of his researches on the various species of cochineal insects.

3000 francs to François de Zeltner, to contribute to the cost of a proposed expedition to the Sudanese Sahara, more particularly in the Aïr massif.

2500 francs to Léonard Bordas, to assist him in pursuing his investigations relating to insects attacking trees and forests, and more especially species which at the present time are devastating the woods of the central plateau and west of France.

3000 francs to Joseph Bouget, botanist at the Pic du Midi Observatory, for realising his cultural experiments on a larger scale, with special reference to the improvement of the pastures of the Pyrenees.

3000 francs to Henry Devaux, professor of plant physiology at Bordeaux, for the continuation of his researches on the cultivation of plants in arid or semi-desert regions.

2000 francs to Victor Piraud, for the continuation of his studies on the fauna of Alpine lakes and torrents, particularly at high altitudes.

2000 francs to Marc Tiffeneau, for the continuation of his studies on the phenomena of molecular transposition in organic chemistry.

THE PRINCIPLES OF CROP PRODUCTION.[1]

IN any discussion of the principles of crop production it is necessary to begin with the year 1840. By that time it was definitely known that plants consist mainly of organic matter along with a little mineral matter—phosphorus, calcium, potassium, sodium, etc. —to which, however, very little importance was attached. The practical man knew that farmyard manure was the great fertiliser; he also knew that other substances, bones, salt, etc., had, in certain circumstances, considerable fertilising value. The most obvious facts were the large amount of organic matter in the plant and the large amount of organic matter in the best manures; and it is only natural that chemists and physiologists should have connected these, and argued that the object of the manure was to furnish organic matter for the plant.

By a brilliant stroke Liebig, in 1840, brushed aside this obvious connection and declared that the true function of the manure was to provide, not organic matter, but the mineral constituents which the chemists had ignored. The first step, he said, was to find out what mineral constituents the plant contains, and then to supply these substances in a suitable form. If any one of them is lacking the soil is rendered infertile, and matters will not be put right until that one is added. Thus the whole art of manuring was reduced to an exact science.

Unfortunately Liebig's prescriptions failed in practice. The Rothamsted experiments showed that his ash constituents gave little better crops than no manure at all. Liebig had left something out; it was necessary to add nitrogen as well before complete growth could be obtained.

The critics urged that the effects would only be temporary; that in time the land supplied with "artificials" would give out. Experience has shown that this is not so; similar good results have been obtained at Rothamsted over the long period of more than sixty years (Fig. 1).

Part, therefore, of Liebig's principle is perfectly correct: the mineral constituents are indispensable and must be supplied to the plant. The mistake was to suppose that they were sufficient. We may take it as established that crops can be grown satisfactorily and indefinitely by supplying proper quantities of suitable compounds of nitrogen, phosphorus, and potassium. This we can call our first principle. Difficulties arise, however, directly one tries to develop it in practice. Trouble began with the attempts to find out what are suitable quantities to use. Liebig had supposed that the requirements of a crop could be gauged by the composition of the ash. Lawes and Gilbert showed that this was not the case. Thus the ash of the turnip crop contains a considerable amount of potash but only little phosphate; according to Liebig, it should have required mainly a potassic fertiliser. Lawes and Gilbert showed, however, that it required phosphates and not potash, and they concluded that the special requirements of a crop could only be discovered by actual trial.

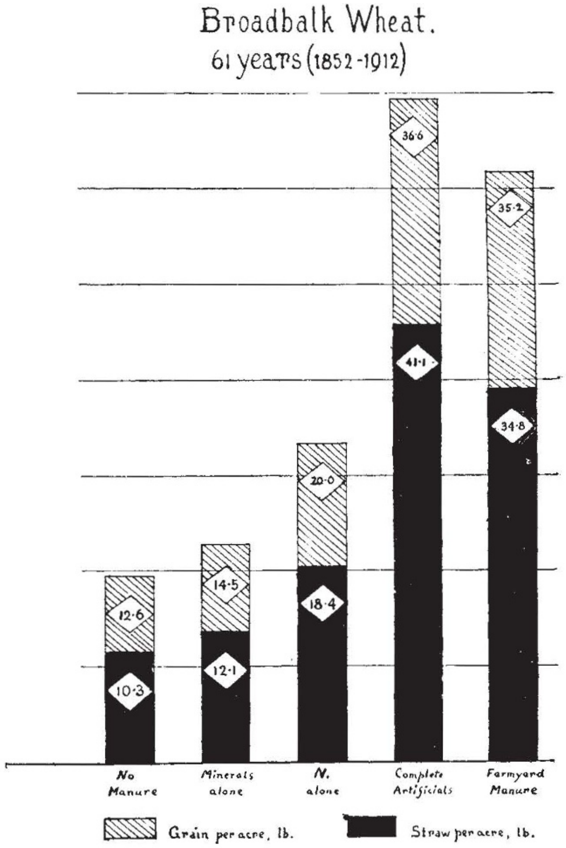


FIG. 1.—Yield of wheat on the Broadbalk plots, average of sixty-one years' results (The figures in the diamond-shaped spaces denote bushels of grain and cwts. of straw respectively.)

When nitrogen compounds are withheld the yield is little better than on the unmanured plot. Complete artificial fertilisers give a full crop which is fully maintained to the present time, and in this case is better than that given by farmyard manure.

This view was developed in the 'sixties in a series of brilliant lectures by Ville. After numerous experiments (he says "many thousands"), he drew up the following list, showing the special need, or, as he called it, "the dominant," for each crop:—

Ville's List of Dominants.

Nitrogen	for Cereals.
,,	,, Beetroot.
Potash	,, Potatoes.
,,	,, Vines.
Calcium phosphate	,, Cane-sugar.
No dominant	,, Flax.

In order to ascertain the special needs of the crop on a particular soil, he grew the plants on a series of plots, one of which was given the complete manure,

---

[1] Lecture delivered before the Chemical Society on November 18, 1915, by Dr. E. J. Russell. Abridged from the Journal of the Society for December, 1915.

whilst the others each had one constituent left out. Thus for wheat he obtained the following results, and, therefore, concluded that on this soil wheat requires a good supply of nitrogen, less phosphorus, and still less potassium :—

	Crop per acre. Bushels.
Normal manure	43
Manure without lime	41
,, ,, potash	31
,, ,, phosphate	26½
,, ,, nitrogen	14
Soil without manure	12

The method, of course, is perfectly sound, and it has been very widely adopted. It is, however, frankly empirical, and empirical work is never very inspiring, so that for a long time soil work came rather to a standstill.

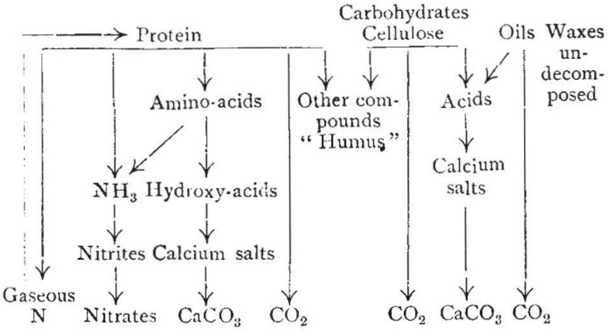
It has several times happened in the history of agricultural chemistry that the new illuminating idea wanted to revivify the subject at a stagnant period has come in from some outside technical problem that had to be solved. So it was here. The growth of the towns and of stricter ideas on public health had brought into prominence the need for better sewage purification, and it was imperative that the problem should be dealt with somehow or other.

Schloesing and Müntz found that satisfactory purification involved the conversion of ammonia into nitrate, and by a brilliant investigation they found that this process was neither chemical nor physical, but biological. Their work was extended to the soil with remarkable results. It was seen that the soil was not a mere inert mass, but that it was teeming with life and pulsating with change. The number of bacteria is enormous, running into millions per gram, and the question is raised: How do these organisms live? They must have food, and they must have energy. We are therefore forced to go back to the soil and study it as a medium for the life of a soil population.

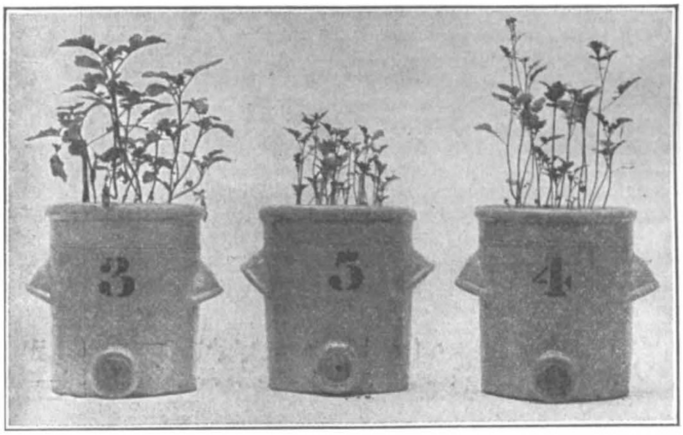
A very cursory examination shows that the soil forms only a thin layer; underneath it lies the subsoil, which is wholly different in colour, texture, and especially in its behaviour towards the plant (Fig. 2).

Yet there was not always this difference. When the soil was first laid down it was all like the subsoil, and whenever a new surface becomes exposed, either by landslips, cliff-falls, etc., it is always the subsoil type that appears. The first vegetation has no great supply of plant nutrients, but plants suited to the conditions nevertheless spring up. They take what they can from the crude soil, they take carbon dioxide from the air, they synthesise sugars, starches, cellulose, proteins, etc., deriving the necessary energy from sunlight. When the plants die they fall back on the soil and return to it all that they took, and a good deal more of new material besides. That introduces a fundamental change.

The new material thus added contains stores of energy and food substances suitable for the bacterial population, which forthwith flourishes. Decomposition goes on, nitrates and other substances are produced, and the conditions are made more favourable for the growth of a new race of plants. One of the most obvious changes is the formation of nitrates, but other products are formed as well. It is proving exceedingly difficult to trace out full details, but the following is probably in the main accurate :—



Unfortunately, not much is known about the details, but the reaction is extremely important. The initial products are of little value to the crop or the soil. The final products are invaluable for plant nutrition, and some of the intermediate products are very valuable for the soil. This, therefore, is the reaction on which plant nutrition depends, and it is of the highest importance that it should proceed rapidly and smoothly. Where for any reason it does not, the soil becomes unproductive.



Soil Sand Subsoil

FIG. 2.—Plants grown in soil, sand, and subsoil respectively, all without manure, showing the marked differences in behaviour towards the growing plant.

Scientific crop production depends largely on controlling this reaction. Three things are necessary: the conditions—the air supply, water, temperature, etc.—must be favourable; the organisms must be of the right kind; and the supply of raw material—plant residues—must be kept up.

We shall see later on how the favourable conditions are obtained. Hitherto little has been done to control the organisms beyond improving the conditions, but beginnings have been made in the direction of inoculation and partial sterilisation. The supply of raw material is kept up in several ways; probably the oldest is to leave the ground alone, so that it covers itself with wild vegetation, which is then ploughed in. This formed part of the Mosaic law; it was the regular medieval custom in our own country, and it is practised to this day in Connemara. It is too haphazard for modern use, however, and so nowadays the farmer grows a special crop with the express intention of ploughing in all or part of it, or of feeding it to animals and ploughing in the excretions.

The second broad principle of crop production is, then, that the biochemical decompositions in the soil must proceed smoothly and rapidly.

New difficulties arise as soon as one begins to develop this principle. Reverting to the scheme just given, it is seen that the decomposition of proteins may proceed in two ways, either ending with nitrate or with nitrogen. Now the nitrate ending is desirable enough, but the nitrogen ending is highly undesirable. Yet this happens directly the process is speeded up too much. The more intense the cultivation becomes the more serious are these losses; they are bad on the prairies, but still worse under conditions of intense cultivation. To some extent this is inevitable; it is equally true of engines, but just as the engineer has increased the efficiency of engines, so the agricultural chemist has to increase the efficiency of the nitrogen utilisation processes.

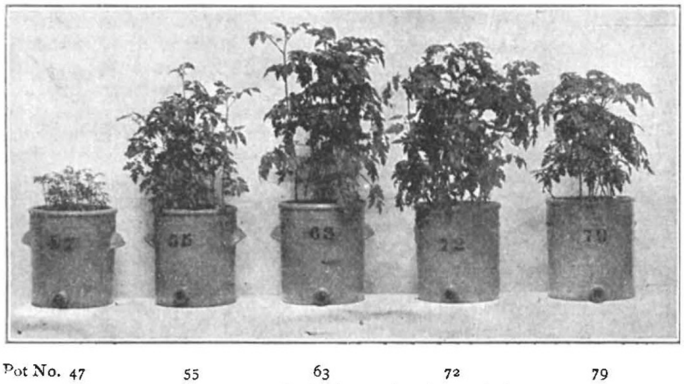


FIG. 3.—Tomatoes supplied with increasing doses of nitrate of soda.

Pot 47.—No nitrate. Pots 55 to 79.—Increasing dressings of nitrate. This increases the amount of growth up to pot 72, but it depresses growth in pot 79, where too much is given. The middle pot, 63, is best for fruit. Phosphates and salts, potassium, calcium, etc., were given equally to all pots.

Unfortunately, the purely chemical work on the decomposition of protein has not gone far enough to enable a full working hypothesis to be mapped out. The decomposition does not stop at amino-acids; under bacterial action there is a further change to bases and acids. These are under investigation in several chemical laboratories, but the results have not yet helped us much. Here, therefore, we have an economic problem of the first importance waiting for the solution of a chemical problem which, at first sight, seems rather academic and remote from practice.

These biochemical changes, important as they are in crop production, do not end the matter. The soil comes directly into the reaction. The calcium carbonate neutralises acids produced during the decomposition. The clay and some of the other constituents possess colloidal properties, so that all these reactions proceed on a jelly-like surface and not in a fluid medium, and they are liable to be affected by all the complications produced by surface actions.

The plant plays an even more active part. Its roots absorb some of the products—the nitrates, the phosphates, etc.—and might therefore be expected to hasten the whole process; but this does not happen. On the contrary, the growing plant appears to retard it, and nitrate is always formed in higher quantities on fallow than on cropped land, even after allowing for what is taken by the crop.

Whether the growing plant affects the nature of the change or only the rate is not yet known. The essential point is that, so far as plant nutrients are concerned, neither the soil nor the plant plays an entirely passive part. The soil is not an inert medium, and the plant is not a mere passive bucket into which the products of the reaction are drawn; each plays an active part, disturbing both the reaction and the distribution of the products.

The recognition that the plant is a living thing has broadened our conception of the factors necessary for plant growth. In much of the literature of the 'seventies and 'eighties it is tacitly assumed that the whole art of crop production is a question of manuring. Whitney's investigations on American tobacco, however, led to the recognition that the type of the soil is an important factor in crop production, which has had some extremely interesting developments. Mechanical analyses to determine the type became an indispensable part of the routine of soil analysis. The perspective was restored, and the fact emphasised that the plant not only wants food, but also proper water supply, air supply, and temperature.

Now there is a very simple rule that applies to all these factors. Plant growth increases with increasing supply of any one of them, but this only happens so long as the supply of every other factor is adequate. When anything is lacking the increase in growth is not kept up, and additional supplies give no extra crop. Finally a stage is reached when extra supplies may do harm, either by direct injury or by cutting out another indispensable substance. This is shown in the tomato experiments of Fig. 3, where successively increasing doses of sodium nitrate are applied in the four pots 55, 63, 72, and 79, although no further growth is obtained in 72 and 79 because of the insufficient water supply. The conditions for favourable growth are all present in pots 72 and 79 excepting only this one, but it effectually prevents the plant from taking full advantage of the good conditions. All this is expressed in a generalised form in the curve of Fig. 4, which thus represents our third principle of crop production. It has only recently been revived in agriculture, although the fundamental idea is old; it can be found in the writings of the political economists of the Malthusian school; it was used in a special form by Liebig in his "Law of the Minimum"; it was developed by Horace Brown and F. F. Blackman. In its full generalised form it is proving extremely useful.

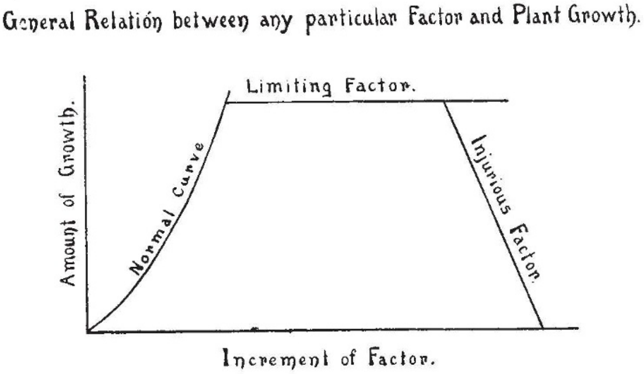


FIG. 4.—Increases in amounts of the various factors necessary for plant growth do not cause indefinite increases in growth. After a time some other factor becomes insufficient and operates as a limiting factor.

Problems of soil fertility generally have to be approached from this point of view. Whenever a case of infertility has to be studied the first question to settle is: What is the limiting factor? And the next: How can this limiting factor be put out of action? As a rule the limiting factor is one of the following:—

Limiting factor.	Put out of action by:
Wetness	Drainage, liming
Dryness	Irrigation, suitable cultivations Addition of organic matter
Lack of temperature	Drainage and cultivation
Sourness or acidity	Liming or chalking

The removal, although simple in principle, may be very difficult in practice: it has often proved to be the rock on which many beautiful schemes for increasing food production have been wrecked.

We have seen that, broadly speaking, three general principles of crop production can be laid down:—

(1) The plant must have a sufficient supply of all necessary nutrients, especially of nitrogen, potassium, and phosphorus.

(2) The biochemical decompositions in the soil must proceed smoothly and quickly.

(3) All the requirements of the plant must be satisfied. Any one left unsatisfied constitutes a limiting factor preventing further growth. Increases in any one factor give increases in growth until something else proves insufficient and becomes a limiting factor.

We go back, then, to our three established principles. Each of these can be recognised broadly in every case of crop production, but considerable difficulties arise when one tries to develop any of them; there are so many factors involved and their interaction is so complex. I can best illustrate this by taking one of the factors in some detail, and I will choose one that has received very much attention from chemists, namely, the supply of phosphates.

Phosphates are indispensable for plant growth, and well conducted physiological experiments in sand have shown a simple connection expressible by a mathematical equation between the amount of phosphate supplied and the amount of growth. But such simple results are never attained in soil. To begin with, there is always some phosphate already present. At first sight it looks easy enough to take account of this, and simply add it on as a constant in the equation. It has proved almost impossible, however, to give any precise value to the amount of phosphate in the soil that is of any use to the plant. Ville showed years ago that the amounts revealed by chemical analysis are far beyond anything the plant can ever get, and he rather gloomily concluded that "chemistry is powerless to throw light on the chemical properties of the soil." One could scarcely expect chemists to acquiesce in that view, nor did they. Instead of using strong acids, they used dilute acids; several were suggested, and by a happy inspiration Bernard Dyer selected 1 per cent. citric acid as being the most suitable; although that was twenty-one years ago, 1 per cent. citric acid still holds the field in this country.

The part extracted by dilute acids was called the "available" portion to distinguish it from the "unavailable." The new method at once proved very helpful; difficulties, however, began to arise. It was found impossible to assign any definite value to the amount of available phosphate present. Variations in the conditions of the experiment gave wholly different values for the amount of "available" phosphate, whilst in the case of nitric acid the longer the acid acted the less phosphoric oxide (P_2O_5) was extracted.

Now that gave the clue to the problem. It is obvious that there must be two actions going on: a direct solvent action and a reverse action, resulting in the withdrawal from the solution of the dissolved phosphoric oxide. The direct solvent action was found to be much the same for all dilute acids.

The reverse action proved to be the ordinary adsorption isotherm, similar in type to that obtained with charcoal and dilute acids. The constants are not the same for the different acids, and from these curves it is possible to go back and explain the apparently erratic action of the different acids on the soil.

Thus it appears that when phosphate is added to the soil for the purpose of increasing the growth of a crop it does not simply stop in the soil, waiting for the plant to take it up. It reacts with the soil; it is adsorbed, and the amount available for the plant at any time depends on the adsorption relationships. There is, in short, a competition between the plant and the soil for the phosphate. The curves for clay and sandy soils show that adsorption is greater for clay than for sand; in other words, the clay competes for the phosphate more vigorously than does the sand. An amount, therefore, which is sufficient for the plant growing in a sandy soil proves inadequate on a clay soil. This has thrown light on an interesting problem in manuring, for it has long been known that clay soils stood in more need of phosphatic manures than sands. The field results bring out this fact: the yield of barley on the heavy Rothamsted soil falls when phosphates are omitted, but it does not react nearly so quickly on the Woburn sand.

It seems a far cry from the logarithmic curve expressing an adsorption isotherm to the management of barley and turnips, but the connection is really simple and direct.

This, however, does not settle the matter. The plant is a living thing, and consequently its requirements are not rigidly constant, but vary with the conditions. There are very good grounds for supposing that the plant actually requires more phosphate on a clay soil than on a sand. The effects produced by phosphates are promotion of early growth, root development, and early ripening; they are specially valuable on clay soils, in wet regions, and for shallow rooting and quick growing plants, for example, swedes and turnips.

It is possible that some simple connection underlies all these, but no one has yet discovered it.

Again, seeing that the need varies with the conditions, it is clear that if the conditions are altered the needs may change. When, for instance, a dressing of farmyard manure is applied, some of the properties of the soil are altered; it becomes more porous and more retentive of water, and phosphates may behave differently from what they did before. That is well shown on the Saxmundham plots.

It is unnecessary to go any further. The point I want to bring out is that the simple and incontrovertible statement that phosphates increase plant growth proves very complex when applied in practice. So it is with the other factors. They can be disentangled and investigated, but it is not yet possible to put them together again and predict the resultant. One cannot set out from first principles and reconstruct the normal case of crop production; the factors are too numerous and too complex.

Yet something has got to be done. The technical chemist has the advantage over his colleague in the purely scientific laboratory that he cannot shelve an inconvenient problem. A method has been evolved, an empirical method, which, whilst not very rigid, has at least the merit that it works. It consists in going into the field and finding out the actual agricultural properties of the soil by observations, inquiries, and direct field experiments; these have to be repeated for two or three years because the first results may only have been a trick of the weather, but if the same result is obtained for several seasons running, one may be sure of being right.

All that is old; it is, of course, Ville's method over again. The new part consists in trying to extend the results to other soils. For this purpose a soil survey of the area, usually the county, is arranged. In this way a collection is made on one hand of the agricultural properties, on the other of the chemical, bacteriological, and physical data, of typical soils. It is obvious that the possession of these standard soils helps the analyst and expert adviser very considerably; if a farmer asks for information it is much easier and safer to compare his soil with the standard than to attempt any absolute measurements. Moreover, these soil surveys are greatly facilitating advisory and analytical work.

They do far more than that, however. The normal case of crop production can never be decided on purely laboratory methods because there are always two or three varying factors, whereas in the ideal laboratory experiment there is only one factor varying. We are not, however, confined to the ordinary laboratory methods. Statisticians have to deal with problems involving two or three variables, and they have worked out a method—the method of correlation—which, when intelligently applied, gives valuable results. It is hoped to apply this to crop production. The necessary masses of data are slowly being accumulated, and it is anticipated that very interesting results will be obtained.

The ordinary laboratory method, however—the one factor method—may still on occasions work satisfactorily. It sometimes happens in nature that one of the various interacting factors overshadows all the rest and virtually eliminates them, so that here, too, it is possible to apply laboratory methods with satisfactory results.

For example, on a certain type of clay soil the whole situation is controlled by the circumstance that phosphates are almost absent, whilst the need of the plant for phosphates is particularly great. The addition of basic slag in these circumstances has caused most remarkable improvement. The best instances are seen at Cockle Park, and the results are given in their bulletins.

Another illustration is furnished by our work on the partial sterilisation of soils. The simplest explanation of the phenomena is that the soil population can roughly be divided into two groups: one favourable to the production of plant food, the other not. The useful population is, on the whole, more resistant to adverse circumstances than the harmful organisms, and therefore survives more drastic treatment. Hence any method that kills some, but not all, of the soil population effects an improvement and leads to good results. A continued spell of favourable conditions, however, enables the harmful organisms to establish some sort of superiority. This hypothesis throws important light on the behaviour of the soil in natural conditions, and it reveals another factor in crop production.

We have not yet succeeded in making much of it in the normal case; indeed, we have scarcely attempted to do so, because there are so many interacting factors. There are, however, cases where this one factor largely dominates the situation. In glasshouses run at a high pitch, where the soil temperature and water content are high, and where large dressings of organic manures are used, the bacterial efficiency falls off so much that the plants begin to suffer. The soil, in the picturesque language of the practical man, is said to become "sick." This sickness proved so difficult to deal with in practice that the soil was thrown out and new soil brought in to take its place.

It was not difficult, however, to suggest a remedy. The reduction of bacterial activity seemed clearly due to an excessive development of the detrimental organisms. It was only necessary to adopt partial sterilisation to get rid of these and to give the useful organisms a better chance of action. The basis of a suitable method was already in existence; steam had been used to kill insect pests in the houses, and by suitable modification this process was successfully used for the treatment of sick soils.

The most fruitful ideas for working out the development of our subject have often been got from abnormal cases brought in by the growers. Practical men have the great advantage that they are compelled to keep their eyes open for nature's problems; they cannot shirk them, or they find their crops suffering and themselves losing money. The close association of science with an industry is, therefore, a great advantage, because it brings in new problems which, if properly investigated, may prove extremely valuable in opening up new fields of knowledge. There is an exhilarating freshness about all this work that one often misses in the more academic investigations.

All the same, while speaking in praise of applied science, one must recognise that science cannot be applied until it is developed. We have seen, and instances might have been multiplied, how the hydrolysis of protein throws light on the proper management of a manure heap, and how the adsorption isotherm worked out for charcoal and dilute acids clears up a difficulty in the manuring of turnips. It is impossible to set any limit to the value of good work in science honestly carried out. The fact is that science and creative industry are one and indivisible, and any attempt to divorce them may only end in disaster.

UNIVERSITY AND EDUCATIONAL INTELLIGENCE.

THE *Morning Post* of January 18 announces an anonymous gift of ten thousand guineas to King Edward's Hospital, Cardiff, towards the cost of new extensions.

THE *Times* of January 14 announces that Sir Alexander M'Robert has given to Aberdeen University an endowment of about 750*l.* per annum for a Georgina M'Robert lectureship on pathology, with special reference to malignant diseases.

THE National Diploma Examination in Agriculture of the National Agricultural Examination Board will be held at the University of Leeds on April 14 and following days, and examinations in the science and practice of dairying will take place in September at the British Dairy Institute, Reading, and at the Dairy School, Kilmarnock. Entries for the first-named examination must be sent in not later than March 1, and those for the latter ones not later than August 15.

THE December issue of the *Reading University College Review* is largely a record of the continued effect of the war upon the work of the college. All the conditions during the first year of the war have affected also the first term of the present session, but in greater measure. The number of men day-students at the beginning of the term had fallen to about forty, and of this number some left at the end of last term in order to undertake military service. More members of the academic staff have undertaken military or Government service, and others are likely to follow their example. Wantage Hall is again in military occupation, and the council has agreed to place rooms