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MINUTE AMOUNTS OF CHEMICAL ELEMENTS IN RELATION TO PLANT GROWTH[1]

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A GENERAL survey of the history of plant and animal nutrition during the past two decades records notable advances in scientific knowledge, many of which have been made possible only because of the recognition and experimental control of organic and inorganic substances in micro-quantities. The investigator of the nutrition of higher plants, which can grow in solutions of purely mineral character, has certain advantages of technique not enjoyed by the investigator of animal nutrition, in the study of the relation to the growth of the organism of very minute amounts of chemical elements. Yet the plant physiologist has not always profited by these advantages. For a long period the standard teaching was that only ten chemical elements (nitrogen, phosphorus, sulphur, calcium, magnesium, potassium, iron, carbon, hydrogen and oxygen) were generally indispensable for the growth of higher plants. Many other elements, if found to be effective at all, were regarded merely as plant stimulants or poisons. Following earlier work in France, Mazé[2] presented in 1914 certain evidence, based on controlled water-culture experiments, of the requirement for normal growth of the maize plant of chemical elements not included in the list of ten, but his experiments

[1] Presented before the National Academy of Sciences, April, 1940, as a highly condensed review, for the information of those who have not had occasion to refer to the literature of this field.

[2] P. Mazé, *Ann. Inst. Pasteur.*, 28: 21–68, 1914.

received but scant attention until much later. Then Warington,[3] at the Rothamsted Experimental Station in England, on the suggestion of a research conducted for another purpose, discovered an essential role for boron in the growth of the broad bean and several other plants. Appreciation of the wider significance of this observation, however, did not immediately follow. About the same time McHargue[4] and others became convinced, as a result of extensive experiments, that manganese was an indispensable component of a nutrient solution. During this period Sommer and Lipman,[5] and Lipman and Mackinney,[6] and Sommer,[7] conducted painstaking experiments with the use of highly refined technique which led definitely to the conclusion that the varied species of plants studied could not complete their cycle, or indeed might show complete growth failure, without minute but determinable quantities of boron, copper and zinc, as well as manganese. Within the past several years two of my colleagues, Dr. Arnon and Dr. Stout,[8] have provided evidence that gives very strong support for the view that molybdenum is likewise one of the indispensable elements for higher plants. It had been shown to be essential for certain fungi by Steinberg.[9] This, of course, does not necessarily complete the list of essential elements. There are indications that still others may be added, but the evidence is not yet conclusive for complete indispensability for a wide range of plant species.

The effective amounts of the elements in question are not quite so spectacularly small as those involved in plant responses to certain hormones and vitamins. Nevertheless, extremely low concentrations produce visible effects, for example, one or two thousandths of a milligram of zinc in a liter of nutrient solution, though much more may be required for continued normal growth. Boron and manganese are now generally accepted as essential elements, but some plant physiologists still seem reluctant to include copper and zinc, although the evidence is equally positive, if not so extensive. In our experience with many species of crop plants, we have not failed in any case to find copper and zinc requirements.

Not infrequently the chemical elements required in minute quantity have been designated as "minor" or "accessory" elements. This may be misleading—such elements are essential for growth just as are nitrogen, phosphorus and potassium. The term "micro-nutrient elements" is possibly suitable as a general designation. The commonly used term "trace" elements seems to me to fail to convey the idea of quantitative relations. Technique for growing plants under controlled conditions has now advanced sufficiently to permit quantitative studies to be made of successive minute increments of the elements boron, copper, manganese, zinc and molybdenum.

To prove decisively the indispensability of elements of the category under discussion, for varied species of plants with different quantitative requirements, the utmost care must be taken in the refinement of methods of culture. At one time the question therefore arose as to whether in general experiments in plant nutrition, and especially in agricultural practice under natural soil conditions, one need be concerned with elements like boron, copper, manganese and zinc. This question can now be answered with complete confidence. In the experiments of the plant physiologist, conducted without special attention to these elements, their presence in adequate amounts depends on accidental factors of choice of chemicals, distilled water or culture vessels, which yield uncontrolled contributions of micronutrients. Earlier investigations on the effects of different nutrient solutions on plant growth will need re-examination in the light of this consideration.

More surprising is the evidence incorporated in hundreds of reports received during the past few years from many parts of the world, that under certain field conditions crop plants may fail to make normal growth, or may become diseased, through deficiency of boron, copper, manganese or zinc, as the case may be. It is too early to draw any general conclusion about molybdenum. Especially numerous are instances of boron deficiency, to which commercially important diseases of the sugar beet, celery, apple, alfalfa and many other crop plants are attributed. Frequently such boron deficiencies have been corrected economically by application to the soil of boron-containing compounds. There is, however, another aspect to the boron question which has been made clear by investigations in California during recent years. Those elements essential for plants in minute amounts may also become toxic at concentrations in the nutrient medium which are still very small. The physiological range is sometimes relatively narrow. Thus, some irrigation waters may add to the soil so much boron that severe injury to sensitive crops is produced. This has become an important economic question in some western areas.

Turning to another illustration of deficiency causing plant disease, an explanation is now available of the previously entirely obscure nutritional disorders of fruit trees known by such names as "little-leaf," "mottle-leaf" and "rosette." These trees are, in fact, suffering from a deficiency of zinc, minute as the requirement is. It was at first very difficult to believe that a simple zinc deficiency was involved. Consider,

[3] K. Warington, *Ann. Bot.*, 27: 629–672, 1923.
[4] J. S. McHargue, *Jour. Agr. Res.*, 24: 781–794, 1923.
[5] A. L. Sommer and C. B. Lipman, *Plant Physiol.*, 1: 231–249, 1926.
[6] C. B. Lipman and G. Mackinney, *op. cit.*, 6: 593–599, 1931.
[7] A. L. Sommer, *op. cit.*, 6: 339–345, 1931.
[8] D. I. Arnon and P. R. Stout, *op. cit.*, 14: 599–602, 1939.
[9] R. A. Steinberg, *Jour. Agr. Res.*, 52: 439–448, 1936.

for example, a specific case of a peach orchard which had become diseased while growing in soil containing within the root zone a total of approximately 3,000 pounds of zinc per acre and that at seven years of age the trees had removed only about one half pound of zinc from the soil. Nevertheless, controlled experiments by water-culture technique, and other evidence, brought conviction that zinc deficiency was indeed the cause of the disease. Obviously, many very difficult questions need answer with regard to the availability of zinc in the soil to the plant. Some experiments made in California suggest that, at least in certain soils, this availability may have a relation to the growth of soil microorganisms which may themselves absorb zinc. There is another type of disease that may affect fruit trees in the field, caused by deficiency of copper. Here also similar symptoms have been reproduced in plants growing in culture solutions lacking only in copper. Manganese deficiencies for various kinds of plants under field conditions are well known and can be reproduced under controlled conditions.

These are only illustrations of the significance to agriculture of chemical elements effective in minute amounts. As I have indicated, the volume of evidence is now impressive. But lest a misunderstanding be created, I should like to emphasize that not all soils are deficient in ability to supply these elements to the plant and, furthermore, when a deficiency exists, it does not necessarily follow that it will be corrected by the use of some fertilizer containing minute amounts of the element in question as an impurity. The so-called fixing power of the soil enters as a most important factor, but I have no time to discuss this point. In practice deficiencies sometimes have to be corrected by direct application to the plant of the deficient element, by spraying or other means.

In the field of study of which I am speaking practical application has followed rapidly on research already performed. But this research is still inadequate in that our knowledge of the functions in plant metabolism of the mineral micro-nutrients is extremely limited. A deficiency of boron has profound effects in all the meristematic regions of the plant. Yet, so far as I am aware, we have no really satisfactory hypothesis concerning chemical reactions in the plant in which boron might assume an indispensable role. And this role is specific to boron, as very extensive experiments with other chemical elements demonstrate. This is a problem of general interest to the cell biologist. The possibility does not seem to have been definitely excluded that minute amounts of boron may have a function in animal cells.

The basis of knowledge is more satisfactory for the development of an understanding of the functions of the metals utilized in minute amounts. Outstandingly important advances have been made in general research on oxidation-reduction systems in living organisms. The oxidation of carbohydrates involves intricate enzyme systems, in which hydrogen carriers, or electron transmitters, have a place. The role of iron, dependent on changes in valence states, has of course been considered for a long time. On the general question of metal catalysis Szent-Györgyi[10] draws the following conclusion: "Such oxidations are catalyzed by metals outside the cells; and when the cell used metals to catalyze oxidation, it did not invent a new principle; it merely applied an age-old reaction, but applied it in a very clever way: linking metal to a specific protein in the cell and thus giving it a chance to act at its best." Recently copper has been reported as an essential constituent of certain oxidase systems, which are of importance in plants. Some recent work indicates that manganese is essential to respiration and nitrate reduction in the plant. Another investigation suggests that a zinc protein enzyme catalyzes the reaction of carbonic acid to water and CO_2. The work was done on blood cells, but a similar enzyme might function in the photosynthetic system, although this has not been proved. In preliminary studies in our laboratory by Skoog a secondary effect of zinc deficiency was observed on the auxin growth substance content of the plant, the zinc deficient plants yielding much less auxin activity than those with an adequate supply of zinc. This seems to be consistent with effects of zinc deficiency in retarding elongation. In general, there appears to be justification for the assumption that minute amounts of inorganic elements and minute amounts of organic substances may frequently be associated in their actions. On the basis of present knowledge, it should be feasible to study some of the possible relations of micro-nutrient elements to the synthesis of vitamins or their precursors by the plant.

Essential metal deficiencies commonly produce chloroses of varied types in green plants, but aside from marked failures of chlorophyll synthesis, suggestions have been made of effects on photosynthetic efficiency. The investigators of photosynthesis are in the midst of a reexamination and reinterpretation of estimates of quantum efficiency in photosynthesis, so that it is not very safe to refer to this question. I might note, however, that Emerson and Lewis[11] in studies on Chlorella utilized certain combinations of mineral micro-nutrients employed in experiments in this laboratory with crop plants, and found large increases in the quantum efficiency, by the particular technique of experimentation adopted. Whatever the final interpretation of these experiments may be, the general question involved is of importance to plant

[10] A. Szent-Györgyi, *Bull. N. Y. Acad. Med.*, 15: 456–468, 1939.

[11] Emerson and Lewis, *Amer. Jour. Bot.*, 26: 808–822, 1939.

nutrition. What are the concentrations and relations of metals in the green cell conducive to the largest synthesis of sugar permitted by other factors in the environment? Evidence on this point is being developed.

Increasingly, the workers in animal and plant nutrition are finding common interests in their researches on minute factors in cell metabolism. We are beginning to appreciate that the plant does not synthesize vitamins or their precursors merely as a philanthropic act for the benefit of the animal. These substances first of all may have a function in the plant itself. Likewise, many inorganic elements, including at least several of the micro-nutrient elements, are indispensable to plant and animal alike. But the qualitative or quantitative requirements are not always coincident. Investigators are now asking how the environmental factors influencing the composition of the plant are related to its value as a food for animals; in other words, how do climate and soil and fertilizer practice affect nutritional quality? The old problem of iodine deficiency in the animal is too familiar to warrant discussion, save to remark that in recent experiments in Berkeley with several types of plants it has not been possible to show so far that iodine is an essential element for the growth of crop plants, within the limits of technique now available. An interesting example of a differential requirement for plant and animal is that of the cobalt-deficiency disease of sheep and cattle extensively studied in New Zealand and Australia. The cobalt deficiency in certain soils did not prevent pasture plants from growing, but the animals suffered for lack of cobalt in the ration. Apparently deficiency of copper for the needs of animal nutrition may also occur in various regions. Manganese deficiencies require further study.

On the other hand, there exists the possibility that the plant might absorb special mineral constituents of the soil in such amounts as to produce a toxic food stuff. One instance of this kind has been carefully investigated by the United States Department of Agriculture, the South Dakota Agricultural Experiment Station and other research agencies. Some species of plants growing on selenium-containing soils absorb so much of this element that the plant becomes severely toxic to the animal. It is an interesting aspect of plant physiology that ability to accumulate selenium from the same soil medium varies strikingly among different species of plants. We also note that plants may absorb fluorine, arsenic, and other toxic elements, if they are naturally present in, or added to the soil.

The whole subject of soil and plant interrelations in its bearing on problems of animal nutrition has been deemed of sufficient importance to warrant its inclusion as a major research objective by one of the Department of Agriculture's new laboratories. The field is ready to be explored, but only long and patient cooperative research on the part of plant and animal physiologists, soil chemists, and probably plant breeders, can determine the extent of existing quality deficiencies in crops and the feasibility of modifying the quality by commercially practicable procedures. Broad generalizations on this aspect of micro-nutrients are not admissable on the basis of present information.

SCIENCE IN GENERAL EDUCATION AT THE COLLEGE LEVEL[1]

By Dr. LLOYD W. TAYLOR
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A few years ago the writer was examining the portraits of Sir Isaac Newton in the British Museum. The museum keeps a file of negatives of portraits that are in the greatest demand. In response to an inquiry whether that file included any of Newton, the attendant replied: "Oh, no, sir. We 'as 'em of the fymous men, sir, but not 'im, sir!"

Instances are not lacking of a similar obtuseness on this side of the Atlantic as to the importance of the sciences. It is true that until fairly recent years sciences in American education were riding a strong wave of popular approval which originated in the last quarter of the nineteenth century. But lately there has been a reaction and the trend is now in the opposite direction. This is being reflected in shrinking registrations in all the high-school sciences on a scale which is positively catastrophic. In colleges the corresponding ebb is being stemmed by the science requirement. But pressure is accumulating toward the elimination of that requirement and the contraction of the sciences in the program of higher liberal education will ultimately be the more pronounced in consequence of its deferment.

Two years ago the American Association for the Advancement of Science set up a special committee to try to identify the problems involved in adapting the sciences to the requirements of general education at the college level. Though this paper is in considerable measure an outgrowth of that study, it is in no sense a report of the committee. Some of its subtopics did

[1] Invited paper, given before the American Science Teachers' Association at its meeting at Columbus, Ohio, on December 28, 1939.