nearly 2750 pounds phosphoric acid (P_2O_5); the 18 pounds in a 4-ton crop of alfalfa to over 40 pounds; and the 7 pounds in the bones of a 1000-pound steer to about 16 pounds.

SUPERPHOSPHATE

Superphosphate is the standard source of phosphoric acid in fertilizers. It is made by treating finely pulverized phosphate rock (Table 89) with about 90 per cent its weight of 53° to 57° Be (67 to

TABLE 89

ANALYSIS OF H_2SO_4, PHOSPHATE ROCK, AND SUPERPHOSPHATE (BUTT)

Compound	H_2SO_4,* Per Cent	Rock,† Per Cent	Super,‡ Per Cent	Rock,§ Per Cent
P_2O_5	.....	34.24	20.50	37
CaO	0.010	49.01	29.34	52
MgO	0.035	0.32	0.19	0.5
Na_2O	.....	0.25	0.15	1.2
K_2O	.....	0.10	0.06	0.6
Fe_2O_3	0.159	1.28	0.84	3.5
Al_2O_3	0.027	1.10	0.65	1.9
SO_3	63.10	0.48	29.86	7.1
F	.....	3.86	1.80	6.9
SiO_2	.....	6.47	3.57	17.3
CO_2	.....	2.48	0.00	5.1
Cl	.....	0.015	0.008	0.07
C (organic)	.....	0.04	0.00	2.7
As_2O_3	0.0015	0.0009	0.0012	0.014
B_2O_3	.....	0.002	0.0012	0.0144
Cr_2O_3	.....	0.008	0.0048	0.028
CuO	0.0008	0.001	0.0009	0.01
PbO	0.0030	0.00	0.0014	.....
MnO	0.0006	0.048	0.029	0.3
MoO_3	.....	0.002	0.0012	0.0208
NiO	.....	0.003	0.0018	0.003
SeO_2	0.0073	0.00	0.0034	0.011
SnO_2	.....	0.002	0.0012	0.002
TiO_2	.....	0.108	0.065	0.108
V_2O_3	.....	0.008	0.0048	0.4
ZnO	0.0046	0.00	0.0020	0.025

* 60° Be acid, *Ind. Eng. Chem.*, Vol. 24, p. 1064, 1932.
† From Noralyn mine, International Mineral and Chemical Corp., Florida.
‡ Calculated by C. A. Butt on basis of 100 pounds rock to 78 pounds acid.
§ Highest values shown in world phosphate deposits reported by K. D. Jacob.

73 per cent) sulfuric acid. One ton of phosphate rock yields a little less than 2 tons superphosphate, each containing somewhat more than one-half as much phosphoric acid as the original rock. High-grade phosphate rock will yield superphosphate containing about 20 per cent

available phosphoric acid. Such a product is known as "20-per cent superphosphate." Most of the phosphoric acid of superphosphate is soluble in water. The term "available" is made to include not only the phosphoric acid that will dissolve in water but the portion that is soluble in a neutral solution of ammonium citrate under the standard

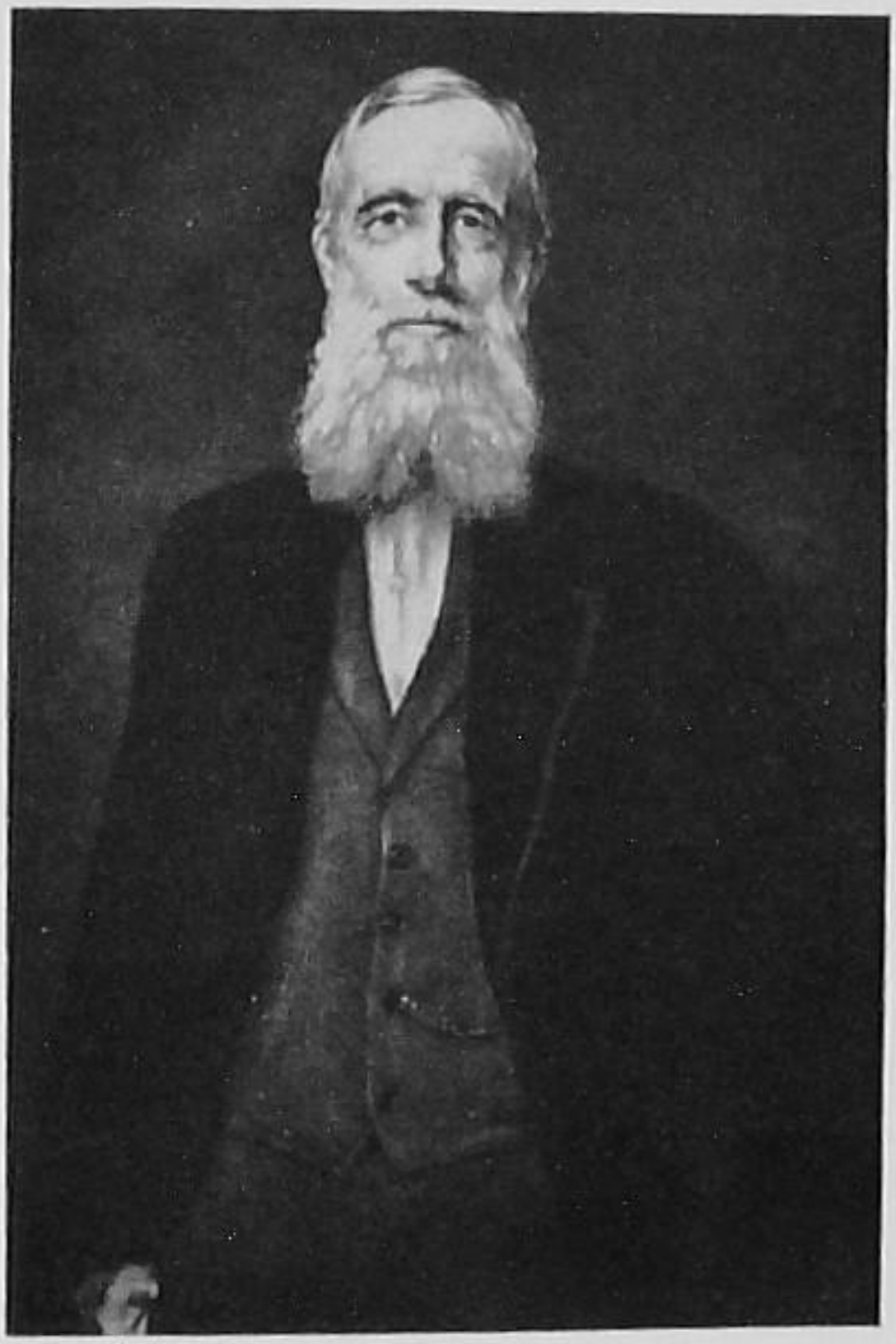


FIG. 60. John Bennett Lawes, first director of the Rothamsted Experiment Station and first manufacturer of superphosphate.

laboratory conditions established by the Association of Official Agricultural Chemists.

Ordinary superphosphate is made up of about 40 per cent monocalcium phosphate, 10 per cent dicalcium phosphate, 45 per cent calcium sulfate, 10 per cent iron and aluminum oxides, silica, and trace elements, and 5 per cent moisture. A considerable part of its fluorine is volatilized during manufacture (Table 89).

A series of superphosphates that contain from 18 to 24 per cent available phosphoric acid are being manufactured. Those with the lower percentages are made from low-grade phosphate rock. Those with



FIG. 61. Deposits of phosphate rock are looked upon as one of the most important natural resources of any nation.

the higher percentages may have been made from very high-grade rock or they may have been produced by mixing double superphosphate with the ordinary grade. Phosphate rock and superphosphate production are shown in Table 90.

TABLE 90

TONS U. S. PHOSPHATE ROCK AND SUPERPHOSPHATE PRODUCTION (NFA)

Tons	Rock Production	Rock Exports	Rock Imports	Rock Consumed *	Superphosphate † Production
1910	2,654,000	1,083,000	21,000	1,593,000	2,595,000
1915	1,835,000	253,000	5,000	1,587,000	2,545,000
1920	4,103,000	1,069,000	100	3,034,000	5,130,000
1925	3,481,000	870,000	2,000	2,614,000	4,040,000
1930	3,926,000	1,225,000	32,000	2,833,000	4,415,000
1935	3,042,000	1,104,000	3,000	1,941,000	2,950,000
1940	4,003,000	756,000	6,000	3,253,000	4,865,000
1945	5,807,000	142,000	491,000	5,458,000	8,038,000
1950	10,254,000	87,000	1,832,000	8,509,000	11,075,000

* In the United States and its possessions, in long tons.
† Basis 18-per cent grade, in short tons.

If, instead of using nearly equal weights of phosphate rock and sulfuric acid, an extra 50 per cent of acid is added, the resulting product will consist of liquid orthophosphoric acid and calcium sulfate. The liquid can be separated from the calcium sulfate. If this liquid

phosphoric acid is used for the treatment of more phosphate rock, the resulting product will contain only a relatively small amount of calcium sulfate. As a result, the percentage of available phosphoric acid in the final product may be at least twice that of ordinary superphosphate and, for that reason, it is called "double superphosphate" (Table 91). In older literature the term "treble superphosphate" is used instead.

TABLE 91

TONS OF AVAILABLE P_2O_5 PRODUCED IN UNITED STATES (JACOB)

Year	Ordinary Superphosphate	Double Superphosphate	Total P_2O_5
1900	260,000	0	260,000
1910	456,000	4,000	460,000
1920	885,000	10,000	895,000
1930	751,000	43,000	794,000
1935	490,000	41,000	531,000
1940	724,000	151,000	875,000
1945	1,334,000	112,000	1,446,000
1950	1,684,000	309,000	1,993,000

Double superphosphate has the advantage that less than half as much is required as of the ordinary grades. This means economy in freight and handling charges. The disadvantage of this product is its lack of calcium sulfate, a compound of considerable value as a source of calcium and sulfur, both of which are essential to plants and frequently are lacking in soils. These elements can be supplied in the form of limestone and ammonium or potassium sulfates, however, so the matter of relative costs of calcium sulfate and of substitutes for it is involved.

AMMONIUM PHOSPHATES

Ammonium phosphate is produced by dissolving ammonia gas in orthophosphoric acid. Usually this process is carried only to the monoammonium phosphate stage, the resulting product containing from 10 to 12 per cent nitrogen (N) and from 48 to 52 per cent available phosphoric acid (P_2O_5). The commercial ammonium phosphate always carries some impurities, of which calcium sulfate and monocalcium phosphate are the most important, but the percentage content of these constituents is relatively small.

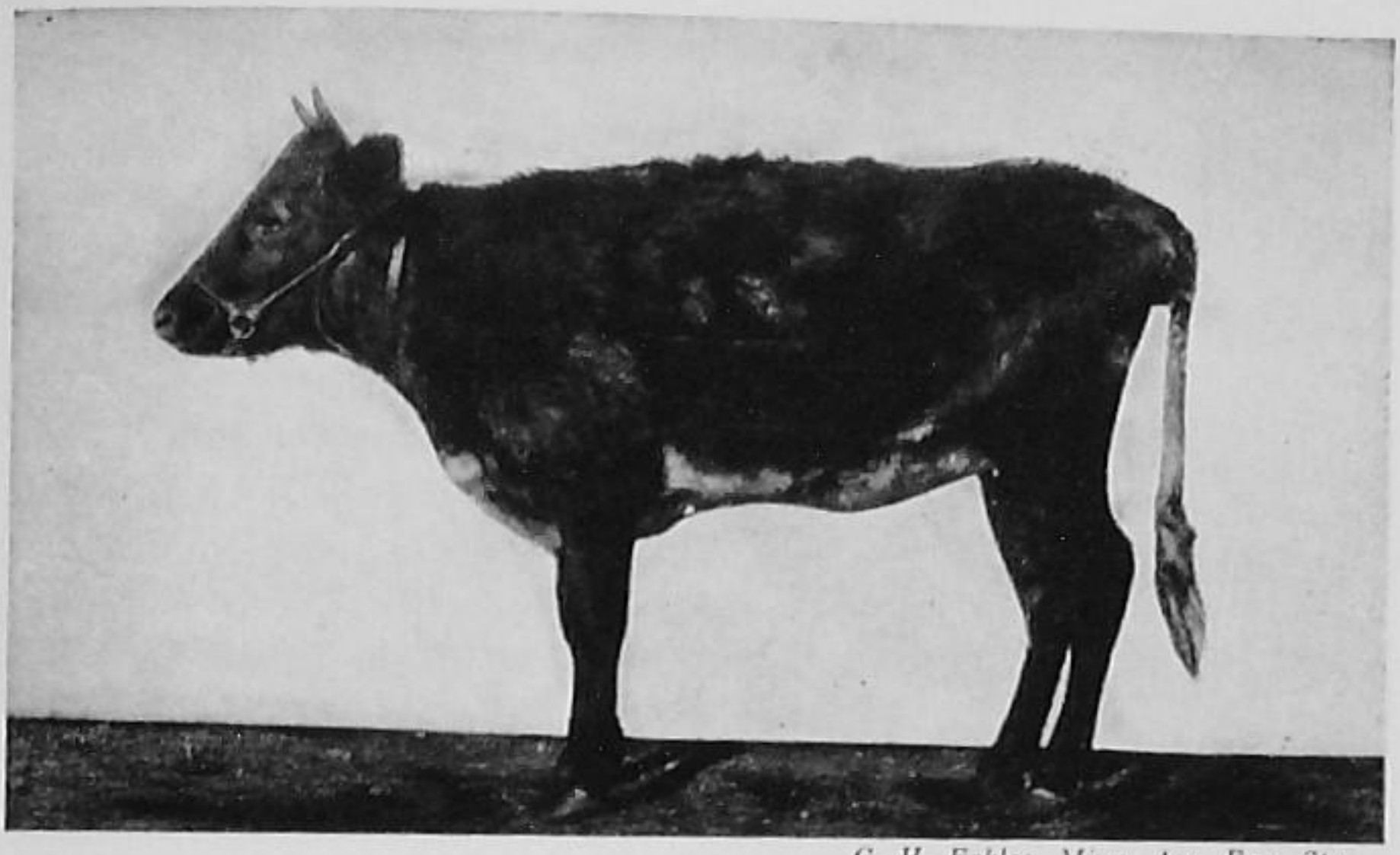
The advantage of ammonium phosphate is that of still greater concentration than double superphosphate, resulting in further reduction in freight and handling charges. Applied as a topdressing, there is

some indication that it has a larger capacity of penetrating the soil than does the soluble portion of superphosphate, and this may be of considerable advantage to the crop under conditions in which the surface inch or more of soil has become so thoroughly dried out as not to be habitable by roothairs. Ammonium phosphate is especially prized for use on highly calcareous soils, such as those in the irrigated areas of western United States.

Many of the advantages that once obtained in the production of ammonium phosphate were set aside by the development of the superphosphate-ammoniation process. In this process, free ammonia is introduced into the superphosphate, with the resulting formation of ammonium phosphate, dicalcium phosphate, and ammonium sulfate. Everything now points to the substitution of the ammoniated superphosphates for the ammonium phosphates for general use in the acid-soil areas of the earth, not only because of the greater economy of the ammoniation process but also because of the added value of the calcium of the ammoniated product.

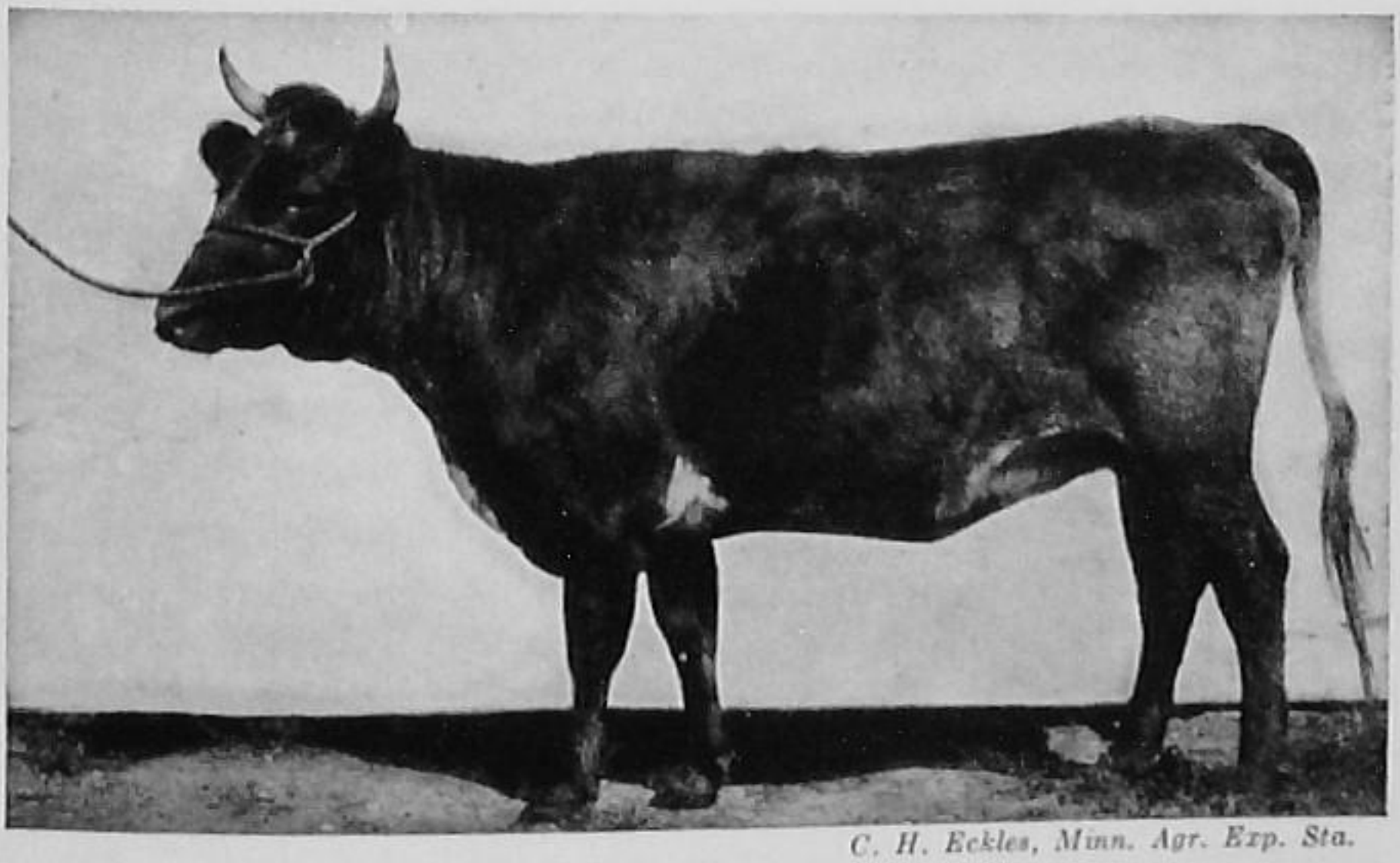
Although calcium can be very economically supplied in the form of liming materials, the importance of the extra supply of it in ammoniated superphosphate in comparison with ammonium phosphate cannot be ignored. Even the elimination of calcium sulfate in the manufacture of double superphosphate has some disadvantages. This compound is known to have marked supplemental value as a source of both calcium and sulfur for plant-nutrient purposes. In some areas, notably in regions far removed from industrial activities and in the peanut-producing states, considerable amounts of gypsum are being applied as such to the land as a source of sulfur, or of both calcium and sulfur, as plant nutrients. Much larger tonnages are being used in alkali-soil regions for the purpose of effecting better granulation and aeration of both the soil and subsoil. Where gypsum is not readily available, ordinary superphosphate is sometimes used as a substitute.

The possibilities in the use of nitric acid in the production of soluble phosphates should not be overlooked, especially in view of the increasing tendency for shortages in supplies of sulfur required in the manufacture of sulfuric acid. The superphosphate resulting from this procedure is a chemical mixture of monocalcium phosphate and calcium nitrate. On ammoniation this is changed to dicalcium phosphate and ammonium nitrate. The economy of such as process, now that large amounts of air nitrogen are at our disposal, are easily demonstrated, according to Turrentine. From the soil and crop point of view these nitrated phosphates should be highly effective.



C. H. Eckles, Minn. Agr. Exp. Sta.

FIG. 62*a*. A cow suffering from a lack of phosphorus on a farm in an area of phosphorus-deficient soil.



C. H. Eckles, Minn. Agr. Exp. Sta.

FIG. 62*b*. The same cow as in Fig. 62*a*, 300 days later. During this interval she received a supplement of tricalcium phosphate, and gained 333 pounds.

Potassium nitrate might well be one of the by-products of such an enlarged production of nitric acid as would be required for this purpose. This is a very useful material for sidedressing purposes. Potassium nitrate could readily be mixed with ammonium phosphate to produce a highly soluble and very effective complete fertilizer.

BASIC SLAG AND BONEMEAL

Basic slag is made by heating iron ore and limestone jointly, with the resulting production of a molten mass of which the bottom portion is metallic iron and the top a liquid slag containing the impurities of the iron ore. One of these impurities is phosphorus. After cooling, the slag is pulverized for use on the land. European basic slag normally contains between 15 and 18 per cent phosphoric acid (P_2O_5) that is soluble in 1 per cent citric acid under standard laboratory conditions. The phosphoric acid of basic slag is not as soluble as that of superphosphate. Its lower availability is compensated for by its alkalinity, 1 ton of the product having a lime value equivalent to about ½ ton of pulverized limestone. American ores contain much less phosphoric acid than those of Europe, those from the Great Lakes region being so low in this constituent as to produce slags of little fertilizing value. Those in the region around Birmingham, Alabama, yield slags containing between 8 and 12 per cent available phosphoric acid, as measured by the citric acid test.

Bone is usually put through a steaming or extracting process before being marketed as a fertilizer. As a result, it becomes more brittle and is more readily pulverized. The rate of availability of its phosphoric acid is determined largely by the degree of its pulverization. Thus, the phosphoric acid of raw bone is only very slowly yielded up to plants, whereas that of the finely pulverized steamed bonemeal becomes available relatively quickly in the soil.

Availability tests are not applied to bonemeal, the assumption being that all its phosphoric acid will become available within a reasonable length of time after the material has been added to the soil. Bones contain between 25 and 28 per cent phosphoric acid (P_2O_5) and an additional 1 to 2 per cent nitrogen (N). Sold as such, they get full credit for their phosphoric acid. If they are used in the manufacture of mixed fertilizers, and thus are subjected to tests for availability, only about two-thirds of their phosphoric acid will be found soluble in the neutral ammonium citrate solution. In such cases it may be

necessary to treat them with sulfuric acid in the same manner as phosphate rock.

Large amounts of bone-containing by-products from fish canneries and packing houses are available for fertilizer use. The skeletons of birds make up a portion of the guanos. Sewage sludges and garbage tankages may also contain considerable amounts of phosphoric acid that was derived from bones.

ROCK PHOSPHATE

Finely pulverized phosphate rock, known as "rock phosphate," is a relatively inexpensive source of phosphoric acid. High-grade rock phosphate may contain as much as 40 per cent phosphoric acid (P_2O_5), or twice as much as ordinary superphosphate. The cost of pulverizing phosphate rock is relatively small, the delivered cost being largely a matter of freight and handling charges. Rock that is to be used for the manufacture of superphosphate is not pulverized as finely as that intended for direct use on the land. The savings in the pulverization of the rock in preparation for the production of superphosphate are more than offset by the extra cost of acidulation. The delivered costs of a ton of material in these two products are not far different, but the cost of a unit of phosphoric acid is only about one-half as much in rock phosphate as in superphosphate. There are areas, however, in which this general statement does not apply. Thus, the selling price of rock phosphate in the vicinity of the mines is relatively low, and that of superphosphate is relatively low at the point of its manufacture.

The use of rock phosphate as such is largely confined to the Corn Belt states, where it is usually applied over the clover sod before plowing the land in preparation for corn. The material is used in much the same manner as pulverized limestone and at the rate of about 1 ton an acre at each application. The original theory of its use was that these 1-ton-an-acre applications would be repeated every 3 to 5 years until the phosphoric acid content of the soil had been doubled. Where such a policy has been carried out in conjunction with a regular crop rotation that included clover every third or fourth year, this program has been quite successful. The supplemental use of limestone and potash salts has been found essential. The rate of increase in consumption of rock phosphate has become relatively rapid (Table 92).



FIG. 63. Hydraulic mining of phosphate rock at Barlow, Florida.

TABLE 92

TONS OF ROCK PHOSPHATE SOLD FOR DIRECT APPLICATION (JACOB)

Year	Florida Phosphate	Tennessee Phosphate	Western Phosphate	Total Phosphate
1940	44,000	74,000	1000	119,000
1945	239,000	220,000	2000	461,000
1946	352,000	238,000	1000	591,000
1947	543,000	311,000	1000	855,000
1948	575,000	303,000	8000	886,000

From 2 to 3 of the 30 to 40 per cent of P_2O_5 in rock phosphate is soluble in neutral ammonium citrate solution. The rate of solution of its phosphoric acid in the soil is relatively slow. Some plants are able to make greater use of it than others (Table 93). Phosphate rock is not tricalcium phosphate, but each molecule is made up of tricalcium phosphate and calcium fluoride, the result being a highly insoluble product. The more finely the rock is pulverized the greater the amount of surface exposed to the solvent action of the soil water and of the organic matter-derived acids that are associated with it. Manufacturers endeavor to pulverize the rock to the extent that most of it will pass a 200-mesh screen (40,000 openings a square inch), some

TABLE 93

RELATIVE CAPACITIES OF PLANTS TO FEED ON PHOSPHATE ROCK (BAUER)

With Low Feeding Power		With High Feeding Power	
Plant	Relative growth *	Plant	Relative growth *
Red clover	33	Rape	54
Wheat	34	Alfalfa	62
Oats	41	Rye	66
Corn	41	Buckwheat	72
Timothy	45	Red top	72
Soybeans	47	Sweet clover	83

* In comparison with normal growth produced by the use of superphosphate valued at 100.

of the material being even much finer than this. Rock phosphate is sold on the basis of its total content of phosphoric acid, not being subject to availability tests in the control laboratories.



FIG. 64. Pebble phosphate rock as mined in Florida.

It seems probable that, on Corn Belt, dairy, and livestock farms, the practice of making use of rock phosphate for broadcast applications and superphosphate along the row at planting time would be more effective than one of using either alone. For potatoes, canning crops, and vegetables there is considerable doubt whether any economic advantage accrues from the use of rock phosphate as such.

Defluorinated phosphates, made by heating phosphate rock to high temperatures in the presence of silica and water vapor, have been receiving considerable attention. By this process the fluorine of the phosphate rock is volatilized and the availability of the phosphorus is increased to a point comparable with that in dicalcium phosphate. Such products are being used both as fertilizers and to replace bonemeal in animal feeds. It has been shown that superphosphate can be almost completely defluorinated by heating it to 1000° C.

OTHER PHOSPHATE FERTILIZERS

Calcium metaphosphate, containing around 63 per cent available P_2O_5, is made by burning elemental phosphorus in contact with phosphate rock. The phosphorus is obtained in gaseous form by heating a mixture of phosphate rock, coke, and silica to around 1500° C. The metaphosphate carries its phosphoric acid in a form that has about the same availability as that in defluorinated phosphate rock. The fertilizer future of neither the defluorinated phosphate nor the calcium metaphosphate seems especially promising, largely because these products do not have the capacity to combine with ammonia, a very important feature of superphosphate. It is conceivable that this disadvantage could be compensated for in the case of metaphosphate by substituting potassium for the calcium, but the economy of this procedure is doubtful. The pure salt contains 40 per cent K_2O and 60 per cent P_2O_5.

Considerable interest has been developed in the production of calcium-magnesium phosphates made by fusing a mixture of phosphate rock and serpentine or olivine at a temperature of 1500° C. The melt is quenched in a spray of water. This process is in operation at Permanenti, California, and at Seattle, Washington. These products contain about 20 per cent total P_2O_5, of which 90 per cent is soluble in neutral ammonium citrate solution.

Elemental phosphorus is produced during the first step in the process of manufacturing the metaphosphates. This product has a phosphoric acid (P_2O_5) equivalent of 229 per cent. It can be shipped in tank cars to the point of need and then burned, the resulting pentoxide being absorbed in water to form liquid orthophosphoric acid. Liquid phosphoric acid is employed as such in irrigation waters in California, 5170 tons being used (1947) in that manner. Orthophosphoric acid is not particularly troublesome to handle, but some precautions have to

be taken in its use. In general, however, it is much safer, both from the point of view of the problem of handling the material and that of its use by plants, to have the phosphoric acid tied fast to ammonium, calcium, or potassium, and most of it finds its way to market in one or the other of these three forms.

SELECTED REFERENCES

1. Bauer, F. C. The relation of organic matter and feeding power of plants to the utilization of rock phosphates. *Soil Sci.*, Vol. 12, pp. 21–43, 1921.

2. Bear, Firman E. The phosphate industry. *American Fertilizer Yearbook*, Ware Bros. Co., Philadelphia, 1946.

3. Bear, Firman E., and Stephen J. Toth. Phosphate fixation in soils and its practical control. *Ind. Eng. Chem.*, Vol. 34, p. 49, 1942.

4. Black, W. H. Effects of phosphorus supplements on cattle grazing on range deficient in this mineral. *U. S. Dept. Agr. Tech. Bull.* 856, 1943.

5. Fox, E. J., and Associates. Thermal defluorination of superphosphate. *Ind. Eng. Chem.*, Vol. 39, p. 329, 1946.

6. Gray, A. N. *Phosphates and Superphosphate.* Interscience Publishers, New York, 1943.

7. Hopkins, C. G. *Soil Fertility and Permanent Agriculture.* Ginn and Co., Boston, 1910.

8. Jacob, K. D. Phosphate resources and manufacturing facilities in the United States. Short Course in Fertilizer Technology, University of Maryland, College Park, 1950.

9. Keenen, F. G. Reactions occurring during ammoniation of superphosphate. *Ind. Eng. Chem.*, Vol. 22, p. 1378, 1930.

10. Grimmet, R. E. R., and I. L. Elliott. Production of serpentine superphosphate in New Zealand. *Am. Fertilizer*, Vol. 110, p. 9, 1949.

11. Mansfield, G. R. Phosphate deposits of the world with special reference to the United States. *Ind. Eng. Chem.*, Vol. 34, 1942.

12. Noyes, A. R. Phosphate rock industries of foreign countries. *Mining and Met.*, Vol. 25, p. 495, 1944.

13. Prince, Arthur L., and Firman E. Bear. Phosphorus needs of New Jersey soils. New Jersey Agr. Exp. Sta., Bull. 744, 1948.

14. Reynolds, D. S., and Associates. Phosphate fertilizers by calcination process. *Ind. Eng. Chem.*, Vol. 28, p. 678, 1936.

15. Ross, W. H., and K. D. Jacob. Availability of calcined phosphate and other new phosphatic materials as determined by chemical and vegetative tests. *J. Assoc. Offic. Agr. Chemists*, Vol. 20, pp. 231–249, 1937.

16. Siems, H. B. Fertilizers. *Encyclopedia of Chemical Technology*, Vol. 6, pp. 376–452, 1951.

17. Spencer, V. E., and Robert Stewart. Phosphate studies: I. Soil penetration of some organic and inorganic phosphates. *Soil Sci.*, Vol. 38, pp. 65–79, 193[illegible]

18. Turrentine, J. W. Processes of phosphate conversion. U. S. Patents 2,134,-013, 1938; 2,170,843, 1939; and 2,211,918, 1940.

19. Volk, Garth W. The use of phosphorus for crop production in the United States. *Soil Sci. Soc. Amer., Proc.*, Vol. 8, p. 37, 1943.

20. Waggaman, W. H., and C. R. Wagner. Analysis of experimental work with ground raw-rock phosphate as a fertilizer. *U. S. Dept. Agr. Tech. Bull.* 699, 1918.

21. Walthall, J. H. Chemistry and technology of new phosphate materials. Short Course in Fertilizer Technology, University of Maryland, College Park, 1950.

·18·

Potassium Resources

Potassium does not exist in the elemental state in Nature but only in the form of its compounds with other elements. The most common of these are the silicate minerals, such as the feldspars and micas that are widely distributed in rocks and soils and the alunite, leucite, and glauconite that are found as large deposits in various parts of the earth. Second in quantity are potassium chloride and potassium sulfate, which are important constituents of the waters of oceans and inland seas and of saline deposits derived therefrom. The silicates undergo slow hydrolysis, with the gradual liberation of their potassium. Chloride and sulfate of potassium are highly soluble in water. The largest known deposits of these soluble salts are at Stassfurt, Germany; in the vicinity of Mulhouse, France; near Barcelona, Spain; in the region of the Caspian Sea in Russia; around Carlsbad, New Mexico; at Searles Lake, California; and in the Dead Sea in Palestine (Table 94). These are always associated with sodium, calcium, and mag-

TABLE 94

ESTIMATED WORLD RESERVES * OF POTASH (REED)

Country	Tons K_2O
Germany	20,000,000,000
Russia	18,400,000,000
Palestine	1,200,000,000
United States	400,000,000
France	300,000,000
Spain	270,000,000

* Maximum figures.

nesium chlorides and sulfates. *The known deposits in the United States constitute only about 1 per cent of the world's estimated supplies of soluble potassium salts.*

SOIL POTASSIUM

Most of the rocks from which soils are formed contain one or more potassium minerals, such as orthoclase, microcline, biotite, and muscovite. As they undergo disintegration, with the resulting formation of soil, a considerable part of the potassium that is contained in their mineral constituents is released and carried off by the drainage waters. The remaining soil still contains a large quantity of potassium, however, both in the form of unaltered mineral silicates and of their degradation products, and this is gradually yielded up for plant use.

The potassium content of the lithosphere is estimated at 2.58 per cent. The average amount of potassium in igneous rocks is around 2.6 per cent, whereas that of limestones is only about one-tenth that percentage. Potassium tends to accumulate during the formation of soil from limestones, but soil derived from igneous rocks normally contains less of the element than did the original rocks. The potassium content of the plow depth of a sand or peat soil may be as low as 0.05 per cent, whereas that of some of the heavier loams may be more than 3 per cent. An average figure would be about 1.5 per cent, or 30,000 pounds potassium in the plowed acre. The percentage of potassium in that portion of the soil lying below plow depth is usually somewhat higher than that of the part turned by the plow. The potassium content of twenty important New Jersey soils is shown in Table 95.

Sands are often made up almost entirely of quartz and contain only very small amounts of potassium minerals. Peats may have lost virtually all their potassium through its having been carried away by drainage waters. In regions of low rainfall, and especially in those areas in which irrigation is essential to crop production, the loss of potassium by leaching is much less than it is in humid areas. In fact, potassium chloride, sulfate, and carbonate may constitute as much as 20 per cent of the total alkali salts contained in the soils of some of our western states. Often, sodium rather than potassium salts make up the major portion of the alkali deposits in those areas.

The rate at which the potassium that is contained in the primary soil minerals is yielded up for plant use is often too slow to meet the requirements, even under conditions in which the total potassium content of the soil is quite high. The rate of its liberation may be speeded up by good soil management. This involves the incorporation in the soil of large amounts of organic matter, which normally contains the potassium that was utilized in its growth. The carbonic acid that is

TABLE 95

CHEMICAL COMPOSITION A_1 HORIZONS 20 VIRGIN NEW JERSEY SOILS (BEAR)

Soils *	Percentages Total Constituents						
	SiO_2	Al_2O_3	Fe_2O_3	P_2O_5	Ca	Mg	K
Collington loam	77.1	6.5	5.1	0.19	0.16	0.35	1.37
Washington loam	71.2	11.5	5.4	0.08	0.35	0.44	2.10
Penn silt loam	52.9	20.7	7.8	0.10	0.09	1.01	2.59
Lansdale silt loam	73.0	11.2	3.0	0.12	0.23	0.37	1.50
Dover loam	79.6	7.7	3.0	0.12	0.34	0.49	2.26
Dutchess shale loam †	66.1	12.6	4.6	0.20	0.47	0.89	1.41
Gloucester loam	69.5	13.0	4.5	0.31	0.80	0.52	2.26
Hoosic loam †	71.1	11.5	4.0	0.14	0.48	0.69	2.55
Sassafras loam	79.4	8.7	3.5	0.15	0.12	0.32	1.26
Merrimac silt loam	74.0	10.8	4.1	0.13	0.49	0.38	1.42
Whippany silt-clay loam	76.4	10.6	2.7	0.06	0.45	0.35	1.66
Hagerstown loam †	61.3	14.9	6.7	0.25	0.72	0.87	4.25
Bermudian silt loam	68.9	13.5	5.3	0.11	0.40	0.74	2.00
Fox gravelly loam †	73.5	10.4	3.5	0.18	1.06	1.17	2.54
Chester loam	65.9	15.2	5.3	0.12	0.25	0.29	3.00
Papakating stony loam	72.9	11.9	4.1	0.12	0.22	0.80	1.73
Sassafras loamy sand	86.1	7.3	2.4	0.04	0.11	0.13	1.27
Colts Neck sandy loam	82.2	4.9	5.7	0.14	0.14	0.37	0.70
Lakewood sand	96.1	1.6	0.7	0.01	0.03	0.02	0.07
Sassafras sand	97.2	1.8	0.1	0.02	0.00	0.09	0.35

* The series names are those of the original soil survey. For changes in these names resulting from recent more detailed survey, see *Soil Sci.*, Vol. 64, p. 200, 1947. The Collington, Sassafras, Colts Neck, and Lakewood soils are from the coastal plain. The others are from the Appalachian province.

† These soils were known to have been farmed and, therefore, the samples represent A_p rather than A_1 horizons.

released during the decay of the organic matter, and that liberated from plant roots as well, tends to effect the solution of additional potassium from soil minerals.

EXCHANGE POTASSIUM IN SOILS

The most readily available portion of the soil potassium is that adsorbed on the exchange complex in replaceable form. The exchange capacity of New Jersey soils is normally between 2 and 20 milli-

equivalents for 100 grams of soii. These two extremes are equivalent to 1564 and 15,640 pounds of potassium, respectively, in 2 million pounds of soil. Only a part of the exchange complex is occupied by potassium, however, since hydrogen, calcium, and magnesium are also adsorbed by the soil. This is well shown in Table 96, giving data on the 20 New Jersey soils previously mentioned.

TABLE 96

*p*H, Exchange Capacity, and Exchange-Cation Values in 20 Soils (Bear)

(Same Soils and in Same Order as Shown in Table 95)

Soils	*p*H	Exchange Capacity *	Exchange-Cation Values *			
			H	Ca	Mg	K †
Collington	4.7	15.9	9.2	4.5	1.3	0.482
Washington	4.6	11.3	7.4	1.6	1.9	0.169
Penn	4.5	19.8	15.3	0.4	1.6	0.407
Lansdale	4.6	13.0	7.5	3.3	1.5	0.359
Dover	7.3	14.0	0.0	9.6	3.5	0.222
Dutchess	7.2	14.8	0.0	15.3	3.5	0.700
Gloucester	5.4	11.9	5.6	1.7	0.6	0.115
Hoosic	6.9	11.4	1.3	8.1	1.0	0.141
Sassafras	4.5	7.5	7.0	0.4	0.4	0.231
Merrimac	4.4	10.2	8.1	0.03	1.5	0.133
Whippany	5.2	8.7	4.4	3.2	1.5	0.144
Hagerstown	7.7	16.5	0.0	12.9	4.2	0.219
Bermudian	6.1	13.2	2.9	6.4	3.4	0.180
Fox	7.4	8.5	0.0	6.1	3.1	0.175
Chester	5.8	10.6	5.6	1.5	1.1	0.174
Papakating	5.6	9.0	3.8	4.0	0.7	0.331
Sassafras	4.4	2.7	3.0	0.01	0.00	0.055
Colts Neck	4.2	9.9	7.1	0.2	0.3	0.127
Lakewood	4.4	2.8	2.4	0.07	0.07	0.006
Sassafras	3.9	2.0	1.9	0.01	0.00	0.001

* Exchange values are expressed as me. in 100 grams soil. Where the total exchange capacity is greater than the sum of the quantities of the exchange cations, the soils contained free calcium or magnesium carbonate.

† The critical lower limit in the soil's supply of K is believed to be at 0.15 to 0.20 me. of the element in 100 grams soil. It will be noted that 12 of the 20 soils contained less than 0.20 me. exchange K.

Under what are believed to be more or less ideal conditions in humid regions it is thought that about 65 per cent of the exchange complex should be occupied by calcium, 20 per cent by hydrogen, 10 per cent by magnesium, and only 5 per cent by potassium. On that basis, the plow depth of a soil with an exchange capacity of 10 milliequivalents would carry 391 pounds adsorbed or exchangeable potassium.

When crops are harvested and hauled off the land, the potassium and other basic cations in the exchange complex are usually removed more rapidly than they are renewed from the primary minerals in the soil. In humid areas the tendency is for hydrogen to occupy a very large part of the exchange complex at the expense of the adsorbed calcium, magnesium, and potassium released to the drainage water. If an alkaline form of lime is applied, the hydrogen is replaced by calcium. This, in turn, will be replaced by potassium, if use is made of a fertilizer that is high in this element.

In proportion as more and more potassium is added to the soil in the form of fertilizer, fixation of the element may occur. This is because of the penetration of some of the applied potassium into the interior of the lattice structure of the montmorillonitic types of clay particles. Its release from such a location is not as rapid as though it were adsorbed on the surfaces of these particles, but its availability to plants increases as the exchange potassium is absorbed by roothairs and is taken off the land in harvested crops. Fixed potassium occupies an intermediate position between that contained in the primary minerals and that in the exchange form.

The amount of exchange potassium in soils is readily determined by extracting them with an ammonium acetate solution. The fixed potassium is not recoverable by this procedure but can be brought into solution by boiling in normal nitric acid.

CATION-EQUIVALENT CONSTANCY IN PLANTS

A study of the calcium, magnesium, and potassium ratios in alfalfa plants that were grown on 20 types of soil (Table 97) showed wide variations, depending not only on the nature of the soil but on the amount of available potassium contained in it. All the lime and fertilizer was applied to the soil in advance of sowing the alfalfa seed. As the successive crops were harvested and removed, their content of potassium tended to decrease, whereas that of calcium and magnesium increased.

TABLE 97

Ca, Mg, and K Content of First and Eighth Crops Alfalfa * (Bear)

(Same Soils and in Same Order as Shown in Tables 95 and 96)

Soil Series	Dry Weight		Ca, Mg, and K in First and Eighth Crops †							
			First crop ‡				Eighth crop			
	Tops	Roots	Ca	Mg	K	Sum	Ca	Mg	K §	Sum
	g.	g.								
Collington	68.0	31.7	90	31	60	181	111	37	30	178
Washington	60.8	46.3	94	29	52	175	141	36	19	196
Penn	60.1	35.0	126	19	53	198	134	23	31	188
Lansdale	59.9	28.7	93	21	59	173	123	26	30	179
Dover	58.0	21.3	81	34	60	175	115	57	19	191
Dutchess	56.8	36.3	95	25	51	171	117	39	29	185
Gloucester	55.6	23.7	81	36	57	174	113	40	24	177
Hoosic	52.3	28.7	86	21	57	164	132	39	23	194
Sassafras	51.3	24.7	93	25	49	167	131	28	18	177
Merrimac	48.9	34.0	101	20	55	176	161	23	19	203
Whippany	48.6	19.3	101	24	38	163	105	60	13	178
Hagerstown	47.1	23.0	71	35	51	157	116	70	20	206
Bermudian	44.4	23.3	101	28	52	181	127	52	22	201
Fox	44.4	19.7	66	40	57	163	109	69	21	199
Chester	42.3	20.0	78	28	59	165	101	43	40	184
Papakating	42.0	25.7	93	26	44	163	144	39	18	201
Sassafras	37.5	30.3	94	23	56	173	134	24	24	182
Colts Neck	37.1	21.7	91	16	50	157	144	27	24	195
Lakewood	26.6	23.7	59	28	74	161	93	32	24	149
Sassafras	12.4	7.0	72	33	61	166	107	33	46	186

* Soils were limed to *p*H 6.5 and fertilized with C.P. salts at rate of 200 pounds P_2O_5, 200 pounds K_2O, and 80 pounds MgO in 2 million pounds soil.

† Me. in 100 grams dry weight of tops.

‡ Na did not exceed 1 me. in 100 grams dry produce, except for that from the Whippany, in which it was 2.04 me.

§ The critical lower limit for K in the alfalfa was believed to be about 25 me. in 100 grams dry matter.

A study of these relationships showed that if the equivalent values for these 3 cations, rather than their percentages, were considered, the sum for any given harvest tended to be fairly constant for all 20 soils. This sum averaged 170 milliequivalents for the first crop and 187 for the eighth. It is especially important to note that potassium was the controlling cation, since the plant tended to absorb this element in very much larger amounts during the first period of growth, when an abundant supply was available, than during the eighth period, when the supply was limited.

POTASSIUM IN LIVESTOCK FARMING

In the livestock system of farming most of the potassium removed from the soil by the roots of plants is returnable to the land, being voided in the manure of the animals. The body of a 1000-pound cow contains only about 1½ pounds potassium, and there are only about 12 pounds of the element in 10,000 pounds of milk. In a carefully controlled experiment (Table 98), 86 per cent of the potassium contained in the feed of dairy cows was recovered in their manure, most of it being found in the urine.

TABLE 98

PERCENTAGE RECOVERY OF FEED ELEMENTS IN MANURE (BEAR)

Element	Total Recovery, Per Cent	Percentage Recovery	
		In urine, per cent	In feces, per cent
Nitrogen	70	50	50
Phosphorus	63	1	99
Potassium	86	84	16
Calcium	65	3	97

Since manure contains not only the urine and feces of animals but bedding as well, its potassium content will be determined in part by the nature of the material used for bedding. Dry wheat straw and hardwood shavings, for example, contain about 16 pounds of potassium a ton. The absorbing power of sawdust is at least twice that of

straw and less of it is required for bedding, the result being that manure containing sawdust bedding takes on more nearly the composition of the animal excrements themselves than does the manure from barns in which straw is used as an absorbent. An average ton of cow manure will contain around 8 pounds of potassium. The use of a 10-ton-an-acre application of such manure results in supplying about 80 pounds of the element.

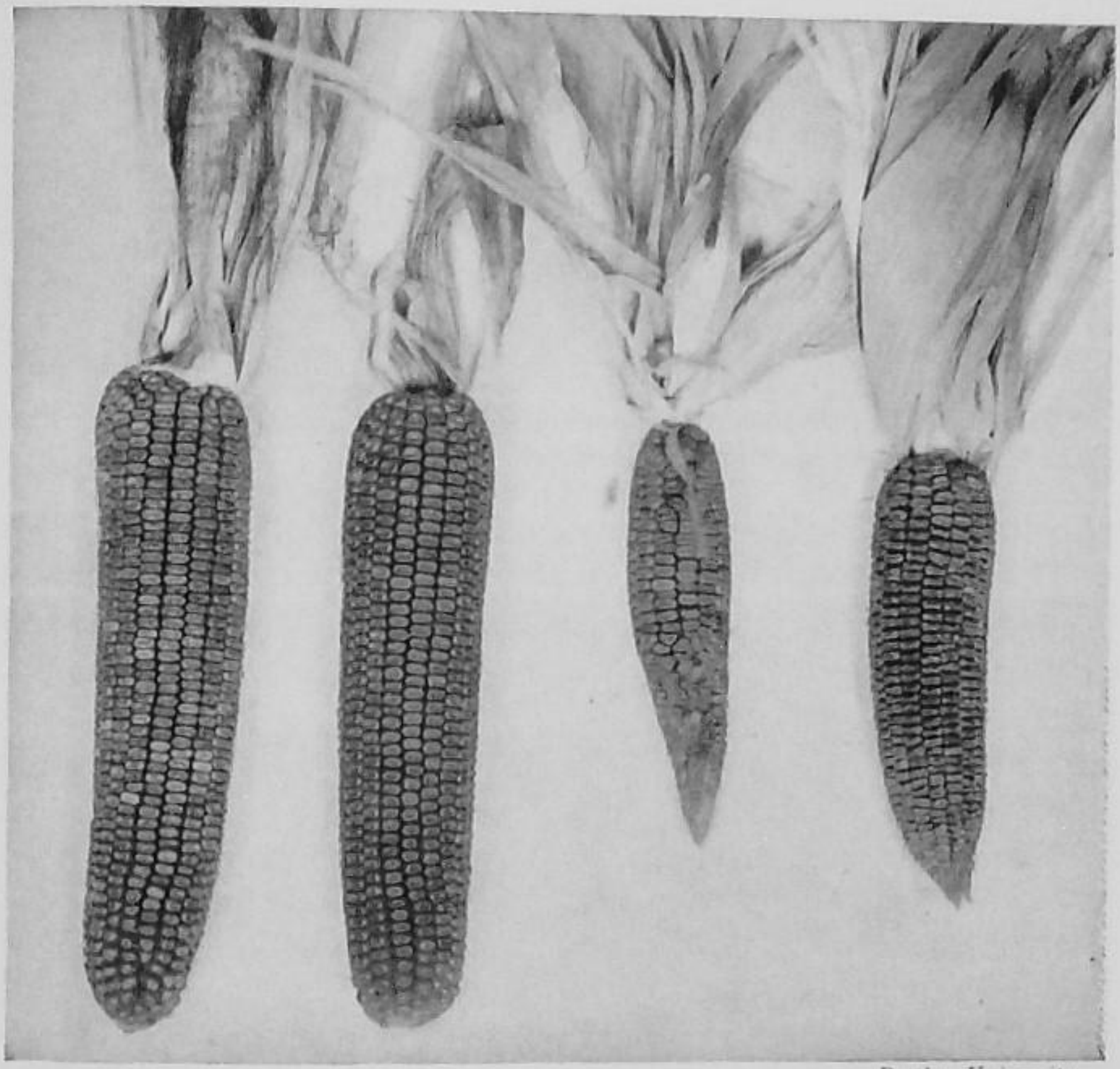
Although a large part of the potassium that is contained in crops is located in their stalks, some seeds or portions thereof contain important quantities of the element. Thus, wheat bran, cottonseed meal, and soybeans contain about 25, 30, and 40 pounds potassium a ton, respectively. On the other hand, corn, oats, and wheat contain only from 8 to 10 pounds of potassium a ton. Such grains are of relatively little value as sources of the element.

POTASSIUM-DEFICIENCY SYMPTOMS IN CROP PLANTS

Most soils contain adequate amounts of available potassium to meet the starting needs of young plants, but the supply of the element is frequently exhausted before the crop has reached maturity. The drain on soil potassium is especially heavy when legume crops are grown, especially if they are of the perennial types, such as alfalfa. It is for this reason that signs of potassium deficiency are so often noted on the leaves of alfalfa plants. It is frequently possible to find alfalfa leaves that are ringed with rows of small white spots, an indication of an insufficient supply of this element. Other common indications of a deficiency of potassium are reddish-brown leaves of cotton, puckered potato leaves with curled-under edges, and corn leaves that have a faded green color between the veins and are fired along the edges. If several of the nutrient elements are in deficiency at the same time, clear-cut symptoms of a lack of potassium may be wanting.

To maintain an adequate supply of potassium presents an especially difficult problem because plants tend toward luxury consumption of this element, piling it up in their tissues in concentrations that may be several times as great as are required for optimum growth. A deficiency of the element soon develops if entire crops are removed, as often occurs with the legume hays or with such vegetables as spinach and celery. This tendency of plants toward excessive absorption of potassium may have an important bearing on their nutritive value, since the extra amount absorbed over and above requirements replaces equivalent amounts of other similar elements, of which cal-

cium and magnesium are the most important. Thus, a high-potassium plant will tend to be low in calcium and, since men and animals have



Purdue University

(*a*) (*b*)

FIG. 65. When corn starves for potash, the leaves fire along the edges, and the ears are chaffy and of poor feeding value. (*a*) Potash. (*b*) No potash.

much greater need for calcium than potassium, the mineral food or feed value of the crop may have been considerably lowered as a result of such a substitution.

COMMERCIAL POTASSIUM

The consumption of potassium in the United States has been increasing very rapidly (Table 99). Most of that contained in fertilizers is now derived from the Carlsbad, New Mexico, deposits. It is present in fertilizers in the form of potassium chloride, or muriate

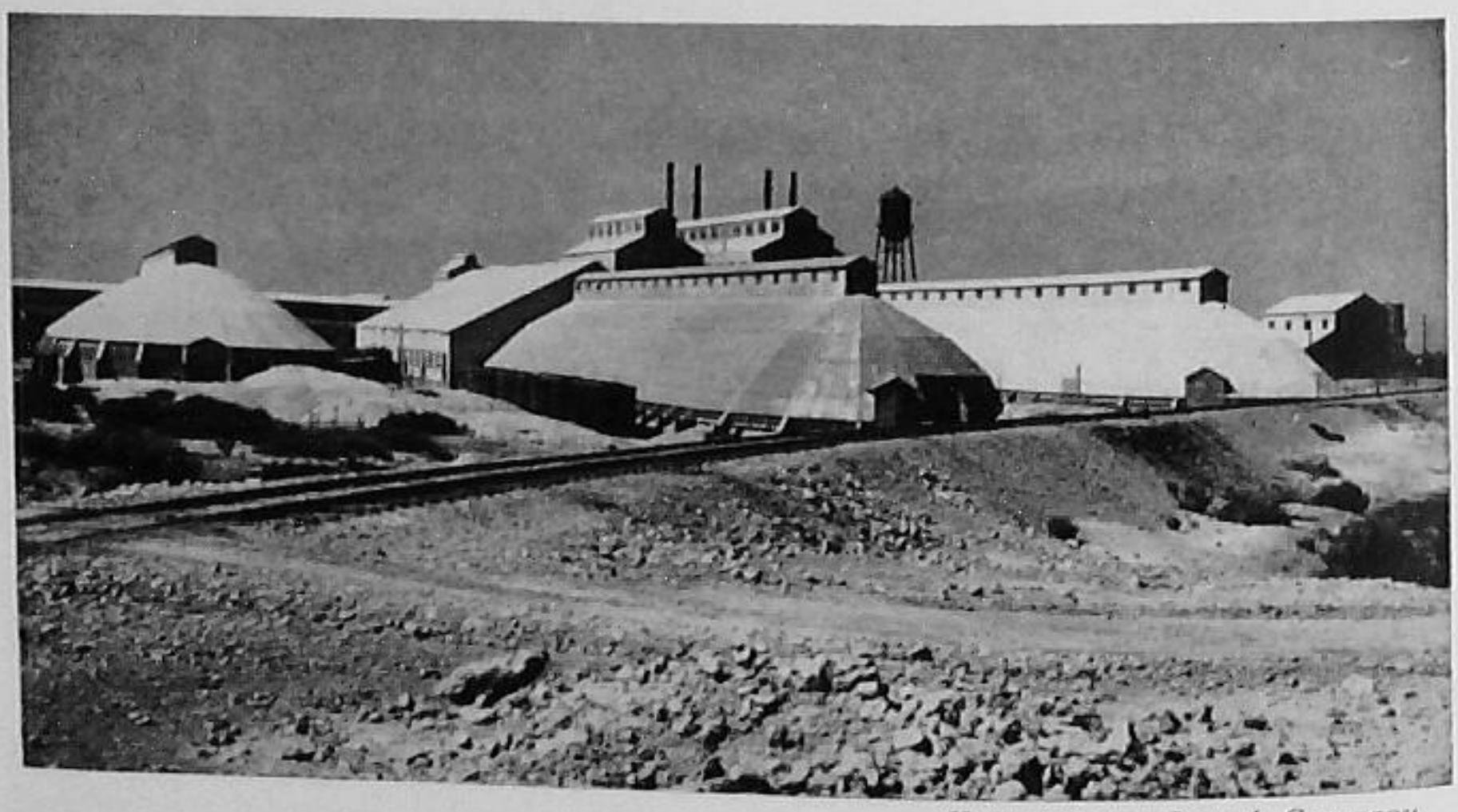
TABLE 99

TONS K_2O CONSUMED ON CONTINENTAL UNITED STATES FARMS (TURRENTINE)

Year	Imported	Domestic	Total
1880	20,000	.....	20,000
1890	30,000	.....	30,000
1900	60,000	.....	60,000
1910	270,000	.....	270,000
1920	170,000	40,000	210,000
1930	305,000	45,000	350,000
1940	70,000	340,000	410,000
1945 *	6,000	855,000	861,000
1950 *	199,000	1,211,000	1,410,000

* From *Fertilizer Sources and Requirements in the United States*, American Plant Food Council, Washington, D. C.

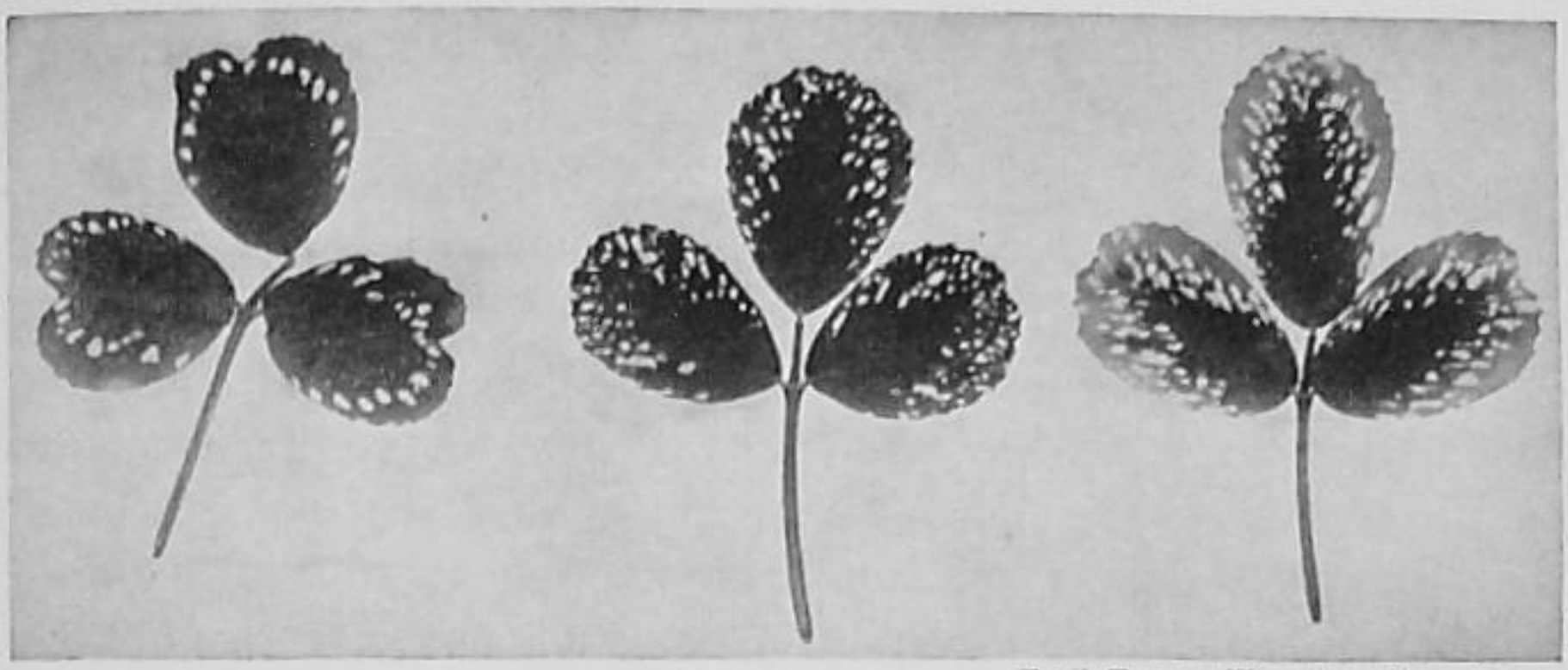
of potash. The Carlsbad deposits are made up of mixed salts. These could be used as such but most of them are put through a refinement process to save freight and handling charges of salts other than those of potassium.



United States Potash Company

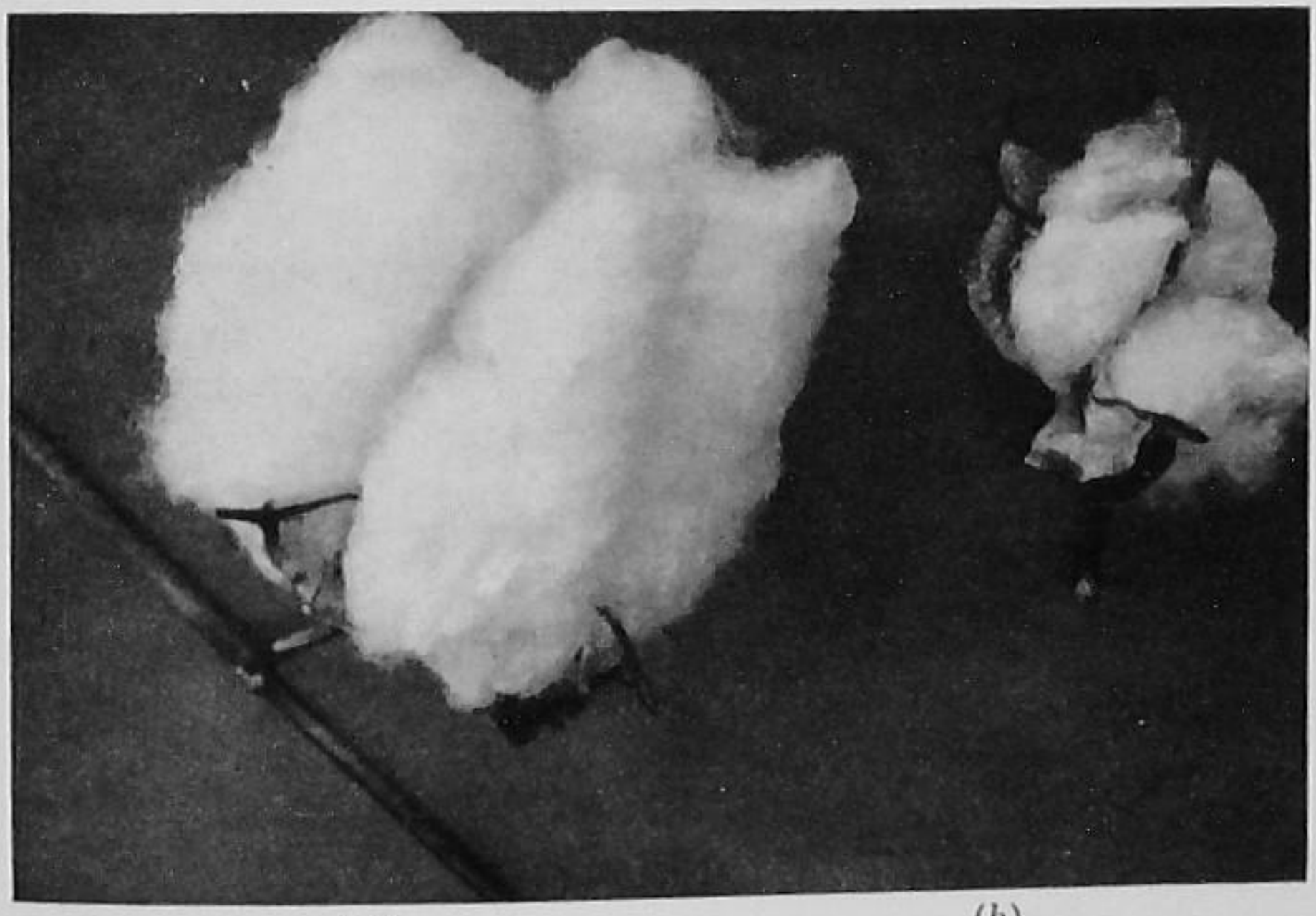
FIG. 66. Modern potash mining and refining plant at Carlsbad, New Mexico.

Of the several potassium salts or salt mixtures that are available for use, the most important are the refined muriate and sulfate of potash and such unrefined products as kainite and langbeinite. The least expensive form of potassium is usually the muriate. Near the deposits, however, some of the crude salts have a commercial advantage. The cost of potassium in the sulfate form is usually higher than



Emil Truog, Wis. Agr. Exp. Sta.

FIG. 67. Effect of potash deficiency on the leaves of alfalfa.



(*a*) (*b*)

FIG. 68. Effect of potash in filling out cotton bolls. (*a*) Plenty of potash. (*b*) Inadequate potash.

as the chloride. For that reason, sulfate of potash is not usually employed as a fertilizer except for crops of high acre value in which some special quality is an important item in determining its selling price. Thus, tobacco growers prefer to use fertilizers containing only about 2 per cent chlorine, and this restricts the content of potassium in the chloride form to about the same percentage. The remainder of the potassium is normally supplied as the sulfate, but the nitrate or carbonate of the element is sometimes used as a partial substitute. Similarly, many sugar-beet growers and some potato farmers favor the use of sulfate of potash. Where the market does not detect any improvement in quality resulting from the use of sulfate of potash, the chloride is preferred because heavier yields can often by obtained by its use than by any other form of the element.

Potassium nitrate is found as an impurity in certain natural nitrate deposits and reaches the market as a mixed salt with sodium nitrate. Potassium carbonate is obtained as by-products from cement mills and blast furnaces and from wool leachings, wood ashes, and molasses residues. The leachings are evaporated to dryness and ignited as a means of concentration and partial purification.

POTASSIUM AND POTASH

Chemists have long been accustomed to calculating and reporting the potassium content of plants, soils, and fertilizers in terms of the oxide rather than of the element itself. The term "potash" is employed for the oxide of potassium. The factor from potassium to potash is 1.20 and from potash to potassium is 0.83. Thus, the 1.5 per cent potassium in the average soil becomes 1.8 per cent potash, and the 30,000 pounds of potassium in the plow depth of an acre become 36,000 pounds. Similarly, the 100 pounds of potassium in a 100-bushel corn crop become 120 pounds of potash, the 160 pounds in a 4-ton crop of alfalfa become 190 pounds, and the 8 pounds in a ton of average cow manure become nearly 10 pounds.

MURIATE OF POTASH

Potassium chloride is sold under the name of muriate of potash. In pure form it contains only potassium and chlorine and none of the oxygen implied in the term potash. Chemically pure potassium chloride contains potassium equivalent to 63.2 per cent potash. None of

the fertilizer-potash salts reach this state of purity. Formerly, most of the muriate of potash of commerce was purified to the point where it contained the equivalent of 50 per cent potash. More recently, however, the potash content of much of the muriate of potash has been raised to between 60 and 62.5 per cent, indicating a purity between 95 and 99 per cent.

A ton of 5–10–10 fertilizer requires 400 pounds of the 50-per cent grade of muriate of potash or 335 pounds of the 60 per cent product. The chief impurity in muriate of potash is usually sodium chloride, but it may also contain small amounts of calcium and magnesium compounds and traces of salts of some of the minor elements, such as those of boron and manganese, as well.

SULFATE OF POTASH

Potassium sulfate, sold under the name of sulfate of potash, is normally made by treating muriate of potash with magnesium sulfate. This means extra cost, and a pound of potash in the sulfate form is more expensive, therefore, than that in the form of the muriate. For that reason sulfate of potash is not used in the formulation of complete fertilizers unless this is specifically demanded by the consumer. Thus, as previously indicated, the use of sulfate of potash in the United States is largely confined to fertilizers that are to be used on tobacco. In some of the sugar beet, potato, and citrus areas, the sulfate is also preferred over the muriate. Occasionally, farmers outside those areas, influenced by some experience of their own or by the arguments of some local fertilizer manufacturer, demand that at least part of the potash in the fertilizer mixture be there as the sulfate. With increasing intensity in the use of fertilizers and further developments in research related thereto it may be found that the sulfate has advantages in the production of some additional crops and for use under certain special soil conditions.

Most of the sulfate of potash of the fertilizer trade contains around 48 per cent potash, indicating a purity of about 90 per cent. The impurities are largely muriate of potash and magnesium sulfate. The product must not contain more than 2.5 per cent chlorine if it is to be sold under the name of sulfate of potash as defined by the association of Official Agricultural Chemists.

CARNALLITE, KAINITE, LANGBEINITE, AND POLYHALITE

A considerable number of crude salt mixtures, as they come from the mines, are available for purchase. Among these are carnallite, kainite, langbeinite, and polyhalite. Carnallite is a double salt of potassium and magnesium chlorides. Kainite is a double salt of potassium chloride and magnesium sulfate. Langbeinite is a double salt of potassium and magnesium sulfates. Polyhalite is a triple salt of potassium, magnesium, and calcium sulfates. Many of these crude salts are red, yellow, gray, or mixed in color. Some of the more important potassium minerals that are used as sources of potash in fertilizers or are contained in rocks and soils are presented in Table 100.

TABLE 100

THE POTASSIUM MINERALS (JOHNSON)

Mineral	Composition	K_2O, Per Cent
Sylvite	KCl	63.1
Carnallite	$KCl \cdot MgCl_2 \cdot 6H_2O$	17.6
Kainite	$KCl \cdot MgSO_4 \cdot 3H_2O$	18.9
Alunite	$K_2SO_4 \cdot Al_2(SO_4)_3 \cdot OH$	11.4
Polyhalite	$K_2SO_4 \cdot MgSO_4 \cdot 2CaSO_4 \cdot 2H_2O$	15.5
Langbeinite	$K_2SO_4 \cdot 2MgSO_4$	22.6
Leucite	$KAl(SiO_3)_2$	21.4
Orthoclase	$KAlSi_3O_8$	16.8
Muscovite	$KH_2Al_3(SiO_4)_3$	11.8
Glauconite	$KFeSi_2O_6 \cdot NH_2O$	8.5
Potassium nitrate	KNO_3	46.5

If a salt is valued entirely for its potassium content, then distance from the mines largely determines whether its crude or refined form is to be preferred, the decision being based on the cost a unit of potash at the point of use. If any of the other elements, such as sodium, magnesium, and calcium, are of added value for increasing the quality or yield of crop, then the choice cannot be based on the potash content alone. It is a well-known fact that these other elements often have value and that, under some conditions, this extra value is sufficient to overcome the disadvantage of the low content of potash in the crude salt. Large areas of land tend to be deficient in magnesium. On such soils a crude salt like langbeinite could be used to advantage.

OTHER POTASSIUM SALTS

In addition to the salts already mentioned, potassium can be purchased as a constituent of fertilizer materials carrying nitrogen or phosphoric acid with resultant further economy in freight and handling charges. The three most important of these are potassium nitrate, potassium phosphate, and potassium metaphosphate. Only relatively small amounts of these are available for fertilizer use. Commercial potassium nitrate contains around 13 per cent nitrogen and 44 per cent potash. A mixture of sodium and potassium nitrates is obtained from certain portions of the Chilean nitrate deposits. This product has been standardized at 14 per cent each of nitrogen and potash. Potassium phosphate exists in the mono-, di-, and tripotassium forms, but no important amount of any of these has been made available for use. These products contain from 30 to 50 per cent potash and from 50 to 30 per cent phosphoric acid. Potassium metaphosphate is being produced in an exploratory way under the auspices of the Tennessee Valley Authority. It contains about 40 per cent potash and 60 per cent phosphoric acid.

AVAILABILITY TESTS FOR POTASSIUM IN FERTILIZERS

Nitrogen fertilizer materials are normally sold on the basis of their total content of the element, but most of the control laboratories apply certain tests to mixed fertilizers in an effort to decide as to the quality of any low-grade organic forms of nitrogen that may be contained in these mixtures. These tests consist of digesting the insoluble portion of the fertilizer in a neutral or alkaline solution of potassium permanganate and determining what portion of its nitrogen still remains in an insoluble state after this treatment. Most phosphate fertilizer materials and all complete fertilizers are subjected to the action either of dilute citric acid or ammonium citrate to determine the solubility of their phosphoric acid. No availability tests other than solubility in hot water are applied to potash fertilizer materials, however, or to the potash in mixed fertilizers. Even the potassium that is contained in plant and animal residues is soluble in water, once the tissues have died.

SELECTED REFERENCES

1. Bear, Firman E. Cation and anion relationships in plants and their bearing on crop quality. *Agron. J.*, Vol. 42, pp. 176–178, 1950.

2. Bear, Firman E., and Associates. Potassium needs of New Jersey soils. New Jersey Agr. Sta., Bull. 721, 1945.

3. Bear, Firman E. The dairy cow as a conserver of soil fertility. New Jersey Agr. Exp. Sta., Bull. 730, 1946.

4. Conner, S. D., and J. B. Abbott. Unproductive black soils. Indiana Agr. Exp. Sta., Bull. 157, 1912.

5. Cooper, H. P., and Committee Associates. Recommendations with reference to the fertilization of flue-cured tobacco grown on average soils in Virginia, North Carolina, South Carolina, Georgia, and Florida for the year 1947. *J. Am. Soc. Agron.*, Vol. 38, pp. 852–853, 1946.

6. DeTurk, E. E., and Associates. Potash fixation in Corn Belt soils, and 11 other potassium-symposium papers. *Soil Sci.*, Vol. 55, pp. 1–126, 1943.

7. Harley, G. T. Production and processing of potassium materials. Short Course in Fertilizer Technology, University of Maryland, College Park, 1950.

8. Johnson, B. L. Potash. U. S. Bureau of Mines. Economic Paper 16, 1933.

9. Reed, J. Fielding. Potash reserves in the United States in relation to world supplies. Short Course in Fertilizer Technology, University of Maryland, College Park, 1950.

10. Turrentine, J. W. *Potash in North America.* Reinhold Publishing Corp., New York, 1943.

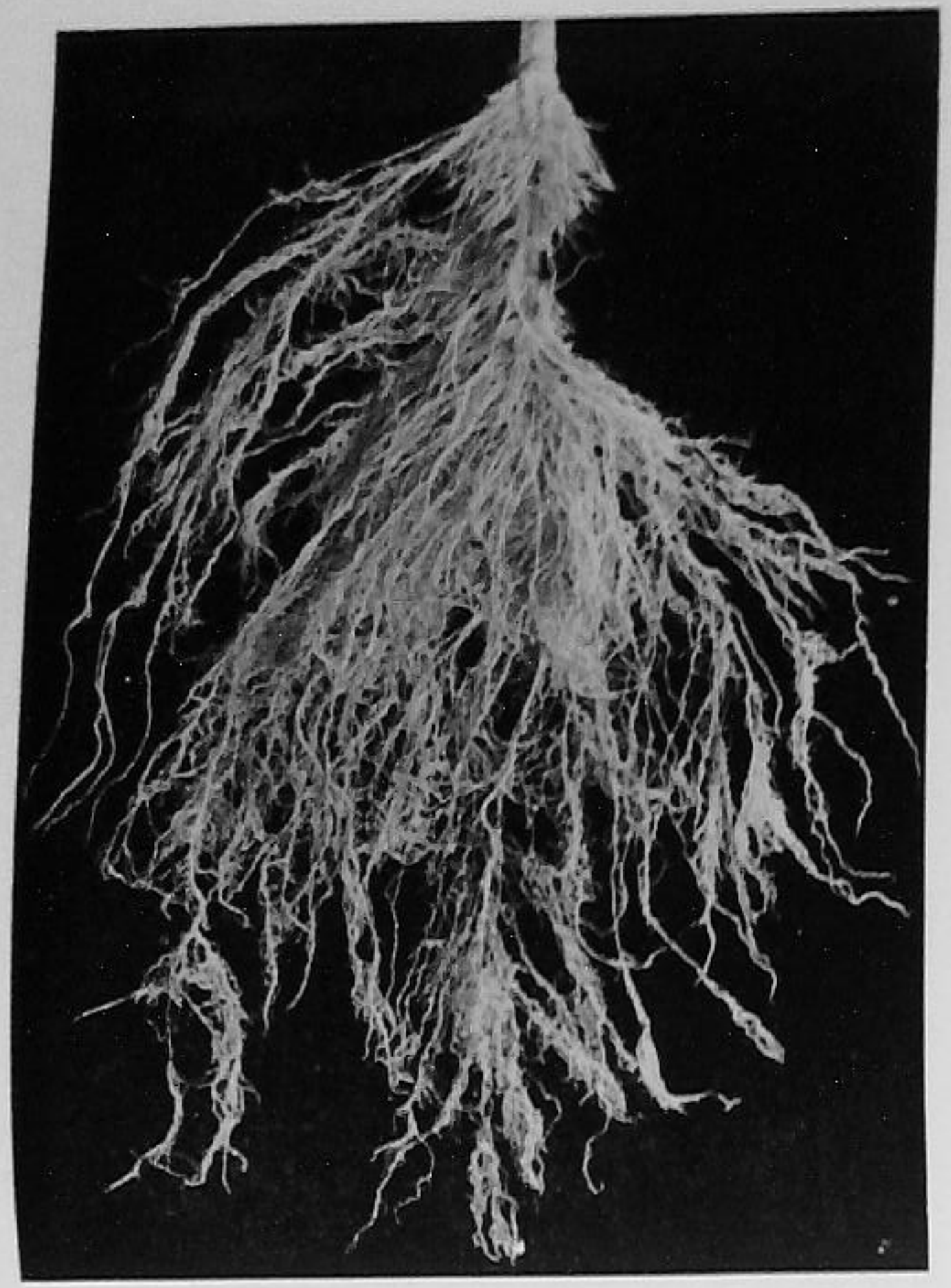
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Calcium Resources

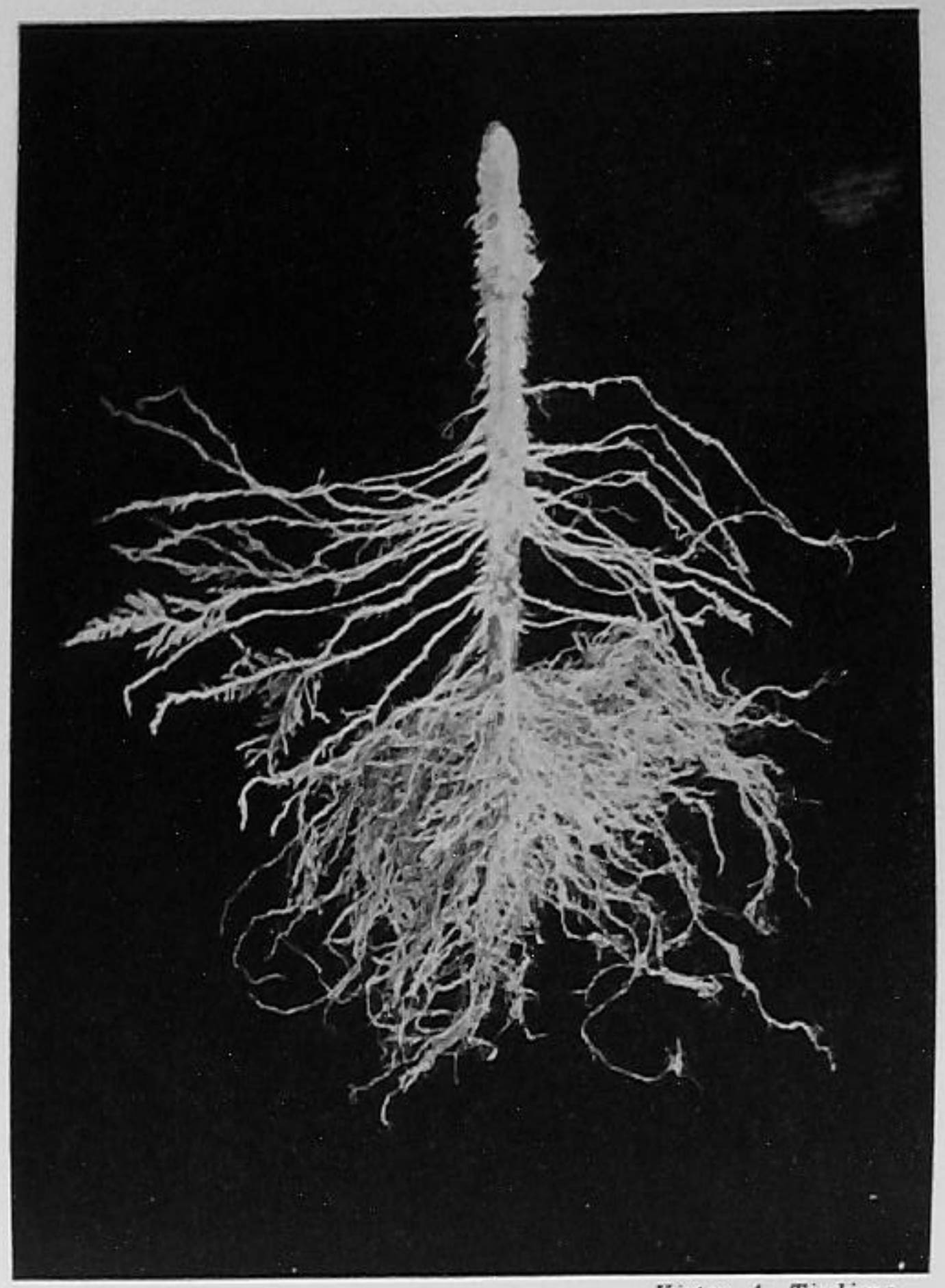
Calcium cannot exist as such in Nature but only in the form of stable combinations with other elements. Limestone, with an average calcium content of 30.44 per cent, is the most widely distributed compound of this element. The calcium contained in limestone had its origin in the silicate minerals that were formed when the earth, originally a molten mass of rock material, cooled down and solidified. As these minerals subsequently underwent hydrolysis, large amounts of their calcium were dissolved and carried into the sea by the rainwater. There the calcium was used by the various forms of marine life for the production of shell, coral, and similar protective coverings, or it was precipitated as the carbonate on the ocean floor. *In time, these calcium carbonate deposits, often many feet in thickness, became consolidated into rock. When subsequently elevated above sea level, the limestone was subject to resolution by the rainwater.* Limestone deposits frequently became hollowed out to form caves, such as those found at Mammoth Cave, Kentucky.

Second in quantity to the limestones and the closely related dolomites, or calcium-magnesium carbonates, are the calcium-containing silicate minerals, of which the most common are anorthite, augite, hornblende, and epidote. These minerals are widely distributed in rocks and soils, where they gradually yield up calcium to the rainwater and to plant roots. The rate at which the calcium in the primary mineral silicates is liberated is relatively slow.

In addition to the carbonate and silicate forms of calcium there are large localized deposits of gypsum and apatite and smaller ones of fluorite that contain the element as the sulfate, phosphate, and fluoride, respectively. Gypsum is frequently applied to the land as such, and closely related forms of calcium sulfate reach the soil as constituents of superphospate. Apatite is widely distributed in soils and constitutes most of the native supply of phosphorus for plant use. Although deposits of fluorite exist as such, the calcium fluoride of which it is composed is more commonly found attached to the calcium phosphate



(*a*)



Victor A. Tiedjens

(*b*)

FIG. 69. Calcium is highly essential for the development of good root systems. In its absence, roots are dwarfed and their tips are swollen. (*a*) Calcium. (*b*) No calcium.

in apatite and phosphate rock. Gypsum is the most readily soluble mineral form of calcium. Large amounts of anhydrite, a close relative of gypsum, are found associated with potassium, sodium, and magnesium chlorides and sulfates in the potash salt deposits of the earth.

SOIL CALCIUM

Soils derived from limestone would be expected to be high in calcium. In humid regions, however, what are known as "limestone soils" consist mainly of the insoluble impurities in the limestone that remained behind after the calcium carbonate had been dissolved and carried away by the rainwater. The top foot of such a soil, the residue from possibly a 50- to 75-foot depth of limestone, may contain little or no carbonate of lime. In the lower horizons of such a soil considerable amounts of fragmentary limestone may persist more or less permanently, and below this may be thick beds of additional unweathered limestone rock. Once the crop has gotten a start, its roots may penetrate to these lower depths and be abundantly supplied with calcium. Limestone soils are usually noted for their productivity, the explanation for part of which is to be found in the calcium carbonate reserves in their *C* horizons. Another important factor in their high state of productivity is their usually good drainage.

Soils derived from noncalcareous sandstones and shales in humid areas normally contain only relatively small amounts of calcium. Most of the supply of this element in the material from which they were made was dissolved out while it was being laid down on the ocean floor. Much of the remaining calcium disappeared during the subsequent period while the sandstones and shales, after being elevated above the ocean level, were disintegrating to form soil.

Soils formed from igneous rocks, such as granites, syenites, diorites, and their metamorphosed derivatives, gneisses and schists, often contain considerable amounts of calcium. The average calcium content of igneous rocks has been estimated at 3.61 per cent. That of the lithosphere has been set at 3.64 per cent.

The range in calcium content of the plow depth of podsolic soils is between 0.1 and 2.0 per cent, the lower figure representing the noncalcareous sands and the higher one the heavier loams and clays. An average figure would be about 0.5 per cent, or 10,000 pounds of calcium an acre (Table 95). The calcium content of the portion of a podsolic soil that lies below plow depth is normally higher than that of the

plowed portion, unless lime has been added to the seedbed for the benefit of the crop.

As with potassium, the calcium content of sand and peat soils is often very low. Some sands were derived, however, from calcareous sandstones and may contain considerable amounts of calcium carbonate in their lower horizons. Similarly, some peat deposits were laid down over marl beds.

Soils of desert regions are normally very productive when water is applied to them. This is because they were not subjected to the leaching action of heavy rainfall over the centuries and, therefore, are abundantly supplied with calcium and other mineral nutrients in relatively soluble forms. Thus, they not only contain the carbonates, sulfates, and chlorides of potassium, sodium, and magnesium, but large amounts of calcium sulfate and carbonate as well. As the distance from the desert in the direction of heavier rainfall increases, the more soluble salts of sodium, potassium, and magnesium tended to be carried off in the drainage water, whereas the less soluble calcium sulfate and carbonate accumulated in the lower soil horizons. In proportion as the rainfall was heavier these deposits are more largely calcium carbonate and they are located at increasing depths. Thus, deposits of calcium salts are found on the surface of the Great American Desert, they are located from a few inches to a foot or more below the surface in the Chernozemic soils extending from the Dakotas to Texas, and they disappear entirely from the lower horizons of the soils that are located farther east and south.

EXCHANGE CALCIUM IN SOILS

The calcium of the exchange complex constitutes the readily available supply of this element. Table 96 records the exchange calcium in 20 important New Jersey soils. It will be noted that the lower the *p*H and exchange-capacity values the smaller the amount of exchange calcium. The acidity of podsolic soils falls finally to an equilibrium value of about 4.5. The capacity of these soils to store calcium at *p*H values ranging between 5 and 6.5 is shown in Table 101.

PLANTS IN RELATION TO CALCIUM SUPPLY

Under natural conditions the type of plant dominating any area is determined in large part by the supply of available calcium. Calcium-loving plants are indigenous to the high-lime soils of the west, whereas

low-lime-requirement plants tend to dominate the poor-land vegetation of the eastern and southern portions of the United States. When land is diverted from Nature to agriculture, the easiest procedure is to select crops on the basis of their natural adaptation to high-lime

TABLE 101

CALCIUM-STORING CAPACITIES * OF 20 IMPORTANT NEW JERSEY SOILS (BEAR)

(Same Soils as Shown in Tables 95, 96, and 97)

Soil Type	Plow Depth				8 Inches of Subsoil			
	Present *p*H				Present *p*H			
	5.0	5.5	6.0	6.5	5.0	5.5	6.0	6.5
	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.
Sassafras sand	240	300	340	400	320	460	540	700
Lakewood sand	440	520	600	700	580	800	1000	1200
Sassafras sandy loam	500	640	780	960	680	740	1020	1220
Papakating stony loam	880	1080	1320	1540	420	520	620	760
Fox gravelly loam	880	1260	1720	2180	500	760	1000	1260
Sassafras loam	1036	1740	2000	2600	2320	3000	3440	3940
Colts Neck sandy loam	1420	1900	2200	2560	1280	620	1900	2280
Dover loam	1660	2020	2400	2840	980	1360	1800	2200
Dutchess shale loam	1700	2080	2480	2900	1200	1600	2000	2600
Gloucester stony loam	1760	2300	2820	3340	1060	1480	1760	2240
Whippany silty clay loam	1760	2080	2440	2780	3680	4300	4720	5200
Washington loam	1940	2300	2600	3340	2340	2800	3320	3640
Merrimac silt loam	2020	2440	3000	3620	1320	1600	1900	2200
Hoosic stony loam	2020	2460	2860	3260	1320	1580	1960	2320
Lansdale silt loam	2020	2560	3180	3840	1600	1900	2340	2960
Chester loam	2080	2160	2400	2640	1800	2280	2760	3000
Bermudian silt loam	2200	2560	3000	3420	2200	2420	2820	3260
Hagerstown loam	2380	2900	3200	4180	1800	2200	2640	3260
Penn silt loam	3120	3700	4660	5420	4280	4920	5540	6260
Collington loam	3240	3840	4240	4760	2900	3380	3920	4440

* Under field conditions, magnesium and potassium would satisfy part of this capacity. The figures represent all three of these elements calculated to their calcium equivalents. About 80 per cent of the total exchange capacity of a soil is taken up by calcium, magnesium, and potassium at *p*H 6.5, the remainder being satisfied by hydrogen. See Table 96 for natural *p*H values and exchange capacities of these soils.

and low-lime soils, respectively. In lieu of that, it becomes necessary to adjust the calcium supply in the soil in relation to the needs of the plants to be grown. Thus, alfalfa and cabbage have high lime requirements, soybeans and oats can readily be grown on acid soils, and blueberries and azaleas are low-lime-requirement crops. By the use of an alkaline form of calcium the conditions may be so altered as



Herbert R. Cox

FIG. 70. Sericea is an important acid-soil legume that is being widely used for soil-improvement purposes, notably in Alabama.

to permit the growing of alfalfa in acid-soil areas. Similarly, by adding sulfur, azaleas can be grown on land that is naturally too alkaline for them. Some relationships between *p*H values and crop growth are shown in Table 102.

Calcium is not the only factor involved in determining whether plants will grow well on acid soils. Except for sands and peats, soils that are low in calcium are high in acid hydrogen and in soluble iron, aluminum, and manganese. It is not easy to determine which of these is the controlling factor. In Table 103 the common crop plants are arranged in accordance with their tolerance to acid soil conditions, irrespective of which of these factors is most involved.

TABLE 102

RELATION BETWEEN *p*H VALUES, BASE SATURATION, AND CROP GROWTH

*p*H	Soil Reaction	Base Saturation, Per Cent	Crop Relationships
3	Extremely acid	Less than 10	Too acid for nearly all crops.
4	Strongly acid	10	Too acid for most crops.
5	Moderately acid	30	Too acid for some crops.
6	Slightly acid	80	All common crops will grow.
7	Neutral	100	Most crops will grow.
8	Slightly alkaline	Free $CaCO_3$	Many crops will grow.
9	Moderately alkaline	Some Na_2CO_3	Too alkaline for most crops.
10	Strongly alkaline	High Na_2CO_3	Too alkaline for all crops.

Considerable amounts of calcium still remain attached to the natural minerals and their degradation products in the soil of high-rainfall regions, and some of this calcium may be released to the exchange complex by good soil-management procedures. The cost of calcium in the form of limestone or its burned products is so low, however, that the most economic procedure is to apply one or another of the various liming materials in the quantities required for the crop to be grown. It happens also that calcium is the carrier of most of the phosphorus that is used for fertilizer purposes, and considerable amounts of the element are thus automatically applied to the soil with the fertilizer.

TABLE 103

RELATIVE SENSITIVENESS OF PLANTS TO ACID SOIL CONDITIONS (HARTWELL)

Very Tolerant	Tolerant	Sensitive	Very Sensitive
Blueberry *	Alsike clover	Barley	Alfalfa
Cowpea	Buckwheat	Bluegrass	Asparagus
Cranberry *	Corn	Cabbage	Beet
Fescue	Cotton	Cauliflower	Celery
Lupine	Crimson clover	Egg plant	Lettuce †
Millet	Cucumber	Muskmelon	Onion †
Oats	Grape	Orchard grass	Parsnip
Peanut *	Rhubarb	Red clover	Pepper
Potato	Strawberry	Sweet clover	Quince
Red top	Tomato	Turnip	Salsify
Rye	Timothy	Tobacco	Spinach †
Watermelon *	Vetch	Wheat	Yellow trefoil

* Especially tolerant of acid soil conditions.
† Especially sensitive to soluble aluminum.

LIME REQUIREMENT OF ACID SOILS

The amounts of lime required to raise the *p*H values of 20 acid soils from various lower levels to *p*H 6.5 are shown in Table 104. The data are in terms of calcium carbonate. The table permits of ready calculation of the amount of limestone required to raise the *p*H values to any intermediate level, or the amount of sulfur to lower them from higher levels.

CALCIUM IN LIVESTOCK FARMING

Studies of the calcium content of the feed and the resulting manure of dairy cows indicate a recovery of about 65 per cent (Table 98).



FIG. 71. Most farmers wait until the land is plowed before applying lime. But there is increasing need that more lime be applied before plowing. Often it would be better to "lime both sides of the furrow." By plowing lime under, conditions are made more favorable for deep rooting.

The annual intake of calcium for a 1300-pound cow producing at the rate of 14,250 pounds of milk a year was estimated at about 60 pounds, of which 20 were recoverable in the milk and 40 in the manure, most of the latter being in the feces.

Fortunately for the calcium supply in the soil of livestock farms, the high-lime legume crops occupy a very important position on such farms, where they are used as agents for collecting atmospheric nitrogen. To grow such crops as alfalfa and sweet clover successfully requires the liberal use of liming materials. On livestock farms, therefore, the soil's supply of calcium is normally held high enough to meet

the needs of these legumes. If they fail to grow satisfactorily, the answer does not lie in any attempt to liberate more calcium from the soil minerals but in the use of larger amounts of liming materials. Very deep plowing may have value as a means of getting the subsoil

TABLE 104

$CaCO_3$ Required * to Raise *p*H Values 20 Soils to 6.5 (Bear)

(Same Soils as Shown in Tables 95, 96, 97, and 101)

Soil Type	Plow Depth †				8 Inches of Subsoil ‡			
	Present *p*H				Present *p*H			
	4.5	5.0	5.5	6.0	4.5	5.0	5.5	6.0
	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.
Sassafras sand	550	400	250	150	1350	950	700	400
Lakewood sand	850	650	450	250	2150	1550	1000	500
Sassafras loamy sand	2000	1150	800	450	2100	1350	1200	500
Papakating stony loam	2050	1650	1150	550	1150	850	600	350
Chester loam	2850	1400	1200	600	4350	3000	1800	600
Colts Neck sandy loam	3200	2850	1650	900	3450	2500	1650	950
Whippany silt clay loam	3450	2550	1750	850	5300	3800	2250	1200
Bermudian silt loam	3900	3050	2150	1050	3950	2650	2100	1100
Dover loam	3950	2950	2050	1100	3850	3100	2100	1000
Sassafras loam	3950	3100	2150	1500	5900	4050	2350	1250
Fox gravelly loam	3950	3250	2300	1150	2200	1900	1250	650
Hoosic stony loam	4200	3100	2000	1000	3250	2500	1850	900
Dutchess shale loam	4300	3000	2000	1050	4500	3500	2500	1500
Washington loam	4800	3500	2600	1850	4600	3250	2100	800
Gloucester stony loam	5000	3950	2600	1300	3750	2950	1900	1200
Merrimac silt loam	5200	4000	2950	1550	3000	2200	1500	750
Collington loam	5300	3800	2300	1300	5150	3850	2650	1300
Lansdale silt loam	5900	4550	3200	1650	4900	4100	2650	1550
Hagerstown loam	6250	4500	3200	2450	5400	3650	2750	1550
Penn silt loam	7400	5750	4300	1900	6600	4950	3350	1800

* These lime requirements are calculated in terms of the amount of calcitic limestone needed to raise the *p*H value from that indicated to 6.5. They may be recalculated in terms of hydrated lime by multiplying by 0.74.

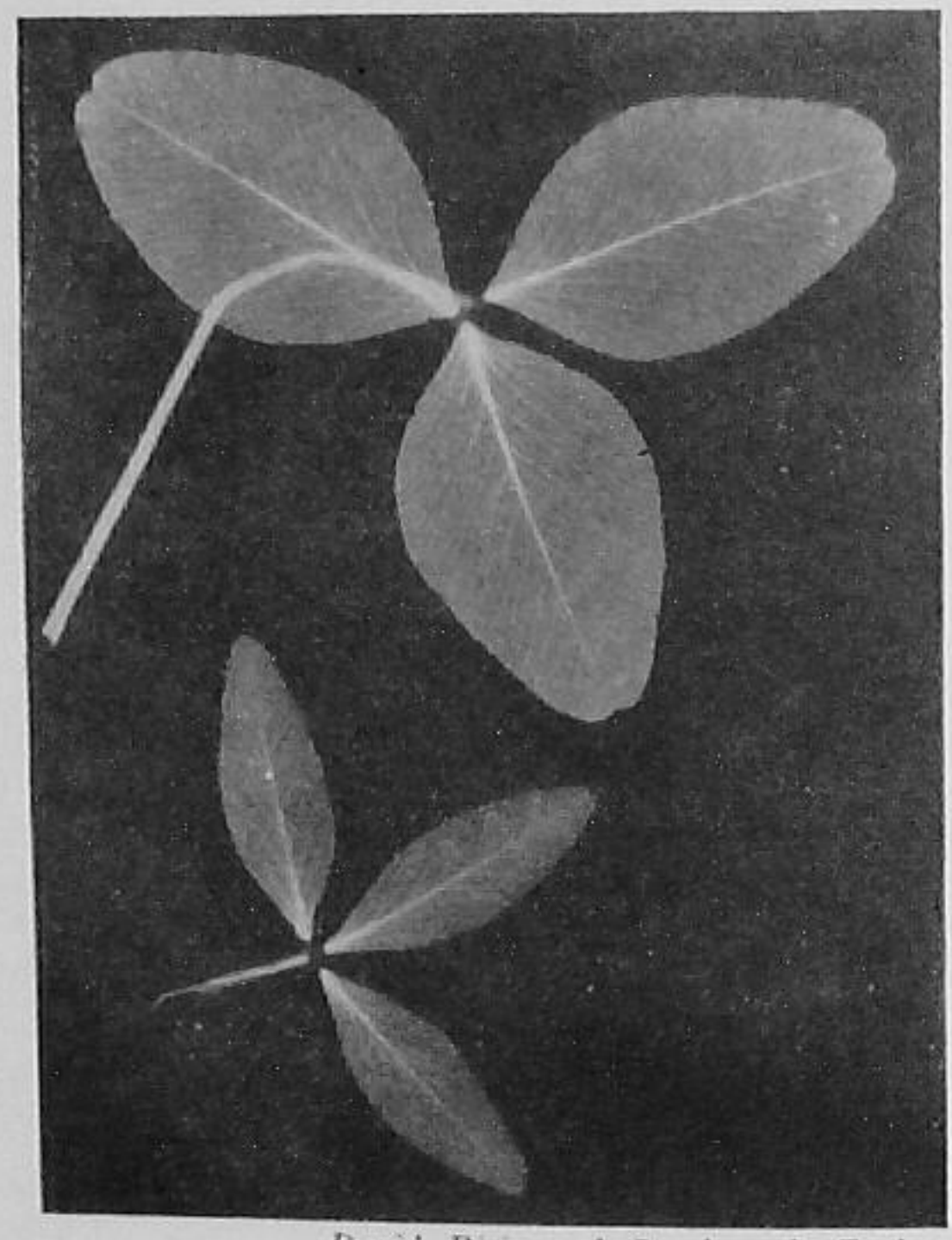
† Plow depth means the top 7 inches of soil. It was usually only *A*-horizon material.

‡ The 8 inches of subsoil is that lying immediately below the plow depth.

calcium of limestone soils up to the surface where it is much more useful to the crop.

CALCIUM-DEFICIENCY SYMPTOMS IN CROP PLANTS

Of the symptoms of calcium deficiency that are shown by plants, those observed on their roots are of special interest. In the absence



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FIG. 72. Location of calcium in clover leaves shown by radiograph. Note absence of Ca^{45} in pulvinus areas.

of an adequate supply of the element the roots tend to be short and stubby, as a result of their having died at the tips. In extreme cases, further evidence of calcium deficiency may be indicated by a mottled discoloration of the leaves, leading finally to the death of the tissues.

Since low supplies of calcium in soils are usually associated with acidity, it is difficult to determine whether the abnormalities noted on plants that are growing on acid soils are the result of an excess of acid or a deficiency of calcium or some other needed nutrient. Acid soils contain more soluble iron, aluminum, and manganese than nonacid soils, and the symptoms one observes may be the result of the toxicity

of one or another of these elements. They are notably low in available molybdenum, and lack of this element may be a limiting factor.

Low supplies of calcium in the soil are not necessarily associated with high soil acidity. Liberal use of nitrate of soda over a period of years or repeated applications of irrigation water that is high in sodium chloride may result in the development of an alkaline soil in which sodium rather than calcium has served to neutralize the acidity. Under such conditions the typical dying-back and restriction of growth of the roots occur just as in acid soils.

In the absence of adequate supplies of calcium in the soil, potassium, magnesium, and sodium tend to take its place in the plant. One of the functions of calcium within the plant is that of combining with pectin to form calcium pectate, a necessary constituent of cell walls. Potassium and sodium pectates are soluble in water and, consequently, cannot form the needed cell structure.

COMMERCIAL CALCIUM

Calcium is supplied to the soil mostly as liming materials. Good soil management normally calls for the regular use of liming materials, by which is meant the carbonate, oxide, and hydrate forms of calcium. All these materials have their origin in limestone. In preparing limestone for use on the land it is necessary either to pulverize it or burn it, the choice depending upon relative costs at the quarry and the distance from market. The burned product, calcium oxide or quicklime, is troublesome to handle because of its caustic properties. Hydrated lime is more popular than the oxide. It contains only as much water as can be made to combine with calcium oxide and yet have a dry product. The relative neutralizing values of the several liming materials are shown in Table 105.

Large amounts of calcium are also applied to the soil in the form of superphosphate, which is largely a mixture of monocalcium phosphate and calcium sulfate. One ton of 20-per cent superphosphate contains over 500 pounds of calcium. That in the monocalcium phosphate form is highly soluble in water, and that in the form of calcium sulfate is also readily available for plant use. A 5–10–10 fertilizer, normally containing the equivalent of one-half ton of superphosphate, will supply a proportionate amount of calcium, plus any additional quantities that may have been added to the mixture in the form of calcium cyanamide or pulverized dolomite. If use is made of rock phosphate, bonemeal, or basic slag instead of superphosphate, somewhat larger

TABLE 105

RELATIVE NEUTRALIZING VALUES OF PURE LIMING MATERIALS * (BEAR)

Liming Materials	Relative Neutralizing Values	Pounds of Liming Materials Equivalent to 1 Ton	
		Calcium Carbonate	Calcium Oxide
Calcium carbonate	100	2000	3570
Magnesium carbonate	119	1680	3000
Calcium oxide	178	1120	2000
Magnesium oxide	250	800	1430
Calcium hydrate	135	1480	2640
Magnesium hydrate	172	1160	2070
Dolomite	108	1850	3330
Dolomitic hydrate	175	1145	2040

* Total consumption of liming materials in the United States was 3,500,000 tons in 1930, 13,400,000 tons in 1940, and 29,800,000 tons in 1950.

amounts of calcium will be added to the soil than if superphosphate were applied.

In some cases, notably as a corrective for the alkali in soils of irrigated arid areas and as a fertilizer for peanuts, calcium sulfate, commonly called gypsum or landplaster, is used by itself. For some uses the value of this material is dependent upon its calcium, in others upon its sulfur, and in others upon the effect of the salt on the physical properties of the soil.

CALCIUM AND CALCIUM OXIDE

The calcium content of soils, plants, and liming materials is usually reported in terms of calcium oxide, rather than as the element itself. The factor from calcium to calcium oxide is 1.40 and that from calcium oxide to calcium is 0.72. Thus, the 0.5 per cent calcium in the average soil becomes 0.7 per cent calcium oxide and the 10,000 pounds of calcium in the plow depth of an acre becomes 14,000 pounds of the oxide. Similarly, the 25 pounds of calcium in the grain and stover of a 100-bushel corn crop becomes 35 pounds of calcium oxide, the 100 pounds of calcium in a 4-ton crop of alfalfa hay becomes 140 pounds, and the

40 pounds of calcium in the yearly output of manure from a 1300-pound cow becomes 56 pounds.

LIMESTONE

Large amounts of limestone are quarried for use in the manufacture of steel, in the building trades, and in highway construction, and that employed for soil-improvement purposes is usually a by-product arising from the preparation of the limestone for nonagricultural uses. These by-product piles of crushed limestone often grow to tremendous size and the only important use to which some of the finer and impurer portions can be put is that of correcting the acidity of soils. The cost of such by-product limestone to the farmer depends largely upon the degree of fineness he demands. Thus, if the relatively coarse by-product material can be used as such, the selling price a ton is but little more than the handling and transportation charges. If the material must be further pulverized, costs are materially increased.

In the Central West many of the more extensive farmers use limestone screenings passing a 4-mesh screen, whereas in the more intensive farming areas of the eastern states a product passing a 10-mesh screen is about as coarse as can be sold. Many farmers prefer to have most of their limestone pass a 100-mesh screen, or one having 10,000 openings a square inch. The finer the material the greater the amount of surface exposed to the solvent action of the soil water and the more rapidly the limestone neutralizes the acidity of the soil (Table 106). Products passing 4-, 8-, 14-, 28-, and 48-mesh screens, in which the diameters of the openings are successively cut in half, have one-thirty-second, one-sixteenth, one-eighth, one-fourth, and one-half as much surface area, respectively, in a unit weight, as the same amount of product passing a 100-mesh screen.

The coarser products, though slower in action, may have advantages in that the particles form points of continuous supply of calcium to the roothairs of plants over long periods of time. It is possible that they would be especially useful on sandy soils where undue loss of the finely pulverized material may occur both by solution in the drainage water and by mechanical movement down into the lower horizons.

Limestones are never pure, many of them containing 5 to 10 per cent of noncalcareous material. Some limestones contain considerable amounts of magnesium carbonate, as a result of which the amount of calcium oxide is lowered. Those containing calcium and magnesium

TABLE 106

RELATIVE SURFACE OF LIMESTONE IN TERMS OF 100-MESH PRODUCT * (BEAR)

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		62.1		100.0		90.3

* 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 $3.10 a ton at the plant as compared to $4.50 a ton for the second. An additional $1.50 a 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 a ton at the plant, or $6.50 if sacked. These figures have relative value only, since actual costs and selling prices tend to rise.

carbonates in the ratio of approximately 54 to 46 are known as dolomites. A ton of pure dolomite contains about 600 pounds calcium oxide.

OTHER ALKALINE FORMS OF LIME

A ton of pure limestone will yield 1120 pounds of calcium oxide or 1480 pounds of hydrated lime. A ton of pure hydrated lime contains about 1500 pounds calcium oxide, or about one-third more than the same amount of limestone. Hydrated lime has the advantage of being a more concentrated product than limestone, which means less material to handle and apply.

Hydrated lime is much more finely divided than even the most finely pulverized limestone and it is much more readily soluble in water. It reacts very quickly with the soil and, for that reason, is preferred by many market gardeners and truck growers who desire to take more or less immediate advantage of everything they add to the soil. The cost

a pound of calcium oxide is usually considerably higher in hydrated lime than in pulverized limestone.

Burned lime can be used as such. Often it is put out in piles to be partially slaked by air and water so that it becomes a mixture of calcium oxide, hydrated lime, and carbonate of lime. One ton of such a product will supply between 2000 and 1120 pounds of calcium oxide, depending upon the degree of slaking that has taken place. Similar liming materials are available as by-products in the manufacture of acetylene gas from calcium carbide and in certain other industrial operations.

Considerable amounts of furnace slag, varying from nearly pure calcium silicate to the phosphate-containing type, known as basic slag, are available for use on the land. Likewise, oyster shells, marble refuse, and other similar by-products are sold to farmers. The values of these products as sources of calcium are determined by their content of available calcium oxide, their degree of fineness, and the rate at which they dissolve in the soil water. Considerable amounts of calcium oxide are also derived from such fertilizer salts as calcium nitrate and calcium cyanamide. Both these products leave lime residues in the soil, once their nitrogen has been utilized by the crop. Calcium cyanamide is especially useful as a source of lime, its pound value for use on acid soils being about the same as that of pulverized limestone.

CALCIUM SULFATE

Alkaline forms of lime have a double effect in the soil. They not only supply calcium but they neutralize any acid that may be present in the soil. Calcium sulfate also supplies calcium but it has little effect on the soil reaction. There are several conditions, however, under which calcium sulfate is of more value than the alkaline forms of calcium. Thus, if the soil is already alkaline, as with the alkali soils containing sodium and potassium carbonates, calcium sulfate reacts with these soluble carbonates to form the relatively insoluble calcium carbonate and the sulfates of sodium and potassium. As a result, the alkalinity of the soil is reduced, with benefit to the soil and crop.

Calcium sulfate also has value in flocculating soils that contain excessive amounts of sodium or that may have become compacted by [illegible] being worked while they were overwet. The net effect of its use is to aid in making the soil more permeable to air and water. In proportion

as water can be made to pass more readily through the soil, the calcium replaces the sodium in the exchange complex and permits its being carried out in the drainage.

In growing potatoes and other acid-soil plants, the calcium sulfate of the superphosphate contained in the fertilizer mixture makes an important contribution to the calcium needs of the crop. As fertilizer concentration is increased through the elimination of this constituent, these acid-soil plants may not be able to obtain adequate supplies of calcium from the soil. Although light applications of limestone or its derivatives are sometimes applied to potato fields, the amounts that may be used without danger from scab are relatively small. It would seem, therefore, that the calcium sulfate of superphosphate may have extra value for use on soils that are to be employed for the production of potatoes, sweet potatoes, blueberries, and all other crops that grow best on soils having low *p*H values.

SELECTED REFERENCES

1. Bear, Firman E., and Associates. One hundred questions and answers on liming land. New Jersey Agr. Exp. Sta., Bull. 754, 1951.

2. Bear, Firman E., and L. Allen. Relation between fineness of limestone particles and their rates of solution. *Ind. Eng. Chem.*, Vol. 24, pp. 998–1001, 1932.

3. Bear, Firman E., and Stephen J. Toth. *p*H values and lime-requirements of twenty New Jersey soils. New Jersey Agr. Exp. Sta., Circ. 446, 1944.

4. 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., Bull. 189, 1922.

5. Colwell, W. E., and Associates. Fertilizing peanuts. North Carolina Agr. Exp. Sta., Bull. 356, 1946.

6. Coville, F. W. The agricultural utilization of acid lands by means of acid-tolerant crops. *U. S. Dept. Agr. Bull.* 6, 1913.

7. Frear, W. Sour soils and liming. Pennsylvania Dept. Agr. Bull. 261, 1915.

8. Harris, F. S. *Soil Alkali, Its Origin, Nature and Treatment.* John Wiley & Sons, New York, 1920.

9. Hartwell, B. L., and S. C. Damon. The comparative effect on different kinds of plants of liming an acid soil. Rhode Island Agr. Exp. Sta., Bull. 160, 1914.

10. Hartwell, B. L., and S. C. Damon. A field comparison of hydrated lime with limestone of different degrees of fineness. Rhode Island Agr. Exp. Sta., Bull. 180, 1919.

11. Kelley, W. P. The reclamation of alkali soils. California Agr. Exp. Sta., Bull. 617, 1937.

12. Kelley, W. P., and S. M. Brown. Ion exchange in relation to soil acidity. *Soil Sci.*, Vol. 21, pp. 289–302, 1926.

13. MacIntire, W. H. Factors influencing the lime and magnesia requirements of soils. Tennessee Agr. Exp. Sta., Bull. 115, 1916.

14. Schollenberger, C. J., and R. M. Salter. A chart for evaluating limestone. *J. Am. Soc. Agron.*, Vol. 35, pp. 955–966, 1943.

15. Small, James. *pH and Plants.* D. Van Nostrand Co., New York, 1946.

16. Truog, E. Soil acidity and liming. *U. S. Dept. Agr. Yearbook of Agriculture,* pp. 563–581, 1938.

17. White, J. W. The value of limestone of different degrees of fineness. Pennsylvania Agr. Exp. Sta., Bull. 149, 1917.

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Magnesium Resources

Magnesium does not occur in elemental form in Nature but only in combination with other elements, principally as silicates and carbonates. The most widely distributed magnesium-containing silicate minerals are augite, hornblende, biotite, chlorite, olivine, talc, and serpentine. Dolomite and magnesite are the best known of the carbonate forms. Large amounts of the chloride and sulfate of magnesium are found associated with the corresponding salts of sodium, potassium, and calcium in the natural deposits from which potash salts are mined for agricultural and chemical use. The complex mineral silicates of magnesium are only very slightly soluble in water, but the carbonates dissolve fairly readily and the chlorides and sulfates are highly soluble. *Limestones always contain some magnesium and are the most common source of the element for agricultural use. Considerable amounts of magnesium chloride and sulfate reach the soil as constituents of impure potash salts.*

SOIL MAGNESIUM

Augite, hornblende, biotite, and chlorite are found in most soils. As these minerals undergo hydrolysis during the process of soil formation, much of their magnesium is released and carried away in the drainage waters. Out of every 100 parts of total salinity in North America river waters, 4.87 parts, on the average, are magnesium. Over 15 per cent of the total salts in the ocean are those of magnesium. Similarly, magnesium salts make up from 5 to 15 per cent of the alkali deposits in the western part of the United States. The magnesium content of the lithosphere is estimated at 2.10 per cent.

Of the several classes of rocks, limestones are the highest in magnesium, averaging around 5 per cent of the element, in comparison with 2.1 per cent for igneous rocks, 1.5 per cent for shales, and 0.7 per cent for sandstones. The amount of magnesium in soils varies from a mere trace in some of the sandier types to as much as 1 per cent in those

containing considerable percentages of clay. An average figure for the *A* horizon of podsolic soils would be about 0.3 per cent, or 6000 pounds in the plow depth of an acre (Table 95). As with potassium and calcium, the most available portion of the soil magnesium is that contained in the exchange complex. The amount of exchangeable magnesium contained in 20 important New Jersey soils is shown in Table 96. Soils derived primarily from dolomite, magnesite, or magnesium silicates, which tend to be very high in exchangeable magnesium, are often very unproductive, sometimes being known locally as "barrens."

MAGNESIUM REQUIREMENTS OF PLANTS

The quantity of magnesium required by plants is considerably less than that of potassium, but it approaches that of calcium. Thus, the magnesium content of the grain and stover of a 100-bushel crop of corn is around 18 pounds, compared with about 100 pounds of potassium and 25 pounds of calcium. Grains tend to be higher in magnesium than in calcium, but the reverse is true of straw and stalks. Legume hay plants are relatively rich in magnesium, a 4-ton crop of alfalfa containing around 30 pounds of the element. Magnesium tends to concentrate in the seeds of plants (Table 107).

TABLE 107

MAGNESIUM IN CROPS AND Ca-Mg RATIOS (BEAR)

Crop	Acre Yield	Mg, Lb.	Ca:Mg *
Alfalfa hay	4 tons	50	2.0
Cabbage, heads	10 tons	4	2.5
Corn, grain	100 bu.	10	0.1
Corn, stover	2½ tons	7	4.3
Oats, grain	50 bu.	2	1.0
Onions, bulbs	400 bu.	5	2.0
Potatoes, tubers	400 bu.	20	0.1
Soybeans, grain	25 bu.	5	1.0
Timothy, hay	3 tons	10	1.5
Wheat, grain	35 bu.	3	0.3

* Alfalfa hay, for example, contains twice as much Ca as Mg.

An extensive literature has been developed on calcium-magnesium relationships in plants. This indicates that a fairly definite balance in the supply of these elements is essential for optimum plant growth. Difficulties from an excess of magnesium do not normally develop in

soils and plants from ordinary liming or fertilizer operations. In most cases the problem is one of deficiency rather than excess.

The rate of release of magnesium from the badly leached soils of humid areas is often too slow to meet the requirements of rapidly growing plants. If the soil contains adequate reserves of the element, its liberation can be speeded up by incorporating organic matter into the soil and taking advantage of the solvent action of the carbonic and nitric acids originating in its decay. The effect of these acids may be spent on soil minerals that contain no magnesium. The magnesium that is tied up in the exchange complex of soils can be released by the use of potassium chloride and ammonium and calcium sulfates. This explains the increasing tendency of heavily fertilized soils to be deficient in this element.

MAGNESIUM-POTASSIUM RELATIONSHIPS IN PLANTS

The magnesium uptake of a plant is determined in large part by the amount of potassium available for its use. If the plant has an abundance of potassium at its disposal, its content of magnesium will be relatively low. In a test of the alfalfa plant in which a succession of crops was harvested, the potassium content of each crop was lower than that of the previous crop. The magnesium content of the successive crops increased even when the alfalfa was grown on soils that were very deficient in available magnesium (Table 108). This indicates the advisability of supplying additional magnesium in proportion as larger amounts of potassium are applied to the soil.

MAGNESIUM IN LIVESTOCK FARMING

The body of a 1000-pound cow contains only about ½ pound of magnesium, in comparison with 11 pounds of calcium. Only about 1½ pounds of the element are found in 10,000 pounds of milk. About 95 per cent of the magnesium in the feed can be recovered in the manure, most of it being in the feces.

Legume crops play a very important part on livestock farms, and these crops have relatively high magnesium requirements (Table 109). This may be related in part to their comparatively large leaf area and the correspondingly large amount of magnesium needed for chlorophyll production. Since legumes require large amounts of lime, the

magnesium problem is readily solved by using high-magnesium liming materials. Where ground oyster shells or calcitic forms of lime are used, however, it may be necessary to purchase magnesium in fertilizer form.

TABLE 108

Me. Mg and K in 100 Grams of Dry Alfalfa, First and Eighth Crops * (Bear)

(Same Soils as Shown in Tables 95, 96, 97, 101, and 104)

Soil Series	First Crop				Eighth Crop			
	No MgO, Mg	80 MgO			No MgO, Mg	80 MgO		
		Mg	K	Mg/K		Mg	K	Mg/K
Collington	18	31	60	0.5	30	37	30	1.2
Washington	22	29	52	0.6	25	36	19	1.9
Penn	20	19	53	0.4	15	23	31	0.7
Lansdale	16	21	59	0.4	22	26	30	0.9
Dover	30	34	60	0.6	53	57	19	3.0
Dutchess	30	25	51	0.5	36	39	29	1.3
Gloucester	23	36	57	0.6	40	40	24	1.7
Hoosic	23	21	57	0.4	38	39	23	1.7
Sassafras	19	25	49	0.5	15	28	18	1.6
Merrimac	13	20	55	0.4	12	23	19	1.2
Whippany	21	24	38	0.6	59	60	13	4.4
Hagerstown	43	35	51	0.7	40	70	20	3.5
Bermudian	25	28	52	0.5	44	52	22	2.4
Fox	35	40	57	0.7	66	69	21	3.3
Chester	25	28	59	0.5	35	43	40	1.1
Papakating	21	26	44	0.6	30	39	18	2.2
Sassafras	15	23	56	0.4	10	24	24	1.0
Colts Neck	14	16	50	0.3	17	27	24	1.1
Lakewood	21	28	74	0.4	23	32	24	1.3
Sassafras	23	33	61	0.5	14	33	46	0.7
Mean	23	27	55	0.5	31	40	25	1.6

*The alfalfa was grown as in the experiment reported in Table 97, except that Mg was the variable and was supplied as $MgSO_4 \cdot 7H_2O$ at rates of 0 and 80 pounds MgO in 2 million pounds soil, indicated by No MgO and 80 MgO, respectively.

TABLE 109

AVERAGE ANALYSES ILLINOIS HAY AND FORAGE (SNIDER)

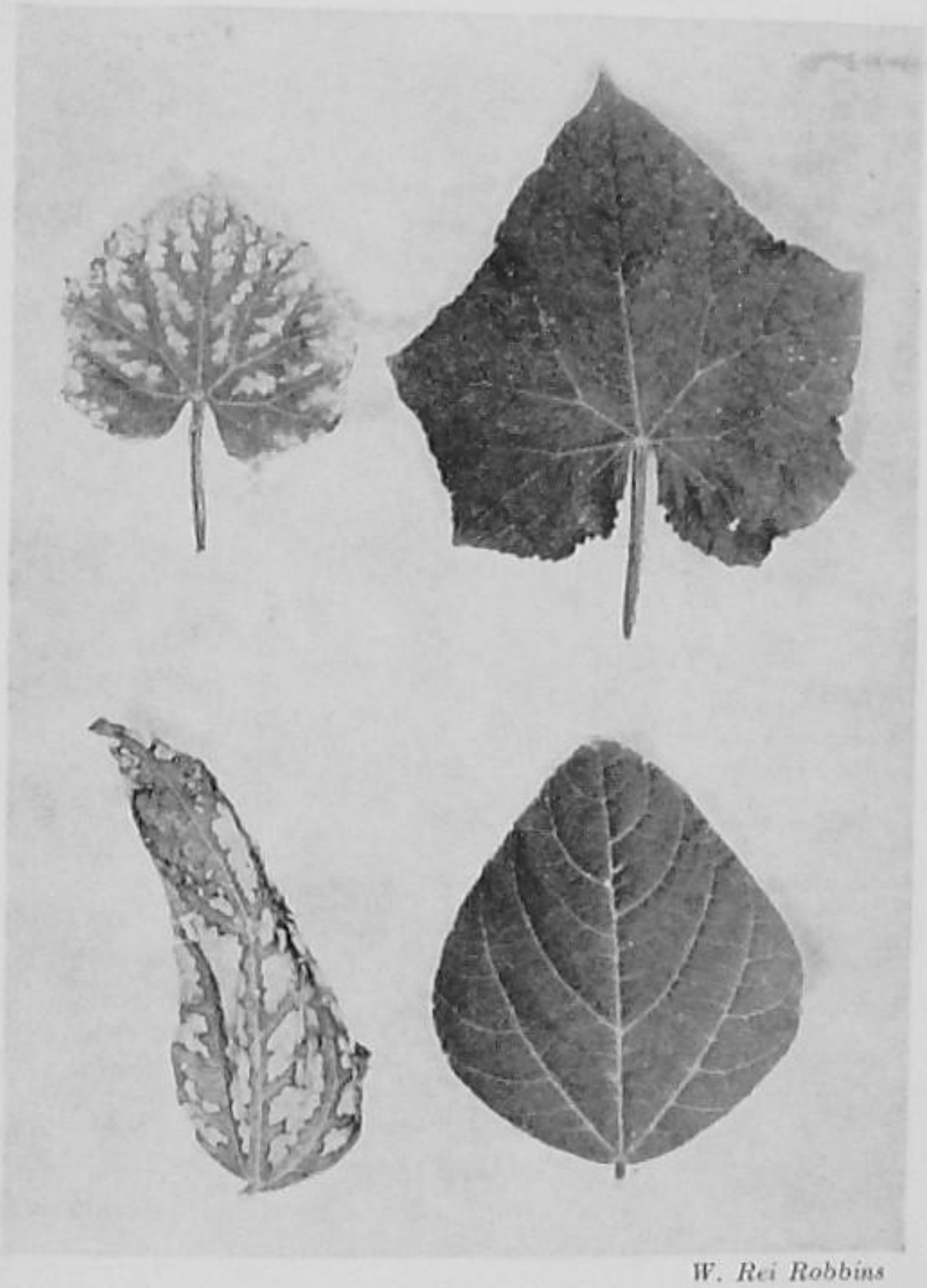
Crop	Number of Samples *	Average Pounds per Ton of Crop							
		N	Protein	P	K	Ca	Mg	Fe	Mn
Alfalfa	50	55.0	344	3.6	25.0	35.0	9.8	0.16	0.02
Red clover	50	47.4	296	3.2	26.0	29.4	9.2	0.28	0.10
Alsike	20	47.0	294	4.2	22.4	26.2	10.6	0.30	0.09
Lespedeza	50	40.4	252	2.9	18.9	17.0	5.7	0.20	0.14
Soybean (podstage)	50	43.6	272	3.4	17.8	25.0	17.4	0.46	0.17
Sweet clover (full bloom)	7	34.4	215	3.0	19.4	42.0	13.4	....	....
Sweet clover (Oct.–Nov.)	17	41.4	259	2.2	16.0	27.0	12.4	0.30	0.20
Sweet clover (Apr.–May)	30	69.0	431	6.0	32.0	32.8	11.4	....	....
Cowpeas †	3	49.6	310	3.5	25.2	30.2	14.2	0.38	0.97
Kentucky bluegrass	50	29.4	184	3.8	32.8	6.2	4.0	0.26	0.19
Timothy	50	19.6	122	3.0	31.4	5.6	3.6	0.16	0.14
Redtop	50	21.2	132	3.4	31.8	8.4	4.4	0.18	0.43
Orchard grass	30	19.4	121	3.6	38.0	5.4	4.2	0.16	0.56
Bromegrass	50	29.8	186	3.4	44.3	8.0	3.0	0.12	0.24
Big bluestem	10	21.4	134	3.0	29.6	7.6	4.1	0.29	0.12
Cornstalks ‡	50	14.8	92	1.8	23.0	9.8	8.4	0.36	0.28
Wheat straw	20	8.0	50	0.8	14.6	3.2	2.2	....	....
Oat straw	10	13.8	83	1.6	31.0	5.0	3.4	....	....

* Samples were taken from experiment fields and farms in various parts of Illinois.
† Cowpeas from Sparta field only.
‡ Cornstalks include blades, sheath, and husk as well as stalk.

MAGNESIUM-DEFICIENCY SYMPTOMS IN CROP PLANTS

Because of the relatively small amounts of magnesium required by plants, deficiencies of this element come into play considerably later in the agricultural history of an area than do those of potassium. As previously indicated, they are seldom observed in irrigated arid areas but are found mostly in regions of heavy rainfall where the soils have lost a large part of their original supply of the element by way of the

drainage water. As to whether the loss by removal in crops is large enough to be of any great importance in relation to the soil's economy of the element is problematical. In other words, if the soil is deficient in magnesium, this deficiency has probably developed more largely because of the losses resulting from the leaching action of rainwater



W. Rei Robbins

FIG. 73. Magnesium-deficiency symptoms in cucumber (top, left), and in snap-bean (bottom, left).

than because of the element's being carried away in the harvested crops. If the plant cannot get as much of the element as is required for those purposes for which magnesium alone will serve, however, its growth will be limited in proportion to the deficiency of this element, assuming that no other growth factor is in deficiency or excess.

Since magnesium is an essential component of chlorophyll, it would be expected that any deficiency of the element would be revealed by

a yellowing of the leaves, and that is what occurs. The fading out of the green color takes various forms, depending on the nature of the plant. The leaves of magnesium-deficient corn plants show a series of alternating green and white stripes, the green representing the veins and the white the tissues in between. In cotton and blueberries the leaves change to a purplish-red color, except for the stems and veins.



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FIG. 74. Magnesium deficiency in spinach is evidenced by dark-green veins and white interveinal tissue.

Soybean leaves take on an over-all yellowish cast, whereas the leaves of apple trees tend to be blotched, showing grayish spots of dead tissue. Similar symptoms are noted on the leaves of tomato plants.

Magnesium deficiency tends to be most prevalent on crops like potatoes that, in humid regions, are normally planted only on acid soils with *p*H values around 5.2 because trouble with scab is experienced at higher values. Since liming materials cannot be added in large quantity to a potato soil because of their alkaline effects, dependence for magnesium has to be placed on magnesium-containing fertilizers. Until recently, potato fertilizers contained little or no magnesium. They did contain considerable amounts of calcium sul-

fate, one effect of which in the soil was to still further reduce the supply of available magnesium by replacing it in the exchange complex, thus releasing it to the crop and the drainage water. As a result, widespread deficiency of magnesium finally developed in the heavily fertilized potato fields in the humid areas of the United States. Table 110 shows the mineral content of potato tops and tubers. It will be

TABLE 110

POUNDS OF NUTRIENTS IN ONE ACRE POTATOES (MAINE)

Variety	Yield, Bu.	N	P_2O_5	K_2O	CaO	MgO
		Tops				
Chippewa	...	48	5	79	54	22
Cobbler	...	65	8	181	56	17
Katahdin	...	71	9	170	39	26
		Tubers				
Chippewa	605	120	32	200	4	12
Cobbler	564	108	33	208	4	15
Katahdin	595	115	29	210	3	13

noted that the magnesium oxide totals about 35 pounds an acre, of which about 40 per cent is in the tubers.

Some of the most marked cases of magnesium deficiency have been noted on cotton at the Sandhill Experiment Station in South Carolina. The leaves of the deficient plants become purplish red, whereas the veins remain very dark green. Certain nitrogen fertilizers aggravate the difficulty, as is shown in Table 111. The fertilizer supplied 50

TABLE 111

EFFECT OF N FERTILIZERS ON PER CENT RED COTTON LEAVES (COOPER)

Material	Red Leaves
Sodium nitrate	28.3
Cal-nitro	24.5
Ammonium sulfate	24.2
Calcium cyanamide	24.2
Urea	20.3
Ammoniated superphosphate	18.4
Ammo-phos	2.7
Ammonium sulfate plus basic slag	1.0

pounds each of nitrogen and potash and 100 pounds phosphoric acid an acre. The percentage of red leaves was determined August 1[illegible] Magnesium nitrate and sulfate are highly soluble, in comparison with the phosphate.

COMMERCIAL MAGNESIUM

Magnesium is supplied to the soil mostly in the form of liming materials that are high in the element. Use can be made either of high-



FIG. 75. Magnesium tends to concentrate in the seeds of plants, such as the wheat grain in this Illinois field.

magnesium limestones or of true dolomites, either in their pulverized state or in the form of their burned and hydrated products. Since good soil management calls for the liberal use of liming materials for most crops, no special problem is presented in those areas that are conveniently located to abundant supplies of dolomitic stone. Even the high-calcium limestones and the hydrated lime produced from them contain some magnesium and, when liberally used, may supply enough of the element to meet crop needs.

In supplying magnesium in complete fertilizers, use is made of magnesium sulfate, sulfate of potash-magnesia, magnesite, and pulverized dolomite, or the product derived from burning it. The choice depends upon economic considerations and the requirements of the soil and crop. Magnesium can also be applied in spray form either as high-magnesium lime in Bordeaux mixtures or as a 0.25 per cent solution of magnesium sulfate alone.

MAGNESIUM AND MAGNESIUM OXIDE

The magnesium content of soils and plants and of the materials supplying this element is usually reported in terms of magnesium oxide or



FIG. 76. Legumes, such as this reseeding crimson clover, which is widely grown for pasture and soil-improvement purposes in Georgia and other southern states, have high magnesium requirements.

"magnesia" rather than as the element itself. The factor from magnesium to magnesium oxide is 1.66, and that from magnesium oxide to magnesium is 0.61. Thus, the 0.3 per cent magnesium in the average soil becomes nearly 0.5 per cent magnesium oxide, and the 6000 pounds of the element contained in the plow depth of 1 acre of average soil in humid regions becomes about 10,000 pounds. Similarly, the 18 pounds of magnesium in the grain and stover of a 100-bushel corn crop, the 30 pounds in a 4-ton alfalfa crop, and the ½ pound in the body of a 1000-pound cow become 30, 50, and 0.8 pounds of magnesium oxide, respectively.

DOLOMITE

The magnesium contained in limestones and in dolomite is present in the form of the calcium-magnesium carbonate rather than as free magnesium carbonate. Magnesium carbonate, as such, is more than 10 times as soluble as calcium carbonate in carbonated water. Dolomite, however, is only about two-thirds as soluble as calcite (Table 112).

TABLE 112

SOLUBILITIES OF LIMING MATERIALS IN CARBONATED WATER (MACINTIRE)

Chemically Pure Materials and Limestones	Grams per Liter *
Calcium oxide	1.0
Magnesium oxide	18.6
Calcium carbonate	1.2
Magnesium carbonate	14.4
High-calcium limestone	0.9
Dolomitic limestone	0.6

* In grams of calcium carbonate-equivalent a liter of solution.

Since dolomites are less soluble than calcites, it becomes necessary to reduce the particle size of such rocks to very fine proportions before they are applied to the soil. The importance of this is apparent from a study of Table 113, which shows the characteristics of a series of limestones and the relative rates at which they were dissolved in an acid soil. The "50-mesh" product was not actually that but one that passed a 40-mesh screen and was retained on a 50-mesh screen. Likewise, the "100-mesh" product was one that passed an 80-mesh screen and was retained on a 100-mesh.

The magnesium-oxide content of limestones varies between 0.5 and 21 per cent and their calcium-oxide content, in accordance therewith, between 54 and 27 per cent. Pure dolomite contains 21.89 per cent magnesium oxide and 30.37 per cent calcium oxide. In intensive-farming areas both calcitic and dolomitic limestones are normally pulverized to pass a 100-mesh screen. The low-solubility disadvantage of dolomite may be overcome in part by its higher neutralizing value a unit of weight. Thus, 100 pounds of pure dolomite is equivalent to 108 pounds of pure calcite in correcting acidity. Some soils, however, have high fixing capacities for magnesium, and this reduces its effectiveness as a corrective for acidity.

TABLE 113

SOME CHARACTERISTICS OF 10 DIFFERENT LIMESTONES (MORGAN)

$CaCO_3$, Per Cent	$MgCO_3$, Per Cent	Impurity, Per Cent	$CaCO_3$, Equivalent	Porosity, Per Cent	Abrasion,* Per Cent	Residual Carbonate † 50-mesh	Residual Carbonate † 100-mesh
96.4	0.86	2.64	97.40	0.29	28.20	6920	4090
96.2	1.17	2.62	97.60	13.40	11.65	6640	3250
95.8	1.77	2.43	97.90	45.00	39.45	6090	3020
89.8	1.98	8.22	92.16	1.46	6.25	5570	2930
81.3	7.68	1.02	90.45	4.43	7.90	7270	4090
82.8	12.39	4.81	97.55	0.49	9.15	7640	4630
79.6	13.85	6.55	96.10	14.10	11.25	7390	4160
46.7	38.86	14.44	92.91	9.23	7.10	7950	5040
51.8	42.17	6.03	101.80	17.62	7.60	8130	5090
54.1	44.00	1.90	106.50	18.21	8.30	8290	5220

* Loss by abrasion in 2 hours: an indication of softness of the limestone.

† Residual carbonates remaining in Trumbull silt-loam acid soil at end of 35 days from an original application of 10,000 pounds of $CaCO_3$ equivalent.

HYDRATED DOLOMITIC LIME

In the process of burning dolomite the bond between the calcium and magnesium oxides is broken, the final product being a mixture of the two oxides. If the temperature is controlled at 600° C., it is possible to produce a selectively calcined product in which the calcium remains as the carbonate, only the magnesium being in the form of the oxide.

Magnesium oxide reacts slowly with water and is known as "cold" lime. Calcium oxide develops a great deal of heat when water-slaked, being known as "hot" lime. One ton of pure dolomitic hydrated lime contains about 610 pounds of magnesium oxide and 840 pounds of calcium oxide, the remaining 550 pounds being water of hydration.

OTHER FORMS OF MAGNESIUM

Magnesium sulfate is known commercially as Epsom salt when it carries 7 molecules of water, and as Kieserite if only one molecule of water is attached to it. The water can be removed by calcination without decomposing the salt. Magnesium sulfate is also contained in the natural potash deposits that are sold without refining under such names as kainite and langbeinite (Table 100). Sulpomag, a re-

fined langbeinite, contains 40 per cent potassium sulfate and 55 per cent magnesium sulfate, equivalent to 21.75 per cent K_2O and 18.75 per cent MgO.

The choice from among these sources of magnesium sulfate is determined largely on an economic basis. Ordinarily, the refined salts are too costly for agricultural purposes and use is made of products that contain some other essential element, such as potassium. The advantage in using magnesium in the sulfate rather than in the carbonate form arises from its high degree of solubility. Thus, cold water will dissolve nearly three-quarters of its weight of Epsom salt, or 72 grams in 100 milliliters.

The fact that the magnesium in seeds is associated with phosphorus suggests that compounds of these two elements might be used to good effect as fertilizers. As to whether any important advantage would accrue from the use of magnesium phosphate over that obtained from a mixture of magnesium sulfate and superphosphate is not definitely known. No natural magnesium phosphates are available for use. Calcium-magnesium phosphates have been made by adding dolomite to liquid phosphoric acid and by calcining mixtures of phosphate rock and olivine or dunite, a rock consisting mostly of olivine.

Magnesium phosphate is also obtained by mixing dolomite with superphosphate, a practice that is widely employed in the United States. Serpentine and olivine are being used for the same purpose in New Zealand and in Russia. Regardless of whether the carbonate or silicate minerals are employed, they react with the superphosphate, with the resulting formation of considerable amounts of soluble magnesium and a reduction in the solubility but not in the availability of the phosphate. On being placed in the soil, the remaining insoluble magnesium is gradually liberated for plant use.

SELECTED REFERENCES

1. Anonymous. Potatoes. Maine Agr. Exp. Sta., Bull. 426, 1944.

2. Bear, Firman E., and Associates. One hundred questions and answers on liming land. New Jersey Agr. Exp. Sta., Bull. 754, 1951.

3. Bear, Firman E., and Allan B. Prince. Magnesium needs of New Jersey soils. New Jersey Agr. Exp. Sta., Bull. 739, 1948.

4. Beeson, K. C., and W. H. Ross. Chemical reaction in fertilizer mixtures. Decomposition of dolomite. *Ind. Eng. Chem.*, Vol. 29, pp. 1176–1182, 1937.

5. Cooper, H. P. Certain factors affecting the availability, absorption, and utilization of magnesium in plants. *Soil Sci.*, Vol. 60, pp. 107–114, 1945.

6. Garner, W. H., and Associates. Sand drown, a chlorosis of tobacco and

other plants resulting from magnesium deficiency. *Science*, Vol. 41, pp. 341–342, 1922.

7. Hilgard, E. W. *Soils, Their Formation, Properties, Composition, and Relations to Climate and Plant Growth in the Humid and Arid Regions.* The Macmillan Co., New York, 1906.

8. MacIntire, W. H. The non-existence of magnesium carbonate in humid soils. Tennessee Agr. Exp. Sta., Bull. 107, 1914.

9. Mehring, A. L. The magnesium content of fertilizers, 1850 to 1937. *Com. Fertilizer Yearbook*, 1939.

10. Morgan, M. F., and R. M. Salter. Solubilities of limestone as related to physical properties. *Soil Sci.*, Vol. 15, pp. 293–307, 1923.

11. Smith, John B. Report on magnesium fertilizers. *J. Assoc. Offic. Agr. Chemists*, Vol. 20, pp. 252–263, 1937.

12. Snider, H. J. Chemical composition of hay and forage crops. Illinois Agr. Exp. Sta., Bull. 518, 1946.

13. Whittaker, C. W., and W. H. Ross. Domestic sources of agricultural magnesium. *Soil Sci. Soc. Amer., Proc.*, Vol. 6, pp. 228–232, 1941.

14. Zimmerman, Miryam. Magnesium in plants (and seven other magnesium-symposium papers). *Soil Sci.*, Vol. 63, pp. 1–78, 1947.

·21·

Sodium Resources

Sodium belongs to the group of elements that are known as the "alkali metals." This group includes lithium, sodium, potassium, rubidium, and caesium, arranged in the order of their atomic weights and related properties. The last two of these elements are found only in traces in most soils and in the plants that grow on them. Apparently, they are of little significance in plant and animal life. Lithium makes up only about 0.005 per cent of the lithosphere and may be of some importance in life processes, but this has not been definitely established. *Sodium constitutes 2.75 per cent of the lithosphere, a somewhat higher percentage than that of potassium. By reason both of its abundance and of the similarity of its properties to those of potassium, this element must be taken into consideration in any study of soils and plants.*

Of the many sodium salts, four come in for most frequent mention and widespread use. These are sodium chloride, commonly called "salt"; sodium nitrate, known as "nitrate of soda"; sodium carbonate, marketed as "soda ash"; and sodium bicarbonate, the common "baking soda." Sodium chloride is widely distributed in Nature and is often found in nearly pure deposits, such as those that are located under large areas in Louisiana, Kansas, Michigan, Ohio, and New York. Very large deposits of sodium nitrate are found in Chile and are sold under the name "Chilean nitrate." Sodium carbonate and bicarbonate are made from common salt by treatment with ammonia and carbon dioxide.

Large amounts of the chloride and sulfate of sodium are found associated with the corresponding salts of potassium, calcium, and magnesium in the oceans, inland seas, and alkali deposits of arid regions, as well as in the European salt deposits at Stassfurt and those in Searles Lake, California, and Carlsbad, New Mexico, that are being worked for potassium for fertilizer purposes. In the Stassfurt area the order of deposits from the top down is: drift, about 25 feet; shales, sandstones, and unconsolidated clays of varying thickness; younger

rock salt of varying thickness; anhydrite, 100 to 250 feet; salt clay, 15 to 30 feet; carnallite, 50 to 100 feet; kieserite zone; polyhalite zone; older rock salt and anhydrite, 500 to 3000 feet; and anhydrite and gypsum. The Searles Lake brine has the composition shown in Table 114. Special attention is directed to the high borax content of the brine.

TABLE 114

SALT PERCENTAGES IN SEARLES LAKE BRINE (TURRENTINE)

Total	K	as KCl	4.70
Remaining	Cl	as NaCl	16.35
Total	CO_2	as Na_2CO_3	4.70
Total	SO_3	as Na_2SO_4	6.96
Total	B_2O_3	as $Na_2B_4O_7$	1.50
Total	P_2O_5	as Na_3PO_4	0.16
Total	F	as NaF	0.01
Other minor constituents			0.30
Water			65.32
Total			100.00

The sodium of these salts had its origin largely in such silicate minerals as albite, analcite, nephelite, sodalite, tourmaline, and plagioclase, which are widely distributed in rocks and soils. In the process of rock disintegration and mineral hydrolysis the sodium was released and subsequently was delivered into the ocean in salt form by the drainage water. Thus, the commercial salt deposits are located in areas that were once deep seas. That sodium should preponderate in such deposits is apparent when one considers that sodium chloride makes up nearly 78 per cent of the total salts in the ocean. Calculated as the element, sodium constitutes 1.14 per cent of the ocean water, in comparison with 0.14 per cent magnesium, 0.05 per cent calcium, and 0.04 per cent potassium (Table 115).

SOIL SODIUM

The sodium content of soils is of the same order as that of potassium, varying between 0.05 per cent and 3.0 per cent, depending in part upon the amount of rainfall to which they have been subjected. In arid regions large amounts of sodium salts are often found as surface incrustations that cause injury to crop plants when attempts are made to grow them by irrigation methods. Sodium salts make up as much as

TABLE 115

PERCENTAGE COMPOSITION OF OCEANIC SALTS (CLARKE)

Material Present	Atlantic Ocean	Gulf of Mexico	China Sea	Black Sea	Mediterranean Sea
Cl	55.18	55.24	55.34	55.12	55.11
Br	0.17	0.17	0.13	0.18	0.19
SO_4	7.91	7.54	7.76	7.47	7.89
CO_3	0.21	0.34	0.03	0.46	0.20
Na	30.26	30.80	30.67	30.46	30.64
K	1.10	1.10	0.97	1.16	1.09
Ca	1.24	1.22	1.19	1.41	1.23
Mg	3.89	3.59	3.75	3.74	3.65
Salinity *	3.63	3.54	3.20	.....	3.87

* Percentage of salts in water.

90 per cent of the alkali in some of the soils in the western states. The most troublesome cases are those in which a large part of the sodium is present as the carbonate, forming what is called "black alkali," the dark color being due to organic matter, which tends to dissolve in alkaline solutions. The effect of the carbonate is to deflocculate the soil and, at its worst, to make the soil nearly impervious to air and water. "White alkali," consisting mostly of chlorides and sulfates, is much less troublesome than the black type (Table 116).

TABLE 116

PERCENTAGE COMPOSITION OF ALKALI FROM FIVE STATES (HARRIS)

Salts	Colorado	California	Washington	Montana	Arizona
KCl	1.64	.....	5.61	.....	22.10
K_2SO_4	.....	3.95	.....	21.41	.....
K_2CO_3	.....	.....	9.73	.....	.....
Na_2SO_4	.....	25.28	.....	35.12	.....
$NaNO_3$	33.07	19.78	.....	.....	.....
Na_2CO_3	.....	32.58	13.86	7.28	.....
NaCl	6.61	14.75	.....	.....	13.77
Na_2HPO_4	.....	2.25	.....	.....	.....
$MgSO_4$	.....	.....	.....	4.06	.....
$MgCl_2$	12.71	.....	.....	.....	3.98
$CaCl_2$	17.29	.....	.....	.....	.....
$NaHCO_3$	.....	.....	36.72	22.06	21.02
$CaCO_3$	21.48	.....	1.87	10.07	32.25
$Ca(HCO_3)_2$	.....	.....	16.48	.....	.....
$Mg(HCO_3)_2$	.....	.....	15.73	.....	.....
$(NH_4)_2CO_3$	.....	1.41	.....	.....	.....

The rate at which the sodium of silicate minerals in soils is released is about the same as that of potassium. The exchange complex of the soil does not retain sodium as it does potassium, however, and if the sodium is not absorbed by the roots of the crop then growing on the land it is quite likely to disappear in the drainage water.

Sodium constitutes such a small part of the total content of the basic elements in the exchange complex of soils of humid areas that it is usually ignored. The situation is altered when excessive use is made of sodium nitrate or, as often happens along the seashore, when storms flood an area with sea water. When areas are diked off from the sea, as has been done on a large scale in the Netherlands, great difficulty is experienced in getting rid of excess sodium salts. Yet when this is done the soils are very fertile.

Notwithstanding the small content of sodium in the exchange complex of soils of humid regions, large amounts of the element may still remain in the soil in the form of mineral silicates that have not as yet undergone disintegration. Igneous rocks contain an average of about 2.5 per cent sodium, shales around 1.0 per cent, and sandstones nearly 0.35 per cent. Limestones have a sodium content of less than 0.04 per cent. An average soil in humid regions will contain about 1.0 per cent sodium, or 20,000 pounds of the element in the plow depth of an acre. The sodium content of sands and peats is very low, as a rule, but that of the alkali soils, or of certain of the heavier types in humid areas, may be 3 per cent or more.

SODIUM IN LIVESTOCK FARMING

The body of a 1000-pound cow contains about 1 pound sodium. Grains and hays of humid regions normally contain between 0.02 and 0.04 per cent sodium. Assuming that the cow eats 3000 pounds of dry weight of feed during the year, she would consume about 1 pound of the element. As will be shown subsequently, the sodium content of certain crops, or of all crops in certain areas or under certain fertilizer systems, may be much higher than these figures would indicate. Larger amounts of sodium are obtained from the common salt that is fed the cow than from the hay and grain she eats. Thus, the average cow consumes about 50 pounds of common salt a year, nearly 20 pounds of which is sodium. Of this, about 5 pounds is recovered in the milk and nearly the same amount in the feces, the remainder being

excreted in the urine. A ton of fresh cow manure normally contains between 1 and 2 pounds of sodium (Na).

SODIUM EFFECTS ON CROP PLANTS

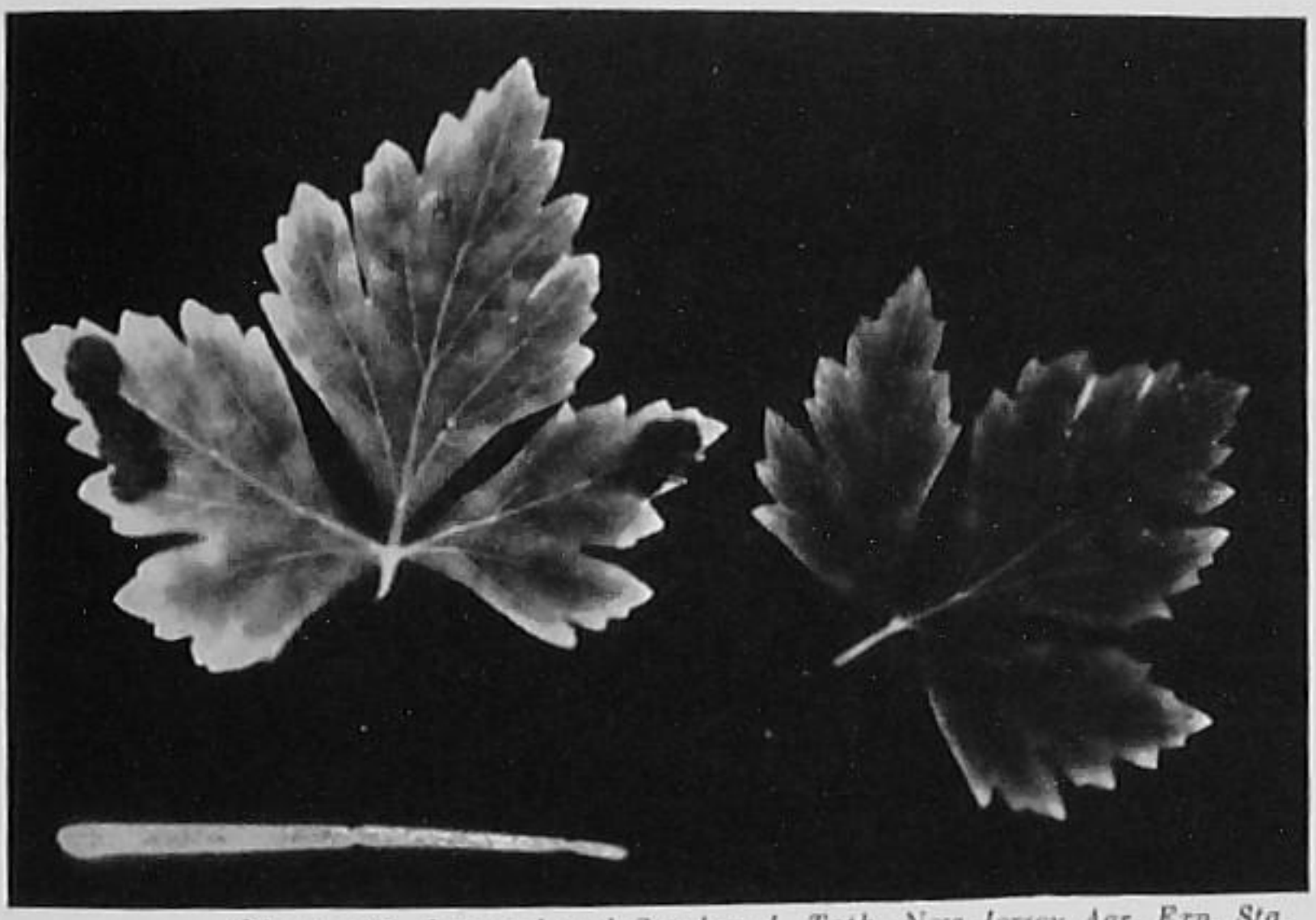
It is doubtful whether sodium is essential to all plants, but certain species seem to be greatly benefited by applications of soluble salts of this element to the soil on which they are growing, especially if the soil is not well supplied with potassium. Four possible explanations have been offered for the benefits thus observed from the use of sodium



FIG. 77. Effect of supplemental sodium on table beets. Plants grown in sand culture with complete nutrient solution containing potassium and sodium in parts per million as indicated:

Pots 1, 2, and 3, 195 p.p.m. K; Pots 1, 4, and 7, 0 p.p.m. Na
Pots 4, 5, and 6, 19 p.p.m. K; Pots 2, 5, and 8, 23 p.p.m. Na
Pots 7, 8, and 9, 4 p.p.m. K; Pots 3, 6, and 9, 115 p.p.m. Na

salts. One is that potassium has several functions in the plant, one of which is specific for potassium whereas the others are more or less general to it and to sodium, calcium, and magnesium. A second is that by the application of sodium salts to the soil more of the soil potassium is released from the exchange complex, with resulting benefit to the crop. A third is that sodium tends to aid in maintaining soil phosphorus in a more available form than would otherwise occur. The fourth is that sodium has value as such for certain species of



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FIG. 78. Location of sodium in celery leaves as shown by radiograph. Note tendency of Na^{22} to concentrate in petiole, in veins, and around edges of leaves.

plants, especially those that tend to be high in their content of the element. This is a common characteristic of plants native to areas along the seashore or to irrigated arid areas.

It is now known that sodium has direct value to certain plants, notably beets, mangels, Swiss chard, celery, celeriac, cabbage, kale, kohlrabi, radishes, rape, and turnips. The element is known to have at least a partial substitutive value for potassium in potatoes and cotton.

The original work on this subject in the United States was done by Wheeler and his associates at the Rhode Island Experiment Station. At that time considerable amounts of sodium were being applied to soils as impurities in the potash salts that were then in use. Since

commercial value was attached only to the potash, the producers of the fertilizer salts chose to eliminate the impurities as much as possible. The result was that the standard potash material in the United States eventually came to be the 60 per cent grade of muriate of potash, which represents a purity of about 96 per cent.

In the past, only sporadic interest has been shown in sodium. Of the studies that have been responsible for a renewal of interest, those from the Michigan, South Carolina, Alabama, and New Jersey Agricultural Experiment Stations are of greatest interest. Specialists at the Michigan Station reported marked increases in yield of a considerable variety of crops from the use of common salt, as shown in Table 117.

TABLE 117

EFFECT OF NaCl ON ACRE YIELD OF CROPS ON PEAT SOIL (HARMER)

Fertilizer *	NaCl Yearly, Lb.	Swiss Chard, Tons	Table Beets, Tons	Sugar Beets, Tons	Cabbage, Tons	Parsnips, Tons	Carrots, Tons	Potatoes, Bu.
0–12– 0	0	8.5	2.6	3.3	5.6	4.9	16.0	109
0–12– 0	600	20.1	5.3	5.6	7.0	4.8	15.2	110
0–12–24	600	30.9	13.7	11.5	15.5	10.1	22.6	175
0–12–24	0	25.5	9.9	9.0	14.2	10.0	23.7	182

* The fertilizer was applied at the rate of 800 pounds an acre annually for the period 1924–30. The muriate of potash used in making up the fertilizer contained 90 per cent KCl and 10 per cent NaCl.

It was found possible to differentiate between plants responding to sodium and those not responding by growing them in a nutrient solution that was rich in both potassium and sodium and then analyzing the resultant plant tissue for both elements. Those having a narrow potassium-sodium ratio showed marked response to the use of sodium as a fertilizer element, whereas little effect was noted with plants having a wide ratio. Examples of plants with wide and narrow ratios are given in Table 118.

Further studies of sodium as a fertilizer resulted in arranging a considerable number of plants into 4 groups, depending on their degree of benefit when potash was in deficiency and when it was present in adequate amounts. The classification on this basis is shown in Table 119.

One of the important reasons for believing that sodium has greater value to plants than is generally admitted by plant physiologists

TABLE 118

K-Na Ratios in Plants Supplied with Both Elements (Harmer)

Immature Plants	K:Na	Mature Plants	K:Na
French spinach	0.43	Celery	0.78
Lettuce	4.21	Table beets	0.91
Tomato	4.29	Sugar beets	1.17
Common poppy	5.00	Rape	2.48
Aster	5.19	Cabbage	3.21
Oats	5.32	Kale	3.59
Tobacco	8.00	Kohlrabi	4.82
Buckwheat	38.00	Onions	12.60
Corn	44.29	Asparagus	13.39

arises from the widespread popularity of sodium nitrate as a fertilizer. This salt has been carefully compared with other carriers of nitrogen by many experiment-station workers and has usually been very highly rated. On the average, it is the best single carrier of nitrogen on the market, notwithstanding the fact that the nitrate is subject to greater loss in the drainage water than the nitrogen in non-nitrate materials. An illustration of this superiority is shown in Table 120, which gives a summary of a large number of comparative tests of ammonium sulfate and sodium nitrate on cotton on Alabama farms.

TABLE 119

Benefit from Use of Sodium as Fertilizer (Harmer)

Benefit in Deficiency of Potash		Benefit in Sufficiency of Potash	
None to slight	Slight to medium	Slight to medium	Large
Corn	Asparagus	Cabbage	Celery
Lettuce	Barley	Celeriac	Mangel
Onion	Carrot	Horse-radish	Sugar beet
Potato	Cotton	Kale	Swiss chard
Rye	Millet	Kohlrabi	Table beet
Soybean	Oat	Mustard	Turnip
Spinach	Tomato	Radish	
Strawberry	Wheat	Rape	

COMMERCIAL SODIUM

More sodium is being applied to the soil as nitrate of soda than in any other form. The nitrate is ordinarily added for its nitrogen value, however, rather than because of any effect the sodium may have. Considerable amounts of common salt are used on some crops, especially on table beets. Kainite, a potash salt carrying large amounts of sodium chloride and other salts as impurities, once enjoyed a good reputation as a fertilizer, no doubt in part because of the extra value of its sodium, but possibly also because of its content of salts other than those of potassium and sodium.

SODIUM AND SODA

Like potassium, sodium is normally reported as the oxide (Na_2O), commonly called "soda." This term is applied also to nitrate of soda and baking soda. Thus, the southern farmer speaks of sidedressing his cotton crop with "soda" and the housewife speaks of "soda" biscuits. Nevertheless, soda to the chemist is sodium oxide of which a little over 74 per cent is sodium and the remainder oxygen. The factor from sodium to soda is 1.35. Thus, the 20,000 pounds of sodium in the plow depth of an average acre of soil is equivalent to 27,500 pounds of soda. The factor from soda to sodium is 0.74.

NITRATE OF SODA

Nitrate of soda contains a little over 35 per cent soda, or about 700 pounds a ton. An application of 200 pounds an acre supplies 70 pounds of soda. If one thinks of soda in terms of its value as a partial substitute for potash, then he is more concerned with the potash equivalent of that amount of soda, which can be obtained by multiplying by the factor 1.52. Thus, a 200-pound sidedressing of nitrate of soda supplies soda equivalent to 106 pounds of potash, which is more potash than is contained in 1000 pounds of a 5–10–10 fertilizer. Where soda has potash-substituting value, a liberal sidedressing of nitrate of soda may well have a marked supplemental effect over and above that produced by the nitrogen it contains. Some of the more intensive market gardeners use as much as 1000 pounds of nitrate of soda an acre for sidedressing purposes in the course of a single season of intensive cropping, and, in so doing, supply a very heavy dose of soda.

Since nitrate of soda is highly soluble in water, its sodium as well as its nitrogen is readily available to the crop. Neither the soda nor the nitrate is fixed by the soil and, if not used by the crop, both are likely to be carried off in the drainage water.

Continued use of large amounts of nitrate of soda have, on occasion, produced an alkaline, sodium soil. When this occurs, the soil granules tend to break down into their component parts. If the soil contains any very large percentage of clay it becomes very compact and sticky, with the result that water can no longer drain through it readily. This means that once a sodium soil has been formed it is difficult to get rid of the sodium. The standard remedy consists in the liberal use of calcium sulfate, or gypsum, which tends to effect a regranulation of the soil by replacing the sodium with calcium to form a calcium soil. The danger of any such damage to the acid soils of humid regions is very limited.

Large amounts of nitrate of soda are being widely used on the sandier soils that permit rapid removal of any surplus sodium in the drainage. It is also being widely used, without any disadvantage, on heavier soils containing the kaolinitic type of clay, such as is common in the southern states. The effectiveness of its soda, whether as a constituent of value *per se* or as a partial substitute for potash, depends upon the physical character of the soil, the nature of its clay minerals, the rate of application an acre, the nature of the crop, and the amount of available potash in the soil. Everything considered, it appears quite logical to believe that a considerable part of the value of nitrate of soda lies in its soda, which has important potentialities for economically increasing the acre yields of many crops (Table 120).

TABLE 120

ACRE YIELDS SEED COTTON—SODIUM NITRATE VS. AMMONIUM SULFATE (HOLT)

At 600 Lb. an Acre	Number Tests	$(NH_4)_2SO_4$ Limestone,* Lb.	$NaNO_3$ Only, Lb.	Increase $NaNO_3$, Lb.
6–8– 4	14	792	931	139
6–8– 8	4	863	1076	213
6–8–12	10	858	993	135
10–8– 4	10	935	1084	149
10–8–12	9	1070	1168	38

* Enough to neutralize acid effect of ammonium sulfate.

SODIUM CHLORIDE

Sodium chloride can be purchased and used as such, or it can be supplied as a constituent of kainite and certain other unrefined potash salts. So far as is known, chlorine is not an essential element for plants, but large amounts of it can be absorbed by many species of plants without damage to yield. The quality of some crops is lowered by the use of fertilizers that are high in chlorine. The chlorine limit for fertilizers for the cigarette tobaccos of Virginia, the Carolinas, and Georgia has been set at 2 per cent.

The sodium of common salt should have the same value as that in sodium nitrate. A ton of sodium chloride contains over 1000 pounds of soda. The cost of common salt is so low that it offers attractive possibilities for use for those crops that respond to sodium applications. Repeated use of 1000 pounds of common salt an acre for 10 years produced no ill effects on the physical condition of muck soils in Michigan. At the Geneva, New York, Agricultural Experiment Station, no adverse effect on the physical properties of mineral soils was found in detailed studies of soil structure after common salt had been applied for 40 years at an annual rate of 500 pounds an acre.

CATION-EQUIVALENT CONSTANCY IN SODIUM-TREATED PLANTS

The evidence presented in Table 97 indicated that the sum of the calcium, magnesium, and potassium equivalents in alfalfa tended to be a constant under conditions in which there was wide variation in the relative amounts of these three elements both in the soil and crop. When sodium was added to the list and the sum of the equivalents of all four cations was determined for sugar beets in Michigan, a similar tendency was noted (Table 121).

Common salt is sometimes used for weed-killing purposes in asparagus. This is a selective process, the shallow-rooted weeds being destroyed whereas the deep-rooted asparagus is not seriously disturbed. This same principle is applied in irrigating alfalfa in semiarid regions. When the use of water is discontinued for a time, the salts tend to concentrate at the surface and aid in killing the weeds. The deep-rooted alfalfa plants are able to survive without water until the weeds have died, and irrigation water is then applied. Asparagus appears also to benefit directly from salt applications. Alfalfa grows luxuriantly on

TABLE 121

EFFECT NaCl ON YIELD AND CATION CONTENT SUGAR BEETS (HARMER)

Fertilized 1932–38, 600–900 Lb.*	Salt an Acre, Lb.	Yield 1937–38, Tons	Cation Values Entire Crop in 100 Grams Dry Matter				
			Ca, me.	Mg, me.	Na, me.	K, me.	Total, me.
0–8–24	0	16.3	77	80	17	52	226
0–8–12	500	22.7	71	65	61	29	226
0–8–24	500	21.3	73	70	68	38	249
0–8–48	0	19.8	75	72	19	60	226
0–8–24	1000	18.3	63	50	68	47	228
0–8– 0	500	11.1	75	91	107	11	284

* All potash in form of 60-per cent grade of muriate of potash.

irrigated arid soils containing considerable amounts of alkali salts. It is possible that sodium chloride might be of considerable value to this crop when it is grown in the humid areas.

SELECTED REFERENCES

1. Cameron, Frank. *The Soil Solution.* Chemical Publishing Co., Easton, Pa., 1911.

2. Clarke, F. W. The data of geochemistry. *U. S. Geol. Survey Bull.* 770, pp. 122–155, 1924.

3. Harmer, P. M., and E. J. Benne. Effects of applying common salt to a muck soil on the yield, composition, and quality of certain vegetable crops and on the composition of the soil producing them. *J. Am. Soc. Agron.,* Vol. 33, pp. 952–979, 1941.

4. Harmer, P. M., and E. J. Benne. Sodium as a crop nutrient. *Soil Sci.,* Vol. 60, pp. 137–148, 1945.

5. Harris, F. S. *Soil Alkali.* John Wiley & Sons, New York, 1920.

6. Hartwell, B. L., and S. C. Damon. The value of sodium when potassium is insufficient. Rhode Island Agr. Exp. Sta., Bull. 177, 1919.

7. Hayward, H. E., and O. C. Magistad. The salt problem in irrigation agriculture. *U. S. Dept. Agr. Misc. Publ.* 607*M*, 1946.

8. Holt, M. E., and N. J. Volk. Sodium as a plant nutrient. *J. Am. Soc. Agron.,* Vol. 37, pp. 821–827, 1945.

9. Johnson, C. T., and Associates. Effect of certain sodium and potassium salts on sweet potato production in eastern Virginia. *Proc. Am. Soc. Hort. Sci.,* 1923.

10. Lehr, J. J. The importance of sodium for plant nutrition. *Soil Sci.*, Vol. 52, pp. 237–243 and 335–349, 1941; and Vol. 53, pp. 399–411, 1942.

11. Leonard, Chester D., and Firman E. Bear. Sodium as a fertilizer for New Jersey soils. New Jersey Agr. Exp. Sta., Bull. 752, 1950.

12. Morgan, M. F., and H. G. M. Jacobson. Soil and crop interrelations of various nitrogenous fertilizers. Connecticut Agr. Exp. Sta., Bull. 458, 1942.

13. Sayre, C. B., and M. T. Vittum. Effect of sodium salts and rate of seeding on the yield of beets. *Agron. J.*, Vol. 40, pp. 235–239, 1949.

14. Turrentine, J. W. *Potash in North America.* Reinhold Publishing Corp., New York, 1943.

15. Wallace, A., S. J. Toth, and F. E. Bear. Sodium content of some New Jersey plants. *Soil Sci.*, Vol. 65, pp. 249–258, 1947.

16. Wehunt, Ralph D., and W. O. Collins. Response of oats to Na and K on Norfolk sandy loam at two residual K levels (and 9 other papers on sodium). *Soil Sci.*, Vol. 76, pp. 1–90, 1953.

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Sulfur Resources

Immense deposits of elemental sulfur occur in Louisiana and Texas, where it exists in pockets that are located at 500 feet or more below the surface. Additional deposits of the element are found as such in Sicily and Japan. Large amounts of sulfur also occur in the form of sulfide ores. The most common of these is iron pyrites, which are extensively mined in Spain and Mexico. Pyrites, gypsum, and anhydrite, a dehydrated form of gypsum, are the most widely distributed mineral forms of sulfur in rocks and soils. In the process of soil formation, pyrites and other metallic sulfides tend to give up their sulfur either as hydrogen sulfide or sulfur dioxide, depending upon the oxygen supply. Much of their sulfur is finally transformed into sulfuric acid and the resulting sulfates accumulate in the soil or are lost to the ocean by way of the drainage water, depending upon the amount of rainfall. Large amounts of gypsum and anhydrite are found in the soils of the drier parts of the earth, under such salt deposits as those being mined for potash fertilizers at Stassfurt, Germany, and Carlsbad, New Mexico, and in the oceans and salt seas. Gypsum tends to accumulate in the soils of regions of intermediate rainfall, where enough water has fallen to wash out the highly soluble sodium and potassium salts but not sufficient to remove the less soluble calcium sulfate. Anhydrite is the first salt to separate out of sea water when an enclosed body of it increases in salt concentration as a result of loss of water by evaporation.

Sulfur constitutes only 0.06 per cent of the lithosphere. Shales tend to be higher in sulfur than other classes of rocks, their average content of the element being 0.25 per cent. Soils of humid areas contain between 0.01 and 0.14 per cent sulfur, the average figure being around 0.05 per cent, or twice that quantity of the dioxide (Table 21). The plow depth of the average cropped soil contains about 1000 pounds of sulfur.

In parts of the United States, notably in Oregon, Minnesota, and Florida, the soil is deficient in sulfur. In such regions, soluble carriers

of the element effect very marked improvement in crop yield, especially of the legumes (Table 122).

TABLE 122

ACRE YIELDS OF ALFALFA WITH AND WITHOUT SULFUR (REIMER)

Treatment	Rate, Lb.	Alfalfa,* Cwt.
None	0	20
Sulfur	300	137
Gypsum	600	164
Monocalcium phosphate	320	29
Superphosphate	820	165
Muriate of potash	530	31
Sulfate of potash	550	153
Nitrate of soda	560	32
Sulfate of ammonia	420	147

* Total crop produced in 3-year period. The soil and subsoil contained 0.20 and 0.017 per cent sulfur, respectively.

Selenium, one of sulfur's close relatives, is found in considerable amounts in the drier parts of North America in an area extending across western Canada, the United States, and Mexico. Two well-known animal diseases, "alkali disease" and "blind staggers," are due to selenium poisoning. The first results in a gradual sluffing-off of the hooves of animals and the second in quick death. Of the selenium-accumulating plants, several of those belonging to the genus *Astragalus* are most troublesome. These plants grow best on highly seleniferous soils, which indicate that selenium plays an important part in their life processes.

SULFUR CONTENT OF PLANTS

Recognition of the importance of sulfur in soil and plant economy was delayed because of the widespread acceptance of Wolff's ash analyses as representing the true picture of the plant's content of this element. When it was discovered that less than 25 per cent of the sulfur of certain plants was recoverable in their ash, a renewal of interest in this element developed.

The sulfur content of the seed portion of most plants is only about half that of their phosphorus (Table 123), but straw, stover, and the stalk portions contain about twice as much sulfur as phosphorus. Certain plants, notably legumes and members of the onion and cabbage

TABLE 123

POUNDS SULFUR AND PHOSPHORUS IN PRODUCE 1 ACRE (HART)

Crops	Dry Wt.	S	P
Wheat, grain	1530	2.6	6.2
straw	2653	3.7	3.0
	4183	6.3	9.2
Corn, grain	1500	2.6	4.4
stalks	1877	2.2	3.5
	3377	4.8	7.9
Beans, grain	1613	3.8	10.0
straw	1838	2.0	2.8
	3451	5.8	12.8
Turnips, roots	3126	23.1	9.8
tops	1531	13.8	4.7
	4657	36.9	14.5
Potatoes	3360	4.6	9.4
Alfalfa hay	9000	26.0	17.4
Cabbage	4800	39.2	26.6

families, contain especially high percentages of sulfur and grow best on soils that are well supplied with the element.

SULFUR IN RAINFALL

The problem of sulfur economy in soils differs fundamentally from that of phosphorus. The atmosphere is a source of considerable amounts of the element that are brought down in the rainfall. Many of the more common fertilizer materials that are used as sources of nitrogen, phosphorus, and potassium supply large amounts of sulfur as well. The sulfates retain a higher degree of solubility in the soil than the corresponding phosphates.

Atmospheric sulfur is largely in the form of sulfur dioxide, which is produced in the burning of coal, oil, and gas, in the smelting of sulfide ores, and in the various chemical operations that involve digesting materials with sulfuric acid. Some of the data on the amount of sulfur brought down in the rain and snow are not dependable because the points of collection were too close to some factory or laboratory from which large amounts of sulfur dioxide were escaping. From a con-

sideration of what would appear to be the most reliable figures, *it seems probable that rainfall delivers between 5 and 30 pounds of sulfur an acre annually to agricultural land. The lowest amounts reported by 10 widely distributed experiment stations were those found in Washington and Wisconsin, and the highest those in New York and Kentucky.*

In the smelting of iron pyrites and other sulfide ores, sulfur dioxide is evolved. This may cause serious injury to surrounding vegetation either from coming in direct contact with the leaves or indirectly as a result of its acidulating effect on the soil. Some of the larger smelters now collect the gas and make sulfuric acid from it. One of the largest of these recovery units is operated by the Anaconda Copper Company in Montana. The acid is used in the manufacture of double superphosphate, large deposits of phosphate rock being located nearby.

SULFUR CONTENT OF FERTILIZER MATERIALS

A total of 3,465,000 tons of SO_3 are estimated by Mehring to have been applied to the land of the United States as a constituent of fertilizers in 1948. Two of the most common sulfur-containing fertilizer materials are sulfate of ammonia and superphosphate. Ammonium sulfate carries more sulfur than nitrogen, and ordinary superphosphate contains approximately equal percentages of sulfur and phosphorus.

It is an interesting fact, however, that many of the more modern fertilizer materials carry little or no sulfur. Thus, anhydrous ammonia, ammonium nitrate, and urea are being produced and used in ever larger amounts as substitutes for ammonium sulfate. Ammonium phosphate and ammoniated double superphosphate, which contain relatively little calcium sulfate, are tending to replace the ordinary grades of superphosphate. Similarly, the soluble sulfates that occurred as impurities in some of the early potash salts have now been largely eliminated.

Two facts explain why the more concentrated materials and mixtures are being employed. The manufacturer prices his fertilizers on the basis of the nitrogen, available phosphoric acid, and water-soluble potash contained in them. The tendency, therefore, has been toward the elimination of elements other than those for which payment is made. Of this group calcium and sulfur are most easily discarded.

SULFUR IN DRAINAGE WATERS

Most of the sulfur in the soil is present in the residues of the minerals that contained this element and in the form of organic sulfur compounds in the soil organic matter. In either form, the sulfur is gradually oxidized to sulfates, most of which are quite readily soluble in water. Here again the contrast between the economy of sulfur and phosphorus is marked. Soluble phosphates are fixed by the soil at or very near their point of contact with the soil, whereas large amounts of sulfates are found in the drainage water. The difference between the losses by leaching of the two elements is well shown in Table 124, which records data from analyses of river waters from regions of high and low rainfall in Virginia and Texas, respectively.

TABLE 124

MINERAL MATTER IN WATERS OF JAMES AND PECOS RIVERS (CLARKE)

Ingredient	James, Per Cent *	Pecos, Per Cent *
Carbonic acid	42.52	1.54
Sulfuric acid	5.26	43.73
Nitric acid	3.32	Trace
Phosphoric acid	Trace	Trace
Chlorine	1.51	22.56
Calcium	18.49	13.43
Magnesium	5.44	3.62
Sodium	3.52	14.02
Potassium	3.58	0.77
Silica	14.74	0.33
Total solids	0.0069	0.2834

* Per cent of solids.

SULFUR IN LIVESTOCK FARMING

Since the stalks of plants tend to be higher in sulfur than the grains, a large part of the sulfur that is contained in plants may be returned to the soil in certain types of farming, particularly in the livestock system. Here again a difference exists between sulfur and phosphorus, in that animal hair and wool are high in sulfur whereas phosphorus is found more largely in bones. The percentage recoveries of both elements in the milk, urine, and feces of dairy cows is shown in Table 125.

TABLE 125

PHOSPHORUS AND SULFUR IN FEED, MILK, AND MANURE OF COW *

Element	Feed, Lb.	Milk, Lb.	Urine, Lb.	Feces, Lb.	Recovery, Per Cent
P	22.5	8.7	0.2	13.8	62
S	17.0	2.7	6.4	7.8	84

* On basis of 10,000 pounds of milk.

Only about one-third as much sulfur as phosphorus is contained in the milk. The sulfur in the manure is about equally distributed between the urine and feces, whereas most of the phosphorus is found in the feces.

SPECIAL USES FOR SULFUR

Sulfur and its salts are used for a variety of soil reasons other than to supply the element for plant-nutrient purposes. The elemental form is frequently applied as an acidulating agent to potato soils that must be lowered to *p*H values around 5.2 to avoid trouble with scab. The same principle applies to the control of pox on sweet potatoes. Similarly, such acid-soil plants as rhododendrons and azaleas are often benefited by the use of a soil-acidulating agent, aluminum sulfate being the one commonly employed for this purpose. Frequently, market-gardeners get into difficulty from overliming, as a result of which the availability of some of the minor elements in the soil is reduced. Here, again, elemental sulfur may be applied as such or sulfate of ammonia may be used as the source of most of the nitrogen, in order to take advantage of the acidulating action of these materials.

The alkalinity of irrigated arid soils is often a much more serious problem than the acidity of the soil of humid regions. Two of the common remedial agents for alkali soils are elemental sulfur and gypsum. On being oxidized by soil microbes to sulfuric acid sulfur serves as a neutralizing agent for carbonates. The principle in the use of gypsum is altogether different in that it reacts with sodium and potassium carbonates with the resulting formation of the relatively insoluble calcium carbonate and neutral sodium and potassium sulfates. The choice between sulfur and gypsum depends upon the concentration and type of alkali salts present.

Gypsum is frequently used for the purpose of replacing sodium in soils that have been reclaimed from the ocean, have been subjected to flooding by sea water, or have received too liberal applications of nitrate of soda. It can also be used to advantage on soils that have deteriorated physically as a result of having been worked while too wet. One advantage of gypsum over limestone or its burned products for these purposes lies in the fact that it is a more soluble product and, therefore, more quickly effective.

SULFUR-DEFICIENCY SYMPTOMS IN CROP PLANTS

Sulfur-deficiency symptoms in plants are similar to those resulting from a lack of nitrogen. The leaves of affected plants tend to turn yellow, the roots become abnormally long, and the stems develop woodiness. But there are certain important differences. Sulfur-deficient plants do not lose their leaves by firing like those suffering from a lack of nitrogen. The new growth rather than the whole plant turns yellow. The stems tend to increase in length rather than in diameter. The fruit of sulfur-deficient trees is light green and tends to be misshapen, the peel is thick, and the flesh is juiceless. A slight deficiency of sulfur may be advantageous in the finer grades of smoking tobacco in that a better color is developed.

Deficiencies of sulfur, like those of potassium, tend to develop in dry seasons. This is in marked contrast to those of manganese and magnesium, which come into play in wet seasons. Moderate cases of sulfur deficiency may be overcome by rain in areas where there is sufficient industrial development to guarantee the presence of considerable amounts of sulfur dioxide in the atmosphere.

The most common forms of commercial sulfur are the elemental form and gypsum. For plant-nutrient purposes, either of these can be used to good effect. Thus, elemental sulfur is readily oxidized to the sulfate form in the soil and has about the same effect as gypsum, except in strongly acid soils where it adds to the acidity. Gypsum is a neutral salt and does not acidify the soil. It tends, however, to drive the acid hydrogen down more deeply into the subsoil.

Since most soils are deficient in nitrogen, phosphorus, potassium, or in two or all three of these elements, the more logical means for sup-

plying sulfur is as a part of the fertilizer mixture in such materials as sulfate of ammonia, superphosphate, or sulfate of potash. If the source of phosphoric acid in a complete fertilizer is ordinary superphosphate, as much sulfur as phosphorus is supplied. If, in addition, the nitrogen carrier is ammonium sulfate, much more sulfur than would be needed



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FIG. 79. Effect of an application of gypsum (right) on bur clover in California, where large areas of land are deficient in sulfur.

by crop plants would be added to the soil. Fortunately, excess sulfates, within limits, cause little or no trouble, and they are readily leached out of the soil.

SULFUR AND SULFUR OXIDES

Sulfur is often reported in terms of one or the other of its oxides. The trioxide is sometimes spoken of as sulfuric acid, although it is the anhydride of the acid. The factor from sulfur to sulfur trioxide is 2.5. That from sulfur trioxide to sulfur is 0.4. The 1000 pounds of

sulfur in the plow depth of the average acre of soil becomes 2500 pounds of sulfur trioxide.

ELEMENTAL SULFUR

Elemental sulfur has a sulfur trioxide value of 250 per cent. An application of 100 pounds of sulfur an acre is entirely adequate for most cases of deficiency of this element. No difficulty is experienced with fixation, such as may occur following the use of phosphoric acid or potash. In some soils oxidation of the sulfur may be delayed because of the scarcity of the specific bacteria that bring this about.

Sulfur is normally used only where the soil is too alkaline. The acidulating action of sulfur is very high a unit of weight, each pound of the element requiring a little over 3 pounds of limestone, or its equivalent in other forms of lime, to neutralize its acid effect. No special problem is presented in the use of sulfur on the heavier soils, but care must be taken not to overdo the rate of application on the sandier types because of their low buffer capacity against excess acidity.

GYPSUM

Gypsum is the common name for natural deposits of calcium sulfate that contain 2 molecules of water of crystallization. The word "land-plaster" was once applied to soil-amendment grades of this product. The name arose when knowledge of its value as a soil-improving agent developed from dust falling off the clothes of French workmen on crops along the paths they took to and from the factory where plaster of Paris was being made. This product is calcium sulfate with one-half molecule rather than two molecules of water attached. The completely anhydrous form of calcium sulfate is called anhydrite.

Large quantities of gypsum are being quarried in various parts of the United States, especially in Iowa, Michigan, and New York. It is used not only for the manufacture of plaster of Paris, but as a paint pigment, and as a filler in paper. Commercial gypsum contains about 18 per cent sulfur (S), equivalent to 45 per cent sulfur trioxide (SO_3). The product is not nearly as soluble as sodium or potassium sulfate, yet it dissolves more readily than ordinary limestone. It has value as a source of both sulfur and calcium for plant-nutrient purposes. One of the most interesting uses of this material is in connection with the growing of peanuts. Since this plant is a legume and, therefore, is relatively high in sulfur, it was assumed that the effectiveness of

gypsum on this crop was due to the sulfur it supplied. Study of this problem revealed, however, that no other sulfate was as effective as gypsum. The conclusion was reached that calcium rather than sulfur is the element that is responsible for the good effects. The evidence further shows that gypsum is most effective on soils that are low in



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FIG. 80. Gypsum is commonly applied on peanut foliage at the rate of 500 pounds an acre when first pegs penetrate the ground. Both the calcium and sulfur may have value on this crop.

available calcium, as is commonly true of those on which peanuts are grown.

AMMONIUM SULFATE

Large amounts of ammonium sulfate are still being used in the manufacture of mixed fertilizers. This material contains about 24 per cent sulfur (S), equivalent to 60 per cent sulfur trioxide (SO_3). It is an excellent source of the element for use on near-neutral or alkaline soils, but has the disadvantage of being too strong an acidulating agent for repeated use on acid soils. A considerable amount of work has been done to determine how much acidity is developed in

soils from the use of given amounts of sulfate of ammonia and similar acid-forming fertilizers. One such study indicates that the net effect of such fertilizer salts on the acid-base balance in the soil can be estimated as shown in Table 126. Andrews believes that considerably

TABLE 126

CALCULATION OF REACTION EFFECTS OF FERTILIZERS (PIERRE)

(On Acid-Base Balance in Soil)

Acid Effects	Alkaline Effects
All sulfur	All calcium
All chlorine	All potassium
One-third phosphorus	All magnesium
One-half nitrogen	All sodium

more acidity is developed by nitrogen fertilizers than is indicated by this method of calculation.

POTASSIUM SULFATE

Potassium sulfate, which contains about 20 per cent sulfur, is an excellent source of the element for crop use because of its high solubility. This material is available as such and in the form of mixed sulfates of potassium and magnesium. Sulfate of potash is used in place of the muriate in fertilizers for bright tobaccos and is believed to be preferable for quality citrus, potatoes, and sugar beets. The mixed sulfate is being increasingly employed as a source of magnesium for acid-soil crops in the coastal-plain areas of the United States.

1. Alway, F. J., and Associates. Sufficiency of atmospheric sulfur for maximum crop yields. *Soil Sci. Soc. Amer., Proc.*, Vol. 2, pp. 229–238, 1937.

2. Andrews, W. B. *The Response of Crops and Soils to Fertilizers and Manures.* Published by author, State College, Mississippi, 1947.

3. Clarke, F. W. The data of geochemistry, fifth edition. *U. S. Geol. Survey Bull.* 770, 1924.

4. Colwell, W. E., and Associates. Fertilizing peanuts. North Carolina Agr. Exp. Sta., Bull. 356, 1946.

5. Cooper, H. P., and Committee. Recommendations with reference to the fertilization of flue-cured tobacco grown on average soils in Virginia, North Carolina, South Carolina, Georgia, and Florida for the year 1947. *J. Am. Soc. Agron.*, Vol. 38, pp. 852–853, 1946.

6. Crocker, William. Sulfur deficiency in soils. *Soil Sci.*, Vol. 60, pp. 149–155, 1945.

7. Forbes, E. B., and Associates. Mineral and organic analyses of foods. Ohio Agr. Exp. Sta., Bull. 222, 1910.

8. Hart, E. B., and W. H. Peterson. The sulphur requirements of farm crops in relation to the soil and air supply. Wisconsin Agr. Exp. Sta., Bull. 14, 1911.

9. Lipman, J. G., and A. B. Conybeare. Preliminary note on the inventory and balance sheet of plant nutrients in the United States. New Jersey Agr. Exp. Sta., Bull. 607, 1936.

10. Pierre, W. H. Determination of equivalent acidity and basicity of fertilizers. *Ind. Eng. Chem.*, Vol. 5, p. 229, 1933.

11. Reimer, F. C., and H. V. Tartar. Sulfur as a fertilizer for alfalfa in southern Oregon. Oregon Agr. Exp. Sta., Bull. 163, 1919.

12. Sauchelli, Vincent. Sulfur in the American fertilizer industry (and 8 other papers on sulfur in relation to soils and crops). *Soil Sci.*, Vol. 70, pp. 1–90, 1950.

13. Trelease, Sam F. Selenium in soils, plants, and animals. *Soil Sci.*, Vol. 60, pp. 125–131, 1945.

14. Voelcker, A. On the composition of waters of land drainage. *J. Roy. Agr. Soc.*, Vol. 35, p. 132, 1874.

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Trace Elements

When chemists report analyses of plants, microbes, animals, and man they normally include only 10 elements. These usually constitute more than 99 per cent of the total dry matter. *Often, however, the limiting factor in plant and animal life is a lack of one or more of the 90 other elements that make up the remaining fraction of 1 per cent. This latter group contains a considerable number of trace or minor elements. Of these, the most commonly mentioned in animal and plant nutrition are iodine, cobalt, copper, manganese, zinc, molybdenum, and boron.* A number of other elements are also believed to be of value for at least some species of plants and animals.

The soils of some regions are naturally deficient in one or more trace elements. The earliest example of such a deficiency in the United States was in an area around the Great Lakes, where incidence of goiter and birth of hairless animals were found to be related to the low iodine content of the soil, vegetation, and water. The situation is now being remedied by the use of iodized salt.

Widespread deficiencies of other trace elements have also been observed. Some of these occur naturally, as in the coastal plain soils along the Atlantic Ocean and the Gulf of Mexico. Others are related to erosion and consequent loss of organic matter. Still others were caused by crop removal and have become intensified with increasing agricultural age of the land. Substitution of the automobile and tractor for the horse has played a part. Higher acre yields resulting from the use of improved seed have made greater demands on the soil's supply of these elements. Ever greater purification of the materials that go into the manufacture of fertilizers has added the final touch to the trouble.

Trace elements may be considered either in relation to the specific needs of plants or to the requirements of the animals that consume these plants. Plants are known to need boron, molybdenum, copper, manganese, and zinc. Animals are known to need copper, manganese,

zinc, iodine, and cobalt. It will be noted that the trace-element requirements of animals are not exactly the same as those of plants. This means that they are not necessarily met by growing high acre yields of crops. In fact, as yields of crops are stepped up, the trace-element content of these crops tends to be diluted. This applies not only to iodine and cobalt but to the others as well.

BORON

Boron has been studied to a greater extent than any other trace element required by plants. A large part of the literature on this element deals with the boron content of soils and plants and with de-



Eldrow Reeve, New Jersey Agr. Exp. Sta.

FIG. 81. Boron deficiency, indicated by dwarfed alfalfa in foreground, was remedied by use of 20 pounds borax an acre, as shown by much better growth in background.

scriptions of deficiency symptoms. Most of the boron in soils is in the form of the highly insoluble mineral tourmaline. The total boron content of soil, which normally varies between 40 and 200 pounds in the plow depth of an acre, is not a reliable index of the need for this element in the fertilizer program. Solubility in hot water is the test that is commonly applied. Laboratory and greenhouse studies indicate that a soil should contain not less than 0.35 ppm. boron soluble in hot water. Of 200 samples of soil chosen from an equal number of New Jersey farms, 88 were found to be deficient in boron. Of 20 representative samples of the more important soil types, 8 were found to be deficient in the element. The boron content of plants ranges between 20 and 200 parts per million dry matter.

Marked increases in yield of a considerable variety of crops have been obtained by applications of from 10 to 40 pounds borax, containing 11.34 per cent boron (B), an acre. The effects on alfalfa (Table 127) are noteworthy. In topdressing alfalfa in New Jersey it is now

TABLE 127

EFFECT OF BORAX ON YIELD * ALFALFA ON SASSAFRAS SANDY LOAM (REEVE)

	Pounds Borax per Acre			
	0 Lb.	10 Lb.	20 Lb.	40 Lb.
Robert Jones farm				
First cutting	2337	2175	3135	3661
Second cutting	1719	2119	1888	2495
Third cutting	1119	1270	1530	1625
Total	5175	5564	6553	7681
H. H. Schafer farm				
First cutting	3178	3242	3380	3637
Second cutting	1418	1803	2121	1760
Third cutting	640	898	854	1025
Total	5236	5943	6355	6422

* In pounds oven-dry weight. On hay basis, 10 per cent should be added to these weights.

common practice to apply 500 pounds of 0–12–24 or similar fertilizer containing 100 pounds of borax a ton.

The common symptoms of boron deficiency are yellowing of the tip leaves of alfalfa, black areas inside the main stalks of cabbage, discoloration of the curd of cauliflower, cracked stem in celery, red leaves on ladino clover, unrolled leaves on corn, death of the growing points of lettuce plants, brown spots in the interior of turnips or other root crops, yellowing and curling of tomato leaves, internal cork in apples, and dieback and rosetting of citrus.

MOLYBDENUM

Molybdenum deficiencies have only recently come into notice. Large areas of land in Australia are incapable of growing clover until molybdenum is applied. This element operates as a catalyst in the reduction of atmospheric nitrogen to ammonia by the bacteria in the nodules on the roots of legumes. It is also essential in the reduction of nitrates to ammonia in nonlegume plants.

Fertile soils contain only between 0.2 and 0.6 pound total molybdenum in the plow depth of an acre, of which only a mere trace is soluble in water. In culture solutions, the need for this element can be met by 1 part molybdenum in 1 billion parts of water. The amount required to be applied under conditions of deficiency in the field is of the order of 1 ounce molybdic oxide an acre. This may be applied directly to the seed or it may be added to the soil. Field tests in New



W. J. Hanna, New Jersey Agr. Exp. Sta.

FIG. 82. Molybdenum deficiency in cauliflower is indicated by leaves that consist largely of midribs, with little tissue development. Newer leaves show recovery following use of spray containing 10 p.p.m. of molybdenum.

Jersey, in which sodium molybdate was applied to alfalfa at the rate of 1 pound an acre, resulted in yield increases averaging a little over 13 per cent.

In acid-soil areas, the solubility of most of the minor elements is reduced by liming. Molybdenum differs from the other trace elements, however, in that liming increases its solubility. There is reason to believe that one of the most important effects of liming is, frequently, that of making soil molybdenum available. It is conceivable that 1 ounce of molybdic oxide could be substituted for 1 ton of limestone in such instances.

Some of the most severe cases of molybdenum deficiency are found in high-lime-requirement crops, such as cauliflower, when planted on soils that have been devoted to acid-soil crops, such as potatoes. For example, a New Jersey farmer had a failure on 50 acres of cauliflower that produced no heads. The symptoms of deficiency consisted of a

counterclockwise turning of the newly formed leaves, which later came to consist mostly of the central stems with very little leaf tissue. On subsequent plantings, the situation was remedied by applying sodium molybdate to the young plants in spray form. An application of 1 pound an acre in 50 gallons of water met the requirements. Molybdenum deficiency has been found in a number of other crops, including Florida citrus.

Molybdenum in excess of the plant's requirements tends to be toxic to animals. Most forage plants contain between 1 and 2 parts per million molybdenum on a dry-weight basis (Table 128). But pastures

TABLE 128

TRACE ELEMENT CONTENT ALFALFA * FROM 11 STATES (BEAR)

State	B, P.p.m.	Mo, P.p.m.	Cu, P.p.m.	Mn, P.p.m.	Zn, P.p.m.	Co, P.p.m.
California	60	1.1	14	16	26	0.17
Minnesota	32	0.4	..	39	..	....
New York	28	0.4	..	26	49	0.21
Wisconsin	32	0.3	18	32	41	0.04
Utah	56	1.0	13	19	13	0.12
Kansas	68	1.7	23	30	21	0.02
Colorado	60	2.8	..	10	..	....
Michigan	24	4.0	..	20	..	....
Oklahoma	44	1.3	..	30	..	....
Nebraska	46	0.8	..	26	..	....
			New Jersey			
Soil Series						
Collington	63	2.1	23	14	20	0.07
Washington	18	2.0	27	48	24	0.14
Hunterdon	33	0.1	31	43	..	0.16
Keyport	48	0.2	44	34	23	0.24
Copake	63	4.6	31	33	15	0.15

* On dry-matter basis.

are known in which the molybdenum content of the forage is 20 parts per million or more. On such pastures, the disease known as "teartness" develops. The affected animals have severe scours, their coats become rough, they lose weight, and, unless the situation is corrected, they die. The antidote for molybdenum poisoning is copper sulfate, fed at the rate of 2 grams daily for mature cattle. If the forage contains sufficient copper, no toxicity effects may be noted.

MANGANESE

Manganese is required by both plants and animals. Its deficiency in plants is indicated by dark green veins in the newer leaves and



P. D. Christensen, New Jersey Agr. Exp. Sta.

FIG. 83. Manganese deficiency (left) and toxicity (right) in soybeans growing in nutrient solutions. Optimum growth (second from left) at 0.1 p.p.m. of manganese.

fading of the interveinal tissues. Soils normally contain between 200 and 10,000 pounds of manganese in the plow depth of an acre. If well farmed, they release enough manganese to meet the requirements of plants. In New Jersey most of the manganese deficiency noted to date has been in connection with overliming. In certain market-gardening areas, deficiency of this element is so widespread as a result of excessive use of lime that farmers regularly apply 50 pounds of manganese sulfate an acre as a part of their standard fertilizer program. Manganese deficiency is widely known in various parts of the earth under such descriptive names as "gray speck" of oats, "marsh spot" in field peas, "streak disease" in sugar cane, and "yellow disease" in spinach.

The manganese content of plants may range between 5 parts per million dry weight and several thousand parts. Analyses of over 200 samples of vegetables from 10 states showed that those grown in the West had a much lower manganese content than those from the more acid soils of the East and South (Table 129). Some foods and feeds

TABLE 129

HIGHEST AND LOWEST TRACE ELEMENT VALUES IN VEGETABLES (BEAR)

(In 204 Samples from 10 States)

	B, P.p.m.	Mo, P.p.m.	Cu, P.p.m.	Mn, P.p.m.	Co, P.p.m.	Fe, P.p.m.
Snapbeans						
Highest	73	8.1	69	227	0.26	227
Lowest	10	0.1	3	10	0.00	10
Tomatoes						
Highest	36	1.3	53	68	0.63	1938
Lowest	5	0.0	0	1	0.00	1
Cabbage						
Highest	42	24.1	48	13	0.15	94
Lowest	7	0.0	0.4	2	0.00	20
Spinach						
Highest	88	5.6	32	117	0.25	1584
Lowest	12	0.0	0.5	1	0.20	19
Lettuce						
Highest	37	4.5	60	169	0.19	516
Lowest	6	0.0	3	1	0.00	9

are known to contain too little manganese. It is conceivable that others may contain too much. The amount required by animals is very small, perhaps of the order of 6 parts per million of dry weight of feed. The manganese requirements of man are not known.

Manganese deficiency in animals is best shown in perosis or "slipped tendon" disease of poultry. This is characterized by enlargement of leg joints, displacement of tendons, arrested growth of leg and wing bones, and malformation of the spinal column. Eggs of manganese-deficient hens hatch slowly. Pigs fed a ration low in manganese tend to develop enlarged hocks and crooked legs. Wheat bran is a good source of manganese.

COPPER

One of the most easily recognized copper-deficiency symptoms in plants is dieback in citrus. This is characterized by death of new growth and formation of many side branches below the dead portions.

Gum pockets develop between bark and wood and the fruit shows brown excrescences. Tomatoes growing on copper-deficient soils are dwarfed, the edges of the leaves roll inward, and the plants have a bluish-green appearance. In onions, copper deficiency is evidenced by pale yellow bulbs that lack solidity. Most plants contain less than 10 parts per million copper, on a dry-weight basis, and they normally show copper toxicity at 30 parts per million or more. The copper content of soils normally ranges between 5 and 100 pounds an acre to plow depth.

Plants growing on peat soils are notably responsive to applications of copper sulfate. Normal applications are 10 pounds an acre yearly or heavier doses less frequently. Considerable interest has been aroused in the effects noted from applications of 20 to 50 pounds of copper sulfate an acre for tobacco. Material increases in yield and improvements in saleable quality have been obtained. Often, copper deficiency has no doubt been prevented by the use of Bordeaux-mixture sprays.

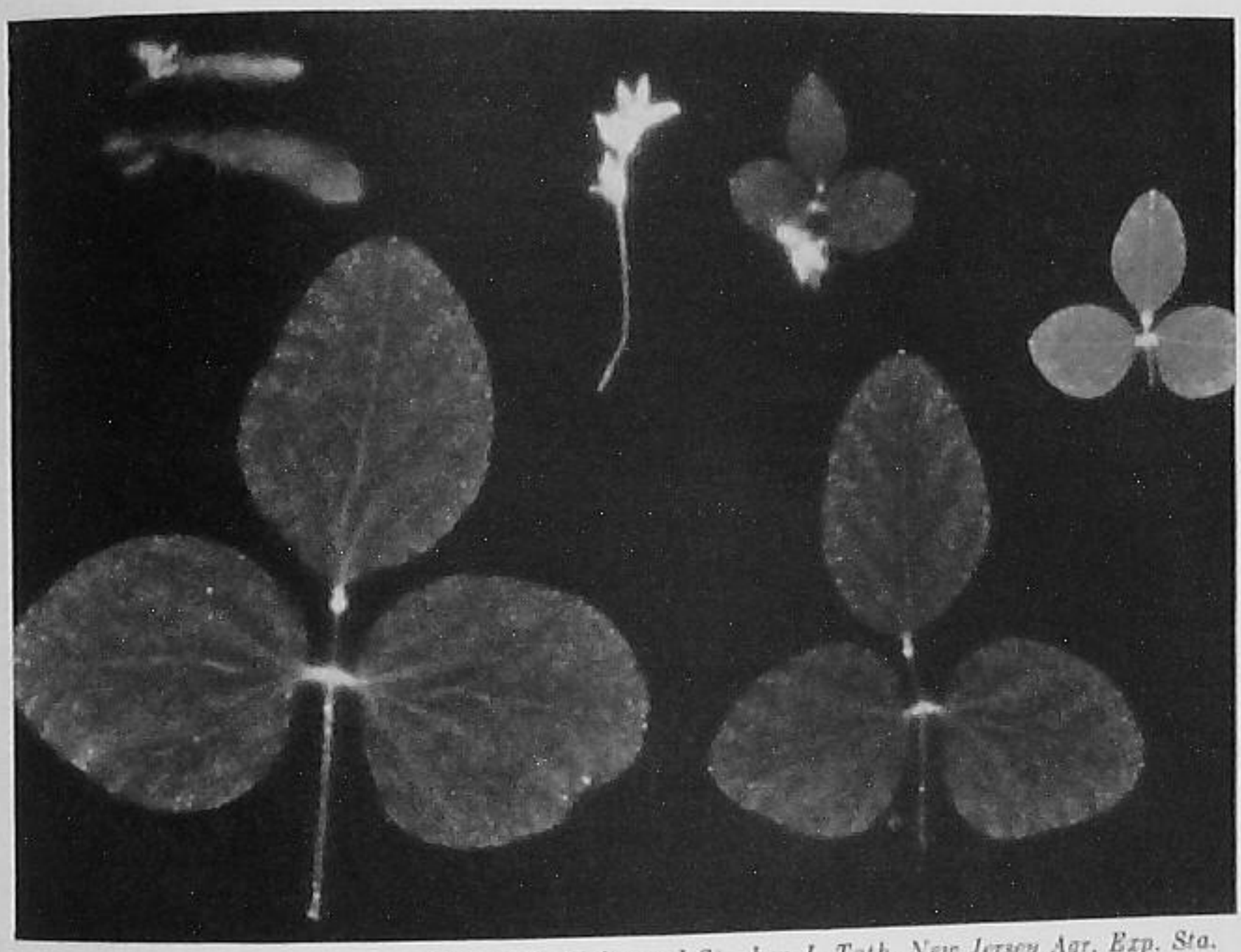
Copper deficiency in animals is characterized by a form of anemia. In copper-deficient areas in Australia, new-born lambs and young sheep suffer from paralysis, which can be prevented by feeding the ewes copper sulfate. In the absence of copper, iron can be absorbed and stored but it cannot be utilized. The copper functions as a catalytic agent or as a necessary part of an enzyme system. It also serves as an antidote against molybdenum poisoning. The livers of new-born animals normally contain more copper than those of older animals. The daily requirement for humans is set at between 1 and 2 milligrams of copper a day.

ZINC

Zinc deficiency in plants was first observed on pecan trees over a wide area in the southern states. The tops of the trees died. Similar deficiencies were noted in tung trees. The most easily recognized symptom of zinc deficiency is shown by corn, which, in the absence of adequate amounts of zinc, produces what is known as "white bud." Plants vary considerably in their zinc requirements, corn, pecans, and citrus having a greater need for this element than alfalfa. The zinc content of plants is usually between 25 and 75 parts per million dry weight. Some weeds, notably ragweed and lamb's quarter, appear to be accumulators of this element. Such weeds may have value as cover crops for plowing-under purposes on zinc-deficient soils. The zinc

content of soils normally ranges between 20 and 500 pounds an acre to plow depth. To overcome deficiencies, zinc sulfate is usually applied at a rate of 10 to 50 pounds an acre.

The human body contains something like 2 grams of zinc, more than that of any other trace element. Zinc-deficient animals tend to develop hyperkeratosis, or thickening of the skin, with loss of hair. It



Shreve S. Woltz and Stephen J. Toth, New Jersey Agr. Exp. Sta.

FIG. 84. Radiograph of soybean leaves showing distribution of Zn^{65}. Note concentration in pulvinus areas, in contrast to absence of Ca^{45} (Fig. 72).

is possible that livestock may suffer from lack of zinc when confined to areas the soils of which are low in this element. Considerable amounts of forage in New Jersey were found to contain relatively small amounts of zinc, ranging between 13 and 25 parts per million dry matter.

Although zinc, manganese, and copper are essential to animals, any deficiency of these elements in the food or feed would normally be met by way of the soil, since plants also require these elements. Nevertheless zinc, manganese, and copper sulfates are [illegible] put in some dairy-cow feeds. It is now common practice to add about 6 ounces of manganese sulfate to every ton of poultry feed as a protective measure against perosis, and small amounts of copper sulfate or carbonate

are added to hog feeds. It has been shown that pigs with no opportunity to root in the soil often suffer from deficiencies of one or more of these elements. One remedy consists in painting the sow's teats with a solution of the salts of these elements.

COBALT

The cobalt content of plants is normally less than 0.1 part per million dry matter. Insofar as is known, the element is not an essential plant nutrient. It is conceivable, however, that more careful work will show that the quantities contained as impurities in nutrient-solution chemicals and in the containers in which the plants are grown are adequate to meet their needs. Extreme care is necessary to avoid contamination with the mere traces of this element that may suffice to meet the needs of plants.

Cobalt deficiency in animals is widespread. It is known variously as "pine disease," "Morton Mains disease," "bush sickness," "salt sickness," "Burton ail," and "Grand Traverse disease." The symptoms include depraved appetite, progressive emaciation, anemia, retarded sexual development, and muscular atrophy. The spleen shrivels. The hair or wool becomes harsh. Sheep are affected more than cattle, and young stock more than old. Sometimes the only evidence of the disease may be the very slow growth of animals or failure to gain weight.

The passing point for cobalt in soils is of the order of 2 parts per million, or about 4 pounds an acre to plow depth. Good forage for sheep should contain 0.07 part per million cobalt, on the dry-matter basis, but somewhat smaller amounts apparently suffice for cattle. The evidence indicates that legumes are higher in cobalt than grasses and that they seldom contain less than 0.07 part per million of cobalt. In proportion as legumes are contained in the forage, cobalt deficiency is less likely to occur. As the manganese content of plants increases, that of cobalt tends to decrease. Similar relationships have been noted between other minor elements.

There is considerable discussion as to whether it is better to add cobalt to the soil so that the element may become an organic part of the plant, or whether it should be fed directly to animals. The normal rate of application of cobalt sulfate to pastures is 2 to 4 ounces an acre annually, in comparison with about 2 grams of the salt, which is what is being added to each ton of large amounts of grain feed for cows. The economy of putting it in the feed is apparent, the cost of this being of the order of ¼ cent a ton.

Insofar as cows and other ruminants are concerned, direct addition of the mineral salt to the feed is entirely satisfactory. The cow's rumen is a living factory where feed is digested and new products are synthesized. In this environment, vitamin B_{12}, of which cobalt is an essential constituent, is produced. With man and other non-ruminants, the bacteria of the lower intestine may accomplish much the same purpose as those in the rumen of the cow. Some of the antibiotics, by reducing the activities of the microorganisms of the intestinal tract, have been shown to lower the synthesis of certain vitamins, with resulting faulty nutrition. It is of interest in this connection that, by adding cobalt, *Streptomyces griseus* produces not only streptomycin but vitamin B_{12} in commercial quantities as well.

MISCELLANEOUS ELEMENTS

A considerable number of trace elements, in addition to the seven mentioned at the beginning of this chapter, should be considered. These include iron, aluminum, nickel, fluorine, bromine, chlorine, and silicon. All of these have effects on plants or animals or both. However, except for iron, their possible functions or values have not been as definitely established as one would like.

The iron requirements of plants are relatively small but the element is essential in connection with the development and activity of chlorophyll in plants and hemoglobin in animals. Deficiency results in serious chlorosis of plants, with termination of growth, and it causes anemia in animals. Since the iron content of soils normally ranges between 0.5 and 5 per cent, deficiency does not often develop except in irrigated arid areas where *p*H values are high and the availability of iron is low. Iron deficiency is also troublesome in soils that are high in manganese, such as those in the Hawaiian Islands.

Iron is much more available to plants in the reduced than in the oxidized state. Reduction can readily be brought about by decomposition of organic matter, especially under conditions of poor drainage. The gray-green discoloration of poorly drained subsoils is due to reduced iron. Wet soils may contain so much ferrous iron at low *p*H values as to be toxic to plants.

Iron deficiency is controlled by spraying plant leaves with a 1 or 2 per cent solution of ferrous sulfate, by injecting iron phosphate into holes that are bored into the trunks of trees, by driving iron nails into trees, by placing ferrous sulfate in soil pockets under the spread of tree branches, or by acidulating the soil. The *chelated forms of iron*

have been found much more effective than others. A chelating agent, of which ethylenediaminetetraacetic acid is an example, has the capacity to combine with metals and hold them in a nonionized form from which they cannot be precipitated.

Soil normally contains more aluminum than iron, the aluminum content ranging between 1 and 7 per cent. Lateritic soils often contain much larger amounts of both aluminum and iron than soils of the temperate regions, the oxides of these two elements sometimes constituting between 60 and 80 per cent of the soil.

Insofar as is known, aluminum is not essential to crop plants or farm animals. But it tends to accumulate in plants growing on acid soils. The explanation of this injury has been variously explained as being due to toxicity, to substitution of the aluminum for some similar essential element, and to its action as a precipitant of phosphates, either in the soil or in the plant. The remedy for excess aluminum lies in liming the soil to a *p*H value between 6.0 and 6.5. Excess liming beyond the neutral point increases the solubility of aluminum. If the crop requires an acid soil, the solution lies in the use of extra quantities of soluble phosphate as a precipitant.

Aluminum sulfate is frequently used, at rates of 5 to 10 pounds for 100 square feet, as an acidulating agent in soils, notably for such plants as mountain laurel, azaleas, and rhododendrons. As to whether the aluminum itself is of value to these plants is not known. Some plants, of which the hickory tree is an example, accumulate large amounts of aluminum as the succinate.

Traces of nickel are commonly found in plants and animals, but evidence of essentiality of this element is lacking. It has been reported that nickel has value in alleviating Morton Mains disease when cobalt is lacking. There are some indications that nickel is stimulative to plants at very dilute concentrations, but it is quite toxic at 5 parts per million of nutrient solution.

The normal nickel content of plants ranges between 0.1 and 5 parts per million dry matter. New Jersey soils contain between 2 and 40 parts per million nickel. Soils of serpentine origin have been found to contain as much as 500 parts per million of the element and this, rather than excess magnesium, may account for their notable lack of productivity.

The iodine content of New Jersey soils ranges between a mere trace and 12 parts per million. That of crop plants ranges between 0.1 and 5 parts per million dry matter. Most crop plants contain less than 1 part per million iodine but concentrations of 2000 parts per million

were developed in plants growing in nutrient solutions to which potassium iodide had been added. Iodine deficiency could not be developed in carefully controlled tests, and no improvement in yield was effected by addition of an iodide to the culture solution.

The fluorine content of New Jersey soils ranges between 30 and 400 parts per million. It tends to increase with depth. The fluorine content of fertilized soils tends to be higher than that of soils that have not been fertilized. A considerable part of the fluorine in soils of industrial areas is brought to the earth in the rainfall. In some such areas extensive damage to crops has resulted both by direct action of the fumes and through absorption by plants by way of the soil. The availability of soluble soil fluorine is readily reduced below the toxic limit by liming the soil to *p*H values of 6.5.

The fluorine content of New Jersey plants normally ranges between 15 and 20 parts per million. Certain trees, notably mulberry, dogwood, and willow, are fluorine accumulators. Plant uptake of the element bears little relationship to that of the soil on which the plant grows. Among the most sensitive plants to fluorine toxicity are sweet potato, white pine, and gladiolus. Ragweed is highly resistant to fluorine injury. There is no conclusive evidence that the element is required by plants. It is known to be essential to animals but the quantity needed is very small. The recommended concentration of fluorine in drinking water is 1 part per million.

Work with bromine has given no evidence of its essentiality to plants. Examination of forage plants showed that none contained over 7 parts per million bromine. Tomatoes grown in nutrient solution to which potassium bromide had been added accumulated up to 6300 parts per million of the element without evidence of injury to the plants.

The chlorine content of soils in humid regions is of the order of 0.01 per cent. It is mainly in the form of residues from manures and fertilizers. In saline soils having high salt contents the chlorine content may be much greater. Chlorine is applied to soils in considerable amounts in such salts as potassium, sodium, and magnesium chlorides.

Evidence on the value of chlorine to plants is conflicting. In general, potassium chloride is as effective as the sulfate, and often more so, insofar as crop yields are concerned. When crop quality is considered, however, the case for the chloride is not so satisfactory. Thus, tobacco to which potassium chloride has been applied often has poor color, slow and irregular burning quality, and does not keep well.

Producers of fine tobacco are asked not to use more than 2 per cent chlorine in the fertilizer mixtures.

Similarly, there is evidence of poorer quality in potatoes and sugar beets from the use of potassium chloride than when sulfate, carbonate, or nitrate of potash was used. The reports on this subject are conflicting. In general, however, the chloride gives a potato with less mealiness, and sugar beets produced by its use tend to have a lower content of sugar than when the sulfate is used.

The chlorine in plants, like that in soils, is largely water-soluble. It ranges from a mere trace to more than 5 per cent. The plant tends to absorb large amounts of the element if available to it. The chlorine ion tends to increase the concentration of cell sap and thus to increase water uptake. In proportion as more chlorine is absorbed by plants, their content of nitrogen, phosphorus, and sulfur will tend to be lowered, in conformity with the principle of *anion-equivalent constancy*.

Silicon constitutes a considerable part of the ash of some species of plants. The grasses are notably high in this element. The corn plant may contain more silicon than potassium. The straw of wheat has a silicon content of about 1 per cent. That of wheat grain is about 0.35 per cent. It is easy to understand why crop plants growing in the field would contain considerable amounts of this element, since the soil itself normally contains silicon equivalent to between 65 and 95 per cent silica (SiO_2). Even when plants are grown in culture solutions, the glass or crockery containing the solutions will release considerable amounts of silicon to them.

The evidence on the usefulness of silicon to plants is conflicting, but there is reason to believe that the element may have some special value in plants that contain large amounts of it. There is some evidence that silicon may be a partial substitute for phosphorus in plants or that, in the form of a soluble silicate, its application to the soil may release adsorbed phosphate for plant use. The element merits more study than has been given it.

SUPPLYING TRACE ELEMENTS FOR PLANT NEEDS

Usually some soluble salt of the specific trace element in deficiency is applied to the soil. This is standard practice in overcoming boron deficiencies, in which case borax is normally used for direct application to the soil. But some of the heavier soils, and especially those that are naturally high in lime or that have been heavily limed, have very high

fixing powers for the metallic trace elements. Under such circumstances, it is common practice to apply them in spray form. In such cases, repeated applications may be required during the crop season.

Much interest has been aroused in the use of mixtures of trace-element salts as a safety factor against possible deficiency of any one



Photograph and fertilizer suggestions by A. F. Camp, Citrus Exp. Sta., Lake Alfred, Florida

FIG. 85. Citrus trees are good foragers for soil P. They have high Mg, Zn, and Cu requirements. Mn and B are frequently deficient. For acid, sandy, leached soils general recommendations are to supply N, P_2O_5, K_2O, and MgO in ratios 4:4:7:3, respectively, in available forms. Based on above values, good practice calls for use of MnO, CuO, and ZnO in values of ½:¼:¼, respectively, as sulfates. For trees on soils of high fixing-capacity, trace elements may be applied as sprays at 3 pounds each of sulfates, neutralized with lime, in 100 gallons of water, either pre- or post-bloom. If boron is deficient, 1 pound of borax in 100 gallons of water is applied as post-bloom spray. Dolomitic lime is used to maintain soil *p*H value at 5.5.

or all of them. Such mixtures are being offered for sale for inclusion in complete fertilizers, for separate application in dry form, and for use in sprays. There is some merit to such general use of these elements, but there is likely to be considerable waste, since many soils are abundantly supplied with all of the trace elements, even to the point of excess of some of them.

Recently, considerable interest has been aroused in *fritted trace elements*. These are silicate forms, the rate of solubility of which can

be controlled by the method of manufacture. The thought in this procedure is to supply the elements in a form that will yield them up gradually to the crop. This avoids abnormally high dosages at the start and greatly reduces fixation by the soil. One such product contains 2.5 per cent manganese, 7 per cent iron, 3.2 per cent zinc, 3.2 per cent copper, 0.7 per cent boron, and 0.13 per cent molybdenum. The suggested rate of application is 100 pounds an acre.

Another development is the use of chelated forms of trace elements. Most of these are nonionized metallic salts of ethylenediaminetetraacetic acid, known as EDTA. Soils have very little capacity to remove such elements from solution. As to just how the chelated element passes into the plant and is delivered to the point of need is not known. But it has been shown that as little as 1 gram of the element in such a product can replace as much as 1 pound of the sulfate form of the element, when applied by way of the soil.

TRACE ELEMENTS IN ORGANIC MATTER

A great deal of publicity has been given to *organic farming*, as distinct from the type in which use is made of chemical fertilizers. In the organic system, dependence is placed on manures and composts. In proportion as these organic materials can be accumulated and used, the available supply of minor elements in soils can be maintained at higher levels than would be possible without specific additions of salts of these elements to the soil (Table 130). This is especially true in connection with the use of garden composts and sewage sludges that contain residues of plant products from all over the earth. Sewage sludges contain trace elements in the form of medicinals and by-products of chemical industries, sometimes in concentrations so high as to be injurious to plants growing on the soil to which they are applied.

Most agricultural experiment stations now have one or more research projects that involve trace elements. At the New Jersey Agricultural Experiment Station, for example, studies on boron, molybdenum, zinc, copper, manganese, cobalt, iodine, nickel, and fluorine are under way (Table 131). Use is being made of radioactive forms of most of these elements. Similarly, the several bureaus of the United States Department of Agriculture are concerned with this problem. The United States Plant, Soil, and Nutrition Laboratory at Ithaca, New York, is engaged primarily in the study of trace elements in relation to plant and animal nutrition. Johns Hopkins University is con-

TABLE 130

MINOR ELEMENTS IN VARIOUS TYPES ORGANIC MATTER (BEAR)

Material	B, P.p.m.	Mo, P.p.m.	Cu, P.p.m.	Mn, P.p.m.	Zn, P.p.m.	Co, P.p.m.
Miscellaneous Sources						
Alfalfa compost	70	2.0	42	260	..	0.11
Lignin	10	0.3	101	10	24	0.00
Peach-tree clippings	30	0.2	13	15	85	0.17
Oak shavings	8	0.3	5	7	19	0.02
Hyperhumus (peat)	13	2.1	7	110	20	0.02
Cornstalks	15	0.4	12	25	66	0.02
Wheat straw	15	0.5	8	47	32	....
Grown on Sassafras Loam						
Bean tops	50	1.6	20	50	112	0.64
Carrot tops	30	0.9	18	120	163	0.38
Rye	15	1.5	12	48	93	0.30
Rye and vetch	90	3.4	17	90	263	0.72
Ryegrass	15	2.9	19	80	123	0.76
Grown on Collington Loam						
Bean tops	75	2.2	19	40	551	0.24
Carrot tops	56	0.8	18	160	460	0.28
Rye	30	1.1	15	32	456	0.20
Rye and vetch	100	11.1	16	80	465	1.32
Ryegrass	30	2.4	20	80	175	0.30

ducting an intensive research program on the functions of these elements. A number of commercial laboratories are being financed by industry in their study. Producers of pharmaceuticals are attempting to determine the importance of these elements as constituents of medicines, and the same applies to the manufacturers of feeds.

It is apparent that a great many people are concerned with one or another phase of the trace-element problem. The most complete picture of the undertakings in this field of research is contained in a 1087-page volume entitled *Bibliography of the Literature on Minor Elements and Their Relation to Plant and Animal Nutrition*, which was published in 1947. That volume contains abstracts from some 10,000 papers covering forty-five elements. Volume 2, published in 1951, contains 1200 additional abstracts.

TABLE 131

Trace-Element Content of 20 Important New Jersey Soils (Bear)

(Samples Chosen from *A* Horizons)

Soil Type	Mn, P.p.m.	Zn, P.p.m.	Cu, P.p.m.	Co, P.p.m.	Mo, P.p.m.	Ni, P.p.m.	B, P.p.m.	I, P.p.m.	F, P.p.m.
Norton silt loam	5200	225	39	30.8	2.2	40	110	12.1	220
Lawrenceville silt loam	1850	45	16	6.1	2.1	12	75	8.2	161
Rockaway stony loam	1300	132	24	9.8	1.8	19	20	4.6	156
Annandale loam	1250	94	60	18.2	2.3	19	27	1.8	110
Washington loam	1120	156	22	8.6	...	17	...	8.0	...
Rockport shale loam	960	105	37	11.6	...	24	...	4.5	...
Palmyra gravelly loam	950	89	12	4.7	2.3	14	25	3.9	249
Bermudian silt loam	900	95	40	11.5	2.1	32	70	4.9	166
Hazen stony loam	600	101	25	8.2	2.0	19	40	1.2	409
Squires loam	580	25	18	4.3	2.3	16	30	0.0	220
Dutchess shale loam	570	77	14	6.6	3.3	15	50	6.2	370
Hoosic gravelly loam	330	92	16	6.3	1.9	23	55	2.4	285
Matapeake loam	210	70	12	3.2	2.2	12	55	1.6	111
Sassafras gravelly loam	200	16	2	0.6	...	3	...	4.0	...
Whippany silty clay loam	160	67	8	4.3	1.5	11	30	2.3	201
Colts Neck sandy loam	160	43	7	1.9	1.6	9	50	4.7	105
Collington loam	160	69	11	2.5	1.8	8	65	2.8	107
Woodstown silty clay loam	150	32	6	1.9	...	10	...	3.6	...
Lakewood sand	120	10	2	0.2	0.8	2	18	0.0	29
Evesboro loamy sand	90	50	19	2.8	1.2	14	30	1.5	105

SELECTED REFERENCES

1. Bear, Firman E., and Associates. Variation in mineral composition of vegetables. *Soil Sci. Soc. Amer., Proc.*, Vol. 13, pp. 380–384, 1948.

2. Bear, Firman E., and Arthur L. Prince. Organic matter in New Jersey soils. New Jersey Agr. Exp. Sta., Bull. 757, 1951.

3. Bear, Firman E., and Arthur Wallace. Alfalfa, its mineral requirements and chemical composition. New Jersey Agr. Exp. Sta., Bull. 748, 1950.

4. Beeson, K. C., and Associates. Factors affecting the nutritive value of foods. *U. S. Dept. Agr. Publ.* No. 64, 1948.

5. Brewer, H. S. *Bibliography of the Literature on Minor Elements and Their Relation to Plant and Animal Nutrition,* fourth edition. Vols. 1 and 2. Chilean Nitrate Educational Bureau, New York, 1948, 1951.

6. Evans, H. J., and Associates. Molybdenum nutrition in alfalfa. *Plant Phys.*, Vol. 25, pp. 555–566, 1950.

7. Evans, H. J., and E. R. Purvis. Molybdenum status of some New Jersey soils with respect to alfalfa production. *Agron. J.*, Vol. 48, pp. 70–71, 1951.

8. Gilbert, Frank A. *Mineral Nutrition of Plants and Animals.* University of Oklahoma Press, Norman, 1948.

9. Monier-Williams, G. W. *Trace Elements in Food.* John Wiley & Sons, New York, 1949.

10. Reeve, Eldrow, and Associates. The boron needs of New Jersey soils. New Jersey Agr. Exp. Sta., Bull. 709, 1948.

11. Stiles, Walter. *Trace Elements in Plants and Animals.* The Macmillan Co., New York, 1946.

12. Shive, John W. Boron in plant life (with twenty other papers on trace elements). *Soil Sci.,* Vol. 60, pp. 1–189, 1945.

13. Stewart, Ivan, and C. D. Leonard. Iron chlorosis—its possible causes and control. *Citrus Magazine,* June, 1952.

14. Wynd, F. L., and Roy A. Bowden. Availability to wheat plants of iron in very insoluble glass frits (with three other related papers). *Lloydia,* Vol. 14, pp. 1–57, 1951.

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Mixed Fertilizers

The mixed-fertilizer industry has enjoyed its greatest popularity in the United States. Farmers of European countries have long purchased fertilizer materials as such, either applying them separately or mixing them on the farm before applying them. In this country, however, a new industry was established, the function of which was to assemble the necessary materials from all over the earth and to mix them together in such proportions as are required in the production of high acre yields of crops, under the wide variety of soil, climatic, and economic conditions that obtain.

A serious objection to the use of mixed fertilizers was soon found. 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 producers of high-quality products without fear of immediate discovery by the farmer.

FERTILIZER CONTROL

As a result, it became necessary to develop controls. Each state now has a state chemist whose function is to collect samples of fertilizer, wherever they may appear on the market or farm, and submit them to analysis. *Each bag or other container is required to carry a printed guarantee as to the percentages of the several ingredients claimed to be contained in it. If the analysis of the state chemist shows a deficiency in relation to this guarantee, fines are assessed.* The laws of the several states with reference to fertilizer control are now fairly well standardized.

Because of the many problems involved in sampling and analyzing fertilizers, as well as prepared feeds, fungicides, insecticides and other products designed for use by farmers, it was found desirable to form the Association of Official Agricultural Chemists. This association has developed official methods of analysis that are now in general use, both by control officials and by industry.

Analyses of complete fertilizers are reported in terms of total nitrogen, available phosphoric acid, and water-soluble potash, in the order indicated. The primary problem is experienced in determining the quality of the various types of organic nitrogen that may have been used in formulating the mixture. These organic sources of nitrogen are widely employed for the dual purpose of conditioning the fertilizer and supplying an organic form of nitrogen. Many claims are made as to the special value of this organic nitrogen because of its slower rate of becoming available to plants. The thought is to have the nitrogen become available for use more or less in proportion to the plant's need for it.

There is very little dependable evidence of any special value of such organic nitrogen, but there are many who adhere to the idea, notwithstanding. The problem remains, however, of determining whether the particular form of organic nitrogen used in the mixture has a relatively high or low rate of availability. The nitrogen in some organics is of such a low degree of availability in the soil that they are processed by addition of sulfuric acid. They may be mixed with the phosphate rock and the sulfuric acid may then be added to both. After many years of study of the problem, methods have been developed for testing the quality of organic nitrogen, and these are being applied to greater or less degree in the several states. The problem is much less troublesome now than formerly, since the supply of organic wastes available for use in fertilizers is relatively limited. Most of the nitrogen in fertilizers is in mineral form or consists of such synthetic organics as calcium cyanamide and urea.

The test for availability of the phosphoric acid in fertilizers consists merely in digestion of the sample in a neutral solution of ammonium citrate at 65° C. For basic slag, a 1-per cent citric acid solution is used. For rock phosphate and bonemeal, only totals are usually reported, although from 5 to 10 per cent of the total P_2O_5 in the rock will dissolve in neutral citrate solution, and about 65 per cent of that in bonemeal. The test for potash is simply one of solubility in hot water.

FORMULATION OF MIXED FERTILIZERS

The fertilizer industry is now largely a chemical industry, one of the largest such industries in the world. Mixed fertilizers are made of relatively few materials. Their nitrogen is derived mostly from anhydrous ammonia, nitrogen solutions, sulfate of ammonia, am-

monium nitrate, calcium cyanamide, and urea, often with some organic ammoniate for conditioning purposes. The phosphoric acid is derived mostly from superphosphate, double superphosphate, and ammonium phosphate, occasionally supplemented with bone or bird guano. The potash is derived mostly from muriate of potash, but use is also made of sulfate of potash and sulfate of potash-magnesia.

In addition to these standard chemical materials, a considerable variety of conditioning agents is employed. These include not only organic wastes and dolomitic limestone but various other products that are added as an aid to granulation or as diluents to make the formulas conform as closely as possible to the guarantees. Dolomitic limestone has both a conditioning value and an acidity-correcting value.

When fertilizer materials are mixed they normally undergo some reaction, depending upon moisture conditions, temperature, the size of the pile, and the fineness of the particles. Double decomposition often occurs, such, for example, as the formation of potassium nitrate and ammonium chloride from ammonium nitrate and potassium chloride. Some compounds enter into neutralization reactions and others are hydrated. Some products decompose.

AMMONIATION OF SUPERPHOSPHATE

One of the most interesting developments in modern fertilizer manufacture is that of ammoniation of superphosphate. It is now common practice to add 50 to 60 pounds of ammonia gas to each ton of superphosphate, which is thus made to serve as a free carrier of nitrogen. As a result of this neutralizing reaction a considerable amount of heat is developed. Each pound of ammonia added will raise the temperature of the superphosphate about 1.7° F. per ton. If the temperature of the pile passes 140° F., loss of ammonia into the atmosphere may result, and the availability of the phosphoric acid in the superphosphate will be reduced. Most of this phosphoric acid exists in the monocalcium, or water-soluble, form. The effect of excessive ammoniation is to change some of this to dicalcium phosphate, which is completely soluble only in the neutral ammonium citrate solution. At still higher ammoniation and temperatures some of the phosphate will not dissolve either in water or in ammonium citrate. This presents no problem to the consumer, who is protected by the control chemist's tests, but it means a loss to the producer. Difficulty along

this line is being overcome through installations that effect rapid cooling of the ammoniated superphosphate.

Producers of ammonia supply it to fertilizer manufacturers either as such or in the form of ammoniating solutions. One company has advertized seven such solutions (Table 132). An example of a com-

TABLE 132

COMPOSITION OF AMMONIA SOLUTIONS (BARRETT)

Solution	NH_3, Per Cent	NH_4NO_3, Per Cent	H_2O, Per Cent	Total N, Per Cent
2A	21.7	65.0	13.3	40.6
3	26.0	55.5	18.5	40.8
4	16.6	66.8	16.6	37.0
5	30.0	0.0	70.0	24.6
6	34.0	60.0	6.0	49.0
7	100.0	0.0	0.0	82.2

plete-fertilizer formula produced by such a procedure is shown in Table 133.

TABLE 133

COMPLETE FERTILIZER FORMULATED WITH AMMONIA SOLUTION (CHUCKA)

(One Ton 5–10–10)

Material	Analysis, Per Cent	Quantity, Lb.	N, Per Cent	P_2O_5, Per Cent	K_2O, Per Cent
Ammonia solution	40.6 N	100	2.03	.....	.....
Ammonium sulfate	20.8 N	286	2.97	.....	.....
Superphosphate	19.0 P_2O_5	1053	....	10.00	.....
Muriate potash	60.0 K_2O	334	....	.....	10.00
To complete ton	.....	227	....	.....	.....
Total		2000	5.00	10.00	10.00

In order to avoid the use of the 227 pounds of material indicated as being required to make the weight up to 1 ton, a somewhat different mixture can be employed, as shown in Table 134.

POPULAR FERTILIZER GRADES

The 5–10–10 is one of the most popular complete fertilizer grades in the more intensive farming areas of the eastern part of the United States. It is apparent, however, that a considerable number of grades is required to meet the needs of farmers the country over. The ones

TABLE 134

COMPLETE FERTILIZER CONTAINING DOUBLE SUPERPHOSPHATE (CHUCKA)

(One Ton 6–12–12)

Material	Analysis, Per Cent	Quantity, Lb.	N, Per Cent	P_2O_5, Per Cent	K_2O, Per Cent
Ammonia solution	40.6 N	150	3.04	.....	.....
Ammonium sulfate	20.8 N	285	2.96	.....	.....
Superphosphate	19.0 P_2O_5	925	....	8.78	.....
Double super.	46.0 P_2O_5	140	....	3.22	.....
Muriate potash	60.0 K_2O	400	....	.....	12.00
Conditioner	.....	100	....	.....	.....
Total		2000	6	12	12

in most common use are shown in Table 135. Many of these grades contain much lower total percentages of N, P_2O_5, and K_2O than would appear to be economic.

TABLE 135

PRINCIPAL FERTILIZER GRADES USED IN UNITED STATES (MILES)

Region	Grade	Grade	Grade	Grade	Grade
New England	5–10–10	6– 9–12	5– 8– 7	0–14–14	8–12– 6
Middle Atlantic	3–12– 6	5–10–10	5–10– 5	4–12– 8	4– 8–12
South Atlantic	4–10– 6	3– 9– 6	4– 8– 6	3–12– 6	3– 9– 9
East North Central	2–12– 6	3–12–12	0–12–12	3–18– 9	4–12– 8
West North Central	2–12– 6	4–12– 4	3–12–12	4–16– 0	4–24–12
East South Central	6– 8– 4	4–10– 7	5–10– 5	3– 9– 6	2–12– 6
West South Central	5–10– 5	4–12– 4	6– 8–12	3– 9–18	8– 8– 8
Mountain States	10–10– 0	10–20– 0	6–30– 0	10–16– 8	10–10– 5
Pacific Coast	10–10– 5	17– 7– 0	8– 8– 4	6–10– 4	8–10–12

The general tendencies are toward nearly equal percentages of N, P_2O_5, and K_2O in the eastern states, higher percentages of P_2O_5 in the north-central states, and still higher precentages of P_2O_5 and lower percentages of K_2O in the mountain and Pacific coast states. Extra N is used for sidedressing and topdressing purposes the country over, but notably in the southern states and in the intensive vegetable-growing areas. However, rapid spread in the use of nitrogen sidedressings and topdressings is certain in the corn, wheat, and dairy-cow areas.

In the country as a whole, the trend is toward higher percentages of N and K_2O, with P_2O_5 tending to remain constant (Table 136). If the tendency toward marked increase in consumption of nitrogen fer-

TABLE 136

AVERAGE AMOUNTS N, P_2O_5, AND K_2O IN FERTILIZERS U.S.A. (MEHRING)

Year	N, Per Cent	P_2O_5, Per Cent	K_2O, Per Cent	Total, Per Cent	Total, Tons
1900	2.00	9.40	2.50	13.90	394,000
1910	2.10	9.30	3.40	14.80	856,000
1920	2.30	9.20	2.40	13.90	1,145,000
1930	3.10	9.80	5.00	17.90	1,523,000
1940	3.76	9.61	6.37	19.74	1,766,000
1949	4.10	10.60	7.30	22.00	2,673,000

tilizer materials is considered separately, it would appear that the movement is in the direction of the use of N, P_2O_5, and K_2O in a 1–1–1 ratio, such as would be exemplified in a 5–10–10 grade with extra N for sidedressing purposes, or a 10–10–10, all applied at one time, as in fertilizing grass crops. In this connection it is interesting to note that world production (1948–49) of fertilizer nitrogen is estimated at 3,353,000 metric tons N, phosphoric acid at 5 million metric tons P_2O_5, and potash at 3,152,000 metric tons K_2O.

HIGH-ANALYSIS FERTILIZERS

The manufacture of a 10–10–10 grade of fertilizer, a more concentrated mixture than is commonly used, is readily accomplished. It can be done either through the use of dry materials or by employing nitrogen solution. One of the latter formulas is shown in Table 137.

In proportion as percentages of the three primary nutrients are raised to higher levels, several problems are presented. Among these

TABLE 137

HIGH ANALYSIS COMPLETE FERTILIZER (LOCKWOOD)

(One Ton 10–10–10)

Material	Analysis, Per Cent	Quantity, Lb.	N, Per Cent	P_2O_5, Per Cent	K_2O, Per Cent
Ammonia solution	40.6 N	150	3.05	.....	.....
Ammonium sulfate	20.8 N	690	7.18	.....	.....
Superphosphate	19.6 P_2O_5	330	.....	3.26	.....
Double super.	47.0 P_2O_5	300	.....	7.0[illegible]	.....
Muriate potash	61.0 K_2O	330	.....	.....	10.07
Dolomite	$CaMg(CO_3)_2$	100	.....	.....	.....
Tobacco stems	N + K_2O	100	0.08	.....	0.30
Total		2000	10.31	10.31	10.37

may be mentioned the matter of condition of the fertilizer, the acidity of the mixture, and the elimination of ingredients other than N, P_2O_5, and K_2O. The problem of condition is being solved by two methods, one of which involves adequate factory controls and the other granulation. It is probably that much additional attention will be paid to granulation of complete fertilizers in due time.

The problem of acidity is related largely to the nitrogen content of the fertilizer. Most of the nitrogen materials and solutions have an acid effect on the soil (Table 84). The potential acidity in 1 ton of high-analysis fertilizer is normally higher than that of 1 ton of a lower-analysis grade. But the acidity a pound of nitrogen is often less. The same applies to salt concentration, which may be troublesome on the sandier types of soils and at the higher rates of application.

The elimination of various ingredients through concentration applies especially to the gypsum of ordinary superphosphate and the several sodium, calcium, and magnesium salts that are discarded in the production of high-grade muriate of potash. All these salts have value. As to exactly how much value they have depends upon many conditions. Suffice it to say that each has been shown to produce very marked increases in crop yields under conditions of deficiency of elements they contain, such as sodium, magnesium, and sulfur.

In general, the tendency is toward a higher degree of concentration of N, P_2O_5, and K_2O in fertilizers, notwithstanding the resulting elimination of extraneous materials that may have considerable value. The assumption is that, in proportion as need for other elements develops, these elements will be added to the fertilizer mixture or they will be applied separately, as conditions may require. High freight costs make it imperative to reduce the tonnage of fertilizers as much as possible. Sometimes, the concentrated grades meet all the requirements. But the increasing tendency toward deficiencies of magnesium, sulfur, boron, molybdenum, copper, manganese, zinc, cobalt, and iodine makes the problem of producing "complete" fertilizers an ever more complicated one.

FERTILIZERS FOR SPECIAL USES

A development of considerable interest in this connection is that of formulating fertilizers that are to be used not only to supply the needed nutrient elements but to serve as pesticides as well. Thus, some companies are producing mixtures that contain weed killers, such as 2,4-D. Others are adding insecticides, such as DDT and BHC. Still

others are including fungicides, such as the salts of mercury, copper, and zinc. Some of the fertilizer materials have value in this connection. This is notably true of calcium cyanamide, which is often used as a weed killer; kainite, which is frequently employed in conjunction with cyanamide; and sulfate of ammonia, which is used to lower soil *p*H values in the control of potato scab.

Because of the scarcity of organic fertilizer materials, considerable effort is being made to accumulate such products for use in fertilizer mixtures. Part of the demand for these is explained by their highly important conditioning properties. But part of it lies in the belief on the part of both producers and consumers that organic materials add value *per se* to the fertilizer mixture. Most of these organic materials fall primarily into the nitrogen group. The percentage of total nitrogen in organic form in mixed fertilizers in the United States is shown in Table 138.

TABLE 138

PERCENTAGES OF N IN VARIOUS FORMS IN FERTILIZERS (MEHRING)

Year	Ammonium	Nitrate	Natural Organic	Synthetic Organic
1900	2.1	6.9	91.0	0
1909	16.1	16.2	67.7	0
1919	23.8	19.7	53.6	2.9
1929	48.2	19.0	22.2	10.6
1939	58.2	15.6	15.3	10.9
1949	72.0	18.0	4.3	5.7

In acid-soil areas there has been considerable tendency toward adding liming materials, including cyanamide, dolomite, limestone, and hydrated lime, to fertilizers. It would seem more logical to merely increase the amount of liming material as such that needs to be applied to the soil in these areas. The case for dolomite and high-magnesium hydrated limes has special merit, since they supply magnesium, the need for which is fairly widespread.

In contrast, considerable areas of alkaline soil exist that require supplemental use of sulfur as an acidulating agent. The use of liquid phosphoric acid in irrigation streams is another example. For many purposes, merely supplying nitrogen in the form of sulfate of ammonia meets the requirements. For small-garden needs, considerable use is made of iron and aluminum sulfates. Mehring estimates the neutralizing value of a pound of hydrated aluminum sulfate at 0.45 pound $CaCO_3$, in comparison with that of elemental S at 3.12 pounds.

Gypsum is another very useful material in alkali soils. It reacts with sodium carbonate to produce the relatively insoluble calcium carbonate and the less harmful sodium sulfate. Large tonnages of gypsum are used for this purpose and for replacing sodium in the exchange complex of alkali soils. This is one of the fundamental steps in reclaiming alkali soils, irrigation water being used to carry the re-



(*a*) (*b*)

FIG. 86. The cotton crop is a large consumer of fertilizer, and produces heavy yields of lint when liberally supplied with a well-balanced mixture. (*a*) 6–8–6 fertilizer. (*b*) No fertilizer.

sulting sodium sulfate away. The same principle is employed in reclaiming land from the sea in The Netherlands.

Tobacco fertilizers require special formulation to reduce the amount of chloride and to supply extra magnesium. For the bright tobaccos it is important also that nitrogen supplies be somewhat limited and that such nitrogen as is supplied be released to the plant more slowly than may be possible from the use of nitrates and ammonium salts.

For legumes, the need for nitrogen is usually eliminated, except in getting a new seeding under way or in the production of early-market vegetable legumes, such as snapbeans and fresh peas. For the full-season field legumes, fertilizers are made up primarily of superphosphate and muriate of potash. The well-known good effects of gypsum

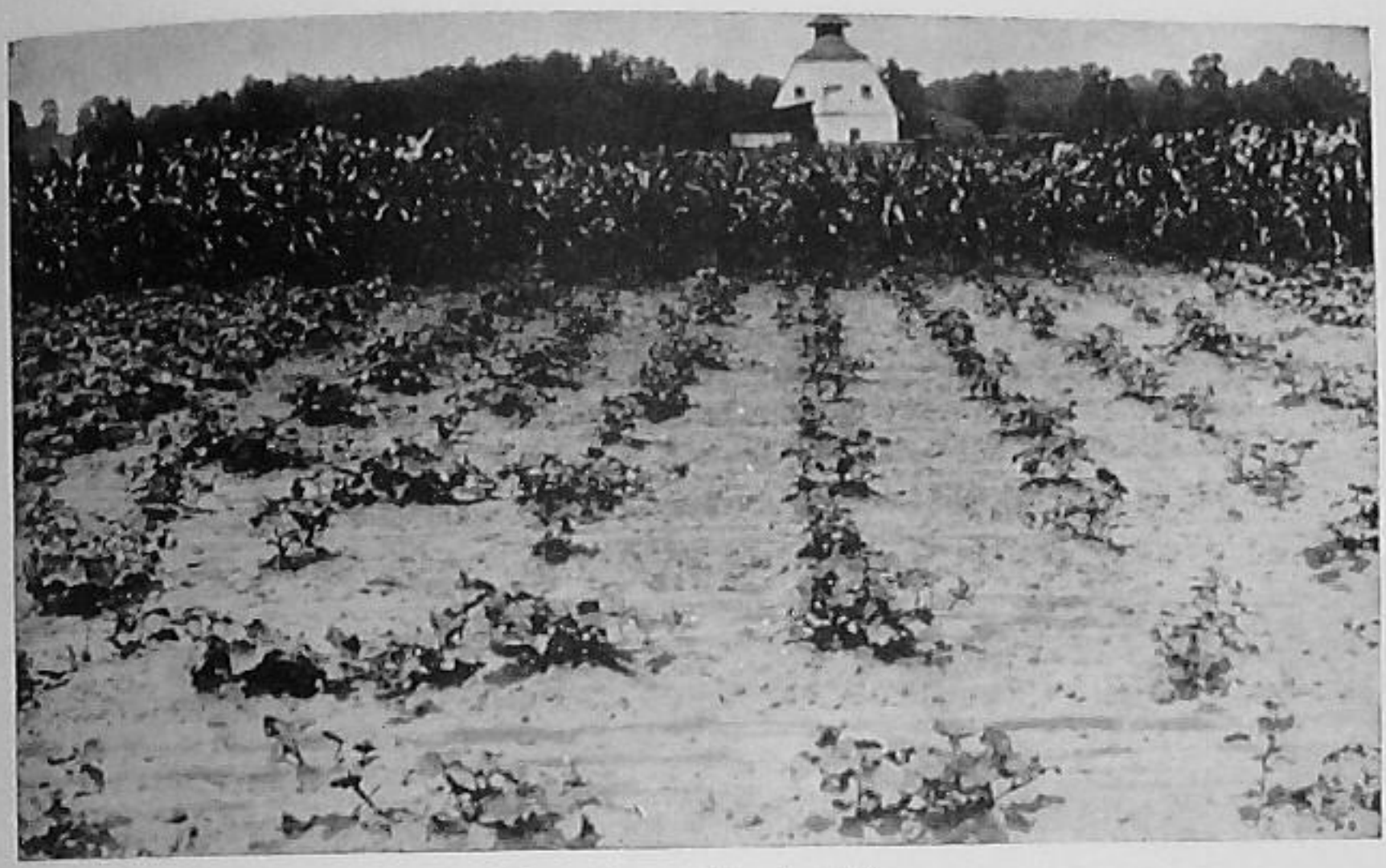


FIG. 87*a*. No fertilizer.

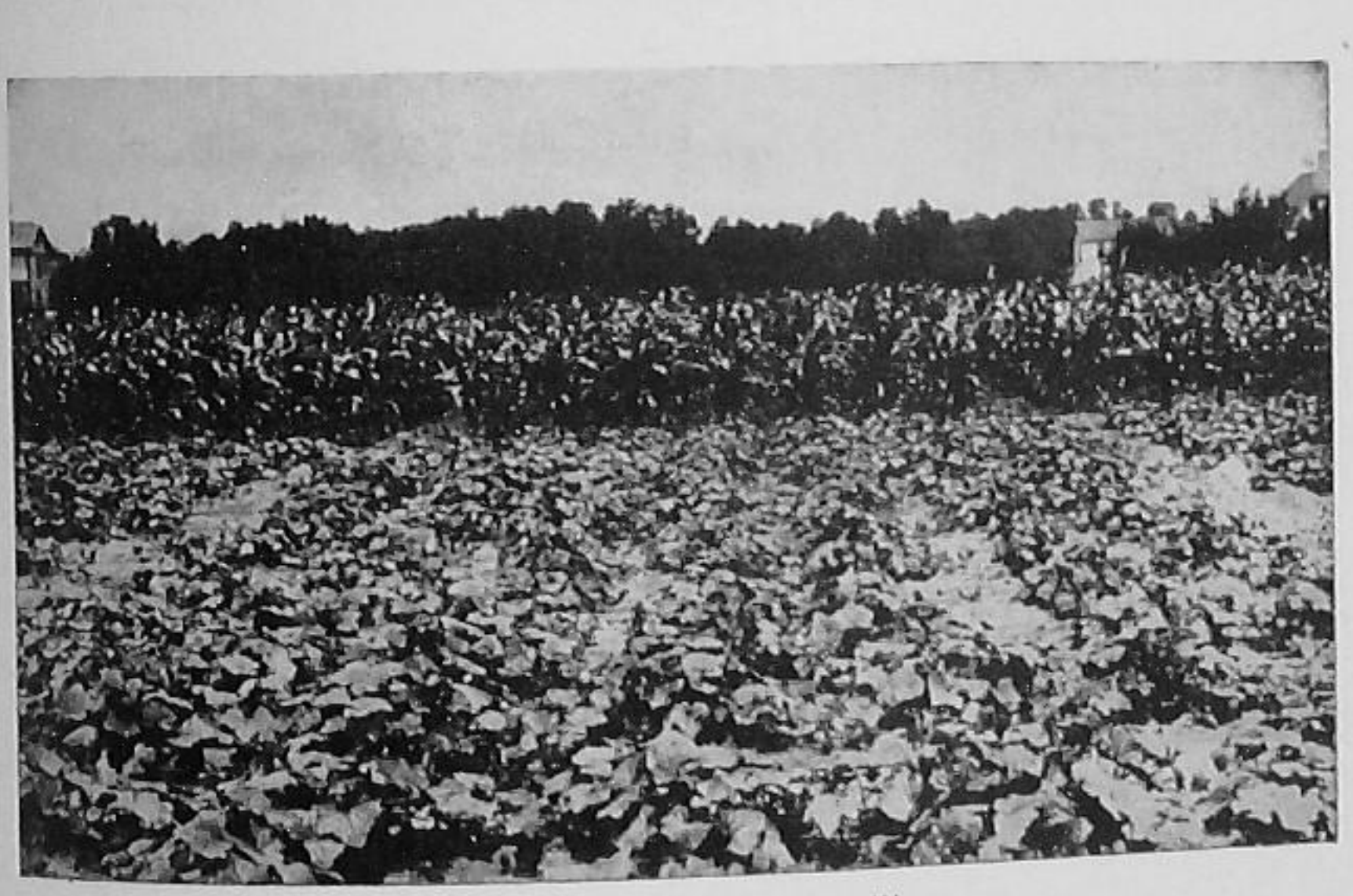


FIG. 87*b*. Complete fertilizer.

In the growing of the more specialized crops little attention is paid to the bank-account method of calculating the necessary return of mineral elements and nitrogen, but large amounts of complete fertilizer are supplied since there is opportunity for additional profit either by reason of a greater yield, a better quality, or the possibility of getting the product on the market earlier than most competitors. These are cucumbers on Ohio Experiment Station Farm, Marietta.

on legumes argue in favor of ordinary superphosphate, rather than double superphosphate, notably in areas that are far removed from industrial centers. Fertilizers for alfalfa often contain as much as 100 pounds borax a ton, and it is recommended that no fertilizer in New Jersey contain less than 5 pounds.

LIQUID FERTILIZERS

A considerable number of liquid fertilizers, or dry fertilizer mixtures that are completely soluble in water, are being offered for sale. Shive, a pioneer in the production of plants by the use of nutrient solutions as such or in sand cultures, suggests the formulas shown in Table 139.

TABLE 139

FORMULAS FOR PRODUCTION OF NUTRIENT SOLUTION (SHIVE)

Formula 1		Formula 2	
Material	Grams *	Material	Grams *
KH_2PO_4	5.9	KH_2PO_4	3.9
$Ca(NO_3)_2 \cdot 4H_2O$	20.1	$NaNO_3$	6.4
$MgSO_4 \cdot 7H_2O$	10.7	$MgSO_4 \cdot 7H_2O$	10.3
$(NH_4)_2SO_4$	1.8	$CaCl_2$	3.2

* The amounts indicated are dissolved individually in water and then made up jointly to a volume of 5 gallons. To this is added 10 milliliters of a stock solution of trace elements made by dissolving 0.8 gram each of boric acid, manganese sulfate, and zinc sulfate in 1 pint of water. A stock solution of 0.8 gram ferrous sulfate and 1 drop H_2SO_4 in 1 pint of water is also kept on hand for addition to the nutrient solution in small quantities as required. (Chetaled iron can be used to replace this last item.)

One of the more popular water-soluble fertilizers on the market, a 5–25–15 grade, is made up of ammonium phosphate, calcium phosphate, nitrate of potash, magnesium sulfate, traces of manganese, iron, copper, and zinc sulfates, a trace of ammonium molybdate, and a small quantity of naphthalene acetic acid.

These completely soluble fertilizers may be used in dry form or dissolved in water. They can be applied before planting, at transplanting, or at seed-sowing time, as sidedressings or topdressings, or

directly on the foliage. For the one mentioned above, the recommendation is to dissolve 6 pounds in 100 gallons of water and use in any manner desired.

SELECTED REFERENCES

1. Association of Official Agricultural Chemists. *Official and Tentative Methods of Analysis*, sixth edition, 1945.

2. Barrett Company Division, Allied Chemical and Dye Corporation. *Barrett's Standard Nitrogen Solutions.* New York, 1945.

3. Bear, Firman E. The fertilizer triangle. *Ind. Eng. Chem.*, Vol. 21, 1929.

4. Chucka, Joseph A. Physical and chemical problems in mixed-fertilizer production. Short Course in Fertilizer Technology, University of Maryland, College Park, 1950.

5. Food and Agricultural Organization of the United Nations. Commercial fertilizers. Bull. 17, Commodity Series, Columbia University Press, New York, 1949.

6. Lockwood, Maurice H. Economics and problems of high-analysis fertilizers. Short Course in Fertilizer Technology, University of Maryland, College Park, 1950.

7. Mehring, A. L., H. A. Wallace, and M. Drain. Nitrogen, phosphoric acid and potash consumption in the United States. *J. Am. Soc. Agron.*, Vol. 37, 1945.

8. Miles, Ivan E. Fertilizer grades and ratios in the United States. Short Course in Fertilizer Technology, University of Maryland, College Park, 1950.

9. Rubins, E. J., and Firman E. Bear. The carbon-nitrogen ratio in organic fertilizer materials in relation to nitrogen availability. *Soil Sci.*, Vol. 42, pp. 411–423, 1942.

10. Shive, J. W., and W. R. Robbins. Methods of growing plants in solution and sand cultures. New Jersey Agr. Exp. Sta., Bull. 636, 1948.

11. Willis, L. G. The value of gypsum as a supplement to concentrated fertilizer. North Carolina Agr. Exp. Sta., Bull. 299, 1934.

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Selection and Use of Fertilizers

In choosing a fertilizer to fit a particular need consideration must be given to soil, crop, climatic, and economic factors. Current fertilizer practice is based largely on the experiences of hundreds of thousands of farmers who have been operating under a "cut-and-try" system for the past century. But these farmers have benefited greatly by the related experiences of fertilizer manufacturers and by the carefully conducted field, greenhouse, and laboratory tests of soil and plant scientists at the several agricultural experiment stations.

DIAGNOSING SOIL DEFICIENCIES

The modern method of determining the fertility status of land is that of subjecting samples of the soil, or of the plants growing on it, to laboratory test. Such tests provide information on the relative abundance or scarcity of the several nutrient elements required by plants from the soil. These tests have been calibrated against field and pot experiments until they have become quite dependable. They are designed to determine whether or not the supply of each of the several soil-derived elements is relatively high, medium, or low. They do not provide the answer as to the exact number of pounds of this or that fertilizer to apply. This is in part because there are no means for predicting how the climatic and associated biologic factors will operate as the crop season advances. In other words, decisions are based on past experiences that may or may not apply to the season ahead.

Preliminary to any laboratory test, it is often possible to predict deficiencies by examining the soil in the field. If the soil is sandy, has a light gray color, is low in organic matter, is very acid, or contains a large amount of straw or similar low-protein material, it probably needs nitrogen. If the soil is strongly acid or strongly alkaline, con-

tains much soluble iron, is high in clay, or low in organic matter, it usually needs phosphorus. If the soil is mostly peat or sand, is of limestone origin, is low in organic matter, or has been subjected to heavy rainfall, it usually needs potash.

If the soil has been derived from serpentine or other high-magnesium rocks or if it is mostly sand or acid peat, it probably needs calcium. If it has been growing acid-soil crops, such as potatoes, has been frequently limed with calcitic limestone or oyster shells, has a high content of sand, or has been liberally fertilized with potassium for some years, it may need magnesium. If the soil is far removed from industrial areas, it may need sulfur. If the soil is sandy, if it is a peat, if it is being used to grow such crops as beets and celery, or if it is deficient in potassium, an application of sodium may have a marked effect on the crops growing on it.

If the soil has been subjected to heavy rainfall, is being used for growing such crops as alfalfa or cauliflower, or has been very liberally limed, it may need boron. If the soil has been very liberally limed and is being intensively farmed, it may need manganese. If the soil is highly calcareous and is low in organic matter, it may be deficient in available iron. If the soil is an acid peat or is of a sandy nature and is being intensively farmed, it may need copper. If the soil has been growing acid-soil crops, it may be in need of molybdenum.

DIAGNOSING DEFICIENCY SYMPTOMS IN PLANTS

If crops are growing on the land, it is often possible, from the appearance of the leaves or from examination of the rate and manner of growth of the plants or their parts, to obtain clues as to possible deficiencies. If the plants grow slowly and the leaves are pale green, if apple trees shed their leaves early in the season, if the lower leaves of plants fire, or if they produce seed prematurely, a lack of nitrogen is indicated. If plants are stunted and the leaves are dark green, if cereals mature slowly and yield poorly, if legumes tend to fail and yields are low, or if the petioles and under sides of the leaves of such plants as tomatoes and peach trees have a purplish tinge, phosphorus is probably deficient. If alfalfa and clover leaves are ringed with white spots, if cotton leaves turn reddish brown and die prematurely, if potato leaves are puckered and curl under at the edges, or if corn leaves fade between the veins and fire along the edges, potassium is needed.

If the roots are short and stubby and tend to develop knobs on their tips, calcium deficiency is indicated. If the older leaves of potatoes, sweet potatoes, cucumbers, and okra show dark green veins and white or dead areas in between, corn leaves show alternate white and green stripes, or cotton and blueberry leaves turn purple, the plants are in need of magnesium. If plants that are native to seacoast regions or to irrigated arid-soil areas fail to thrive in regions somewhat removed from these locations, they may be in need of sodium. If leaves turn yellow, roots grow abnormally long, and stems are woody, sulfur deficiency is indicated.

Boron deficiency symptoms are indicated by brown or black areas in the flesh of turnips and beets, by yellowing and stubby growth of alfalfa, and by discoloration of cauliflower heads. Manganese deficiency is suggested if the veins of newly formed leaves are dark green but the interveinal tissues are yellow. Zinc deficiency is shown by white corn seedlings and by elongation of new growth on fruit trees, with widely separated leaf buds. Copper deficiency is shown by a yellowish cast instead of the desired golden brown on onion tubers and tobacco and by gray-speck disease in oats. Need for iron is indicated if peach-tree leaves show fine green veins on a yellow background and twigs are very slender. Deficiency of molybdenum is indicated on cabbage and cauliflower by badly deformed leaves, consisting mostly of midribs.

Many other soil and plant indications of deficiency are known. They differ from soil to soil and from plant to plant. Often, more than one deficiency develops, in which event no clear-cut symptoms are found. The most complete report on nutrient deficiencies in plants is contained in *Hunger Signs in Crops*. The several chapters in this book were written by men who have had a great deal of experience with the crops in question. Many of the illustrations are in natural colors.

It should be kept in mind that yields may drop off long before symptoms of deficiency are apparent. In other words, if a farmer waits for deficiency symptoms to appear, his yield will already have been materially reduced under what it would have been if the deficiency had not been permitted to develop. The aim of the successful grower is to so manage his soil that no such symptoms, except possibly those of slight nitrogen deficiency, develop.

It must also be remembered that balance is involved. Magnesium deficiency can be developed by excessive use of potassium. Iron and manganese have antagonistic effects. Acid soils that have been limed

to *p*H values above 6.5 often develop deficiencies of boron, manganese, zinc, copper, and cobalt. Those that have not been limed adequately may not be able to supply plants with enough molybdenum to meet their requirements. Use of too large amounts of nitrogen tends toward the production of plants with excessive top growth and limited root systems.

SOIL MANAGEMENT PROGRAM IMPORTANT

In overcoming nutrient deficiencies in soils and plants, it is neither necessary nor desirable to confine one's practice to the application of fertilizer. In all humid regions lime applications sufficient to maintain *p*H values between 6.0 and 6.5, except for such acid-soil crops as potatoes, sweet potatoes, blueberries, and rhododendrons, are necessary for the most economic production of crops.

It is also highly important to know something about the history of a given field or soil area before deciding on what fertilizer to apply. If very little manure has been available for use, if the land has been kept under more or less continuous cultivation, except for occasional catch crops and winter cover crops, if legumes have not been grown regularly as a part of the definite crop-rotation program, and if the surface soil has been lost in large part by erosion, nitrogen deficiency is certain to be serious.

Similarly, if cereal crops are grown continuously and sold from the farm, if legumes are produced for direct sale, if livestock is the primary product of the farm, or if large amounts of milk are produced and sold, phosphorus deficiencies are likely to develop. If little or no manure is available for use, if large amounts of hay, straw, or similar materials are sold off the farm, or if legume hays are grown for sale, potassium deficiencies are certain to develop on most soils.

Various economic problems enter into the picture. If a farmer changes from an extensive to an intensive system of crop farming, if the crop value of the land becomes too high to permit of growing clover for green-manuring purposes, if motor power is substituted for horsepower, as is now usually the case, or if the selling price of crops rises, nitrogen fertilizers are required in larger amounts than otherwise.

Similarly, if a farmer changes from an extensive to an intensive system of livestock farming, if larger acreages and higher acre yields of legumes are required for feeding purposes, or if [illegible] prices for cereal crops make it desirable to grow larger acreages of legumes, more phosphorus will be required. Extra potassium will be needed as the

farming is intensified, if tractors are substituted for horses, if straw, cornstalks, and other crude plant wastes find a market for the production of articles of commerce, or if the large areas of sand and peat that are now lying waste are brought under cultivation.

QUICK TESTS FOR DEFICIENCIES

Many quick tests for soil and plant nutrients have been developed for determining the nutrient status of soils. Some of these involve growing seedlings in the soil in question and analyzing them. Others are designed for longer-term growth of plants under conditions in which supplemental fertilizer applications are made and yield increases are measured. Still others consist entirely of testing the soil or plant for its content of the needed nutrients. Probably the most complete presentation of this subject is that contained in *Diagnostic Techniques for Soils and Crops*, in which the thinking of some of the most skilled soil and plant chemists in this country has been brought to bear on this subject.

The starting point is a test for the *p*H value of the soil. For good systems of livestock farming, in which plenty of manure is available, large acreages of legumes are grown in regular rotation systems, and extra feed, including possibly a trace-element supplement, is purchased, the fertilizer requirements on a naturally fertile soil are relatively simple. Often they can be confined to phosphorus alone, at least for a considerable number of years. Thus, rock phosphate or superphosphate, scattered over the manure in the stall or as it is being hauled to the field at the rate of 40 pounds a ton, has been proved to be a highly profitable practice on livestock farms (Table 140).

TABLE 140

ACRE YIELDS FROM USE OF REINFORCED STALL MANURE * (OHIO)

Treatment	Corn, Bu.	Wheat, Bu.	Clover, Lb.
Unmanured	39.1	15.6	2930
Manure	63.5	24.3	4040
Manure and superphosphate	67.3	29.9	4770
Manure and rock phosphate	67.4	27.5	4400
Manure and gypsum	66.3	26.2	4000

* Forty-year averages from use every third year of 8 tons of manure, each ton reinforced with 40 pounds of superphosphate, rock phosphate, or gypsum, as indicated. The manure was applied to the clover sod before plowing, in preparation for corn.

In proportion as less livestock is grown and fed on the farm, as the land is under cultivation a larger percentage of the time, and as less

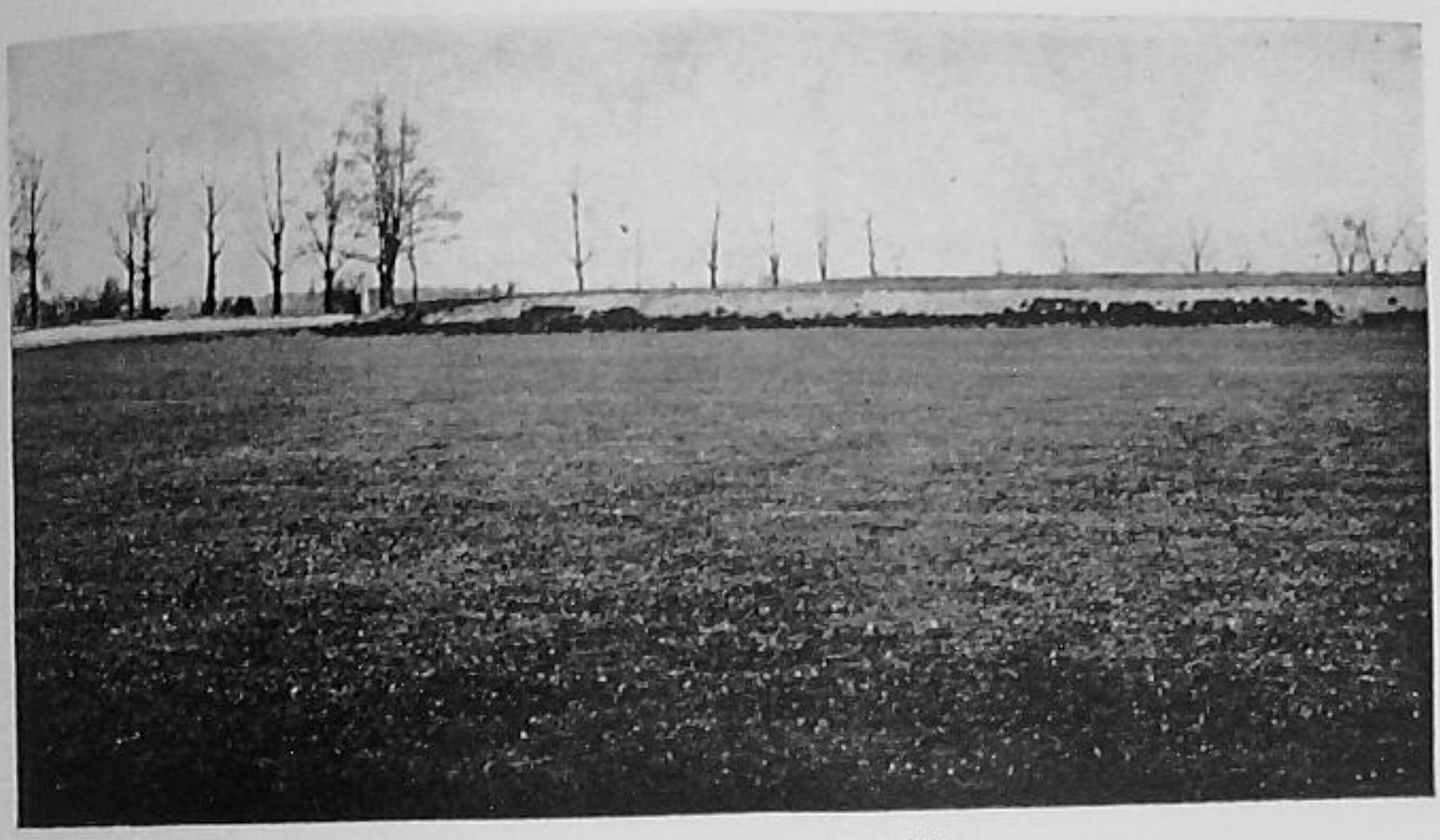


FIG. 88*a*. *One ton of 5–8–6 fertilizer per acre.*



O. J. Noer, Wis. Agr. Exp. Sta.

FIG. 88*b*. *No fertilizer.*

High nitrogen fertilizers are especially important in the growing of grasses. Photographs of fairway of golf course.

definite crop-rotation programs are in effect, larger amounts of nutrient elements and a greater variety of them have to be supplied in fertilizer form. If, in addition, the land originally was in a low state of productivity or the soil is one of the more extreme kinds, such as

sand, peat, or eroded clay, the problem becomes much more complicated.

One needs also to know something about the physical makeup of the soil and the conditions with respect to drainage. Given a soil of the loam type that is well drained and the color of which is brown in the *A* horizon and a yellowish or reddish cast in the lower horizons, yields can be raised to high levels in a very short time. In fact, an unproductive soil of that type can be changed to one of high productive capacity within the short period of time required to apply the necessary lime and fertilizer.

The several species of plants differ greatly in their soil requirements. Plants are found growing luxuriantly under a wide variety of soil *p*H values. Some plants thrive only on acid soils. Others grow well on soils that are alkaline in reaction. Similarly, there are differences in the nitrogen, phosphorus, and potassium requirements of plants. Attempts have been made to classify plants on the basis of their relative response to applications of each of the nutrient elements. A great deal remains to be done before such a classification can be made dependable for practical purposes. In fact, the selection and breeding of crop plants tend to nullify advances in this field of study, since the nutrient requirements of any given species of plant can be altered. The work of Hartwell is of interest, nevertheless, in this connection.

SOME STANDARD FERTILIZER ANALYSES

Perhaps the best method of procedure in developing a fertilizer program is first to have the soil tested for *p*H and for its supplies of the several nutrient elements and then to select a standard fertilizer grade that would appear to meet the general needs of the crops to be grown. Five fertilizer ratios would be adequate for most conditions. These are the 1–1–1, 1–2–1, 1–2–2, 0–1–1, and 0–1–2, in such analyses as the 10–10–10, 8–16–8, 5–10–10, 0–20–20, and 0–12–24. The actual analyses could be lower or higher than these, depending on relative costs a unit of nutrients and on the availability of a given grade for purchase.

With these as the starting point one could adjust the quantity and kind of fertilizer according to the nature of the soil, climate, previous management of the land, economic factors, and the peculiar needs of the crop to be grown. The rate of application might well be 3000 pounds or more an acre for market garden crops, 2000 pounds for potatoes, tomatoes, tobacco, orchards, and sugar beets, 1000 pounds

for cotton, corn, alfalfa, and intensively managed pastures, and 500 pounds an acre for small grains, soybeans, and grain sorghums.

Use of supplemental nitrogen for topdressing or sidedressing would often be profitable on pastures, nonlegume meadows, and grass-hay



Photograph by C. H. Nissley, New Jersey Agr. Exp. Sta. Fertilizer suggestions by Jackson B. Hester, Soil Technologist, Campbell Soup Co., Camden, New Jersey.

FIG. 89. For tomatoes, the soil should have a *p*H value between 6.2 and 6.8, and it should contain more than 100 pounds of replaceable magnesium an acre. An acre application of 1500 pounds 5–10–10 fertilizer containing 10 pounds of borax is suggested, 500 pounds in row previous to planting or in bands along row at planting, and two 500-pound sidedressings after greater part of fruit has set. In seasons of excessive rainfall a sidedressing of 200 pounds of ammonium nitrate or similar nitrogen fertilizer should be made. Plant and soil analyses during the season are essential for maximum production.

crops, on small grains, on corn, especially in the southern states (Table 141), on the types of vegetable crops of which the leafy portions are sold, on fruit trees and small fruits, on cotton and sugar cane, on sugar beets, on tomatoes, melons, cucumbers, eggplant, and squash, and on rhubarb, asparagus, and similar perennials.

Supplemental applications of potassium might well be used on potatoes, sweet potatoes, sugar beets, and mangels, on the heavier types of tobacco, on onions, celery, and similar sandy-soil and peat crops, on asparagus, on strawberries and other small fruits, on cabbage, cauliflower, Brussels sprouts, and similar crops, and on legumes, notably

TABLE 141

EFFECT OF EXTRA N ON CORN YIELDS * IN SOUTH (KRANTZ)

(On Acre Basis)

Nitrogen, Lb.	Yield, Bu.	Nitrogen, Lb.	Yield, Bu.
0	28	80	71
40	53	120	81

* Average yields for 49 experiments in North Carolina during 1944–48.

those like the perennial alfalfa and ladino clover, from which several crops are harvested during each growing season.

FERTILIZER PLACEMENT

Placement of fertilizer with reference to the seed has been emphasized to a greater degree in the United States than in any other country. On the heavier types of soil and for crops that are planted in late fall or early spring it is often possible to apply the fertilizer in direct contact with the seed. This applies to the small grains, on which the rates of application are relatively small, usually less than 500 pounds an acre.

For most row crops the modern tendency is to place the fertilizer along the row on both sides of the seed and a little below the level of the seed. Machinery for planting corn is made to apply up to 500 pounds an acre, that for cotton up to 1000 pounds, and that for potatoes 2000 pounds or more.

For seeding such crops as alfalfa it is common practice to apply the fertilizer with a grain drill attachment at rates up to 1000 pounds an acre and to drop the seed on top the soil. The seedbed is then firmed by the use of a cultipacker type of implement.

The practice of applying fertilizer broadcast, hauling it in bulk direct from factory to farm, and applying it as a service that is sold to the farmer, is growing. Here, the fertilizer is often applied before the land is plowed. The same direct from-factory-to-farm method is employed in topdressing meadows and pastures.

Where nitrogen sidedressings or topdressings are used, these are applied by the grain-drill type of machine or by the use of broadcast sowers attached to the rear of trucks. Where anhydrous ammonia is used, it is placed in the soil by the use of an opener to a depth of 4 or 5 inches. For sidedressing corn, it is common practice to apply the ammonia halfway between the rows, usually at the last cultivation.

For small grains the machinery for applying the ammonia is operated across the rows.

If fertilizers are placed above the seed, below them, or directly in contact with them, considerable damage may be done unless the rate of application is relatively low (Table 142). The fertilizer dissolves in the soil water and tends to move with it. The higher the analysis



Fertilizer suggestions by J. C. Campbell, New Jersey Agr. Exp. Sta.

FIG. 90. Use of 2000 pounds of 5–10–10 fertilizer, or its equivalent in a higher analysis, an acre, placed in bands 2 inches to the sides of the row and level with the seedpiece, is suggested for potatoes grown in rotation with wheat and clover.

of a fertilizer the less the likelihood of damage from its use at any given rate of application of nutrient elements.

Band placement of fertilizer was especially designed to reduce phosphate fixation. By placing the fertilizer in this manner, its degree of direct contact with soil that is unsaturated with respect to phosphate is greatly lessened. The same applies to magnesium and, to a lesser extent, to potassium.

The use of an airplane or a helicopter as a fertilizer distributor for extensive farming, as on vast areas of pastureland, is growing. There is reason to believe that such types of distributors may have special usefulness on rolling land in the eastern part of the United States, notably in the northeastern region.

TABLE 142

POTATO YIELDS AS AFFECTED BY FERTILIZER PLACEMENT (CUMINGS)

(Bushels per Acre in Good Potato Years)

State	Me.	Me.	N. J.	N. J.	Vir.	N. Y.	Ohio	Mich.
Year of test	1934	1934	1931	1931	1934	1935	1934	1934
Fertilizer placement	bu.	bu.	bu.	bu.	bu.	bu.	bu.	bu.
Mixed with soil *	436	487	292	274	232	282	195	237
1 in. each side †	515	...	...	...	318	348	198	256
2 in. each side †	582	522	331	332	307	327	195	274
4 in. each side †	525	489	307	311	328	328	199	280
2 in. each side ‡	499	541	329	330	291	326	198	267
No fertilizer	341	341	207	207	57	...	174	239
Fertilizer grade	4–8–7	8–16–14	5–8–7	10–16–14	6–6–5	4–8–5	4–10–6	4–12–8
Pounds an acre	2000	1000	2000	1000	2000	2000	1500	800

* Largely under seed. † On seed level. ‡ Two inches below seed level.

The practice of applying fertilizers in solution, either at transplanting, when sidedressing, in connection with sprays for fruit trees, or in the more intensive systems of market-gardening and floriculture, is growing. Some of the standard nitrogen solutions could well be used as such, or when diluted, depending upon the circumstances. Entirely soluble complete fertilizers are available for purchase, although at fairly high cost. They can be produced at much lower cost if the demand for them develops.

SOME SPECIAL FERTILIZER PROBLEMS

Sandy soils present some special problems, in that damage from heavy applications of fertilizer are higher on them and they have less capacity to retain the fertilizer against the action of heavy rains. This makes it necessary to divide the total application into several parts to be applied from time to time during the growing season. Fertilizers for such soils need to contain a greater number of nutrient elements than those normally required for heavier soils.

Nitrogen applications merit special mention. If applied at liberal rates in highly soluble form at planting time they may cause heavy top growth at the expense of a good root system. Furthermore, nitrogen in nitrate form is very readily lost in the drainage water. If any large amount of nitrogen is to be used, a large part of this should be saved for sidedressing or topdressing. For small grains and grasses such applications should be made early in the season; otherwise, the nitrogen will tend to produce increased protein rather than increased

yield. Sometimes, of course, extra protein may be what is wanted, as, for example, for hard wheats.

For perennial plants, such as fruit trees, a long-time program designed to feed the tree continuously is desirable. Usually, any phos-



Photograph and fertilizer suggestions by Frank N. Hewetson, Fruit Research Laboratory, Arendtsville, Pennsylvania

FIG. 91. For mature apple orchards in bluegrass sods, use of 400 pounds of 10–10–10 fertilizer an acre, applied broadcast annually, is recommended. In addition, 10 to 15 pounds of sodium nitrate or its equivalent under the spread of the branches of each tree may be necessary. For ladino clover sods it may be possible to eliminate the nitrogen.

phate or potash that is applied is designed primarily for the cover crop in the orchard and secondarily for the trees. Nitrogen, however, is of primary value in fruit production. Here again, if its application is delayed in the spring it may be used for growth or protein production in the cover crop and not reach the roots of the trees until the resulting organic matter becomes a part of the soil.

Plowing fertilizer under is effective in well-drained soils, but it needs to be supplemented with fertilizer along the row. The same applies to broadcast applications of rock phosphate, which also are normally

plowed under. Here again some readily available phosphate along the row is of great help in getting the crop under way.

If the water content of the soil can be controlled, as by irrigation or dependably regular rainfall, heavy applications of fertilizer can be used to crop advantage. In the drier regions of the United States, however, the rate of application of fertilizer cannot be raised to such high levels. Often, the fertilized crops get off to an excellent start, only to suffer the consequences of an inadequate supply of water.

It may be well at this point to consider once more the amounts of nitrogen, phosphorus, and potassium that are removed by crops at acre yields of the type toward which we are striving and are beginning to attain (Table 143). To raise the level of production to any such

TABLE 143

N, P_2O_5, AND K_2O IN 1-ACRE STANDARD CROPS * (BEAR)

(Refers Only to Part Usually Sold)

Crop	Acre Yield	Part of Crop	N, Lb.	P_2O_5, Lb.	K_2O, Lb.
Alfalfa	5 tons	Hay	235	50	200
Corn	100 bu.	Grain	85	35	20
Cotton	1000 lb.	Seed lint	75	35	30
Potatoes	500 bu.	Tubers	100	35	150
Soybeans	50 bu.	Grain	175	40	60
Sugar beets	20 tons	Roots	100	35	130
Tobacco	2000 lb.	Leaves	70	15	100
Tomatoes	20 tons	Fruit	60	25	150
Wheat	50 bu.	Grain	65	30	15

* Analyses vary greatly, depending upon variety, soil, and climate. These are given as reasonably dependable averages.

heights on a large scale will require a combination of good soil management, coupled with the use of large amounts of fertilizer.

EUROPEAN VERSUS AMERICAN PRODUCTION

There is a fundamental difference in the philosophy of crop production in European countries and that of the United States. Europe is a food-importing country and the United States is a food-exporting country. In Europe it is highly important that acre yields be raised to high levels, especially during periods of war and the aftermaths of war. In the United States the aim is more toward large operations

with much less intensity on each acre. This difference is readily apparent when one studies the amounts of fertilizer consumed an acre (Table 144). In Europe the land is agriculturally old and must be

TABLE 144

ACRE RATE OF APPLICATION OF FERTILIZERS IN VARIOUS COUNTRIES (NFA) *

Country	N, Lb.	P_2O_5, Lb.	K_2O, Lb.
Austria	12	18	15
Belgium-Luxemburg	86	90	108
Denmark	18	25	23
France	15	30	22
Germany	42	50	62
Greece	8	11	2
Iceland	60	20	20
Ireland	6	52	7
Italy	9	17	3
Netherlands	96	106	116
Norway	34	34	48
Portugal	8	16	2
Sweden	11	17	12
Switzerland	20	80	38
United Kingdom	27	41	25
United States	6	13	5

* National Fertilizer Association. The estimates are for the year 1949–50.

maintained at a high level of productivity. Here it is relatively new and much more dependence is placed on the native fertility of the soil.

Crowther and Yates have formulated a table of standard response curves for use in connection with fertilizing the land in England (Table 145). Many other systems have been developed for calculating the curve of growth response to fertilizer application, of which that of Wilcox is of considerable interest. These contemplate very heavy use of fertilizer and the production of much higher acre yields than are as yet necessary or economic in the United States.

It is important to keep in mind, however, that our soils are getting older, large reserves of fertility have been wasted or exhausted, and our population is still growing rapidly. The potentialities in food production in the United States, once the need develops, are tremendous. Of necessity, fertilizer will play an ever greater part in this expanded program.

TABLE 145

STANDARD RESPONSE CURVES FOR N, P_2O_5, AND K_2O (CROWTHER)

(European Experiments)

Cwt. N an Acre	Relative Response	Cwt. P_2O_5 or K_2O	Relative Response
0.1	0.48	0.2	0.51
0.2	0.85	0.4	0.87
0.25 *	1.00 *	0.5 *	1.00 *
0.3	1.14	0.6	1.11
0.4	1.36	0.8	1.28
0.5	1.53	1.0	1.40
0.6	1.67	1.2	1.48
0.7	1.77	1.4	1.54
0.8	1.85	1.6	1.58
0.9	1.91	1.8	1.60
1.0	1.96	2.0	1.62

* The standard dressings, used as a base of 1.00, were 0.25 cwt. N and 0.5 cwt. each of P_2O_5 and K_2O, which represent the average dressings used in the experiments during a single season. An English cwt. is 112 pounds.

SELECTED REFERENCES

1. American Society of Agronomy and the National Fertilizer Association. *Hunger Signs in Crops*, second edition. Judd and Detweiler, Washington, D. C., 1949.

2. Bear, Firman E., and Associates. Effect of increasing fertilizer concentration on exchangeable cation status of soils. *Soil Sci. Soc. Amer., Proc.*, Vol. 16, pp. 327–330, 1952.

3. Bear, Firman E., and Associates. *Diagnostic Techniques in Soils and Crops.* The American Potash Institute, Washington, D. C., 1948.

4. Crowther, E. M., and F. Yates. Fertilizer policy in war time. *Empire J. Exp. Agr.*, Vol. 9, pp. 77–97, 1941.

5. Cumings, G. A., and Associates. Methods of applying fertilizers. National Fertilizer Association, Washington, D. C., Pamphlet 149, 1948.

6. Cumings, G. A., and G. V. C. Houghland. Fertilizer placement for potatoes. U. S. Dept. Agr. Tech. Bull. 669, 1939.

7. Hartwell, B. L. Relative growth response of crops to each fertilizer element and the use of this response in adopting a fertilizer analysis to a crop. *J. Am. Soc. Agron.*, Vol. 13, pp. 353–359, 1921.

8. Hester, Jackson B. Mineral elements and nitrogen in plants versus manure. *Commercial Fertilizer*, Vol. 82, p. 52, 1951.

9. Krantz, B. A. Fertilize corn for higher yields. North Carolina Agr. Exp. Sta., Bull. 366, 1949.

10. Wilcox, O. W. Absolute values in fertilizer experiments. *J. Am. Soc. Agron.*, Vol. 36, pp. 480–486, 1944.

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Yield Potentialities of Crop Plants

Willcox has called attention to the goals in acre yields of crop plants toward which he thinks we should strive. He sets the ultimate yield of corn at 250 bushels an acre, that of wheat at 170 bushels, that of potatoes at 1550 bushels, and that of lint cotton at 2300 pounds, with correspondingly high yields of other crops. These yields are very high in comparison with those being currently produced.

Willcox's conclusions are based in large part on concepts that were developed earlier by Mitscherlich and Baule. The first principle on which these concepts rest is that "the increments in yield corresponding to successive equal increments in fertilizer applied to a crop tend to constitute the terms of a decreasing geometric series. Thus, if R represents the ratio of the second yield increment to the first, then the ratio of the third yield increment to the second, the fourth to the third, and so on is also R."

LAW OF DIMINISHING RETURNS

On this basis, if 100 pounds of a given fertilizer increased the acre yield of corn 20 bushels and 200 pounds increased it 30 bushels, 300 pounds would have increased it 35 bushels and 400 pounds 37½ bushels. Studies of large numbers of field tests, in which such studies of increasing quantities of fertilizer have been made, strongly indicate that this concept is valid.

The law of diminishing returns can be expressed by the formula $dy/dx = (A - y)c$. In this formula, dx represents the increment of any given growth factor that produces a dy increment in yield, A is the maximum yield that can be obtained by raising the amount of the growth factor to the optimum. The c is a proportionality constant that varies with each growth factor. According to Willcox, "it is a

cardinal point in Mitscherlich's effect law that the effect factor of a growth factor is independent of the kind of plant and is also independent of the type of soil."

A great many growth factors must be controlled for maximum crop yields. These include temperature, light, moisture, oxygen, carbon dioxide, soil *p*H value, nitrogen, phosphorus, potassium, and all the other mineral nutrients. No growth factor must be permitted to be in such excess as to have a negative effect. All factors capable of injuring the crop, such as insects and diseases, must be eliminated. Only as negative factors are under control and all the growth factors are at the optimum can the maximum yield be produced.

But no matter what the growing conditions may be, it is still possible to apply the Mitscherlich law to the solution of the problem of deciding how much fertilizer to use for optimum yields under the conditions that obtain. This calls for a knowledge of the general ability of the soil in question, under the climatic conditions that exist, to grow the crop at hand. It also requires that a test be made for available supplies of the fertilizer nutrients that are stored in the soil.

Mitscherlich's law was based on a study of data from thousands of field and pot tests with a wide variety of soils and a wide variety of crop plants. The same law was discovered independently by Spillman shortly afterward, while he was studying some data on the effects of increasing quantities of fertilizer on cotton yields. In fact, a considerable number of applications of this law had been made to other phenomena long before it was applied to crop yields by either Mitscherlich or Spillman.

BAULE VALUES FOR PLANT NUTRIENTS

After studying Mitscherlich's data, Baule, a mathematician, developed a very useful set of units, now called *baules*, that can be employed to advantage in dealing with several growth factors at the same time. Assuming that all growth factors save one that is under study are kept constant at some reasonable level, the quantity of the absent factor required to raise the yield from 0 to 50 per cent of the possible production under the conditions of the test may be defined as 1 baule of that factor.

Willcox evaluates a baule of nitrogen (N) at 223 pounds an acre, a baule of phosphoric acid (P_2O_5) at 45 pounds an acre, and a baule of potash (K_2O) at 76 pounds an acre. If phosphoric acid is the nutrient under study, any kind of plant, with 1 baule of available

P_2O_5 at its disposal, will produce 50 per cent of the yield it is capable of producing with optimum quantities of this nutrient. Each successive baule of P_2O_5 will permit the production of half the quantity remaining for this full yield. Thus, 1 baule permits the production of



Photograph and fertilizer suggestions by L. M. Thompson, Iowa State College, Ames, Iowa

FIG. 92. For a corn-hog-beef system in Iowa a 4-year program of corn, corn, oats, and red clover-alfalfa is suggested. The pigs graze the meadow, but enough hay is made for winter feeding of beef calves. Part of the corn is hogged down. All the stover remains on the field and is plowed under. The oat straw is used as bedding. All manure is applied to the meadow in preparation for the first crop of corn. The soil is limed to *p*H 6.5. An application of 125 pounds of 4–16–8 an acre is made along the row for corn. The second corn crop receives, in addition, 125 pounds of ammonium nitrate at the second cultivation. The oats and the clover seeded in them, receive 200 pounds of 10–20–0. Yields of corn around 100 bushels an acre under this system.

a 50 per cent yield, 2 baules of a 75 per cent yield, 3 baules of an $87\frac{1}{2}$ per cent yield, and so on, until, at 10 baules, a yield of virtually 100 per cent of the maximum is produced.

Three points must be kept in mind in this connection. The first is that the maximum yield referred to is maximum only for the conditions of the test, in which all growth factors, except the one under study, are kept constant, although not necessarily at the optimum. Second, this maximum yield can never quite be attained in practice, it can

only be very closely approached. Third, if other controllable growth factors are below their optimum, higher yields can be produced in proportion as the quantities of these are also increased.

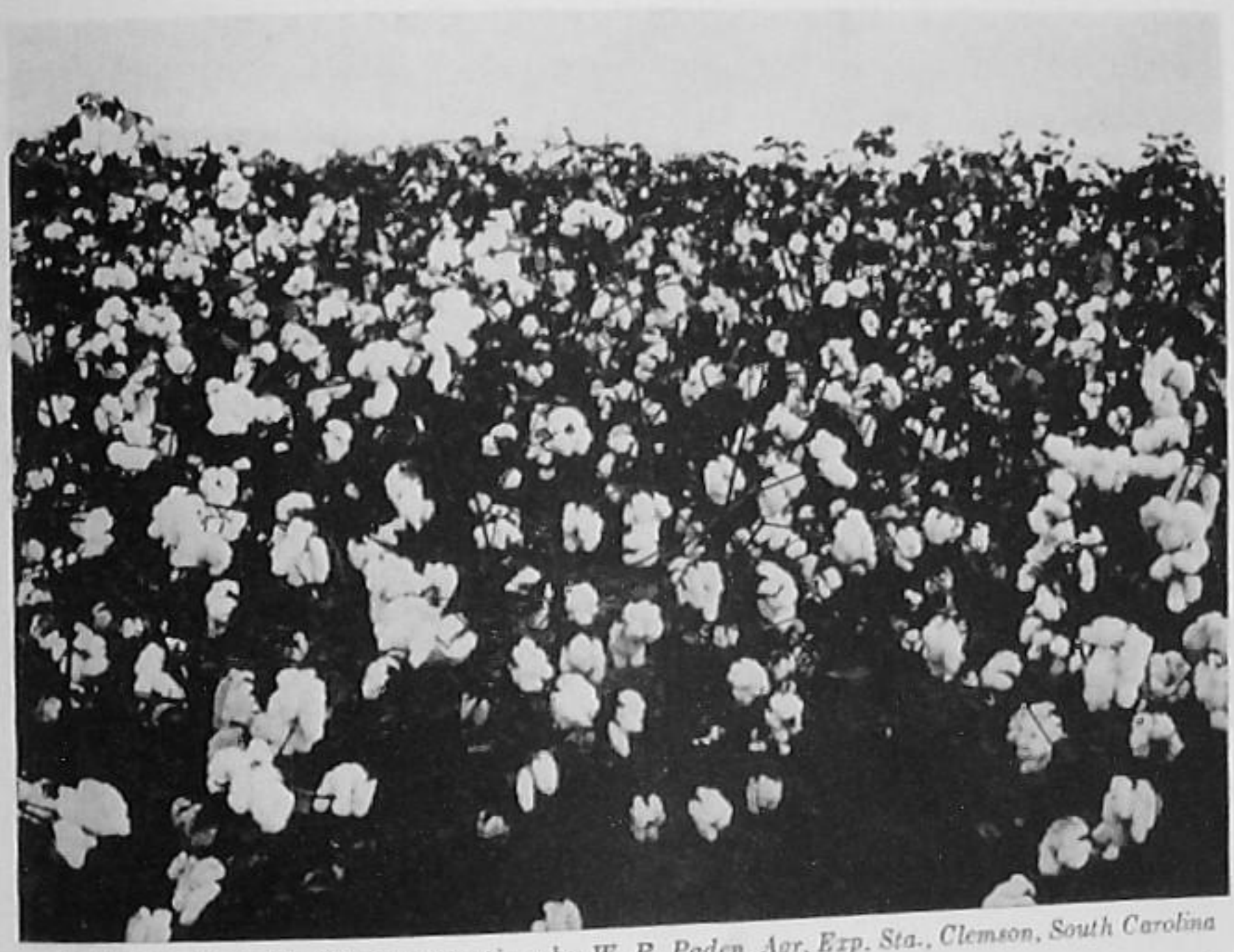
The Baule principle is of special interest in connection with this third point. It allows determining to what extent yields could be increased if two or more deficient growth factors were increased simultaneously. Thus, if P_2O_5, K_2O, and all other factors are present except N, addition of 1 baule of N will permit the yield to be raised to 50 per cent of the maximum attainable under the existing conditions. If K_2O and all other factors are present, but no N or P_2O_5, addition of 1 baule each of these two will raise the yield to only 50 per cent of 50 per cent, which is 25 per cent of the attainable maximum. Further, if all other factors are present but no N, P_2O_5, or K_2O, addition of 1 baule of each of these three will permit of a yield of only 12.5 per cent of the attainable maximum.

In practice, we do not start with zero quantities of any of these nutrients, but usually with considerable amounts, which can be determined by soil tests. The problem before us is one of knowing what constitutes a reasonable yield of a particular crop on a particular soil, under a particular set of climatic conditions. If knowledge of this yield possibility has been arrived at, whether by farmer experience or field test, one has a means of determining what quantity of each fertilizer nutrient should be supplied to arrive at predetermined yield goals within the range of practicality.

Using corn as an example and assuming that all growth factors except N, P_2O_5, and K_2O are at their optimum, the yield possibility when these three are supplied in optimum quantities is, according to Willcox, 250 bushels an acre. This yield could be obtained if the crop had at its disposal 10 baules of each nutrient, or 2230 pounds N, 450 pounds P_2O_5, and 760 pounds K_2O. With 1 baule of each, the yield would be only 31 bushels, with 2 baules each, 105 bushels, and with 3 baules each, 167 bushels (Table 146). If the environmental conditions other than the nutrient supply permitted of a maximum yield of only 125 bushels an acre, then the yields from 1, 2, and 3 baules each of N, P_2O_5, and K_2O would be only one-half those indicated in these examples.

INVERSE NITROGEN-DRY MATTER LAW

To obtain the 167-bushel yield requires that 669 pounds N, 135 pounds P_2O_5, and 228 pounds K_2O an acre, or such variations in the



Photograph and fertilizer suggestions by W. R. Paden, Agr. Exp. Sta., Clemson, South Carolina

FIG. 93. An application of 400 to 1000 pounds of fertilizer an acre is recommended for cotton. For the poorer types of heavier soils the 5–10–5 is suggested; for average soil types the 5–10–10; and for productive sandy soils the 8–8–8, or higher-analysis fertilizers of the same ratios. From 30 to 50 pounds of extra nitrogen an acre should be applied when the plants begin to set fruit. The soil should be limed to a *p*H value of 6.5.

TABLE 146

PERCENTAGES CORN YIELD FROM 1 OR MORE BAULES N, P_2O_5, AND K_2O
(WILLCOX)

(Assuming That All Other Growth Factors Are at Optimum)

N, Baules	P_2O_5, Baules	K_2O, Baules	Percentage Yield	Actual Yield
10	10	10	100–	250–
1	10	10	50	125 *
1	1	10	25	62+
1	1	1	12.5	31+
2	1	1	18.7+	46+
2	2	1	28.1+	70+
2	2	2	42.1+	105+
2	2	3	49.2+	123+ *
3	3	3	66.8	167+

* Note the similarity in percentage and actual yields between these two very different fertilizer applications.

number of baules of these nutrients as will give the same percentage product, be available to the crop during the growing season. This does not mean that the crop will take up these quantities of nutrients. In fact, Willcox has set a maximum value for nitrogen use by 1 acre of crop plants during any one crop season at 318 pounds. According to his concept, all crop plants have the same capacity for using nitrogen, but they differ greatly in their ability to produce non-nitrogenous substances. On this basis, the maximum yield of soybeans, containing 2.6 per cent nitrogen in the whole plant, is 12,230 pounds dry matter an acre. That of corn, with 1.2 per cent nitrogen, is 26,500 pounds dry matter. That of sugar cane, with 0.285 per cent nitrogen, is 111,560 pounds dry matter. If a plant with only 0.1 per cent nitrogen could be developed, its yield potentiality would be 318,000 pounds dry matter an acre.

ONE-PLOT FIELD SYSTEM FOR TESTING A FERTILIZER MATERIAL

In order to apply the Mitscherlich-Baule concepts to agricultural practice, Willcox developed a standard-yield diagram for use in connection with a one-plot system of testing any given fertilizer material. The test itself involves applying a known weight of the material to a narrow strip of land across the field in question and comparing the yield on this strip with the average yield of two like strips lying on both sides but to which this extra treatment was not applied.

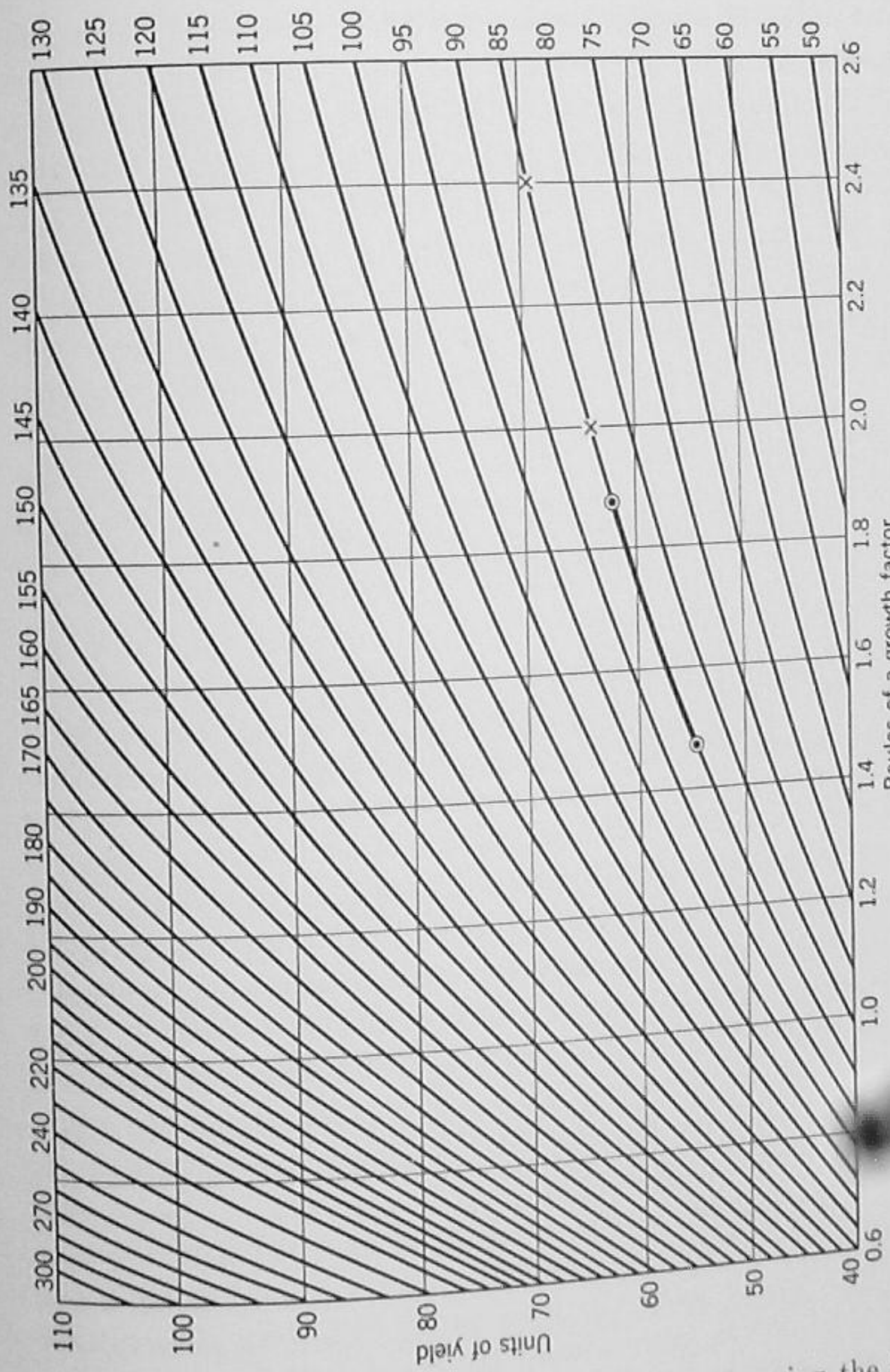
The two yield values can be made to fall on one of the curves of the standard-yield diagram. The bottom line of this diagram shows baules of growth factors, the vertical line to the left shows units of yield, and the other two border lines show a set of values ranging from 50 to 300.

Taking corn as an example, Willcox assumes an application of 30.4 pounds K_2O an acre, representing 0.4 baule, on the test strip. He assumes that the yield on this plot was 62 bushels, in comparison with 55 bushels as the average for the check plots alongside.

The experimenter then proceeds as follows. On a piece of transparent tracing paper he draws a straight line on which 2 points, exactly 2 inches apart, are marked. For this particular test this line will represent 50 bushels an acre, and so it will be placed over the 50-unit line on the diagram. Directly above the point that was placed on the left-hand side of the line on the tracing paper a dot is placed over the 55-unit line to represent the check yield. Similarly, a dot is placed

directly above the point on the right-hand side of the line on the tracing paper to represent the 62-bushel yield.

The next procedure is to fit the two points established by the yield



By O. W. Willcox, Consulting Agrobiologist, Ridgewood, New Jersey

Fig. 94. Diagram for use in a one-plot system for testing a fertilizer to determine what further possibilities exist in its use in increasing the yield of crops on a given soil.

data on the standard curve. This is done by keeping the 50-bushel straight line on the transparent paper on the 50-unit straight line on the diagram and moving it to the left or right until the two points both lie on one of the curves. Here, the curve sought for is found to be

No. 85. This indicates that the maximum corn yield one could expect from the use of additional increments of K_2O on that field will be found by projecting that curve.

By study of this curve the experimenter finds two important facts. One is that his soil already contained 1.48 baules or 112.5 pounds available K_2O an acre. The other is that his yield could have been raised to 72.5 bushels by the use of 54.7 more pounds of K_2O, or a total application of 85.1 pounds. This quantity, together with that already contained in the soil, is equivalent to 2.6 baules.

This system can be applied to any given fertilizer material or to a complete fertilizer. It can also be applied to any other soil amendment or to any physical operation. It merits study as a possible means of arriving at some of the answers desired. It is apparent, of course, that the effects of all factors may vary from year to year. It is also important to consider such matters as thickness of stand. But the principle appears sound for recommending to those who desire a method of field testing as a supplement to the usual soil- and plant-testing procedures.

NITROGEN IN DIFFERENT CATEGORY THAN PHOSPHORUS AND POTASSIUM

Bray divides the three standard fertilizer constituents into two groups, placing nitrogen in the first and the other two in the second. He believes that nitrogen tends to follow Liebig's law of the minimum, whereas phosphorus and potassium follow Baule's percentage-yield concept. Liebig's law of the minimum states that crop yields are determined by the quantity of the element that is present in least abundance. In other words, if nitrogen is available in least amount in relation to the needs of the crop, little is gained by adding any other nutrient element until the nitrogen level has been raised as high as that of the next-lowest limiting factor.

Nitrogen is placed in a different category because it becomes available to the crop mostly as water-soluble nitrate, whether from the soil's supply of organic matter or from added fertilizer. The nitrate is highly mobile, it can move toward the roots, and its availability within the root zone is virtually 100 per cent. On the other hand, phosphorus and potassium are stored in relatively immobile forms in the soil. The plant roots have to forage for them. The more favorable the soil conditions physically and the more nearly optimum the

moisture supply, the better the development of the root system and the greater its foraging capacity.

On this basis one might assume that, even though the phosphorus and potassium supplies in the soil were relatively low, the plant roots could obtain adequate supplies of these nutrients by extensive foraging.



Photograph and fertilizer suggestions by James H. Fischer, Beet Sugar Development Foundation, and Robert Gardner, Agr. Exp. Sta., Fort Collins, Colorado

FIG. 95. Sugar-beet production with irrigation in Colorado is closely related to the livestock-feeding industry. From 50 to 60 per cent of the beet acreage receives between 10 and 20 tons of manure an acre before plowing. There is little evidence of potassium deficiency. The average fertilizer recommendation is 40 pounds of nitrogen and 60 pounds of P_2O_5 with 12 tons of manure, or 80 pounds of each where no manure is used.

But Bray points out that "if, for example, potassium is only 80 per cent sufficient for a given crop, it will restrict yields by a[illegible]0 per cent over a wide range of productivity." That is, the roots will forage over a larger area and the plant will contain more potassium, but it will still fail by that amount to get what could be used to advantage. This is what he terms "elastic availability," in contrast with the total availability of nitrate nitrogen.

This suggests that the supplies of such elements as phosphorus, potassium, calcium, and magnesium, as well as those of most minor elements that might be in deficiency, should be raised to relatively high levels, since they are readily stored for plant use. The same

might apply, at least in part, to the nitrogen that is contained in the soil in the form of organic matter. It does not apply to nitrogen that is added to the soil in inorganic forms, especially nitrates.

SOIL TESTS NEEDED IN DETERMINING FERTILIZER APPLICATION

On the basis of Bray's concept, it follows that one needs to know the total quantities of the immobile but available or exchangeable forms of phosphorus and potassium that are present in the soil. He needs to know also how variations in these quantities are related to yields under each given set of soil, crop, and climatic conditions. He can then calculate what quantities are necessary to be added to the soil to raise the yields to the point that appears most economic.

In obtaining such values, Bray made use of plot tests on 23 Illinois experimental farms. To establish correlations between crop yields and potassium supplies, plots that had been limed and phosphated (LP plots) were compared with plots that had not only been limed and phosphated but had received applications of potash as well (LPK plots). The LP plots, so far as was known, represented areas that were "fully fertile, except for potassium." They had received, over the years, regular applications of limestone and rock phosphate. Legume green-manure crops and residues of grain crops had been plowed under. Presumably, a lack of potassium was the primary limiting nutrient. The extent to which its lack did limit yields was readily determined by comparing the yields of the LP plots with those of the nearby LPK plots, to which potassium had been applied at an annual rate of 100 pounds KCl (50 per cent K_2O) an acre. The evidence indicated that this quantity of potassium was adequate, even on the soils that tested lowest in this element. The yields on the LP plots were expressed as percentages of those on the LPK plots. The data for potassium in Table 147 were established by this procedure, and similar data for phosphorus are shown in Table 148. Attention is called to the fact that Bray's proportionality factor (c) differs for each crop. According to Willcox, this is not permissible under the Mitscherlich law.

Bray's next problem was that of determining how to correlate the nutrient test with the fertilizer requirement. He found that, for the two experimental fields that were lowest in available potassium, an application of 400 pounds KCl each 4-year period had apparently

TABLE 147

RELATION BETWEEN SOIL K VALUES AND PERCENTAGE CROP YIELD (BRAY)

Available K, Lb.*	Corn † $c = 0.0065$, Per Cent	Soybeans $c = 0.0077$, Per Cent	Wheat $c = 0.012$, Per Cent
40	45	51	66
60	60	65	80
80	70	76	90
100	78	83	94
130	85	90	97
150	90	93	98
200	95	97	..
300	98	..	..

* In plow depth of 1 acre.
† Also includes clovers. c = proportionality factor.

given optimum yields for the conditions that existed. These soils showed by test approximately 50 pounds exchangeable potassium in the plowed acre. It was assumed, therefore, that any soil testing lower than 50 pounds available potassium would need more than 100 pounds KCl an acre annually during the rotation, and that any soil testing higher than 50 pounds would need less. It is on this basis that the data shown in Table 149 were established.

TABLE 148

RELATION BETWEEN SOIL P VALUES AND PERCENTAGE CROP YIELD (BRAY)

Available P, Lb.*	Corn $c = 0.015$, Per Cent	Soybeans $c = 0.017$, Per Cent	Wheat † $c = 0.009$, Per Cent
36	71	76	53
50	82	86	65
60	87	90	71
70	91	93	75
80	94	95	81
90	96	97	84
110	97	98	90
125	98	..	93
170	..	..	97
190	..	..	98

* In plow depth of 1 acre.
† Also includes clovers. c = proportionality factor.

TABLE 149

SUGGESTED ACRE APPLICATION K_2O ON BASIS SOIL TEST (BRAY)

Available K, Lb.*	Corn, Lb.	Soybeans, Lb.	Wheat, Lb.
40	76	47	31
60	68	42	25
80	62	36	18
100	55	31	12
130	46	23	..
150	37	18	..
200	20	..	..

* In plow depth of 1 acre.

TISSUE TEST USED IN DETERMINING NITROGEN NEEDS

The problem still remained as to how to proceed in determining when and how much nitrogen to supply. Although this element can be stored in the soil in potentially available form, it is only as it is released in the ammonia and nitrate forms that it contributes, in any large way, to the need of the corn plant. But even when this has been done, the supply is not enlarged as the foraging power of the plant roots is increased. The answer to this problem appears to lie in testing the plant tissues for nitrate from time to time, and adding extra nitrogen as required by the tests.

There is, of course, the possibility of plowing under a heavy crop of some leguminous green-manure crop, such as sweet clover. The nitrogen from such a crop is yielded up to the next crop more or less in proportion to the crop's need for it. Thus, as the soil warms up during the summer and the rate of growth of the crop increases, the rate of delivery of the soil's nitrogen to the crop is correspondingly speeded up.

By and large, however, it is not feasible to try to maintain an adequate supply of readily decomposable organic matter in the soil to meet the nitrogen needs for very high acre yields of crops. Neither is it advisable to apply large enough quantities of the inorganic forms of nitrogen at the beginning of the season to meet the entire requirements of the crop. Such practice defeats its purpose in that it tends to result in the development of an abnormally large early top-growth of plants at the expense of their roots. The best procedure is to apply extra nitrogen in a readily available state when the test indicates a need for it. This can be in the form of a nitrate, an ammonium salt,

or anhydrous ammonia, the time of application and placement of the fertilizer varying with the material used.

SANDY SOILS PRESENT SPECIAL PROBLEM

It is important to keep in mind that there are large acreages of sandy soils, notably on the coastal plains along the Atlantic Ocean and the Gulf of Mexico. These soils have relatively low exchange capacities. Under such conditions, nitrogen and potassium tend to fall into much the same category, in that neither can be stored in the soil in adequate amounts to meet the needs for high acre yields of crops over an entire season. It becomes necessary, therefore, to consider both of these elements in terms of supplemental applications during the course of the growing period.

Under such circumstances, heavy applications of potassium at the start of the season tend to result in luxury consumption of this relatively expensive element in place of other lower-cost basic elements, such as calcium and magnesium. Large amounts of these less expensive elements can be stored in soils of high exchange capacity, where they serve to counteract the tendency of the plant to absorb more potassium than it needs. In sandy soils no such possibility exists. If heavy applications of potassium are made at the start of the season, large excesses of the element are harvested with the crop. This means unduly heavy costs of production and a lowering of the mineral quality of the crop.

The possibility of what Willcox calls "far-end-depression" effects on the growth curve must be kept in mind in dealing with sandy soils. These effects are related largely to the lack of buffering materials, such as clay and organic matter, in sandy soils. In the absence of such materials to serve as storage agents it becomes necessary to apply fertilizers in frequent small doses throughout the growing season. It is important also that extra supplies of water be made available by irrigation. The only other possibility lies in the use of very heavy applications of well-rotted manure or compost as a means of storing both plant nutrients and moisture.

FERTILIZER USE AND CROP YIELDS IN THE UNITED STATES

The Fertilizer Work Group of the National Soil and Fertilizer Research Committee has made a detailed study of current usage of liming materials and fertilizers on 547 million acres of cropland in the United

States (Table 150). Estimated crop acreages in the United States and consumption of nutrients by crops are shown in Table 151.

TABLE 150

AVERAGE ACRE RATE OF USE OF N, P_2O_5, K_2O, AND CaO IN UNITED STATES AND NORTHEASTERN REGION (PARKS)

	N Lb.	P_2O_5 Lb.	K_2O Lb.	CaO Lb.
United States	4	9	5	192
Northeastern Region	8	20	13	251

TABLE 151

ESTIMATED FERTILIZER USE BY CROPS IN THE UNITED STATES (PARKS)

Crop	Total Acreage, 1000 Acres	Nutrient Applied			
		N, tons	P_2O_5, tons	K_2O, tons	Lime, tons
Corn	82,496	286,808	442,884	292,464	
Sorghum	10,363	4,533	4,293	1,798	
Wheat	68,447	65,037	220,382	102,047	
Rye	1,833	2,770	13,290	5,015	
Barley	12,249	36,252	23,654	9,515	
Oats	39,600	55,677	162,648	85,950	
Soybeans	12,889	2,310	27,685	22,879	
Rice	1,618	11,665	5,350	2,880	
Peanuts	2,819	4,346	20,098	12,578	
Cotton	18,649	157,926	138,457	89,687	
Tobacco	1,611	32,582	72,205	57,107	
Sugar beets	1,007	15,322.5	20,325	4,953	
Sugar cane	353	5,492	1,028	2,455	
Flaxseed	2,334	2,774	5,492	1,661	
Dry beans and peas	647	1,345	2,306	.....	
Seed and specialty crops	477	5,183	3,445	200	
Potatoes	1,813	43,685	69,295	65,170	
Vegetables	5,096	107,977	163,024	112,653	
Fruits	5,226	108,354	59,590	54,746	
Hay	57,422	19,114	229,476	54,941	18,843,528
Pasture	220,002	39,263	359,977	87,618	5,329,195

* All lime applications to land other than pasture are assumed to have been to hay land. Tonnages include all alkaline forms of lime.

SELECTED REFERENCES

1. Bear, Firman E. Cation and anion relationships in plants and their bearing on crop quality. *Agron. J.*, Vol. 42, pp. 176–178, 1950.

2. Bray, Roger H. Correlation of soil tests with crop response to added fertilizers and with fertilizer requirement. *Diagnostic Techniques for Soils and Crops*, American Potash Institute, Washington, D. C., pp. 53–86, 1948.

3. Parks, R. Q., and Associates. Fertilizer use and crop yields in the United States. Fertilizer Work Group, National Soil and Fertilizer Research Committee, Report No. 5 (Preliminary draft), 1951.

4. Spillman, W. J. Use of the exponential yield curve in fertilizer experiments. U. S. Dept. Agr. Tech. Bull. 348, 1933.

5. Spillman, W. J., and Emil Lang. *The Law of Diminishing Returns*. World Book Co., New York, 1924.

6. Willcox, O. W. *ABC of Agrobiology*. W. W. Norton and Co., New York, 1937.

7. Willcox, O. W. Verification of the Mitscherlich effect law. *Agron. J.*, Vol. 41, pp. 225–229, 1949.

8. Willcox, O. W. Quantitative agrobiological evaluation of some phosphate fertilizer tests with vegetable crops in Alabama. *Agron. J.*, Vol. 43, pp. 83–90, 1951.

9. Willcox, O. W. One-plot fertilizer test III, *Sugar*, 46, No. 9, 1951.

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Miscellaneous Topics

A variety of other problems is presented in the manufacture and use of fertilizers, detailed discussions of which do not fall into any very well-defined category. For example, marked success has been attained in the production of highly stable granules of hygroscopic fertilizer materials, and the question has been raised as to whether these processes can be applied advantageously to the production of complete fertilizers.

GRANULATION OF COMPLETE FERTILIZERS

The drillability of fertilizer materials and mixtures often leaves much to be desired. A great deal of effort has to be put into their processing to avoid stickiness and caking. Most manufacturers of mixed fertilizers add small amounts of some type of conditioning agent. This may be dolomitic limestone, calcium cyanamide, hydrated lime, tobacco stems, or any one of a great variety of other inorganic or organic conditioners, such as alkyl aryl sulfonate.

Many mixed fertilizers have excellent drillability, and no difficulty whatever is experienced in applying them evenly along the row or broadcast over the field. Thorough mixing, cooling, curing in the pile, and regrinding have been employed in their processing. But much depends on the weather conditions at the time these operations are taking place.

The ideal answer to this problem lies in the production and mixing of granular materials or in the granulation of mixtures of materials. If the separate materials are granulated, the granules must be of approximately the same size and shape, otherwise segregation will take place between factory and farm, and even in the fertilizer drill.

That granulation can be effected and maintained even with hygroscopic materials has been amply demonstrated with sodium and ammonium nitrates. The spherical granules of these materials that are

now being produced are so stable that even when they are exposed to moist air for considerable periods of time hard cakes do not form.

Granulated complete fertilizers, in which the mixtures rather than the separate materials are processed, are also on the market, but in only relatively small tonnages to date. Considerable extra expense is involved in their production, and the advantages must be measured against this added cost. It becomes less troublesome as higher analyses are produced. Thus, the cost of granulating a unit of nutrients is much less for a 12–24–12 than for a 6–12–6 grade. The fact that uniform distribution increases the effectiveness of fertilizers, especially when used in relatively small amounts, weighs heavily in favor of granulation.

CONCENTRATED FERTILIZERS

Low-analysis fertilizers have been especially popular in the southern states. This is in part explained by the South's proximity to Florida, the source of phosphate, and to the seacoast, where shipments of potash fertilizers from Europe were readily available close at hand. With the spread in the use of fertilizers away from the coast; heavier rates of application in the intensive farming areas; development of the American potash industry in distant New Mexico; and the opening up of large phosphate deposits in the far west, more interest in concentrated fertilizers began to develop.

The first move toward increased concentration was made by the superphosphate industry. The raising of the 2–8–2 to the 2–12–2 grade fitted in nicely with that industry's needs. The producers advocated high-analysis fertilizers to sell more superphosphate. In due time it became apparent that this extra phosphate needed to be balanced with more potash, and so analyses such as the 2–12–6 came into existence. As more nitrogen became available, such analyses as the 6–12–6 were developed. When concentrated fertilizers came into the [illegible]. "double-strength" mixtures, such as the 12–24–12, were made. Here again the trend was soon toward equalizing the contents of N, P_2O_5, and K_2O, and so analyses such as the 10–10–10 were developed. Since often it was not desirable to add all the nitrogen in one application, a need developed for a grade like the 5–10–10 and its high-analysis relative, the 10–20–20.

One disadvantage of concentrated fertilizers lies in the reduction in the ainounts of the secondary and trace elements they contain. Concentration is, in effect, a purification process. Thus, substituting am-

monium nitrate for ammonium sulfate eliminates sulfur. Use of double superphosphate instead of the ordinary 20 per cent grade eliminates calcium sulfate. Purification of crude potash salts to the point where they contain 60 per cent K_2O does away with such salts as sodium and magnesium chlorides and sulfates. The likelihood of the product's containing any very large amounts of trace elements is reduced as increased concentration is effected.

It is known that much more calcium sulfate is contained in the ordinary fertilizer grades than is required to meet the sulfur needs of plants. It is also apparent that to depend on fertilizer impurities to supply the necessary minor elements is a hit-and-miss system that could be improved upon. In general, it can be expected that fertilizer analyses will gradually move upward to much higher levels than many of those now being used, and that such secondary and trace elements as are required will be added in proportion to the need for them.

BULK APPLICATION OF FERTILIZERS

As applications of fertilizers increase to 1000 pounds or more an acre, interest grows in the possibility of lowering costs and reducing farm labor through the use of bulk distribution direct from factory to farm. Great improvement has been effected in trucking and distributing machinery for limestone, and this same type of combination truck and distributor is being employed with fertilizers.

Where the intention is to maintain the fertility status of the entire plowed volume of soil at a high level, there is no good reason why bulk application should not be employed. The fertilizer can be applied either before or after plowing or cultivating the land in preparation for planting the crop. The safest procedure for the trucker is to apply the fertilizer to sod or cover-crop land before the soil is plowed or worked with a toolbar cultivator. Yet it is often desirable that such applications of fertilizer be located in the plow depth of soil rather than to have them turned completely under.

The bulk system is almost ideal for topdressing haylands and pastures with liberal amounts of fertilizer. It can be used to good advantage in orchards and groves. Where the terrain is rough or where vast expanses of land are to be covered, the airplane is being substituted for the truck. By the use of the airplane or helicopter one avoids running over the land with heavy trucks. Since bad weather interferes greatly with the use of truck distributors and often leads to their

being used when the ground is too wet, more consideration will no doubt be given to the use of flying distributors.

DIRECT USE OF ANHYDROUS AMMONIA

Cotton and cane farmers in the Mississippi Delta have long been practicing a nitrogen-only type of fertilizer program. These rich alluvial lands are normally well supplied with available phosphorus



Photograph by Hunter V. Herndon, Development Manager, Suburban Farm Service, Whippany, New Jersey

FIG. 96. Tractor attachment for use in making applications of anhydrous ammonia, which is released through small tubes in the tips of soil openers that [illegible] it between 4 and 6 inches deep. Ammonia must not be allowed to escape [illegible] the picture, because it kills leaves.

and potassium. The primary need in most southern locations is for nitrogen. Accordingly, large tonnages of nitrate of soda, sulfate of ammonia, ammonium nitrate, and calcium cyanamide have been purchased and applied.

In due time Andrews and his associates saw important possibilities in using anhydrous ammonia, since it can be synthesized and delivered to the user at a lower cost a unit of nitrogen than any other synthetic

form of air-nitrogen fertilizer. Already large tonnages of liquid ammonia were moving into fertilizer factories where it was being tied to superphosphate to form solid fertilizer. It was soon demonstrated that this liquid ammonia could likewise be delivered to the farm and placed directly in the soil (Table 152), and rapid development of this practice has taken place.

TABLE 152

COMPARISON ANHYDROUS AMMONIA AND AMMONIUM NITRATE AS SOURCES OF N IN 11 TESTS ON CORN IN MISSISSIPPI (ANDREWS)

Material and Placement	Plants an Acre	Acre Rate N,* Lb.	Acre Basis	
			Yield, bu.	Increase, bu.
Anhydrous ammonia				
Preplant and early sidedressing	16,000	300	75.8	48.2
Preplant and early sidedressing	12,000	200	79.2	51.6
Late sidedressing	8,000	100	70.3	42.7
Early sidedressing	8,000	100	68.0	40.4
Preplant	8,000	100	68.8	41.2
Ammonium nitrate				
Preplant and early sidedressing	12,000	200	77.8	50.2
Preplant and early sidedressing	8,000	100	68.4	40.8
Late sidedressing	8,000	100	71.2	43.6
Early sidedressing †	8,000	100	67.9	40.3
Preplant	8,000	100	63.3	35.7
No nitrogen	8,000	...	27.6	....

* Applied at depth of 5 inches, except for early sidedressing of ammonium nitrate,† which was applied on the surface.

But in the greater part of the country the need is for phosphorus and potassium as well as nitrogen, and the question is as to how far extra applications of nitrogen in the form of anhydrous ammonia can be used to advantage. It is quite apparent that, by and large, a seriously limiting factor to maximum crop production is the lack of adequate supplies of nitrogen at the right period of the crop season. There is abundant evidence that mid-season applications of nitrogen can be used to marked advantage to supplement at-planting applications of complete fertilizer on cotton, corn, cane, wheat, grasslands, and vegetable crops.

Anhydrous ammonia can readily be used for this purpose, especially on those crops that are planted in rows sufficiently far apart to permit of applying the material in bands between them. The usual procedure is to have a high-pressure tank of the gas attached to a tractor, with tubes running down to openers that penetrate the soil to a depth of at least 4 inches. Ammonia is held by the soil with little danger of loss from leaching until it has been changed to nitrate. This change is usually delayed for some time, since the ammonia has a partial sterilizing effect on the soil in the immediate vicinity of its point of contact with it.

LIQUID FERTILIZERS

In place of anhydrous ammonia it may be found desirable to use the highest concentration of a salt form of nitrogen in water that can be developed. One such liquid fertilizer is made up of 35.7 per cent urea, 44.3 per cent ammonium nitrate, and 20 per cent water, and contains 32 per cent nitrogen (N). A small amount of ammonia is added as an inhibitor to corrosive action on metals. Crystals do not form until the temperature drops to 32° F. The solution has no vapor pressure at ordinary temperatures. It will take up moisture at relative humidities above 18, and apparently can be applied directly on plants like wheat without burning the foliage. Such a product has important advantages over a liquefied gas like anhydrous ammonia. It is less troublesome to handle and it can readily be stored for continued use. No doubt there are plenty of situations in which it and others like it will find important places in the fertilizer program.

Considerable interest has developed in the use of urea as an added constituent of sprays that are applied to fruits and vegetables for control of insects and diseases. For apples, the recommended dosage is 5 pounds in 50 gallons water. Up to 30 pounds have been used in that amount of water to advantage on citrus. For tomatoes [illegible] pound rate seems best, but 10 pounds in 50 gallons can be used on potatoes. Lower concentrations appear preferable on turf, ornamentals, and plant beds. One of the great advantages of these spray applications lies in the almost immediate effect on the plant, usually with marked improvement in color. This is of special interest to producers of leafy vegetables. In some cases, liquid complete fertilizer is to be preferred over one that supplies nitrogen only.

Liquid ammonia and phosphoric acid (H_3PO_4) are being fed into irrigation streams in arid regions. Their distribution is readily effected

by the water with satisfactory results. With lack of precaution, however, concentrations of both are somewhat higher near the point of entrance of the water to the irrigated area than at the ends of the water channels. There is also the possibility of considerable loss of ammonia by volatilization if the water or soil have *p*H values higher than the neutral point.

Some data obtained by Tiedjens and associates suggested that possibly liquid complete fertilizers, such as are employed for starter solutions, could be used to considerable advantage at planting time as substitutes for dry fertilizers for tomatoes and other vegetables. The point made was that the quantity of fertilizer required for an acre could be materially reduced by this procedure. It now appears that this applies only to conditions in which large reserves of the nutrient elements have been built up in the soil as a result of heavy applications of manure or fertilizer over a period of years. In other words, there is little reason to believe that small amounts of fertilizer in liquid form can replace the larger amounts that have long been used in dry form.

For highly specialized purposes, however, such as producing plants for transplant or growing potted plants, garden flowers, and vegetables, frequent use of small amounts of complete fertilizer in liquid form gives excellent results. This is notably true in sandy soils. Such a practice gives quick results and tends to avoid overfeeding. The extra water that is applied with them may have considerable value in itself. In general, liquid fertilizers find their most important place in highly specialized types of plant growing rather than in the production of large acreages of field crops. The formula for one of the popular fertilizers that is being used in liquid form is shown in Table 153.

NITROGEN TOPDRESSING FOR WHEAT

The practice of topdressing wheat with nitrogen fertilizers has grown to considerable volume in Ohio and Indiana, two important central-western wheat states. The Ohio Agricultural Experiment Station has carried on topdressing tests for 20 years, with somewhat erratic results. Surveys have indicated that when the rainfall of the previous summer was normal or higher, good results were obtained. After dry summers, applications of nitrogen did not give dependable results.

More exact studies showed that if the available nitrogen in the soil was 30 parts per million or more in early spring, nitrogen topdressings

TABLE 153

EXAMPLE OF SOLUBLE COMPLETE FERTILIZER * CONTAINING TRACE ELEMENTS AND HORMONE

Nutrient Element	Salt Form Used in Mixture	Expressed As	Guarantee, Per Cent
Nitrogen	Urea †	N	16.00
Phosphorus	Ammonium phosphate	P_2O_5	16.00
Potassium	Potassium nitrate	K_2O	16.00
Calcium	Calcium phosphate	CaO	5.24
Molybdenum	Ammonium molybdate	MoO_3	0.088
Boron	Sodium borate	B_2O_3	0.19
Magnesium	Magnesium sulfate	MgO	0.26
Manganese	Manganese sulfate	MnO	0.166
Iron	Ferrous sulfate	Fe_2O_3	0.152
Copper	Copper sulfate	CuO	0.166
Zinc	Zinc sulfate	ZnO	0.078
Hormone	Naphthalene acetic acid	.....	.....

* Produced by Miller Chemical and Fertilizer Corp., Baltimore. The standard recommendation is 6 pounds in 100 gallons water, applied at seeding or transplanting time or as a spray or sidedressing.

† Note that N is supplied also as ammonium phosphate, ammonium molybdate, and potassium nitrate. Naphthaleneacetic acid is of special value for establishing roothairs on seedlings and transplants.

did not pay. If they were below 20 parts per million, yield increases of the order of 10 bushels an acre were obtained from the use of 25 to 40 pounds nitrogen (N) an acre, when applied before April 15.

Since the advent of the cornpicker and the combine, much more low-nitrogen organic matter is being added to the soil. This greatly alters the situation, since the microorganisms that decompose these materials require more nitrogen than they supply. Thus, the microorganisms compete with the planted crop for the available supply of nitrogen in the soil.

Much of the original nitrogen and organic matter in the soils of this area have been used up, and a large percentage of the farmers have not developed adequate methods for their replacement. The Indiana Agricultural Experiment Station suggests the use of 25 pounds of nitrogen (N) an acre for wheat for silt-loam soils and up to 40 pounds on light-colored sandy soils. Karraker reports that yield increases from nitrogen sidedressings in Kentucky will be of the order of ⅓ to ½ bushel of corn, ¼ to ⅓ bushel of small grain, 5 to 6 pounds of tobacco, or 30 to 40 pounds grass hay for each pound of nitrogen (N) applied, at rates of application of 30 to 40 pounds an acre.

Two important reasons for some hesitancy in the use of nitrogen as a topdressing on wheat are the fear of lodging of the wheat and of possible bad effects on stand of clover seeded in the wheat. But there is substantial evidence that neither of these difficulties is due to the extra nitrogen as much as to a deficiency of potassium. In proportion as more nitrogen is applied, more potassium is required, and the wheat



Photograph and fertilizer suggestions by H. R. Lathrope, Agr. Exp. Sta., Lafayette, Indiana

FIG. 97. In fertilizing wheat in Indiana enough fertilizer is applied to meet the needs of both the wheat and the legume seeded in it. The use of 500 pounds of 5–20–20 is suggested. In one test the yields were: no fertilizer, 7 bushels; 500 pounds of 5–20–20, 29.8 bushels; 500 pounds of 5–20–20, plus 25 pounds of nitrogen applied in the spring, 31.5 bushels; and with 50 pounds of nitrogen, 38.5 bushels.

becomes a serious competitor of the clover for the available potassium in the soil.

Nitrogen topdressings are equally effective on oats, barley, and rye. In general, the farther north and the farther west toward the desert in the United States the less the response to nitrogen topdressings on small grains. Conversely, the farther east and the farther south the greater the response, all other conditions being equal. The evidence suggests the use of 20 to 40 pounds of nitrogen an acre as an early spring topdressing for all small grains as far west as Central Kansas, except after very dry summers.

It is important also to consider the effects of nitrogen topdressings on the production of grass seed. The Kentucky Agricultural Experi-

ment Station reports that early-spring applications of 200 pounds ammonium nitrate an acre doubled the yields of Kentucky 31 fescue seed and of commercial orchard grass seed. Almost equally good effects were observed with the forage, the untreated fescue and orchard grass plots yielding only about 60 per cent as much as those receiving the ammonium nitrate. Workers in Rhode Island, Virginia, Georgia, and Oregon have reported equally marked increases in grass-seed yields from the use of nitrogen topdressings.

CHLORINE IN FERTILIZERS

Most of the potassium in fertilizers is in the form of the chloride, which is much less costly to produce than the sulfate, nitrate, or phosphate of potassium. Considerable amounts of sulfate of potash-magnesia are being produced, but no large-scale production of the nitrate or phosphate is known to be under contemplation. If nitric acid is

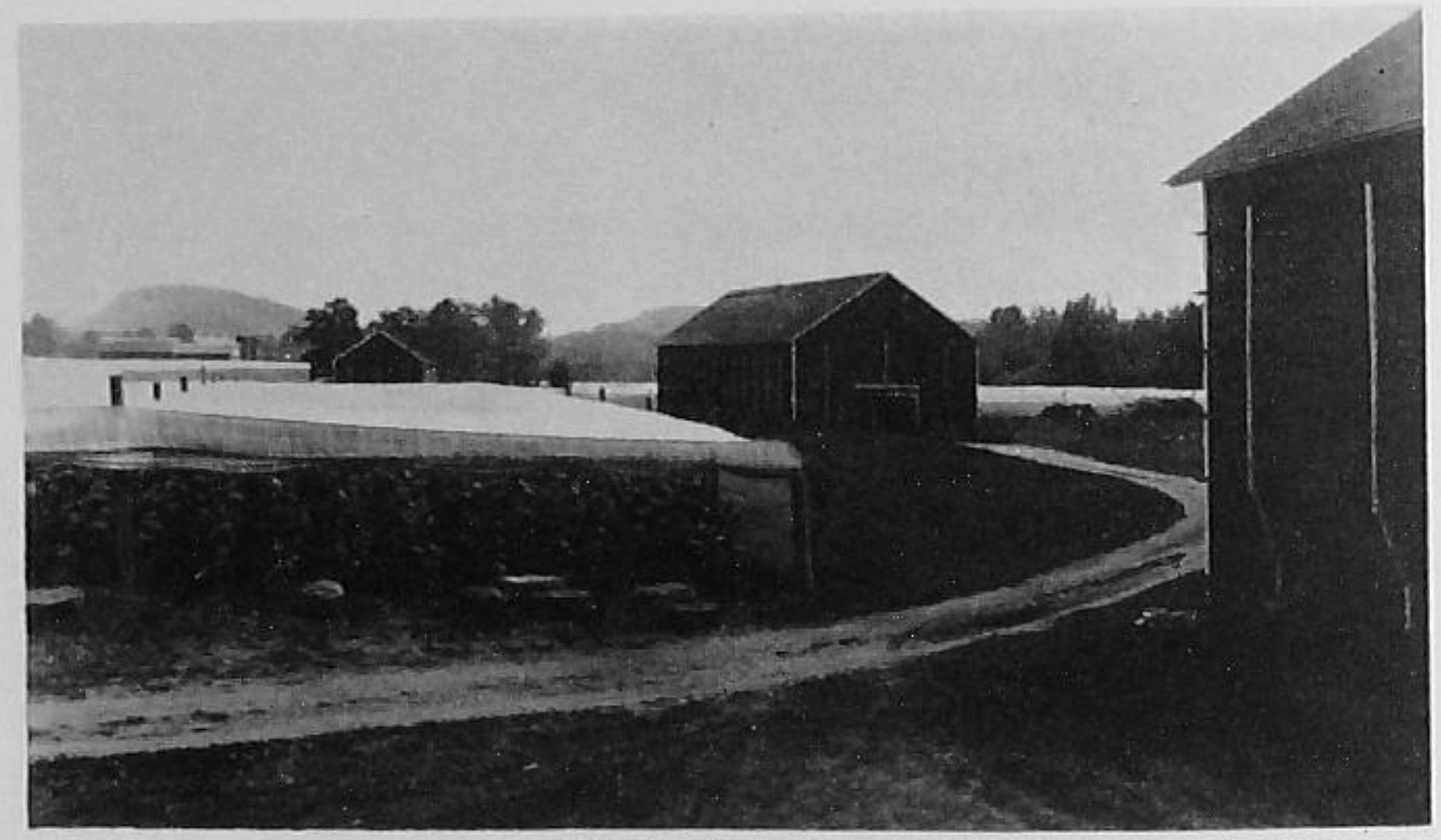


By A. E. Kretschmer and S. J. Toth, New Jersey Agr. Exp. Sta.

FIG. 98. Radioautograph of snapbeans showing distribution of Cl^{36}. Note concentration in flower buds, stems, and root nodules.

ever used for the production of superphosphate, however, potassium nitrate could be made as a part of this procedure.

The evidence on chloride versus sulfate of potash is somewhat confusing. In general, the chloride tends to produce somewhat higher yields than the sulfate, but there is evidence that the quality of the



Photograph and fertilizer suggestions by P. J. Anderson, Tobacco Agr. Exp. Sta., Windsor, Connecticut

FIG. 99. For shade tobacco, 200 pounds of nitrogen, 100 pounds of P_2O_5, and 200 pounds of K_2O an acre should be applied in such analyses as the 6–3–6 or 8–4–8. About 75 per cent of the nitrogen should be in cottonseed meal or similar high-grade organic ammoniate. Bonemeal is the preferred source of phosphoric acid. Potash may be applied in carbonate, nitrate, or sulfate form, but never as chloride. Use of 60 pounds of magnesia (MgO) is recommended, subject to soil test. The quality of tobacco may be improved by adding small amounts of borax.

produce is not as high as when the sulfate is used. The best known example of this is tobacco. Tobacco growers in the southern states are cautioned not to use fertilizer containing more than 2 per cent chlorine and those in Connecticut are advised not to use any chloride.

Sugar beets and potatoes are two other crops, the quality of which is said to be improved by substituting sulfate for chloride of potash. Marked increase in yield of beets is obtained by the use of sodium chloride, but this appears to be due to its sodium rather than its chlorine. Yet there is some evidence indicating that chlorides tend to protect plants somewhat against drought, the chloride-containing plants tending to maintain a higher moisture content.

Chlorine is essential to the production of red, violet, and blue pig-

ments in plants, being a constituent of the authocyanins. As to how important this may be either in relation to quality or yield of plants remains to be determined.

Chlorides are of special interest in relation to the principle of anion constancy in plants. The ion is highly mobile and moves into the plant in competition with other anions, notably nitrate. The sulfate ion, being much less mobile than either the chloride or nitrate ions, is much less troublesome from this point of view.

Halophytic plants, which developed this tendency as a result of exposure to salt either in the soil or from ocean spray, grow best under such an environment. In its absence, applications of salt are beneficial.

Studies of radioactive chlorine show that the element tends to concentrate in the veins and floral parts of bean plants and in the nodules on their roots. Much more study is required before the possible function and importance of this element in plants can be established.

NITROGEN FERTILIZERS FOR LEGUMES

Nitrogen is frequently added to fertilizers that are to be used in establishing new seedings of legumes. This practice seems to be especially important with alfalfa when it is seeded on soil not well supplied with organic matter. The explanation of the good effects of this practice lies in the fact that a week or more is required after the seedlings are started before the nodule bacteria can begin functioning. In the interim, some extra nitrogen is required to tide over the young seedlings.

Another standard use of nitrogen on legumes is in connection with the production of snapbeans, peas, and lima beans, notably in market-gardening. As a result of its use, a higher-quality product, a higher yield, and extra earliness to market are realized. The returns on the investment in nitrogen are such as to make it illogical to wait for the nodule bacteria to become established or even to depend on them after they have begun to function. In regions of less intensive production of these crops for the cannery only relatively small amounts of nitrogen are being used, and more attention is being paid to inoculation of the seed.

Nitrogen applications have been suggested for soybeans that are being grown on relatively poor soil. The thought is that, at the seed-production stage, the nodule bacteria alone may not be able to fix ade-

quate amounts of nitrogen for maximum yields. Solution-culture experiments indicate the validity of this concept. The data suggest that, unless the soil contains a reasonably large amount of available nitrogen that has been derived from organic matter, fertilizer nitrogen is required.

Many farmers topdress their alfalfa with manure, and to very good effect. In lieu thereof, it is common practice in some areas to apply complete fertilizer after the first crop of each season has been harvested. The question that arises is as to whether the good results that are usually obtained are due to the nitrogen in the manure and fertilizer or to the other elements, especially potassium. A 10-ton application of cow manure supplies about 100 pounds each of nitrogen (N) and potash (K_2O), and half that quantity of phosphoric acid (P_2O_5). It is known that the use of either nitrogen fertilizer or manure increases the percentage of grass in alfalfa-grass mixtures. Extra potash favors legumes more than grasses.

Studies of molybdenum as an essential trace element for alfalfa suggest that possibly a lack of this element may limit the efficiency of the nodule bacteria. Substantial increases in yield have sometimes resulted from the use of 1 ounce of molybdic oxide (MoO_3) an acre, when applied on the seed with the inoculant, or 1 pound sodium molybdate an acre applied broadcast. Additional molybdenum can usually be made available by liming the soil, and this has been found to be a highly important practice in growing alfalfa. If the alfalfa remains on the land for some years, topdressing with both lime and molybdenum may produce marked increases in yield. Possibly, if the supply of available molybdenum was adequate, applications of nitrogen would be of little value to well-established stands of this crop.

SYNTHETIC ORGANIC AMMONIATES

As the supplies of guano, slaughterhouse wastes, fish by-products, cottonseed meal, and other organic materials diminished relative to the total tonnage of fertilizers used (Table 154), and as other important uses were found for many of them, attempts were made to find satisfactory substitutes. Among these substitutes were calcium cyanamide and urea. Although these materials had some similarity to natural organics they did not resemble them to a sufficient degree to be accepted in their place.

The primary purpose of the natural organic ammoniate in the fertilizer is to supply nitrogen as the crop has need for it. The nitrogen

TABLE 154

NATURAL ORGANICS USED IN MIXED FERTILIZERS (CLARK)

Materials	Amounts Used Annually			
	1900, tons	1919, tons	1939, tons	1944, tons
Seed meals	151,000	269,000	139,000	130,000
Animal products	209,000	300,000	95,000	9,000
Process tankage	.....	10,000	93,000	105,000
Garbage tankage	103,000	116,000	31,000	15,000
Sewage products	.....	.....	57,000	115,000
Manures	.....	33,000	35,000	25,000
Plant materials	10,000	61,000	145,000	145,000
Peat	.....	25,000	40,000	40,000
Total	473,000	814,000	632,000	584,000
Organic N, % *	91.1	53.6	15.2	8.3

* Per cent of total nitrogen in mixed fertilizers.

of the organic material is not released as ammonia and changed to nitrate until the soil has warmed up in the spring and the crop has been planted. Then, as the crop grows, the nitrogen is gradually yielded up to it.

Some maintain that the necessary organic nitrogen can be stored in the soil in the form of crop residues and cover crops. In proportion as larger amounts of fertilizer are used and larger yields are produced, more roots and other residues are left behind in the soil. The evidence on this point is quite conclusive. The fact remains, however, that many farmers are planting crops on land that is extremely low in organic matter. This may be because of poor systems of soil management, because the soil is sandy and maintains only a limited [illegible] of organic matter, or because of a warm climate where the rate of decomposition of organic matter is very rapid and little accumulation takes place under any circumstances.

More recently, a great deal of attention has been given to reducing waste wood, trimmings from orchards, and various kinds of brush to chips for use as mulching material on the soil, sometimes after it has first been used for livestock bedding. The effects of these additions

are excellent, when the materials are rightly employed. Normally, no difficulty whatever is experienced, whether they are used first as livestock bedding or directly as mulches. If worked into the soil in considerable quantities in their crude state, extra nitrogen may be required to feed the microbes that effect their decomposition. Also, on heavy soils, some toxicity may be experienced, notably with material derived from pine trees.

Much interest has been aroused in "organic gardening," in which use is made of composts that are produced from plant and animal wastes and used with or without supplemental fertilizer, depending on the philosophy of the individual concerned. Notably good results are obtained from such composts, as is also true when animal manures and most types of sewage sludge are employed.

This widespread interest in organic matter adds continued interest to the possibility of providing larger amounts of organic ammoniates for use in mixed fertilizers. Since the quantities of natural organics that are available for use in fertilizers are relatively small, considerable attention has been directed to the possibility of producing materials of similar qualities synthetically. The most promising product so far developed is *urea-form*, a resin produced by combining urea with formaldehyde in such amounts and under such conditions as to yield a product that gives up its nitrogen in a manner analogous to that of high-grade natural organics. It remains to be determined to what extent products of this type may be produced for commercial use, either alone or as constituents of complete fertilizers.

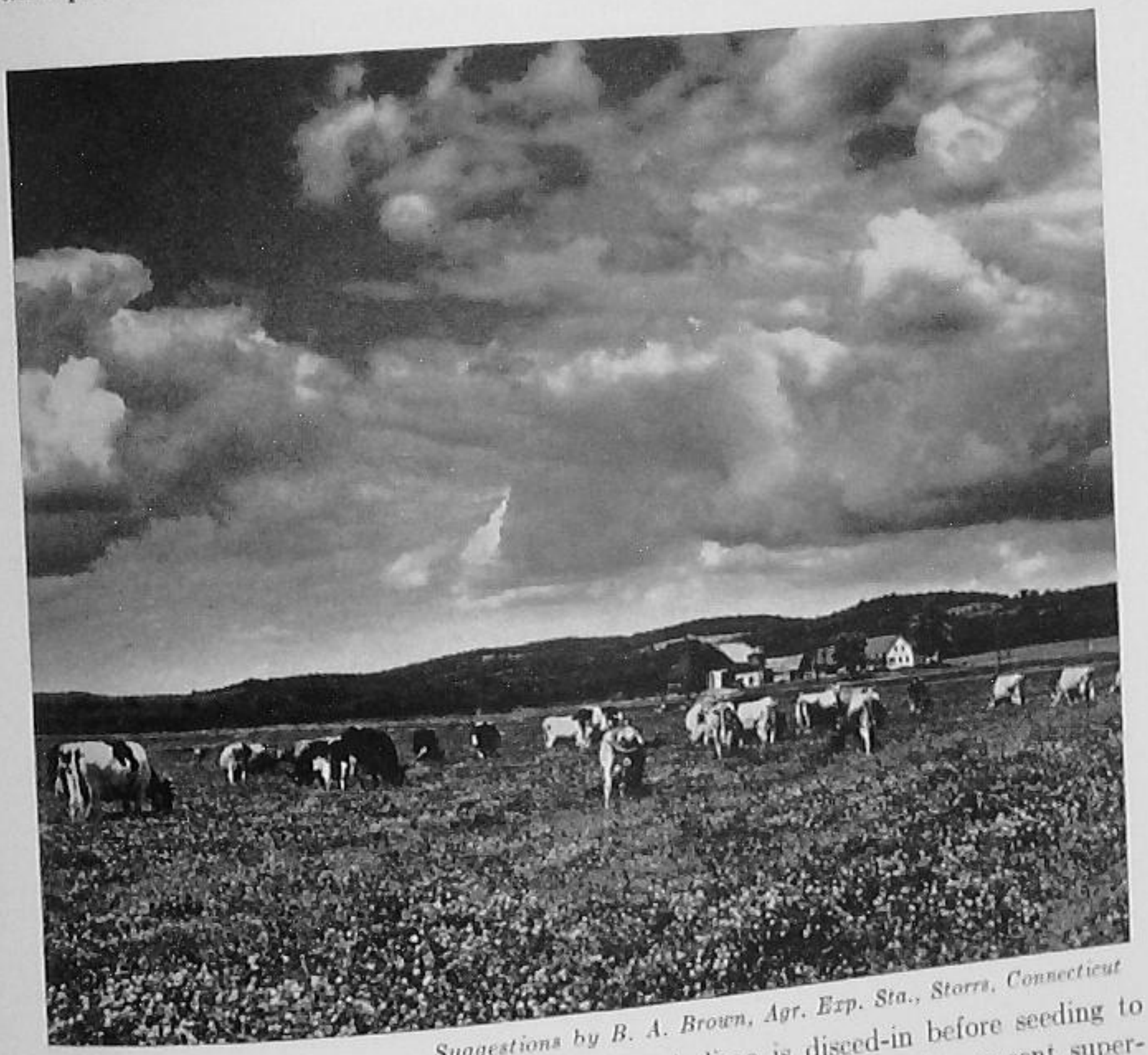
Another series of organic long-chain products is being produced for possible use as an aggregating agent in soils. When one of these is mixed with moist soil, granules are formed that tend to be considerably more permanent than those resulting from additions of organic matter of plant origin. This is because these products are highly resistant to microbial decomposition.

INTENSIVE GRASSLAND FARMING

Most pastures have been receiving relatively little fertilizer or any other type of soil amendment. But within recent years, and notably in areas of intensive milk production, large amounts of lime and fertilizer are beginning to be applied to them. The results from such practices have been quite remarkable in that better mixtures of grasses and legumes are being grown, the quantities of forage available for

grazing are much larger than formerly, and the quality of this forage, as reflected in milk yields, is greatly improved.

The general tendency is to assume that if sufficient lime, phosphate, and potash are applied to permanent pastures, the natural growth of



Suggestions by B. A. Brown, Agr. Exp. Sta., Storrs, Connecticut

FIG. 100. For ladino clover pastures enough lime is disced-in before seeding to raise the *p*H value to 6.5, and a minimum of 300 pounds of 20 per cent superphosphate and 100 pounds of 60 per cent muriate of potash are applied. If tests show that soil is low in phosphorus and potassium, the amounts of fertilizer are doubled. After seeding, 1 ton of limestone is suggested every fourth year and a minimum of 60 pounds of P_2O_5 and 120 pounds of K_2O annually.

white clover, or that of any ladino clover or other legumes that may have been sown in its place, will supply adequate amounts of nitrogen. If the stand of the pasture legume can be maintained at 50 per cent or more, the results are usually quite satisfactory. In proportion as it drops below this percentage, extra nitrogen can often be used to advantage. This nitrogen may be obtained from manure or it may be supplied in the form of fertilizer. For highest yields of these mixed stands of grass and clover, the normal practice is to use a complete

fertilizer in the late fall or early spring, and then to apply an additional quantity of nitrogen fertilizer after the first flush of forage has been grazed off. Fertilizers of the 10–10–10 grade have come into use on intensively managed grass-legume pastures, being applied normally at a rate of about 500 pounds an acre annually.



Photograph and fertilizer suggestions by J. A. DeFrance, Agr. Exp. Sta., Kingston, Rhode Island

FIG. 101. A 10–6–4 fertilizer made of 12.5 pounds of sodium nitrate, 25 pounds of ammonium sulfate, 50 pounds of "Milorganite," 22.5 pounds of 20 per cent superphosphate, and 6.7 pounds of muriate of potash is suggested for general-purpose use on Colonial, Creeping, and Velvet bentgrasses for golf greens, grass tennis courts, and bowling greens in New England. To eliminate clover, the potash is omitted. The rate of application is 10 pounds to 1000 square feet of area in early April, May, and September, and 5 pounds in early June, July, and August. An annual application of 25 pounds of dolomitic limestone is also recommended in early fall for slightly acid soils.

It has been the general impression that white clover disappears when nitrogen-carrying fertilizers are used on pastures. This may or may not occur, depending on the method of fertilization and pasture management (Table 155). To maintain the clover it is essential that potash be applied liberally and regularly and that close rotational grazing be followed. Thus, by applying the fertilizer in late fall or early spring, grazing the early spring growth closely, and using a mower from time to time as required to control the weeds and the

TABLE 155

Effect of N, P_2O_5, and K_2O * on Yield and Clover Content of Grassland (Eby)

Bluegrass-White Clover Pastures, Sussex, New Jersey

(Average Annual Acre Yield Dry Matter and Percentage Clover)

Field	Plot	Fertilizer *			Dry Matter an Acre, Lb.	Clover 1941, Per Cent	Clover 1945, Per Cent
		N, lb.	P_2O_5, lb.	K_2O, lb.			
1	1	0	50	50	2113	23	19
	2	25	50	50	3024	15	16
	3	50	50	50	3663	9	7
	4	100	50	50	3937	0	6
2	1	50	0	50	2514	6	8
	2	50	25	50	3154	21	10
	3	50	50	50	3417	16	9
	4	50	100	50	3431	15	8
3	1	50	50	0	2993	0	3
	2	50	50	25	3488	0	6
	3	50	50	50	3519	10	19
	4	50	50	100	3594	6	23
4	1	0 manure			2900	0	35
	2	$2\frac{1}{2}$ tons manure			3406	0	48
	3	5 tons manure			3820	0	54
	4	10 tons manure			3190	0	42

* Nitrogen was supplied as sulfate of ammonia one year and as calcium cyanamide the next. The P_2O_5 was supplied as 20-per cent superphosphate and the K_2O as muriate of potash. Limestone was applied to maintain *p*H levels between 6.0 and 6.5. The grass was close grazed with dairy cattle on a rotational basis.

grass around the urine spots, the clover stand can be maintained without difficulty. This is possible even if an extra application of 50 pounds of nitrogen is made later in the season.

Where pastures are rotated with tilled crops, and mixtures of grasses and legumes are reseeded from time to time, the need for nitrogen is largely eliminated. Under such circumstances, it is especially important to make liberal applications of potash to maintain the stand of legumes. This calls for the use of fertilizer grades of the 0–12–24 type, applied at the rate of about 500 pounds an acre annually.

FERTILIZERS ON COVER CROPS

Where manure is not available for use on the land and where the soil is kept under cultivation a large percentage of the time, as in highly intensive market-gardening, there is need for a well-developed system of growing organic-matter crops. These may be catch crops between cash crops or winter green manures. A 1-year-in-4 land-resting program is sometimes employed, in which the land is seeded to small grains, for harvesting, and to legumes and grasses that are permitted to grow up and fall back on the soil.

Since the purpose of all these is to provide extra organic matter for the soil, it seems logical that special effort be made to grow as much high-quality organic matter as possible. This can readily be accomplished by the liberal use of fertilizer. For the nonlegume types, such as rye winter cover, the use of a complete fertilizer of the 10–10–10 type at a rate of 500 pounds or more an acre, may be good practice. The nutrients thus supplied are stored in the larger amounts of organic matter produced by their use, and they are released when the cover crop becomes a part of the soil. Thus, the fertilizer is used twice, first to produce more organic matter and next to grow a cash crop the following season.

Where a whole year or a considerable part of a summer can be devoted to the production of a legume organic-matter crop, the nitrogen can be eliminated from the fertilizer. Often, excellent yields of such crops as soybeans or lupines can be grown for plowing-under purposes without any fertilizer except that remaining in the soil from previously fertilized cash crops. Even so, it is often surprising the extent to which additional growth can be obtained by the supplemental use of lime and fertilizer for the legume crop itself.

The important feature of this practice is the transformation of mineral fertilizers into organic manures. Once the organic-matter crop becomes a part of the soil, it has an effect quite similar to that of a liberal application of well-rotted manure. If summer-grown organic matter is left on top the ground during the winter, a large part of it will have disappeared by the following spring, having been decomposed by the soil microorganisms. In many ways, it is better to grow a crop that can be plowed under green, such as a winter cover crop of rye, ryegrass and vetch, or sweet clover, or a summer catch crop of soybeans or liberally fertilized sudan grass. In the south crimson clover, lupines, crotalaria, Austrian peas, and cowpeas are employed for this purpose.

FALL VERSUS SPRING APPLICATION OF FERTILIZER TO WINTER CROPS

In the growing of winter grain, hay, and pasture crops, one has a choice between fall and spring applications of nitrogen, either alone or in the form of a complete fertilizer. This applies particularly to perennial hay and pasture crops. Fall application is of special interest because the condition of the land is much better at that season of the year than in the spring, and there is less danger of getting into trouble with trucks and tractors. Furthermore, the fertilizer producer likes to distribute his sales over the year, and fall application on these crops permits his getting this business out of the way of the early-spring rush.

Better results, however, are usually obtained from spring than from fall applications of fertilizer to grass hays and pastures (Table 156).

TABLE 156

FALL VS. SPRING APPLICATIONS * OF FERTILIZERS TO GRASSLAND (BEAR) PERMANENT UNGRAZED GRASS PLOTS NEW BRUNSWICK, NEW JERSEY

(Acre Increases Dry Matter from 4 Plots over 6-Year Period)

Materials †	Spring, Lb.	Fall, Lb.
Sodium nitrate	5962	4488
Ammonium sulfate	5616	4001
Ammonium nitrate	5299	....
Uramon (urea)	4538	....
Phosphate and potash ‡	5026	4133

* Fall applications were made in September or October and spring applications in March or April to a loam soil.

† The nitrogen materials were used in such amounts as to supply 20, 40, 60, and 80 pounds N an acre annually, with four plots for each material, both in the fall and spring tests. All plots were limed as required to maintain [illegible] between 6.0 and 6.5, extra lime being used on the sulfate of ammonia plots.

‡ The phosphate and potash mixture supplied 60 pounds each of P_2O_5 and K_2O, one-half each of all the N-test plots receiving it in the fall and the other half in the spring.

A considerable part of the nitrogen is stored in the leaves of the plants, many of which die during the winter months, leaving their nitrogen on the soil in a less quickly available organic form. Another possible difficulty with fall application of nitrogen fertilizers is that some of the element may be lost in the drainage water. Nevertheless, it is often

found advisable to proceed with the fertilizer program in the fall, notwithstanding the yield disadvantages of applying it at that season of the year.

For small grains, however, early-spring applications often get the crop off to a quicker start, aid in stooling, and bring the plants through to much heavier yields. Thus, a 40-pound spring application of nitrogen an acre to wheat on nitrogen-deficient soil is quite likely to add between 8 and 10 bushels grain to the yield. Better results are obtained in years following high or average rainfall during the summer months of the previous year than following a droughty summer. If high-protein wheat or hay is desired, the application must be delayed until heads are beginning to form. The nitrogen is then translated into extra protein rather than extra straw or grain. Where clover is seeded in the small grain, the rate of application of nitrogen must be kept relatively low to avoid reduction in stand of the clover. This is especially true if the seed is low in available potassium.

TESTING THE PLANT FOR NITROGEN DEFICIENCY

Nitrogen deficiency is widespread and tends to become more serious with increasing agricultural age of the land. An important reason for this is that the soil has virtually no capacity to fix nitrates, losing them readily either to the crop or to the drainage water. It becomes important, therefore, to have some means of determining the status of the available nitrogen in the soil during the growing period. This can be done by testing the soil for nitrate, after having established experimentally the soil-nitrate level that is required for best growth of the plant in question.

Possibly a better procedure for determining whether a crop needs nitrogen is that of testing the tissues of the plant itself. Such tests are readily made in the laboratory by subjecting the tissues to the action of a Waring blender and then adding a reagent that gives a color in the presence of nitrate. If desired, this test can be made in the field on a qualitative basis.

It seems probable that a great deal more will be done in due time to give farmers more specific advice as to their fertilizer needs (Table 157). The usual soil tests can be made during the winter months in anticipation of applications of lime, phosphate, and potash to be made the following spring. However, there is need for further service in checking-up the plants in the field. If the necessary soil correctives

TABLE 157

Suggested Fertilizer Applications for Vegetables (App) *

Crop	Nitrogen			Phosphoric Acid			Potash		
	Organic Matter, per cent	Manure		P, P.p.m.	Manure		K, P.p.m.	Manure	
		None, lb.	Used, lb.		None, lb.	Used, lb.		None, lb.	Used, lb.
Peas	1 –1½	100	50	20	120	95	150	100	50
Peas	1½–2	75	35	30	80	55	250	50	0
Limas †	1 –1½	25	0	10	120	95	150	100	50
Limas †	1½–2	10	0	20	80	55	250	50	0
Asparagus	1 –1½	100	50	20	200	175	150	200	150
Asparagus	1½–2	75	35	30	160	135	250	150	100
Spinach	1 –1½	175	100	20	75	50	150	70	20
Spinach	1½–2	150	75	30	50	25	250	40	0
Tomatoes	1 –1½	100	50	20	120	95	150	150	100
Tomatoes	1½–2	75	35	30	80	55	250	100	50

* Seabrook Farms, January, 1948. These recommendations to farmers are made on the assumption that *p*H values of the soil are maintained at approximately 6.5. The P and K tests are made by the Morgan method. Tests for nitrates are made throughout the crop season and extra nitrogen is applied as required. In the absence of such tests the amounts indicated are suggested.

† Dwarf varieties.

have been applied in relation to soil deficiencies and anticipated crop needs, possibly the only remaining deficiency will be nitrogen.

Field testing as to adequacy of the nitrogen supply in the plant has the added value of permitting an examination of the general well-being of the crop as well. This may reveal that some insect, disease, bad physical state of the soil, or bad management in the use of cultivators and other machinery is responsible for poor growth of the crop. It is anticipated that soil- and crop-testing laboratories will eventually be developed in large numbers on a fee basis to meet this in[illegible] need of farmers.

HEAVY APPLICATIONS OF FERTILIZER

In general, the ideal method of placement of small quantities of fertilizer is in bands along the row at planting time. The fertilizer is placed a little to each side and possibly a little below the plane of the seed. For wheat and other small grains, however, the fertilizer is usually allowed to run down the hose with the seed. This gives good

results with grains that are sown in late fall or early spring if the rate of application an acre is relatively low and the soil maintains a reasonably high percentage of moisture.

For potatoes, a ton or more fertilizer an acre is often applied in bands a few inches away from the seedpieces. For corn, the quantity thus applied is usually less than 300 pounds an acre. For wheat, the rate of application in direct contact with the seed may be as much as 500 pounds an acre on the heavier types of soil. Some difficulty may be experienced with direct contact applications on the sandier types of soil.

When the quantity of fertilizer for crops other than potatoes is raised to a ton or more an acre, a problem is presented in knowing where to place it. Thus, if one wanted to produce yields of corn of better than 100 bushels an acre, he might find it advisable to apply 1000 pounds of 10–10–10 fertilizer an acre at planting time, or he might prefer to use a 5–10–10 at planting and supply the extra nitrogen as a sidedressing when the corn was about 18 inches high.

Normally, a few hundred pounds of the complete fertilizer would be applied along the row at planting time. However, there is need to keep this quantity small to reduce the labor problem so that the period of planting is not too prolonged. Furthermore, there is reason to believe that better results will be obtained if the remainder of the complete fertilizer is placed down more deeply into the soil, where the feeding roots will be protected against drought later in the season. If the soil is well drained, good results are obtained by plowing the fertilizer down. In the wetter types of soil the results are likely to be better if the fertilizer is drilled into the soil as deeply as possible but not as deep as the bottom of the furrow. Surface applications, when disced-in, remain too close to the surface to be fully effective in dry seasons.

The evidence is quite conclusive that a large part of the nitrogen should be applied after the plants are well under way. Here again it is important that the fertilizer be located in soil that will not become too dry to support growth of roots and roothairs. In one New Jersey test, an application of 100 pounds of nitrogen in the form of anhydrous ammonia, placed at a depth of 4 inches midway between the rows in mid-July, raised the yield of corn on a nitrogen-deficient soil from 26 to 107 bushels an acre. The leaves of the untreated corn were fired from the ears down and those above the ears were yellowish green. From looking at these plants one gained the impression that it had been a very dry season. In contrast, the nitrogen-fertilized corn was

dark green from top to bottom, as though the season had been very favorable.

For intensive farming systems, or when such materials as rock phosphate and limestone are applied in liberal amounts, the better procedure is to mix the fertilizer with the entire volume of soil. This is accomplished by year-after-year heavy applications, the unused residues from which become an intimate part of the soil. Even so, however, there is need for small applications along the row at planting, and supplemental nitrogen sidedressings or topdressings may be required.

COMBINATION PESTICIDES AND FERTILIZERS

Interest in combination pesticides and fertilizers is widespread. Sometimes the need is for control of parasites that harbor in the soil and at others for control of those that are making direct attacks on the foliage. In the first case, the fertilizer may constitute the larger part of the mixture. When used in conjunction with sprays, the acre rate of application of the fertilizer must be relatively small. Here, the primary purpose is usually to supply small amounts of missing trace elements or relatively small doses of quick-acting forms of nitrogen. A number of thiocarbamates carrying zinc, iron, copper, and nitrogen. A number of thiocarbamates carrying zinc, iron, copper, and manganese, respectively, are being employed as fungicides. These serve as carriers of the respective trace elements as well. Urea is the common nitrogen carrier that is added to sprays.

Calcium cyanamide has long been used as a pesticide, notably for weed control. When used in liberal amounts and well mixed with the soil, it partially sterilizes the soil and may eliminate a large percentage of the weeds. The essential point is to have the sterilizing effect accomplished and the cyanamide changed to hydrated lime and urea before the crop is planted.

Fairly effective combinations of some of the more modern pesticides with fertilizers are being applied to the soil. Included among these are chlordane, dieldrin, aldrin, parathion, toxaphene, and benzene hexachloride. There are several objections to this procedure. One is that better results are likely to be obtained if the fertilizer and the pesticide are each chosen for its particular purpose and used in accordance with the need. Another lies in that some of the fertilizer-pesticide mixture may be left over and the fact that it is such a mixture may be forgotten until later, when damage from improper use results. A third is that such mixtures present a very difficult problem to the control chemist. The Southern Feed and Fertilizer Control Officials, in June, 1951,

adopted a report to the effect that the danger of contaminating crops and soils through inappropriate use of such mixtures was too great to warrant the risk of approving them for wide-scale use. They concluded that if they were to be thus used such use should be formally approved by the officials vested with such powers. Fertilizer and Economic Poison Control Officials adopted a similar resolution later in the year.

SELECTED REFERENCES

1. Andrews, W. B., J. A. Neely, and F. E. Edwards. Anhydrous ammonia as a source of nitrogen. Mississippi Agr. Exp. Sta., Bull. 482, 1951.

2. Armiger, W. H., K. G. Clark, F. O. Lundstrom, and A. E. Blair. Urea-form: greenhouse studies with perennial ryegrass. *Agron. J.*, Vol. 43, pp. 123–128, 1951.

3. Bear, Firman E., and Associates. Effect of increasing fertilizer concentration on exchangeable cation status of soils. *Soil Sci. Soc. Amer., Proc.*, Vol. 16, pp. 327–330, 1952.

4. Clark, K. G., and Firman E. Bear. Use of natural organics in mixed fertilizers. *Am. Fertilizer*, Vol. 108, No. 3, 1948.

5. Clark, K. G., *et al.* New synthetic nitrogen fertilizer; preparation and properties of urea-form. *Ind. Eng. Chem.*, Vol. 40, pp. 1178–1193, 1948.

6. Eby, Claude, Carl B. Bender, and Firman E. Bear. Fertility levels in pasture land. New Jersey Agr. Exp. Sta., Bull. 749, 1950.

7. Evans, H. J., and E. R. Purvis. Molybdenum status of some New Jersey soils with respect to alfalfa production. *Agron. J.*, Vol. 43, pp. 70–71, 1951.

8. Farrar, M. D. Insecticides in fertilizers. *Assoc. Offic. Agr. Chemists*, Official Publication No. 4, pp. 58–64, 1950.

9. Jones, Earl, and G. W. Volk. Ohio fertilizer recommendations 1950–51. Ohio Agr. Ext. Service, Bull. No. 315, 1950.

10. Karraker, P. E. Fertilizers, their purchase and use on field crops. Kentucky Agr. Exp. Sta., Circ. 70, 1951.

11. Lathwell, D. J., and C. E. Evans. Nitrogen uptake from solution by soybeans at successive stages of growth. *Agron. J.*, Vol. 43, pp.. 264–270, 1951.

12. McIntyre, Arthur C. Wood chips, water, and soil. *J. Soil Water Cons.*, Vol. 6, pp. 20–25, 1951.

13. Spencer, J. T. Seed production of Ky. 31 fescue and orchard grass as influenced by rate of planting, nitrogen fertilization and management. Kentucky Agr. Exp. Sta., Bull. 554, 1950.

14. Tiedjens, V. A., and L. G. Schermerhorn. Growing vegetables with fertilizer in water. New Jersey Agr. Exp. Sta., Bull. 694, 1943.

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