Chemical Problems in Crop Production.

DELIVERED BEFORE THE CHEMICAL SOCIETY ON NOVEMBER 15TH, 1934.

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THE classic chemical problems in crop production centre round the feeding of plants. It was in 1840 that Liebig by chemical reasoning and Lawes by empirical trials applied in practice the knowledge gained by plant physiologists about the nutrition of plants. Up to that time many agriculturists, knowing nothing about the scientific evidence to the contrary, had assumed that plants feed on the organic matter in the soil. Liebig in his vigorous writings showed them that this was not so; he pieced together the scientific knowledge and gave a convincing picture of the plant deriving most of its food from the air in the form of carbon dioxide and oxygen, and the remainder from the soil: water, and simple compounds of nitrogen, phosphorus, sulphur, potassium, calcium, magnesium, iron and other elements. These are then built up into the complex carbohydrates, proteins and other substances which finally form the plant tissues. Liebig argued that the soil resources could be increased by the addition of the appropriate chemical compounds, and Lawes showed how to do it; he set up experimental fields at Rothamsted and a factory in London, thus starting the artificial fertiliser industry which has now grown to such enormous dimensions that some 35 or 40 million tons are made annually in the different countries of the world. There are many technical problems connected with the industry that could profitably be discussed, but I shall confine myself to those relating to the agricultural side. For many years these were mainly concerned with showing how to fit the fertilisers into everyday farm use. The results were very striking.

Crop increases of 30 or 50% were not uncommon: the cereal crops were greatly increased by nitrogenous manures, and the very important root crops by superphosphate; the Rothamsted field plots started in 1843 afforded such striking demonstrations as farmers had never before seen. In the words of Gilbert, the distinguished collaborator of Lawes, the unmanured crops growing alongside of their neighbours might almost be fancied to say: " If you won't feed me I won't grow." Those were spacious days for the farmer; prices were high and costs low; there was no need for stinginess in applying fertilisers. They were put on the ground in adequate amounts and a good response fully repaid the cost.

As years went by, costs began to rise and prices to fall; the margin of profit became exceedingly narrow and finally disappeared. New and more economical methods were required and the chemist was called in to find how little of the various fertilisers needed to be added to soils to serve for a particular crop. The first hypothesis had been that plants took from the soil those things they needed, and if, therefore, one wished to discover the fertiliser requirements of plants it was only necessary to find out what quantities of fertiliser constituents the plant contained. Average crops were therefore analysed so as to discover the amounts of phosphorus, potassium, nitrogen, etc., present; the soils also were analysed to find the amounts per acre of these elements present in suitable form for plant nutrition, and a simple subtraction sum showed how much, if any, artificial fertiliser need be supplied. The method was much used some 30 or 40 years ago: it was highly developed in the United States by Cyril Hopkins, who spoke of drawing up the " Invoice of the Soil " :

Phosphate in crop . . .	30 lb. per acre.
,, ,, soil . . .	600 ,, ,, ,,
Average of good soils in district	2000 ,, ,, ,,

There seems sufficient phosphate for a number of crops, but, as the amount is far below the average content, there will certainly be need for phosphatic fertiliser if the average soils are known to respond—which in the region in question they were. This procedure was simple; it had, however, the weakness that it was not adequate—for two reasons:

(1) one cannot say exactly how much available plant food there is in the soil; and (2) the plant is not a fixed definite entity, it has considerable range of variation.

It might seem relatively easy to determine how much phosphate or potash a given soil contains, but actually the total values given by ultimate analysis have had only limited utility. Hopkins was able to get something out of them, as also was Prescott in Australia, but in normal English experience they are not helpful. Better results have been obtained by adopting some analytical method that distinguishes between the more and the less soluble constituents—a distinction first emphasised by Daubeny in 1845 and reduced to laboratory terms by Dyer in 1894: indeed Dyer's method still remains the most useful we have.

The amounts of nutrient and other materials in the plant, however, are not determined by the needs of the plant but by the quantities available. The plant roots act like a partially permeable membrane; they absorb some of everything that is soluble in the soil; not, however, in the proportion in which it exists in the soil, but in a proportion modified by certain characters of the plant. This is well illustrated by the following figures showing the mineral constituents of grasses and clovers growing intermingled on the Rothamsted grass plots:

Variation in Composition of Mineral Matter in Plants growing side by side (Rothamsted—Park Grass).

	% in pure ash.			% in pure ash.	
	Grasses.	Legumes.		Grasses.	Legumes.
CaO	7·6—11·8	21·4—30·3	P_2O_5	5·7— 9·7	5·1—8·6
MgO	2·4— 3·7	3·6— 7·5	SiO_2	17·3—36·6	1·3—1·9
K_2O	22·6—37·9	11·2—31·3			
Na_2O	0·4— 5·3	0·6— 9·6			

Some of these absorbed substances greatly stimulate the production of carbohydrates and proteins in the plant: others do not. The final composition of the plant is therefore profoundly affected by the composition of the soil, and, except in cases of extreme deficiencies, is not a good index of the fertiliser requirements of the plant.

A different approach has therefore become necessary. It is recognised that the subject is much more complex than had been supposed and it has had to be put on a much broader basis. The purpose of modern work is to discover the factors that govern the the growth and composition of plants, and having done that, to find the simplest and most economical method of bringing them under control. The study of soil fertility thus resolves itself into two parallel sets of investigations. Plant physiological work shows what the plant needs in order to attain its maximum growth: more precisely, how growth is affected by variations in the conditions, especially in the supplies of nutrients, water and air for the root, reaction of the medium, etc. Studies by soil investigators show how far a particular soil is likely to satisfy the conditions for full plant growth, and how it can be made to do so better than it naturally would. Soil fertility is dependent on five main factors:

Adequate plant food supplies. Adequate water supply. Air supply to the roots. Adequate space for the root system. Absence of injurious substances.

In practice these are closely linked. A food supply adequate for one level of water supply is quite inadequate for another. F. G. Gregory and F. Crowther made some good experiments in the Sudan showing that, as the amount of irrigation water increased, the response to added nitrogen fertiliser also increased. It is therefore impossible to speak of the adequacy of the soil supplies of plant food except in terms of water supply. The same holds true of the other conditions of growth, particularly of air supply, which is largely a matter of soil texture.

The relation between the quantity of nitrate in the soil and the quantity of nitrogen present in the plant is fairly simple. The total quantity of nitrogen in the crop is roughly proportional to the supply, but the way in which the nitrogen is used varies according to the amount present and the water supply. The added nitrogen can lead to a corresponding increase in crop without particular change in nitrogen content, or if for any reason it fails to increase the yield it can cause an increase in nitrogen content that may become very marked.

Extreme cases being omitted, the variations in composition due to increases in nitrogen supply are much less than the increases in yield. The first increments of nitrogen give considerable increments of crop : later ones give less. So the percentage of nitrogen in the crop, and especially in the grain, is first unchanged or even falls as the nitrogen supply increases, but with later increments of nitrogen it rises steeply. Over a fairly wide range the nitrogen content is more affected by the water supply than by the nitrogen supply. This is what happens in normal fertility conditions; it holds not only for nitrogen but for the other elements that increase plant growth : the fertiliser causes the plant to grow more but does not much affect its composition or its quality.

Thus sulphate of ammonia in conjunction with superphosphate and potassic fertilisers usually increases the potato crop by some 15 to 20 cwts. per acre for each cwt. that is given up to 2, 3, or sometimes 4 cwt. per acre. The change in composition is only slight, as also is the change in marks assigned by an expert chef for quality. On the other hand the effect of soil differences is very great, as shown by a comparison of the Rothamsted with the Woburn results :

Marks for Quality of Steamed Potatoes (1929).

Cwts. K_2O per acre.	Woburn (light soil).	Rothamsted (heavy soil).	Cwts. N per acre.	Woburn (light soil).	Rothamsted (heavy soil).
0	32·6	28·5	0	34·4	29·2
0·5	33·6	29·5	0·3	33·3	29·3
1·0	34·5	29·6	0·6	32·9	29·1

Percentage of Dry Matter in Tubers grown with Different Potassic Fertilisers.

	No potassic fertiliser.	Sulphate of potash.	Muriate of potash.	"30% Potash salt."	Rate of dressing, cwt. K_2O per acre.
Woburn, 1929	27·5	26·7	26·2	24·8	1·0
Rothamsted, 1929	26·1	25·9	24·9	24·2	1·0
,, 1930	23·1	23·3	22·7	22·1	0·8
,, 1931	20·9	20·5	20·2	20·2	0·8
,, 1932	22·6	22·1	—	—	0·8

Remarkable results are obtained when one gets away from the normal fertility range to the extremes of deficiency or excess. The form of the plant changes, in extreme cases considerably; this is well shown in the Rothamsted experiments with mangolds. A large excess of nitrogen and a prolonged deficiency of potassium bring about striking changes in the plant and affect its reaction to insect and fungus attack. Wallace at Long Ashton has shown that nitrogen starvation of apple trees heightens the colour of the fruit.

Although it is not possible to lay down precise fertiliser recipes, crops do show certain general requirements. Practically all crops respond to nitrogenous fertilisers. Root and potato crops frequently respond also to superphosphate, and grass land to basic slag; leguminous crops, mangolds, potatoes and fruit commonly to potassic fertilisers also. Wallace has shown that potassic and nitrogenous fertilisers are as a rule the most important fertiliser elements for fruit, phosphate being advantageous only for cover crops and for strawberries. In the West country at least, the potassium supply is the key to the successful nutrition of fruit trees, and by extending the use of potassic fertilisers it has been possible to extend fruit growing and improve greatly the yields and quality in existing plantations. Trees suffering from shortage of potassium show a curiously high phosphorus content.

Differences in composition of the crop may have far-reaching consequences. Varieties of wheat have been bred at Svalof for resistance to winter frost; successful ones are found (Bengt Lidfores; Åkerman) to contain a higher percentage of sugar in the leaf than the others. It is not supposed that the sugar confers frost resistance : the evidence is rather that the freezing of water in the intracellular spaces of the leaf causes water to pass out from the cell, making the cell sap more and more concentrated till finally the protein is irreversibly precipitated, apparently by a salting-out process, and the cell then dies. Maximov has shown, however, that the presence of sugar in the sap protects the protein against precipitation.

There are also some unexpected results. The same sugar that is associated with frost resistance also makes the leaves attractive to hares, so that winter resistant varieties tend to be eaten more than others.

The composition of the crop naturally affects its value as food, especially as animal food; this is particularly so for grass, which forms a large part, sometimes indeed the whole, of the food of the animals. In its early stage grass is richer in protein and in mineral matter than at any later period; it therefore has high feeding value and efforts are now being made to preserve dried young grass for winter feeding. Among its other valuable constituents is carotene, the precursor of vitamin-*A* and the cause of the rich yellow colour in cream. Experiments at Jeallots Hill have shown that yellow cream can be obtained in winter if the animal is given some of this dried grass.

In the southern hemisphere, notably Australia and South Africa, and occasionally in England and Scotland, pronounced deficiencies of calcium, phosphorus, or other elements sometimes occur in soil, causing equally pronounced deficiencies in composition of the vegetation, and these lead to marked nutritional troubles with the animals. These were first studied by Arnold Theiler and his colleagues in South Africa and the subject is being developed at the Rowett Institute, Aberdeen. Typical analyses of herbage associated with healthy and with diseased conditions of the animals are as follows :

Percentage of Mineral Constituents in Dry Matter of Herbage.

	Scottish hill pastures.		Kenya.		New South Wales.	
	Healthy.	Diseased.	Healthy.	Diseased.	Healthy.	Diseased.
CaO	0·65	0·21	1·00	0·49	0·465	0·168
P_2O_5	0·67	0·29	0·93	0·19	0·184	0·047
K_2O	2·66	1·51	2·25	0·83	0·143	0·087
Na_2O	0·37	0·12	0·07	0·02	—	—
Cl	0·64	0·52	0·42	0·18	—	—
N	2·50	2·05	—	—	—	—
Total ash	7·18	5·33	—	—	—	—
Silica-free ash	5·85	2·82	—	—	—	—

The remedy consists in supplying the missing elements as " licks " or in fertilisers.

Where the diet includes a number of foods (as the ordinary human diet), differences in composition of individual foods tend to even out, so that for practical purposes the composition of individual items has usually little dietetic significance.

The factor of competition comes into play and introduces complications when several plants are growing together, such as the mixture of leguminous and non-leguminous plants grown for silage or fodder purposes or occurring naturally in grass land. Leguminous plants derive their nitrogen from the bacteria living in the nodules on their roots; these fix nitrogen from the air and make the plants independent of nitrogenous fertiliser. The non-leguminous plants, however, are much favoured by nitrogenous fertiliser, and grow so vigorously that they tend to crowd out the leguminous vegetation. Thus it may happen that additions of nitrogenous fertiliser cause no increase in the amount of protein produced per acre. Phosphates, on the other hand, favour the leguminous plants, so that these increase when phosphatic fertiliser is supplied. This accounts for the remarkable improvements effected by basic slag on pasture land.

In regard to these principal elements of plant nutrition it is now recognised that more and better field experiments are needed to provide the main facts on which the agricultural chemist can then proceed to work. The methods of field experiments have recently been completely overhauled; the experiments of course can never be exact, but they are now done in such a way that each experiment gives a measure of its own error. Simultaneously, chemical examination of the soils is made.

In recent years it has been found that certain elements other than the classical ones are needed in very small amounts. Larger quantities become harmful, but the proper small quantity is indispensable.

Boron has been much studied at Rothamsted. Miss Warington found that it is essential for the proper development of broad beans, and later workers have shown that other plants need it also. Sugar beet affords an interesting example: in absence of the necessary trace of boron a certain disease appears, which has caused some trouble in central Europe and in the Irish Free State.

Manganese has been studied by Samuel and Piper at the Waite Institute, Adelaide. A trace of manganese sulphate (1 part per million) was found to be essential to the growth of plants. In its absence oats become liable to the grey fleck disease.

Allison in Florida has shown that minute traces of copper are essential to plant growth: he has obtained dramatic increases of yield on the Everglade soils by additions of traces of copper sulphate. We have, however, not yet found soils in this country that respond to copper salts. Zinc appears to be essential at any rate for fruit trees: in its absence the curious rosette diseases set in.

Lithium salts are stated by Sir Rowland Biffen to confer resistance to mildew and yellow rust on wheat grown in pots.

Molybdenum salts injected into plants have been found by Miss Sheffield to induce a trailing habit of growth and also to produce symptoms apparently identical with those of virus disease in *Solanum nudiflorum*. W. A. Roach shows that the roots of fruit trees vary in their power of assimilating molybdenum from the soil: some can do it and others cannot.

Some of these curious stimulating substances are organic. They were first called auximones or growth promoters; now they are called auxins or growth enzymes. Owing to the difficulty of working with them it has not always been possible to distinguish their effects from those of the inorganic promoters, and some of the auximone effects of the older workers are probably attributable to iron. But these are cases where the active agent is probably an organic substance, though owing to difficulties of working it is not possible to be quite sure. F. W. Went and Kozl have recently isolated from the growing point of plants an auxin which increases the growth of the upper parts by stimulating the elongation of the cell, and restricts the growth of the roots; they have gone so far as to ascribe the formula $C_{18}H_{32}O_5$ to one form of the auxin and $C_{18}H_{30}O_4$ to another.

A remarkable substance has recently been isolated by H. G. Thornton at Rothamsted. The invasion of the root hairs of leguminous plants by the nitrogen-fixing bacteria is preceded by an excretion from the roots, which causes the bacteria in the soil to multiply. In turn the bacteria excrete something which causes the root hairs to multiply and to curl: on the inner bend of the curl the bacteria enter. This substance has been isolated and is being studied.

The late S. U. Pickering obtained evidence of plant excretions capable of injuring other plants: these results have never yet been satisfactorily explained. There is much empirical knowledge about the harmful effect of growing plants on soil: fruit stocks, for instance, cannot be raised in succession on the same land, but new land is needed for each crop. Whether this is the result of excretions or of exhaustion of some essential minor element is not known.

The growing plant also affects the soil in other ways. Wallace has shown that grass grown as a cover crop raises the potassium and the iron content of the soil water and may thus cure iron and potassium deficiencies on certain soils; it also lowers the N/K ratio. He thus explains the paradoxical result that clean culture of fruit is not always the best: weeds in the orchard have their uses.

The production of cellulose in the plant is now being studied at Rothamsted by A. G. Norman and is opening up considerable possibilities in view of its importance in industry.

The ripened seed has its own group of problems. Barley has been studied most completely and L. J. Bishop has found surprising regularities in the make-up of the grain under various conditions of growth. The nitrogen content may vary from 1·2 to 2·4% and the proteins and carbohydrates change correspondingly, but always in accordance with a definite pattern which remains constant for any given variety. The value of barley for brewing depends to a considerable extent on the quantity of nitrogen compounds present, large amounts being detrimental, especially for beers that have to be kept for some time before consumption. The value of wheat for baking, on the other hand, is usually enhanced by high protein content, but it is also much affected by the physical state of the protein.

Many of the chemical problems in agriculture are shifting over to the direction of physical chemistry and especially to the branch that deals with colloids.