rivers like the Congo, Rufiji, Zambesi and Orange still flows to sea virtually unutilized. As soil surveys proceed it will be possible, in the light of present scientific knowledge, to classify as arable large areas of land previously rejected as unsuitable.

Once soil mapping of the world is adequate and meteorological observations made meaningful in an agricultural sense, it should be possible to accelerate exploration of the possibilities and economics of development of agricultural zones for world food production, with particular reference to supplementary irrigation. If the same, or better yields can be obtained in a humid zone with an application of 1 ft of water as that from applications of 3 ft in an arid zone, the implications, by all standards, become obvious. In the meantime, no country with adequate water resources, whether self-sufficiency is ultimately attainable or not, can afford not to irrigate. The agricultural efficiencies achieved in countries like the Netherlands and the UK are examples of target standards.

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Soil and plant nutrient content in relation to crop yield

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Introduction

Plant growth and crop yield are conditioned by two sets of factors: (1) the external factors such as light, temperature, water, nutrient supply, management and the incidence of pests and diseases and (2) internal factors, mainly nutritive but also hormonal. This paper is concerned generally with the inorganic nutrition of plants growing in soil, and more specifically with factors that affect soil nutrient availability and plant nutrient uptake, and with the relationship between plant nutrient content and crop yield.

Factors influencing nutrient availability

Texture, structure, moisture content, pH, management, microbial activity and the chemical nature and physicochemical properties of soil colloids all have an important bearing on the retention, movement and availability of soil nutrients. In a sandy soil, most nutrients will be present in solution, or as salts, and their availability will be controlled largely by moisture content and pH. However, in the presence of soil colloids (clays and organic matter) the distribution and availability of soil nutrients may be quite different. Cations will be adsorbed on the negatively charged colloids, or chelated by the soil organic matter, and the equilibrium concentration of any one cation in the soil solution will be affected by the nature of the soil colloids and the nature and amount of the complementary cations (Wiklander, 1955). Furthermore certain cations, such as potassium and ammonium, may migrate from the particle surface into the clay lattice and so become fixed, or become relatively unavailable for plant use (Kardos, 1955). Nitrogen may also be fixed temporarily in the form of microbial organic constituents, some of which may condense with modified lignin to form relatively stable humic compounds (Quastel, 1963). The availability of phosphorus compounds also varies greatly with the nature of the soil and its pH (Kurtz, 1953). It is clear, therefore, that the restrictions imposed by soil on the movement and availability of nutrients, and on their uptake by plants, will vary greatly. Some of these factors will now be discussed in more detail. (For a more comprehensive account, see Bould & Hewitt, 1963.)

The effective absorbing roots only occupy a small percentage of the total soil volume at any one time, so that the supply of nutrients in the immediate vicinity of the absorbing roots is rapidly exhausted. The speed with which these nutrients are replaced can, therefore, influence the rate of nutrient uptake and subsequent plant growth. Two processes are concerned in the supply of nutrients to the roots, namely, mass-flow and diffusion (Barber, 1962). The mass-flow concept does not infer that the cations are taken into the plant at the same rate as water is absorbed, it only concerns the movement up to the root surface. If the concentration of an ion in this solution is such that more is brought to the root interface by mass-flow than is absorbed, then the ion accumulates at the interface. If the concentration of an ion is so low that mass-flow does not bring as much to the root surface as the root can absorb, then additional quantities of the ion must reach the root by diffusion; ion diffusion then becomes the determining factor in supplying the plant roots. Barber, Walker & Vasey (1963) calculated that mass-flow alone would supply the magnesium requirement of lucerne (*Medicago sativa* L.) when the magnesium concentration in the solution flowing to the roots was >7 ppm. Clearly, therefore, since soil texture and soil structure influence mass-flow and nutrient movement, they may constitute restrictive factors in plant nutrition, apart from their effect on aeration and root respiration.

Soil pH plays a major part in nutrient availability. Hewitt (1953) summarized the factors that contribute to the 'soil acidity complex' thus:

(1) Direct injury by hydrogen ions.

(2) Indirect effects of low pH.

(a) Physiologically impaired absorption of calcium, magnesium and phosphorus. (b) Increased solubility, to a toxic extent, of aluminium, manganese, and possibly iron and heavy metals. (c) Reduced availability of phosphorus, partly by interaction with aluminium or iron before, or after, absorption by the plant. (d) Reduced availability of molybdenum.

(3) Low base status.

(a) Calcium deficiency. (b) Deficiencies of magnesium and potassium.

(4) Abnormal biotic factors.

(a) Impaired nitrogen cycle and nitrogen fixation. (b) Impaired mycorrhizal activity. (c) Increased attack by certain soil pathogens.

(5) Accumulation of soil organic acids or other toxic compounds owing to unfavourable oxidation–reduction conditions, or pH that limits micro-organisms.

Arnon & Johnson (1942) have shown that acidity *per se* is not necessarily injurious to plants, and that growth between pH 4 and 8 is unaffected provided an adequate supply of plant nutrients is maintained. Evidence for the toxicity of manganese in acid soils has been provided by Wallace, Hewitt & Nicholas (1945), Morris (1949) and others.

Soil pH also plays a major part in the availability of phosphorus. Three general reactions account for the loss of solubility of applied phosphate: adsorption, isomorphous replacement and double decomposition. At neutral pH, the first reaction is one of adsorption of phosphate on the colloid surfaces. With increased time of contact a further reaction takes place that leads to fixation of phosphate. This second reaction may be due to isomorphous substitution of phosphate for hydroxyl or silicate ions in the clay crystal lattice. The double-decomposition reactions fall into two categories: those at low pH that involve iron and aluminium with the formation of compounds of the type $M(H_2O)_3(OH)_2H_2PO_4$, and those at high pH that involve calcium with the formation of compounds such as hydroxyapatite, fluorapatite and carbonatoapatite (Hemwall, 1957).

At high soil pH it is difficult to maintain adequate supplies of available manganese and iron in the soil solution. This is due to unfavourable oxidation–reduction conditions resulting in the formation of insoluble manganese and iron compounds. For manganese, which is normally taken up by plants as the divalent-ion, pH values around 6–6·5 appear to be critical, lower values favouring reduction, and higher values oxidation. Mann & Quastel (1946) believe that in slightly alkaline soils this oxidation is almost entirely due to micro-organisms. Similarly, iron is normally absorbed as the ferrous ion. (When chelated it may be absorbed as a complex anion.) At pH values above 7 the ferric form predominates and, in the absence of a strong chelating agent, it is precipitated as ferric hydroxide. Thus, at soil pH values >7, manganese and iron deficiencies may occur in crops even though the soil may contain large amounts of total manganese and iron. For the correction of manganese deficiency at high soil pH it is better to by-pass the soil and to apply the manganese as a foliar spray of manganous sulphate. This is more economic than attempting to lower the soil pH or trying to reduce the forms of manganese of higher valency.

In the past decade (Wallace, 1962), new synthetic chelating agents have been developed which form iron chelates with high stability constants (log K for Fe^{3+}–EDTA=25·1 and log K for Fe^{3+}–EDDHA=>30). These chelates are biologically stable and, in addition, the most recent iron chelate to be introduced, iron-ethylenediamine bis (o-hydroxyphenylacetic acid), or Fe-EDDHA, is not adsorbed to any extent by the clay colloids (Hill-Cottingham and Lloyd-Jones, 1958). Thus, it is now possible to control lime-induced iron chlorosis by soil treatment and to maintain

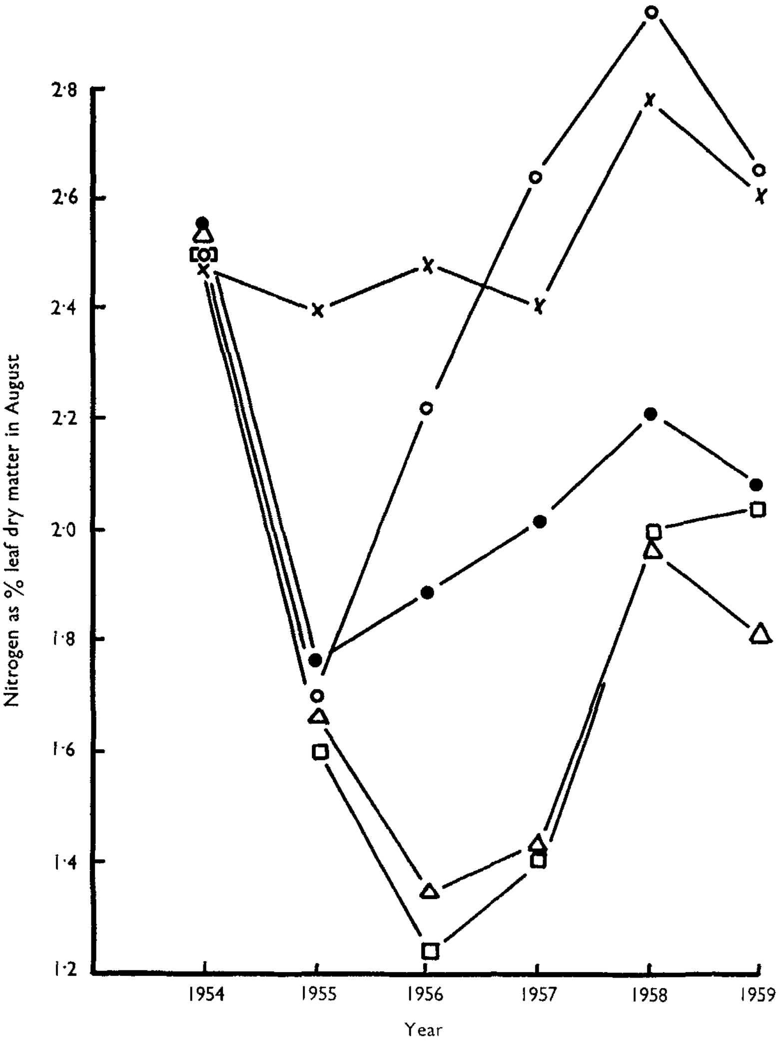

Fig. 1. The effect of soil management on the nitrogen status of apple leaves, var. Cox's Orange Pippin. All trees grown in arable culture until 1954. From 1955 onwards: ×, clean cultivation; ○, white clover sward; ●, indigenous grass sward; △, timothy grass sward; □, perennial ryegrass sward. (From Bould & Jarrett, 1962.)

the growth of calciphobes in calcareous soils. They may, however, need a manganese foliar spray to prevent manganese deficiency.

In orchards, the nutritional status of the trees can be influenced more readily by the nature of the cover crop than by fertilizer treatment (Bould & Jarrett, 1962). This applies particularly to nitrogen (Fig. 1).

It is well known that micro-organisms play an important part in soil nutrient availability and plant nutrient uptake (Quastel, 1963). This is due to a variety of reasons, the more important being: (1) metabolic turnover of nutrients such as nitrogen, phosphorus, sulphur, manganese and iron, (2) the formation of organic acids that prevent fixation of phosphate by inactivating iron and aluminium, or that chelate calcium from insoluble calcium phosphates and so liberate soluble phosphate, (3) oxidation–reduction changes of iron and manganese compounds and (4) mycorrhizal associations that facilitate the uptake of nutrients and in particular of phosphate.

Finally, the physicochemical properties of soil colloids, especially of clays, influence availability as they control the concentration of cations in the soil solution and the ease with which they are replaced. These properties are better dealt with in the next section.

Soil–plant relationships

In order to characterize the nutrient status of a soil two measurements are required: (1) an estimate of the concentration, or intensity, of available nutrients present at any time, and (2) the ability of a soil to maintain adequate nutrient concentrations throughout the growing season, or soil nutrient capacity. Most accepted soil analytical methods will give a fair estimate of nutrient intensity, and will allow soils to be classified as deficient, or sufficient, with respect to a particular nutrient (with some reservations over nitrogen) but, owing to ion antagonism and the variation in bonding energies of different colloids for different cations, the relationship between soil nutrient intensity and nutrient uptake by plants is not always good. This has resulted in a fresh approach to soil–plant nutrient relationships, based either on the energy of replacement of cations from the soil colloids (Woodruff, 1955; Arnold, 1962), or on a study of cation activity ratios in equilibrium soil extracts (Schofield, 1955; Salmon, 1962; Beckett, 1964). Clay colloids have different cation exchange capacities and different bonding energies for different cations. Furthermore, the energy of replacement of a particular cation from a clay depends on the degree of saturation of the clay with that particular cation, and on the nature and distribution of the complementary cations (Marshall, 1957).

Woodruff (1955) determined the energy of exchange ($\triangle F$ or $\triangle \bar{G}$) of calcium by potassium in calories per chemical equivalent at 25°, from the equation:

$$\triangle F = 1364 \log (a_K/\sqrt{a_{Ca}}), \qquad (1)$$

where a_K and a_{Ca} are the activities of potassium and calcium in moles/l. Arnold (1962) applied this method to the uptake of potassium from soils by ryegrass (*Lolium perenne* L.) and found a better relationship ($r = -0{\cdot}64^{**}$) between $\triangle G_{Ca,K}$ and plant potassium than between exchangeable potassium and plant potassium ($r = +0{\cdot}35^{*}$). Beckett (1964) found that the ratio,

$$a_K/\sqrt{a_{Ca}+a_{Mg}},$$

where a= activity of the cations in an equilibrium soil extract, using 0·01 M-$CaCl_2$ as the equilibrating solution, was a satisfactory measure of the chemical potential of the labile soil potassium. Salmon (1962), working with soil magnesium and the magnesium content of ryegrass, found it necessary to include most of the cations in the activity ratios thus:

$$a_K/\sqrt{a_{Ca}+a_{Mg}}+B.a_K+C.a_H,$$

where a=activity of the cations in the equilibrium extracts, and B and C are proportionality factors. In acid soils, it may be necessary to include in the ratio the activity of aluminium present in the equilibrium soil extracts (Tinker, 1964). This approach, using activity ratios of cations instead of concentrations of cations in equilibrium extracts, is a more fundamental one than the older approach of extracting soils with dilute acids and salt solutions and attempting to correlate the levels of nutrients so extracted with crop performance and fertilizer response. Olsen & Peech (1960) had previously come to the conclusion that the composition of the soil solution, or the equilibrium dialysate, should completely characterize the ionic environment of plant roots in soil–water systems.

Although it is possible to estimate the nutrient intensity of a soil sample at any given time, routine methods are not available for estimating the supplying power, or nutrient capacity of a soil. A further difficulty arises because one cannot estimate readily the volume of soil explored by the roots of any particular plant. For these reasons, there is a growing tendency, particularly with perennial crops, to turn to leaf analysis as a guide to plant nutritional status. This will be dealt with briefly in the next section. (For more detailed accounts see Goodall & Gregory, 1947; Lundegårdh, 1951; Bould, Bradfield & Clarke, 1960; Smith, 1962.)

Plant nutrient composition and crop yield

Early workers used plant analysis as a guide to soil fertility, but the present trend is to use leaf analysis as a guide to the nutritional status of the plant, first to establish threshold levels for nutrients below which plants show deficiency signs, and secondly to establish nutrient levels associated with optimum growth, or crop yield. The use of leaf analysis as a diagnostic method is based on the contention that the leaf is the principal site of metabolism, that changes in nutrient supply are reflected in the composition of the leaf (Bould *et al.* 1960; Hewitt, 1956; Steenbjerg, 1954), that these changes are more pronounced at certain stages of development than at others (Bould & Catlow, 1954), and that the concentrations of nutrients in the leaf at specific growth stages are related to the performance of the crop (Bould, 1964; Reuther & Smith, 1954). Goodall & Gregory (1947) summarize their views on leaf analysis and crop performance very clearly thus: 'for each factor there is an optimum intensity level: growth will be increased if the intensity is brought up to this level, and decreased if it is raised further. These optima are not fixed but depend on all factors simultaneously, nevertheless, in theory one may postulate an optimal concatenation of factors at which development of the plant would be maximal'. This interrelation between leaf nutrients is shown in Fig. 2, for potassium and magnesium in relation to crop yield of raspberry.

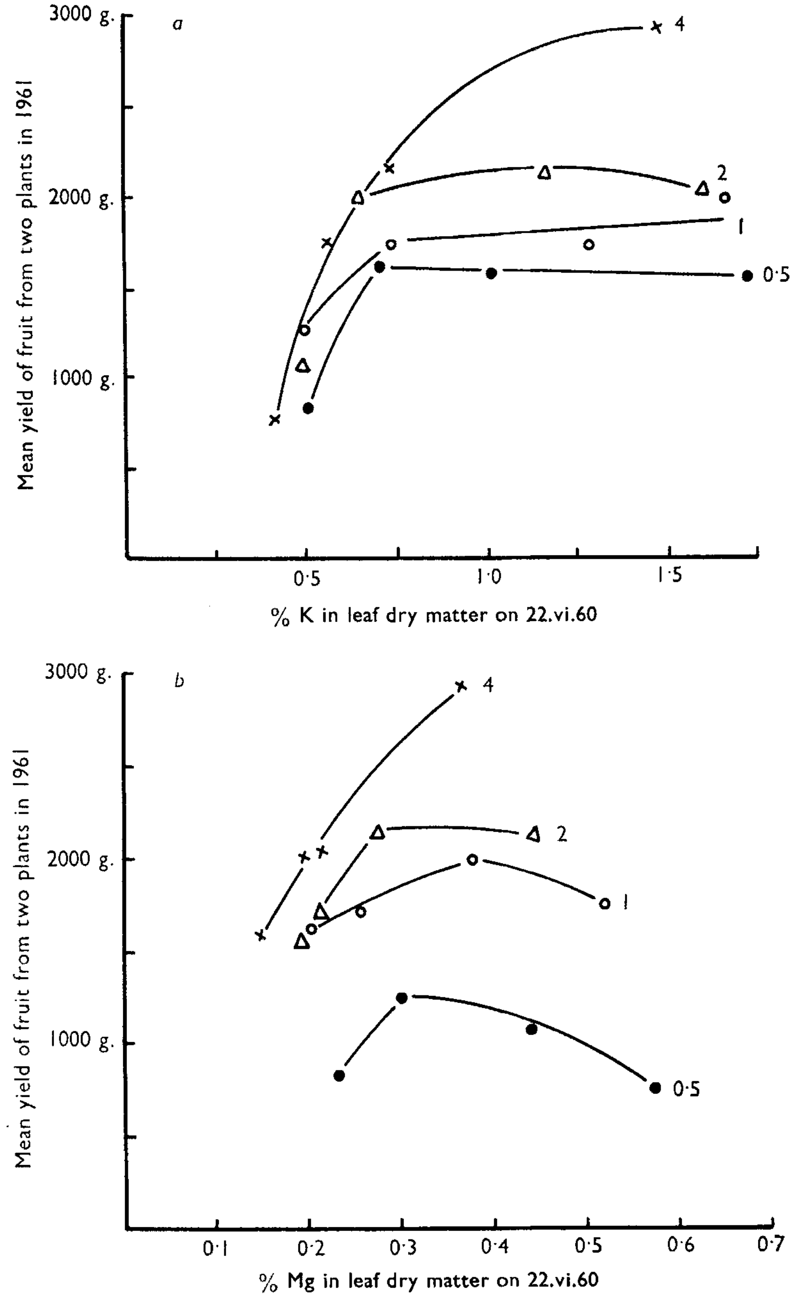

Fig. 2. The relation between leaf nutrient status of non-fruiting raspberry canes, var. Lloyd George, and crop yield in the following season: (*a*) leaf potassium and crop yield as affected by nutrient magnesium; (*b*) leaf magnesium and crop yield as affected by nutrient potassium. The figures at the ends of the curves are the m-equiv./l. of the nutrient element. (From Bould, 1963.)

Under conditions of severe nutrient deficiency, when growth is very restricted, leaf nutrient concentrations may give a misleading picture of nutritional conditions. Steenbjerg (1954) has shown this to be so for copper in barley. However, when dealing with the major nutrients, many workers have shown that there is a curvilinear relationship between leaf nutrient concentration and crop performance (Reuther, 1961). Bould (1964) has made a comprehensive study of the relationship between leaf nutrient status, at specific growth stages, and crop yield of strawberry. Table 1 shows the range of nutrient concentrations associated with deficiency, marginal supply and sufficiency. Limited field experience has shown that, in the absence of non-nutritional limiting factors, strawberry plants respond (yield) to fertilizers if the leaf values are less than those classed as deficient in Table 1; they may or may not respond if the leaf values are marginal and they do not respond if the leaf values are greater than those given as sufficient. Leaf analysis enables one to define the optimal nutritional status of a crop (for growth or crop yield) and, once these values have been established, to assess the nutritional status of a crop in the field. In the absence of precise information relating soil nutrient status and plant nutrient content, it is not possible yet to predict how much fertilizer is required to raise the nutrient status of a crop from deficiency to sufficiency but, having diagnosed the current nutritional status of a crop by leaf analysis, one knows which nutrient, if any, is limiting growth and the appropriate treatment can be applied.

Table 1. *Tentative standards (% dry matter) for classifying the nutrient status of strawberry* (Fragaria *sp.*) *in relation to crop yield, based on the concentration of nutrient elements in the laminae of recently matured leaves from 1-year-old plants (from Bould, 1964)*

		Flowering			Fruiting*			After fruiting	
	Deficient	Marginal	Sufficient	Deficient	Marginal	Sufficient	Deficient	Marginal	Sufficient
Nitrogen	<2·5	2·6 –2·9	>3·0	<2·0	2·0 –2·5	2·6 –3·0	<1·5	1·6 –2·0	>2·0
Phosphorus	<0·25	0·25–0·30	>0·3	<0·20	0·20–0·24	0·25–0·30	<0·15	0·16–0·20	>0·20
Potassium	<1·0	1·0 –2·0	>2·0	<1·0	1·0 –1·4	>1·5	<0·6	0·6 –1·0	>1·0
Magnesium	<0·10	0·10–0·15	>0·15	<0·10	0·10–0·14	>0·15	<0·06	0·06–0·10	>0·15

*Most sensitive stage for diagnosis.

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Effects of organic manures on soils and crops

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All soils which carry crops or vegetation contain organic matter, which consists of or is derived from the plants, animals and micro-organisms which live or have lived in or on the soil. Agricultural and especially horticultural soils contain also organic matter derived from whatever organic manures have been incorporated in the soil. The quantities of organic matter in soils range from below 1% (dry weight) in the soils of arid and semi-arid regions to over 80% in organic soils such as peats in which acidity, waterlogging or other conditions have checked the oxidation of the organic materials. Many British agricultural soils contain 1–3% of organic matter. The amount of organic material in the soil represents the equilibrium between additions (parts of plants and animals and their excreta, crop residues and organic manures) and losses, mainly by biological oxidation, and for any particular, and more or less stable, set of technological or ecological circumstances it tends to a steady value.

On the Broadbalk plots at Rothamsted, on a heavy clay-with-flints soil, plots which have received no manure, or mineral fertilizers only, for over 120 years, contain about 2% of organic matter; in those which have received both mineral and nitrogen fertilizers the larger amounts of crop residues have raised this figure to about 2·4%; and the plot to which 14 tons per acre of farmyard manure has been added each year