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PHOSPORUS AND POTASSIUM REQUIREMENTS OF CEREALS

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CONTENTS

Page

1 Abstract 1

2 Glossary 5

3 Introduction 7

4 Physiology and disease resistance in relation to P and K nutrition 10
   4.1 Physiological needs of cereals for P and K 10
   4.2 P and K nutrition in relation to resistance to diseases 12

5 Soil Phosphorus 15
   5.1 A perspective on soil P 15
   5.2 Soil P compounds of a transitory nature 17
   5.3 Soil organic P 18

6 Soil Potassium 20
   6.1 A perspective on soil K 20
   6.2 Processes in K uptake from soils 23
   6.3 K in soil solution 24
   6.4 K-exchangeable to ammonium ions 26
   6.5 Leaching losses of K 27

7 Responses of cereals to P and K fertilisers 28
   7.1 Evidence for response to phosphate 28
   7.2 Evidence for response to potash 33

8 Broad strategy for P and K fertilisation 39

Page

9 Critical sufficiency versus build-up and maintenance of soil P and K reserves 40

10 Soil and plant analysis 42
  10.1 Soil analysis - interpretation 43
  10.2 Assessment of P status by soil analysis 44
  10.3 Assessment of K status by soil analysis 49
  10.4 Releases of nonexchangeable K assessed by Ca-resin 52
  10.5 A note on mechanistic modelling of P and K uptake by roots 53
  10.6 Plant analysis - general considerations 55
  10.7 Plant analysis in relation to 'Diagnostic and recommendation integrated system' - DRIS 55

11 The maintenance of P and K status 59
  11.1 Crop off-take of phosphate and potash 59
  11.2 Changes in soil P and K levels - residual affects 65
  11.3 Timing of P and K applications with special reference to fertilising on a crop rotation basis 67
  11.4 Residual P and K *versus* fresh fertiliser applications 72

12 Nutrient interactions and the need for balanced cereal nutrition 74

13 Conclusions 77

14 Recommendations for futher investigations 84

15 Acknowledgements 87

16 References 88

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PHOSPHORUS AND POTASSIUM REQUIREMENTS OF CEREALS

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ABSTRACT

The aims of the review were to evaluate the present approaches to assessing the P and K requirements of cereals grown in the UK and to identify sectors where technical change or further research might benefit growers. The close links of P and K with N are discussed.

Growers in many areas of the UK have gradually built up the P status of their soils such that cereals tend not to respond significantly to fresh applications of P and, similarly, cereals on many soils do not respond to K. This general lack of response, confirmed by hundreds of field trials, led to the extensive use of a system of maintenance applications of both P and K designed simply to replace the nutrients which are removed in grain and straw. The main danger is that a system of maintenance dressings is introduced before soils become unresponsive to P and K, which can lead to a gradual run-down in fertility.

Some of the underlying chemistry of both P and K in soils is discussed with comments on both inorganic and organic forms of P and the nature of the main reserve of soil K, along with factors affecting its release. Also some background information is given on methods of soil analysis some of which are used routinely,

while others are more suitable for research. It is argued that the main use of soil analysis is to identify soils which are most likely to respond to P and K and also to indicate where the nutrient status is high enough to suspend P and/or K applications for a while. An almost equally important role for soil analysis is to monitor changes in available nutrient status with time.

Once adequate reserves of P and K have been built up in soils there is considerable flexibility in the timing of fertiliser applications and this is discussed in the light of field experimental evidence. There are advantages in applying P and K to the most responsive crops grown in any rotation and basing long-term fertiliser applications on input/off-take balance sheets on a field by field basis. Growers on very sandy soils cannot expect to use a build-up and maintenance approach to K manuring which depends upon soils possessing adequate K buffering power, but they should rather plan to meet the needs of each crop in turn on such soils.

On soils of low P status, combine drilling of P fertiliser is still the most effective method of application. This may also be the case for K on some low K status soils. Estimates of available P and K as measured by routine methods of soil analysis change only slowly in the majority of soils even when no P and K are being applied. Hence on most well-managed fertilised soils it is not worthwhile having soil analysis for P and K done more often than every 4 or 5 years.

Removals of P and K in grain and straw depend mainly on yield and on the method of straw disposal. Studies in England & Wales and in Scotland have shown that, on average, barley straw, especially that of spring barley removes more potash by 2 or 3 kg K_2O/t from soil than wheat straw. However, the potash contents of straws can be very variable.

Some of the inherent limitations of soil analysis, particularly when different soil types are involved, are discussed. Soil analysis should continue to provide the main means of identifying the need for P and K fertiliser but a more balanced mix of soil and plant analysis is recommended for diagnostic purposes where any uncertainties exist.

Some of the difficulties of interpreting plant analysis are discussed. Reasons are given for expressing the K concentrations in actively growing cereals on a plant tissue water basis rather than on a dry matter basis, which largely overcome the problems of interpretation caused by the natural maturing of the crop. Although viewed as extremely promising for diagnostic purposes, the K concentration in the tissue water of cereals does not yet on its own offer a quick and easy way of cross-checking on the K status of crops. This is partly because lack of K can be compensated by increasing calcium, magnesium and sodium uptakes. However, the main reason is because growers and their advisors need more basic information on the subject. It is recommended that information is sought as quickly as possible on the relationships between final grain yields and levels of K in plant tissue water between tillering and flowering.

In the longer term, studies on K levels in tissue water could be extended to include enhanced disease resistance, increased resistance to lodging and, particularly, the optimisation of water usage by cereals. It is interesting that some of the benefits of correcting K deficiency in cereals may arise from reducing calcium intake. A satisfactory understanding of these aspects of cereal nutrition will require more detailed studies on the distribution and function of potassium, sodium, calcium and magnesium in different types of plant cells.

At present there is little easily accessible data on the P concentrations in developing cereals grown in the UK. It is suggested that greater use of plant P analysis could resolve uncertainties where P status is borderline between sufficiency and deficiency and where a single set of Index ranges for the interpretation of soil analytical data may not be satisfactory for different sorts of soils. The relative merits of three different approaches to cereal plant P analysis should be examined in detail. These are, simple P concentrations expressed on a dry matter basis, P concentrations coupled with total N concentrations, possibly as products, and finally, a method of analysis involving the estimation of the inorganic P concentration in the developing cereal plant.

Even though cereal roots are efficient at taking up nitrate, more information is required on the beneficial influence of K in soil and subsoil on nitrate uptake. In fertile K-sufficient soils, the K seems to stimulate N uptake, probably in a cyclical manner, and provided the soils are P-sufficient, N uptake stimulates P uptake in amounts which are adequate for optimum growth. Caution is recommended when interpreting data on N and K interactions which have not been studied under field conditions.

Although there are well-known differences in the way in which different cereal species react to soil conditions, for many of the more general purposes of P and K nutrition all cereals except maize can be grouped together. In terms of detail, however, there are discernable differences such as spring barley requiring a higher P status than winter wheat.

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2 GLOSSARY

The metric system is used in the review.

Phosphorus and potassium, along with other nutrients, are referred to in elemental form e.g. P and K, whereas amounts of phosphate and potash are expressed as P_2O_5 and K_2O, respectively. To convert P to P_2O_5 multiply by 2.291 and to convert K to K_2O multiply by 1.205.

cmol(+)/kg refers to one-hundredth of a gram molecular weight of a singlely charged cation per kilogram soil.

mmol/l and mmol/kg refer to one-thousandth of a gram molecular weight of an element or compound per litre and per kilogram, respectively.

μmol/l refers to one-millionth of a gram molecular weight of an element or compound per litre.

ADAS	-	Agricultural Development and Advisory Service
CEC	-	Cation Exchange Capacity
EHF	-	Experimental Husbandry Farm
NAAS	-	National Agricultural Advisory Service (predating ADAS)
MISR/SAC	-	Macaulay Institute for Soil Research/Scottish Agricultural Colleges

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Capacity of soil to supply a nutrient - the total amount of a nutrient in soil which is or can become available over a growing season.

Chloroplasts - the rounded green bodies which make plant leaves and stems look green.

Cytoplasm - the material excluding the nucleus which occupies plant cells.

Exchangeable K (or other cations) - the K ions (or other cations) which, being positively charged, are held loosely by electrostatic forces at the negatively charged soil colloid surfaces. Exchangeable or 'labile' cations are constantly entering and leaving the soil solution.

Intensity of nutrient supply - usually taken to be the concentration of a nutrient in soil solution (or some closely related measurement).

Mechanistic model - a working model of known or presumed components which can be quantified; unique solutions to models involving soil and plant roots are not possible.

Mycorrhiza - fungus living symbiotically with plant roots.

Quantity-intensity ratio (Q/I) of a nutrient - used to quantify the ‘buffer power’ of soil insofar as nutrient supply is concerned.

Vacuoles - the spaces in plant cells which are usually filled with sap.

3 INTRODUCTION

The principal aims of this review are two-fold. The first is to appraise the present approaches to assessing the phosphorus (P) and potassium (K) fertiliser requirements of cereals grown in the UK and the second is to attempt to identify aspects of the subject in which technical changes or further research might be advantageous to growers. There is no doubt that large grain harvests are associated with healthy plants made up of succulent cells. To obtain high grain yields the plants should not be subjected to undue stresses and, particularly at the grain filling stage, the leaves and other green parts should be able to trap the optimum amount of light. Even the angle of inclination of the leaves to the stem, particularly the flag leaf, is important in this respect and plants should be able to maintain turgor and be capable of synthesising and transporting photosynthates efficiently. The futility of attempting to grow high yielding crops and maximise the uptake of N without adequate P and K is now very widely appreciated. In brief, it can be argued that in K-sufficient soils, K stimulates N uptake and provided the soils are P-sufficient, N uptake stimulates P uptake.

Compared with the long debate associated with the use of N on cereals it seems that most growers have already solved the problems of ensuring that soils are able adequately to meet the P and K requirements of cereals in all the principal grain growing areas. It is interesting to recall that yields in many parts of Britain were once limited more by low P status than by any other single factor, as is the case in many parts of the less developed world today. In the early days of fertiliser use there was resignation and even some gloom about the low recovery of fertiliser P and the apparent worthlessness of P fertiliser residues which had been in the soil for more than two or three years. Measured recoveries of fertiliser P in crops rarely reached 30 per cent and were often less than 10 per cent in the year of application and the prospect of having to add much more P than was ever recovered seemed to be generally accepted as inevitable. The P which was accumulating in soils underwent what was then universally known as 'fixation' and both laboratory studies and most field trials done up to the end of the 1940s had given such 'fixed' P zero availability to plants after it had been in the soil for two or three seasons. However, as recently pointed out by Johnston (1987), Lawes and Gilbert well before the turn of the last century found soils with P and K residues yielded better than unmanured soils and the effect of fertiliser residues often lasted many years. It was, in fact, not until about 1950 that the value of accumulated P residues was more fully and widely appreciated.

In contrast to P, in the early days of fertiliser use most loams and clayey soils seemed able to supply nearly all the potassium that cereals needed at the then modest levels of production. Even after years of intensive cropping there are in Britain some soils which are still more than adequately supplied with available K which comes mainly from natural mineral reserves of micaceous clays, usually referred to as illites. Once soils were subjected to intensive cropping it was found that, with the notable exceptions, the majority were unable to supply enough K at a fast enough rate from native reserves and increases in K fertiliser usage have tended to follow increases in N usage.

Viewed nationally and regionally the most striking feature of P and K usage on cereals has been its uniformity over recent years. Surveys of Fertilizer Practice conducted in England and Wales and in Scotland have shown a consistent pattern of P and K usage on wheat and barley. The point is illustrated by data on the overall P and K fertiliser usage on winter wheat and spring barley in England and Wales for the years 1982 to 1985, reported by Elsmere (1986):-

	Winter wheat				Spring barley			
	1982	1983	1984	1985	1982	1983	1984	1985
P_2O_5 (kg/ha)	51	51	56	54	38	39	39	38
K_2O (kg/ha)	45	46	53	52	41	44	44	44

Although there are some very clear differences in the way in which different cereal species react to soil conditions (e.g. oats and rye being more tolerant of acid soil conditions than wheat and barley) for many of the more general purposes of P and K nutrition all cereals except maize can be grouped together. In terms of detail, however there are recognised differences such as spring barley requiring a higher P status than winter wheat, as stated by Johnston *et al.* (1986). It is most noticeable and not unexpected that the bulk of investigational work done in the cereal sector in this country has been concentrated on wheat and barley. In most situations growers are able to view the P and K needs of oats and rye in a similar way to those of barley.

Many farmers who keep ruminant livestock face a much more difficult problem with their K fertiliser use than those in the purely arable sector because of the dangers of hypomagnesaemia. It is probable that on some mixed farms the K status of soils is on the low side but the dilemma in which such farmers find themselves is real. At the other end of the scale it is known that excessive amounts of slurry can lead to levels of both P and K which are high. In the long-term there can be considerable amounts of K circulated by the grazing animal and in slurry but the K status of fields in arable rotation needs careful monitoring. Removals of K in grass cut for silage and in other fodder crops can be large and the problem of K fertilising is probably best viewed primarily in terms of a balance sheet drawn up on an individual field basis.

The merits of different P and K fertiliser commodities will not be discussed because there is ample information available on the subject in textbooks e.g. Cooke (1982). The fact that certain insoluble phosphatic fertilisers only become effective when applied to acid soils should, of course, always be borne in mind.

There is no doubt that changes in the P and K nutrition of cereals can influence grain quality in various ways such as in grain size and baking quality, however, it is not intended to include such very detailed aspects of cereal production in this review.

4 PHYSIOLOGY AND DISEASE RESISTANCE IN RELATION TO P AND K NUTRITION

4.1 PHYSIOLOGICAL NEEDS OF CEREALS FOR P AND K

Both P and K are involved in a large number of the metabolic processes in cereals but whereas much of the P becomes incorporated into macrostructure, most of the K acts as an osmotic influence and mobile charge carrier, with very small amounts becoming associated with the organic constituents. According to Marschner (1986) the P requirement for optimal vegetative growth of leafy plants is usually in the range 0.3-0.5 per cent of the plant dry weight. In line with its very different type of metabolic involvement, the cytoplasmic K concentration in vigorously growing plants is usually maintained in the range 100-120 mmol/kg, with the K concentration in chloroplasts being much more variable, ranging up to 200 mmol/kg. According to Leigh and Johnston (1983a and 1983b) the K content of K-sufficient barley between tillering and anthesis is about 200 mmol/kg (≈7800 mg/kg) when expressed on a tissue water basis, whereas for barley grown without K fertiliser on low K status soils it is only 50-70 mmol/kg (≈1950-2740 mg/kg). Scherer *et al.* (1982) found that in wheat seedlings the K concentration in tissue water ranged from 100 to 170 mmol/kg without significant growth depressions below about 100 mmol. The barley used by Leigh and Johnston was grown on some soils which were very rich in available K and it may be that the high K contents of around 200 mmol/kg may represent so-called luxury uptake.

Unfortunately, according to Leigh *et al.* (1986), information about the K concentration in the tissue water of cereals does not yet on its own offer a relatively quick and easy way of cross-checking on the K status of crops. This is mainly because lack of K can be compensated by increased divalent cation and sodium uptakes as well as by some modification to the sugar metabolism of plants. In particular, greater calcium uptake occurs in place of K and, interestingly, it seems that some of the benefits of correcting K deficiency may arise from reducing calcium intake.

Because of the interplay between cations, further studies are needed in order to establish the quantities of K which are optimum for growth and, as mentioned in Section 4.2, sufficient for maximum resistance to lodging and a variety of diseases. If the range between deficient and adequately supplied cereals is small, for example, from about 140 to 160 mmol K/kg on a tissue water basis, and uptake is cyclical, then plant analysis as a diagnostic tool would be difficult to use. There is, however, general agreement that interpretation of plant analyses for diagnostic purposes, expressing the K concentrations on a dry matter basis, is definitely not easy to use because of the rapid decline in K concentration with the age of the plant. A move towards expressing the K concentrations of plants on a tissue water basis is, therefore, a logical step to take. A high concentration of monovalent cations in vacuoles, particularly K, in cereals which are crops which have a rather short span of very active growth, is critical in cell extension and other turgor-regulated processes.

Although the development of a vigorously growing cereal crop may appear to be an entirely gradual process, it is in fact made up of a series of checks and balances including compensatory physiological responses. Root growth and activity are to a large extent regulated by the above ground parts of the plant and nutrient uptake is to some extent cyclical, as stated by Nair and Talibudeen (1973). In the present context the objective is not to review broadly the involvement of P and K in cereal metabolism, but rather to highlight certain functions of the nutrients and focus on topics which may help in separating sufficiencies from deficiencies.

Neither P nor K is likely to be uniformly distributed within cereal plants. Under conditions of high P supply, the element tends to accumulate in older leaves but will to some extent be translocated from older to younger leaves under conditions of P shortage. Ozanne (1980) suggested that if the older leaves are higher in P content than the young, then adequate or even luxury uptake is likely but if old leaves are much lower in P than the young, then P deficiency is likely.

According to Rejadó (1978) practically all grain dry matter is assimilated after flowering, so yield depends upon the level and duration of photosynthesis in those parts of the plant which remain green after anthesis. Premature leaf senescence, whatever the cause, is most undesirable except for those leaves very low down in the canopy. Potassium is a mobile nutrient in cereals, tending to move from older to younger leaves. When supplies of K are inadequate its movement to younger leaves can lead to both reduced photosynthesis in the plant as a whole and to early senescence of older leaves during the critical period of grain filling. In these days of supposedly adequate general use of both P and K it is very unlikely that classical symptoms of K deficiency, namely chlorosis and necrosis on older leaves, will be encountered. But under conditions of high light intensity a restricted supply of K makes leaves become rather dark green or blue-green due to high densities of chloroplasts in small cells. If rather acute K deficiency arises when older leaves are already mature, then deficiency symptoms can develop in medium-aged leaves because K is preferentially moved from leaves with a high rather than a low metabolic activity. According to Ralph and Ridgman (1981), under field conditions there is no one mechanism by which lack of K in the soil restricts grain yield; it can decrease the area of the upper leaves, the dry matter produced in the upper internodes and ears, and reduce the number of grains per unit area and the size of grains.

There is extensive literature on the role of K in controlling the water relationships of cereals, higher K usually leading to the more efficient use of water because K ions are the major osmotic agents in stomatal movement as discussed by Wyn Jones *et al.* (1979) and Haeder and Beringer (1981). The relationship between K accumulation in the guard cells of illuminated plants and stomatal opening is well established. Osmotic pressure in the guard cells is increased by K influx which leads to water uptake and an increase in turgidity of guard cells and opening of stomata favouring CO_2 uptake.

4.2 P AND K NUTRITION IN RELATION TO RESISTANCE TO DISEASES

It is accepted that adequately nourished plants are better able to withstand the ravages of both diseases and pests than inadequately nourished plants, however, in studies on the subject it is almost invariably K which has been associated with vigorous, disease resistant crops.

For cereals the topic is well documented and there are useful summaries of observations made, for example, on the reduced incidence of rusts on crops growing on K-treated plots as discussed by Perrenoud (1977). In contrast, the incidence of eyespot was not influenced by treating soil with K fertiliser. Much of the information which does exist has been obtained incidently by scoring experimental cereal plots laid out for purposes other than studying the incidence of lodging, disease and pest damage. Often any differences in the incidence of damage to crops has been pursued no further than its correlation with or without a K fertiliser application to the soil and hence there is virtually no information on the relationships between useful benefits and actual plant composition. There is no doubt that this whole subject is complicated and interwoven with weather patterns including microclimates within crops as well as with the inherent disease resistance characteristics of crop varieties. Nevertheless, it would seem that, with notable exceptions, the understanding of the subject is still somewhat rudimentary. Clearly, there is much scope for following studies through from soil treatments to K concentrations in plants, possibly best expressed on a tissue water basis. In one instance the benefit derived by the crop was traced to the chloride in the KCl fertiliser treatment rather than to the K.

As summarised by Beringer and Northdurft (1985), K-treated soils can produce plants with cell walls which are thicker, providing more tissue stability and improving the resistance of crops to lodging, pest attack and certain diseases. According to Skogley (1977) K fertiliser can boost wheat stem thickness and strength. Huber and Arny (1985) included cereals in their extensive review of the interaction of K with plant disease.

There is no evidence to show that the disease and pest resistance of cereal crops can be increased by boosting K levels beyond those which are just adequate in other respects. As with other aspects of the study of the role of K in cereal production, the fact that other cations, particularly sodium, can to a certain extent substitute for K should not be forgotten. In conclusion it can be stated that progress in this sector of the cereal industry is most likely to come from relating the incidence of crop disease and damage to plant composition and not merely to soil treatment. Further studies in this sector may be stimulated by a desire to reduce the need for crop spraying in some instances.

As with possible benefits in terms of increased disease resistance from optimal K nutrition so it is possible that changes in the K contents of cereals may be correlated with changes in winter hardiness, but this topic has not been pursued in this review.

There is evidence from advisory practice that the symptoms of take-all can be exacerbated by both soil acidity and low soil P status. It is not yet known if the placement of P fertiliser, particularly over phases in rotations when crops are most susceptible to take-all, would reduce the symptoms or not.

5 SOIL PHOSPHORUS

5.1 A PERSPECTIVE ON SOIL P

Although many temperate soils contain up to about a quarter of their total P in organic forms, it is the inorganic P which is the main focus of attention in assessments of P fertility. For a variety of purposes the most widely recognised divisions in the inorganic P content of soils are:-

Soil solution P $\rightleftharpoons$ Labile (adsorbed) P $\rightleftharpoons$ Non-labile P

No precise boundaries exist between the fractions but they are viewed as being in quasi-equilibrium with each other. Although approaches to equilibrium between the labile and soil solution P can be rapidly attained, Vaidyanathan and Talibudeen (1970) found that, following depletion, significant recoveries of labile P occurred over about eight weeks, but a full recovery was not possible, especially if large removals were effected. In broad terms, the level of P in solution corresponds to an intensity factor and the labile P is often closely linked with the capacity of the soil to supply P. Before the days of mechanistic modelling (see Section 10.5), Mattingly and Talibudeen (1967) found that the initial growth of grass, and by inference we can include cereals, depends principally on the P intensity, but total yield and P uptake increase with estimates of the isotopically exchangeable, or labile pool, P. In some soils the intensity parameter can be almost independent of capacity, however, in Rothamsted soils, for example, intensity and capacity are closely correlated, so that either measurement predicts their P status satisfactorily at least in relative terms. For advisory purposes in the Netherlands, as outlined by Henken (1980) estimates of P in solution (P_w) are used to assess P status and there are sound theoretical reasons for selecting such an 'intensity' measurement. Such estimates are, however, probably more liable to be upset by, for example, the drying of soil prior to analysis than are estimates obtained by methods which extract a large proportion of the available pool of P. Most single figure P extractions, such as the widely used bicarbonate method first introduced by Olsen *et al.* (1954) are much more closely related to the capacity of soils to supply P than with intensity. Olsen and Khasawneh (1980) discussed in general terms the relationships between amounts of P in soil as assessed by isotopic exchange, resin extraction and various chemical extractants. Several other studies have thrown light on the relative sizes of the pools of P extracted by different extractants or characterised in some other way, as for example, by Brookes *et al.* (1983) who used bicarbonate extraction and isotopic exchange.

As summarised by Larsen (1967) a relatively simple working picture of inorganic phosphate behaviour in soil can be formulated in terms of adsorption and precipitation reactions, thus 'when only a small quantity of phosphorus is present it will be strongly adsorbed and the concentration in solution will be below that for the precipitation of any mineral, its level in solution being controlled by the amount present and the size of the adsorption system. If phosphorus is added, the concentration in solution will rise until an equilibrium level corresponding to the solubility product of some phosphorus mineral is reached, a crystalline phase will then precipitate and the phosphorus in such a lattice would be non-labile'. Larsen viewed the adsorbed P as labile and the precipitated P as non-labile, but more recently the separation of P into adsorbed and precipitated forms has not been seen so clearly. Nevertheless, the general concept as put forward by Larsen has served as a useful platform for later developments of the subject.

Much attention has been given over the years to the fate of water soluble P during its transitory stages (see Section 5.2) before it reaches at least a near-equilibrium state of the type described by Larsen. The information about transitory phases is more relevant to situations where the P status is being built-up than to situations where maintenance applications alone are needed because in the former there are advantages to be gained by maintaining maximum P in solution for as long as possible, so encouraging maximum beneficial effects from single applications.

Evidence for the presence of precipitated P-containing minerals which could have a relatively long-term life in soils has been obtained largely through solubility relationships. It is mainly the calcium phosphates which feature in this sector and the implications of their presence, particularly in calcareous soils is referred to later in the review (see Section 11.4). In theory at least, there are predictable low

P status problems in calcareous soils, but in practice such problems may well have been over-emphasised because they have been viewed too narrowly in physico-chemical terms.

5.2 SOIL P COMPOUNDS OF A TRANSITORY NATURE

Much is known about the reactions undergone by water-soluble fertiliser phosphorus in soils, especially involving transient compounds of intermediate solubility formed around fertiliser granules while they are interacting with moist soils, as described by Mattingly and Talibudeen (1967) and by Sample *et al.* (1980). Knowledge about such compounds is useful in understanding the relatively short-term 'reversion' reactions which take place during the weeks and months when soil is in a state of disequilibrium and roots can benefit from the presence of P in relatively soluble forms in pockets in the soil. For soils which have been brought to a satisfactory P status - and are receiving modest maintenance P dressings - the chemistry of the transitory forms of P is of less interest than is an understanding of the nature and solubility of the bulk of the accumulated P residues upon which the long-term P status depends.

Although there has been much interest in sorption and precipitation, often seen as competing processes in controlling the solubility of P in soils, there is little doubt that sorption is the much more dominant fixation or, more accurately described, temporary immobilisation process. Whereas the sorption was originally viewed very much as an adsorption by soil colloid surfaces there is considerable evidence to support the theory that phosphate ions diffuse into some poorly ordered soil colloids as described by Ryden *et al.* (1977), and then rather slowly diffuse out when the direction of the concentration gradient allows this to happen. This process of phosphorus sinking into some of the poorly ordered soil colloids has been investigated and modelled particularly by Barrow (1983) and his colleagues. Some of the features of the latter model overlap with the unreacted shrinking core model used by van der Zee and van Riemsdijk (1988). Such models have no unique solutions but provide means for identifying and putting into perspective some of the factors which control nutrient supply.

It should be mentioned that modelling plant nutrient uptake, involving plant as well as soil parameters, which has received some attention later in the review (see Section 10.5), is even more complex than the sorption-desorption topic. Insofar as P is concerned it must be stressed that physico-chemical parameters, such as diffusion coefficients of ions, are much more easily quantified than are some of the biological influences on availability which, as described by Tinker (1985), stem from mycorrhizal activity or from the production of root exudates.

5.3 SOIL ORGANIC P

The role of inorganic P liberated from organic matter has long been recognised as important in plant nutrition in hot humid climates but evidence for its significance in plant nutrition in temperate regions is scant. Memories of the very large responses of cereals to P fertiliser on ploughed-out grassland in the UK in the 1930s and 1940s may still colour present day views on the subject. It is well-known that the Carbon:Organic P and Nitrogen:Organic P ratios in decomposing organic matter are crucial in determining whether or not the release or immobilisation of P occurs. Fifty years ago much ploughed-out grassland was very often acutely P-deficient and immobilisation of inorganic P occurred during the breakdown of the P-deficient humus. Now that the P status of most lowland is very much higher than it used to be, especially that which has been through many arable rotations, a significant net mineralisation of organically bound P is not only possible but is to be expected. Suffice to state that Brookes *et al.* (1984) found the annual flux of P through biomass was 23 kg P/ha (0-10 cm) when land was ploughed out of grass, which was approximately three times the flux in an arable soil. The flux of P through the biomass is not the same as net mineralisation but any P added temporarily to the labile inorganic pool could influence plant growth. Brookes *et al.* (1982) had previously reported that mineralisation of P from organic sources did not appear to contribute significantly to plant uptake which was in accord with the findings of Chater and Mattingly (1980) who concluded that the rate of mineralisation of organic P only amounted to about 4 mg/kg soil per year under field conditions, and was negligible. The latter is equivalent to about 10 kg P/ha or 23 kg P_2O_5/ha per year. The weight of present evidence is thus against organic

P contributing significantly towards plant nutrition under UK conditions, however, the flux of inorganic P from organic forms may be a significant factor in preventing P reserves ending up in the most highly insoluble forms.

6 SOIL POTASSIUM

6.1 A PERSPECTIVE ON SOIL K

Whereas much of our understanding of P behaviour in soils is concerned with adsorption and desorption and possibly precipitation, the behaviour of K is very much tied to the behaviour of K-containing illitic clays, involving expanded and collapsed aluminosilicate sheets. Despite the presence of considerable amounts of potash feldspars in many soils, such minerals have little influence on fertility, partly because the particles are protected by their own decomposition products. UK soils, like most temperate soils, vary greatly in their K status and, as discussed by Bertsch and Thomas (1985), the complex reactions - with some tending towards equilibrium states - between the mineral, exchangeable and solution phases of soil K makes the assessment of the available K pool quite difficult. They state that it has long been recognised that exchangeable K is an indifferent index of available K for many temperate region soils, yet this measurement, or something very close to it, remains the basis for most assessments of K status.

The various categories of K are probably best represented diagrammatically as:-

$$\begin{tikzcd}
& \text{Plant uptake} & & & \\
\text{Fert. K} \arrow[r] & \text{Soil soln. K} \arrow[u] \arrow[d] \arrow[r, phantom, "\gtrless"] & \text{Exchangeable K} \arrow[rr, phantom, "\gtrless"] & & \text{Nonexchangeable K (including fixed K)} \\
& \text{Leached K} & & \text{Mineral Reserves} \arrow[ul] \arrow[ur] &
\end{tikzcd}$$

Because the exchangeable K tends to come to equilibrium with some other categories it can be a good index of whether or not the K status is changing.

The entrapment of K in layer aluminosilicate lattices is favoured by the low hydration energy of the ion. It was once believed that the size of the hexagonal voids in layer aluminosilicates was responsible for the strong tendency for K retention but this has been superseded by a more complicated and accurate understanding as recently summarised by Sparks and Huang (1985). Release of K from micaceous lattices is a largely diffusion controlled process. Whereas potassium-rich biotite-like micaceous crystals - which have a relatively short life in soils - are good sources of non-exchangeable K, muscovite-type micas are relatively poor sources of K simply because the K is held more tightly.

Despite many detailed studies on the subject, it is still very difficult to predict from mineralogical information whether or not a particular mix of partially weathered micaceous minerals in soil will or will not release much K from reserves which often exceed 25,000 kg K/ha. Many of the reasons for this are at least partially understood; for example, it is generally agreed that illitic clays tend to become significantly more stable as their K contents fall to something less than about half the maximum possible content. This trend of a mineral becoming more stable as it disintegrates is surprising, but it has been explained. Although all interlayers may release K, the release is favoured from alternate layers because of a shift in -OH bond direction once K is removed from one interlayer to favour greater bonding of K in adjacent interlayer. According to Fanning and Keramidas (1977), K seems to remain in alternate interlayers in smaller crystals whereas it tends to get removed from all interlayers in larger crystals. The general trend is that in highly weathered illitic soils the smaller the total amount of K that is present in fine clay, the more strongly it is held. It thus seems that as well as smaller-sized illite crystals being able to release significant quantities of K until they acquire renewed stability, larger-sized crystals can contribute towards the release because on weathering they buckle and fracture to a greater extent than small crystals, exposing new surfaces from which K escapes.

Without the benefit of local knowledge or, alternatively, the results of rather detailed laboratory studies it is difficult to make predictions about the ability of soils to release K both in the short and long term. Talibudeen *et al.* (1978) developed a relatively mild, non-destructive, laboratory procedure involving Ca-saturated synthetic resin (see Section 10.4 for further information) as a renewable sink to remove K as it is released from soil over periods of days or weeks which permits a classification of the release ability, at least on a comparative basis. The method has been used by Goulding (1984) and Goulding and Loveland (1986) to assess the amounts of useful non-exchangeable K in various soils in England and Wales.

It has been known for many years that numerous crops, including cereals, can at least in the long-term make use of non-exchangeable K as well as exchangeable K. Until recently, however there was considerable doubt as to whether or not cereals could exploit much non-exchangeable K during the relatively short period of very active growth. It is well-known that the rate of replacement of interlayer K is controlled by diffusion and that the potassium concentration in solution is one of the important factors that determines whether replacement will or will not take place. For well-defined minerals there are critical K concentrations which, if exceeded, will stop the replacement and the same principle will apply to most if not all mineral containing interlayer K. According to Rausell-Colom *et al.* (1965) many natural waters including soil solutions contain enough K to inhibit the release of K from very large crystals of muscovite, hence such minerals can be ignored as potential sources of K in agricultural soils. For soils containing different K-containing minerals which are at various stages of weathering, it is virtually impossible to link any particular low solution concentration of K with the release of any particular category of K (Goulding, 1984). It has recently been shown by Mitsios and Rowell (1987a and 1987b) (see Section 6.2) that the K concentration in the vicinity of active roots in some agricultural soils will be low enough to trigger the release of considerable amounts of initially non-exchangeable K. The rate of diffusion of K out of the mineral reserves is likely to be sufficiently rapid in many soils which contain appreciable K fertiliser residues or are rich in natural reserves to contribute very significantly to K uptake by cereal roots. In some soils (e.g. Worcester Series) releases from natural reserves are sufficient on their own to provide all the K requirements of cereals for the foreseeable future.

6.2 PROCESSES IN K UPTAKE FROM SOILS

Plant available K is at least ten times more mobile than plant available P in most UK agricultural soils and this influences the way in which the nutrient behaves. Heming and Rowell (1985a and 1985b) found that for the soils they studied, given sufficient moisture, diffusion in soil outside crystal lattices will not significantly restrict the movement and uptake of labile K, except from soil aggregates larger than about 30 mm diameter which are not penetrated by roots. Insofar as initially non-exchangeable K is concerned, as already mentioned in the previous Section, it is known that its release will not take place until a critical relatively low solution concentration has been reached.

There is, in fact, some good evidence that cereal roots are able to reduce the K concentration to low values of about 10 μmol/l so enabling them to rely heavily on initially non-labile K, as measured by Heming and Rowell (1985b). High uptake efficiency requires both a high root density and soil aggregates <4 mm diameter. Leading on from this work, Mitsios and Rowell (1987a and 1987b) exploited the single root technique of Drew *et al.* (1969) to confirm that reserves of initially non-labile K in the soils they studied can make large contributions to plant nutrition even over periods of a few days. At high root densities such as normally produced by cereals, their model showed that >60 per cent of the total K uptake after 28 days was from initially non-exchangeable sources. An additional unquantified effect has been described by McLean and Watson (1985) which tends to keep K in solution near roots as a direct result of the build-up of calcium and magnesium brought towards roots by mass flow. They describe this boost to K delivery to roots as a kind of sweeping action which drives K - by mass action - towards the root. There are no reports of the effect having been modelled, but it would appear that any extra K mobilised in this manner would probably only be significant in soils which are rather K deficient.

In any modelling of nutrient uptake (see Section 10.5) it is not surprising to find that the concentration of the nutrient in the soil solution is of key importance. The problems associated with estimating the concentration of nutrients in soil solution are considered in Section 6.3, and here it is sufficient to state that for K the concentration in solution will, of course, change with changing anion levels in the soil and it is known that mere dilution of soil solution will change the proportions of mono- or di-valent cations such that adsorption by the soil of di-valent cations will be favoured relative to mono-valent cations. These facts would appear significantly to limit the development of modelling for advisory purposes. It is interesting that modelling studies by Silberbush and Barber (1983), and Barber (1985b), using sensitivity analyses - by varying one parameter and holding others constant - showed that the extent of the root surface, or root length, was the most important single factor influencing uptake, however, this was closely followed by nutrient concentration in the soil solution.

From studies on high yielding winter wheat in the field, examining nutrient uptakes and nutrient inflows into the roots based on the Baldwin *et al.* (1973) model, Barraclough (1986a and 1986b) was able to calculate minimum soil solution concentrations of both P and K necessary for maximum growth. The minimum concentrations for P and K were different for September and October-sown crops, namely 8 μmol P/l and 36 μmol K/l for the earlier sown crop with the bigger root system and 14 μmol P/l and 56 μmol K/l for the later sown crop. Such concentrations are perhaps surprisingly low and he concluded that nutrient transport of both P and K is unlikely to limit uptake by winter wheat crops in moist 'well fertilised' soils - provided, of course, the root systems are healthy, which was a point high-lighted by Barber and his associates in their sensitivity analyses.

6.3 K IN SOIL SOLUTION

Although the importance of K in solution and the kinetic aspects of nutrient supply in soils has been appreciated for many years, practically all routine soil testing has depended on determinations of exchangeable K. Only in the research sector has much attention been given to K in soil solution and here the emphasis has been on equilibrium or near-equilibrium approaches, such as those based on quantity-intensity (Q/I) relationships. Attempts to exploit the latter led to criticisms of the use of concentration or activity ratios in plant nutritional studies because K uptake is concentration (or activity) dependent and, as was stressed by the critics, plant roots are not sensitive to ratios. Infact, ratios such as $a_K/a_{Ca}^{1/2}$ were not intended to replace simple measures of concentrations but rather to get around the problems of changing proportions of mono- to di-valent cations in soil solution, caused by changing moisture contents and changing soil solution anion concentrations (e.g. nitrate) on a more or less day-to-day basis.

For all practical purposes, UK soils obey the Ratio Law as described by Beckett (1964) and hence at low electrolyte concentrations the activity ratios, or, as a first approximation, concentration ratios of the type $(K)/(Ca)^{1/2}$ are constant regardless of the precise values of the electrolyte concentration, provided the amounts of the various labile cations associated with the soil colloids remain constant. The generally accepted theory behind this topic has been summarised many times and activity ratios can be used to characterise unequivocally the potassium potential of a soil, albeit in the form of a ratio. To work back from a ratio to a simple potassium concentration requires knowing or assuming a particular anion concentration in the soil solution, and this is perhaps one of the reasons why activity ratios are unlikely to play a significant role in advisory practice. However, in instances where adsorption and/or desorption characteristics are needed in connection with soil fertility studies, use can be made of Q/I relationships involving near-equilibrium states between soil and soil solution. Adsorption/desorption curves based on Q/I data can be used to estimate the proportions of added potassium ions which become non-labile, but the approach requires several determinations of K in solution and hence is not suitable for routine use. The extent of any fixation which does occur would be that under wet conditions, and any attempt to modify the technique to include the effects of drying and re-wetting would be even more time consuming. However, as a research tool this very simple approach can characterise soils in which, for various reasons, a conventional broadcast addition of K only marginally alters the K concentration in solution, as has been found for some highly buffered soils.

6.4 K-EXCHANGEABLE TO AMMONIUM IONS

It is known that soil extractions or leachings with ammonium acetate or ammonium nitrate solutions give clear-cut estimates for the amount of K displaced by the ammonium ions. Leaching with solutions containing other cations such as calcium or magnesium often give no such clear-cut end-point and the amount of K displaced gradually declines with prolonged leaching. In many soils, the effects of the ammonium ions are two-fold. First, in a single extraction the ammonium ions often exchange with significantly more K than, for example, calcium ions, showing that probably because of its size the ammonium ion can displace K from crystal edges or similar sites which are not so easily accessible to most other ions. Second, an excess of ammonium ions which after saturating the more easily accessible exchange sites on the soil mineral matter - leading to an increase in the proportion of collapsed aluminosilicate layers - effectively blocks the release of more K ions. If labile K is defined as the K in exchange equilibrium with ions in soil solution, then the net result of the two effects described above is that ammonium-containing solutions will tend to extract more than the labile K in the majority of soils. In other words, K which is exchangeable to ammonium will often include K which is in a borderline category between exchangeable and non-exchangeable depending upon the displacing ion and the experimental procedures which are used. Heming and Rowell (1985a and 1985b) and Mitsios and Rowell (1987a and 1987b) have discussed some of the problems of characterising ammonium-exchangeable K particularly in terms of so-called planar and peripheral exchange sites on micaceous clay particles.

There is a danger in a few types of soil, with examples among calcareous soil series such as Lulsgate, Sherborne and particularly Icknield, that measures of ammonium extractable K will considerably overestimate the amounts of K which might enter soil solution and hence be available for transport to root surfaces. Such soils appear to be particularly highly buffered and extra care may be required when interpreting data concerning K which is exchangeable to ammonium ions. Thus although the K Index may be >2, the supply of K may be below optimum.

There is scope in such cases for plant analysis to be used to assist in the interpretation of soil data.

6.5 LEACHING LOSSES OF K

There is very little information on the leaching of K from UK soils. This is understandable because of the pre-occupation of investigators with the fixation or immobility of K and the fact that a high proportion of K lost from topsoil will probably not get past the subsoil (Johnston, 1987). The usually very small concentrations of K found in land drainage waters is not surprising because drains from which the seepage is collected are usually in heavy land which almost invariably retains K rather strongly. Lysimeter studies done by ADAS staff at Reading (MAFF, 1981), showed that leaching losses of K from soils of the Windsor Series (clay loam over clay) were unusually large compared with those of the Sonning Series (silty loam over very find sandy loam) and also larger than those from soils of the Shedfield Series (loamy sand over sandy loam). Traditionally it has been generally understood that K immobilisation and retention by soils is more likely in high rather than low pH soils. It has, however, been suggested (Rowell, Personal comm.) that appreciable K can be leached out of some shallow calcareous soils which have been K-fertilised, but this is a matter which has not yet received much attention. There is no doubt that leaching losses of K from many sandy soils could be large and hence must influence growers attitudes towards K fertiliser practices on such soils.

No reports of 'K pollution' of streams and rivers from agricultural land have been encountered by the reviewers, and it is unlikely that the present legal limit of 10 mg K/l set by the authorities will be exceeded even in very sandy cereal growing areas provided K fertiliser on such soils is managed like N fertiliser and given to each crop rather than once or twice during a crop rotation.

7 RESPONSES OF CEREALS TO P AND K FERTILISERS

Relationships between cereal crop yields and soil P and K levels as determined by soil analyses have been investigated over many years using field trials. The relevance of data obtained years ago has to be questioned because grain yields were much smaller than they are today, mainly because much more nitrogen can now be used on modern varieties. However, this trend towards increased grain yields has to some extent been compensated by increased harvest indices, with up to about 50 per cent of the crop now ending up as grain.

7.1 EVIDENCE FOR RESPONSES TO PHOSPHATE

7.1.1 Devine and Holmes (1964) reported on 72 trials done between 1958-62 on spring cereals (63 on spring barley, 9 on spring wheat). All trials included two rates of phosphate (50 and 200 or 225 kg P_2O_5/ha as superphosphate) broadcast on the seedbed. Twenty trials also included 50 kg P_2O_5/ha combine drilled. Sites covered a range of soil types in major cereal growing areas. Soils were analysed for available phosphate by extracting for 24 hours with 1 per cent citric acid, which with the benefit of hindsight, was viewed by many as an unfortunate choice of extractant.

The average response to 50 kg P_2O_5/ha was 0.15 t/ha. At todays prices of grain at £100/t and P_2O_5 at 26p/kg, response just covered the cost of the fertiliser. There was a high average response to P in a group of soils with low P status (<200 ppm). There was also a group of soils with very high P (>569 ppm) where P addition had no significant effect on yield. Soils between these levels showed no consistent relationship between yield increase and applied phosphate, though average response did generally decline with increasing P status. There were no differences in behaviour between soil types. It was also noted that combine drilling on low P status soils gave a higher response than broadcasting P. This advantage was not shown on soils of higher P status. P application was often associated with greater crop vigour.

The authors concluded that the main value of soil analysis was that it indicated:

(a) low P status soils where mean response to P was greatest

and

(b) high P status soils where response was lowest.

It was suggested that 34 kg P_2O_5/ha was sufficient for crops of 3-4 t/ha on most soils or 68 kg P_2O_5/ha on low P soils, but only 38-50 kg P_2O_5/ha if combine drilled. Also noted was that on high P status soils response was unlikely, as was response in a cereal following a heavily fertilised root crop.

7.1.2 Webber *et al.* (1968) re-examined the above data after re-analysing 57 of the soils for extractable P by the NAAS then standard method. They fitted a linear regression of response against the logarithm of soil P determinations and concluded that there was no evidence that response was related to the content of soluble P in the soil as determined by either method of soil analysis.

Webber *et al.* (1968) also reported on NAAS trials carried out on spring barley between 1964 and 1966. There was a total of 77 one year trials covering a range of soil types and locations. The basic trial design was a 3^3 factorial design testing 0, 38 and 75 kg P_2O_5/ha or the same rates of K_2O, with 3 rates of N. In some trials the design was altered to accommodate comparisons between broadcasting and combine drilling. The mean responses of (P_1-P_0) and (P_2-P_1) were similar at 0.06 t/ha. Such a response did not cover the cost of the fertiliser. Comparisons of the responses with extractable P contents showed that there was no consistent relationship between the two measurements. However, further examination of the data suggested that the real value of soil analysis is to indicate sites where the chance of a large response is greatest. The series of experiments was designed so that similar soil types were included in different regions of the country. For example, trials on Hanslope Series soils in the East Midlands which had a low average P status showed a higher mean response to 38 kg P_2O_5/ha than Hanslope soils with a higher P status in the Eastern Region. Eleven experiments also tested the effect of combine drilling the fertiliser. Most sites showed no effect, though in general, combine drilled fertiliser gave slightly larger yields than broadcast fertiliser. Because it was only on soils exceptionally poor in P that any immediate response was expected, Webber *et al.* (1968) suggested cereal growers apply P (and K) to maintain the available nutrients in the soil, applying 44 kg P_2O_5/ha for a 4.4 t/ha grain yield.

7.1.3 Williams *et al.* (1971) investigated the value of soil analysis in relation to crop response. At six sites at Experimental Husbandry farms, two rates of P applied annually (25 and 50 kg P_2O_5/ha) were compared with triennial dressings at three times these rates. Trials covered the period 1951-64 and treatments were applied to rotations which were typical for the farms. Response data were therefore collected on a range of crops as were data on soil P levels. A number of different soil analytical techniques for the determination of available soil P were also tested. Confining remarks to barley and soil analysis by the bicarbonate method, 5 of the 6 sites all with soil P Indices in the 0 and 1 ranges showed no significant relationship between responses and contents of extractable soil P. However, one site possessing a large amount of extractable P was not responsive to P.

7.1.4 Russell (1965) examined the worthwhileness of soil analysis at several sites which received either 0, 50 or 100 kg P_2O_5/ha on large plots for a number of years, ranging from 6 to 9, known as the build-up period. Differential K treatments were also applied (see Section 7.2.3). In the final testing year the same treatments were applied as sub-plots in the main plots, allowing the response at different levels of residues to be tested. There were 8 sites.

Soil analyses by both the bicarbonate and Morgan's methods were able to pick out low P status plots and these generally gave a response to P in the trials. Soils from each site were also collected and grass grown on them in greenhouse pot experiments; P uptake by the grass correlated exceptionally well with soil analysis, particularly by the bicarbonate method ($r^2=0.92$). When rooting is restricted to the soil that has been analysed and a crop is grown under controlled conditions there is often a very good relationship between the soil analytical data and P uptake (and, by inference, response to fertiliser). For crops under field conditions, much of the high correlation is unfortunately lost.

7.1.5 Whereas the above trials were restricted to 3 rates of phosphate, Johnson *et al.* (1977) included 6 rates of N, P and K to look further at the shape of response curves. There were 16 sites in spring barley on the chalk soils of Southern England and rates of P_2O_5 and K_2O ranged up to 175 kg/ha. Fertiliser was applied to the seedbed and harrowed in before drilling. Most soils were moderately to well supplied with P, with only two sites at Index 0. There was very little response to phosphate, particularly at P Index 2/3 - with one notable exception which could not be explained. At P Index 1 there were small responses to phosphate at the lower levels of application. As the value of the average response was much less than the cost of fertiliser, it was concluded that manuring for cereals should be on a maintenance or insurance basis.

7.1.6 In 1987 Edwards (Personal comm.) summarised data from long-term phosphate experiments. Nine trials were done at locations chosen for their history of even cropping and previous low manuring. Each trial comprised 4 annual treatments laid in a randomised block design with 2 replicates. Plot sizes were within the range 0.06-0.08 ha. The treatments were 0, 50, 100 and 150 kg P_2O_5/ha as triple superphosphate. At two sites the highest rate was increased to 250 kg P_2O_5/ha.

Through the build-up or run-down period the fields were cropped normally by the farmers. Several years of these treatments meant that each site had a range of soil P residues. In the final 'testing' year the large plots were split into 8 sub-plots and randomised duplicates of the 4 testing treatments were applied. Test treatments were 0, 50, 100 and 150 or 250 kg P_2O_5/ha. The test crop was spring barley except at one site where it was winter barley. The length of the build-up period varied from site to site so that the test year was not the same for every site. For the test year, soils were analysed and the blocks were distributed as follows:

P Index 0	- 9 blocks
P Index 1	- 9 blocks
P Index 2	- 9 blocks
P Index 3 and above	- 13 blocks

Yields were variable, but several conclusions could be drawn from them.

Yield responses to fresh phosphate were frequently experienced where the P status had dropped to Index 0 by the end of the run-down period. The response was usually only to 50 kg/ha fresh phosphate but some sites showed significant responses to 100 kg/ha and 150 kg/ha fresh phosphate.

The 50 kg P_2O_5/ha build-up treatment resulted in most sites reaching or remaining at Index 1 by the end of the build-up period. Yields were always higher than those measured on the no-P treatment for both residual effects and in the presence of fresh phosphate on this treatment. In general there was also a positive response to fresh phosphate, the biggest response being to 50 kg/ha fresh phosphate. This confirms that if soil P is Index 0, spring barley, and by inference other cereal crops, will not give maximum yield on low P status soils regardless of how much fresh phosphate fertiliser is applied.

The 100 kg P_2O_5/ha build-up treatment increased soil P levels to Indices 2 and 3 at most sites. There were no responses to fresh phosphate in the test year on this treatment. These results therefore show that at Index 2/3 only maintenance dressings are necessary to balance crop off-take and maintain the soil nutrient level. This is confirmed by the results form the highest build-up treatment (150/250 kg/ha). During the build-up period this latter treatment resulted in a significant increase in soil P levels. Yields in the test years were similar on the 50 and 100 kg P_2O_5/ha build-up treatments, both in the presence and absence of fresh phosphate. This confirms that at high phosphate levels of ADAS Index 4 or above, maintenance dressings can be omitted and soil can be allowed to run down to Index 2 or 3 without suffering a significant yield penalty. They also agreed with the findings of Johnston *et al.* (1975) and others that there is an upper limit to soil phosphate reserves above which additional P will not give any extra yield.

7.2 EVIDENCE FOR RESPONSE TO POTASH

7.2.1 Lessells and Webber (1965) reported on 37 experiments with spring barley in which 3 rates of potash were combine drilled. The data showed K fertiliser had little effect on yield.

7.2.2 Boyd and Frater (1967) reported on 54 NAAS trials (30 barley, 24 wheat) which tested 0, 37 and 75 kg K_2O/ha on soils derived from Oolitic limestone and chalk. The trials covered the period 1956-62. Mean response over all sites was only 0.06 t/ha.

The ability of different methods of soil analysis to predict K response was tested. Data were analysed by determining the variance of K response (K_2-K_0) after fitting a linear regression on soil K. In two groups of experiments (spring barley on both chalk and Oolitic limestone soils, with K combine drilled) virtually all the apparent differences in response between sites were due to experimental error. For two of the remaining groups of experiments involving spring wheat and spring barley, none of the analytical methods was of any real value. At best in one series of experiments one method of analysis accounted for one-third of the variance. Although the authors concluded that soil analysis was ineffective, response to K at the 54 sites was generally low, suggesting that the trials did not include K deficient soils. As the real value of soil analysis appears to lie with its ability to detect responsive soils, it is not surprising that correlations were poor.

7.2.3 Russell (1967) also investigated the usefulness of soil analysis for predicting responses to potash. In a series of trials already mentioned in the phosphate Section, 7.1.4, annual potash applications were made at one rate of phosphate, namely 50 kg P_2O_5/ha. Potash rates were 0, 112 and 225 kg K_2O/ha, shown as K_0, K_1 and K_2, respectively. After the build-up period, the same treatments were applied to sub-plots on each main plot. Therefore, at each testing the responses to potash were measured on plots with different histories of potash manuring. Soil samples were taken before testing and analysed for K by various methods. Test crops were either winter wheat, spring barley or grass.

Responses to potash were only small, even on plots which received no K during the build-up period. To look at the worthwhileness of soil analysis, a potash balance was calculated for each treatment. Obviously the no-K treatment was in negative balance; it was found that a slight excess had been applied compared with off-take in the case of K_1 treatments and a large excess over off-take had accrued from K_2 treatments. Table 1 shows the mean percentage increases in the soil analytical data obtained by different methods, relative to K_0 treatments. All methods of soil analysis reflected the size of the K residues which had been accumulated. However, correlations between soil analyses and cereal yields were poor, with r=0.56 for the best correlation. The value of the analyses was to group sites into responsive and non-responsive.

Table 1 Percentage increases in soil analytical data, relative to K_0 (mean of 8 sites); after Russell (1967)

Analytical method	K_1-K_0	K_2-K_0
Sodium acetate/acetic acid	48	120
Ammonium acetate/acetic acid	34	91
0.5 M Acetic acid	42	103
1.0 M Nitric acid	15	26
Ammonium nitrate	26	80
$CaCl_2$ (0.01 M)	77	200

7.2.4 Webber *et al.* (1968) looked at the response of barley to K in 77 trials. Averaging responses over all 77 sites showed K fertiliser gave no increase in yield. Using the then standard NAAS method for assessing the K status of soils, the authors concluded that establishing the soil Index was ineffective in predicting response, however, the mean, albeit very small, response was larger at Index 1 than at higher Indices. Even at Index 1, average response at these levels of production would have been insufficient to pay for the cost of the fertiliser. As with phosphate, it was concluded that as it is only low K status soils that are likely to respond to potash, cereal growers should manure the barley crop mainly to maintain satisfactory soil reserves of potash i.e. balance inputs with off-takes by the crop. Webber *et al.* (1968) estimated off-take in a 4.4 t/ha crop to be 62 kg K_2O/ha in grain and straw, and only 37 kg K_2O/ha if straw was not removed. Suggested maintenance dressings of about this size were at variance with work done by Williams *et al.* (1963) and Widdowson *et al.* (1967) which confirmed that a barley crop may contain about 200 kg K_2O/ha at earing. On the basis of this, it was suggested that larger potash applications were necessary. However, many trials have shown that response by cereals to K is small and would not cover the cost of large dressings.

7.2.5 Whereas Webber *et al.* (1968) were mostly concerned with trials on heavy soils in which cereals might make considerable use of initially non-exchangeable K, two further series of trials were concentrated on lighter chalk soils. Cromack (1972) investigated three sites on Andover Series (silty loam over chalk) between 1968-70. Treatments were 3 rates of potash (112, 150 and 188 kg K_2O/ha). Potash was applied to the seedbed along with 50 kg P_2O_5/ha. Results averaged over the three years showed that no more than 50 kg K_2O/ha was required for spring barley on these soils. In fact, all three sites were moderately to well supplied with K (two sites Index 2, one site Index 3), and so it is perhaps not surprising that there was a lack of response to potash. The work did confirm, however, that even on lightish soils with supposedly little K supplying power, cereals show only a small response to potash despite the large demand for the nutrient.

7.2.6 Johnson *et al.* (1977) also examined the responses of spring barley grown on 16 chalky soils, involving 6 levels of potash fertiliser ranging up to 157 kg K_2O/ha. Most sites had K Indices 2 or 3 and on average they showed only a small response to K and then only at the smallest K application rate. On 4 out of 7 sites of lower K status there was no significant response but on the other 3 (two at Index 1 and one at Index 0) K response continued up to the largest dressing tested. The trials also investigated NPK interactions. Whereas P did not interact with the other two nutrients, at five sites which were low in K status, N was used inefficiently when little or no potash was applied.

7.2.7 In 1988 Edwards (Private comm.) collected data from long-term potash experiments carried out between 1965 and 1983. Similar in design to the long-term phosphate experiments described in Section 7.1.6, six sites were selected on soils with a history of even cropping and low manuring. The duration of individual trials varied and also all trials were not started in the same year. Each trial comprised 4 annual treatments laid in a randomised block design with 2 replicates. The treatments were 0, 50 and 100 or 150 kg K_2O/ha. At one site the highest rate was increased to 250 kg K_2O/ha. Through this build-up/run-down period the fields were cropped normally by the farmers. Several years of these treatments meant that each site had a range of soil K residues. In the final testing year the large plots were split into 8 sub-plots and randomised duplicates of 4 testing treatment were applied. Test treatments were 0, 50, 100 and 150 or 250 kg K_2O/ha. The test crop was spring barley. In the test year the soil analyses were distributed as follows:

K Index 0	-	0 blocks
K Index 1	-	8 blocks
K Index 2	-	13 blocks
K Index 3	-	7 blocks

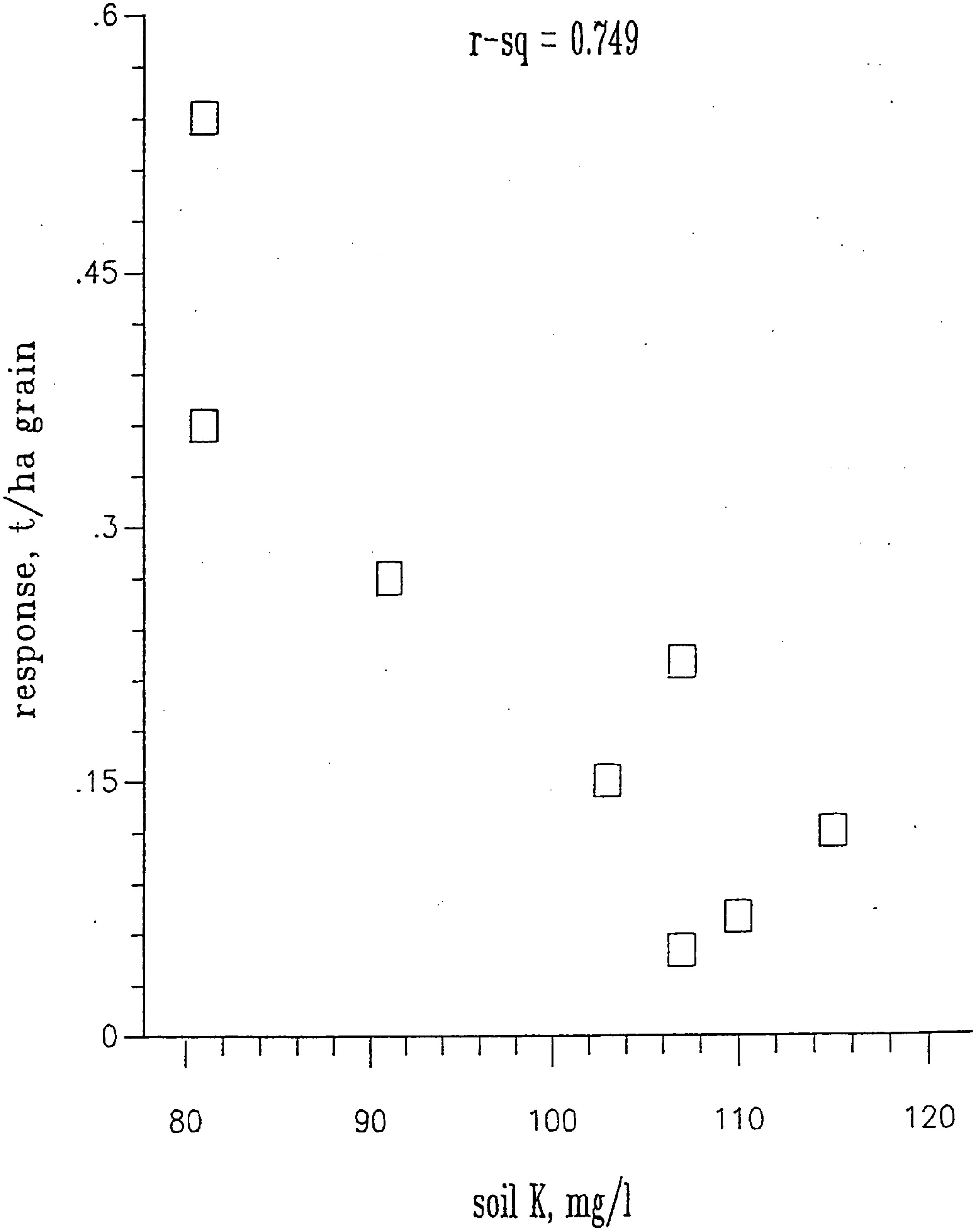
No block at any site fell into K Index 0 and as a result there were few significant responses to fresh potash. Looking at the average response at each Index the data support current recommendations. At Index 1 the mean response to 50 kg K_2O/ha was just sufficient to pay for the fertiliser. At Indices 2 and 3 there were no responses to potash.

Within Index 1, unlike earlier data, soil K analysis was a good indicator of size of response. Figure 1 shows the relationship between response to 50 kg K_2O/ha and soil K level. Extrapolating from this relationship, no yield increase would be found on these soils above 120 mg K/l.

The data confirm that soil analysis is mainly of benefit in indicating responsive sites, i.e. Index 0 for both P and K.

Figure 1. Response to 50kg/ha Potash

After Edwards (1988)



8 BROAD STRATEGY FOR P AND K FERTILISATION

As summarised by Needham (1980), three situations can be identified involving the application of P and K to arable soils.

(a) Situations where there is a direct response to P and/or K because the nutrient status of the soil is low. Such direct responses of cereals to P and K in the principal cereal growing areas are now believed to be rare and soil analysis has provided the main check on whether or not responses are to be expected.

(b) Situations where only maintenance dressings of P and K are needed, merely to replace nutrients removed in the form of grain and straw. Except on very sandy soils, the timing of P and K applications for cereals is not critical and hence should logically be made to the most responsive crops in any rotation. This ultra-simple 'balance sheet' approach is a direct and inevitable result of the long-continued use of P and K in amounts which for many years exceeded the off-take by crops.

(c) Situations where no fertiliser applications are recommended because the nutrient status of the soil is high enough for at least the coming season, as for example where accumulated residues are large or, in the case of potash, where soils are derived from certain potassium-rich clays e.g. soils of the Worcester Series.

Clearly, it is important to be able to recognise the stage in the build-up of P and K reserves when it is not only safe but economically advisable to switch to maintenance dressings and also, should such a situation arise, identify the soil levels of P and K at which not even maintenance dressings are needed. Much of the review centres on these two issues.

9 CRITICAL SUFFICIENCY VERSUS BUILD-UP AND MAINTENANCE OF SOIL P AND K RESERVES

Now that so many cereal growing soils are regarded as non-responsive to P and K, it has become common-place to provide so-called maintenance applications of both nutrients as described in previous sections of the review. These may be applied annually to individual crops, which still seems the common practice, or they may be applied once or twice in a crop rotation (see Section 11.3). A similar situation has arisen in the USA and Olsen *et al.* (1987) state "Clearly there are vested interests that prefer the build-up and maintenance approach over the sufficiency concept in soil test interpretation; the more fertilizer sold the better the immediate business of the fertilizer dealer and his supplier". From the tone of the writing the disagreement between the supporters of 'sufficiency' and the supporters of 'build-up and maintenance' seems quite heated. In this country, as set out in Section 8, the normal recommendation is for no P or K fertiliser applications when the results of soil analysis are above specified limits. However, this raises three issues:-

a) how reliable is the dividing line between sufficiency and deficiency as determined by soil analysis?

b) is the soil analysis undertaken often enough to monitor changes in the nutrient status?

and c) are there methods which are more sensitive than soil analysis for identifying what might be described as the completion of the P and K build-up operation?

Church and Skinner (1986) have reported on detectable upward trends in the P and K status of some soils, as established by soil analysis. On the other hand, unpublished data from some areas indicate that P and K status is drifting downward, possibly because maintenance dressings are being used on soils which are still short of nutrient reserves.

It is generally accepted that the build-up strategy is not necessarily geared to the needs of the most demanding crop or crops in a rotation which invariably receive special extra fertiliser treatments. As discussed later in the review, there is little doubt that once firm control over P and K status has been obtained on a rotational basis, then a nutrient balance sheet system of P and K management has many attractions.

In the drawing up of nutrient balance sheets it is important to know that all the P and K in farmyard manure and slurry can be regarded as effective in the long-term. In other words, for the purposes of maintaining soil reserves no distinction need be made between the total P and K in organic manures and in soluble inorganic fertilisers. According to Vaidyanathan (Personal comm.) there is evidence from the results of Surveys of Fertilizer Practice that farmers tend to underestimate the long-term value of the P and K supplied in the form of organic manures. This is particularly likely to happen when rotations include potato and sugar beet crops, about one-third of which receive considerable amounts of organic manure. It should, however, be remembered that in the short-term the availabilities of nutrients in organic manures and slurries are known to cover ranges of values as discussed in 'Profitable use of farm manures' (MAFF, 1986).

10 SOIL AND PLANT ANALYSIS

Nutrient status problems in soils can be tackled via the soil by soil testing or by appropriate plant analysis, as illustrated by Walsh and Beaton (1973). Viewed on a world-wide basis and in terms of different crops it is usually a combination of the two approaches which is used to solve growers' problems but in this country, particularly when dealing with the P and K requirements of arable crops, it is soil testing which has maintained its dominance. In some respects the dominance of soil testing is not surprising because checks on soil via the plant are 'one step removed' and there is a danger that misinterpretation of plant analytical data may occur due, for example, to drought or inadequate root systems. Also plant analysis is usually too late for any necessary remedial action to be taken in the current growing season, which, of course, is not in its favour. For some purposes it can, however, be argued that the growing crop is the ideal agent for detecting deficiencies of nutrients in soils and much more use might be made of plant analysis.

It is well-known that the concentrations of most mineral nutrients in a plant, usually expressed as a percentage of the plant material on a dry weight basis, decrease often quite rapidly with the physiological maturity of the crop. For both P and K the percentages of the elements on a dry matter basis usually fall with time mainly due to the dilution of the elements with accumulated plant material, much of which is structural in nature e.g. cellulose, lignin. Thus, unless the physiological stage of development of plants is known rather precisely, analytical data cannot be interpreted with any confidence. On the other hand, routine soil analyses, based on some chemical extraction procedure, do not always assess nutrient status with enough precision.

According to Cooke (1982) "Many farmers lack confidence in soil analysis for purposes other than liming. Probably this is because there is no generally accepted numerical definition of 'deficiency' in P (or K) and because they cannot assess the risk involved in accepting advice based on analysis". This lack of confidence is understandable in that there is no ambiguity about pH values or lime requirements both of which are well defined and, unlike analyses for P and K, need no further quantitative interpretation. As indicated in Section 10.2, soil analysis is only a guide to the chance of response to fresh fertiliser. If more precision is sought, then the following are possible, a) adopt some forms of plant analyses, b) abandon single figure soil analysis in favour of something more complicated involving more information on the soil, or c) use some appropriate combination of both soil and plant analyses.

10.1 SOIL ANALYSIS - INTERPRETATION

It has been argued by, for example, Olsen and Khasawneh (1980) that single figure soil test data for characterising the P status of soils are of restricted value unless kept to soils with similar properties or accompanied by, for example, values of the buffer power of the soil. Similar views can be expressed about K which is usually at least ten times more mobile than P, so that the immediate soil buffer power will be less important, with its place being taken by another form of buffer power: namely the K releasing power - which is seldom estimated. Soil analytical data have traditionally be calibrated against the results of fertiliser response trials under field conditions, but because responses to fertiliser additions can vary from year to year and be influenced by unmeasured intrinsic soil properties there can be no firm line between sufficiency and deficiency. Thus, it has to be accepted that soil analysis based on some simple extraction cannot alone identify a clear dividing line between sufficiency and deficiency of either P or K in field situations involving different soils. What is found in practice is that when the responses are averaged, for example, in groups and plotted against soil analytical data as illustrated by Cooke (1982) for sugar beet in relation to P status, a practically useful trend can be identified. One very interesting conclusion drawn by Cooke was that although recognising that some methods of soil analysis are undoubtedly better than others, there was little point in attempting to improve the correlation between soil analysis done by the best rapid methods and field responses simply by trying to devise even better methods of laboratory extraction. Usually single figure soil analyses do not account for more than 50 per cent of the variance in crop response and frequently for much less than 50 per cent. In view of the effort which has been put into devising and calibrating soil analytical procedures it is disappointing that the correlations are so poor, but as stated by Grimme and Nemeth (1978) it seems that the low level of correlation cannot be improved.

As explained by Cooke (1982), in developed agricultural systems where much fertiliser is used, a sounder alternative to advice based on annual field experiments is to plan manuring so that soil P and K are maintained at levels sufficient for the range of crops to be grown - which, of course, means that the levels of sufficiency must be identifiable.

In many pot experiments done under controlled greenhouse conditions almost all the variance in crop response to added nutrient has been accounted for by soil analysis. Such findings show that the best methods of soil testing are discriminatory and, as has been established under field conditions, can be ideally suited for detecting whether nutrient levels are rising or falling. In many respects soil analytical data are site-specific and, ideally, should be interpreted with this in mind. The key issue remains that of identifying the boundary, with acceptable margins of error, between sufficiency and deficiency. Some of the reasons for the limitations of soil analysis are discussed in more detail in other Sections of the review.

10.2 ASSESSMENT OF P STATUS BY SOIL ANALYSIS

The limitations of single figure values for measuring nutrient status, particularly in relation to P, are very widely documented. Even a cursory consideration suggests that single figures must fail at least to some extent to allow for soil differences which influence the more dynamic aspects of nutrient supply to plant root surfaces.

As a broad generalisation it can be stated that single figure indices will tend dominantly to reflect either 'intensity' or 'capacity' characteristics of the nutrient supply - with the latter being the more common. The simple idea that in a fertile soil the supplies of a nutrient should be sufficient to bring the soil solution around absorbing roots to a required concentration (seen as an intensity of nutrient) may fail to recognise the important effect of the buffer power of the soil. As already mentioned, three main physico-chemical factors interact to influence the relation between P status and the delivery of P to the root: namely, intensity, quantity and buffer power. The inverse relationship between buffer power and intensity was high-lighted by Olsen and Watanabe (1970) who found that a poorly buffered sandy soil needed an initial P solution concentration (intensity) eight times greater than a better buffered soil of higher clay content. Khasawneh (1971), considering intensity, quantity and buffer power, postulated that P uptake would be proportional to both intensity and quantity, but in soils of equal P intensity, P uptake would be proportional to buffer power while in soils containing equal quantities of P, uptake would be inversely proportional to buffer power.

Holford and Mattingly (1976a and 1976b) examined in a practical context the relationships between quantities and intensities of phosphorus and the phosphorus buffer power of soils. An important conclusion of their work was that the critical levels of quantity and intensity alter according to the buffer power of the soil and the rate at which crop demands are made. Critical levels of quantity increase and critical levels of intensity decrease as the buffer power of soils increase. It is, therefore, not possible to set a universal value for either quantity or intensity of P in a group of soils unless the buffer powers and the crop uptake patterns are uniform. They found a 13-fold variation in the P buffering power of 24 soils all from the Sherborne Series which demonstrated the great variability in the buffer powers. In groups of unrelated soils the buffer powers are likely to be even more variable.

It follows from previous paragraphs that the use of one standard table of Indices applied to all soils for interpreting single figure soil analytical data obtained by a particular method is unlikely to be always dependable. As mentioned in Section 7.1, a simple chemical extraction procedure can be satisfactory for showing whether or not P status is changing with time and also for separating soils into broad categories of P status. Thus, such chemical extraction techniques provide only a guide to the chance of obtaining a response in grain yield to fresh P fertiliser addition, as follows:

P Index 0	response probable
P Index 1	response possible
P Index 2 and above	response unlikely (Applies similarly to K Indices)

Apart from seasonal influences, individual soil properties may blur the already imprecise boundaries regarding the likelihood of obtaining a response. There is no doubt that improved correlations between the soil test and crop behaviour are obtained when soils with very different characteristics are excluded or even better, only soils possessing similar characteristics are included. Working along these lines Reith *et al.* (1987) found that using different ranges of extractable P for different soil series led to more reliable estimates of P status and this refinement is likely to be extended as more information becomes available. In Scotland an extraction based on 0.43 M acetic acid at 1:40 soil:solution ratio is being used, partly because P, K and both Mg and Ca, if required, can be determined on the one extract. Examples of using different ranges of extractable P for different soil series taken from MISR-SAC (1985) are:-

		P status		
Soil Series	Very low	Low	Medium	High
		mg/litre		
Countesswells	<10	10-35	36-90	91-600
Insch	<10	10-25	26-65	66-450
Tarves	<10	10-20	21-50	51-400
Dreghorn	<10	10-35	36-130	131-750

(MISR-SAC, 1985)

Support for the use of acetic acid rather than bicarbonate (the latter being used extensively in England & Wales and Northern Ireland) as an extractant for available P has continued in Scotland partly because bicarbonate may over-estimate the availability of P in some acid soils, which are likely to be more common in Scotland than further south.

From January 1971 the bicarbonate method devised by Olsen *et al.* (1954) has been used in England & Wales to estimate 'available phosphate'. It replaced the old ammonium acetate-acetic acid extraction procedure and the analytical figures corresponding to P Indices 0, 1, 2 etc., which link the old and new methods were established as:-

Ammonium acetate - acetic acid extractant	'Available P' P Index	Sodium bicarbonate extractant
0 - 2.0	0	0 - 9
2.1 - 5.0	1	10 - 15
5.1 - 10	2	16 - 25
11 - 20	3	26 - 45
21 - 40	4	46 - 70
41 - 70	5	71 - 100
71 - 125	6	101 - 140
126 - 200	7	141 - 200
201 - 300	8	201 - 280
>300	9	>280

Apart from the reports concerning the general superiority of the bicarbonate method over other rapid methods of assessing P status, the replacement of an acid extracting solution by an alkaline one was widely acclaimed because the former over-estimated the P status of calcareous soils, by dissolving otherwise very insoluble P (Mattingly, 1980) partly in the form of basic calcium phosphates.

In Scotland, data from an anion exchange resin extraction procedure described by Reith *et al.* (1987) were found to correlate marginally better with crop performance than four simpler extraction techniques involving solutions. This finding parallels those of many other investigators who used resins, but the rather high time/cost factor of resin based methods makes it unlikely that this type of approach will be used on a routine basis in the near future.

Over the years several workers, for example Bache and Williams (1971) using Scottish soils, showed that a phosphate sorption index provided a more reliable measure of P status than P extraction data but, unfortunately, a sorption index is not likely to be widely used because it takes more time and effort than a simple extraction. Very recent evidence of Klages *et al.* (1988) also supported an adsorption technique rather than an extraction (bicarbonate) procedure for predicting the fertiliser needs of winter wheat in Manitoba. Their P requirement test, based on that of Fox and Kamprath (1970) measured the amount of P sorbed by the soil when the equilibrium solution level is raised to 0.2 ppm P (6.4 μmol/l). A high value obviously indicates a low P availability and should therefore be negatively correlated with P extraction data. As with extraction data, there is no doubt that improved correlations between the test results and crop performance are obtained when only soils possessing similar characteristics are included.

In a very detailed study of the subject of P status on the chalky boulder clay site (Beccles Series) at Saxmundham, Johnston *et al.* (1986) were able to draw many conclusions about the value of residual and fresh P applications for both spring barley and winter wheat. As in nearly all field experiments there were some complications ranging from mildew and the tendency of the heavier crops to lodge, to a dry spring followed by the exceptionally dry summer of 1976. The paper draws attention to how difficult it is - even at one site - to be precise about the level of soil P below which cereals respond significantly to fresh fertiliser P. Apart from seasonal effects, the previous cropping - which may have caused differential infection with mycorrhizae - was found to have influenced the level of soil P at which responses to fresh applications occurred. Whereas at a relatively low N input (63 kg N/ha) maximum yield of spring barley was achieved at 25 mg P/kg soil, at the higher N level (94 kg N/ha) a phosphorus level of about 33 mg P/kg soil was needed. For soils containing most soluble P, fresh dressings or 1- or 2-year-old residues did little to improve yield. For yields of 6 t/ha on such soils, which was the maximum obtained, sufficient soluble P can be maintained with either small annual dressings or larger dressings applied periodically. On soils containing <16 mg P/kg, barley given fresh P (60 kg P_2O_5/ha) or having 1-year-old residue from 160 kg P_2O_5/ha gave similar yields which were better than on soil without fresh P. Once a residue was 2 years old in the lower P status soil, it did not give as large a yield as that given by a fresh P application.

For winter wheat a regression model showed that yields levelled off at about 20 mg soluble P/kg soil which should perhaps be regarded as near the critical value for this crop. It can be concluded that so-called maintenance dressing of P fertiliser for winter wheat should be adequate at this site when the bicarbonate soluble P is in the range 15-20 mg P/kg soil. It is interesting that the long-term field evidence is that spring barley, and by inference, other spring sown cereals, requires a higher soil P status than winter wheat.

10.3 ASSESSMENT OF K STATUS BY SOIL ANALYSIS

McLean and Watson (1985) have given an account of several present-day methods used to assess the K status of soils or to obtain an estimate of the K fertiliser requirements of crops. For advisory purposes it is necessary that methods of soil analysis should be relatively simple, inexpensive and rapid. Analytical procedures for research purposes are often relatively expensive and complicated so that there is little prospect of their being used on a routine basis. In all but the lightest of soils it has to be accepted that cereals can be expected to use both readily exchangeable and non-exchangeable sources of K. Therefore unless there is some known relationship between the proportions of the two categories of K, a determination of the exchangeable K will not reflect the availability of the nutrient. When attempting to estimate the role of initially non-exchangeable K in cereal nutrition only a relatively small percentage of the soil volume will be sufficiently stressed to cause the release of non-exchangeable K, estimated to be in the region of 15 per cent; it follows that attempts to apportion K uptake between the two sources is not a simple matter.

Although exchangeable K is a poor indicator of 'available' K insofar as cereals are concerned, it can be argued that if the pool of exchangeable K is large enough on its own to meet both the total K requirement and peak demands throughout the growing season, then any uptake from non-exchangeable sources and the subsoil can be viewed as an additional buffering effect. As a general rule it was concluded by Edwards (1988) that cereals do not respond to fertiliser K when the available K is at the very top of Index 1 at about 120 mg K/l, however, there are, no doubt, exceptions to this.

Measurements of exchangeable K or their near equivalents are used in the UK and very widely across the World for assessing the K status of soils; the procedure is simple and provided the soil sampling is done at an appropriate time of year, a reasonably well defined category of soil K is quantified. However, as already made clear, in most soils exchangeable K is a poor indicator of 'available' K mainly because so much use can be made of initially non-exchangeable K during a growing season. According to Cooke (1982), measurements of exchangeable K usually account for no more than 30 per cent of the variance in response to K-fertilisers by sensitive crops in annual field experiments; crops that respond less to potassium give poorer relationships. Cooke (1982) concludes that 'soil type determines K supply, and knowing soil types has often been more successful than knowing soil analysis in interpreting tests of K fertilisers'. In fact, some caution is needed in reading too deeply into the last statement because K status can be determined as much by the cropping history and previous land management as by soil type. As might be inferred from the tendencies for different categories of K to come at least to near-equilibrium states with each other, exchangeable K is a good indicator for monitoring changes in K status especially on a long term basis.

When interpreting exchangeable K data it is quite common practice in some parts of the World to make allowance for the cation exchange capacity (CEC) of soils, the simple explanation being that, on average, more exchangeable K is needed to reach sufficiency levels in soils possessing higher CECs. Thus, McLean and Watson (1985) state that for some crops in Ohio a sufficiency level (K_{SL}) of K in mg K/kg soil is given by

$$K_{SL} = 110 + 2.5 \times CEC$$

where the CEC is in cmol(+)/kg and preferably refers only to the mineral matter i.e. excluding the CEC attributable to organic matter. Similarly the approach adopted when interpreting exchangeable K data in the Netherlands (van der Paauw, 1973) uses a relationship which allows for clay content and also a pH factor if lower than 7.0.

Because of differences in mineralogy, and the extent to which soils have been depleted of or supplemented with K, it is difficult to predict the fraction of added K which may end up immobilised or 'fixed' - albeit temporarily. When attempting to determine the amounts of K fertiliser needed to bring soils up to sufficiency levels of exchangeable K there is, in theory, a need to determine individual tendencies of soils to immobilise K, but there is little evidence that this is actually done on a routine basis anywhere in the world. According to McLean and Watson (1985) between 20 and 90 per cent of added K can remain exchangeable in the soils they are familiar with in the USA, and so it is unsatisfactory simply to use the practice of applying 1.66 units of K for each 1.0 unit required increase in exchangeable K (based on an assumed 60 per cent recovery). In the UK it is uncommon to make any allowance for different K fixing tendencies of soils except insofar as K placement may be recommended on some low K status soils in order to maximise K recovery in the season in which it is applied. In the vast majority of soils it is seldom if ever a question of trying to move very quickly from low to satisfactory K status - which would probably be uneconomic and possibly cause salt damage. The procedure is gradually to raise K status using marginally higher than average K applications.

According to Johnston (1987), in a detailed consideration of a K balance sheet it is necessary to know how much added K remains exchangeable, and he illustrated his argument with data from long-term field trials. Because cereals are among the most efficient crops at taking up K from initially non-exchangeable sources, the need to make allowances for K fixing powers is, presumably, of more importance for crops which are less efficient at taking up soil K.

10.4 RELEASES OF NON-EXCHANGEABLE K ASSESSED BY Ca-RESIN

Laboratory methods for obtaining estimates of the ability of soils to release non-exchangeable K have, with few exceptions, been destructive of the mineral lattice and hence probably too severe to provide realistic results. As mentioned in Section 6.1, Talibudeen *et al.* (1978) successfully used Ca-saturated cation exchange resin as a sink for soil K and by periodically renewing the resin, were able over periods of days and weeks to obtain estimates of the reserves of useful non-exchangeable K. The criticism that too low an ambient concentration of K was maintained in such systems was recognised by Talibudeen *et al.* (1978) and they suggested that a more reliable estimate of the maximum amount of K soil could release during a given time to a crop should be measured at a K concentration of about 10 μmol K/l ($\simeq$0.40 ppm K).

Goulding (1984) interpreted Ca-resin induced K release curves in considerable detail in terms of amounts of K, and rates of release. Working on the basis that K held on flat crystal faces, crystal edges and inside crystals comes as near as possible to describing the categories of K, he attempted to interpret the shapes of release curves. Because of the effects of aggregation on the movement of K through the pore solution of soil micro-aggregates, it was not realistic to read too deeply into the shapes of release curves. Goulding and Loveland (1986) stated that although the Ca-resin method is too slow and complex for routine use in advisory work, it has considerable potential as a feasible means of assessing the long-term reserves of K, and hence the strategic value of soils. It was on this basis they employed two complementary procedures, namely, Ca-resin and acid-extraction, to investigate the K status of a range of English and Welsh soils.

It is not realistic to consider using Ca-resin extractions to characterise the K releasing powers of cereal growing soils on an extensive scale and hence other approaches, probably involving K balance sheets and some simple analyses on both soils and crops are likely to be used. For certain problem solving purposes, however, the Ca-resin technique has much in its favour. Very recently, Wimaladasa and Sinclair (1988) tested a novel method using ammonium-ion exchange resin for studying the dynamics of soil potassium, but its general suitability for use - perhaps in the form of a combined P and K test - remains to be confirmed. The technique of electro-ultrafiltration (EUF) which also provides information on the ability of soils to supply nutrients to plants in the longer term was found by Sinclair (1982) to be generally unsatisfactory for the Scottish soils he examined.

10.5 A NOTE ON MECHANISTIC MODELLING OF P AND K UPTAKE BY ROOTS

Overall, the P and K uptake by roots is a complicated matter influenced by soil factors other than those directly related to simple estimates of the sizes of 'available' pools of P and K. Mechanistic modelling of nutrient uptake has increased our understanding of P and K behaviour in soils, but there is doubt about the economic worth of obtaining on an extensive scale some of the soil measurements needed for modelling in order to obtain better control over the P and K nutrition of cereals.

A model for calculating the solute uptake by a randomly dispersed root system developing in a given volume of soil was put forward by Baldwin *et al.* (1973). Their results supported Barber's (1962) qualitative conclusion that mass flow contributes a rather small proportion of the total K and a very small proportion of the total P taken up by a crop in a growing season and a surge of interest in both the soil and crop characteristics which affect crop nutrition was created. Different aspects of the progress made in mechanistic modelling are mentioned in different parts of the review which deal with P and K, but there are many similarities between the two nutrients, at least in principle. In most soils, however, P is at least ten times, perhaps even a hundred times less mobile than K. The whole subject was well documented by Nye and Tinker (1977) and, as described by Barber (1985a), has continued to develop during the last decade, with significantly more progress being made with K than with P.

As explained by Barber (1985b) in connection with K uptake by roots, the Cushman model as used by Silberbush and Barber (1984) has 11 parameters. Three describe the root geometry and its development, three the K influx, three the soil characteristics, and there are two additional parameters, namely the water influx into the plant and the mean half distance between root axes. Insofar as the soil parameters are concerned, two are related, namely, the effective diffusion coefficient of K and the buffer power of the soil, as set out by Nye (1968) in his widely used formula accounting for the fact that as buffer power increases, the diffusion coefficient decreases. The third soil parameter is the concentration of K in the soil solution before nutrient uptake begins. Like the Baldwin *et al.* (1973) model, the Cushman model involves the K concentration in solution and the exchangeable K but makes no allowance for releases of initially non-exchangeable K, which now must be recognised as of considerable relevance to both cereals and grasses and many other crops when grown on a wide variety of soils. It was, therefore, a considerable advance when Heming and Rowell (1985a and 1985b), included both the slow release of initially non-exchangeable K and the effect of soil aggregate size in their modelling.

It should be mentioned that although cereals, like all plants, require very much less total P than K, and complexities surrounding P nutrition, often involving problems of a biological nature, are such that modelling studies as outlined in the previous paragraph are likely to be less useful than for K; as stated by Barraclough (1983b), the present approach to modelling plant nutrition is still 'too simplistic' for P.

10.6 PLANT ANALYSIS - GENERAL CONSIDERATIONS

Over the years there has been rather little confidence surrounding the use of plant analysis for diagnosing P and K deficiencies in cereals. The reasons for this are mainly to do with the problem of decreasing mineral concentrations with age and the interactions between nutrients, especially when more than one nutrient is in short supply. Viewed in very general terms, a restricted supply of a nutrient must normally mean less overall growth and therefore the nutrient concentrations in the developing plant expressed on a percentage dry matter basis may tend to be similar under different nutrient regimes. In fact, the difference between critical deficiency and adequate percentages can be quite small as found by Baker and Tucker (1973) for P in winter wheat plants in Canada where the critical divide was put at 0.3 per cent P. As discussed in Section 4.1, some thought has to be given to the functions of nutrients when considering the manner in which analytical data are expressed as, for example, the apparent advantage which comes from expressing K on a tissue water basis.

In any attempts to use plant analysis to diagnose soil nutrient shortages it is, of course, vitally important to know that the plant root system is healthy and adequate in size, otherwise it is highly likely that the wrong conclusions will be drawn from the analysis which is done.

10.7 PLANT ANALYSIS IN RELATION TO THE 'DIAGNOSIS AND RECOMMENDATION INTEGRATED SYSTEM' - DRIS

As discussed by Sumner and Farina (1986), highest yields are obtained where nutrient and other growth factors are in a favourable state of balance. In most agronomic circles it is accepted that the field study of synergistic and antagonistic effects between nutrients is not possible without factorially designed experiments, however, the number of plots required, involving several levels of treatments, makes the cost of such trials very high, especially as the work has to be done over several growing seasons. Among other ways of examining nutrient balance the technique known as Diagnosis and Recommendation Integrated System (DRIS) has received appreciable attention in recent years and has been reviewed by Walworth and Sumner (1987). It has several interesting features, including the fact that as originally introduced it uses nutrient ratios in the plant material rather than nutrient contents on a simple percentage basis, which tend to decline as crops mature. Perhaps the most attractive feature of DRIS is that it is supposed to do away with the need to know the values of the critical or threshold concentrations of nutrients in plant materials for optimum growth at various stages of growth. The procedure involves the collection of data in surveys of growing crops involving plant analysis and yield data, together with other factors likely to influence yield. The resulting population is divided into two sub-populations of high and low yielders and nutrient element ratios are tested as discriminating functions. Those ratios found to be discriminating are kept as useful diagnostic indicators. It has been found that the nutrient ratios are largely independent of the age of the crop and virtually independent of the location of where crops are grown. Data for wheat grown in parts of the USA were examined first by Sumner (1977) and more recently by Amundson and Koehler (1987).

It would seem that DRIS is better suited for examining the more severe imbalances in crop nutrition, and putting the imbalances in an order of priority, rather than for the 'fine tuning' of nutrient balances. In fact, DRIS is likely to be of limited value in agriculturally developed areas because when yields are high the crops tend to be rather little affected by interactions. Nevertheless there may be scope and advantages in using the principles of DRIS without the rigid adherence to the more conventional nutrient ratios. According to Sumner and Farina (1986) the use of a ratio such as N/P for expressing plant composition could be taken to imply antagonism between applied N and P which is certainly not the case for maize upon which they worked extensively. When considering the mutually synergistic effects of N and P, Sumner and Farina (1986) suggested that the correct way of considering the data in the model would be to use the product N x P (which can be regarded as N/1/P) as a discriminating function, and not the N/P ratio which implies that N and P are antagonistic in their influence on the composition of the leaves.

In view of the difficulties of interpreting plant analytical data for diagnostic purposes it is recommended that an attempt should be made to collect together existing data on the N, P and K concentrations in cereal leaves at different stages of development. Even if it is found that full DRIS treatments of data are not justified, it might well emerge that some of the procedures associated with DRIS might help with the spotting of instances where cereals are not receiving properly balanced nutrition.

Only a detailed investigation will reveal whether or not some combined function of the P and N concentrations in cereal plants can be used as an index of P sufficiency, which should perhaps be examined in the first place at various stages of growth between tillering and flowering. Any conclusions which emerge will depend to some extent upon the amount of N and the manner in which it is provided for the crop. If, as is most likely, the ability of soils to sustain the supply of P is of primary concern, then the position at flowering or even slightly later in the development of the crop would have to be covered. At present it is unusual to use more than the total P concentration in the whole or some preferred part of the plant for diagnostic purposes, usually setting the critical or threshold concentration in the range 0.25-0.30 per cent P on a dry matter basis. The latter approach is used by advisors who have experience of the composition of crops under different nutrient regimes and it could provide at least a basis against which other, perhaps improved, techniques could be tested. There are, in fact, rather few sources of published information regarding the P concentration in cereal plants grown under UK conditions. When considering total P concentration in well developed cereal crops in relation to increasing levels of soil P status, it is usually found that the total P concentrations in plants tend to rise steadily with a rising level of available P in the soil, but the yield of grain rises rapidly over a fairly narrow range of rising soil P status.

Ward *et al.* (1973) discussed different aspects of plant analysis as an aid in fertilising small grains, including so-called quick tests comparable to the nitrate-

N estimation used to determine the need for N top dressings. Clearly there is scope for further work on the inorganic P concentration (as opposed to the total P concentration) in cereal plants as an aid to diagnosing deficiencies and sufficiencies as discussed by Burns (1988), but such approaches may well lack the rigour which is needed and which might come from a combined N and P parameter which has already been mentioned.

It should be emphasised that the long term hope is that periodic soil testing will continue to provide information about whether the P status and K status of soils are changing and site-specific cross checking of soil tests - at least capable of quantifying a reliably determined sufficiency level - could come from appropriate plant analysis where any uncertainties exist. Insofar as the K concentrations in cereal plants are concerned, levels of sufficiency are most likely to be characterised by expressing K concentrations on a tissue water basis and some of the advantages and existing problems associated with this have been outlined in Section 4.1.

11 THE MAINTENANCE OF SOIL P AND K STATUS UNDER CEREALS

11.1 CROP OFF-TAKE OF PHOSPHATE AND POTASH

The now widely used practice of applying maintenance dressings of P and K to soils which contain adequate reserves has meant that close attention has to be given to the factors affecting nutrient losses. The losses associated with cereals, apart from leaching losses which for P and K are usually assumed to be negligible, depend upon:-

(a) Yield of grain and nutrient content

(b) Yield of straw, nutrient content and method of disposal

(c) Prevailing nutrient status of soil.

It is widely recognised that the K taken up by cereal crops does not tend to accumulate in ripe grain and straw, with often between 30 and 40 per cent of the maximum above ground K content in the growing crop getting back in the soil before harvest. In contrast, seeds are particularly good accumulators of P and hence a high proportion of the P taken up by cereal plants is removed in the grain harvest. Growers who farm soils which are well above average fertility will tend to harvest produce, particularly straw, which contains significantly more than the amounts of P and K needed for optimum yield.

Following early experiments, recommended maintenance dressings were in the range 20-40 kg/ha for both P_2O_5 and K_2O when grain yields were much lower, around 4.5 t/ha. Recent data on phosphate and potash off-takes by some cereals have been collected and are discussed separately.

11.1.1 OFF-TAKE OF PHOSPHATE

Grain and straw were taken annually for analysis from long-term phosphate experiments and the results were summarised by Edwards (Private comm.) in 1987. Table 2 shows the P_2O_5 percentages in grain and straw for each treatment over the phosphate build-up/run-down period during which the cereal was grown.

Table 2 P_2O_5 percentages (on 85 per cent dry matter basis) in grain and straw during 'build-up/run-down' period of long-term phosphate experiments

	Treatment kg P_2O_5/ha per year			
	0	50	100	150(250)
Grain				
Means of all sites	0.64	0.68	0.70	0.72
Range	0.43-0.88	0.45-0.86	0.47-0.86	0.45-0.86
Straw				
Means of all sites	0.14	0.16	0.16	0.17
Range	0.04-0.35	0.04-0.37	0.04-0.37	0.04-0.43

Phosphate fertiliser had a very slight effect on the P_2O_5 percentages in both grain and straw. At 0.7 per cent P_2O_5 in grain the off-take would, of course, be 7.0 kg P_2O_5/t which is very similar to the current ADAS recommendation of 7.8 kg P_2O_5/t. Similarly, for straw, off-take based on the data in Table 2 should be about 1.6 kg P_2O_5/t, which is the figure currently recommended by ADAS.

Table 3 shows the results of recent P_2O_5 analyses done on 867 straw samples reported by Withers (Private comm. 1989) from ADAS trials.

Table 3 P_2O_5 removals (on 85 per cent dry matter basis) in cereal straws, 1986-1988 harvests (after Withers, 1989).

	Mean removal kg P_2O_5/t straw (85% dry matter)
Winter wheat	1.36
Winter barley	1.17
Spring barley	1.56

The mean P_2O_5 removal in cereal straw was 1.36 kg P_2O_5/t, which is slightly lower than the 1.6 used by ADAS (MAFF, 1985).

11.1.2 OFF-TAKE OF POTASH

Grain and straw samples were taken annually for analysis from long-term potash trials which included cereals in the rotation and the data were summarised by Edwards (Private comm.) in 1988, as shown in Table 4.

Table 4 K_2O percentages (on 85% dry matter basis) in grain and straw during 'build-up/run-down' period of long-term potash trials.

	Treatment kg K_2O/ha per year			
	0	50	100	150
Grain				
Mean of all sites	0.48	0.49	0.49	0.49
Range	0.27-0.58	0.25-0.69	0.27-0.67	0.25-0.68
Straw				
Mean of all sites	0.78	0.95	1.02	1.11
Range	0.32-1.38	0.38-2.05	0.37-2.05	0.41-2.27

In the grain there was little variation in potash percentage with the different fertiliser regimes. The average K_2O percentage was equivalent to a removal of 4.9 kg K_2O/t grain (at 85 per cent dry matter). There was considerable variation at each site from year to year. The current ADAS recommended figure for potash off-take in wheat and barley grain is 5.6 kg K_2O/t. Potassium fertiliser levels had a considerable effect on the K_2O percentages in straw, but a few showers of rain can greatly reduce the potash contents of straw because it is so easily leached.

Table 5 shows the results of recent K_2O analyses done on 867 straw samples reported by Withers (Private comm. 1989) from ADAS trials.

Table 5 K_2O removals (on 85 per cent dry matter basis) in cereal straws, 1986-1988 harvests (after Withers, 1989).

	Mean removal kg K_2O/t straw (85% dry matter)
Winter wheat	9.3
Winter barley	10.1
Spring barley	12.6

There were, in fact, large variations between sites and within years but the overall tendency in each year was for barley, especially spring barley, to have a higher potash off-take than wheat. Whereas in the past ADAS has not differentiated between potash off-takes in wheat and barley straws, the present ADAS recommendations for potash removals in barley and wheat straws as 12.6 and 9.3 kg K_2O/t, respectively, come very close to Scottish experience. These figures slightly over-estimate the K removal by winter barley. In 1986 at 12 sites where straw samples were taken from plots treated with a range of nitrogen rates, results showed that increasing N rate increased straw potash percentages in both wheat and barley.

11.1.3 ESTIMATES OF PHOSPHATE AND POTASH OFF-TAKES IN SCOTLAND

In Scotland, where wheat and barley have been dealt with separately for some time, MISR/SAC (1985) recommend the use of the following estimates for P_2O_5 and K_2O removed per tonne of crop.

		P_2O_5	K_2O
		kg/t	
Wheat	- grain	8.3	5.5
	- straw	1.4	8.4
Barley	- grain	8.0	5.7
	- straw	2.0	13.1

Thus, for Scottish conditions harvesting 5 tonnes of barley grain along with 3 tonnes straw per hectare will remove 46 kg P_2O_5/ha and 68 kg K_2O/ha. The present P and K fertiliser recommendations for spring cereals producing a 5 t/ha yield in Scotland are:

	Soil P status				Soil K status		
	low	moderate	high		low	moderate	high
kg P_2O_5/ha	80	50	30	kg K_2O/ha	80	50	30

and for winter wheat producing 7 t/ha the corresponding figures are:

kg P_2O_5/ha	100	70	50	kg K_2O/ha	100	70	30

It thus emerges that for spring cereals in Scotland the recommended rate of P_2O_5 for moderate P status soils is very slightly above the calculated off-take whereas the recommended K_2O rate is slightly less than the calculated off-take for the moderate K status soils.

A concise treatment of this topic for conditions in England and Wales is given in the MAFF Booklet 2496 (1985), entitled Phosphate and Potash for Rotations.

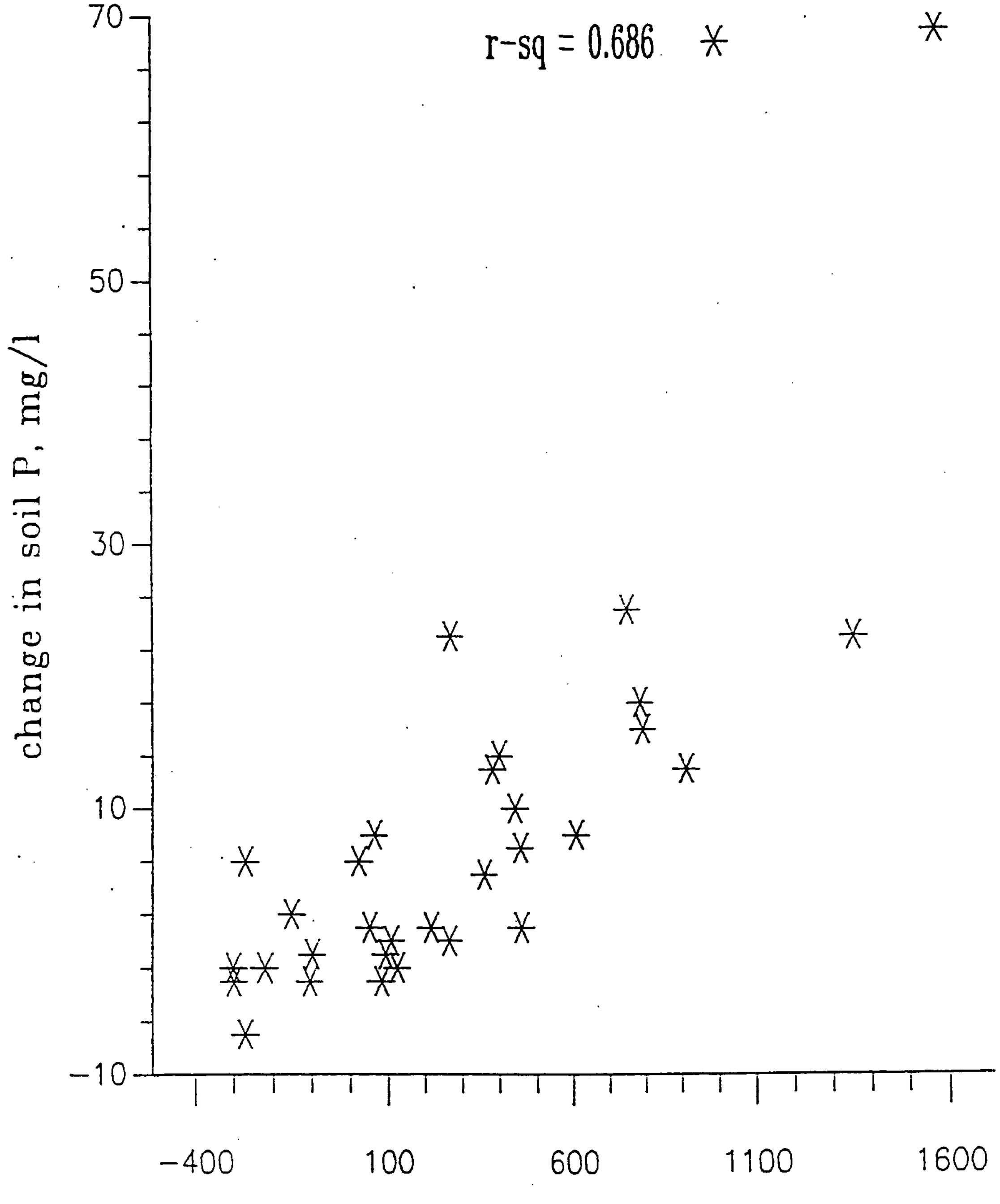
11.2 CHANGES IN SOIL P AND K LEVELS - RESIDUAL EFFECTS

In long-term fertiliser experiments, soil analysis can identify the effects of previous manuring practices, being almost invariably able to pick out lower and higher manuring regimes. This is not surprising because individual trials are usually done on one soil type and most methods of soil analysis are discriminatory on particular or closely related soil types. Evidence to support this has come from Russell (1967), Russell and Batey (1971) and Williams *et al.* (1971). More recent data have also been used to follow changes in soil P and K levels with fertiliser treatments and over time.

In 1987 Edwards (Private comm.) examined some of the results from nine experimental sites, originally chosen for their history of even cropping and low manuring, which carried the long-term P fertiliser experiments already referred to in Section 7.1.6. P residues were built-up or run-down over several years by applying annual applications of 0, 50, 100 and 150 or 250 kg P_2O_5/ha. Soils were analysed annually for 'available' P using the standard bicarbonate extraction method. When the difference between fertiliser inputs and crop off-takes (kg P_2O_5/ha) were calculated for the build-up period and plotted against the changes in 'available' soil P (mg P/l) measured annually, an indication of the amount of fertiliser needed to maintain soil P levels can be obtained. Figure 2 summarises the findings using all the treatments. There was a satisfactory correlation between fertiliser inputs minus crop off-takes and measured changes in soil P, with r^2 = 0.69 for all treatments, and r^2 = 0.58 when the 150/250 treatments were excluded. Figure 2 shows that the 50 kg P_2O_5/ha treatment is sufficient to maintain soil P levels and confirms the basis for the current ADAS recommendation for maintenance dressings of phosphate for grain yields up to about 5 t/ha. At the prevailing yields, inputs greater than 50 kg P_2O_5/ha would result in a gradual increase in 'available' soil P levels unless there is a tendency for downward drift as mentioned in Section 11.4. The data in Figure 2 show that about 40 to 50 kg P_2O_5/ha would be needed to raise the P status of the soils by 1 mg P/l. An

Figure 2. Effect of Phosphate on Soil P Reserves

After Edwards (1988)



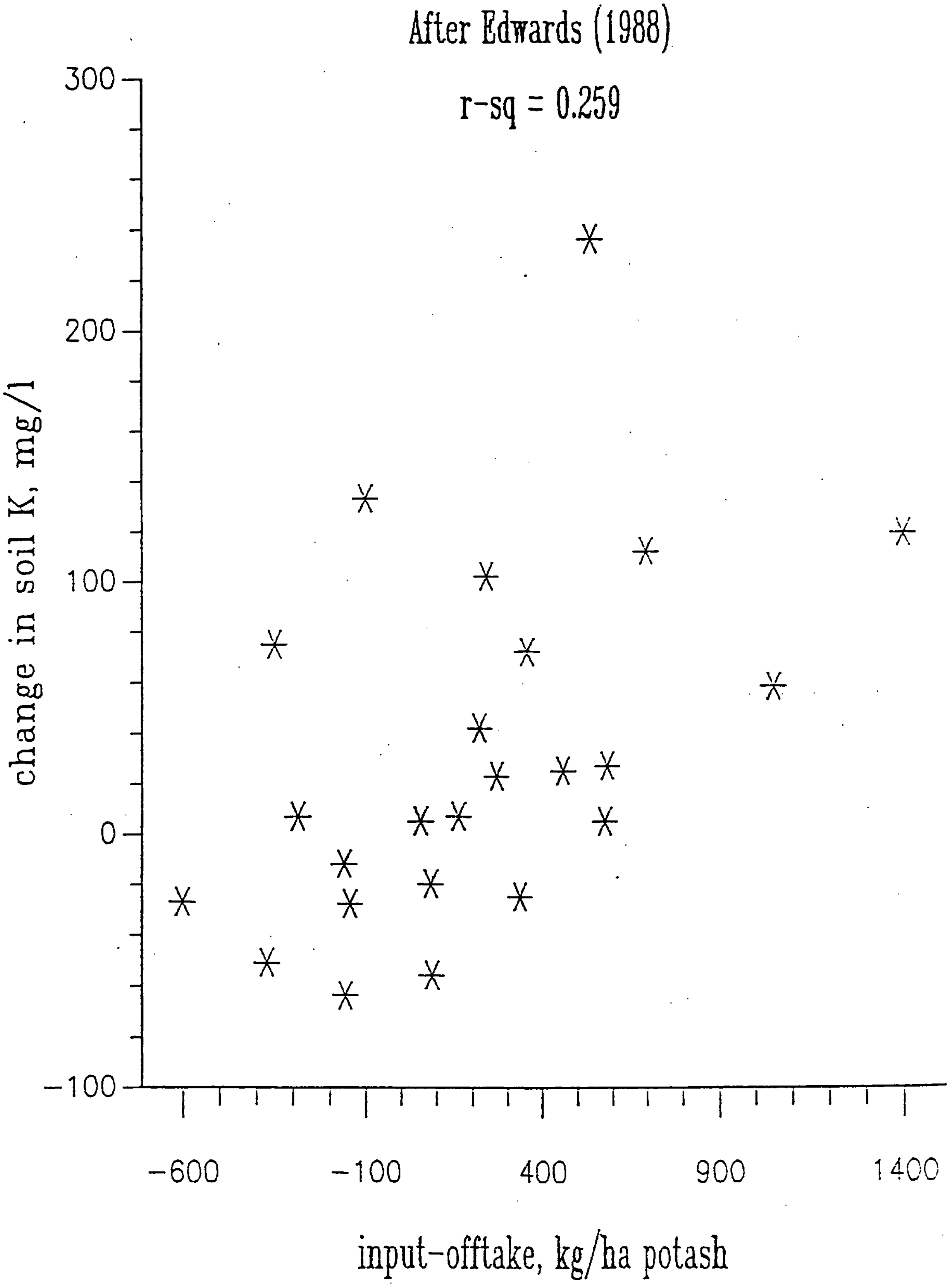
important point to note was that chalky soils behaved no differently from non-calcareous soils (see Section 11.4).

Turning her attention to potash, Edwards in 1988 (Private comm.) examined the K balance and soil analytical data from six long-term trials, already briefly described in Section 7.2.7. Measurements of 'available' K (mg K/l) plotted against input minus off-take data for K_2O (kg/ha), shown in Figure 3, give some indication of the amount of potash required to increase soil reserves. The relationship is weaker than that obtained for phosphate, with $r^2 = 0.26$, which is, no doubt, mainly explained by the way in which K can behave in soils, with both topsoil and subsoil involved. For the heavier soils in question there is an indication that between 400-600 kg K_2O/ha is required to raise the soil K level by one Index 'unit', however, the main conclusion is that different soils may be expected to cover a wide range of K supplying characteristics which are usually difficult to predict.

11.3 TIMING OF P AND K APPLICATIONS WITH SPECIAL REFERENCE TO FERTILISING ON A CROP ROTATION BASIS

In all the early trials examining the response of cereals to P and K, the fertiliser was either applied to the seedbed and worked into the soil or combine drilled. Combine drilling only showed an advantage with phosphate on low P status soils; the advantages of combine drilling with potash were small (Webber *et al.*, 1968; Devine and Holmes, 1964). The trials confirmed that response to P and K was most likely on soils of low P or K status, as established by soil analysis, and on such soils seedbed applications were necessary, usually well mixed into the soil (Boyd *et al.*, 1972). For cereals which were generally non-responsive to P or K, the aim of fertilising was to maintain current levels of available nutrients which in most cases was simply to match inputs with off-takes. As discussed in Chapter 7, such a policy is usually satisfactory for maintaining soil reserves. When soil reserves were high enough to make response to P and K in cereals most unlikely, researchers concluded that dressings could be applied every 3, 4 or 5 years.

Figure 3. Effect of Potash on Soil K Reserves



Several field trials have examined this concept of 'rotational manuring', as described below.

11.3.1 Clare and Caldwell (1972) reported on an experiment at Boxworth EHF on a low P status soil, of ADAS Index 0, which compared superphosphate and basic slag at 56 kg/ha P_2O_5 applied annually and 281 kg/ha P_2O_5 applied at the beginning of the experiment. After five years it was concluded that a single large application of P was as effective as annual dressings for winter wheat, spring wheat and spring barley even on the low P status soil. Responses to P at the site were small over the first four years but response was large at 0.69 t/ha grain in the 5th year.

11.3.2 The effects of several rates of phosphate on crop yields on a rotational experiment done over the years 1960-70 at Terrington EHF were reported by Eagle (1974). The rotation, involving potatoes, winter wheat, sugar beet, spring barley and spring beans, was started at different times on the 3 blocks of the experiment. The potato crop was the most responsive on the silty loam, giving significant yield responses every year except 1963 even though the soil P status as assessed by soil analysis was high when the experiment started. No response occurred in sugar beet until 1967. With barley and beans there was no response to phosphate at all. With wheat the only significant response occurred in the final year of the trial. In view of this general lack of response in cereals it was concluded that on soils of high available P status, maintenance applications of phosphate about every 4 to 5 years applied to the most responsive crop, which in this case was potatoes, should be quite satisfactory.

11.3.3 Harris and King (1985) reported on the results of a P and K trial comparing annual (56 kg/ha P_2O_5 and K_2O) and triennial (168 kg/ha P_2O_5 and K_2O) applications to continuous barley grown on a shallow calcareous silty loam over chalk between 1967 and 1977. Treatments were repeated in three successive years. Similar yields were obtained regardless of whether the P, supplied as triple superphosphate, and K were applied annually or triennially. Basic slag which was also tested in the trial was not as effective. The loss in yield on the zero phosphate and potash treatments increased from about 0.2 t/ha in the first two years to approximately 2 t/ha in 1975, but in the last two years the yield depression was about 1 t/ha.

It was concluded that rotational manuring was a feasible option at this site. However, it was noted that there was a trend towards a lower yield in the third year after rotational applications, supported by evidence of lower leaf K levels, so it was suggested that potash should not be applied at intervals greater than 2 years. Applications of phosphate, however, could probably be safely applied at longer intervals.

11.3.4 Palmer and Stevens (1982) reported on the practice of rotational manuring following experiments using three 3 year rotations involving sugar beet and two cereals between 1973 and 1981 at the Norfolk Agricultural Station. Treatments were as follows:

Nutrition and Timing kg/ha	Rotation		
	Sugar beet	Cereal	Cereal
P_2O_5 Rotational	139	-	-
Annual	63	38	38
K_2O Rotational	227	-	-
Annual	151	38	38

At the start of the experiment the P Index stood at 2 (21 mg/l) and the K Index at 1 (115 mg/l) on the sandy loam over chalky boulder clay. Crop responses, meaned over the three rotations are shown in Table 6. Comparing soil analysis at the start and end of the trial, plots receiving no P and K had declined in reserves to P Index 0 (9 mg P/l) and K Index 1 (70 mg K/l). The P and K applications reduced the decline but were insufficient to maintain starting levels. Yields averaged over the three rotations showed that there were no differences between annual and rotation dressings. The authors concluded that provided that initial soil indices were well into Index 2 for P, and Index 1 for K there would be adequate nutrient reserves in this and similar soils to permit a policy of triennial manuring on an off-take replacement basis without loss of yield.

Table 6 Mean crop yields over three rotations at NAS (after Palmer and Stevens, 1982).

	Sugar	Cereal (1)	Cereal (2)
	t/ha	t/ha grain	
	(+0.127)	(+0.077)	(+0.088)
Phosphate			
Nil	7.36	5.96	6.01
Annual	7.53	6.04	6.24
Triennial	7.61	6.06	6.28
	(+0.098)	(+0.060)	(+0.069)
Potash			
Nil	7.20	5.89	6.04
Annual	7.66	6.01	6.08
Triennial	7.68	6.06	6.16

Cereal (1): Winter wheat - spring barley - winter wheat
Cereal (2): Spring barley - spring barley - winter wheat

It was, therefore, concluded that rotational manuring is a safe alternative to annual dressings for cereals when soil nutrient reserves are adequate.

11.4 RESIDUAL P AND K VERSUS FRESH FERTILISER APPLICATIONS

As discussed by Johnston and Mattingly (1976), it is now quite widely accepted that in many soils no conventional amount of fresh P fertiliser addition can substitute for useful P residues which have been built up over many years. Although the build-up of useful P residues often involves the judicious use of lime as discussed by Hayes (1984), there is a common belief that water-soluble P is transformed into residues of little or no value in calcareous soils. This view probably stems from the known very low solubility of the more basic calcium phosphates, particularly hydroxyapatite, which is a predictable product of so-called reversion to insoluble form of water-soluble P added to calcareous soils. In fact, the bulk of the practical evidence shows that there are no clear differences in the P solubility relationships in calcareous soils and in near neutral and slightly acid soil types.

Barber (1985a) stressed the P uptake is a complex of chemical and biological processes and P flux into the root is a dynamic process implying that P in soil near roots is unlikely to reach an equilibrium state. Calcium accumulates around growing roots, brought by mass follow, and this in theory should reduce the solubility of P. This, with the significant rise in pH around roots when nitrate is the main form of N, should tend to reduce P uptake. Hoffmann and Barber (1971) investigated the effect of Ca accumulation on P uptake by wheat from four soils and found that on soil with pH above 6.8 addition of gypsum reduced P uptake. The higher pH soil contained solid phase calcium phosphates and the common ion effect would be expected to reduce P in solution. It is interesting that there is at least circumstantial evidence for the accumulation and persistence of octacalcium phosphate, which is more soluble than hydroxyapatite, in high P status soils; so long as there is some present the concentration of P in the soil solution does not seem to fall below 1 mg/l, which is an adequate concentration for cereals. From studies on the inhibition of hydroxyapatite precipitation in the presence of humic and related acids, Inskeep and Silvertooth (1988) concluded that the sustained oversaturation of many soil solutions with respect to hydroxyapatite may be due to the presence of organic matter.

For many years P fixation was regarded very much as a surface phenomenon of certain soil colloids, but more recently P has been regarded as sinking into some types of soil colloids (Barrow, 1983), and then very slowly diffusing out when the concentration gradient is reversed. For practical purposes it is important to know whether the P status of soils drift downwards on uncropped soil when no fresh dressings are given, as found at Saxmundham by Johnston *et al.* (1986) or become more or less stabilised as tends to be the case at, for example, Rothamsted. There is at present insufficient information available even to provide clues about an explanation for such differences but it might be worthwhile bearing in mind the possibility that relatively young soil colloids (Saxmundham) may be more disordered, and hence more porous to P than are much older, more highly weathered, soil colloids (Rothamsted).

It has already been stated that placement of P is the recommended technique for making the best use of P fertiliser on P deficient soils. Although it is not likely to become a widespread practice in the UK, the possibility of including P in cereal sprays to combat transitory P deficiency should also be borne in mind. There may be occasions on soils of low P status, particularly when rotations are in take-all susceptible phases, when it might be advantageous and relatively easy to boost P levels in plants by foliar application.

12 NUTRIENT INTERACTIONS - AND THE NEED FOR BALANCED CEREAL NUTRITION

In field situations the main need is to arrive at a satisfactory balance of P and K in relation to other nutrients, particularly N. Now that field responses of cereals to P in this country are uncommon in the main cereal growing areas it is difficult to obtain information on the N and P interaction using modern high yielding varieties.

Sumner and Farina (1985), working with maize, drew attention to the fact that N and P interaction effects on yield are primarily attributable to N-induced increases in P absorption. They discussed the interaction of P with several nutrients for a range of crops and concluded that at least for maize, the leaf P concentration at flowering was found to be closely related to the final yield of grain. However, as stated in Section 10.7, it may be difficult to interpret the significance of total P concentration in cereal foliage without knowing its N concentration.

Regarding the N and K interaction in cereal production, there has been considerable interest and some uncertainty about the subject. It is generally agreed that adequate K is needed for both the uptake and utilisation of N. Although on the one hand the idea of luxury uptake of a nutrient, including K, is generally recognised as a likely occurrence on nutrient rich soils, on the other hand, even given a large supply of available K, there is evidence the plant absorbs only the quantity required for the full utilisation of the N which is taken up. The conclusion reached by Nair and Talibudeen (1973) that N and K uptakes by wheat under field conditions are cyclical, with the rates of uptake of the two nutrients periodically accelerating and peaking several days apart, confirms the existence of a strong link between K and N. With regard to maximising N uptake, it is interesting that McEwen and Johnston (1979) found that increased uptake of nitrate from depth was stimulated by high K levels in the sub-soil. According to Boyd (1975) there have been instances in which for barley (and potatoes) the addition of more K fertiliser can so increase the efficiency of N use as to double the yield while halving the N requirement.

It has already been mentioned that cereal growth tends to be influenced by checks and balances with 'feedback' from the tops to roots and, no doubt the opposite, playing an important role. This applies to such features as tillering, number of grains set per ear, grain size, form and extent of root system, to mention but a few. For example, Forster (1982) described how oats were able to increase the size of the root system when grown at rather low K status, so in a field situation the crop is able to exploit subsoil K as well as searching topsoil more thoroughly. This is one example of how plants behave very differently in a field situation as compared with their behaviour when confined in pots. Sumner and Farina (1985) have recently drawn attention to the fact that most nutrient interaction studies have been done in pots, or even in culture solution, mainly because of the high cost of multi-level factorial experiments in the field.

It is highly likely that some of the confusion which exists about the interaction between N and K in cereal production stems from the very different ways in which various studies were done. Steineck and Haeder (1978) pointed to the very different results obtained when the N and K interaction was studied in pots and under field conditions. Whereas under field conditions in Austria they found grain yield of spring barley was increased through plant population as a result of additional K, Forster (1976) working on spring wheat in pots found no effect on plant density but increased numbers of grains per ear and increased 1000 grain weights at the highest K rate. Such findings demonstrate the difficulty of extrapolating to field conditions the results of many studies including those of MacLeod (1968) who found a strong N and K interaction in barley grown in culture solution.

It has to be accepted that the average results of a number of fertiliser response trials done in a region can only apply to the average field within each division of estimated nutrient status which, in fact, in most arable systems is usually no better than 'low', 'medium' or 'satisfactory', corresponding approximately to ADAS Indices 0, 1 and 2+. As stated by Cooke (1982) average advice is rarely applicable and 'it must be improved by adjusting fertilising to the local supply of nutrients in each field and to the crops' potential'. It is now accepted that on very many soils it is more important to get the P and K status adjusted on a rotational basis than to attempt to get the inputs exactly correct crop by crop. This is, of course, especially true of situations where there is a danger of hypomagesaemia, which are usually the same situations where large removals of nutrients occur in fodder crops - hence the vital role of balance sheets, especially for K. Cooke (1982) states that farmers should aim only to get near the optimum inputs of P and K and there is no need to change fertiliser inputs continually to try to allow for small changes in fertility or prices - seasonal effects will always have a large effect on the fertiliser responses and weather cannot be forecast when crops are sown. To a considerable extent cereals, with their normally extensive and efficient root systems, can thrive on the residues of P and K applied to the more responsive crops in rotations. Nevertheless, there is still a strong tendency among growers to apply both P and K annually, from which small benefits - though difficult to prove through normal field experimentation - are sometimes obtained.

There is no doubt that some cereal crops show signs of magnesium deficiency, especially during the early growth both on some acid and on some chalky soils. As is well-known, the condition can be aggravated by raising the K status of soils. However, there is as yet little evidence to show that final grain yields are adversely affected by magnesium deficiencies. It is now customary to use dolomitic limestone when magnesium levels in acid soils are low, but yield increases and other benefits of adding magnesium seem to be obtained in the non-cereal sector, including, of course, in livestock enterprises.

13 CONCLUSIONS

13.1 Hundreds of field trials done over the last 30 to 35 years have shown that cereals are not very responsive to P and K fertiliser applications when grown on most soils in the UK. Much of the older response work was done with relatively low yielding varieties and with moderate nitrogen inputs but even the more recent trials involving higher grain yields have supported the conclusion that responses to P and K are usually small.

13.2 Large responses to P or K are more likely - but by no means guaranteed - on soils which are low in 'available' P or K reserves. The main use of soil analysis is to identify such soils. Once soils are moderately to well supplied with P and K there is not always a strong correlation between responses and the measured soil levels of P or K. It is therefore best to use soil analysis to gauge *likely* response to P or K fertiliser applications. Thus using ADAS Indices:-

Index 0 - response probable
Index 1 - response possible
Index 2 and above - response unlikely

Treated in this way, soil analysis has greatly helped and will, no doubt, continue to help in formulating fertiliser policies.

13.3 In individual long-term fertiliser experiments, soil analysis can identify the effects of previous manuring practices, being almost invariably able to pick out lower and higher manuring regimes. This is not surprising because individual experiments are usually done on one soil type and most methods of soil analysis are discriminatory on particular or closely related soil types. The fact that correlations between the results of routine soil analytical data and P and K responses in cereal crops tend to be generally weak could be due to a number of factors including:-

(a) cereals are not usually very responsive to P and K and small effects are often overshadowed by experimental errors,

(b) seasonal and site effects, including the physical condition of soils, play an important part in determining crop responses,

(c) soil samples for P and K analysis are usually taken to a depth of 15 cm whereas cereal roots can draw on nutrient reserves from considerably greater depths,

(d) as apparent from mechanistic modelling studies, nutrient uptake by roots is complicated and influenced by several interacting soil factors other than those directly linked to estimates of the sizes of 'available' pools of P and K, which come from so-called routine single figure soil analyses.

If greater precision is being sought in the control of crop nutrition, so it must be realised that a single set of 'index ranges' used for the interpretation of soil analytical data obtained by a particular method may not necessarily serve for very different sorts of soils.

13.4 Optimum timing and methods of application of fertilisers depend on soil nutrient reserves which are already present. For soils with low reserves of P, combine drilling of phosphate fertiliser is the most effective method of application. This may also be the case for potash on some low K status soils. Combine drilling is no more effective than broadcasting on soils possessing larger nutrient reserves.

13.5 Because the response of cereals to P and K is small on most soils, the policy on all but low residue soils is to maintain current reserves by applying maintenance dressings, the proviso being that reserves can sometimes be sufficient to enable cereal growers to dispense with maintenance dressings for a while. Crop off-take of nutrients will depend mainly on yield and the method of straw disposal. There are differences in the potash contents of barley and wheat straws, amounting to 2 or 3 kg/tonne, and this is recognised in the latest ADAS recommendation for calculating K off-takes, bringing it into line with Scottish experience. Growers on very sandy soils cannot expect to adopt a build-up and maintenance approach to K manuring, which depends upon soils possessing adequate K buffer power, but they should rather plan to meet the needs of each crop in turn. This need not be the case with P because many quite sandy soils do possess appreciable P buffer capacity.

In some soils, particularly among the heavier type, even after years of P fertilisation, there is a tendency for slow just detectable P fixation to occur, leading to the need for larger than mere maintenance applications of P calculated on a balance sheet basis. In contrast, where releases of plant available K from mineral reserves or uptake from the subsoil occur, then K fertiliser requirements can drop below estimated removals. Nevertheless, in the first instance, any removal of K from soil must be seen as constituting a drain on reserves - which may or may not be justified in the longer term.

13.6 Soil reserves of P and K, as measured by most routine methods of soil analysis, change only slowly in the majority of soils, even when no phosphate and potash are being applied. This has both good and bad implications for growers. If growers wish to reduce fertiliser inputs for low response crops such as cereals grown on high Index soils, they can do so without a rapid decline in soil nutrient reserves. Conversely, if soils are low in plant available P and K it will take large quantities of the nutrients, normally applied over many years, to raise the fertility. On some soils, extra large single fertiliser applications tend not to match the benefits which come from the presence of adequate reserves of P and K built-up over many years. On most well-managed fertilised soils it is not worthwhile having soil analysis for P and K done more often than every 4 or 5 years. However, one of the more important functions of soil analysis is to establish long-term trends, for which the technique is well suited.

13.7 Once adequate soil reserves of P and K exist there is much flexibility in the timing of fertiliser applications, with manuring once in a crop rotation often being satisfactory. Obviously there are advantages in applying P and K to the most responsive crops grown in any rotation and basing long-term fertiliser policy on balance sheets for P and for K on a field by field basis. For cereals in England & Wales the ADAS calculated off-take of P_2O_5 per tonne of wheat or barley grain at 85 per cent dry matter is 7.8 kg and 1.6 kg/tonne for straw, which are almost identical to the figures used in Scotland. Whereas in the past ADAS has not differentiated between potash off-takes in wheat and barley straws, the present estimates of potash removals in wheat and barley straws are 9.3 and 12.6 kg K_2O/t, respectively, which come very close to Scottish experience. Those farmers who apply P on an annual basis to soils which may lead to responses to the nutrient are most likely to benefit in cold wet springs, and under such conditions the regular annual application can be seen as an insurance.

13.8 Comparatively little use has so far been made of plant analysis for assessing the P and K status of cereal crops in the UK, mainly because the timing of sampling is such a crucial matter and the chance of the misinterpretation of data has been regarded as high. It is now recognised that expressing the K concentrations in the actively growing vegetative parts of cereals on a tissue water basis, rather than on a dry weight basis, can overcome some of the difficulties of interpretation which arise from the natural maturing of the crop. Viewing the K concentrations in developing cereals on a tissue water basis does recognise the metabolic role of K as an important osmotic influence and charge carrier as compared with P, much of which becomes incorporated into the organic constituents of the plants.

According to Leigh and Johnston of Rothamsted Experimental Station the concentrations of K on a tissue water basis in spring barley over the whole period between tillering and flowering can be from around 70 mmol/kg on K-deficient soil to about 200 mmol/kg on K-sufficient soil. However, the actual benefits of levels much above 100-130 mmol/kg of tissue water are not yet clear when viewed in terms of yield, grain quality, possible enhanced disease resistance and resistance to lodging.

Unfortunately, within the limits of existing knowledge, information about the K concentration in the tissue water of cereals does not yet on its own offer a relatively quick and easy way of cross-checking on the K status of crops. This is mainly because lack of K can be compensated by increased calcium, magnesium and sodium uptakes as well as by some modification to the sugar metabolism of plants. In particular, greater calcium uptake occurs in place of K and it seems that some of the benefits of correcting K deficiency may arise from reducing calcium intake. It would seem to be a matter of some urgency that gaps in knowledge in this sector are filled, especially as K through its effect on stomatal control is capable of optimising both water use and photosynthesis.

Insofar as the P status of plants is concerned, there is evidence from studies on maize to suggest that P concentrations in foliage - expressed on a simple dry matter basis - can only be properly interpreted when examined along with nitrogen concentrations, possibly in the form of products, N x P. There is, however, an alternative to using determinations of total P in plant material for reflecting plant P status, which involves estimating the inorganic or acetic acid-soluble P in the growing plant (traditionally referred to as tissue testing), which deserves a re-examination for field use. With any form of plant analysis for diagnostic purposes, it is important to establish that crops are supported by satisfactory root systems, which require reasonably well structured, adequately drained soils, otherwise low nutrient uptake may be quite wrongly taken to indicate inadequate nutrient supplies in the soil.

If it is accepted that single figure soil analyses for P and K cannot be expected to allow for differences in some of the soil factors involved in the delivery of nutrient ions to plant root surfaces, then appropriate plant analysis might profitably be brought in to get round the difficulty, with plant analysis being used to cross-check on the significance of routine soil analytical data on a site-specific basis. Such an approach involving occasional soil and plant analysis would seem to have the potential to provide confirmation that an existing system of fertilising, particularly on a rotational basis, is sound or not.

Most P and K fertiliser policy problems in the cereal sector fall under two headings, both concerned with maintenance dressings. The first centres on doubts about whether soils have ceased to be responsive and hence whether or not a strict regime of maintenance dressings is adequate. The second concerns the uncertainty that a maintenance policy of intermittent P and K dressings, once or twice in a rotation, is sufficient to keep soil in the required unresponsive state. It is in these connections that some plant analysis could prove more helpful than yet more soil analysis.

13.9 Although there is much evidence to sustain the view that cereals are not particularly responsive to K fertiliser applications, there is appreciable evidence that adequate available K in soil stimulates nitrate uptake by the crop, with the added corollary that adequate K in subsoil can stimulate the uptake of N from the subsoil - which, if it is generally true, is both economically important and environmentally important. Some of the confusion which exists about the N and K interaction in cereal production stems from the fact that some of the findings from greenhouse and water culture experiments do not necessarily apply to field situations.

13.10 Even though adequate K in soils has for many years been associated with more disease resistant cereal crops, there is not much scientific evidence to support this other than that which came from incidental observations of differences between K-treated and untreated plots. There is, in fact, very little data concerning relationships between possible enhanced disease resistance and the actual chemical composition of cereal plants.

13.11 Without occasional measurements on soils and/or growing plants it is most unlikely that a control of P and K inputs can be obtained in rotations involving cereals. Growers whose holdings carry ruminant livestock face a much more difficult problem with their K fertiliser use than those in the purely arable sector because of the dangers of hypomagnesaemia. Hence it is to be expected that, on average, they should benefit most from guidance emerging from appropriate K analysis on soils and crops. For maintenance purposes the whole of the P and K in animal slurry and other organic manures can be rated as effective, as in appropriate inorganic sources of P and K.

13.12 Although there are well-known differences in the ways in which different cereal species react to soil conditions, for many of the more general purposes of P and K nutrition all cereals except maize can be grouped together. In terms of detail, however, there are discernible differences such as spring barley requiring a higher P status than winter wheat, a point which may not be very widely appreciated.

Mention is made in the review of several procedures which though not necessarily suited for routine use, are well suited for more detailed soil studies relevant to assessing the P and K fertiliser needs of crops, particularly on a long-term basis.

14 RECOMMENDATIONS FOR FURTHER INVESTIGATIONS

14.1 It is recommended that soil analysis should continue to provide the main means of identifying the need for P and K fertilisers in the cereal sector, but that more attention be given to the possibility of using a better mix of soil analysis and plant analysis for identifying deficiencies and checking on the long-term efficiency of fertiliser policies. If greater use is made of plant analysis, then checks on the size and health of root systems becomes even more important, otherwise data obtained from plant analysis could so easily be misinterpreted. Once a satisfactory control over P and K status is achieved, the use of nutrient balance sheets on an individual field basis is recommended as an aid to identifying the size of maintenance inputs of P and K.

14.2 There are good reasons why K concentrations in growing plants up to the grain filling stage should be expressed on a tissue water basis, rather than a dry matter basis. However, more experience is needed before the significance of this type of data can be fully exploited. It is recommended that quantitative data on relationships between final grain yield and levels of K (and sodium) in plant tissue water from tillering to flowering be obtained as a matter of urgency. Such data - which is much needed both to help with the solution of immediate problems and with the identification of future profitable lines of detailed research - might come from additional measurements on plant samples from existing field plots. In the longer term the effects of different levels of K and Na in plant tissue water might profitably be extended into studies on possible enhanced disease resistance, increased resistance to lodging and, particularly, the optimisation of both water usage and photosynthesis by cereals. There seems little doubt that a satisfactory understanding of these aspects of cereal nutrition will require more detailed studies on the distribution and function of K, sodium, calcium and magnesium in the different types of plant cells.

14.3 Despite the fact that soil analysis has served many growers extremely well, especially insofar as assessing P status is concerned, it is suggested that greater use of plant analysis could reduce uncertainties about P status (a) where P status may be below optimum, particularly for spring sown crops, and (b) where a single set of 'Index' ranges for the interpretation of soil analytical data may not be satisfactory for very different sorts of soils. It is recommended that effort be made to examine the relative merits of three different approaches to cereal plant P analysis, namely, P concentrations expressed on a simple dry matter basis, P concentrations coupled with total N concentrations e.g. N x P, and finally, a method of analysis involving the estimation of the inorganic P concentrations of the developing cereal plant, traditionally referred to as 'tissue testing'. At present there is very little easily accessible data on the P concentrations in developing cereal crops grown in the UK.

14.4 More research is needed to help in the identification and characterisation of soil colloids which are capable of continued slow immobilisation of P despite generous phosphate fertilisation in the past.

14.5 In the light of advisory experience that the incidence of take-all can be exacerbated by soil acidity and low soil P status, it is recommended that the benefits of P placement be re-evaluated particularly when rotations are in take-all susceptible phases. In a similar context, the inclusion of phosphate in cereal sprays to combat transitory P deficiency - by foliar application - is currently viewed as a matter for further debate and possible testing in the field.

14.6 Although the roots of cereals are regarded as very efficient at taking up nitrate, it seems desirable that the influence of different K levels in soil and subsoil on nitrate uptake and utilisation be quantified in more detail. Apart from the hope that the results of such studies would contribute towards improving the recovery of N in arable systems, they may be of special relevance to the management of soils under systems of minimum tillage. It is recommended that caution be exercised in the interpretation of data concerning N and K interactions which have not been studied under field conditions.

14.7 Because much of the past work on responses of cereals to P and K has been concerned with low yielding cereal crops it is important to extend the enquiry into high yield situations, examining particularly the use cereals make of accumulated soil reserves of P and K. Such relatively long-term studies would need to be coordinated nationally, involving a range of soil types and cropping systems, making use of facilities and back-up mainly available at appropriate ADAS experimental husbandry farms, college farms and research stations.

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