CROP ROTATION, WITH SPECIAL REFERENCE TO THE PRINCIPLES OF GREEN MANURING*

It is proposed in this lecture to discuss in general terms the subject of crop rotation, paying particular attention to the scientific principles involved in that form of crop rotation which is known colloquially as "green manuring".

It is an axiom of agricultural science that continuous cropping to the one crop is likely to be one of the worst possible practices of husbandry. And particularly is this to be condemned when the crop in question is one which requires constant and intensive cultivation as is the case with maize and sugar-cane. When opening the conference in Cairns last year the Minister for Agriculture drew attention to certain undesirable trends in the direction of soil erosion and impoverishment and made a plea for balanced agriculture.

At the conference held in Bundaberg in 1935 I submitted a paper entitled "Sick Soils", and at this stage we will review briefly some of the points presented in that paper:

It is a significant fact that the permanent agricultural systems of the old world, with their centuries of experience, are all built upon well-planned programmes of crop rotation. Such programmes usually involve about a five-year cycle, any particular crop appearing not more than twice in the cycle, while the succession is planned so that a particular crop plant is not followed by one of similar habit, type, diseases, and method of cultivation. Thus in a planned rotation corn would not follow sugar-cane and *vice versa*.

What then, one may now ask, are the unhappy results which may follow continuous cropping to a crop plant which requires constant and intensive cultivation. The answer is that under such conditions as prevail in these dry, unirrigated areas the soil will suffer a gradual but remorseless loss of fertility while at the same time it develops a chronic "sickness".

During the 40-year period from 1898 to 1937 the average yields of sugar-cane in tons per acre in the Bundaberg-Gin Gin district have been as follows:—

1898–1907	1908–1917	1918–1927	1928–1937
14·6 ..	15·3 ..	14·4 ..	15·9

During this period much new land has been brought under cultivation, the use of artificial fertilizers has developed from nothing to a highly important farm practice, while new and better varieties have been grown. Yet the yield of cane has barely held its own, and one might well ask why it has not progressed.

* By A. F. Bell in the *Queensland Agricultural Journal*, Vol. L., Pt. I., July, 1938.

In an exhaustive analysis of rainfall data made by Mr. Norman King and published in the "Canegrowers' Quarterly Bulletin" for October, 1936, we find that (many opinions to the contrary) the seasons have not changed; the average annual rainfall has been maintained. Obviously, then, the explanation of this static position must lie in a gradual loss of the inherent fertility of the soil, which is balanced by improved varieties and otherwise improved farm practice.

Now it has so happened, through the fortunate foresight of one of the old pioneers of the Woongarra, that there was left standing a patch of the original virgin scrub. Some few years ago we carried out comparative tests on this virgin soil and a field immediately adjacent which had been cultivated for twenty-two years. Of course, a great deal of this land has now been cultivated for over fifty years, and a comparison with this would without doubt be even more depressing, but it is bad enough as it is. Figures observed from some of the tests were as follows :—

	Virgin Soil. Per cent.	Adjacent 22 years cultivated. Per cent.
Moisture Equivalent*	38	30
Organic Matter (or Humus)	7·8	3·6
Nitrogen	0·48	0·22

In short, the native fertility is being rapidly lost as a result of growing continuously a crop which is a gross feeder and which requires that constant cultivation which brings about fertility depletion and soil erosion; the soil is becoming "dead".

We pass now to another side of the picture—the development of a "sick" condition of soil. The normal fertile soil literally teems with countless numbers of minute, invisible plants known as bacteria and fungi; they are so small that 15,000 or 20,000 bacteria laid out end to end would only stretch about an inch. These lowly microscopic plants include both benefactors and enemies of the plants we cultivate. The great majority, fortunately, have a beneficial effect or at least do no harm; they are concerned in the decay and rotting of vegetation, making the enclosed plant-foods available to the growing crop, assisting in the weathering of the soil, converting nitrogen to forms suitable for the plant, and so on. Generally speaking, the more fertile the soil the greater will be the numbers of these beneficial and harmless little organisms.

It is possible to count these organisms with reasonable accuracy by means of a very simple process: A small amount of the particular soil under investigation is taken and gently shaken with a measured quantity of water so that the bacteria and fungi become evenly distributed through the water. A known fraction of the watery suspension is then drawn off and mixed with a substance known as nutrient agar. This agar is poured into a glass plate, where it solidifies like gelatine and, in the course of a few days, the bacteria and fungi

* This soil contains a high proportion of so-called "hygroscopic" moisture which is not available to the plant; therefore about 20 per cent. should be subtracted in each case, giving *effective* moisture-holding capacities of 18 and 10 per cent.—a decline of nearly 50 per cent. Small wonder then that cane on these soils now commences to show distress a fortnight after good rain. Similarly the humus, nitrogen, and other plant-foods have declined to low levels.

multiply, and each forms a colony which later becomes visible to the naked eye. We are then able to count the numbers poured into the plate, and so, by multiplication, the numbers in the amount of soil taken. Such numbers are usually given as the numbers per gram of soil—an amount equal to about a quarter of a teaspoonful of soil.

We made counts of this type on two soils which were separated by only a headland, but, while one farmer has allowed his soil to run down and become dead, the other has consistently practised trash conservation and green manuring for many years, and so has largely maintained the fertility of the soil. The counts were—

Organisms per Gram of Soil

	Bacteria	Fungi	Total
Fertile soil ..	.. 16,800,000 ..	2,200,000 ..	19,000,000
Worn-out soil ..	.. 3,100,000 ..	50,000 ..	3,150,000

But in addition to these beneficial and harmless bacteria and fungi the soil contains parasites which attack the roots of the plant, and the less beneficial or harmless organisms there are the better chance the parasites have. Now, soil which is virgin soil in so far as a particular type of crop is concerned will contain few, if any, parasites which will attack it. However, as successive plantings of a particular crop are made, so do the parasites which will attack it increase in numbers, and ultimately are present in sufficient numbers to distress the plant and stunt its growth. Many root parasites will attack a large number of closely related plants and the planting of corn, for example, in " sick " cane land will only serve to further increase those parasites which attack members of the grass family generally. On the other hand, during the period of continuous planting to sugar-cane, the parasites which might attack, say, a legume are left without a host, and so they diminish greatly in numbers and may even become extinct.

This, then, is a basic point in the planning of rotational programmes. No one plant is left in the ground long enough for its particular parasites to build up in great numbers ; it is displaced by a second crop plant, and the numbers have diminished before the first crop is returned to the soil again.

The agricultural phase of the Queensland cane-sugar industry is based upon the practice of continuous cropping to this one crop, a crop which, moreover, requires extensive cultivation and which has little protective influence on the soil. We say continuous cropping because a possible green-manure crop every four years cannot be regarded as crop rotation. The time has come when the trends resulting from this unfortunate combination of circumstances must be recognized and faced, even though farmers do not control two important factors which have largely determined the adoption of this practice. These are (*a*) the almost complete absence of payable alternate crops and (*b*) the existing system of cane land assignment, whereby a farmer must restrict cane production to a certain certified area, precludes the adoption of a rotational programme if a farmer is growing up to his full assignment.

It does not appear probable that there will be developed in the near future any extensive production of alternate crops which can be marketed as such, although there does seem to be some scope for the utilization of land for intensive grazing and fodder production. In this connection we might make passing reference to the very successful experiment in lucerne production at the Bundaberg Station and the interesting fat lamb raising experiment which is being carried out at the Mackay Station.

There is, however, another aspect of crop rotation which warrants your consideration and attention, and that is rotation to crops which may not in themselves be directly payable propositions, but which will help to restore the fertility of the land to such a level that the same amount of cane may be grown more profitably on a reduced area of land. We have in progress at the Bundaberg Station a long-range experiment which will test the economics of this proposition over a number of years within the limitations of the assignment system. In this experiment part of the field will be cropped according to usual practice, that is, we will take off a plant and two ratoon crops, the second ratoon crop being harvested at the end of the season, ploughed out, and prepared for planting in the following autumn. In the other portion of the field a plant and one ratoon crop only will be taken off, and the field will then be planted to a succession of leguminous crops for a period of sixteen months. We are now carrying out trials to find additional legumes which will be suitable for this type of rotation, including types which may be either ploughed in or grazed if the occasion warrants.

The reason for the advocacy of legumes as a rotational crop is twofold. Firstly, they are very widely removed from sugar-cane in so far as plant relationships are concerned, and it therefore follows that parasites of legumes are most unlikely to attack sugar-cane and *vice versa*; therefore a prolonged period of cropping to legumes will see a vast reduction in the ranks of the army of sugar-cane parasites. Secondly, a legume possesses the peculiar power of obtaining its nitrogen requirements from the nitrogen of the air instead of drawing them from the soil, as do other plants. Consequently, when a leguminous crop is ploughed into the soil, the soil may be enriched in nitrogen to an amount equivalent to a substantial dressing of sulphate of ammonia, but for which no account will be rendered at the end of the month. The explanation of the manner in which this free nitrogen supply is obtained will constitute the second part of the talk.

It has long been recognized by farmers that the growth of leguminous crops tends to enrich the soil. Later it was found that this was due to the fact that in some way or another these plants could actually add to the store of nitrogen in the soil. Consequently legumes came to be more and more used as rotational crops, particularly when soils showed a tendency to become run down, or immediately preceding the growth of a crop which needed large amounts of nitrogen for its proper growth. Trial and experience showed that it often happened that a particular legume would not grow when planted in fields which had never grown legumes or had not been planted to them for a long time. In other cases a variety which did well in one part of the world was for some unexplainable reason practically a complete failure when taken to another country with a similar climate. Observant farmers had, however, discovered the fact that they could often improve yields in a new field by "inoculating" it with a few loads of soil taken from a field in which the particular crop grew well; doubtless many of you have seen this practised by old lucerne growers.

Investigation of these phenomena by trained agriculturists has removed the veil of mystery, and we are now able to present a pretty clear picture of why and how legumes assist in the regeneration of soil, why there are fluctuations in growth, and why there may be almost complete failures.

Leguminous crops planted in a soil rich in nitrates and other plant-foods will grow vigorously in the same way as do other crops. It so happens, however, that, unlike other crops, they would also grow vigorously, and possibly even more satisfactorily, if the same soil were very deficient in nitrates. The reason for this somewhat contradictory performance lies in the fact that leguminous plants, in association with a certain type of bacterium, can draw their supplies of nitrogen from the atmosphere instead of being forced to take it in the form of soil nitrates as is the case with other plants.

As you know, some four-fifths of the atmosphere in which we live is composed of nitrogen, and, of course, this atmosphere diffuses into the soil, so that in a well-aerated soil there is always atmospheric nitrogen in contact with plant roots. This atmospheric nitrogen, however, exists in the form of an inert gas, and in that form it cannot be absorbed and utilized by man, animals, or crop plants. It may, however, be "fixed" and converted into forms suitable for such use, and in various overseas countries there are vast works for capturing this nitrogen and converting it into the sulphate of ammonia which you apply to the soil, and which is converted into nitrates in the soil. As suggested above, it may also be captured and converted into suitable forms by legumes working in association with bacteria.

Upon digging up a legume and washing the roots free of soil, it will be noticed that in most cases there are small galls or nodules attached to the roots. These nodules represent the tiny workshops within which the fixation and conversion of the nitrogen of the air is carried out by bacteria of the genus *Rhizobium*. The relationship is a mutual benefit society, since the plant supplies the bacteria with free board and lodging, while the bacteria, on the other hand, help the plant to free supplies of nitrogen. This nitrogen is not stored in the nodules, as many people seem to think, but is immediately distributed over the rest of the plant for use in making new growth.

In the normal course of events these *Rhizobium* bacteria live in the soil, obtaining their plant-foods, including nitrogen, from the soil. When the seed of a legume germinates in their vicinity these minute bacteria attach themselves to the very fine hairs on the young rootlets and work their way way into the roots. Here they commence to multiply greatly in numbers, stimulate the plant to produce the galls or nodules and the work of nitrogen fixation proceeds. After the crop has been harvested or ploughed in the nodules break up and decay and the bacteria are distributed into the soil again, where they can continue to live for considerable periods (sometimes years) and await the growing of another suitable legume.

It will readily be seen that if the land has never grown legumes before, or over a long period, there may be none of this type of bacterium left in the soil; in such a case, of course, there will be no nodules formed, no atmospheric nitrogen fixed, and the plant will have to depend on the nitrogen supplies of the soil. Even when the necessary bacteria are present, if there should be a high reserve of nitrates present in the soil, this will depress or prevent the activities of the bacteria, and there will be little or no gall formation and nitrogen fixation; in such a case the ploughing in of the green manure crop would merely result in returning to the soil the nitrogen which had been taken out by the crop, and would not increase the nitrogen stocks one little bit. Obviously, then, the time for the planting of a green manure crop (as distinct from a mere cover crop) is when the nitrate stocks are low—but more of this later.

Up to the present we have spoken as though there were just a single species of this *Rhizobium* or nitrogen-fixing bacterium. Actually there are a large number of strains, which are each limited in their activities to certain plants or groups of plants. It has been found that there is a certain number of so-called "cross-inoculation" groups of plants, and any one *Rhizobium* can only work in association with plants within one particular group. For instance, the cowpea, poona pea, velvet bean, and lima bean lie within one group, while lucerne, the sweet clovers, the trefoils, and melilotus constitute another group, and so on. Now, the *Rhizobium* species which forms nodules on the roots of the members of the first group, will not form them on members of the second group, and *vice versa*. Therefore the fact that land has grown an excellent crop or poona pea does not mean that it contains the right bacteria for the growth of, say, New Zealand Blue Lupin.

But not only do we have different groups of bacteria which will not work in association with other groups of leguminous plants, but there is a great variation in the efficiency of the strains within any one group. The meaning of this statement will best be illustrated by summarizing some experiments with poona pea and soybeans, which were the right bacteria for the growth of, say, New Zealand blue lupin.

In view of what we believe to be the increasing importance of legume culture it was considered desirable to initiate some experimental work with a view to finding highly efficient strains of *Rhizobium* which could be used for the inoculation of crops at planting time. Consequently, cultures were collected from laboratories in various parts of the world, and, in addition, some cultures were isolated from the nodules of very well-grown Queensland crops.

In order to test the efficiency of the various strains the seeds are inoculated and then planted in sterilized sand which is free of plantfood. We use medium-sized earthenware pots waterproofed to prevent evaporation. The plants are grown in a glass house, and every care is taken to prevent contamination with bacteria which might blow in with dust. The plants are watered with a sterlized solution of plantfoods from which nitrogen is missing—that is to say, they are forced to get their nitrogen from the air.

Cultures for the Poona pea group were obtained from Western Australia, South Australia, Victoria, New South Wales, and Queensland, while soybean group cultures came from England, Canada, United States, and Australia. It is of interest to note that as far as these two crops are concerned the most efficient strains were isolated in Queensland from very well-grown crops at Cairns and Lawnton respectively.

We would also direct attention to the formation and distribution of nodules in both Poona pea and soybeans. In the case of the highly efficient strains the nodules are concentrated around the crown of the plant, while with the less effective strains the nodules may be equally or more numerous, but they are scattered through the root system. The roots of the uninoculated plants bear no nodules, and neither did the roots of a Poona pea plant which was inoculated with a strain specific to the New Zealand blue lupin.

So much, then, for the theory of green manuring ; we will pass now to the consideration of a few points of field practice. We have seen that while legumes will grow in soils containing adequate nitrates they will also grow vigorously in nitrogen-starved soils provided they can make contact with an efficient strain of the proper species of nitrogen-fixing bacteria. For the full development of the plant it is not only necessary that the particular strain be present but that it be present in large numbers in order to ensure early and complete nodulation. When planting any legume, therefore, the wisest course to take would be to inoculate the seed with the appropriate culture immediately before planting. This is a very simple operation, and is now widely practised in the United States, where there are several commercial organizations which culture and sell inoculum for various crops. In Australia, both the Western Australian and New South Wales Departments of Agriculture sell for a nominal price cultures for the inoculation of seeds of some eight to ten groups of leguminous plants. It is proposed to continue our search for highly productive strains, and, on completion of this work, it will be possible for us to set up a similar service for Queensland cane farmers should they so desire it. Of course, the provision of the right strain of *Rhizobium* is only part of the story, and the crop will not grow if seed bed, moisture, and general plantfood balance are not right.

These nitrogen-fixing bacteria require that soils shall not be too acid, and they also like phosphates. Thus, farmers on land which requires liming (as tested by Bureau officers) should apply lime before planting, and a dressing of phosphate should be made where this plantfood is deficient.

However, one of the most important factors in the restriction of the activities of these bacteria is the presence of considerable amounts of nitrates in the soil. When there is sufficient nitrate present for the good growth of the plant without any nitrogen fixation taking place, the bacteria slow down on the job, and may form no nodules and actually become parasites of the plant. Under these conditions you may get an excellent crop, but it has only been a cover crop, and has not netted you the equivalent of a few hundredweight of sulphate of ammonia, which it should have done. Therefore, the right time to plant a green manure crop is when the nitrate supplies of the soil are low—that is, as soon as practicable after harvest, and while rotting of roots, trash, &c., is still going on.

Under the influence of moisture and warmth the organic matter of the soil is converted into nitrates by other forms of bacteria, and if a field is ploughed out and followed before or early in the rainy season there will usually be considerable nitrate reserves available by late autumn. If, then, a winter-growing legume is planted a good crop will result if weather conditions are favourable, but there will have been little or no nitrogen fixation. Thus the crop will have been a cover crop but not a green manure crop in the strict sense of the term. Consequently, if only a single leguminous crop is to be grown, it should be planted before the old stubble and crop debris has had a chance to rot; if a second crop is to be planted, then it should be sown while the first crop is still in a state of decomposition.

Green manuring, then, should be done with one eye on the future, but with at least half an eye on the past history of the field.