

Some Hypotheses of Soil Testing

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Although many procedures and techniques for determining the nutrient status of soils have been proposed, tested, and even used, soil testing has emerged as the diagnostic procedure most often utilized in established, commercial cropping systems. In most agricultural areas, soil testing has become the most standard and widely-used tool.

Other techniques and procedures have their roles and make valuable contributions, for example, the literature of soil fertility of one period contained many descriptions and illustrations of plant deficiency symptoms. With experience and practice, considerable skill and success can be attained in visual recognition of certain nutritional problems of plants and these skills are certainly helpful. Usually, however, the deficiency must be quite severe before the visible symptom is apparent. Thus a crop may appear normal but still respond to a fertilizer that eliminates some "hidden hunger". When a crop is grown commercially in a region for many years, a fertilizer program is usually evolved to meet its needs. By that time, nutrient deficiency symptoms have become rather rare and are of little assistance.

In a similar way, plant tissue tests or chemical tests for nutrients in plant sap, were developed and still find much use. These rapid field procedures are helpful to confirm or eliminate the adequacy or deficiency of a nutrient for the plant at the time the test is made. Such procedures are often very useful for trouble-shooting and identifying difficulties in an unfamiliar situation and provide good supplementary evidence along with the nutrient deficiency symptoms.

Total plant analyses are very useful in establishing the adequacy or deficiency of nutrients provided the critical levels in that plant part at that stage of growth of that cultivar has been established by previous research. Total plant analyses, in spite of improved analytical techniques, remain largely a research procedure and a post-mortem method of recognizing problems

Biological tests, involving the growth of a microorganism, have been used successfully to rate the relative capacity of soil samples to supply nutrient. *Aspergillus niger*, for example, was extensively used as a test organism and was particularly useful for testing soils for the micronutrients. Advances

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in analytical chemistry have now made it unnecessary to utilize such techniques. Greenhouse trials are still extensively utilized for research purposes but, again, they are not very practical and not very widely utilized in commercial agriculture. When we survey the list of diagnostic techniques for inorganic nutrients for soils and crops, we conclude that soil testing is the workhorse among all the methods and the one which carries the major responsibility for guiding fertilizer use.

In this generation, it is often customary for soil scientists to think of chemistry, physics, and plant physiology as the "mother sciences" upon which our applied sciences draw for analytical methods, information about biochemical pathways, and knowledge of fundamental process". This situation has not always existed and, in fact, the reverse situation was the rule in the early history of science and indeed may still predominate in some areas of knowledge.

We sometimes forget that many of the early chemists and scientists were motivated by the need to understand the nutrition and production of crops. The search for the "principle of vegetation" contributed to the recognition and classification of substances that become known as elements. Discovery of oxygen, for example, was aided by the observation that green plants renewed air after it had been "exhausted" by being breathed by animals. The recognition of the essentiality of carbon dioxide, nitrate, potash, and phosphate for plants contributed to the classification of the chemical elements involved and to the development of the periodic table. It is a credit to the pioneer agricultural scientists, that the mineral nutri-

tion was being established before the periodic table was arranged. Often in the applied sciences, phenomena have been observed and practices have been developed before the comprehensive theory explaining them could be developed. Explanations based on the inadequate theory then available have sometimes been of questionable value if not actually detrimental. The determination of early soil chemists to use total soil analyses as a diagnostic method probably delayed the development of more applicable methods. In this connection, it appears that Liebig was credited with being the father of agricultural chemistry when the mother (the science of basic chemistry) was scarcely in existence.

At the time of Liebig (1803-1873), when knowledge of chemistry and mineralogy was still very rudimentary, about the only produce that could be suggested to study the soil was total analysis. Whether he deserved it or not, Liebig has often been credited with starting an era of total analyses of soils. The hypothesis was that soils containing larger proportions of nitrogen, phosphorus, potassium, and other essential elements would be sources of larger amounts of those elements for crops. For decades, it was believed that total analyses would supply useful information about crop nutrition and fertilizer needs. Furthermore, total analyses were regarded as something of an inventory of soil resources and were considered to indicate their durability under prolonged cropping. In some places, total analyses were made routinely on soil samples until around 1930.

While there is a general broad relationship between the total elemental

content of soil and amounts of the elements taken up by crops, the correlation is very approximate. A great proportion of the soil is practically inert as far as crop growth is concerned. It is very difficult to analyse the bulk of soil material and measure the small variations that are responsible for plant growth.

Gradually the inadequacy of the total analysis approach became recognized. A method that was to become widely known was proposed by the British soil scientist, Dyer (1894). This approach involved using an extracting solution which would imitate the plant in removing nutrients from the soil. This hypothesis was adopted by numerous researchers who in one way or another sought to prepare an extractant that would remove from the soils the same nutrients that the plant could absorb. During the next several decades, a great variety of soil testing extractants appeared. It seemed that each region, or institution, or soil chemist was advocating a unique extractant that was better but different from any other. In the United States, a series of procedures appeared during a relatively brief period of years. Following the Bray procedure in 1929, were well-known methods by Truog at Wisconsin (1930), Spurway at Michigan (1933), Thornton at Purdue (1934), Morgan at Connecticut (1935), and Miles of Maryland and Mississippi (1937), to name a few.

The common hypothesis of nearly all the procedures of that period was that the soil extractant would imitate the plant. Studies by plant scientists had indicated that plant roots excrete carbon dioxide and organic acids. These were assumed to dissolve the minerals of

the soil and the ions were thus released for absorption by the plant roots. Many of the extractants were weak organic acids or dilute solutions of inorganic acids highly buffered to maintain the pH level thought to exist around plant roots. As examples, Dyer suggested citric acid and Truog utilized a wide soil : solution ratio of 0.002 N sulfuric acid strongly buffered at pH 3.0. A number of variations of the Morgan reagent (originally 1 N sodium acetate buffered at pH 4.8) were used in different geographic locations. By the decade of the 1930's more scientific methods and advances began to be felt. Distinctions between clays and the coarser minerals of the soils were substantiated. Cation exchange reactions became accepted across all fields of science. Fractionations of natural materials into compounds instead of into elements began to be accomplished.

During this period, soil chemists began to gain some understanding that soils like proteins or feeds might be fractionated into portions of varying utility. A major proponent of this view, R. H. Bray (1937) called attention to the futility of expecting a chemical extractant to imitate the plant (for example, which plant?). He argued that soil chemists should point their research at learning about the nature and reactions of nutrients of soils. With knowledge of the chemical forms of different plant nutrients in the soil, methods could surely be devised to separate and measure those different fractions. It should also be possible to learn which chemical fractions were important for crop growth and to calibrate the amount of the different fractions against some function of crop growth. With this hypothesis, there is strong

direct encouragement for the soil scientists to learn about the chemistry and reactions of each nutrient in the soil. With this information the probabilities are high that a satisfactory soil test can be devised for each element in each situation. Also with this hypothesis, it is not surprising if different procedures are used in different geographic regions where the soils are different. For example there would have to be questions about using only the Bray P-1 procedure in a geographic region where most of the soils are calcareous.

Futhermore, if this philosophy of measuring the soil form (s) is adopted, it is not surprising if different extractants are used for different nutrients. When the general objective of the soil test extractant was to imitate the plant, a single extractant for all nutrients might be expected and some soil tests still utilize a "universal extractant" that is presumably expected to remove a number of elements.

In his discussions of soil testing, Dr. Bray was quite critical of the idea of "universal extractants." Since the chemistry of each plant nutrient in the soil is different, it follows that an extractant may be efficient for one nutrient but inappropriate for another. From a practical standpoint, a different extracting reagent for each nutrient would be impossible and the utilization of the same extractant for more than one nutrient is certainly to be encouraged. In present practice, exchangeable cations are usually extracted with one reagent; phosphorus with another; and trace metals with still a third. Such groupings, of course, are made with the properties of the nutrients in mind and with related elements of similar

chemical behavior grouped together. Unfortunately, some procedures that are still in use ignore these principles.

Over thirty years ago in the classic papers on the subject, Dr. Bray wrote on the "Requirements for a Successful Soil Test" (1948) and summarized the concept of "measuring the soil form." He listed three general, important requirements: The extracting solution should remove as quantitatively as feasible the soil form (s) of the nutrient important to plant growth; the amount removed should be measured with reasonable accuracy and speed; and there must be a useable relation between the amounts removed and some function of growth or response of the crop to the nutrient in fertilizer rate trials under appropriate conditions. Some of the desirable characteristics add appropriate conditions for the field trials for "calibrating" soil tests were also mentioned.

When we discuss the hypotheses of soil testing, we must note that most of the more successful procedures in use today are based on the concept of measuring the soil form. Soil tests for potassium, magnesium, calcium, sodium and similar elements are almost always intended to extract exchangeable cations. While difficulties are recognized, no other method has yet been widely accepted.

In like manner, nearly all the soil tests for phosphorous that are widely used today are based on measurement of the soil form (s): We like to think that the longevity and extensive use of the Bray P-1 and the Olsen bicarbonate procedure is at least partially due to their conformity with the "measure the soil form" hypothesis.

In contrast to the requirement for identification of the soil forms that contribute to plant growth, other approaches have been proposed that presuppose on specific chemical fractions of nutrients in the soil. The terms "intensity" and "capacity"; which are often used in connection with soil test procedures, have somewhat variable meanings depending on the user. It seems to me that the terms are sometimes used with a considerable identification to a chemical form or reaction, while in other cases the terms used on a try-and-see-basis. As I understand them, the term "intensity" roughly translates in to the concentration under specified conditions in the soil solution or equilibrating extract. "Capacity" indicates the amount of the nutrient that can be added (or removed?) for each unit change in concentration (Beckett, 1964). Apparently, the assumption is made that the crop be adequately supplied if the concentration is maintained at a satisfactory level and that there is no requirement to identify or measure a soil form(s) that is serving as the source.

In actual practice, a soil scientist acquainted with the soil of his bailiwick will be able to estimate from experience their "capacity". For example, except for our sands, I know that the agricultural soils of Illinois will have adequate "capacity" if the phosphorus concentration in solution is 0.3 ppm or similar concentrations recommended by authors of these procedures (Beckwith, 1964) (Fox and Kemprath, 1970).

Studies with Illinois soils by my co-workers have also shown a close correlation between Bray P-1 values and concentrations in equilibrating water solutions. Since the P-1 procedure is

much easier to carry out than is the determination of concentrations in equilibrating solutions, there is little incentive to abandon the P-1 procedure that has served so long and well.

The fact that the P-1 procedure, with local modifications, has for so long been the accepted routine procedure for testing soils for phosphorus throughout the North Central Region of the United States may tend to perpetuate its use. Suggested regulations for controlling pollution from soil erosion and water runoff proposed limiting the phosphate fertilizer application if the P-1 exceeds a specified value in the soil of that field. In the absence of pronounced or widespread dissatisfaction with the accepted practice, a proposed a new procedure must probably offer a marked advantage before it will be accepted.

Still another hypothesis which has become familiar to soil fertility specialists is the measurement of the "labile pool." This concept was given impetus in the period after World War II by funds and efforts devoted to the encouragement of the utilization of isotopes in research. This concept was discussed by Viets (1962) in a way that reconciles it with the soil form hypothesis. Thus, some workers consider the "labile pool" as discrete chemical forms (Williams, *et al.* 1980) while others make no assumption as to chemical nature of the nutrient in the pools.

The general principle is the isotope dilution principle utilised in many fields of science and many variations and permutations of applications have been made. Generally the idea is that the isotope equilibrates quickly with the active fractions of soil

phosphorus (or the labile pool). The extent of the labile pool can then be calculated from the dilution of the isotope. Numerous procedures and approaches have been used and the amount of phosphorus important to plant growth can apparently be estimated very well. While the concepts and several methods (Larson, 1967) have been worked out very well on a research basis, the utilization of isotopes to determine the "labile pool" is simply not practical for routine soil testing

Still another procedure for selecting a method to use for soil testing might be called a "no-hypothesis" method. In this case a group of soils are selected and they are tested routinely by several different procedures that are in use or are recommended for use somewhere. Data by the different methods are compared and a decision on which procedure to adopt is made on some basis. If the soil samples used came from field experiments where the responses to the nutrient had been demonstrated, the best correlation between soil test results and field results across the responding range would probably indicate which procedure would be most useful. Such experiments are very convincing. However, there are a number of methods and it is difficult to compare them all. If a favorite procedure has not been included in the comparison, the experiment will likely to be claimed inadequate. It is usually difficult to collect a large number of soil samples on which responses have been carefully measured. Sometimes samples from soils reputed to be low or high in nutrients are utilized with the risk that the actual performance of the samples may not coincide with their reputation.

Since so much research and practice has been done with soil testing it would seem that a knowledgeable investigator could indeed select a minimum number of procedures, conduct such a study, and find a serviceable soil test for his area. Unless he has a decidedly different hypothesis from those that have already been tried, it hardly seems fruitful to propose a new soil test at this time in soil science.

Frequently a greenhouse experiment is used as a basis for comparing soil tests. Although such experiments may serve the purpose of giving a comparative rating among soils or even of soil test methods, greenhouse trials are no permanent substitute for solid, carefully-conducted field experiments as a basis for calibration of soil test procedures.

Required concentrations of nutrients in soils in greenhouse pots are usually well above those in the field. One important difference, of course, is the ratio of amount of soil to number of plants. In the case of maize, a dense population in the field might be 62,500 per hectare. If we calculate on a soil depth of only 20 cm, there is more than 40 kilos of soil per plant. For a smaller plant with a seeding rate ten times that of maize, there would still be over 4 kilos of soil per plant. Greenhouse experiments normally have several plants in a kilo of soil.

Since greenhouse and laboratory studies have been made almost continuously for 40 years, it is difficult to guess about the additional information that can be obtained from further such experiments. One would suppose that so many comparisons of soil tests versus plant yield, per cent sufficiency, plant

compositions, plant uptake, and other functions have been made that little additional information or few new principles could be expected. Nevertheless, comparisons of soil tests continue to be made. Sometimes it appears that the original objectives and assumptions involved in a method have been forgotten. For example, the Bray P-1 was developed primarily for non-calcareous soil while the Olsen procedure was developed in regions where calcareous soils were the general rule. Both were based on measuring the soil form(s) of the nutrient and on sound chemistry. These two procedures have been compared in many studies in the past and both have been shown to be good procedures. Sometimes a slightly higher correlation with some function of plant growth will be obtained with one procedure and sometimes with the other.

A recent paper (Holford, 1980) reported the evaluation of four methods—Bray, Olsen, Colwell, and Mehlich. Reactions of the 30 soils ranged from pH 5.4 to 8.1. The conclusions indicated that although two procedures were equally correlated with relative yield, the Bray test underestimated the available P more than the other in strongly buffered soils. Also the Olsen was more closely correlated with plant uptake of phosphorus. Just how these nuances would be reflected in field results is not clear. In many fertilizer experiments, highly soluble phosphorus fertilizers often increase the phosphorus content of the crop beyond the point of maximum yield. In such cases, the conclusion is usually that increased plant uptake without increased dry matter is useless.

After this recitation of the hypotheses behind soil testing reagents and

procedures, a reflection upon these different ones leads to at least one fairly clear conclusion. The hypothesis for measuring the soil form has been by far the most successful and most widely used approach. Most of the widely used methods and most of the highly active soil testing operations today are based on this approach.

Research in soil testing continues, however, and other concepts have been and are being proposed continually and some are being put into use. For example, in testing for potassium, some workers have attempted to use per cent potassium saturation of the cation exchange capacity instead of amount of exchangeable potassium (e.g. kg/ha.). The Bear hypotheses (Hunter, 1949; Bear and Toth, 1948; Bear *et al.* 1944, 1945) that the cation exchange capacity of soils should be occupied 65% by Ca^{++} , 10% by Mg^{++} , 5% by K^{+} and 20% by H^{+} has received a great amount of attention but very limited verification over any extended range of soils. In many soils of Illinois, for example, exchangeable $\text{Ca} + \text{Mg}$ should be more than 75% and 5% K is unnecessarily and economically high. Conclusions by Bear and co-workers were based as much as on attaining the desired composition of alfalfa for cattle feed as on attaining maximum yield. Evidence supporting the desirability of specific ratios of cations in the cation exchange capacity is quite limited and few experiments bearing on that concept are being reported. Evidence and consensus opinion seems to be that rather wide ratios of nutrients are tolerated by crops without appreciable effect on yield (Key *et al.* 1962).

Baker (1971) states that ratio and amounts of ions as well as the nature of the exchanger influences availability. A concept that availabilities are related to ionic activities rather than ionic concentrations has been debated (Bache, 1963).

Changes in concepts underlying soil testing are in some respects reflections of changes in practices and goals in land management. In situations where plant nutrients play a very major role in overall profit, the farm operator is encouraged to strive for near maximum yields on all land under cultivation. Under such conditions, he is less interested in a soil test that is calibrated for different yield levels. Instead, he expects from soil testing the assurance that the nutrient in his soil exceeds the level above which a fertilizer response will occur. Furthermore nutrients being measured are often those that have been added rather than those native to the soil.

Accepting the conditions that the role of soil testing is changing from one designed to prevent deficiencies to one that will maintain soil optimum levels and balance among all essential chemical elements, Baker (1973) has proposed an approach that is different both in concept and in practice. In this approach, an equilibrating solution containing calculated concentrations of the essential nutrient ions is used. If a given ion is released from the soil to solution during equilibration, a response to fertilizer containing that element would not be expected. The reverse would be expected if the ions were removed by the soil from the equilibrating solution. Whether or not, this hypothesis comes into wide use remains to be seen.

Among the criteria for successful soil tests, Bray listed that of 'reasonable accuracy and speed'. Indeed, in many endeavors the necessity for convenience, rapid, routine procedures become very important. Even if total soil analysis had been found to predict crop yields with great accuracy, the method could not have found extensive use under the early conditions. Total analyses were simply too laborious, tedious, and expensive for widespread use in crop production practices. Some procedures in use have been selected, not because they are based on the most sound principles or extensive experience but because they advice the determination of several elements in the same extract and the convenience factor is a major consideration (Mohlich, 1953; Nelson, *et al.*, 1953).

In a similar way, more sensitive and more interference-free analytical procedures permit the testing of hypotheses that formerly could not be investigated. For example, measurement of concentrations in equilibrating solutions has only become possible in recent years.

Acceptance of soil testing and its general use in agricultural systems does not imply that research has ceased and that other methods or modifications will not evolve. Prolonged use of reasonably accepted and satisfactory procedures may, however, make changes more difficult. Much information about the soil and plant processes involved in ion absorption by plant is coming available. Bray's concept of 'mobile' and 'immobile' nutrients has been expanded by Barber (1962) allows for refinements in tests for individual elements. Developments in membrane chemistry

will perhaps contribute to further understanding. Current interest in mycorrhiza in plant nutrition is high. These and many other developments will doubtless spawn new hypotheses and attitudes in soil testing.

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