SOILS AND MANURES.

CAUSES OF INFERTILITY IN SOILS IN RELATION TO BACTERIAL ACTION.*

C. M. HUTCHINSON, C.I.E., B.A.,

Imperial Agricultural Bacteriologist.

Infertility as a negative term suggests the absence of elements required for fertility; it is necessary, however, to realize that infertility may result from the presence of substances or conditions inimical to the growth of plants.

The causes of infertility in soils may, therefore, be divided into two main groups or classes:—

(1) Those associated with the absence of substances or conditions necessary for fertility.

(2) Those depending for their action upon the presence of deleterious substances or conditions liable to interfere with the growth of plants.

To the layman an infertile soil suggests either a desert tract entirely bare of vegetation, or perhaps an area at one time under cultivation but now abandoned because of its infertility. The agriculturist, however, has a much higher standard of fertility in mind; to him an infertile soil is one which it does not pay to cultivate or at the best is of such poor quality or condition that nothing but necessity would make him spend his time and labour in doing so. To this latter class belongs a large proportion of the arable lands now under cultivation; these have come down from their original condition of high fertility as virgin soils to their present state of comparative infertility as a direct result of the artificial conditions of plant growth to which they have been subjected during years of crop cultivation. It is with this class of soils requiring highly expert treatment and knowledge that we are mainly concerned, those in which the degree of fertility is so low that relatively small causes, or infertility factors may at any moment reduce their yield below the point at which it ceases to pay to cultivate them. It is therefore of prime importance for the agriculturist to be well acquainted with the various and numerous causes of infertility which may reduce the condition of his soil and the amount of his crop below the paying minimum.

One of the most common and well understood causes of infertility is the lack of a sufficient supply of those ingredients in the soil which are necessary for fertility. It is impracticable here to deal with these except to point out that an insufficiency of plant foods not only affects the growth of crops directly but also indirectly by limiting the activities of those bacteria upon which fertility depends. This is more especially the case with reference to the supply of humus, for reasons to be dealt with later.

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Water supply of course is a vital factor and must be taken account of both from the point of view of deficiency and of excess; this implies management of the soil in such a way as to avoid both deficiency or excess of water, the latter with its concomitant result of lack of air being especially conducive to infertility by reason of its effect on bacterial activities in the soil.

On the other hand, infertility may result from the presence of harmful substances in the soil such as excess of organic acids or of alkali salts and in some cases of neutral salts including chlorides, sulphates and nitrates. With these causes of infertility we are not for the moment concerned, but others more generally distributed exist which are of great importance although perhaps not fully recognized as such. Under certain conditions toxic bodies are produced in soils and their influence upon fertility depends largely upon the quantities in which they are present. Generally speaking, their production depends upon the existence of anaerobic conditions due to waterlogging and is the result of bacterial action of the class associated with this condition. In order to understand not only how such bacterial action takes place but to arrive at an adequate conception of its importance as a factor in soil infertility, it is necessary to know something about that class of soil organisms known as anaerobic bacteria. There is no definite dividing line between aerobes and anaerobes, that is between such bacteria as require oxygen and those that do not; there is an intermediate class the members of which can tolerate varying degrees of aeration or the reverse and even those species which are apparently obligate anaerobes can function in presence of small amounts of oxygen, especially in conjunction with certain aerobic species whose activities reduce the oxygen tension in the soil water. The fact that it is necessary to bear in mind is that soil conditions, so far as anaerobism or the reverse is concerned, determine whether anaerobic or aerobic bacteria shall predominate in such soils with results which will vary in accordance with the characteristic differences of their action.

Anaerobic bacteria and anaerobic fermentations are generally associated with unhealthy conditions of one kind or another; thus putrefaction as opposed to decay is produced mainly by anaerobes, which are also responsible for most septic conditions and incidentally for tetanus.

Anaerobic bacteria in soils produce infertility in several ways :—

(1) By the production of colloidal bodies resulting from decomposition of organic matter, plant residues, roots and stubble, dead leaves, green manures, oilcakes and cattle manure. These colloidal bodies take the form of bacterial waxes or slimes which coat the surfaces of the soil particles and tend to block up the pores of the soil, thus interfering with aeration and drainage. It is of interest to note that the coating of the soil particles both organic and inorganic with bacterial wax has the effect of protecting them from further bacterial action, thus reducing the rate and amount of such important processes as nitrification or organic matter and solubilization of mineral phosphates. The fertilizing action of such partial sterilizing agents as toluene can be partly attributed to their solvent action upon this coating, exposing fresh surfaces to bacterial action; a similar result is produced by the mechanical rubbing and grinding action of cultivation processes such as ploughing and harrowing, and also by the aeration and desiccation resulting from the latter which tends to destroy the colloidal condition of the bacterial

slimes. It is important to realize that anaerobism in soils tends to increase by reason of the fact that the anaerobic classes of bacteria, whose growth and preponderance results from the prevalence of this condition, are themselves capable of contributing to and increasing it by the production of colloids; thus the vicious circle is completed and this tendency becomes of great practical importance.

(2) by the production of toxic bodies which reduce fertility either (*a*) directly as plant poisons, or (*b*) indirectly by their interference with nitrification.

The first case involves exceptional conditions such as waterlogging, or a soil of naturally high non-porosity such as a heavy clay.

Waterlogging in the presence of organic matter results in the production not only of colloids but of plant poisons by anaerobic bacteria. The presence and action of such poisons can be demonstrated by watering plants with extracts of anaerobically incubated soils, apart from the well known effects of attempting to grow plants in soils in which drainage has been interfered with or in which anaerobic fermentation of organic matter has been carried out to excess.

The maize plant affords an interesting case of natural provision against poisoning by organic toxins resulting from soil anaerobism; the secondary aerial root system commonly found in this plant is a provision against the absorption of toxins resulting from anaerobic conditions due to excess of moisture in the subsoil, which the plant is able to avoid by putting out secondary roots into the surface soil at that period of its growth when flooding of the soil is liable to occur.

Intoxication of the seedling maize plant is also liable to occur in wet soils as a consequence of bacterial invasion of the seed whilst the latter is still attached to and is providing nutriment to the young plant. This form of damage is probably due to mechanical injury to the seed-coat generally as a result of insect attack.

A special case of anaerobism is that produced by the growth of grasses, the closely interwoven roots and stoloniferous stems forming a sod or layer not only relatively impervious but giving rise to extra quantities of CO_2 in the surface soil by their decay. There is reason to believe that under certain conditions especially in wet seasons, toxins are formed as a result of the decay of parts of this growth; this result may be noticed where cut grass from the mower is allowed to lie during wet weather on the surface of turf, which is completely killed by this treatment and may not recover for months afterwards. In addition, the partially anaerobic conditions induced in the soil interfere with nitrification and consequently reduce fertility; this effect may be observed and measured and is probably responsible for the very marked and well known inhibitory action of grass upon the growth of trees.

Indirect action of toxins on fertility.

Nitrifying bacteria are known to be highly susceptible to the action of toxins of various kinds. Soil sterilized by heat is not only lacking in nitrifying organisms but when these are reintroduced by inoculation their normal action is inhibited by toxic bodies produced by the action of heat upon the organic matter present. Similarly anaerobic incubation of soil results in the production of toxins having an inhibitory effect upon nitrification, and in addition cases have been observed where anaerobic conditions in a soil have resulted in the multiplication of specific bacteria, capable of inhibiting nitrification by the toxic action upon the nitrifiers of the bye-products of their metabolism. This action is most pronounced in presence of organic matter, which will fail to nitrify in a soil under reduced air supply, whereas the same soil under similar conditions of aeration will nitrify ammonium sulphate. That this inhibition of nitrification is due to the production of toxins from the organic matter is shown by the fact that nitrification does not immediately take place in a soil treated in this manner when complete aeration is provided subsequently, but only commences after a period of time (some ten to fourteen days) sufficient to allow of destruction by oxidation of the toxins thus formed.

In this case therefore we have an instance of infertility caused by interference with nitrification and resulting from the action of toxins not present in sufficient amount to produce directly harmful action on plants. The importance of recognizing this source of infertility lies in the frequency of the occurrence of the conditions giving rise to it. Any condition of the soil causing any degree of anaerobism will encourage the growth of those classes of bacteria responsible for the effects described above; such conditions may arise from improper soil management, such as ploughing when too wet, or from physical properties of the soil itself rendering it peculiarly liable to this source of infertility.

Relation of the above facts to Agricultural Operations.

Agricultural operations consist mainly of:—

(1) Cultivation, *i.e.*, stirring the soil.

(2) Irrigation or drainage, *i.e.*, controlling the water supply and with it the air content.

(3) Manuring—the addition of plant food in a suitable form.

(4) Selection of suitable crops and of improved varieties to make the most of natural fertility or to minimize the effects of natural infertility.

Cultivation.—The principal function of cultivation is to regulate the water supply of the soil and promote formation of available, *i.e.*, soluble plant food, especially nitrates. Nitrification depends upon a suitable balance between air and water supply and upon removal or oxidation of certain bye-products of bacterial metabolism; if this is not provided for, either nitrification does not proceed at a sufficient rate or the reverse action, *i.e.*, reduction of nitrates by bacterial action occurs, the bacterial balance being then against the accumulation of nitrates sufficient for fertility. Therefore the operations of ploughing, harrowing, rolling and inter-cultivation must be carried out with a view to maintaining in the soil such conditions of water supply and aeration as will promote nitrification at that time of year when the growing crop is ready to absorb it. Hot weather cultivation has other functions besides that of killing out weeds; this operation has a very decided action in lowering the percentage of anaerobic bacteria, destroying many of the deleterious bye-products of their growth, including some colloids, by oxidation and desiccation, and probably strongly discouraging certain infective and pathogenic organisms such as *Ps tritici* and *Bact. solanacearum*. Ploughing wet has an extremely bad effect on many soils; the result is infertility due mainly to destruction of the mechanical condition or tilth, this is brought about largely by the operation of a most important factor in soil physics, namely the film of air which coats and closely clings to the soil particles and is only displaced with difficulty; this air film plays an important part not only in the biological activities of the soil, but in maintaining its physical condition, and exercises a vital influence in preventing waterlogging of the soil particles. Ploughing the soil when it is dry, by breaking up the particles, increases the area of their surfaces and with it the content of the air held in the form of the air film upon these surfaces. Ploughing when wet, however, abrades the air film and rubs it off, replacing it with water, removing the permanent air supply and bringing the soil particles into close and adhesive contact. The puddling of clay such as is effected in a pug mill depends upon the action.

Apart from the deleterious influence of compaction upon the biological processes of soil, especially nitrification, it must be remembered that plant roots have to penetrate soil by sheer mechanical pressure and that many crops fail to do this in soils or subsoils whose texture is so close as to present mechanical resistance too great for easy penetration; the " pan " liable to occur in arable soils at the lower limit of cultivation is a familiar instance of this condition.

Drainage.—The principal object of drainage is to prevent the formation or persistence of anaerobic conditions in the soil; it is unnecessary to repeat the reasons for considering anaerobism fatal to fertility, but it may be pointed out that in a soil of average texture and fertility not only may the whole existing supply of nitrates be destroyed in a few days' time by the existence during that period of anaerobism due to waterlogging, but conditions may be set up which will seriously interfere with the process of nitrification after removal of the excess of water.

Irrigation.—Where irrigation is the standard method of water supply for the crops, knowledge of the infertility factors above described is of even greater importance than in unirrigated areas. Control of the water content of the soil not only places in the hands of the cultivator the power of supplying the water requirements of his crop, but makes it essential that he should possess all the information available as to the relation between soil moisture and the numerous and complicated biological processes making for fertility or the reverse, and dependent on appropriate or mistaken use of this control. As the writer pointed out in a paper in the *Agricultural Journal of India*, * there is great need for research and investigation into the water requirements of soils under irrigation; such enquiries could only be effectively carried out in irrigation areas and must give due weight to the biological factor. It is probable that the highly important problem of natural fixation of nitrogen in Indian soils is more likely to be solved by study of irrigated than unirrigated soils, and the results of the application of the solution will most probably be more readily attained in the former.

* Agri: Jour. India, XX, 4, p. 270.

Manuring.—The practice of manuring is a recognition of the depletion of soil fertility by the artificial cultivation of crops. It is of course impossible here to deal with this large subject in any way except to mention one or two points in connection with the relationship between the use of manures and the action of soil bacteria. We may consider as examples the supply of available nitrogen and phosphates as of practical interest and importance.

Nitrogen.—Reference has already been made to the conditions, both favourable and the reverse, which occur in soil and which influence the conversion of unavailable organic nitrogenous food into nitrates. It has been pointed out that suitable conditions so far as air and water supply in the soil are concerned must be provided by appropriate cultivation; it is also necessary to know something about the capacity of particular soils to deal with the sources of nitrogen in question, *i.e.*, whether the soil of an area under manurial treatment is capable of nitrifying the material available for this purpose. This introduces the interesting fact that instances have been found of soils in which not only does nitrification not occur, but examination has shown that nitrifying organisms are absent altogether. Although such soils are in most cases of a low grade of fertility and will carry only certain crops, in other instances such as some tea soils, the crop flourishes and responds to ordinary manurial applications in such a way as to suggest that nitrate nitrogen is not necessary to its growth or well-being. This of course is also the case with rice under swamp conditions, to which crop nitrates are apparently not only unnecessary but actually harmful, except in the seedling and in the latest stages of growth. In certain soils from the neighbourhood of Ranchi containing no nitrifiers I have found it possible to induce nitrification by artificial inoculation with nitrifying bacteria, but this improvement would probably not be a permanent one unless intensive cultivation and applications of lime were maintained over considerable periods.

Another consideration arises in connection with the nitrification of organic manures, this being the suitability of the latter for the process. Observation of the nitrification rate of various nitrogenous materials shows a wide variation in their suitability as evidenced by this rate; *mahua* cake for example only nitrifies in soil after prolonged periods of time, probably owing to its content of saponin. In practice, it is important not only to keep this in mind, but to be aware of the fact that nitrification is inhibited both by unsuitable soil conditions and by the application of excessive amounts of organic nitrogenous material. Other important factors come into operation in this connection and must be taken into account, but time forbids reference to them except to mention the possibility of loss of nitrogen as nitrate under conditions where the nitrification rate is so high as to lead to removal of nitrate by leaching by rain water passing through the soil. For this reason it is frequently advisable to apply dressings of cake in separate doses during the growing season of the crop, in place of all at one time.

Phosphates.—The availability of phosphatic manures is intimately connected with bacterial action in the soils to which they are applied. Two distinct styles of bacterial activity are concerned: (1) those which tend to solubilize otherwise insoluble phosphates; (2) those whose action results in diversion of phosphate from the supply originally available for the plant.

(1) It is probable that a large proportion of the naturally available, because soluble, phosphate in the soil is in this condition as a result of acid reactions set up by bacterial activity, either by formation of organic acids or of carbon dioxide. It was originally considered that this action, generally associated with the decomposition of plant residues, such as green manures, oilcakes and cattle manure, resulted in the direct supply of soluble phosphates to the crop, and might be intensified by the method of composting mineral phosphates with organic matter. Experience, however, has yielded disappointing results with this method when utilized with the intention of obtaining supplies of soluble phosphates, and it has consequently been largely abandoned; this in my opinion is a mistake, as the apparent failure of the method is due to the appraisement of the results in terms of directly soluble phosphate as is the practice with superphosphate, whereas so far as work at Pusa on this subject has gone it appears that changes in the condition of the original insoluble phosphate due to bacterial fermentation in the compost, take place leaving a certain proportion in a relatively available condition in the form of organic phosphorus compounds, probably constituents of the bacterial cells themselves. Evidence exists leading to the conclusion that the P_2O_5 held in this combination can serve as plant food under soil conditions, either directly owing to the death of the bacterial cells or to later changes in the soil of an indeterminate nature. My present opinion based on field and laboratory experiments is, that bacterial action under suitable conditions is able to convert phosphate into organic combination and remove it from those influences which would otherwise tend to produce chemical reversion to the insoluble tricalcic condition; this organic combination will later present a source of phosphate food of relatively higher availability than the tricalcic form resulting from purely chemical reversion, or existing as such originally. The practical agricultural method of securing this result depends merely upon the provision of adequate soil moisture and sufficient organic matter to promote vigorous bacterial growth and activity; this is one of the principal functions of such operations as green-manuring.

A more specialized style of solubilization of phosphates occurs in the case of that effected by sulphur oxidizing bacteria. Time does not permit of anything more than reference to this process which I described in an article in the " Agricultural Journal of India " (January, 1924) and at the last meeting of the Board of Agriculture at Bangalore. It is of course an artificial method depending on the use of sulphur and bacterial cultures capable of producing sulphuric acid therefrom, but it is of interest to note that the method is now being tried on a commercial scale as a source of phosphatic manure.

(2) With reference to that class of bacterial action resulting in removal of phosphate from the root range of the growing crop it must always be remembered that bacteria are plants and as such will compete with the agriculturist's crop for plant food in the soil. We have seen that this happens in

the case of nitrates and there is reason to believe that it is an equally important phenomenon as applied to the supply of phosphates; thus superphosphate when applied to a soil is partly taken up by the crop, partly reverted by chemical action, and partly absorbed by bacteria. As we have seen above, there is reason for supposing that this last portion remains relatively available as compared with that which has undergone chemical reversion, so that there is no reason for treating this form of bacterial activity as one likely to produce infertility in the soil.

On the other hand practical experience shows that in our Pusa soils the combination of green manures with superphosphate produces the best results, so that on the whole we may consider bacterial action in the soil as a favourable influence so far as supplies of available phosphate are concerned, and the aim of the agriculturist should therefore be to encourage such activity as much as possible. This can be done mainly by maintaining adequate supplies of organic matter, and the inclusion of the usual methods of doing so in agricultural practice forms another instance of a correct method based on empiricism derived from experience.

The selection of crops and use of improved varieties is too large a subject to be dealt with here. One point may be referred to and that is the selection of varieties with special reference to the depth of root range of the plant; here we come in direct contact with soil conditions involving degrees of anaerobism or the reverse, varying in accordance with the character of the soil and its agricultural treatment. Knowledge of the unfavourable effects of anaerobism such as have been described above will not only serve as an additional incentive to the use of such agricultural operations as will tend to diminish this condition, but may lead to the use of shallower rooted varieties in situations where soil and climate may render this additional precaution necessary.

In conclusion, it may be emphasized that so far as soil fertility is concerned, this condition or its opposite can never be ascribed to one simple cause alone but is associated with the interaction of several. It is incorrect to say, for example, that lack of oxygen causes infertility only because plant roots require oxygen for healthy growth; we have seen that conditions in the soil producing an insufficiency of air tend to cause infertility through the combined operation of a number of factors, some positive such as the production of toxins and of colloids by anaerobic bacteria, and others negative such as the failure to form nitrates for want of sufficient oxygen to maintain the proper bacterial balance in the soil. The complete investigation of the reactions and especially the bacterial activities underlying and ultimately responsible for the complex changes and conditions in a soil, is essential and necessary for any understanding of the problem of soil fertility; in this country especially, owing to the high soil temperatures which prevail during a large part of the year, and the correspondingly rapid bacterial changes resulting therefrom, any advance towards solution of this problem must depend upon adequate recognition of the intimate connection between soil fertility and soil bacteriology.—Agricultural Journal of India, Vol. XXI, Part 2.