Crop Production without Soil

By Prof. W. F. Gericke, University of California

THE tenets of water culture are known to plant physiologists from an extensive literature. The first papers appeared more than three-quarters of a century ago. Although water cultures are used widely in experimental studies of plant physiology and soil science, the literature is singularly devoid of any suggestion of the economic possibilities of the method—crop production without soil. A brief paper in 1929 was the first announcement that crop production by water culture is practicable[1]. Beginning in 1935, a number of growers, convinced that the method had possibilities, established the first production plants; these are under the author's supervision and, although organized as commercial ventures, are administered as the author's experiments. The largest plant covers two acres.

While a history of the development of the economic use of water culture would not be complete without mention of the laboratory experiments, nevertheless the idea was not born wholly out of the laboratory concepts. Crop production by water culture is not a large-scale use of previously employed technique. Much of the idea was developed from extra-laboratory observations and considerations, from studies and analyses of the physiological and ecological conditions of practical farming operations; and these gave the cue to the devising of suitable techniques, and providing favourable ecological conditions. The technique of the laboratory as heretofore used and that of practical operation differ not only as to physical features but also primarily in physiological concepts and interpretations.

With the establishment of the economic use of water culture, it appeared well to have a word that would distinguish between the two uses. It was found that 'aquiculture' had already been appropriated. 'Hydroponics'[2] was then suggested by Dr. W. A. Setchell, University of California, to designate the "art and science of crop production in liquid culture media". The term 'water culture' can thus be reserved to its historic use and meaning—the growing of plants in nutrient solutions for experimental studies in plant physiological laboratories.

In order to prove the economic feasibility of water culture, evidence was needed that yields sufficiently large were possible to warrant the investment for the equipment required. Consequently, experiments were designed to obtain data on productive potentiality of unit areas of nutrient water surface so that comparison could be made with known production by agriculture.

The 'limiting factor' in yields by agriculture in climates suitable thereto are usually pedological. If these inhibitions could be overcome by water culture, then it should be possible to increase yield per unit area of surface by closer spacing of the plants. Increase in yield would then simply be a function of increase in stand, granted, of course, that the individual plants grown by water culture are as good as those grown by soil. Experiments showed it was possible to use closer spacing for some crops in hydroponic production than in field production; this gave, therefore, expectation of corresponding increase in yield.

Crop production comes as the result of many processes, some of which oppose each other in operation. Ideal conditions could not be prescribed from the findings of laboratory experiments, because these were designed to study specific plant processes as phenomena more or less detached from their agricultural concept and interpretation. Ideal conditions for crop production are virtually compromises between or among various opposing elements and represent essentially the best coordination which the circumstances permit of all important growth-affecting factors. The physiological basis of hydroponics lies in the functions of cultural technique and equipment, designed to obtain yields of crops which, when measured by the standards of the farmer, compare favourably with those of agriculture. Heretofore no comparison was possible because the scale of the water culture experimentation employed in plant physiology laboratories was far too small and restricted to warrant interpretation of data in the standard of the farmer's 'yield per area'. But more serious, however, was the fact that the ecological conditions created by the technique used was quite foreign to the natural pattern for plant growth, so that the data had very restricted interpretation and application. Essentially it was not the physical limitation of size of equipment used which obscured the productive potentiality of water culture, but rather that small size created unfavourable ecological conditions. These in turn created physiological limitations.

While the importance of climatic and ecological conditions to crop production is so widely and generally recognized that it seems presumptuous to make allusion thereto, nevertheless, in view of the historic use of water culture in scientific studies, it appears not out of place to direct attention to the conditions under which the experiments were conducted, and invite comparison of the laboratory with that of Nature. Essentially, the temperature of the soil, except the surface layer, does not vary from day to day; the air temperature varies according to the diurnal changes of solar radiation. It follows, therefore, that the gradient of the root-top temperatures of the plants must change therewith. Complete reversal of gradient comes in the course of twenty-four hours wherever a marked difference prevails in the air temperature of day and night. It is obvious where plants are grown in small containers set on laboratory benches that either a maintained or changing temperature of the room creates a different ecological condition from that which exists in Nature with respect to the root-top gradient. The different parts of most economic plants do not have the same climatic requirements, and consequently cultural technique which exposed the different parts to the same temperature environment cannot be expected to favour growing conditions. The more or less rhythmic change in root-top gradient by virtue of change of the air temperature from day to night and constant root temperature, is an ecological condition that the laboratory climate did not provide.

Classical water-culture experimentation required pure or refined chemicals, pure water, and glass or glazed earthenware containers which resisted solvation. The nutrient solutions were therefore of fairly well-defined character and composition. Obviously these materials are economically prohibitive for economic use of water culture. Consequently investigation had to be undertaken to determine the suitability of ordinary and less expensive materials. Hitherto untried materials had to be studied: crude chemicals and ordinary ground water for the nutrient solutions; building materials—concrete, wood, sheet metal, and various plastics for containers; and various kinds of vegetable litter for the seed-bed.

The equipment must supply the functions of a fertile soil—supply vegetation with water, with the necessary elements, and provide support to hold the seed and growing crops in proper juxtaposition to the environment (Figs. 1 and 2); the feeding roots in the water, the root crown in moist porous media above the water, the leaves in the air.

Basins now in use are constructed of the following materials: concrete, wood, sheet metal (iron) and various asphaltic preparations. The concrete basins constructed as trays range from $2\frac{1}{2}$ ft. to 6 ft. in width with 50 ft. as the maximum length of single units. In some cases units are joined end to end, making even longer basins. Also basins 50 ft. × 100 ft., providing continuous water surface of 5,000 square feet, are being tried. Wooden basins range from trough-like structures 1 foot wide and 40 feet long to flat tanks 12 feet wide and with length sufficient to provide 1/200-acre water surface in single units. Black iron sheet metal has proved serviceable for smaller basins; the largest used are $2\frac{1}{2}$ feet wide and 10 feet long. Certain asphaltic preparations, where proper care was taken in construction, have made fairly serviceable equipment—that is, more or less durable. The depth of the basins range from 4 inches to 8 inches; 6 inches is probably the most satisfactory for most crops.

Remedial measures taken to overcome harmful substances in the materials were as follows. For the alkalinity of the concrete, leaching with water, treating with acid, and coating with non-toxic, water-resistant paints proved effective. For unknown organic substances that may diffuse from wood, brush treatment with strong alkali solution gave good results. Black iron sheet metal gave no trouble—it is conceivable that iron which has appreciable quantities of zinc, copper, manganese, nickel, and presumably other metals, would give trouble unless the iron is coated with a non-toxic paint or enamel. Some of the asphaltic preparations used were found to be toxic and care must, therefore, be taken in the choice of all asphaltic or bituminous materials which are used as plastics or to coat and waterproof equipment.

While the size of basins in the several plants was determined wholly from mechanical considerations, observations, however, have shown that size has physiological importance. This was suggested in several ways, but the information available does not yet warrant a definite statement.

The seed-bed is a mat of vegetable litter—excelsior, straw, sawdust, peat moss, etc., mounted over the surface of the nutrient solution. It rests on wire netting strongly secured to a portable frame. This rests on the top of the basins. The seed-bed provides support for the seed and growing plants, and by protection against sunlight inhibits the growth of algæ. It also protects against desiccation, and extreme temperature fluctuations. The nature and quantity of litter used reflects itself in the water-air properties of the seed-bed and thereby affects ecological conditions. The greater the amount of water that can be held in the seed-bed, compatible with good air supply therein and with other plant requirements, the less fluctuation will there be in the temperature of the roots and of the root-crowns of the plants with changes in the air temperature, because of the high specific heat of water. The root-crown requires different ecological conditions from the feeding roots immersed in the solution. Classical technique with the plants held in the solution by a nonporous support precluded the attainment of these important conditions

The elements essential to plant growth in liquid culture media are generally known. These elements can be grouped into three classes. First those required in fairly large amounts, which can be supplied in considerable excess without toxic effect, and each of which is absorbed in varying quantities, so that the composition of the plants will thereby vary; these elements are nitrogen, phosphorus, potassium, calcium, magnesium. Their range as possible variants in the plant composition must be considered in devising formulæ. In the second class is the element which can be supplied in large excess without toxic effects and is not absorbed in markedly varying amounts, hence is a minor variant in plant composition. This element is sulphur; the sulphate, therefore, becomes in effect a balancing agent. The third class includes the elements required in small amounts and which are toxic if the concentration exceeds certain low values—fractions of a part per million. These elements are iron, manganese, copper, zinc and boron.

The salts should be chosen so that mixtures can be made which will conform in a general way to the proportions found in the composition of the plants, considered as the aggregate of the compositions of different parts. The salt which provides the cation required in largest amount shall provide the anion required in largest amount. Likewise the cation required in smallest amount can be supplied with the anion required in smallest amount, and for those elements between these extremes, the same principle holds. Thus, potassium nitrate, calcium phosphate, and magnesium sulphate are the chief commercial sources of the major elements. In the original experiments, magnesium phosphate and calcium sulphate were used instead of the last two of the above, but, inasmuch as the desired combinations can also be obtained from chemicals already extensively used as land fertilizers, the former set is recommended. Whenever it is desirable to have some combinations which the above three salts cannot provide, a fourth salt can be added; sulphuric acid is added to the mixtures to obtain any required reaction. Sulphates as already noted are not absorbed in great excess of the plants' need and, therefore, large quantities can be used if necessary. The sources of the minor elements is essentially immaterial, unless plant products relatively high in

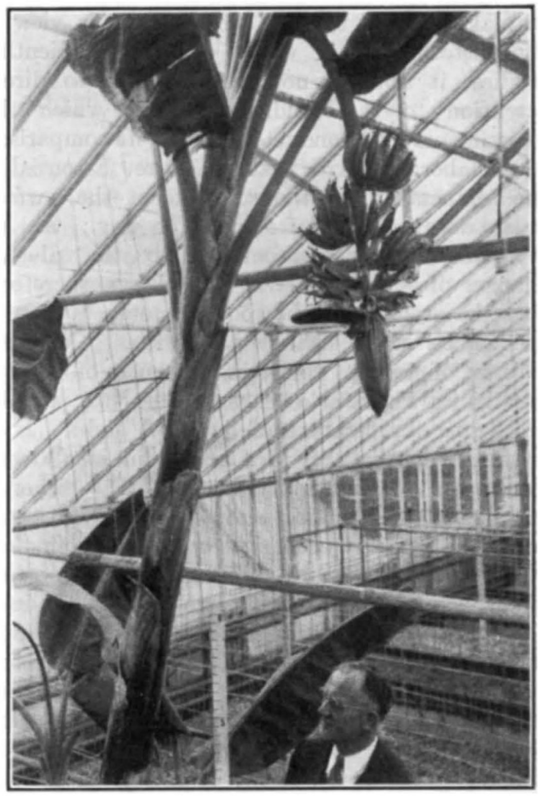

Fig. 2.
BANANA, ONE YEAR FROM BUD.

Fig. 1.
TANK OF TOBACCO.

Fig. 3.
TOMATOES, $4\frac{3}{4}$ MONTHS AFTER PLANTING.

some of these elements are desired. In such cases one would choose the least toxic forms, which in some cases would be organic compounds.

The purpose of having the nutrient solutions conform as nearly as possible to the composition of plants, is to preclude excessive absorption of certain elements causing an abnormal composition. The fact that plants vary as to composition is in itself evidence that nutrient solutions, somewhat different in chemical composition from those compounded by the principles stated above, will support plant growth with more or less satisfactory results. But excessive absorption of any element, especially in the early growth stage, may have unfavourable effects on subsequent plant activities. On the other hand, the early growth stage is also most labile, permitting use of stimulatory conditions which can be very beneficial if not too greatly prolonged. For example, a relatively large supply of certain elements in the culture during the early growth stage, which in case of nitrogen could be supplied both as cation and anion, and more or less complete absence of them in the latter growth period, will be more effective for certain crops than a maintained supply—the quantity absorbed being equal in both cases.

Answer to the question "How much plant food shall be added to a given quantity of water ?" can be given by the description of experiments with some of the crops, for example, with tomato (Fig. 3) : 20 plants set in a basin 10 feet long, $2\frac{1}{2}$ feet wide, and 8 inches deep (thus $16\frac{2}{3}$ cubic feet of water) received nutrients in 1-pound lots, supplied as a mixture of dry salts. When the plants were about two months old, the nutrients were practically exhausted and then another pound was added. Subsequent additions were made at shorter intervals, 7 pounds being the total amount supplied; but the solution was exhausted two months before the experiments were concluded, being then one year old. (The average yield of ripe fruit per basin was 306 pounds—more than five sixths of the total was harvested nine months after planting. There were four basins, each a different treatment; the largest yield was 532 pounds. The basins, including space between, occupied 130 square feet of greenhouse floor.) No difference was noted when smaller applications were made at frequent

Fig. 4.
HARVEST OF 1/100-ACRE POTATO CROP, 18 WEEKS AFTER PLANTING.

intervals or larger applications at less frequent intervals. Apparently any concentration within the range defined for the lower limits of about half a pound, and the upper limit of about two pounds per 16 cubic feet of water, gives satisfactory results. This means that the stirring in of additions of nutrients was not necessary; the mixture was merely added at one point. Obviously there is a practical limitation to the distance salts will diffuse and consequently appropriate means must be employed where large basins are used.

A field of 1/100 acre area planted to potatoes produced a yield of 24·65 bushels, or 1,479 pounds (Fig. 4); 40 lb. of chemicals was used. This experiment was in 1934. In subsequent trials each year thereafter, the above-stated large yields were not obtained; apparently certain features of the techniques, ideal in 1934, did not produce ideal growing conditions in the subsequent tests. I believe, however, that the technique can be designed to obtain consistent results with the potato.

The retail market price of the chemical used in largest amounts, and the most costly, namely potassium nitrate, was 70 dollars per ton. Chemicals were of the grade used in compounding fertilizers for land.

The greatest item of cost in crop production by hydroponics is the investment in basins. Also the cost of the chemicals will be a major item in some crops. For example, about two pounds of chemicals were required to produce four pounds of dry wheat grain. Even though the yield per unit area of water surface in basins of the size mentioned for tomatoes was exceptionally high (computed to acre basis it was 142 bushels), the ratio of the quantity of plant food required (at first glance one may think this quantity too high; the weight of oxygen accounts for the apparent large quantity of plant food required) to that of yield obtained makes the cost of production of wheat and other crops that are predominantly 'dry matter' prohibitive by water culture under present conditions. Crops the marketable products of which are characterized by high water, starch, or sugar content, give promise in an economic appraisal of production by hydroponics.

It is, of course, not inconceivable that industry may develop and manufacture equipment at markedly greater economy than prevails at present, thereby increasing the number of crops that can be grown economically.

There are no specific formulæ or cultural techniques that can be prescribed to be followed too literally because of the somewhat unknown character of the materials and equipment that will be used; cultural technique must be designed to meet the conditions where the crops are grown. The principle of making the adjustments, the elucidation of the physiological basis for all features of the method, together with concrete description and data of experimental plants, need to be made available for the guidance of prospective hydroponicists. To provide this is the programme of research now being pursued.

[1] Gericke, W. F., "Aquiculture—A Means of Crop Production", *Amer. J. Bot.*, **16**, 862 (1929).
[2] Gericke, W. F., "Hydroponics—Crop Production in Liquid Culture Media", *Science*, **85**, 177 (1937).

Centenary of the Atlantic Steam Ferry

IN April 1838, the paddle steamer *Sirius*, 703 tons gross, won for herself the distinction of being the first vessel to cross the Atlantic Ocean under continuous steam power. To celebrate the centenary of this notable achievement, a special exhibition, "One Hundred Years of Transatlantic Steam Navigation", is being held at the Science Museum, South Kensington, and will be open until mid-September, to show in outline the developments that have marked the growth of this service. An illustrated handbook bearing the same title (London: H.M. Stationery Office. 6*d*. net) prepared by Mr. H. P. Spratt, the Museum officer responsible for the organization of the exhibition, gives a brief account of the history of the Atlantic steam ferry together with descriptive and historical notes on each of the steamships represented. These exhibit the striking developments which have taken place in naval architecture and in the methods of steam propulsion.

The change from wooden hulls, first to wrought iron construction and finally to steel, is exemplified in the size of the vessels and in new methods of construction. Paddle wheel propulsion gave way to single screws; twin, triple and quadruple screws followed in quick succession. The early engines derived most of their power from the condensation of the steam, and the nature of the evolution was first to simple expansion engines and then to compound, triple and quadruple expansion engines which, in their turn, have been superseded by the Parsons direct-drive, then single-reduction and now double-reduction turbines. It is to be remembered that each of these developments has