IN GENERAL, three methods for determining the fertilizer needs of soils are now in use by scientists: (1) The so-called quick tests, made with chemicals, and biological tests, sometimes made with fungi and bacteria; (2) pot and greenhouse tests, involving samples of soil; and (3) plot tests, where the plants are grown under controlled field conditions. Extensive use of quick tests is comparatively new; the plot tests have been used for a long time. This article gives a critical account of all four methods, showing the procedures involved, the results to be expected, and the limitations of each.

Determining the Fertilizer Requirements of Soils

By Oswald Schreiner and M. S. Anderson

Evaluation of the fertility of a soil and of the quantity and quality of fertilizer required for profitable yield and quality of crop is indispensable to economical fertilizer usage and essential to efficient crop production. Three general types of procedures are being used for this evaluation—plot tests with specific crops in the field, pot tests with field crops or selected test crops, and laboratory procedures involving chemical and biological factors.

Since the laboratory tests have been recently popularized and are at present attracting widespread attention, they will be discussed first in this article. Every farmer would like to know whether it is possible, by testing a sample of the soil in a field, to determine just what fertilizer elements are needed for the best economic production of a particular crop, and in what quantities.

LABORATORY MEANS OF DETERMINING FERTILIZER NEEDS OF SOIL

Much attention has been given by chemists and agriculturists to the development of chemical means for the determination of the availability of various mineral constituents in a particular soil. It is, of course, highly desirable to know not only the total or potential supply of a particular element present but also the part of the whole which is capable of serving the immediate and progressive needs of growing plants.

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After many years of intensive research along this line in various parts of the world, the objectives have been only partially accomplished. Experience with growing plants still serves as the main source of information upon which an agriculturist must rely in judging the probable response of plants to particular fertilizer applications upon any kind of soil. Chemical information can be and is a distinct aid, but with the present state of knowledge it must play a supplementary and usually minor part. Valuable use can often be made of chemical data in the diagnosis of the needs of a soil, but if an agriculturist were dependent upon chemical data or any kind of laboratory data alone the results would be very disappointing.

It is a relatively simple matter to make an inventory of the total plant-nutrient resources of a soil by means of an ultimate chemical analysis, but it is well known that no close relationship has been found between the total quantities of various soil constituents and the supply available to plants. Furthermore, the amount of various nutrient elements removed from the soil by water, by plants, or by any one of various extracting solutions bears a very definite relationship to the whole quantity of a particular element present.

In some kinds of soil a fairly good relationship may be found between the total quantities of certain soil constituents and soil fertility. In other cases the composition of the water-soluble material may give a better clue to fertility. In still other cases, perhaps, the chemical data that appear to be best correlated with crop growth and with response of plants to fertilizer applications are most frequently those obtained by the use of some one of a large and varied group of extracting solutions.

The quantity of various elements ordinarily added to a soil in a commercial fertilizer application in any one season is so small as compared with the total normal supply of any one of these elements in the soil, that a chemical analysis for total constituents would ordinarily fail to detect the addition of commercial fertilizer well mixed through the plow depth of soil. Although additions of fertilizer constituents amounting to not more than a few thousandths of 1 percent of the surface soil weight may greatly influence plant growth, they must be detected chemically by their partial solution in selected solvents rather than by their determination in total quantity.

Because of the disappointing results from most of the varied efforts directed at precisely evaluating availability of soil constituents by chemical means, many agriculturists have begun to use approximate tests that are known to be far from perfect.

Anyone interested in rapid soil tests naturally would like to know how accurately these tests may serve as an index of plant growth on the soils tested. Many statements indicating correlation of tests with crop growth in general terms have been published. A few writers have attempted more definite mathematical statements, but for the most part these are not very convincing. Much difficulty is involved in satisfactory correlation because of the varied considerations concerned. Agronomists are interested not only in whether a certain fertilizer does or does not produce a crop increase on a particular soil, but also in whether the increase, if any, is economically advantageous when all factors are considered, as in long-term field experiments.
Extent of Present Usage

Rapid chemical tests in one form or another are used in many of the State agricultural experiment stations as an aid in furnishing advice to farmers regarding fertilizer use and soil management. There is a constantly increasing use in the United States of rapid test methods of estimating the phosphoric acid and potash requirements of soils for the aid of practical agriculturists. So far, however, there is little standardization. The wide variation in soils, climate, character of crops, and other factors makes such soil testing essentially a regional, sectional, or local problem, and the different State experiment stations are sponsoring the development and application of procedures found empirically to yield results correlating best with the results of field plot and other vegetative trials under particular soil and crop conditions.

For routine soil testing, preference is given various forms of the so-called rapid or quick chemical tests that may be conducted with very limited laboratory facilities or in the field. These tests afford approximate quantitative estimations rather than absolute determinations. When standardized against field results and employed intelligently under the conditions for which they were developed, they are reported to be of marked diagnostic value; but great reliability for all crops on all kinds of soils cannot be claimed for any single test.

According to a survey made in 1935 and reported by R. P. Thomas of the Maryland Agricultural Experiment Station (398), 26 States, principally in the central-western area, Corn Belt section, and eastern Atlantic region, make extensive use of soil tests for evaluating plant-food requirements. Seventeen other States, mostly South Atlantic and Gulf, as well as Northwestern States east of the Rockies, make limited use of such tests. Only five States are reported as not using such tests in their soil examinations.

Of the tests for plant-food requirements, those for phosphorus find widest application, as deficiency of this element is probably the most widespread of all. Thirty-six States report the use of one or more methods for phosphorus, with largest interest in the Middle Western and Eastern States. No one method was reported as entirely satisfactory for all cases. Various modifications of the sodium acetate extraction procedure seemed to be more widely used than any others—largely in the eastern United States.

Tests for potassium were reported as less extensively used than those for phosphorus or for lime. Only 24 States made such tests and a number of these made them only on request.

This survey showed that at the present time most research workers feel that the rapid tests have been checked under field conditions only

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2 Italics numbers in parentheses refer to Literature Cited, p. 1181.

3 Sixteen States, mostly east of Ohio, use some form of extraction with sodium acetate solutions as typified in the Morgan tests, or with dilute acetic acid, as in the Spurway tests. (See table 2, p. 476, for summaries of the tests mentioned.) Twenty-one States, mostly west of Ohio, employ stronger extracting solutions, as represented in the Truog, Bray, and Thornton procedures and their modifications. Thirteen States reported use of the Bray tests, but only 7 exclusively; 13 used the Truog procedure, but only 3 solely. Fourteen States used various modifications of Morgan's tests, eight exclusively. The Spurway tests were used in five States and exclusively in two. The Thornton procedure for phosphorus was used in two States. Four States, Colorado, Montana, Oklahoma, and Texas, reported use of special tests of their own for phosphoric acid, including modifications of other chemical tests, various biological tests, etc.

4 Eleven States employed Morgan's method, eight exclusively; the Spurway method was used in seven States, but in only three exclusively. Eight States employed the Truog, Bray, and Thornton methods for potash.
to a limited extent and that there needs to be considerable collaboration on the treatment of soil samples and interpretation of the results before a satisfactory comparison of the methods can be made and precision in rapid soil testing attained comparable with field results and practical experience.

**Results by Different Methods and Procedures**

In view of the extensive use of quick chemical tests by trained and untrained persons, the Department of Agriculture set about to obtain some information regarding comparative results obtainable by various published methods and by the use of various convenient test sets. Some results of this investigation have recently been published in Miscellaneous Publication 259 entitled "Comparison of Various Chemical Quick Tests on Different Soils" (16). The results are, as one might expect, inconclusive. Some variations were found in the results by different operators using the same method on one soil, and much poorer agreement was found between results by different methods on certain soils. With some soils all of the methods agreed fairly well; with other soils results were very erratic.

Most students of quick test methods have recognized that different soils respond differently to most soil tests. It is to be expected that the available nutrient constituents of an acid Red or Yellow soil might respond differently to the action of various solvents than would the corresponding constituents of a nearly neutral Prairie or Chernozem soil. Soils receiving many applications of fertilizers accumulate residues that are transformed into different compounds, depending upon the nature of the soil. Also the purpose for which a test may be made is not always the same. In the case of a lawn, the main object is to obtain a good grass cover; in the case of major field crops, an economic return on a crop of relatively low value is desired; while with truck crops the object of the test is often to find out how to grow vegetables of the finest quality with only secondary emphasis on quantity. Under such varying circumstances it is apparent that several kinds of tests may be useful.

Tests using a dilute solution of a weak acid such as that described by Spurway of the Michigan Station (382) and marketed under the name "Simplex Soil Test Outfit" may be of particular value for detecting instances of overfertilization in cases of intensive agriculture. Systems employing relatively strong acid in extracting solutions, one of which is used by the Illinois Station, appear to be of particular value in certain regions. However, when applied to soils having accumulated residues of phosphates from former applications, the apparent values of availability may be relatively much greater than indicated by crop response. The use of mildly acidic, heavily buffered solutions (i.e., not easily changed in reaction one way or the other), such as those employed by the Connecticut Station and others, appears to be growing in popularity, although absolute values obtained by the use of this or any other system are of very limited usefulness without the practical experience of a good agriculturist.

It is difficult to evaluate the usefulness of the various laboratory quick tests as a sole source of information for the guidance of fertilizer practice and for knowledge of the adaptability of crops to the various
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kinds of soils. It may appear to some that the statements here given of their practical worth are more conservative than is justified by the experience of several State laboratories. Attention is called, however, to the fact that in these institutions the tests are made and interpreted by agriculturists who have had broad experience with the groups of local soils being tested.

How the Data Are Interpreted

The manner in which chemical soil data are interpreted in terms of crop production is illustrated by reports from several of the State experiment stations. Work at the Texas Station (114) led to the conclusion that soils in that State from which 20 to 100 parts per million of phosphoric acid were extracted by 0.2 normal nitric acid usually did not contain enough phosphorus for the proper growth of corn. Potash extracted by the same solvent showed no traceable relationship to weight of crop grown.

The Oklahoma Station (146) has issued certain generalizations regarding the relationship of phosphorus extracted with 0.2 normal sulphuric acid and response of crops to phosphorus fertilization. The quantity of phosphorus in Oklahoma soils above which added phosphorus is unprofitable varies with different crops, with approximate limits as follows: 40 to 60 pounds in the soil for alfalfa, 30 to 40 for oats, 20 to 30 for corn, 15 to 20 for grain sorghum.

The Colorado Station (129) found water-soluble phosphorus the most reliable index of phosphorus availability in calcareous soils. The phosphorus was determined in a water extract of the soil by treatment with an acid molybdenum solution which, in the presence of reducing agents, gives a blue color when phosphorus is present, the intensity of the color depending on the amount of phosphorus. Positive and negative crop responses only were recorded with no indication as to the extent of crop increase as a result of phosphate application. In spite of the good showing made by the water-soluble phosphate test in this instance, the consensus of opinion from tests made on soils in different regions seems to be that its usefulness is more limited than tests employing certain acid or salt-extraction methods.

Many general statements have been made by investigators concerning the correlation of crop results with those of the popular quick tests, but definite data appear to be few or lacking.

Nature of Rapid Soil Tests

The methods that have been used and those now in use for soil testing are many and widely varied in character. A portion of the equipment in a laboratory where various tests are used and compared is shown in figure 1. Figure 2 shows the operation of one of these test kits. A synopsis is given in table 1 of some of the procedures that are of historical interest as well as some of the methods now in use in various countries of the world and to a limited extent in the United States. A synopsis of methods in common use in the United States at the present time is given in table 2.

It is evident from the information in tables 1 and 2 that the rapid soil tests used in recent years vary widely. Some are quick in the
sense that they require only a few minutes' time, others are biological in character, or in some cases chemical tests are made upon plants grown for stated periods of time in the soils to be tested. The *Aspergillus niger* test, for instance, is purely biological, while the Neubauer method involves actual chemical determination of a single element, either phosphorus or potassium, on seedlings grown under conditions prescribed in the test.

Various State experiment stations have investigated quick tests as applied to the soils of their respective States. Many methods and modifications of methods have been published by these institutions. In several cases the methods have been commercialized. Several of the firms selling testing sets, however, give no indication as to the chemical composition of the reagents used in their various tests, expecting to furnish refills when needed.

The chemical methods, including the nature of the extracting solution, vary in respect to acidity and other characteristics. Some procedures employ a single extracting solution for dissolving the various constituents to be determined. M. F. Morgan, of the Connecticut Station, and J. B. Hester, of the Virginia Truck Station, each follow this plan. The solution used by Morgan is made as follows: 100 grams of sodium acetate crystals are dissolved in 500 cubic centimeters of water, 30 cubic centimeters of glacial acetic acid is added, and the whole is made up to 1 liter. This mixture of salt and acid is strongly buffered at the mild acidity value of pH 4.8. The solution used by Hester is made by adding 20 cubic centimeters of glacial acetic acid and 10 grams of sodium hydroxide to sufficient water to make a volume of 2 liters. The extracting solutions used for individual constituents are numerous and varied; many of them are more acid than those noted above.
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**Figure 2.** One of the soil-testing outfits used for phosphorus and potash. On right is shown a step in the preparation and filtration of the test solution. At left is shown color comparison against a standard color chart for phosphate. In center is shown a turbidity test for potash, in which the intensity of the black lines visible through the turbid solution is compared on a standard chart.

**Table 1.** Rapid methods of soil testing developed in different parts of the world

<table>
<thead>
<tr>
<th>Author and reference</th>
<th>Year and place originated</th>
<th>Extracting reagent</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daubeny (90)</td>
<td>1845, England; 1872, Germany; 1884, France</td>
<td>Carbonic acid; Dilute hydrochloric or acetic acid; 2-percent ammonium oxalate; 1-percent citric acid</td>
<td>Analysis of seedlings grown in soil. Potassium and phosphorus are both considered. For phosphorus only. For calcareous soils potassium and sodium carbonates better than ammonium carbonate. Various reagents used on cornstalks indicate deficiencies of nitrogen, phosphorus, and potassium. Test plants are grown in pots.</td>
</tr>
<tr>
<td>Von Liebig (217)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lechartier (219)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dyer (98)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Association of Official Agricultural Chemists (465); Neubauer and Schneider (278)</td>
<td>1907, United States; 1923, Germany; 1926, India; 1926, Indiana</td>
<td>0.2 normal hydrochloric acid; Analysis of seedlings grown in soil; Alkaline carbonate solutions</td>
<td>A single test may be for either phosphorus or potassium. For calcareous soils potassium and sodium carbonates better than ammonium carbonate. Various reagents used on cornstalks indicate deficiencies of nitrogen, phosphorus, and potassium. Test plants are grown in pots.</td>
</tr>
<tr>
<td>Das (89)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hotter (167)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oden (884)</td>
<td>1927, Sweden</td>
<td>Electrolysis</td>
<td>Conventional base exchange procedure. Test plants are grown in pots.</td>
</tr>
<tr>
<td>Murphy (274)</td>
<td>1934, Oklahoma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mitscherlich (888)</td>
<td>1924, Germany</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) To Literature Cited, p. 1181.
Table 2.—Rapid chemical tests for phosphorus and potassium in soils, commonly used in the United States

<table>
<thead>
<tr>
<th>Author and reference</th>
<th>Agricultural experiment station where originated</th>
<th>Extracting reagent</th>
<th>Method of estimating element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morgan (270)</td>
<td>Connecticut</td>
<td>Sodium acetate + acetic acid; 5 normal, pH 4.8</td>
<td>Sodium molybdate + stannous oxalate.</td>
</tr>
<tr>
<td>Spurway (382)</td>
<td>Michigan</td>
<td>Dilute acetic acid; about pH 3.2</td>
<td>Ammonium molybdate + tin.</td>
</tr>
<tr>
<td>Truog (117, 428)</td>
<td>Wisconsin</td>
<td>0.062 normal sulphuric acid buffered at pH 3.0 with ammonium sulphate.</td>
<td>Ammonium molybdate + stannous chloride with precautions to eliminate effects of arsenic and silicon.</td>
</tr>
<tr>
<td>Bray (44)</td>
<td>Illinois</td>
<td>Ammonium molybdate in 0.1 normal hydrochloric acid solution.</td>
<td>Add tin.</td>
</tr>
<tr>
<td>Thornton (40)</td>
<td>Indiana</td>
<td>Ammonium molybdate in 0.1 normal hydrochloric acid solution.</td>
<td>Stannous chloride or stannous oxalate.</td>
</tr>
<tr>
<td>Fraps (111)</td>
<td>Texas</td>
<td>do.</td>
<td>Gravimetric or volumetric molybdate method.</td>
</tr>
<tr>
<td>Fraps (115)</td>
<td>do.</td>
<td>do.</td>
<td>Colorimetric molybdate method.</td>
</tr>
<tr>
<td>Hester (169)</td>
<td>Virginia Truck</td>
<td>Sodium acetate + acetic acid; 0.167 normal (acetate) pH 5.0.</td>
<td>Do.</td>
</tr>
<tr>
<td>Harper (146)</td>
<td>Oklahoma Truck</td>
<td>Sodium acetate + acetic acid; 0.5 normal hydrochloric acid.</td>
<td></td>
</tr>
<tr>
<td>Hance (140)</td>
<td>Hawaiian Sugar Planters Association</td>
<td>0.2 normal sulphuric acid.</td>
<td></td>
</tr>
</tbody>
</table>

POTASSIUM TESTS

<table>
<thead>
<tr>
<th>Author and reference</th>
<th>Agricultural experiment station where originated</th>
<th>Extracting reagent</th>
<th>Method of estimating element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morgan (270)</td>
<td>Connecticut</td>
<td>Sodium acetate + acetic acid; 5 normal, pH 4.8</td>
<td>Sodium cobaltinitrite + isopropyl alcohol.</td>
</tr>
<tr>
<td>Spurway (382)</td>
<td>Michigan</td>
<td>Dilute acetic acid; 1:3</td>
<td>Sodium cobaltinitrite + alcohol.</td>
</tr>
<tr>
<td>Thornton (40)</td>
<td>Indiana</td>
<td>Sodium cobaltinitrite in acetic acid.</td>
<td>Add alcohol.</td>
</tr>
<tr>
<td>Bray (44)</td>
<td>Illinois</td>
<td>Sodium acetate + nitric acid.</td>
<td></td>
</tr>
</tbody>
</table>

1 To Literature Cited, p. 1181.

consist of acids well buffered with salts. The ratio of soil to extracting solution varies, as does also the time of contact. In most cases a measured volume of an extracting solution is shaken with a definite volume of soil for a specified short period, then the mixture is either allowed to settle or is filtered.

Different soils, of course, form water extracts which vary widely in the rate at which liquid passes through the filter; thus the period of contact of soil with extracting solution is unavoidably varied. Methods employed for quick tests in various institutions and materials furnished with some of the commercial outfits change frequently. Outfits sold a few months ago may not be identical with those currently offered for sale, and the methods of institutional workers may likewise be amended through revised bulletins on the subject.

Chemical Reactions Involved in Tests

Probably all of the chemical rapid tests for phosphorus utilize some modification of the Deniges method for determining minute quantities of phosphates. According to this method a blue color is developed when soluble soil phosphate in an acid molybdate solution is treated with a stannous salt or stirred with metallic tin. A definitely per-
ceptible blue color is obtained with solutions containing as little as 0.1 part per million of phosphorus.

Potash is determined in most, but not all, of the chemical procedures by precipitating with sodium cobaltinitrite in the presence of ethyl alcohol or isopropyl alcohol. The turbidity produced is then estimated in some prescribed manner. For example, in several cases the soil solution together with the reagents, amounting to a definite volume of perhaps 2 cubic centimeters, is placed in flat-bottom glass tubes of uniform diameter. These tubes are moved over a series of colored lines of varying clearness of definition against a white background (fig. 2). The line which is first visible through the turbid solution corresponds with the supply of available potash designated as high, low, medium, or by similar designations. The potash turbidity method as ordinarily used is somewhat less sensitive than the phosphorus color test. About 5 parts per million of potassium in solution usually represents approximately the minimum detectable turbidity.

The determination of available nitrogen is complicated by the fact that organic compounds, many of which are of low water solubility, are slowly ammonified and nitrified in the soil during a growing season. Thus a supply of readily soluble and available forms of nitrogen is considered as being produced at a rate more or less comparable to the rate of their absorption by plants. If not taken up by plants, the excess may be lost in drainage water. Hence, the quantity of nitrates present at any one time is seldom high in soils of humid regions, and furthermore is a poor index of the capacity of a particular soil to produce a sufficient available supply regularly.

Most of the soil-testing systems include a procedure for determining nitrates, and they ordinarily use the same reagents. Small quantities of soil solution are treated with diphenylamine and concentrated sulphuric acid. A blue color develops, which is compared with a color chart the tints of which correspond to definite quantities of nitrate. A definitely blue coloration is detectable when quantities as small as 0.3 part per million of nitrate nitrogen are present. Ammonium nitrogen is frequently determined by the production of a yellowish-brown coloration with the well-known Nessler's reagent. This reagent is a complex one, but consists essentially of a strongly alkaline solution of mercuric iodide. This solution has long been used as a standard reagent for the detection and estimation of minute quantities of ammonia, particularly in sanitary water analysis. The color of an unknown solution is compared with a color produced in a solution of known strength or with a standard color chart. Organic nitrogen is sometimes determined by the use of some oxidizing agent, which produces either some direct color change or ammonia, which is then determined as above.

Tests for Calcium, Magnesium, and Other Soil Constituents

In addition to the ordinary fertilizer constituents—phosphorus, potassium, and nitrogen—other elements are often included in the more complete systems of chemical soil testing. Systems such as those de-
scribed by Morgan and Spurway (270, 382) include tests for these. In making a diagnosis of soil conditions it is sometimes important to know the relative concentrations of such constituents as calcium, magnesium, aluminum, manganese, and sodium, as well as chlorine and sulphur. Soils are frequently deficient in some one or more of these, and frequently excessive quantities of certain of these elements present a problem. The coincidence of the various constituents is in many cases perhaps of even more importance in soil diagnosis than is the concentration of any one element alone. In the case of these less commonly considered constituents information is so scant regarding the normal concentrations found in soil extracts that much comparative work is usually necessary in a particular locality before it can be ascertained whether or not it is practical to attempt soil adjustments on the basis of such chemical information.

In addition to the constituents mentioned, certain trace elements such as copper, boron, and zinc are known to be of normal occurrence in soils, and the available supply of one or more of these appears sometimes to be inadequate. Little is known regarding the normal limits of any of these trace elements or of suitable laboratory methods for testing for them in an adequate manner. Here, as with the fertilizer elements, the response of plants is a more positive guide than are chemical tests.

**Methods of Expressing Results**

Rapid chemical soil tests should be looked upon as having good qualitative or semiquantitative accuracy. The modes of expressing results are not uniform. Some express results as parts per million of a particular constituent in available form in the soil. Others interpret them directly from color comparisons in terms of probable applications of a particular element needed for good crop growth. The available supply of a particular constituent is often indicated only in general terms, such as high, medium, low. In still other cases a general expression of results is further broken down into five groups by adding the additional classes “very low” and “very high.” By the exercise of some judgment on the part of the operator not contemplated by the author of certain methods, results from any one of the procedures may be interpreted as falling into one of the five groups just mentioned. It is doubtful whether the accuracy of the results or their susceptibility to practical interpretation ordinarily justifies more detailed expression than is possible in these five groups.

**BIOLOGICAL METHODS**

Several biological methods have received considerable attention in this country as well as in Europe. Some of them involve the growth of ordinary field crop plants under specified conditions in a greenhouse; other procedures utilize the growth of lower forms of plants, such as fungi and bacteria, to detect differences in soil fertility.

The Mitscherlich method (368), widely used in Europe, has been tried in a few laboratories in this country. It consists of growing selected test crops under controlled conditions in specially constructed pots. This method involves considerable expense for equipment and considerable time in operation. Experience alone must be relied upon
to determine whether or not the results obtained, using a particular test crop on a particular soil, provide a reliable growth index for other crops whose nutrient requirements are different.

The Neubauer procedure (278), also of European origin, has been used by various investigators in this country. The method, in brief, consists of growing a definite number of seedlings of some test plant, often rye, in a definite weight of soil in a shallow dish. Moisture conditions are kept at an optimum and all elements supplied in optimum amount except the one being tested. Either phosphorus or potassium deficiencies may be determined, but the method is not applicable to nitrogen. After a definite period of growth the plants are analyzed for either phosphorus or potassium. Experience is necessary to determine the probable border line between sufficiency and deficiency of an element in a soil as revealed by the seedling composition. Owing to the time involved in the conduct of such tests and the indefinite character of the results obtained, they have not been widely used in the United States.

Other biological tests of an indirect character include the growth of cultures of Azotobacter, Aspergillus niger, or Cunninghamamella organisms. Unpublished data obtained in the Division of Soil Microbiology of this Department convinced the investigators that such methods lack practicability. Much experimentation is involved in standardizing these tests so as to make the growth data capable of interpretation in terms of the fertilizer needs of various crops on different kinds of soil.

**POT AND GREENHOUSE METHODS FOR DETERMINING FERTILIZER NEEDS OF SOIL**

Pot experiments, particularly with rapidly growing indicator crops, permit tests with a large number of soil treatments within limited space and in relatively short time. The results are often directly applicable in practice, although allowance must be made for the fact that the conditions of the test are different from those in the field—the soil has been disturbed, and the more uniformly controlled temperature, moisture, and other factors modify the influence of the soil treatments themselves. In supplying information on the fundamental fertility characteristics of soils and particularly on the effects of specific substances on plant growth, pot experiments have the advantage of being less influenced by variable environmental factors than are field trials. The pot tests with soil, sand, or solution culture are most valuable in the study of certain specific factors such as the relative value of different forms of nitrogen, the toxicity of certain constituents and the variable absorption of particular elements by plants. Figure 3 shows a system of pot tests in a greenhouse.

Pot tests have long been in use. Sometimes they are conducted out of doors but most frequently in a greenhouse where conditions are more definitely under control. In some cases the technique is simple, in others special techniques, including special types of containers, are developed for the solution of particular fertility problems.

In the simplest form of experiment, earthenware pots of 1 to 5 gallons’ capacity, frequently provided with a drainage vent near the bottom, are filled with the soil to be tested. Since soils are severely
disturbed by transfer from the field to a pot there is usually no attempt made to simulate the naturally successive soil layers.

Testing Fertilizers or Amendments

The uniform incorporation of various ingredients with soil presents considerable difficulty. A heavy application of fertilizer, corresponding to 1 ton per acre, would require only about one-third of an ounce for treatment of a 2-gallon pot containing about 20 pounds of soil. Uniform distribution is most easily accomplished by mixing the contents of each pot separately in a small mixing machine. If some treatment requires only minute quantities of a constituent, such as are used when effects of such elements as zinc, copper, or manganese are being investigated, the material may be dissolved in water and a definite volume sprinkled over the mass of soil previous to mixing.

The soil is in each case added to the pot with some arbitrary but uniform method of compacting. Frequently the pot is half filled, then lightly tamped with an appropriate implement. Seed are sometimes planted in the soil and the weaker seedlings removed to leave a uniform number fairly evenly distributed over the soil surface. In other cases, seeds are sprouted in a moist chamber and a definite number placed in each pot.

It is important that light, heat, and moisture conditions be kept as nearly uniform as possible throughout the growing period of the plants. Plants are grown to varying degrees of maturity. Sometimes they are harvested after a specific period of time and the weight of the

Figure 3.—Greenhouse tests are made with soils and fertilizer materials under controlled conditions, using many crop plants, in pots, for the study of fundamental problems of soil fertility and plant nutrition.
whole plant, green or dry, is taken as a basis for comparison. In other cases, plants are grown to maturity and comparison made on the basis of weight of fruit or seed or dry weight of total growth. Figure 4 shows such an experiment in progress with several different crops. The sunken tiles and surrounding gravel when kept wet prevent excessive temperature and moisture fluctuations in outdoor experiments.

New fertilizer materials are frequently best tested out under such controlled conditions. In this work the new material is added to definite amounts of soil in pots and the relative growth obtained is observed and recorded. The untreated soil serves frequently as a comparison, or soil treated with some standard fertilizer material of known efficiency may be used.

A recent experiment of this kind by the Department was a comparison of a new synthetic organic nitrogen compound known as formamide, proposed as a potentially cheaper nitrogen carrier, with more commonly used nitrogenous compounds such as ammonium sulphate and urea. By pot experiments in which oats, wheat, and millet were used as test plants, it was shown that this new source of nitrogen compared favorably with the standard compounds. Such preliminary tests justify more elaborate and expensive field tests to evaluate the economic worth of formamide. Pot tests of this kind are extensively used in the nitrogen industry, to eliminate unfavorable nitrogen

Figure 4.—Pot tests made under outdoor conditions in wire-netting enclosures, with the pots inserted in submerged tiling to control temperature and moisture, are often used in soil and fertilizer studies.
carriers from further consideration. Similarly, various phosphate and potash compounds can be evaluated.

In fertilizer testing in the greenhouse, especially in studying the relative fertility of different soil types, larger containers are frequently necessary. Greenhouse benches that provide an area 4 feet square for each soil type or treatment provide conditions under which crops can readily be grown to maturity.

Pot tests are especially valuable in the determination of deficiencies of certain minor elements, such as iron, manganese, zinc, boron, or others. An experiment in this Department with a mysteriously unproductive soil showed through pot tests that the difficulty was due to manganese deficiency. A few milligrams of a soluble manganese compound added to the soil in a pot produced normal plant growth and fruit in a tomato plant, while a similar plant in the original soil without the manganese showed chlorosis and bleaching of the leaves and died without producing flower or fruit. Subsequent experimentation on a field scale confirmed the indications of the pot test, and large areas of this unproductive soil were made available for profitable truck farming by the application of the deficient element. Numerous other illustrations might be chosen from the experiment station literature to show the value to agriculture of the pot method of experimentation.

FIELD EXPERIMENTS FOR DETERMINING FERTILIZER NEEDS OF SOIL

For evaluation of fundamental soil fertility factors and specific soil properties affecting the level and proportions of available plant nutrients, the pot cultures and laboratory procedures are highly advantageous, since environmental influences modifying the effects of the strictly soil factors, as measured by crop growth and yields, are minimized and controlled. But for direct evaluation of fertilizer requirements, taking into account all factors affecting crop production, field trials remain the ultimate criteria. Field experiments are, however, relatively slow and expensive, particularly as regards labor and area of land required and the necessity for replication of treatments and for averaging seasonal fluctuations over a period of years.

In field trials, different fertilizers and other cultural treatments are tested with various crops under essentially the same conditions as prevail in practice. The results reflect the effects of all climatic and other influences to which the crop and soil are subject during the season. They are directly indicative of the results to be anticipated in practice under the same or similar conditions.

A typical lay-out for this work requires a considerable area of fairly uniform land. The contour should be such that none or very little of the surface run-off from precipitation passes from one plot to another. The plots of different experimental fields vary in size. Frequently about one-twentieth of an acre is used for each treatment. Check plots are interspersed with plots receiving definite fertilizer treatments and specified crop rotations. Numerous replications (341) are required for accurate results and to make possible statistical handling to determine experimental errors and smooth out irregularities. In the eastern Coastal Plains region emphasis is necessarily placed upon
kind and quantity of fertilizer added while on prairie soils the plan of crop rotation is often the subject of most profitable study by this system.

Crops adapted to the region are planted on the various plots and are given uniform tillage treatments according to what appears to be the best practice of the region. At the proper season, the crop of each plot is harvested separately and weighed or measured under the direction of a competent agriculturist.

Several important lines of information are obtained from this class of experiments. By reference to the check plots it is determined whether or not crop improvement, in quantity or quality, has taken place as a result of any particular soil or fertilizer treatment. The most valuable results are obtained only after a period of years when it is possible to determine from average yields and from the changing trends of yields what treatments give greatest response.

The economic aspect of the work can also be evaluated from the cost of fertilizers and value of crops each season. These are features which only a carefully considered series of field-plot tests can show, since these more nearly simulate farm operations and conditions than do pot tests or any of the chemical or biological tests previously described.

Farmers as a class are conservative. They do not undertake important changes in methods of farming without good reasons. While most farmers have faith in the programs of their State experiment stations, this faith becomes conviction when they can go and see crops of markedly different size and vigor growing side by side as a result of different treatments or rotations. This work of the stations is an important factor in improving local farm practices. For instance, through it a farmer is often influenced to try some treatment or other on a strip of his own field. Thus the experiment is expanded from the part-acre plot basis to open field trials of many acres. Farmers who do not visit the formal experimental plots are often in contact with someone who has; others read the station bulletins where the results from the plots are described in detail. Almost every local paper contains reviews of statements given out by the agricultural extension service of the State. These are often founded upon the results of the field-plot tests which have later been extended to greater acreage.

**SOME RESULTS OF LONG-TERM SOIL-FERTILITY EXPERIMENTS**

Special mention should perhaps be made here of long-term experiments in the United States that were inaugurated in the earlier periods of fertilizer experimentation at the Illinois, Pennsylvania, and Ohio Agricultural Experiment Stations. The type of information that can be issued by a station after such long-continued plot experimentation is illustrated by the results of some of these older stations.

The Morrow plots at the Illinois Station (fig. 5), begun in 1879 by George E. Morrow, are the oldest existing soil experimental plots in the United States. The series originally contained seven plots, on part of which use was made of fertilizers and manure. Three of the original plots still remain; the others have been used for building purposes in the development of the University of Illinois. Other experi-
mental plot work in Illinois was begun in 1902 on the North Farm and in 1903 on the South Farm of the experiment station, by Cyril G. Hopkins, and these plots are still under observation. On one of the Morrow plots, corn has been grown continuously; on a second plot a rotation of corn and oats has been practiced for the entire period; and on the third, corn, oats, and clover have been grown in rotation since 1902 (91). Results from these three plots are briefly as follows:

Crop rotation has noticeably improved the yields over continuous corn growing. Clover has been of much benefit in the cropping system.
On the untreated land, crop yields have steadily declined.
Cropping the land without treatment has used up phosphorus, nitrogen, and other elements, and has resulted in the destruction of organic matter.
Manure-limestone-phosphate treatment has converted a downward trend in yield into an upward trend.

The oldest extensive plot tests of fertilizers are those by the Pennsylvania Agricultural Experiment Station, laid out in 1881 by W. H. Jordan. Four tiers of thirty-six plots, each one-eighth of an acre in size, are used for the growing of corn, oats, wheat, and mixed clover and timothy in rotation on Hagerstown clay loam, a prominent soil of the district. The objects were to test the comparative effects of the following treatments on the crops grown: Single fertilizer ingredients; combinations of two ingredients; complete fertilizers; nitrogen in different forms and amounts; superphosphate and ground...
bone; manure in different amounts in comparison with commercial fertilizers; burnt lime and ground limestone used alone, and burnt lime used with manure; and land plaster. Jordan applied nitrogen, phosphoric acid, and potash at the rates of 24, 48, and 100 pounds per acre, respectively, as the standard treatment every second year; and on the corn and wheat crop different rates of nitrogen, namely 24, 48, and 72 pounds per acre, were applied in alternate years, using three different forms of nitrogen—dried blood, sodium nitrate, and ammonium sulphate.

After 40 and 50 years of continuous experimentation on the Jordan plots, conclusions issued by the station state that phosphorus is a limiting element of first importance in this Hagerstown loam soil. When used alone or in any fertilizer combination it resulted in substantial increase of crop yield. Potash alone gave only a slight increase, but when added with phosphorus the increase was greater than with phosphorus alone.

Investigational plot work on fertilizers was begun at the Ohio Agricultural Experiment Station in 1893 by Charles E. Thorne, growing corn, oats, wheat, clover, and timothy in rotation, with applications of nitrogen, phosphoric acid, and potash, singly and in combination. With these tests at Wooster and a number of other points in the State, Ohio has probably the most extensive outlay of plots in the United States. Another important older series of experimental plots is that of the Missouri Agricultural Experiment Station.

There should also be mentioned the long-term cylinder experiments of the New Jersey Station begun in 1898 and continued to this day by J. G. Lipman and A. W. Blair. Corn, oats, wheat, and timothy were grown in rotation in 60 cylinders, each 4 feet deep and 23½ inches in diameter, open at both ends and set into the soil to simulate natural drainage as much as possible. The availability of nitrogen from different sources being the main object of the experiments, manures, dried blood, sodium nitrate, and ammonium sulphate were used in various combinations.

Twenty years of plot experimentation on Barnes silt loam at the South Dakota Station led to the definite conclusion that on this soil phosphorus was the one element notably deficient and that its use as a fertilizer was economically profitable.

At the Iowa Station emphasis has been placed upon crop rotation. Rotations of 4 or 5 years have been shown to be of more value than a shorter 3-year rotation. Barnyard manure has played an important part in the treatment of these plots. The best amounts to apply to this Carrington loam soil are between 8 and 16 tons per acre.

It is not feasible here to review further the results of the work at the various State experiment stations. These have been considered by the respective States, and in most cases public reports have been issued covering the crop yields and interpretations of their meaning for practical agriculture. It is desirable, however, to call attention to the local information obtained by long-time field experiments. There appears to be no other way of accurately evaluating the influence of various farm practices upon crop yields.

Field tests have been the longest and most widely used of any form of soil experimentation, and they remain the most reliable means of
determining directly the fertilizer requirements of a given crop on a
given soil. They are the only means of studying the varying crop-
producing power of soils in place, with the subsoil undisturbed, and
with the crop plants subject to the climatic and other environmental
influences that frequently materially modify the effects of the soil-
fertility factors.

The results of field tests reflect all these influences and are indicative
of the results to be anticipated in practice under the same conditions.
Valuable as field-plot experimentation is to the advancement of
agriculture, the plot testing system cannot escape criticism entirely.
Some of its shortcomings should be recognized. Agricultural practice
is slowly undergoing changes on several fronts. Plans initiated 50 or
even 25 years ago may in some ways be impractical today. A con-
tinuous-crop plot probably contributed valuable information for a
period of years, but now the disadvantages of continuous cropping as
a general practice are so well known that it hardly needs further
emphasis.

Early experiments frequently called for particular fertilizer in-
gredients which have since been supplanted by cheaper products as
good or better. To make a change breaks the continuity of the ex-
periments and thus eliminates one element of their distinctive value.
Then, too, some of the older plots were laid out in fields which have
since been shown to consist of more than one soil type. In other
cases, the soils have been shown to lack the typical qualities of any
one soil series, or to be laid out on a soil type of only limited extent.
Another feature not always properly safeguarded is the possibility of
outwash from one treated plot onto another.

In spite of certain moderate criticisms that may be directed at
long-time field-plot experiments, there is no doubt that they have
contributed much toward the improvement of agricultural practice
in our country. Some modifications may be needed from time to
time, but the results warrant their continuation.

For these reasons the State experiment stations and the Depart-
ment also have been conducting soil and fertilizer studies on farms
selected for this purpose, conducting the experiments cooperatively
with the farmers under the supervision of competent agriculturists.
The county agents cooperate in most of these practical tests on the
farmers' own land. Much of the value of such experiments lies in
their continuance over a period of years, and their repetition in many
localities, thus giving a broader cross section of soil and fertilizer
behavior over large areas of soil types or crop regions. This type of
scientific testing brings the results closest to the farmer's local prob-
lems and needs.